ERUPTIVE HISTORY AND LONG-TERM BEHAVIOR OF KILAUEA VOLCANO

By Robin T. Holcomb

ABSTRACT

Long-term variations in Kilauea's eruptive behavior are revealed by mapping, paleomagnetic dating, and morphologic analysis of the surficial lava flows.

About 70 percent of Kilauea's surface is younger than 500 years, about 90 percent younger than 1,100 years. Much of its present caldera dates from the 18th century. An earlier caldera collapse about 1,500 years ago was followed by an eruptive hiatus outside the caldera until summit overflows began about 1,100 years ago.

Kilauea's surface is dominated by the products of sustained eruptions; it consists of 67 percent tube-fed pahoehoe, 14 percent surface-fed pahoehoe, and 16 percent aa. Eruptions are sustained longer at the summit and are briefer along the rift zones away from the magma reservoir beneath the summit. More than 50 percent of Kilauea is still covered by lava flows from long-sustained eruptions at the summit, despite an absence of such overflows in the last 250 years. Local variations in eruptive behavior along different rift structures probably reflect different connections to the principal reservoir.

Changes in eruptive behavior have occurred over intervals of decades and centuries. Some changes have been repeated, and some appear to have been evolutionary. Two caldera collapses and accompanying large explosive eruptions have been followed by intervals of little activity along the subaerial rift zones. Rift activity waxed as summit activity waned, and one waxing sequence resembles an evolutionary progression: rift eruptions, at first brief and widely separated in time and space, gradually became frequent along restricted segments of the rift zone and culminated in sustained activity at localities progressively farther from the summit. The current rift-zone activity resembles that which occurred in the 18th century preceding the explosive eruption of 1790.

The causes of long-term eruptive variation remain undetermined, though shifts in the sites of principal magma storage are probably involved. Slow development of integrated plumbing along the rift zones is probably interrupted by sudden subsidences of the summit and the unbuttressed south flank. Possible behavioral models are classified as evolutionary, cyclical, and stochastic; they differ greatly in their implications on long-range forecasting.

INTRODUCTION

By the early 1970's it was clear that an eruption history of Kilauea Volcano was needed for the period preceding the 19th century. The Polynesian oral history had been lost early in that century, and only a few scattered traditions had survived. During the following one hundred years Kilauea's eruptive behavior had shown little change, being nearly continuous and almost completely restricted to the caldera (fig. 12.1*A*). As a result, rift eruptions were thought rare and volcanic hazards small, and the Puna District was extensively developed (fig. 12.1*B*). However, summit activity had become episodic after collapse of Halemaumau and explosions in 1924, and a flurry of rift eruptions began in 1955. Continued rift activity through the 1960's raised the possibility of a higher long-term eruption frequency outside the caldera and of consequent greater hazard (fig. 12.1*C*). When I joined the staff of the Hawaiian Volcano Observatory in 1971 I began to reexamine the risk and the usefulness of the historical record for assessing it.

One impediment to study of long-term eruption histories had been a feeling that they could tell little about future behavior. According to the idealized life history of Hawaiian volcanoes (fig. 12.2), a shield undergoes distinct developmental stages, including a youthful growth stage and a mature caldera stage. The caldera develops when magma supply can no longer overcome a tendency for the summit to founder (Macdonald, 1965). Though eruptions may continue vigorously for some time afterward, caldera formation marks the end of shield growth. According to this view, Kilauea had recently entered its mature stage; behavior preceding caldera formation differed from that occurring now, so little could be learned about present hazards through study of precaldera events.

Powers (1948), however, had inferred that an ancient caldera was filled and buried before the present one formed. If there had been one earlier caldera there could have been many; perhaps the volcano had no distinct shield-building and caldera stages but underwent repeated caldera collapse and filling as it grew (Holcomb, 1976b). If so, Kilauea might continue to grow long into the future, and events that occurred before caldera formation might be repeated. In particular, collapses might interrupt dikes transporting magma into rift zones (Fiske and Jackson, 1972) and thereby cause changes in long-term eruption patterns. If repeated patterns occurred, they might tell much about the operation of the volcano and lead to better forecasts of its behavior. The work reported here was focused on those possibilities.

ACKNOWLEDGMENTS

Many friends and colleagues have provided assistance. R.L. Christiansen and D.W. Peterson have contributed frequent discussions since 1971. D.E. Champion and M.O. McWilliams collaborated in much of the paleomagnetic work. N.G. Banks, T.C. Casadevall, R.R. Doell, D. Dzurisin, R.M. Easton, P.W. Lipman, J.P. Lockwood, R.B. Moore, and M. Rubin provided unpublished ^{14}C ages, paleomagnetic data, and other information. Contributions were made also by many others, especially the staff of

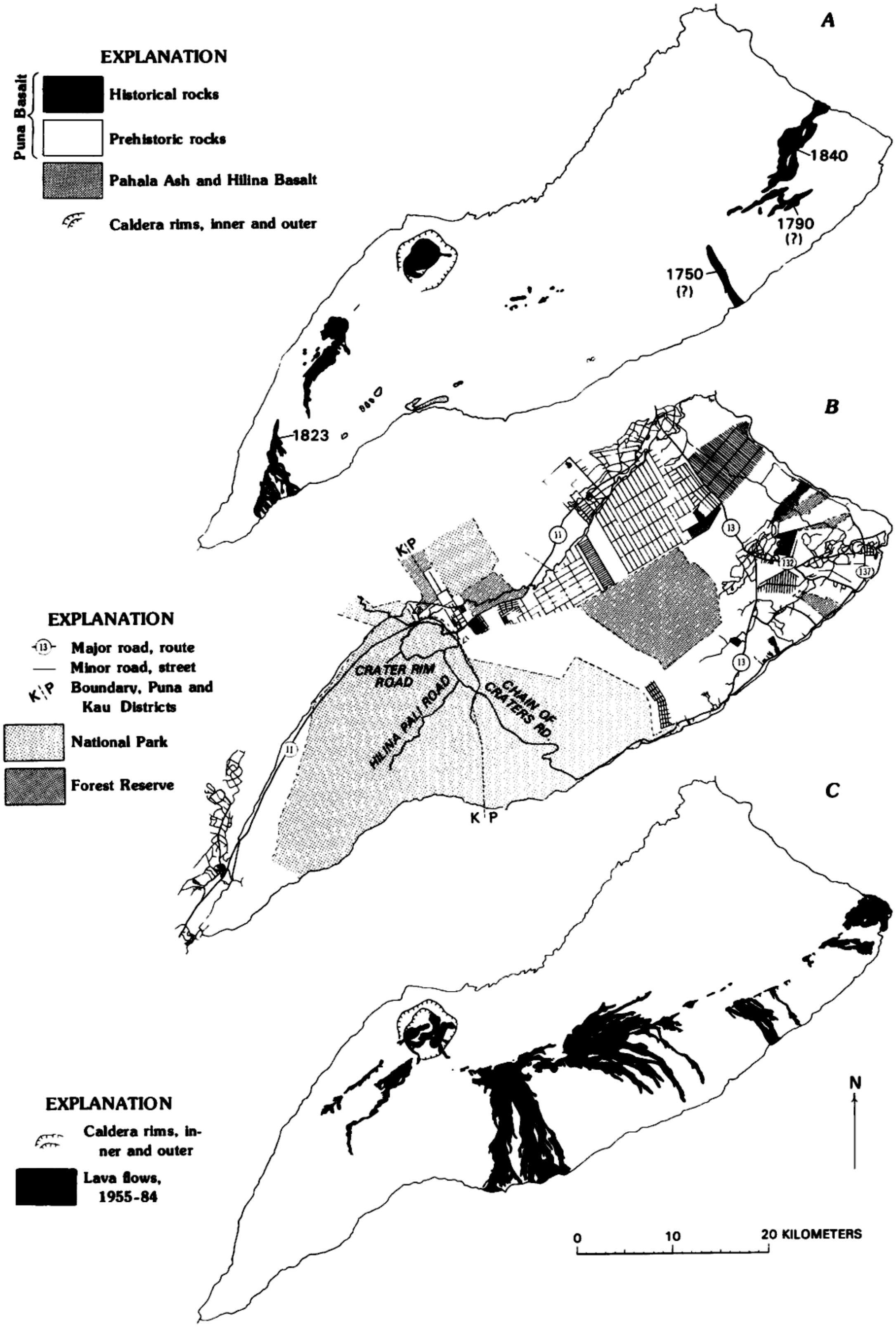


FIGURE 12.1.—Historical eruptions and property development on Kilauea Volcano. ***A***, Stratigraphy of Kilauea, showing historical lava flows erupted before 1954, with dates given for some flows, from Stearns and Macdonald (1946). ***B***, Property subdivisions, developed mostly after 1950. ***C***, Lava flows erupted during 1955–84.

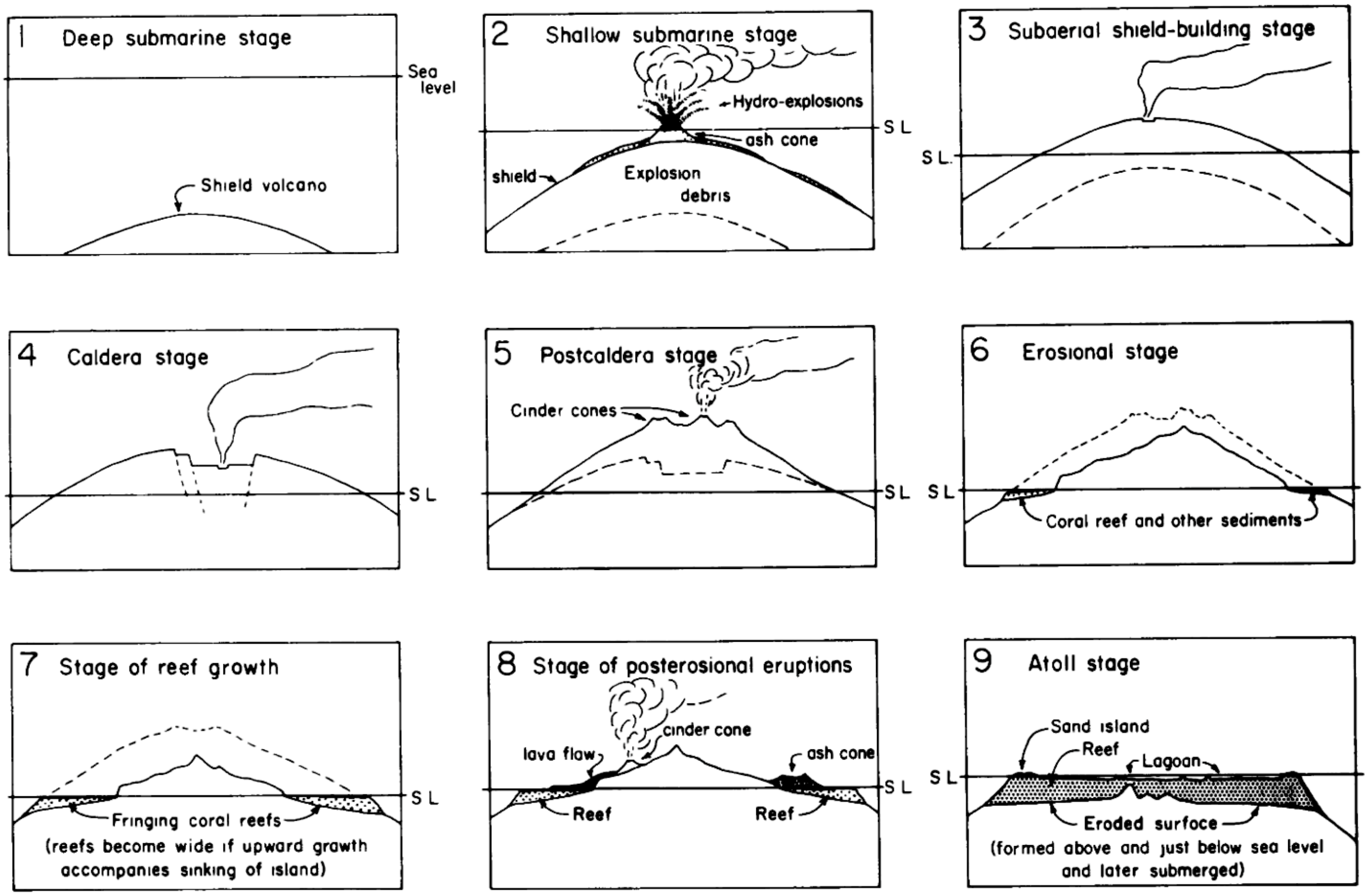


FIGURE 12.2.—Life cycle of a Hawaiian volcano, from Macdonald and Abbott (1970).

the Hawaiian Volcano Observatory, residents of Kilauea, and the faculty and students of Stanford University. Some of the work was supported by a grant from the Piton Foundation of Denver, Colorado. This report has benefited greatly from encouragement by R.W. Decker and reviews by D.E. Champion, R.L. Christiansen, D. Dzurisin, R.B. Moore, and D.W. Peterson. The maps were colored by B.M. Myers, G.R. Stoopes, and D.E. Wieprecht.

PURPOSE AND PROCEDURE

Kilauea's recent history has been surveyed to evaluate long-term eruptive changes. The work has focused on the interval recorded by the surficial lava flows; a tentative history for this interval has been derived from geologic mapping, age determinations, and morphologic analysis of eruption products (Holcomb, 1980b).

GEOLOGIC MAPPING

In order to establish stratigraphic sequences and gather other information, a reconnaissance geologic map of Kilauea's subaerial edifice was made at a scale of 1:50,000 (Holcomb, 1980a; many subsequent illustrations herein are adapted from that map, as indicated in fig. 12.3). Four years of general familiarization (1971–75) were followed by several months of systematic photograph interpretation (1975–76) and three months of ground checking (1977). Emphasis was placed on lava-flow morphology. Standard procedures were adapted to suit the particular goals of the work, time available, and characteristics of the mapped area.

The subaerial part of Kilauea is about 80 km long, averages about 20 km wide, and includes about 1,500 km^2. It is a long, domelike ridge rising to a summit elevation of about 1,240 m (fig. 12.4*A*). The orographic rainfall pattern renders it climatically and

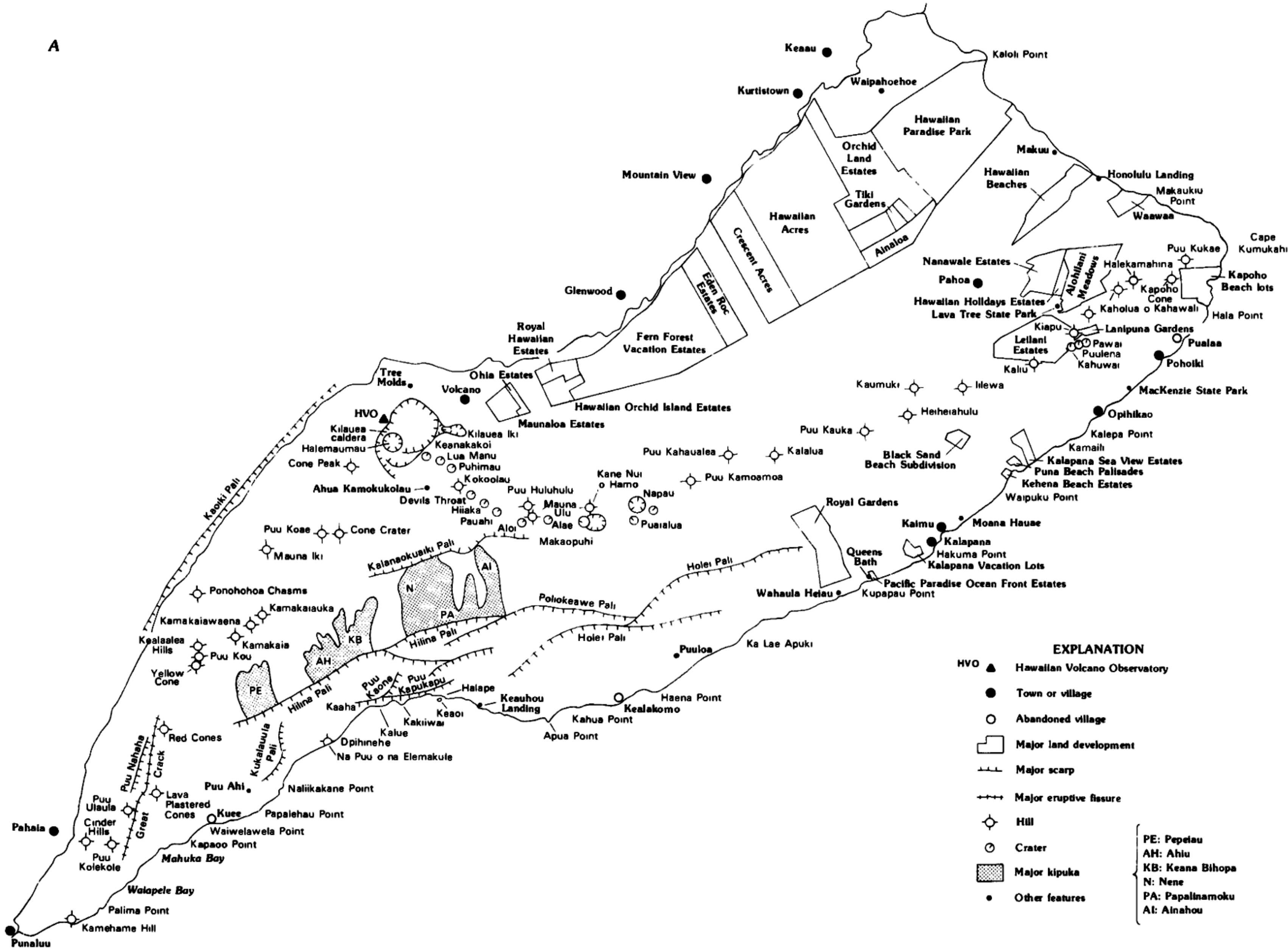


FIGURE 12.3.—Index maps for Kilauea Volcano. ***A***, Some named localities; others are shown on figure 12.5. ***B***, Coverage of map and aerial-photograph illustrations in this report; numbers refer to figure numbers.

B

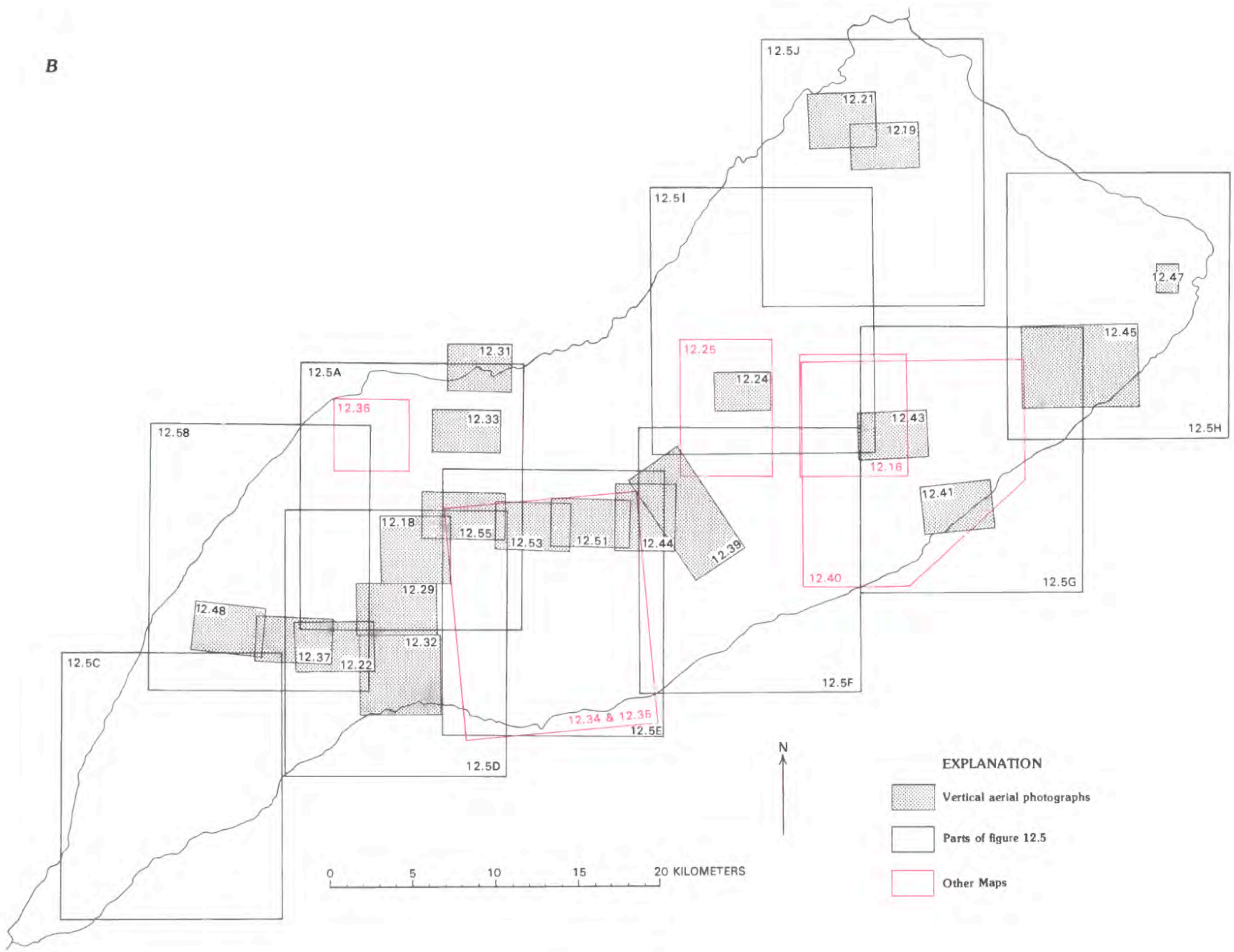


FIGURE 12.3—Continued.

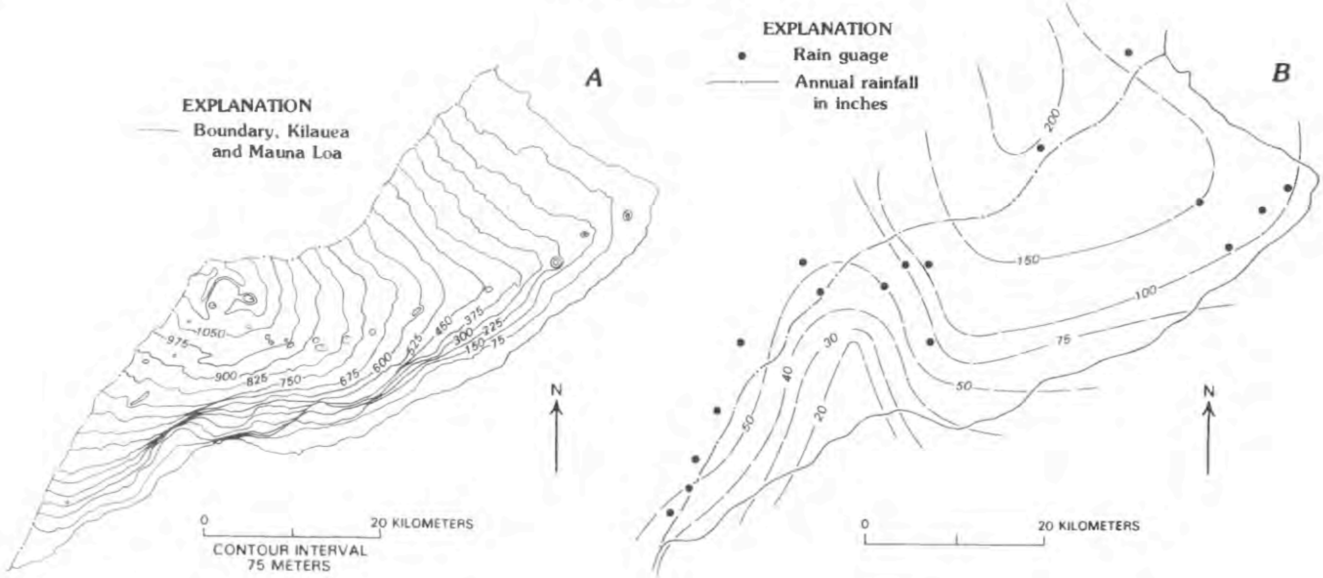


FIGURE 12.4.—Variation of geographic and mapping conditions on Kilauea Volcano. ***A***, Topography. ***B***, Annual rainfall, from Taliaferro (1959). ***C***, Vegetation, from Ripperton and Hosaka (1942). ***D***, Mapping confidence.

botanically diverse, and large parts range from tropical rain forest to barren desert (fig 12.4*B*,*C*). These variations made the mapping procedure very different from one flank to another, and as a result mapping confidence varies widely (fig. 12.4*D*).

A simplified version of the geologic map is presented here as figure 12.5. Though the original is more detailed than maps of most other shield volcanoes, it still represents merely a reconnaissance for the goal of a detailed eruption history.

CLASSIFICATION OF LAVA FLOWS AND ERUPTIONS

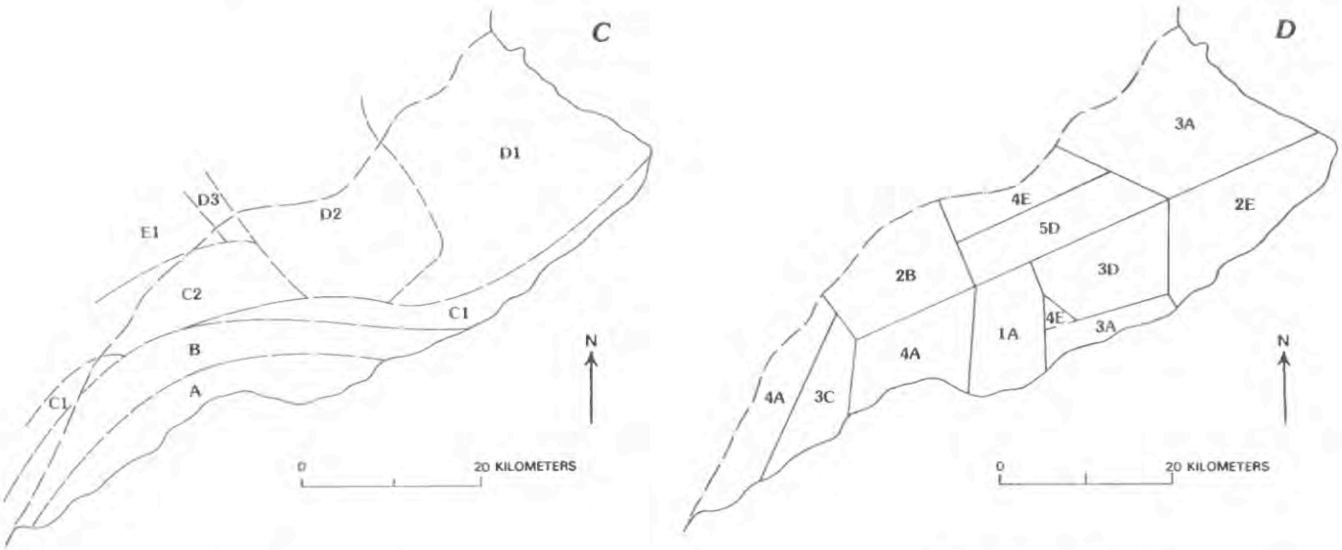
In order to examine more than simple eruption frequencies, the eruptions were classified according to their behavior. This was done through morphologic classification of eruption products (fig. 12.6) using interpretive principles developed during the Mauna Ulu eruptions of 1969–74. The morphology of a lava flow is influenced by the behavior of the eruption that produces it, with sustained effusion leading to a high degree of channelization and formation of lava tubes (fig. 12.7; Peterson and Swanson, 1974). Different kinds of eruptions produce different kinds of vent edifices and flow assemblages (Swanson, 1973; Holcomb, 1976a). Brief eruptions produce small edifices and simple assemblages of surface-fed pahoehoe and aa, while long-sustained eruptions produce large lava shields and assemblages dominated by tube-fed pahoehoe (table 12.1). Eruptions of intermediate duration, several weeks to a few years, typically produce small shields and complex assemblages of all three flow types. The flow assemblages and vent types were used to classify Kilauea's eruptions (fig. 12.8).

DATING

Most of the ages obtained in this work used a paleomagnetic method based on the secular variation of the Earth's magnetic field (Holcomb and others, 1986). Oriented rock samples were collected during four 2-week to 3-week trips in 1978, 1979, 1981, and 1983. Directions of remanent magnetization were measured first at 67 sites on lava flows dated previously by ^{14}C. Most of these sites were on the southeast flank of Mauna Loa (fig. 12.9), where many flows have spread over weathered ash well suited for charcoal preservation (Lockwood and Lipman, 1980). Results from these sites were used to define a history of Hawaiian secular variation during the last few thousand years (fig. 12.10). Kilauea flows of unknown age were then dated by comparing their magnetization with this history of secular variation.

Flows could not be dated precisely using this method, because of dispersion in the results between paleomagnetic sites on lava flows of similar ^{14}C age. Instead, it was necessary to infer approximate ages using a semi-quantitative classification procedure. When directions of dated flows younger than 2.5 ka were plotted on an equal-area projection, they defined fields mutually exclusive in age (fig. 12.11*A*). Undated flows were then assigned ages corresponding to fields in which they fell (fig. 12.11*B*–*F*). The chronology offered here is tentative; refinements in the history of magnetic secular variation will no doubt lead to revisions in the eruption history.

In this report the chronology of Holcomb and others (1986) has been revised using results from paleomagnetic sites not yet published. In paleomagnetic citations that follow, sites prefixed by



EXPLANATION

Vegetation zone	Approximate yearly rainfall (inches)	Approximate altitude limit (feet)	Characteristics of the vegetation: Natural cover	Characteristics of the vegetation: Typical plants
A	20	1,000	Xerophytic shrub with a coastal fringe of trees	Algaroba, koahaole, swollen fingergrass, feather fingergrass, piligrass, bristly foxtail
B	20-40	3,000	Xerophytic shrub with some trees in the upper part	Lantana, koahaole, kiu, cactus, uhaloa, ilima, falsemallow, Natal redtop, piligrass, native panicums, kakonakona
C Low phase (C1)	40-60	2,500	Mixed open forest and shrubs	Koahaole, guava, lantana, Spanish clover, Bermudagrass, kukaipuaa, pilipiliula
High phase (C2)		2,500-4,000	Mixed open forest	Bermudagrass, Spanish clover, wild geranium, bristly-fruited mallow, plantain, rattail
D Low phase (D1)		1,500	Shrub and closed forest	Guava, sensitive plant, Boston fern, Hilograss, ricegrass, basketgrass, honohono, staghorn fern
Middle phase (D2)	60	Variable	Closed forest	Ohia lehua, tree fern, staghorn fern
High phase (D3)		4,000-7,000	Open forest	Koa, pukamole, sheepgrass, mountain pili, rattail, alapaio fern, tree fern
E Low phase (E1)	50	4,000-7,000	Open forest and shrub	Koa, mamani, heu pueo, mountain pili, large Hawaiian lovegrass, kalamaloa, sweet vernalgrass, bracken fern, alapaio fern, Kentucky bluegrass

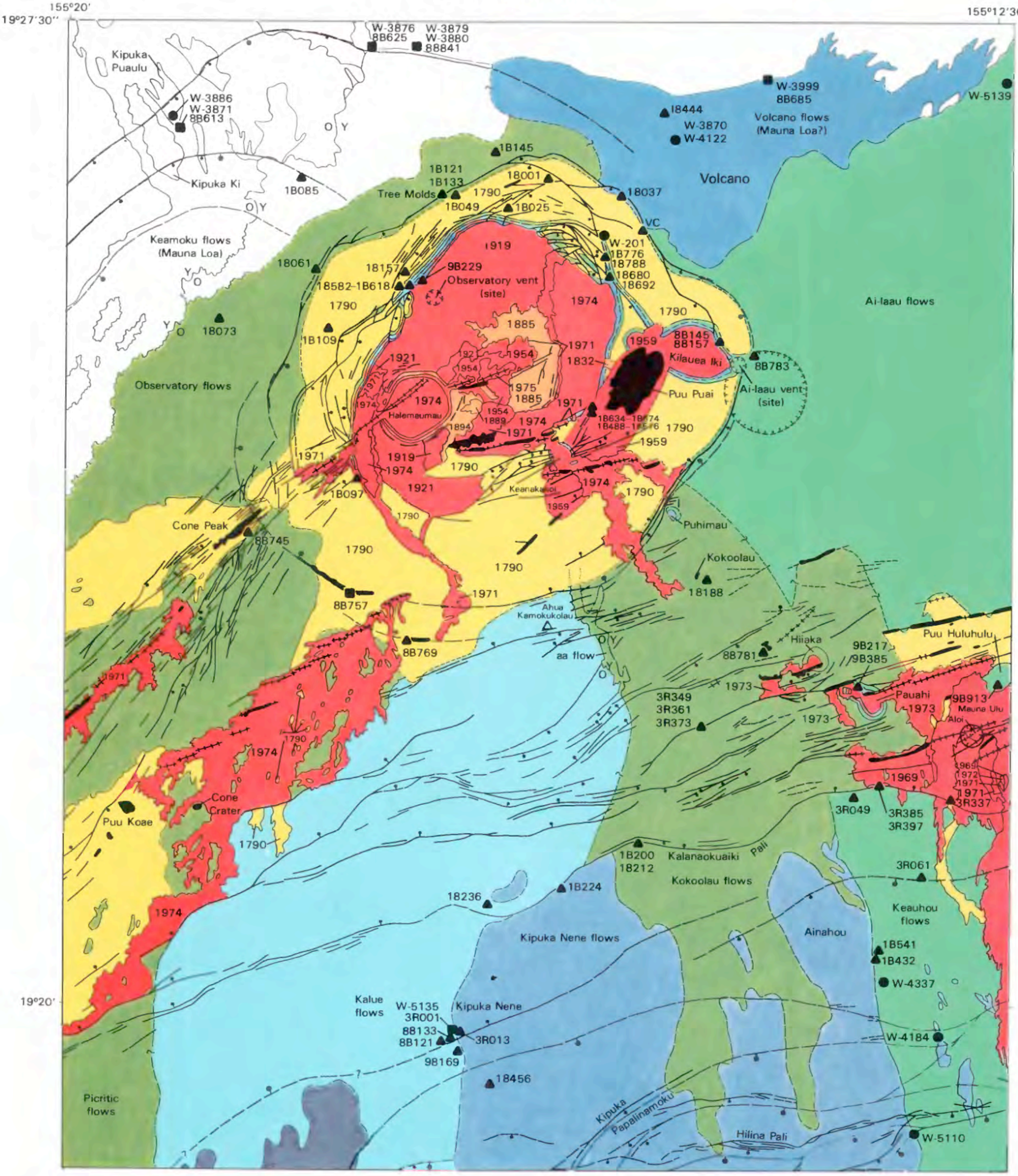
EXPLANATION

GENERAL DEGREE OF CONFIDENCE	MAIN FACTOR LIMITING CONFIDENCE
1 Very good	A Adjacent pahoehoe flows have inherently obscure contacts
2 Good	B Tephra obscures relations between underlying units
3 Average	C Vegetal sparsity on nonadjacent flows obscures chronology based on plant succession
4 Poor	D Rain forest obscures geology
5 Very Poor	E Human forest modification obscures plant succession

FIGURE 12.4.—Continued.

8B and 9B were collected in 1978–79 and published by Holcomb and others (1986). Unpublished sites prefixed by 1B were collected by Holcomb and D.E. Champion in 1981; those prefixed by 3R were collected by Holcomb and J.D. Ward in 1983; one prefixed by 4A was collected by J.P. Lockwood in 1984.

Also used are ^{14}C ages by the U.S. Geological Survey radiocarbon laboratory in Reston, Virginia, directed by M. Rubin. Such ages are cited by their laboratory identification numbers prefixed by W. All of the cited ages are included in compilations by Kelley (1979), Kelley and others (1979), or Rubin and others (chapter 10). Though published originally with laboratory precision to the nearest 10 yr, most of the ages are expressed here only to about the nearest 100 yr. Replicate ages and comparisons with paleomagnetic data suggest that dating precision is about 200 yr



A

FIGURE 12.5.—Reconnaissance geologic map of Kilauea Volcano showing lavas erupted through 1977, revised and simplified from Holcomb (1980a), which also shows topography and cultural features. In this version, lava flows are classified only by age; in original map they were classified also by flow morphology and eruption type. Age uncertainties are discussed in text. Year of eruption is indicated for historical flows. ***A***, Summit region and Koae fault system. Volcano flows may have been fed by eruptions of Mauna Loa. VC, visitor center sampling site of Coe and others (1978). ***B***, Upper southwest rift zone. Some Observatory flows(?) may have been erupted

EXPLANATION

Ages of rock units

Puna Basalt:

- 20th century — Year of eruption is indicated
- 19th century — Year of eruption is indicated
- 18th century, including Keanakakoi Ash Member
- 250-350 yr B.P., including Observatory flows
- 350-500 yr B.P., including Ai-laau and Keauhou flows
- 500-750 yr B.P., including Kalue flows
- 750-1,000 yr B.P., including Volcano flows
- 1,000-1,500 yr B.P., including Kipuka Nene flows
- 1,500-10,000 yr B.P. including Uwekahuna Ash Member

Other units:

- 10,000-25,000 yr B.P., including Pahala Ash
- >25,000 yr B.P., including most of Hilina Basalt

Structural and morphologic features

Y / O ?-- Contact; dashed where uncertain, queried where highly uncertain; older and younger units indicated by O and Y

Fissure; dashed where uncertain

Eruptive fissure; dashed where uncertain

Pyroclastic cone or rampart

Surficial fault; dashed where uncertain; ball and bar on downthrown side

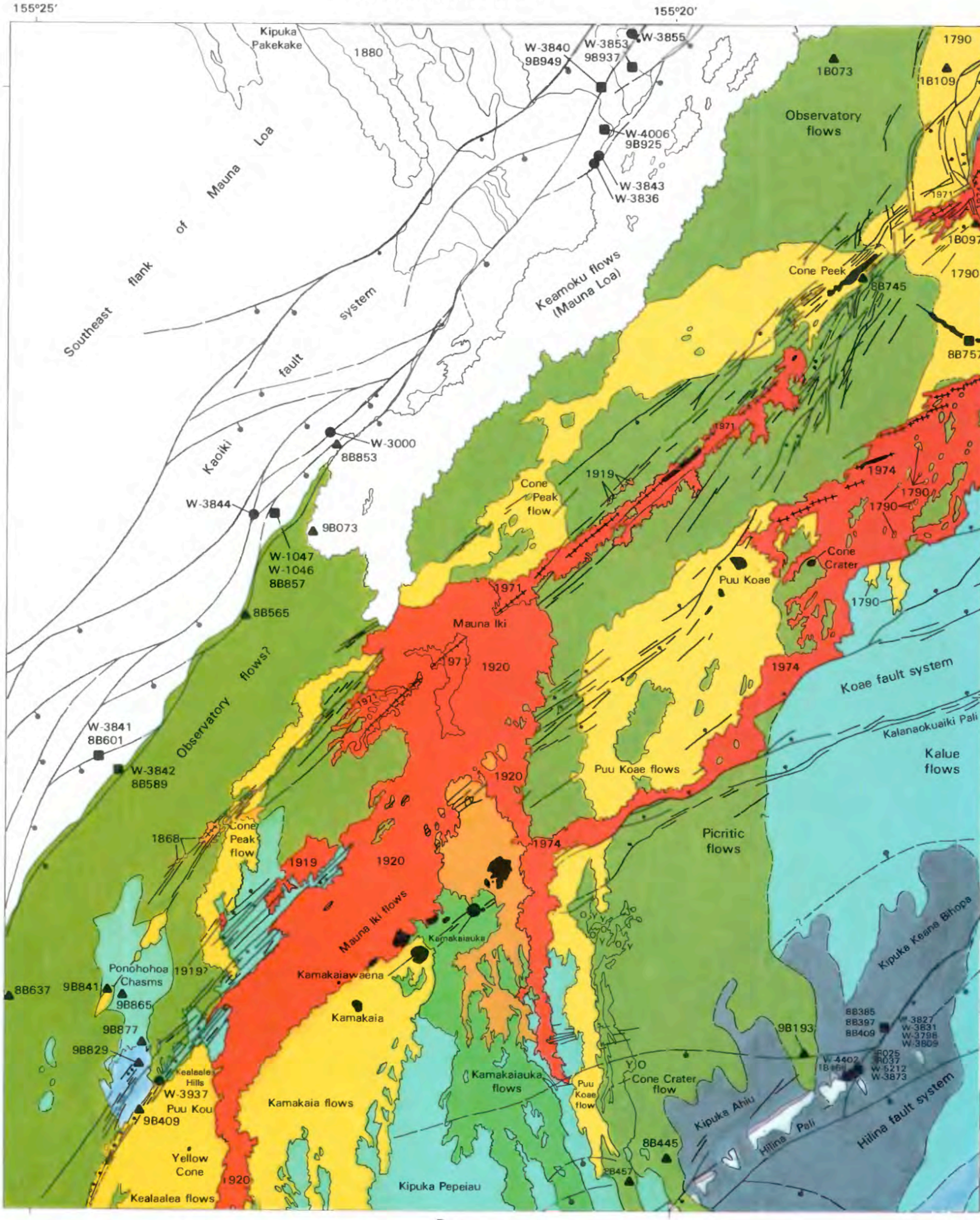
?– Buried fault; dashed where uncertain, queried where highly uncertain; ball and bar on downthrown side

Buried craters; dashed where inferred

Measurement sites

W-201	^{14}C age only, with no paleomagnetic samples. Code is laboratory identification number
W-3871 8B613	Paleomagnetic site of this study at a ^{14}C collection site or on a flow of otherwise known age. Codes are laboratory identification numbers; see text
1B444	Paleomagnetic site of this study on a flow of otherwise unknown age
	Paleomagnetic sites of previous studies; identification omitted
△	Triangulation station (only a few included as geographic references)

from Mauna Loa, as mapped by Stearns and Macdonald (1946). ***C***, Lower southwest rift zone. Flows west of Great Crack may belong to more age groups than indicated here. ***D***, Flank south of summit region. Area encompasses much of Hilina and Koae fault systems, and the Papau submarine landslide (Moore and Peck, 1965; Fornari and others, 1979) occurs offshore. ***E***, Upper east rift zone and south flank. Much of this area shown also in figure 12.35, in which lava flows are classified by morphology. ***F***, Part of middle east rift zone and south flank. South flank here covered largely by lava flows from Kane Nui o Hamo. ***G***, South flank and east rift zone from Heiheiahulu to Malama. Especially prominent in this area are 18th-century lava flows of Heiheiahulu, which in figure 12.40 are classified by morphology. ***H***, East rift zone from Kaliu to Cape Kumukahi. Flows of 17th and 18th centuries not distinguished confidently in this area. Transform fault as inferred by Zablocki (1977). ***I***, Part of flank north of middle east rift zone. This heavily forested area includes poorest known part of Kilauea. ***J***, North flank southeast of Keaau. All flows older than Ai-laau shield in northern part of this area may have been erupted on Mauna Loa.



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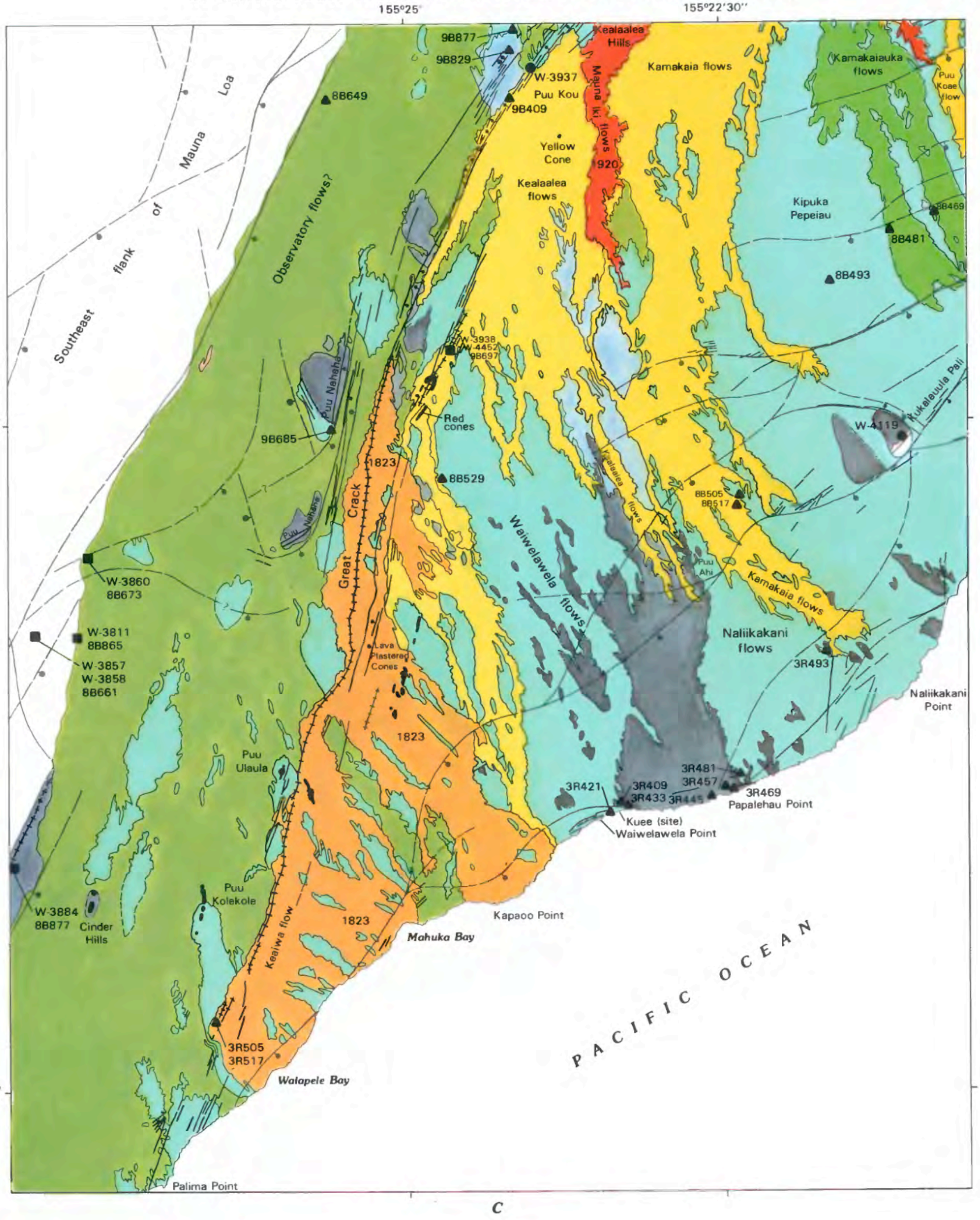

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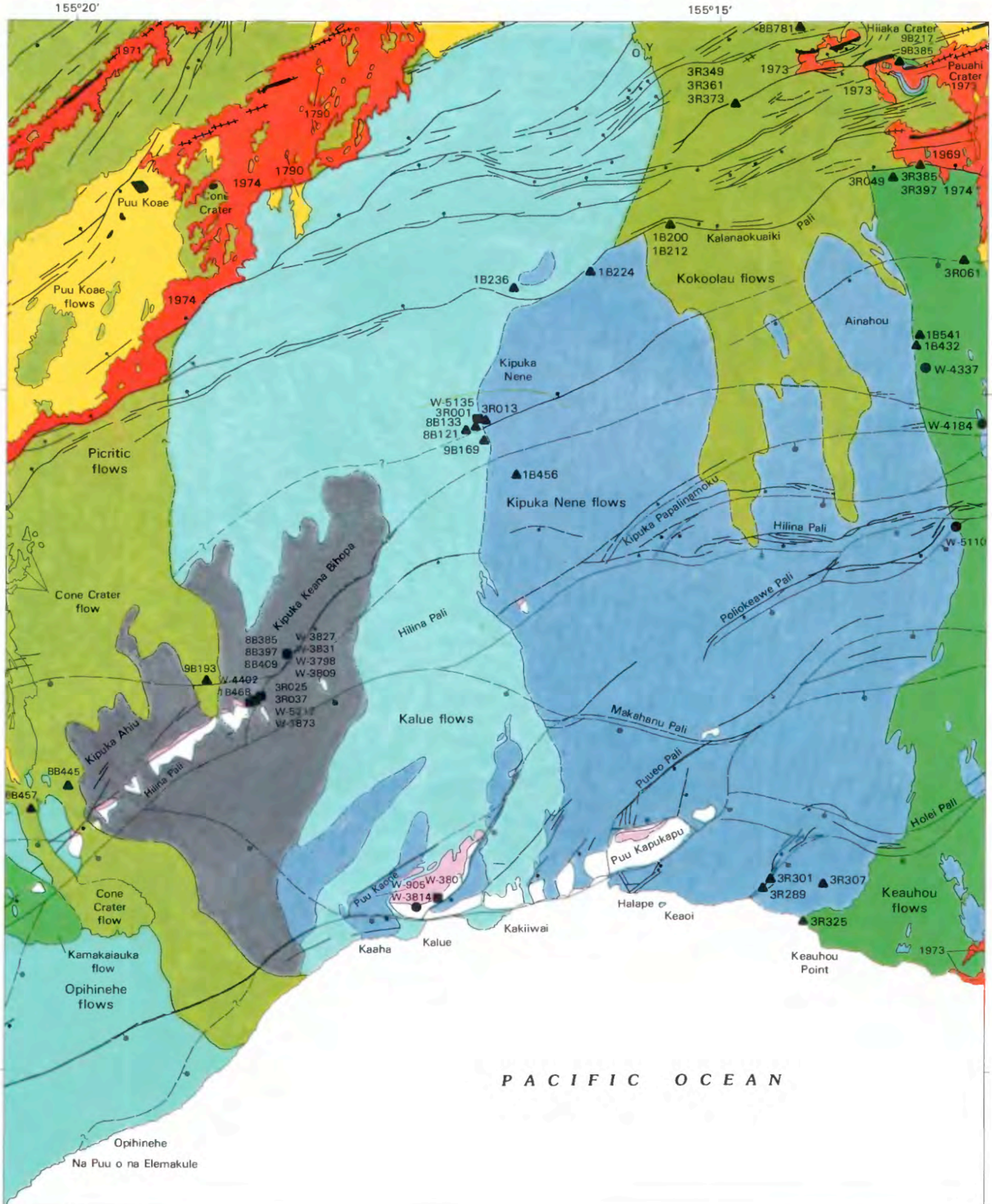

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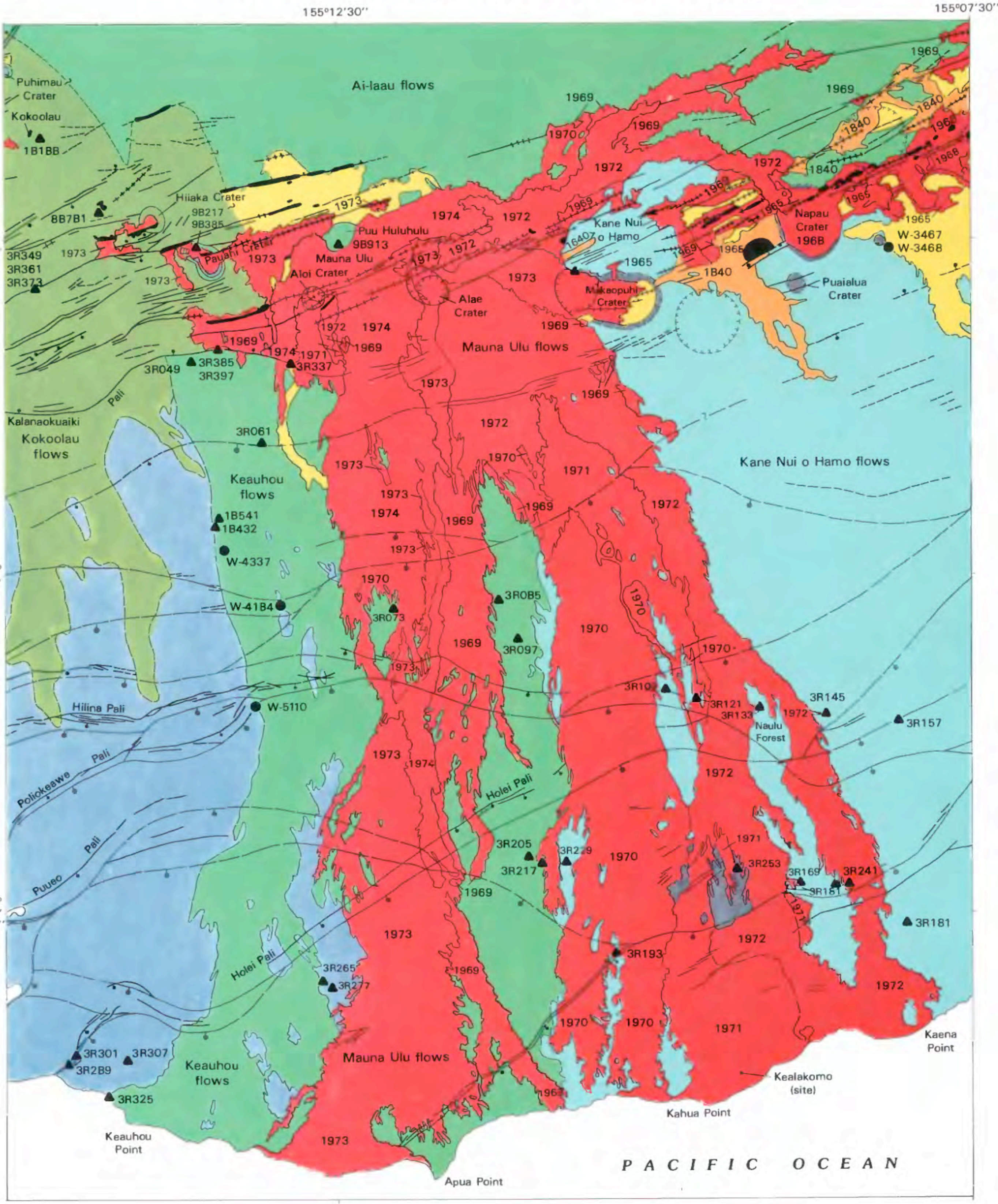

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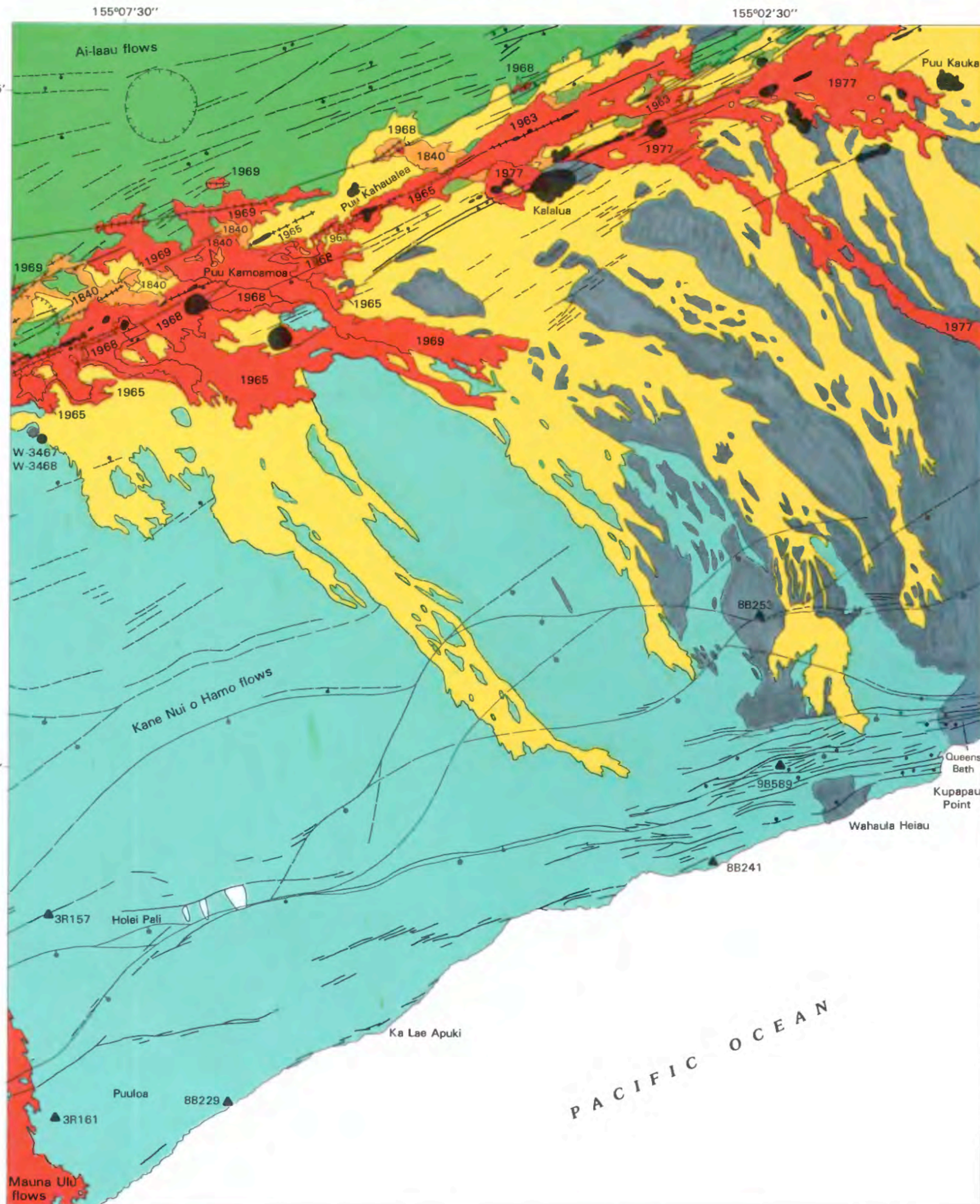

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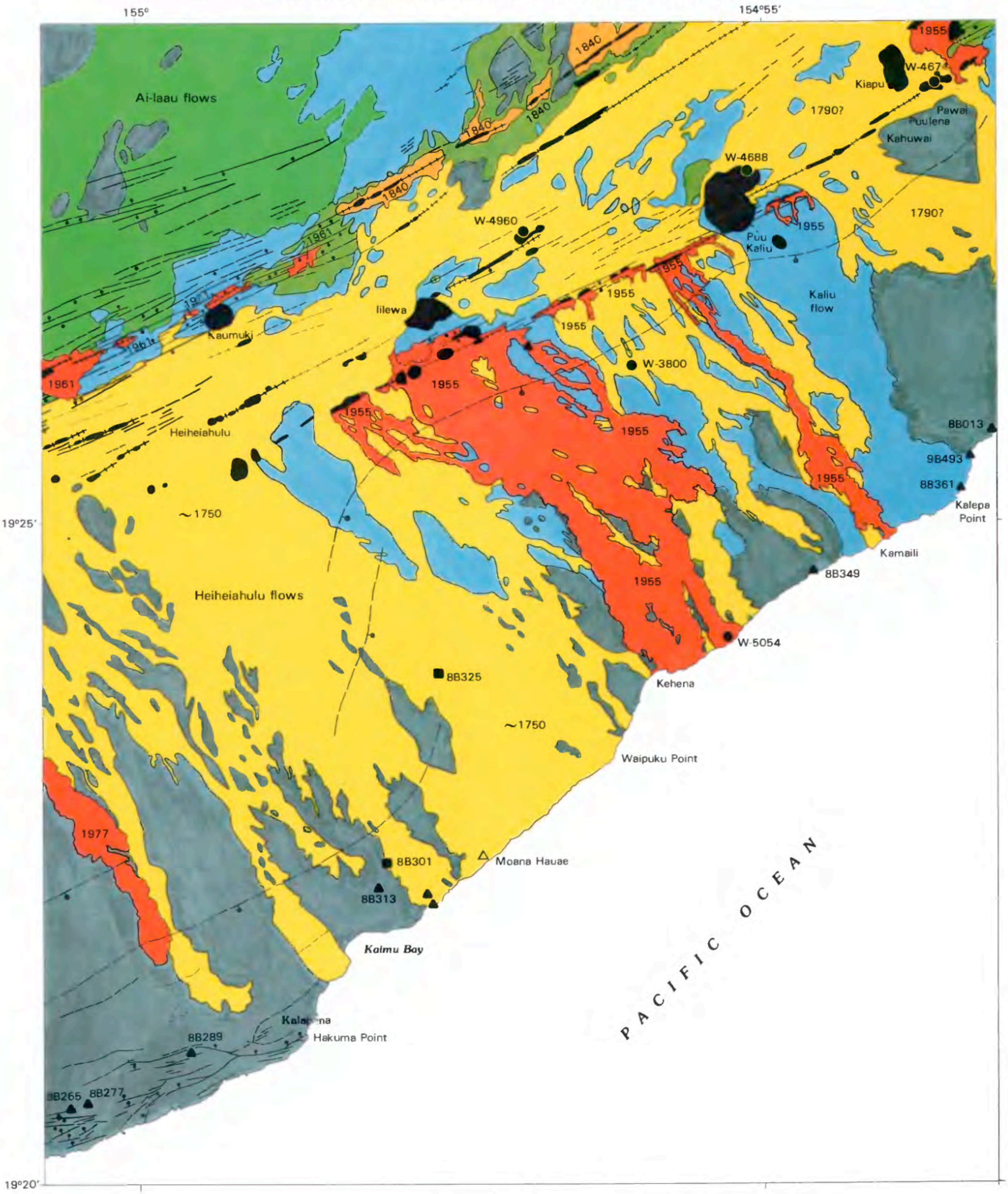

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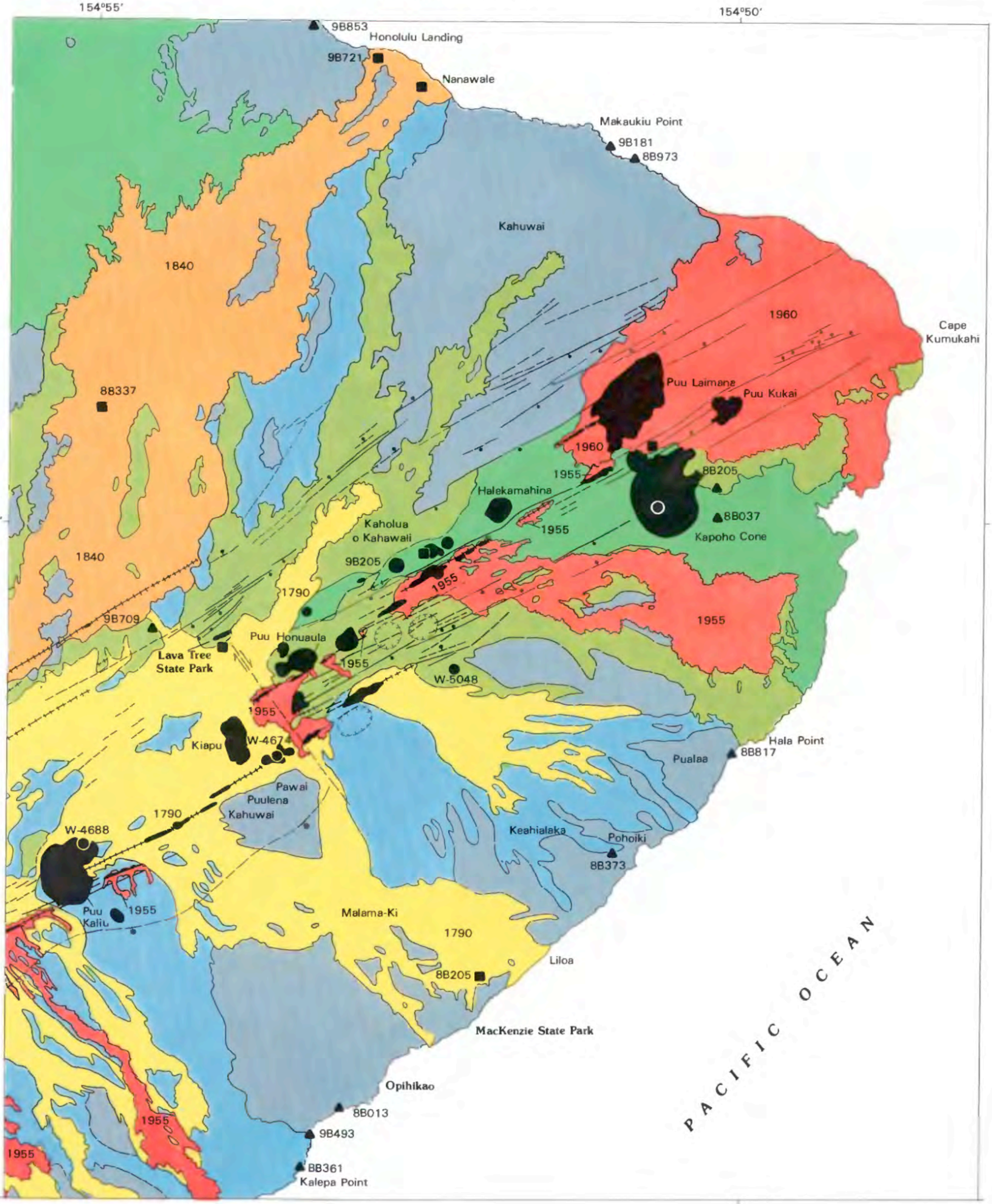

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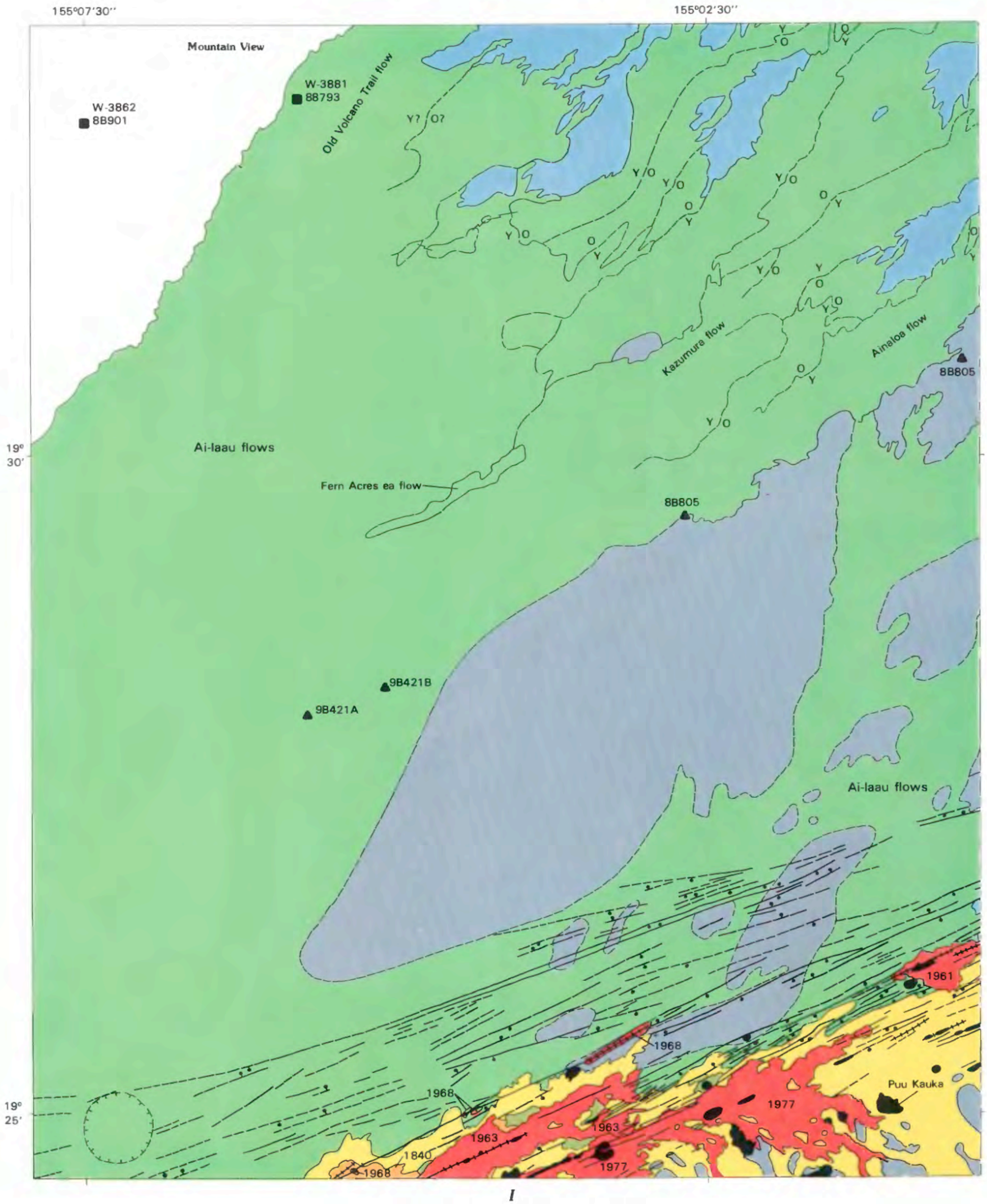

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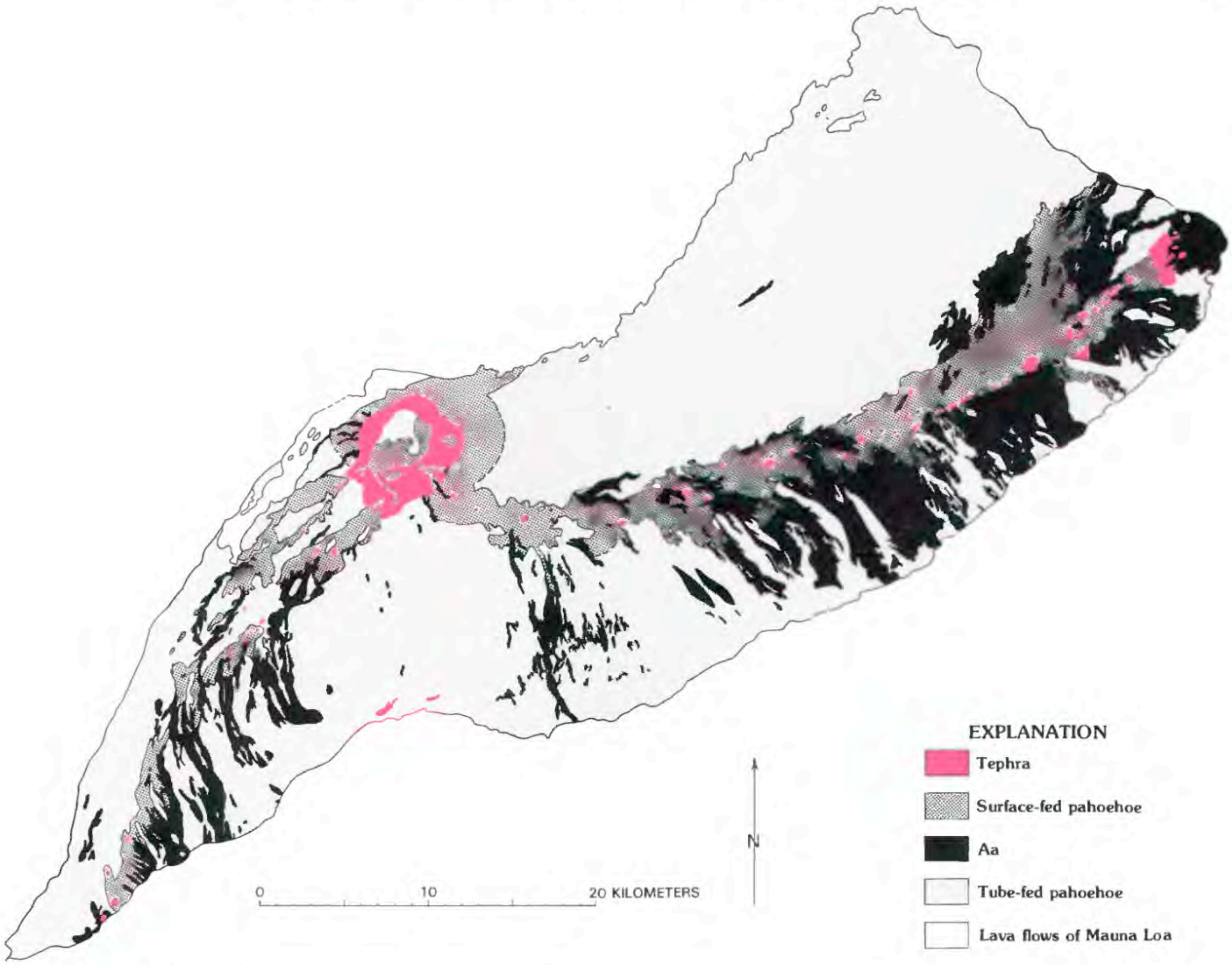


FIGURE 12.6.—Kilauea lava flows, classified by morphology; extensive tephra units are shown separately in red. Dashed lines, gradational or uncertain contacts.

(Holcomb and others, 1986). Large errors may arise from contamination by modern organisms in subtropical rainforest and by old fumarolic carbon elsewhere (Rubin and others, chapter 9).

AGE OF KILAUEA'S SURFACE

Most surficial flows have magnetization corresponding to ages of 250–1,100 yr (green hues on fig. 12.12). About 70 percent of the surface is younger than 500 yr, 90 percent younger than 1,100 yr (fig. 12.13; table 12.2). This is about ten times younger than was commonly believed as recently as a decade ago. When the mapping was begun, it was thought that a large part of Kilauea's surface was 5,000–10,000 yr old, largely because of a 2.57-ka ^{14}C age (now known to be erroneous) on the Keanakakoi Ash Member of the Puna Basalt near the rim of Kilauea'a present caldera (Rubin and Suess, 1956). The caldera is older than the ash because the ash is draped unbroken across caldera faults. Lava flows truncated by the caldera are older still; because vegetation patterns reveal clear age differences among these flows, many were thought to be much older than 2.5 ka. It was therefore puzzling when ^{14}C dating in the late 1970's found few ages older than 1 ka (Kelley and others, 1979). This dating suggested that Kilauea's surface was younger than expected, and when paleomagnetic work was planned in 1978 it was thought that a majority of surface flows were as young as 2–4 ka. The paleomagnetic results actually show that they are even younger.

This youthfulness is not inconsistent with other information about Kilauea's rate of magma supply. Assuming a supply rate of 9×10^6 m^3/mo (Swanson, 1972) and mean flow thickness of 2 m, an estimate for Kilauea's rate of surface coverage is 54,000 km^2/1,000 yr, 36 times the rate needed to cover the volcano's 1,450-km^2 subaerial surface during such an interval. This coverage rate is a

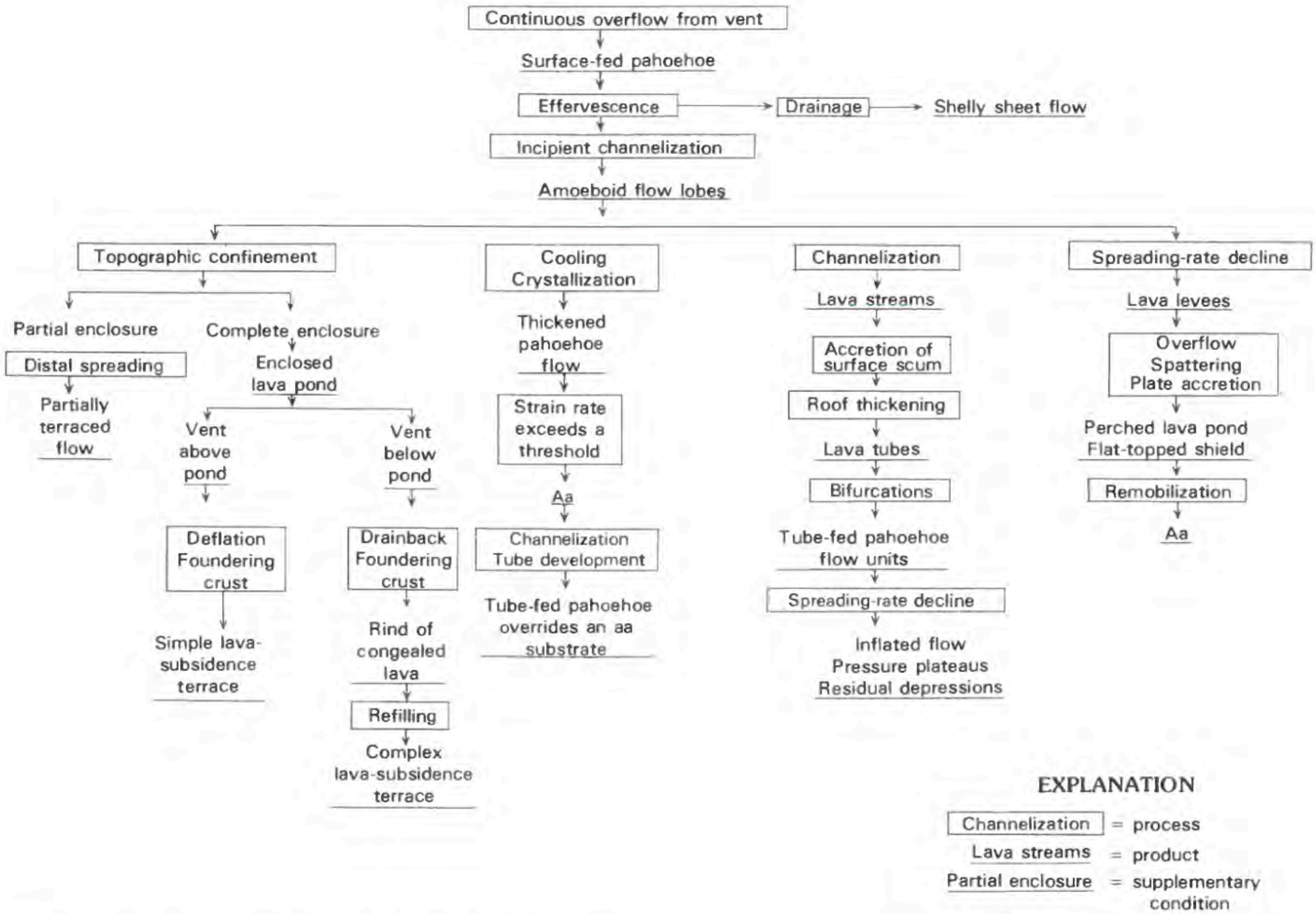


FIGURE 12.7.—Patterns of possible evolution of a lava flow. Summarized here are some processes and environmental factors affecting morphology of basaltic lava flows. In order to infer eruptive behavior it is necessary to distinguish between landforms resulting mainly from topographic influences and those resulting mainly from character of an eruption. Not all branches shown in this flow chart have been useful for interpreting eruptive behavior.

maximum value because it is not corrected for overlapping of flows or, extension of flows onto submarine flanks. Despite those omissions, however, the supply rate seems adequate to explain the rate of surface renewal graphed on figure 12.13.

STRUCTURAL SUBDIVISIONS

Different parts of Kilauea differ in eruptive behavior, so that temporal variations must be extracted from an overprint of spatial variation. Magma rises into Kilauea beneath its summit and then moves laterally for great distances along its rift zones (Fiske and Jackson, 1972). Different behaviors characterize different parts of the system, which is commonly divided into six structural subdivisions (fig. 12.14). A review of these subdivisions will provide a background for the historical account.

SUMMIT

The summit is dominated by collapse features (fig. 12.5*A*). Caldera faults form an annulus of arcuate blocks stepped downward toward an inner sink. All major displacements on caldera faults occurred before eruption of most of the Keanakakoi Ash Member in 1790 (Christiansen, 1979). Other collapse features include Kilauea Iki, Keanakakoi, and smaller prehistoric craters and the Halemaumau pit formed in 1924. Though most eruptive fissures trend east-northeast across caldera structures, other trends occur; some late prehistoric lava erupted from fissures concentric to the caldera.

Eruptions of all types occur in the summit area, but those of long duration are characteristic. Nearly continuous activity at Halemaumau for more than a century built a lava shield that filled the inner sink to overflowing by 1921. Similar eruptions buried an earlier caldera; still preserved are parts of two lava shields, one surrounding a vent at the east end of Kilauea Iki (the Ai-laau shield), and the other centered in the northwest caldera (the Observatory shield). Tube-fed flows from these vents cover much of Kilauea. Explosive eruptions occur also at long intervals; a small one occurred in 1924, and several much larger ones occurred earlier (Decker and Christiansen, 1984).

EAST RIFT ZONE

The east rift zone forms a ridge extending more than 60 km beyond Cape Kumukahi, the easternmost point on the Island of Hawaii (fig. 12.15; Moore, 1971). Its subaerial part is 4–6 km wide and is loosely divided into an upper segment extending from the caldera to Napau Crater, a middle segment from Napau to Heiheiahulu lava shield, and a lower segment from Heiheiahulu to Cape Kumukahi. The upper segment is dominated by pit craters, and the other segments are marked by closely spaced fissures, faults, and grabens having net seaward subsidence.

The rift zone is straighter and wider than commonly portrayed. Kinks inferred in the lower segment (Skokan, 1974; Furumoto, 1976) are merely offsets in recent eruptive fissures, not in the rift zone as a whole (fig. 12.5*G*,*H*). Seaward migration of the middle segment (as suggested by Swanson and others, 1976a) has not occurred recently; historical eruptions have followed its axis, 18th-century lava having obscured the structures of its southern half (fig. 12.16). All recent flows from the middle segment have spread seaward because the rift zone has subsided below its northern margin, but some older flows of the north flank were erupted from it. The upper segment was almost entirely buried by lava from the Ai-laau vent about 400 years ago; it is probably wider and straighter than the curved chain of young pit craters, which may reflect recent localization to its southwest edge (fig. 12.5*E*). Magma intruding west along Koae faults (Unger and Koyanagi, 1979) may have produced westward widening of the rift zone.

Eruptions are briefer along the rift zone than at the summit. Flows from eruptions of moderate duration are prominent along the upper and middle rift segments, and less so along the lower segment. Brief eruptions are especially numerous along the middle and lower segments, and pyroclastic vents are more common there.

SOUTHWEST RIFT ZONE

The southwest rift zone does not form a distinct ridge like the east rift zone, its seaward subsidence is more obvious, and it does not extend far beyond the shoreline (Moore and Fiske, 1969). It parallels the Kaoiki fault system of Mauna Loa; its structures may follow buried Kaoiki faults. It consists of an inactive zone inland and an active zone seaward. The active zone contains strands of closely spaced fractures separated by unbroken blocks. The rift zone can be divided into segments where it bends near Yellow Cone; the upper segment trends about S. 50° W. and the lower segment trends about S. 15° W.

In the lower segment a seaward zone of recent rifting about 1 km wide is dominated by the Great Crack (fig. 12.5*C*). Other strands in the active zone extend through Puu Ulaula and Puu Kolekole (inland) and Red Cones and Lava Plastered Cones (seaward). Most faults are down to the southeast, toward the sea. More than 20 m of displacement has occurred on faults along the northwest side of the active zone; some landward blocks like Puu Nahaha stand high enough to escape draping by young flows from the rift, though they are draped by young flows from the summit. A seaward migration of eruptions may have occurred; all vents seaward of the faults appear young, while all inland vents are older than 1,000 years. But the most recently active Great Crack is inland from some other vents of the active zone.

The upper segment appears to be a broad graben or sag. It has no large pit craters, though a few small pits do occur. The seaward zone of active rifting flares from a width of 1 km in the southwest to more than 3 km in the northeast (fig. 12.5*B*). It is currently split into three strands converging downrift; each strand consists of closely spaced fractures breaking the sheet of late prehistoric summit flows.

The middle strand extends from the main center of summit tumescence (south of the caldera) through Cone Crater and Puu Koae to the lower segment of the rift zone. Eruptions from this strand have been vigorous and brief, producing spatter cones and aa flows but little tube-fed pahoehoe. The flows have olivine-controlled compositions similar to lavas erupted at the summit (Wright, 1971). This strand probably connects directly to a deeper magma reservoir and taps magma that is changed little by differentiation or loss of volatiles but cannot sustain eruption after the gas-rich fraction has escaped.

The northern strand passes from Halemaumau through Cone Peak and Mauna Iki. Its fissures end 5 km southwest of Mauna Iki without reaching the lower segment. Its historical eruptions have followed shortly after summit activity and have produced little tephra. Lava feeding the Mauna Iki eruption (1919–20) drained from Halemaumau along shallow fissures (Jaggar, 1947). This strand probably is connected to the deeper plumbing by way of Halemaumau so that its magma loses gas through summit eruptions and fumaroles. Eruptions can be sustained for months or years by drainage of degassed lava when Halemaumau acts as a shallow holding tank. (For supporting chemical and deformation data, see Duffield and others, 1982.)

The southern strand passes from the Koae faults through Kamakaia and Yellow Cone; it may intersect the middle strand where the latter bends into the lower rift segment. Its eruptions have been brief to moderately long, but they are unique on Kilauea because they produce cinder cones and viscous lava flows (fig. 12.17) of (for Kilauea) highly differentiated compositions (Wright and Fiske, 1971). This strand may have only a tenuous connection to the main plumbing, its magma residing at shallow depths for long intervals after backing up along Koae structures.

KOAE FAULT SYSTEM

The Koae fault system extends east-northeastward between the rift zones (fig. 12.5*A*,*D*). Its faults have their downthrown side mainly toward the caldera and have had recurrent movement (Duffield, 1975). Some scarps were large enough by the 18th

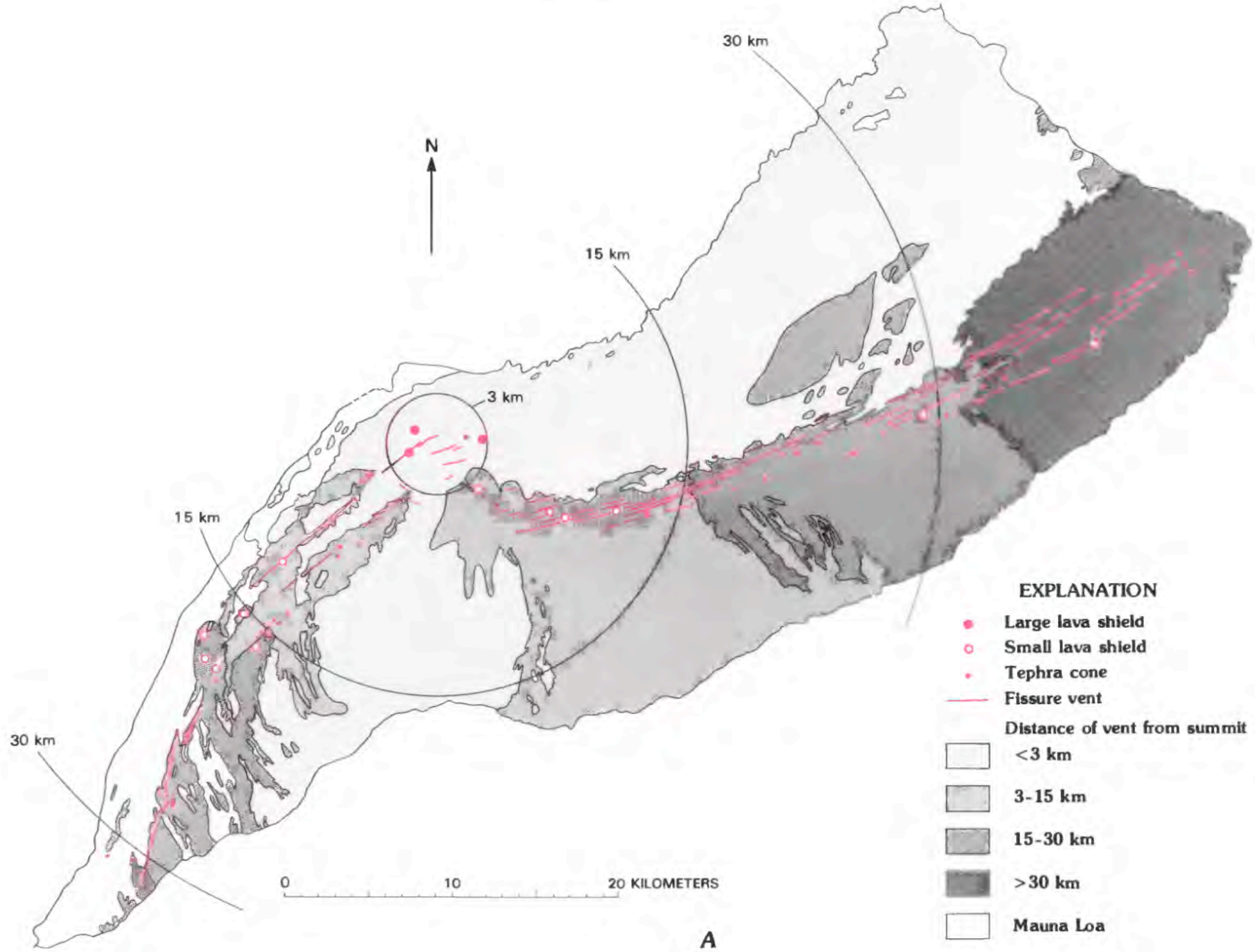


FIGURE 12.8.—Kilauea lava flows classified by location and by type of eruption. ***A***, Flows classified by location of eruption. Lava flows from summit cover large areas of north flank and southwest rift zone as well as flank south of summit. ***B***, Flows classified by eruption type. Eruptions tend to be briefer at greater distances from summit. Because it is difficult to group older flows into eruption assemblages, some older aa flows alone are inferred to represent brief eruptions and older tube-fed flows alone are inferred to represent sustained eruptions; these inferences may not always be correct.

century to deflect lava flows from Cone Crater and Puu Koae. Most present scarps postdate the Kalue flows thought to be 500–750 years old, but some scarps are older. A segment of Kalanaokuaiki Pali extending 2 km east of the Hilina Pali Road crossing is rimmed by Kipuka Nene flows thought to be about 1,100 years old (fig. 12.18); the younger Kalue flows failed to overtop the scarp, and lava tongues oozed down into the open fracture at its base. The southernmost Koae fault extending eastward from Kipuka Nene campground is overlapped by Kalue flows and has had little displacement during the subsequent 500 years.

Few eruptions are known from the Koae fault system, and most of them have been from near its intersection with the southwest rift zone. Some lava was erupted from eastern Koae structures in 1973 (Tilling and others, chapter 16). Spatter found beneath Kokoolau lava along Kalanaokuaiki Pali may be clots ejected by heated air or steam after surface flows invaded the fracture. It remains possible that true eruptions from the central Koae system have occurred and then been obscured by the younger flows from the summit.

The Koae fault system may be an ancient feature of Kilauea, or it may have been produced recently by contraction or migration of the rift zones and caldera. An anomalous area of caldera-concentric structures along the central Koae (Duffield, 1975) may reflect the buried rim of an earlier caldera, and the fault segments extending to the east and west may follow former eruptive-rift structures radial to

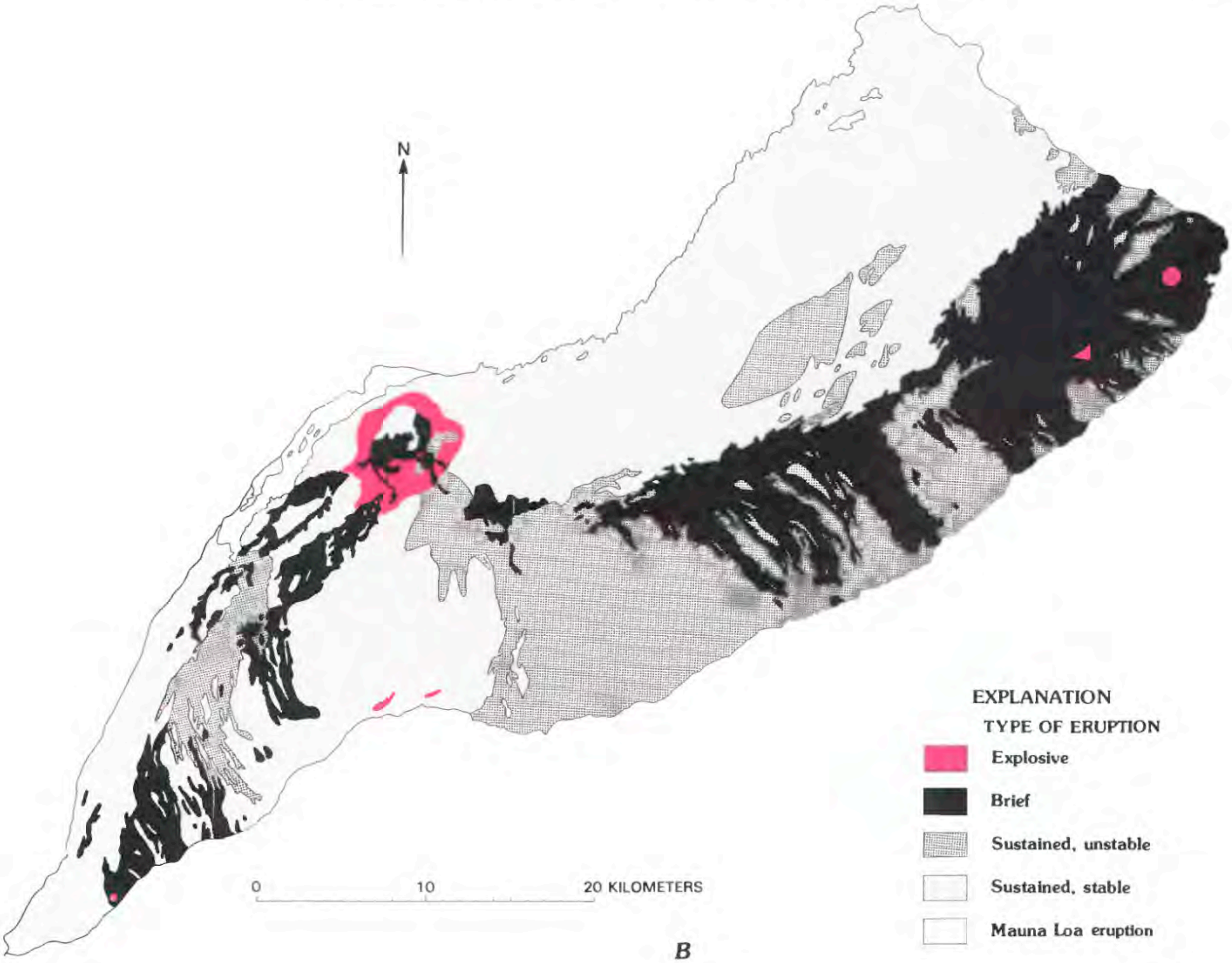


FIGURE 12.8.—Continued.

that caldera. If so, the bend in the east rift zone could have arisen from northward migration of summit collapse instead of southward migration of the rift zone.

SOUTH FLANK

The south flank is the area seaward of the rift zones and the Koae fault system. Faults of the south flank (Hilina fault system) mainly show displacement down to the south (fig. 12.5*C*–*F*). The most prominent faults, such as those of Hilina, Poliokeawe, and Holei Palis and of Puu Kapukapu, occur in the seaward part of the south flank; this has led to a distinction between faulted and unfaulted parts of the flank (Swanson and others, 1976a). Buried Hilina faults, however, inferred from steepened slopes, occur inland close to the Koae system and probably extend into each of the rift zones (Holcomb, 1980b). The Hilina fault system probably is not isolated from other Kilauea structures but grades into them; its apparent isolation arises from the restricted extent of its recent displacements.

The age of the Hilina system is not known. Stearns and Clark (1930) considered the faults to postdate the base of the Pahala Ash, about 23 ka (Easton, 1978), because the ash caps some blocks (Puu Kapukapu and Puu Kaone) truncated by the faults. Puu Kapukapu is about 300 m high. If the block seaward of Puu Kapukapu subsided to sea level in 3-m increments similar to the displacement of November 29, 1975 (Tilling and others, 1976), it would have required 100 such episodes recurring at intervals of about 230 years. The highest part of Hilina Pali undraped by younger lava also is about 300 m high, and the youngest Pahala Ash truncated by this fault could be as young as about 11 ka (Easton, 1978). That displacement could have been accomplished by 3-m subsidence episodes repeated every 110 years. These frequencies are reason-

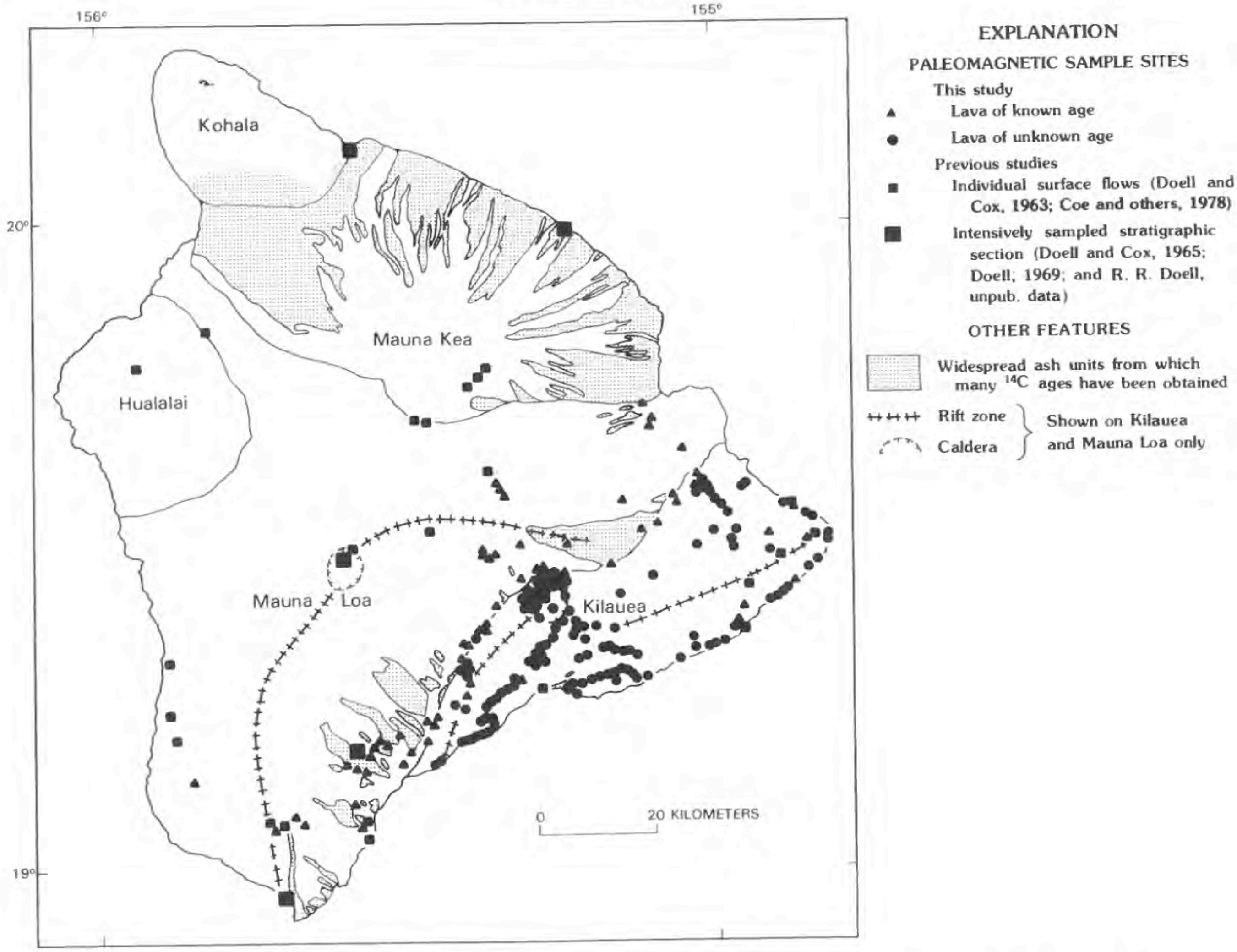


FIGURE 12.9.—Paleomagnetic sampling locations on five volcanoes that make up Hawaii. Map modified from Stearns and Macdonald (1946).

able, and the interpretation by Stearns and Clark may be correct. However, the faults could be younger and could have had large, catastrophic displacements earlier in their development, or they could be older and draped by Pahala Ash that is now buried or subsided beneath the sea. The Hilina fault system could be older than Kilauea and could have developed from seaward migration of the Kaoiki fault system as older inland faults were stabilized by the growing edifice.

No eruptions are known from the south flank; sparse dikes along Hilina Pali were fed by lava flows spreading down into open fissures (Walker, 1967; Easton and Lockwood, 1983). Nonetheless, episodes of Hilina displacement may affect Kilauea's eruptive behavior by dilating the rift zones and disrupting the magma plumbing system.

NORTH FLANK

The north flank does not show surficial structures, though inactive structures may be buried. Only one possible buried fault is inferred, with great uncertainty, subparallel to the coast at an elevation of about 60 m, 5 km inland from Kaloli Point (figs. 12.5*J*, 12.19). Several kipukas (inliers) in the youngest flows are truncated along this line, and no kipukas of older Mauna Loa lava occur seaward of it. The surface slope decreases across it from 1.6° inland to 1.0° seaward, and the seaward lava has assumed a thickened elephant-hide appearance (Stearns and Macdonald, 1946) below the break in slope. The discontinuity may be a normal fault, its downdropped eastern block buried by younger lava, or it may parallel a buried seacliff several dekameters high. Alternatively, it

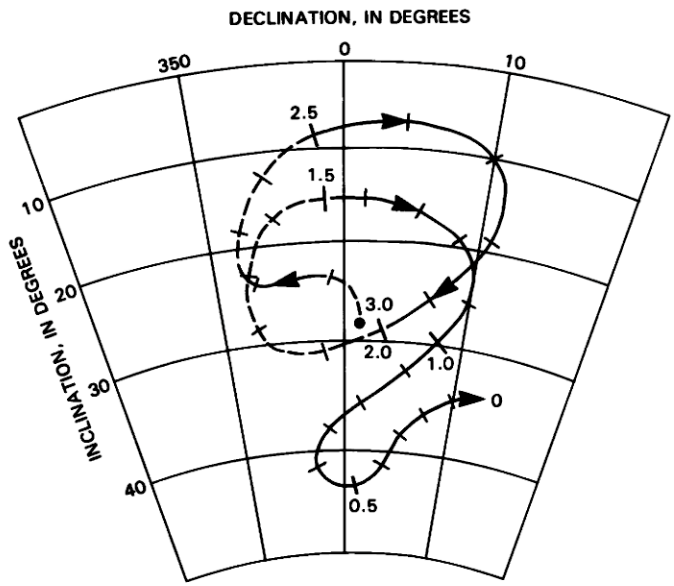


FIGURE 12.10.—Generalized history of Hawaiian geomagnetic secular variation during the last 3,000 years. Track dashed where confidence is less. Ticks are shown at approximate 100-yr intervals, and numbers indicate thousands of years before present. Unpublished data have been used to modify earlier version by Holcomb and others (1986).

could be the edge of a very broad, flat cone of lava banked against an older, steeper slope. Such a cone could develop from several causes; for example, a rise in relative sea level could have raised the baselevel to which the slope was formerly adjusted.

No eruptions are known from this flank; for at least the last few millenia it has passively accumulated lava, mostly as tube-fed flows from the summit.

EARLIER PREHISTORIC ACTIVITY

Because of incomplete exposures and dating uncertainties, a full eruption history of Kilauea is not yet possible, even for the last few thousand years. Available information does, however, permit a general history, having increased detail with younger age. The history is reviewed in the following sections, in which many dating uncertainties are discussed. Readers not interested in these details may want to skip ahead to the section entitled "Summary of Eruptive History."

PLEISTOCENE SHIELD GROWTH

Kilauea's early history was studied by Easton (chapter 11, 1978), who estimated that the volcano began to grow around 200–300 ka. Only the later subaerial part of shield growth has been available for study; it is recorded by the Hilina Basalt, Pahala Ash, and lower part of the Puna Basalt exposed in the Hilina fault scarps of the central south flank (fig. 12.20). The lowermost Hilina flows now exposed are estimated to have ages of 100 ka, and the Pahala Ash was deposited between 25 ka and 10 ka (Easton, chapter 11). Rocks below the Pahala Ash are mostly tube-fed pahoehoe flows, probably from sustained summit eruptions. Interspersed among the flows are ash layers, probably erupted at the summit in large explosions associated with successive caldera collapses. Little is known about rift-zone activity during this interval.

OLDER HOLOCENE FLOWS

About 10 percent of Kilauea's surface consists of rock older than about 1,100 years. Some of the older lava flows are veneered by ash deposits. Among these are kipukas of picritic aa of about 5.2 ka (W–4536) on the north flank southeast of Keaau (fig. 12.21), probably erupted from the northeast rift zone of Mauna Loa (Lockwood and Lipman, chapter 18). Pahoehoe above ash in one kipuka has been dated at about 3.7 ka (W–4177, fig. 12.5*J*). The source of this lava is unknown; it could have come from the summit of Kilauea or from the northeast rift zone of Mauna Loa. As discussed later, it may be coeval with flows previously thought to have been erupted 750–1,000 years ago. Buried flows resting on Pahala Ash below the rim of Hilina Pali have been dated at about 6.6 ka and 4.8 ka (W–3873 and W–3798, fig. 12.5*D*). Younger flows, separated from the older ones by thin ash and forming much of the surface in Kipuka Ahiu and Kipuka Keana Bihopa (fig. 12.22), have been dated at about 3.5 ka (W–3831, fig 12.5*D*). These flows are veneered by ash and eolian sand thick enough to support a carpet of high range grass and scattered ohia trees (*Metrosideros polymorpha*). The ash on and between these older Puna flows suggests that explosive eruptions occurred more than once between 6.6 and 1.5 ka, but the number of eruptions is not known. The flows have various directions of magnetization, but not enough ^{14}C ages are available to derive a continuous magnetic history.

Several vents still exposed in kipukas along the east rift zone may be older than 2,000 years; among them are Kapoho Crater, Kiapu, Iilewa, and Kalalua (fig. 12.5*F–H*). Some vents along the lower southwest rift zone may also be older. The Cinder Hills 2 km southeast of Pahala are overlapped by a lava flow dated by ^{14}C at about 3.5 ka (W–5324, fig. 12.5C). A thin lava flow issuing from a prominent fissure along the Kilauea-Mauna Loa boundary 1 km southeast of Pahala has been dated at about 3.6 ka (W–3884, fig. 12.5C); though Lipman and Swenson (1984) mapped this fissure as an eruptive vent, a lava flow erupted elsewhere could have flowed into it farther upslope and then overflowed its rim.

FLOWS BENEATH UWEKAHUNA ASH MEMBER OF PUNA BASALT

Much of Kilauea may have been covered by lava in a short interval preceding deposition of the Uwekahuna Ash Member. In stratigraphic sections of the summit and upper east rift zone, flows below the Uwekahuna Ash Member have remanent magnetizations (crosses, fig. 12.11C) distinct from those of flows of the last millenium. Examples occur in Uwekahuna Bluff (9B229A; sites 133 of Doell and Cox, 1965; 137D,E of Doell, unpublished work), Tree Molds (1B121), Kilauea Iki (8B145), and Pauahi (9B385). Surficial flows inland from Papalehau Point (3R457, fig. 12.5C) may have been erupted at the summit also.

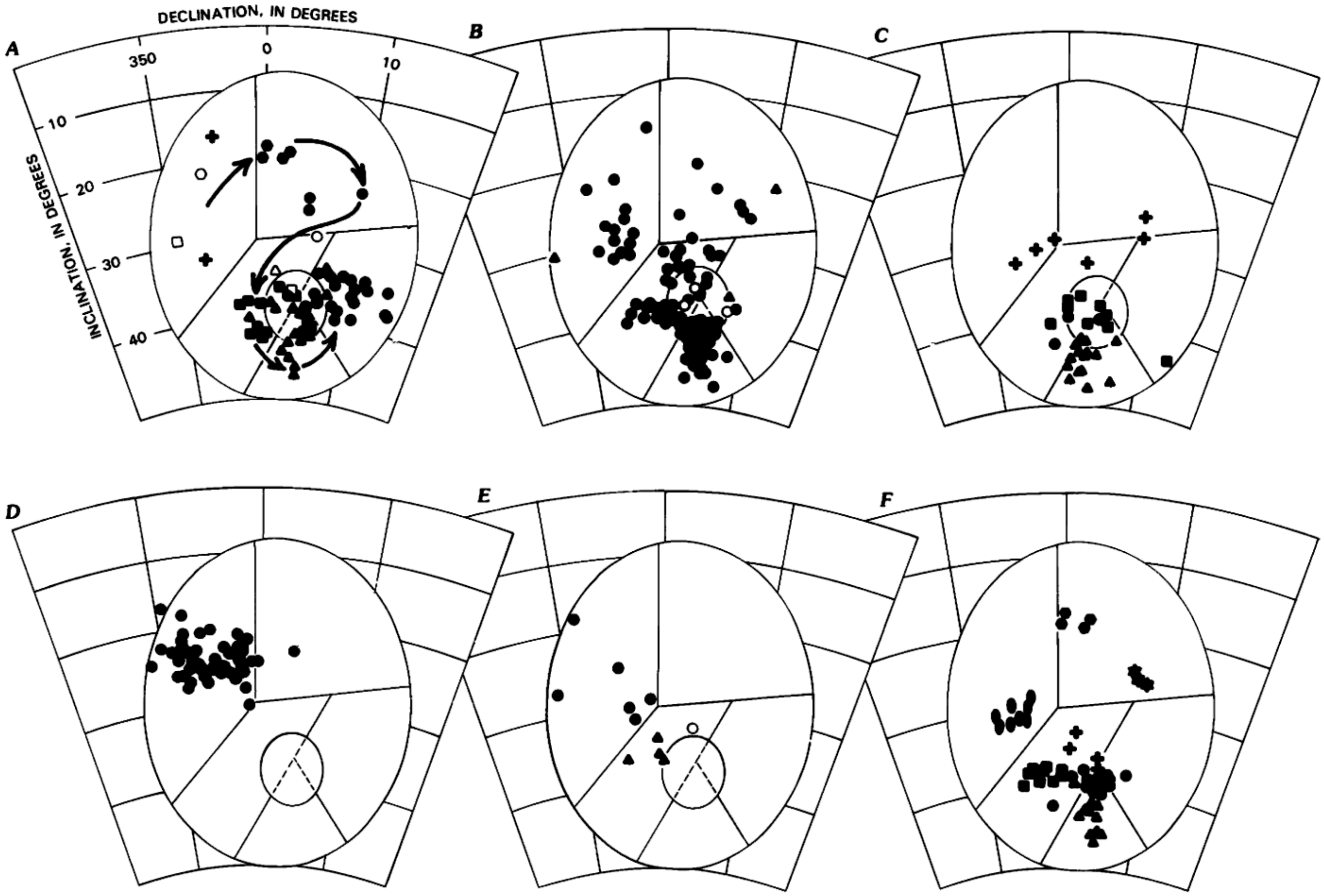


FIGURE 12.11.—Semiquantitative method used to infer ages of lava flows. Unpublished data have been used to modify version by Holcomb and others (1986). Large ellipse divided into fields containing sites of similar age; smaller ellipse is area of confusion having diverse ages clustered together. ***A***, Age classification from dated flows; symbols represent different ages: dots, younger than 250 years B.P.; triangles, 250–500 years B.P.; squares, 500–1,000 years B.P.; hexagons, 1,000–1,500 years B.P.; crosses, 1,500–2,000 years B.P. Open symbols are doubted results. Arrows approximate secular variation. ***B***, Site mean directions for undated surface flows of Kilauea. Dots, pahoehoe; triangles, aa. Open symbols indicate doubted results. ***C***, Stratigraphic section in Uwekahuna Bluff (Doell and Cox, 1965; R.R. Doell, unpublished work). Symbols denote different parts of section: crosses, below Uwekahuna Ash of Puna Basalt (nos. 131–133, 137C–137E); squares, lower section above Uwekahuna Ash Member (nos. 134–137B, 137F–137H); triangles, middle part of section; dots, upper part of section. ***D***, Stratigraphic section in west wall of Mokuaweoweo caldera, Mauna Loa Volcano (Doell, 1969). ***E***, Buried flows of Kilauea, exposed in walls of caldera and pit craters. Symbols indicate stratigraphic position: dots, below hiatus; triangles, above hiatus. Circle indicates anomalous magnetization below hiatus in Makaopuhi Crater. ***F***, Groups of surface flows thought from independent evidence to be closely similar in age: dots, Observatory; triangles, Ai-laau; squares, Kalue; crosses, Volcano; stars, Kipuka Nene; hexagons, Kukuau (Mauna Loa); ellipses, older flows of Kalapana.

Flows with similar magnetization crop out along both rift zones. Among them are a red tephra cone and lava flows (paleomagnetic site 9B345) exposed beneath a yellow tephra layer in the west wall of Pauahi Crater (fig. 12.23). Mixed flow assemblages (8B253, 8B349, 8B313, 8B289, 8B277) between Kaimu and Kupapau (fig. 12.5*F*,*G*; older Kalapana flows of fig. 12.11) indicate sustained eruption from the middle east rift zone near Kalalua, and other mixed flows around Kapoho (9B181, 8B973, 8B817) may represent sustained eruption from the lower east rift zone near Puu Honuaula (fig. 12.5*H*). Tube-fed flows with similar magnetization on the north flank in Hawaiian Beaches (9B853) and Ainaloa (8B805) subdivisions (fig. 12.5*H*) may have been erupted from the summit or from the middle east rift zone. This old north-flank lava supports a monotonous forest in which separate flows cannot be distinguished (figs. 12.24, 12.25); forest patchiness probably is caused by ohia dieback (Jacobi, 1983) rather than flow boundaries.

Their similar magnetizations suggest that these flows were erupted within a few centuries preceding the Uwekahuna Ash Member, but ages are not yet well constrained. Because a Mauna Loa flow (8B697) dated by ^{14}C at about 1.8 ka (W–3850) is magnetically similar, these Kilauea flows were assigned ages of 2.0–1.5 ka by Holcomb and others (1986). But Lockwood and Rubin (1986) now judge the Uwekahuna Ash Member above them

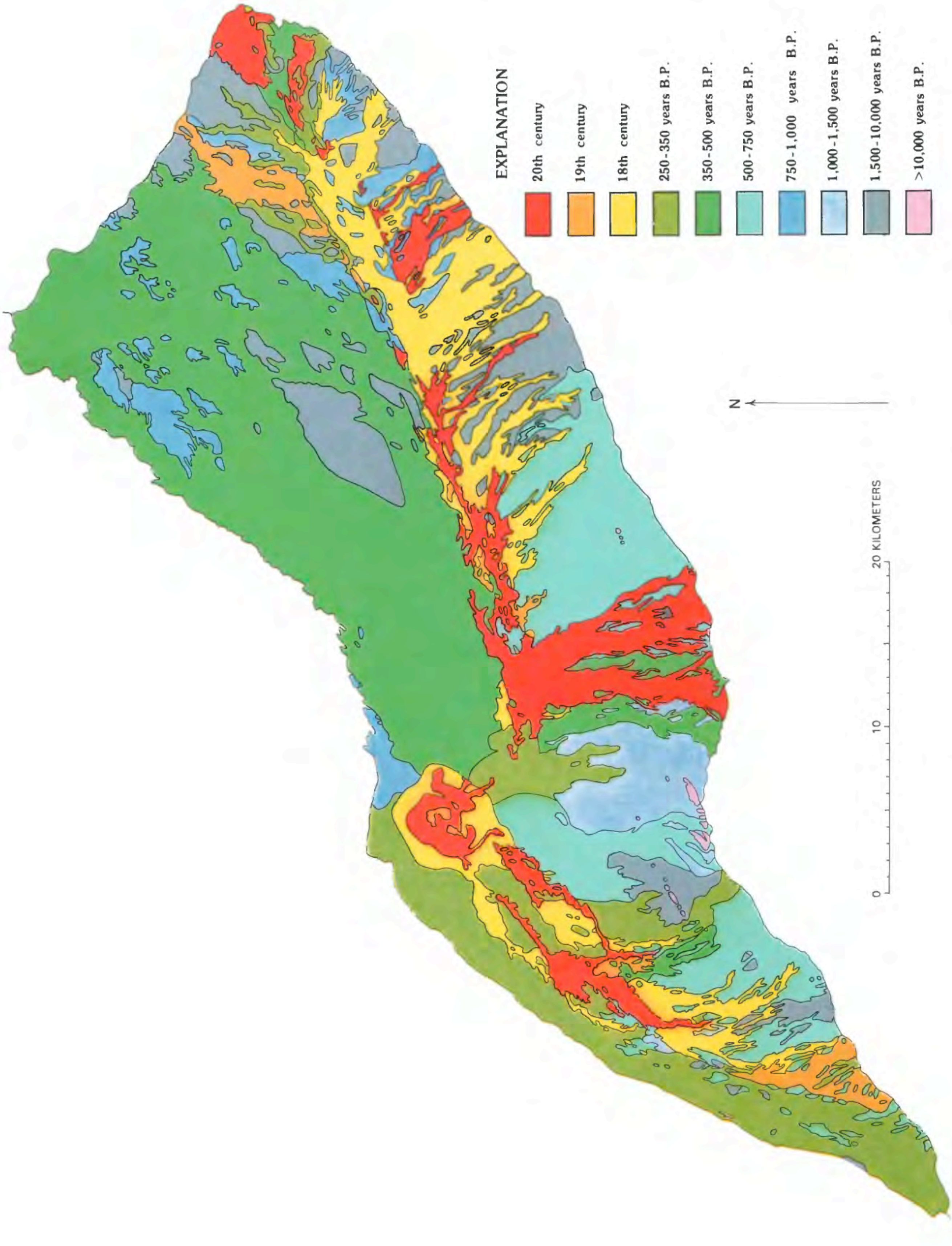


FIGURE 12.12.—Stratigraphic map of Kilauea, showing approximate ages of surficial lava flows. Modified from Holcomb (1980b).

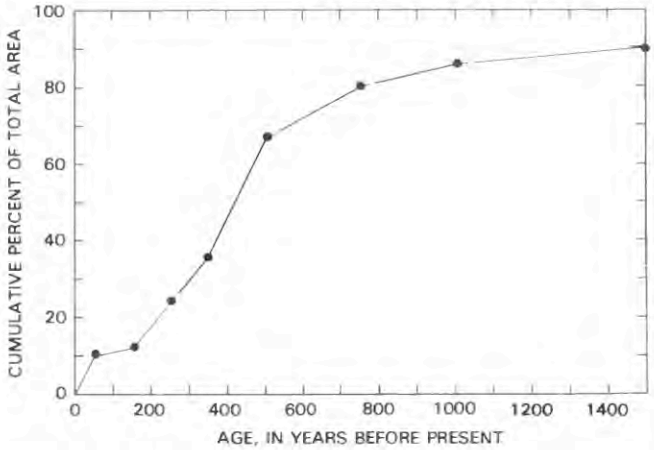


FIGURE 12.13.—Age of Kilauea's surface, a graphical presentation of data in table 12.2. Large variation is shown in rate of flooding, intervals 0–100 and 400–600 yr B.P. having high rates and intervals 100–200 and 1,000–1,500 yr B.P. having low rates. Lower apparent rates of earlier intervals arise partly from later coverage of older flows by younger lava.

to have an age of 2.1 ka, and stratigraphic relations permit most of the flows to be older. Lava east of Kaimu, possibly correlative with 8B313, has been dated at about 2.4 ka by ^{14}C (W–5052, fig. 12.5*G*). Ages of about 2.1 ka and 2.2 ka have been obtained for pahoehoe in a quarry at 786-m elevation along the northeast margin of Kilauea (W–4369 and W–3885). Ash-veneered aa on the rim of Kukalauula Pali is dated at about 1.8 ka (W–4119, fig. 12.5*C*), but its magnetization is not known. Though their ages remain uncertain, lava flows from the summit and east rift zone probably covered much of Kilauea within the few hundred years before the development of the Powers caldera.

POWERS CALDERA

That an ancient caldera was buried before the present one developed was inferred by Powers (1948) because the Uwekahuna Ash Member occurs in the base of Uwekahuna Bluff at an elevation of about 1,100 m, while at Tree Molds it occurs at about 1,220 m (Doerr, 1933). The exposure in Uwekahuna Bluff must cap an old caldera block that subsided about 120 m. This inference is confirmed by paleomagnetic data; flows above the Uwekahuna Ash Member are magnetically similar to Kilauea's surface flows (fig. 12.11*C*) and indicate rapid accumulation in the last millenium. If this thick section is coeval with the thin carapace elsewhere but is younger than higher flows beneath the Uwekahuna Ash Member at Tree Molds, it must fill a caldera.

The configuration of the Powers caldera is poorly known. A buried outer rim is inferred to coincide with the outermost structures of the modern caldera because the outer fault west of Uwekahuna predates the most recent collapse (fig. 12.5*A*). This outer rim did not bound a deep sink because it is little more than 100 m higher than older rock exposed beneath the Uwekahuna Ash Member in Uwekahuna Bluff; a shallow subsided annulus at least 1 km wide, similar to the present one, must have existed. Faulting within that annulus is suggested by draping of the Uwekahuna Ash Member over a step 30 m high formerly exposed in the face of Uwekahuna Bluff (Powers, 1948).

The age of the Powers caldera also is not yet well constrained. It is probably older than 1,300 years because its oldest overflows are thought to be about 1,100 years old, and at least a few hundred years of filling should have preceded overflow. The caldera and Uwekahuna Ash Member should be close in age if caldera collapse caused the explosive eruption. Holcomb and others (1986) inferred an age of about 1.5 ka for both caldera and ash, but they may be older. Eight ^{14}C ages currently available for the Uwekahuna Ash Member range from about 1.0 ka to about 2.2 ka. Lockwood and Rubin (1986) now believe that the younger ages reflect sample contamination and judge the age of the ash to be about 2.1 ka. An age of 1.5 ka is retained in this report; several generalizations herein may need revision if further work confirms the older age. Casadevall and Dzurisin (chapter 13) adopt the older age and discuss some of its possible consequences.

SUMMIT HIATUS

Collapse of the Powers caldera was followed by a caldera-filling interval in which no lava spread from the summit onto the flank. Dzurisin and Casadevall (1986) believe that this interval was very short (only a few years) because the uppermost pumice of the Uwekahuna Ash Member in Uwekahuna Bluff was not eroded before it was covered by lava. But the uneroded pumice could be much younger than the rest of the ash, and paleomagnetic data suggest a long interval between flows below and above the ash. Lava beneath the ash has magnetization consistent with an age greater than 1.5 ka (9B229A; sites 133, of Doell and Cox, 1965, and 137D,E of R.R. Doell, unpublished work), while lava above the ash has magnetization consistent with an age of about 0.75 ka (1B618; sites 137F,G,H of R.R. Doell, unpublished work).

A surface marking a hiatus is exposed also in three pit craters. In Kilauea Iki Crater (fig. 12.26) it lies between flows separated by a red cinder layer. In Pauahi Crater (fig. 12.27) and Makaopuhi Crater (fig. 12.28) it lies above weathered ash and debris on which a forest grew, so that tree molds were produced when the area was flooded by lava. Paleomagnetic samples have been collected from lava flows just above and just below the hiatus in each crater (Kilauea Iki, 8B145 below, 8B157 above; Pauahi, 9B385 below, 9B217 above; Makaopuhi, 9B157 below, 9B241 above). The flows above are all younger than 1.0 ka (fig. 12.11*E*). Flows below have directions indicating pre-Powers caldera ages older than 1.5 ka, except for one. The lower flow in Makaopuhi has a direction corresponding to less than 1.0 ka; if the direction is correct, it suggests only a brief hiatus and rapid forest growth there. But because no stratigraphic evidence bounds its age, the flow could be much older; alternatively, it may have been remagnetized during rapid accumulation and slow cooling of the Kane Nui o Hamo lava shield above it. With this possible exception, the hiatus is correlative

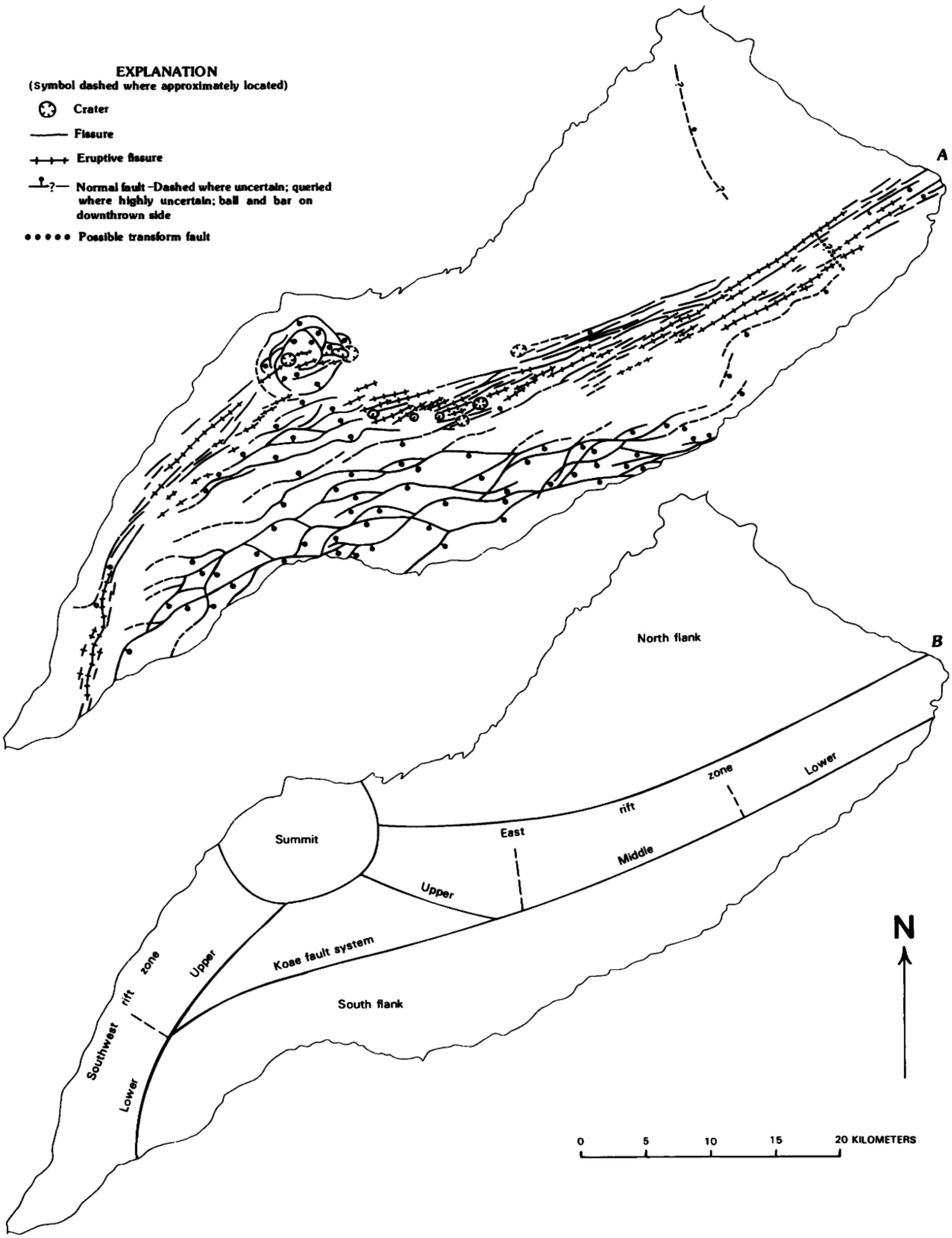


FIGURE 12.14.—Structure of Kilauea. ***A***, Mapped structures, simplified from Holcomb (1980b). ***B***, Structural subdivisions, modified from Swanson and others (1976a).

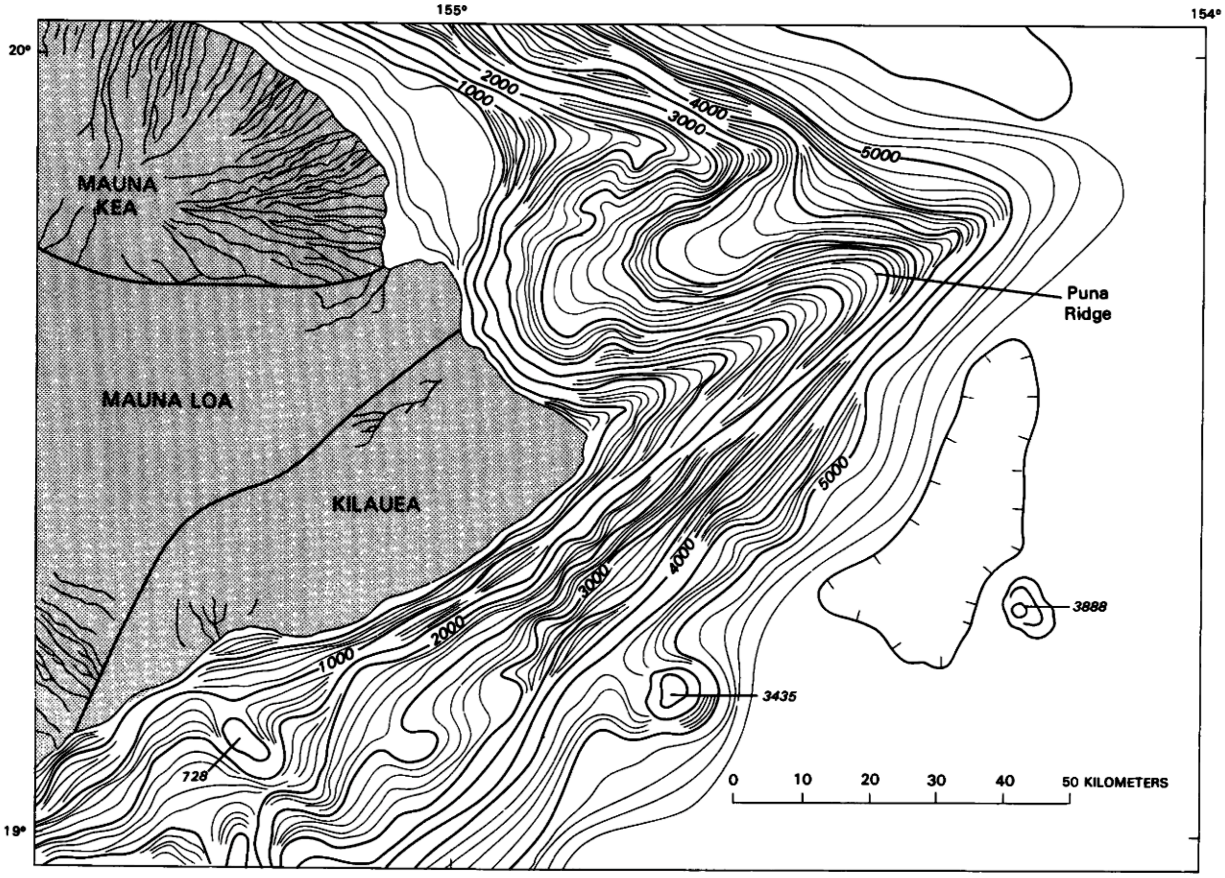


FIGURE 12.15.—Bathymetry around eastern part of Hawaii, showing Puna Ridge. From Wilde and others (1980); depths in meters; contour interval 100 m. Hachures indicate area of closed low depression.

at all sites and spans more than 500 years from more than 1.5 ka to less than 1.0 ka.

Coincident with this hiatus is a paucity of eruptions along subaerial parts of the rift zones. A small pyroclastic cone of the lower east rift zone east of Kiapu has been dated at about 1.3 ka by ^{14}C (W–4674, fig. 12.5*H*), and paleomagnetic data have suggested one group of flows (9B829, fig. 12.5*B*; 3R409, fig. 12.5*C*) in this interval along the southwest rift zone. No others are known, however; most eruptions in this interval were probably confined to a deep inner sink or submarine segments of the rift zones.

KIPUKA NENE FLOWS

The earliest overflows from the Powers caldera may be the tube-fed flows of Kipuka Nene and Kipuka Papalinamoku, which form much of the coast between Keauhou and Kaaha (fig. 12.5*D*). The flows have a distinctive magnetization (1B224, 1B456, 3R013; table 12.5) similar to Mauna Loa flows (4A276) dated at about 1.1 ka by ^{14}C (W–3910, 1,270 years B.P.; W–5083, 1,030 years B.P.). If the Kipuka Nene flows do postdate the Powers caldera, they are probably about 1.1 ka. Available stratigraphic evidence, however, does not require them to postdate the caldera. Additional uncertainty is caused by other nearby flows having different magnetizations but ^{14}C ages also of about 1.1 ka, as noted later in discussion of the Kalue flows.

Initial errors in dating the Kipuka Nene flows illustrate well the difficulties encountered in work of this kind. Though the Kipuka Nene flows are clearly veneered by surficial deposits and vegetation that are absent on overlying Kalue flows (fig. 12.29), it was difficult to find the exact boundary between them. Initially inferring the boundary to parallel the west side of a prominent band of trees, I collected paleomagnetic samples in 1978 from sites 8B121 and 8B133 on each side of this boundary (fig. 12.30*A*). The results revealed the same magnetization at both sites (table 12.5; fig. 12.30*B*). Wanting to make sure that I had really sampled the older flows, in 1979 I collected from site 9B169 south of a fault that extended through Kipuka Nene. This fault seemed to be overlapped to the west by the younger Kalue flows, and I reasoned that lava on the southern rim of the fault scarp must belong to the older flows. The results again gave virtually the identical magnetization, so I

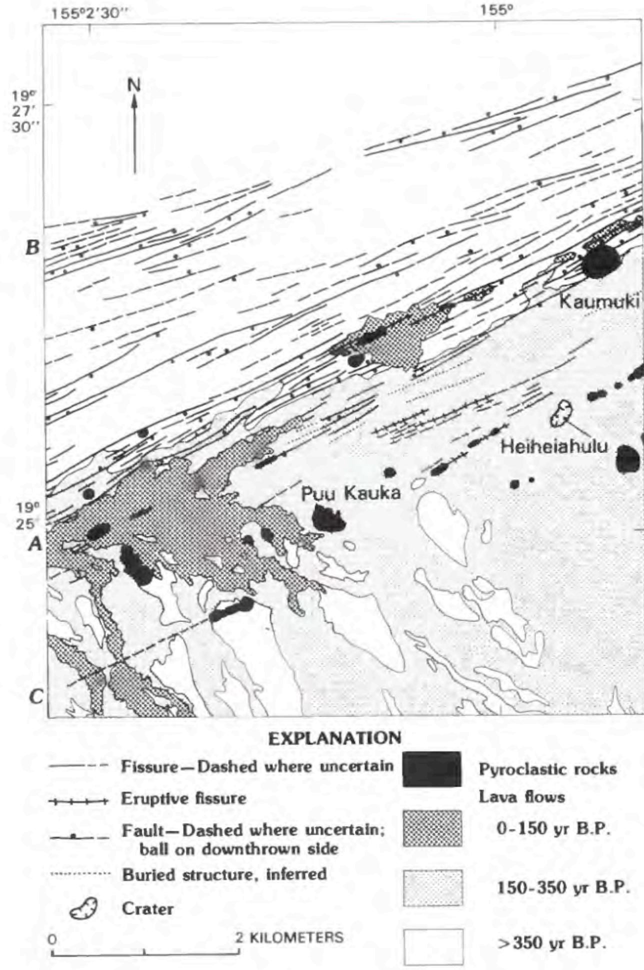


FIGURE 12.16.—Eastern part of middle east rift zone, with contrasting surficial structure north and south of active zone A–A'. North edge of rift zone is along B–B'; south edge along C–C'. Lava flows 350–500 years old north of A–A' broken by many fissures but no eruptive vents; flows 150–250 years old south of A–A' have many vents but few younger fissures. Flooding south of A–A' probably followed large dilation of rift zone a few hundred years ago.

FIGURE 12.17.—Unusual eruption products of Kamakaia Hills. Photographs by R.T. Holcomb, 1977. ***A***, Kamakaiwaena, one of several cinder cones found only in this area of Kilauea, and peculiar near-vent lava flow in foreground. View northeast (see figure 12.48 for location). ***B***, Closer view, looking west, of same flow, which consists of thick, cylindrical, toothpastelike extrusions that twisted back on themselves and then broke as they cooled. These protrusions are morphologically distinct from all other flow forms seen on Kilauea and resemble some elongate pillows of submarine lava flows. Scale indicated by aerial-photograph case (about 25 cm wide) perched on day pack.

assigned the Kipuka Nene flows a young age similar to that of the Kalue flows and tried to explain the difference in surficial cover by inferring that a tephra-producing eruption at Kane Nui o Hamo (which shares the same magnetization) had occurred during a short interval between the two sets of lava flows. However, still not being satisfied, in 1981 I collected from two more sites, 1B236 on the rim of Kalanaokuaiki Pali and 1B456 deep within Kipuka Nene. This time I found a distinctly different magnetization (fig. 12.30*B*). Then N.G. Banks found beside the Kipuka Nene picnic shelter a contact between two lava flows, with a thin deposit of ash between them. In 1983 I collected 3R001 and 3R013 on each side of this contact and found two different magnetizations corresponding to the two measured previously: the boundary had finally been discovered. Though I have not traced it away from the picnic shelter, it must extend roughly as shown in fig. 12.30*A*, about 100 m east of the contact inferred initially.

The distinctive Kipuka Nene magnetization is also shared by the flows of Opihikao (8B013; fig. 12.5*H*); they may have been erupted from Puulena or Kahuwai, which are notable for their phreatomagmatic ash blanket (Moore, 1983). Other eruptions of this age are not yet known from elsewhere along the rift zones.

VOLCANO FLOWS

Volcano village is built on flows forested differently from younger Ai-laau flows (fig. 12.31). One of these older flows is dated

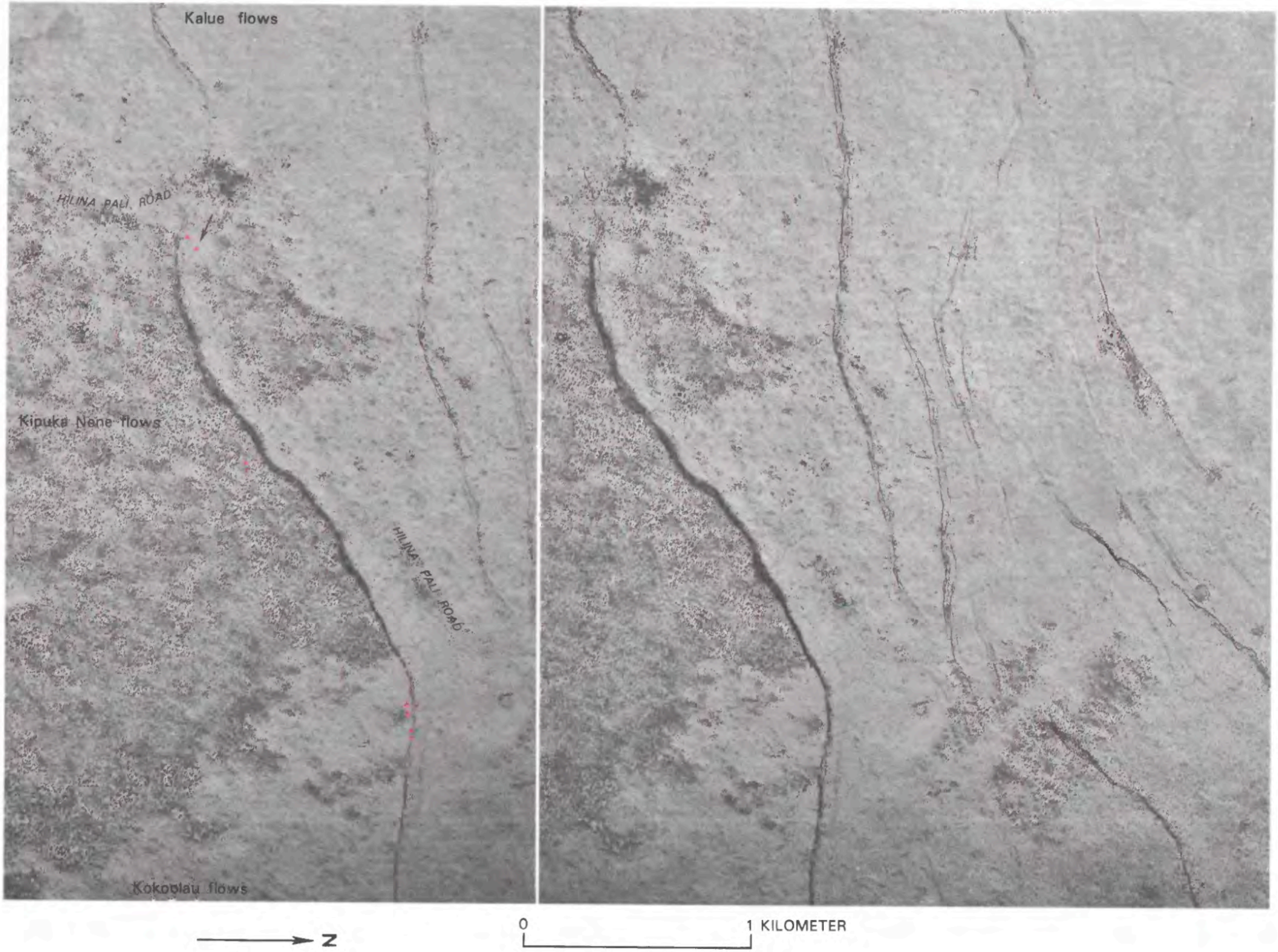


FIGURE 12.18.—Contrasting vegetation patterns along Kalanaokuaiki Pali. Barren Kalue and Kokoolau flows interpreted to postdate much of fault displacement, while tree-covered Kipuka Nene flows are thought to predate it. Pattern of polygonal plates (arrow) at base of cliff is characteristic of ponded lava. Duffield (1975, p. 10) argued against ponding because similar smooth surface is found on south side of fault, but smooth surface is not extensive there, lacks polygonal pattern, and could have formed from spreading of pond as it rose above scarp that initially held it back. Pairs of small red dots, paleomagnetic sample sites. Stereo pair prepared from frames 74, 75 of roll 14CC, USDA series EKL, 1965.

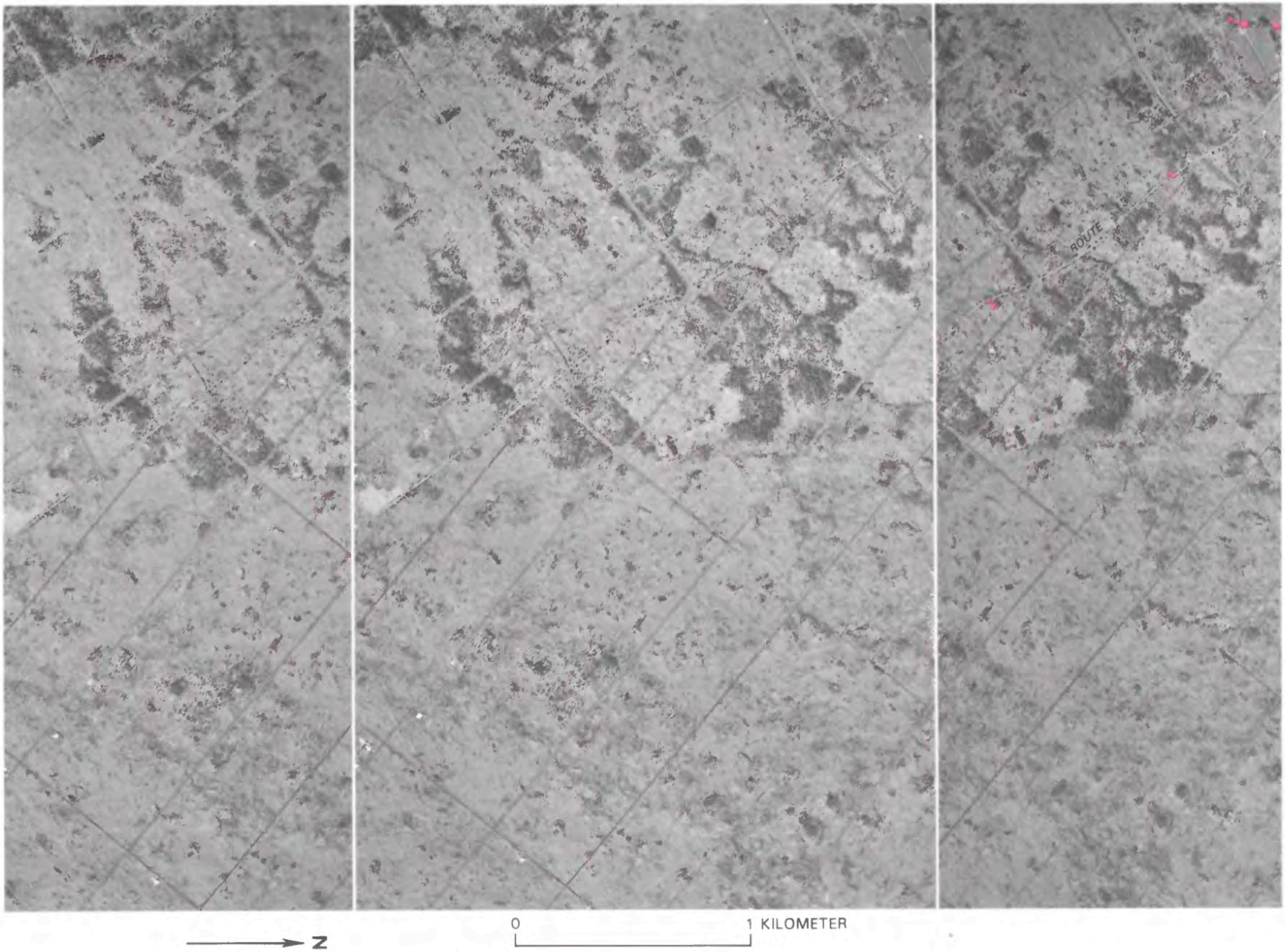
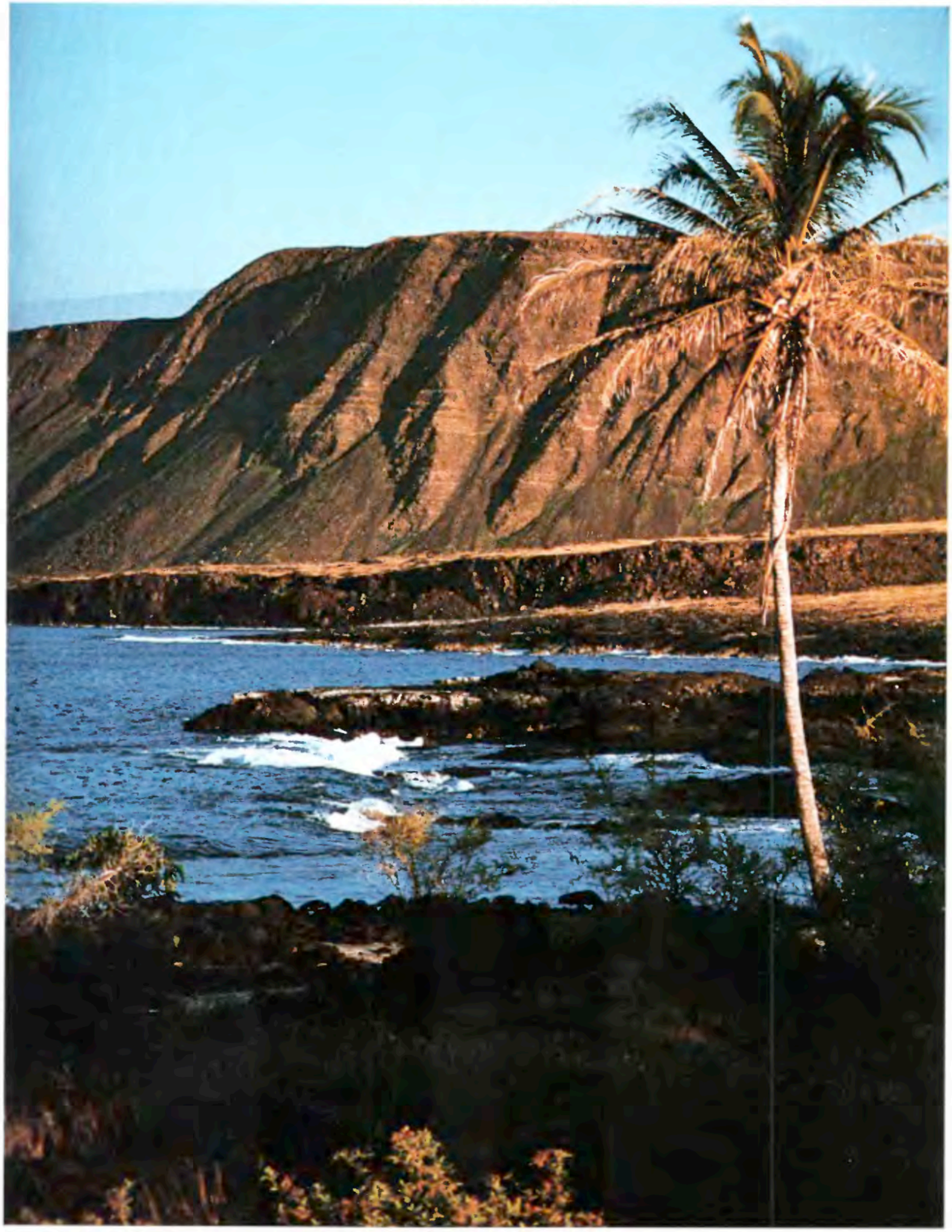


FIGURE 12.19.—Topographic and geologic discontinuity southeast of Keaau (see fig. 12.3). Sharp vegetation change extending north-south corresponds to flow boundary; young Ai-laau flows to east are highly inflated on a wide coastal plain, while older flows to west form kipukas elongate northeast-southwest between less inflated lobes of young lava extending down steeper slope to coastal plain. Pairs of small red dots, paleomagnetic sample sites; larger red dots, ^{14}C sample sites. Stereo triplet prepared from frames 64–66, roll 12CC, USDA series EKL, 1965.



A

FIGURE 12.20.—Oldest rocks exposed on Kilauea. ***A***, Puu Kapukapu, viewed from Keauhou Landing. Most of visible stratigraphic section, about 300 m thick, is included in Hilina Basalt, with cap of Pahala Ash 10–20 m thick. Lower fault scarp in front of Puu Kapukapu displaces lava flows of Kipuka Papalinamoku thought to be about 1,100 yr old. Foreground, composed of lava 350–500 yr old, subsided beneath sea level during earthquake of November 29, 1975. Profile of Mauna Loa visible beyond Puu Kapukapu, to left. Photograph by R.T. Holcomb, April 1974. ***B***, Closer aerial view of Puu Kapukapu, showing lava flows and prominent ash layers in Hilina Basalt. Rim of Hilina Pali visible beyond Puu Kapukapu, to left. Photograph by D.A. Swanson, June 1971.

B

FIGURE 12.20—Continued.

at 730±80 years B.P. by ^{14}C (W–3999), and its magnetization (8B685) is consistent with age of 750–1,000 years B.P. A flow resting above the Uwekahuna Ash Member in the Volcano rubbish dump has been dated at about 1,000 years B.P. by ^{14}C (W–5319). A source has not been established for these flows; Holcomb (1980a, b) interpreted them as caldera overflows, and this is consistent with their magnetic similarity to flows in the eastern caldera wall below Waldron Ledge (1B776, 1B788) and to the flow above the hiatus in Kilauea Iki (8B157). They could have come from the northeast rift zone of Mauna Loa, however; nearby Mauna Loa flows draped over a Kaoiki fault scarp 2 km north of Tree Molds (fig. 12.5*A*) have similar magnetization (8B841) and ^{14}C age (830±60 and 530±60 years B.P., W–3879 and W–3880, respectively). It is conceivable too that flows exposed in Kilauea Iki (8B157) and the eastern caldera (1B680, 1B692, 1B776, 1B788) also were erupted from Mauna Loa and flowed into the Powers caldera.

The Volcano flows may extend far down the flank of Kilauea. Much of the north flank is surfaced by younger Ai-laau flows, but older flows above the Pahala Ash are exposed in kipukas south of Keaau (fig. 12.5*J*). Aerial photographs reveal rudimentary fluvial drainage on the kipukas but not the younger flows (fig. 12.21). The

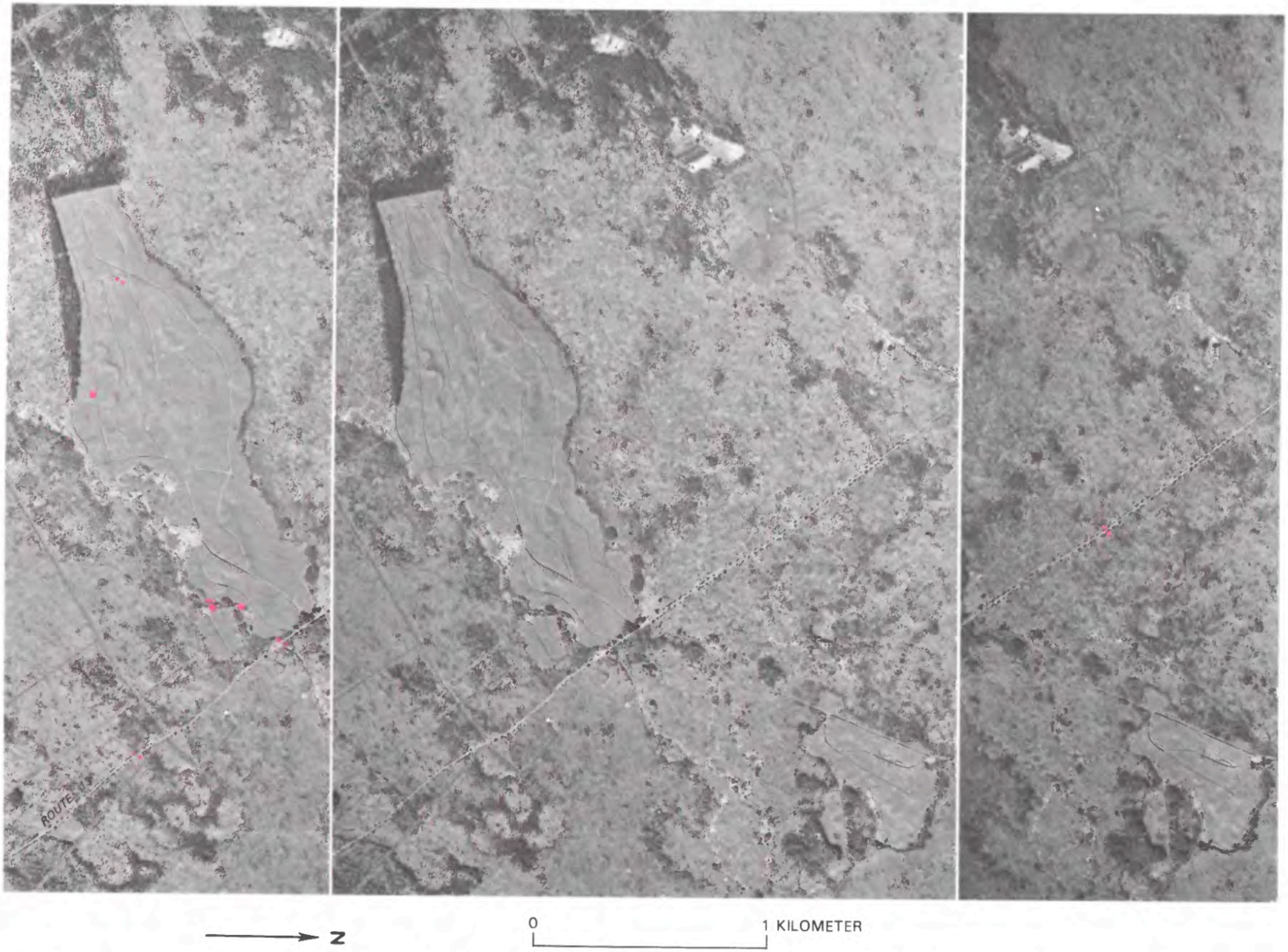


FIGURE 12.21.—Lava flows of three ages southeast of Keaau. Old ash-covered Mauna Loa flows are occupied by truck farms and fields of sugar cane, while Kilauea flows are uncultivated. Two groups of Kilauea flows differ in age and appearance: Older flows have blotchier vegetation pattern and incipient drainage channels absent on younger flows; ohia trees cluster atop younger flows near their margins. Flow groups differ in their directions of remanent magnetization. Large red dots, ^{14}C sample sites; pairs of small red dots, paleomagnetic sites. Some small clumps of ohia along axes of younger flows are known to occur above lava tubes. Thick stand of trees bordering southern and western sides of largest cane field is an artificial planting of Norfolk pines and other trees. Stereo triplet prepared from photographs 81–83, roll 12CC, USDA series EKL, 1965.

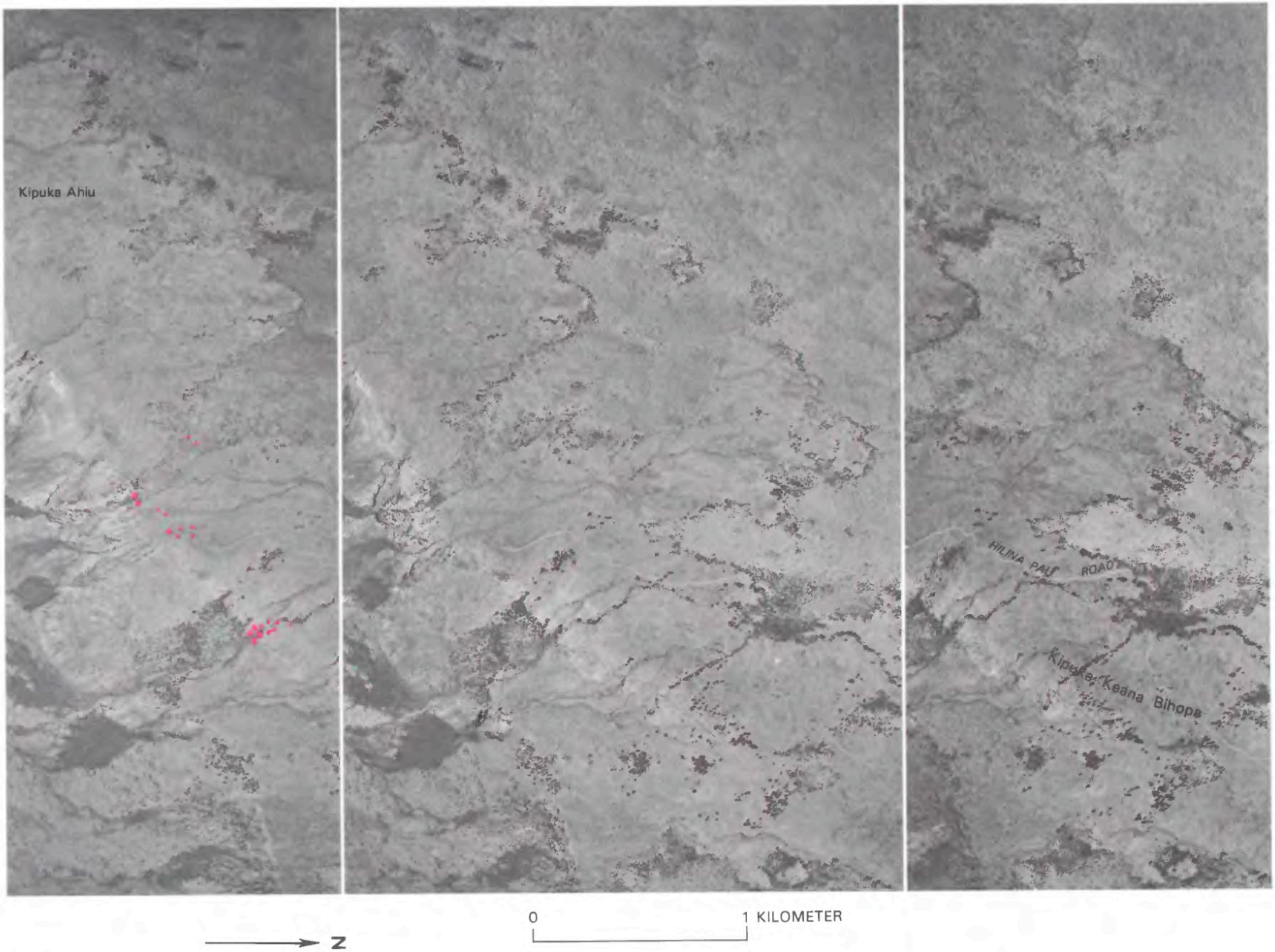


FIGURE 12.22.—Vegetation contrasts near end of Hilina Pali Road. Kipukas are carpeted by range grass on veneer of ash and sand, while barren areas to north are dotted only by low trees and shrubs. Walker (1967) thought contrasts arose from partial stripping of an ash deposit, but Holcomb (1980b) believed them to reflect lava flows of different ages. Some bare patches within kipukas may arise from stripping or nondeposition; others may be tongues of younger lava flows. N.G. Banks (unpublished work) has found lava younger than 1,000 yr at some places within kipukas. Large red dots, ^{14}C sample sites; pairs of small red dots, paleomagnetic sites. Stereo triplet prepared from frames 4–6, roll 5CC, USDA series EKL, 1965.

FIGURE 12.23.—Red tephra cone left of center exposed in west wall of Pauahi Crater. Crater of cone was choked with coarse debris and then filled by ponded lava, which cooled to produce massive block with radial jointing. Exquisitely detailed molds of tree ferns are found in lower part of pond. Yellow tephra layer of figure 12.27 occurs higher in wall on both sides of cone and dips down toward crater. Hiatus above yellow tephra is apparently correlative with hiatus beneath lava pond, and yellow tephra may be coeval with coarse debris within buried crater. People at upper left stand on overlook along Chain of Craters Road; overlook was later moved about 100 m to right. On crater floor at lower right is perched lava pond (Holcomb and others, 1974) active on this day. Workers on crater floor are measuring deformation of floor, which is crust of fresh lava lake being domed by continued injection of lava. Foreground, septum between west pit and larger central pit of Pauahi; septum is veneered by thin crustal plates of lava lake that subsided within central pit a few weeks earlier (Tilling and others, chapter 16). Lava has since broken through crust of west pit and dribbled across septum into central pit. Photograph by R.T. Holcomb, December 4, 1973.

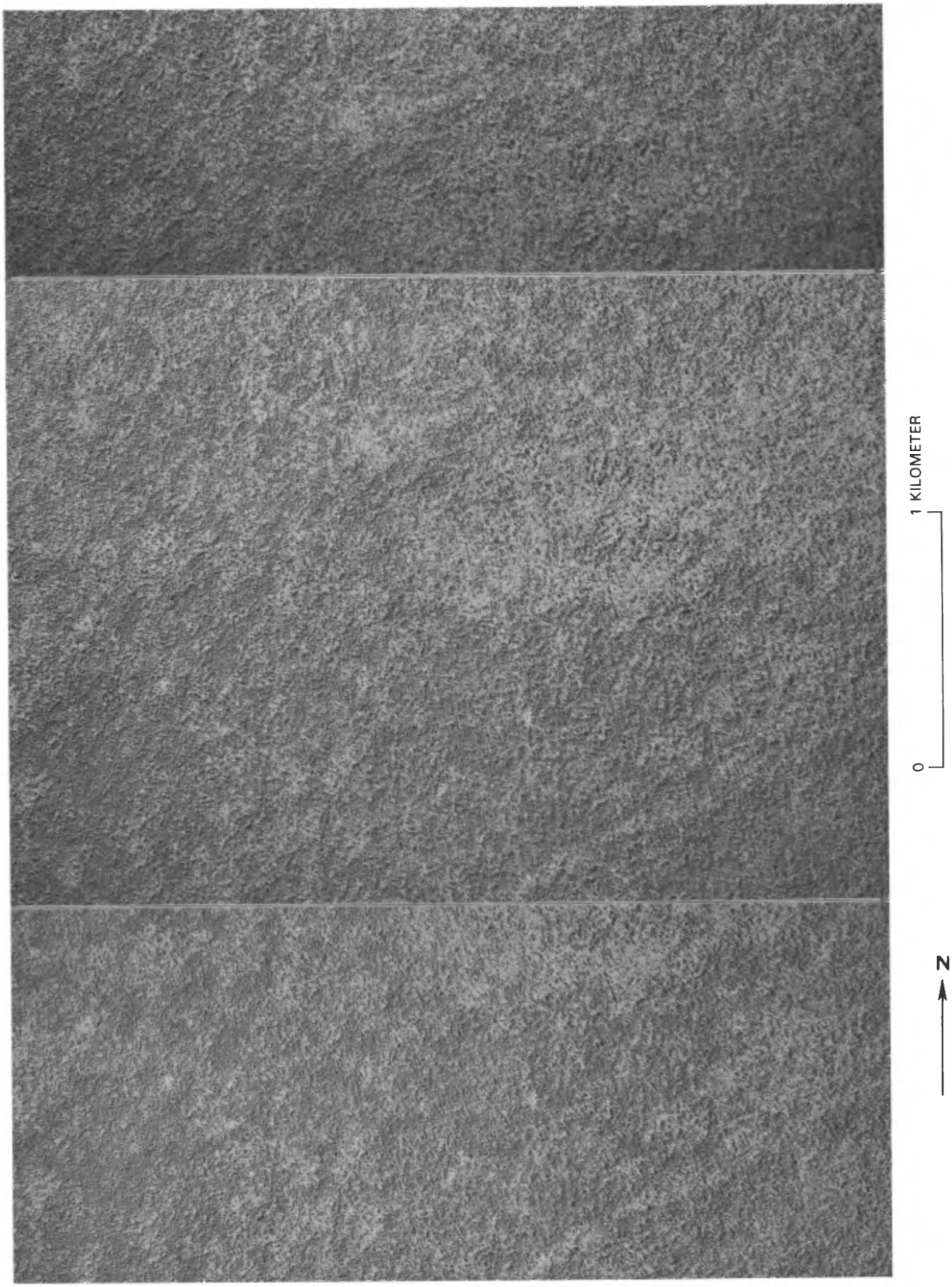


FIGURE 12.24.—Monotonous forest along north side of middle east rift zone, developed on lava flows older than 1,500 years. Aerial photographs could not be used to identify lava-flow boundaries here, but ground traverse showed that major boundaries must exist (fig. 12.25). Prominent rift structures are visible in southeast corner, and broad low swell, elongate east-northeast to west-southwest near center of this view, may be an ancient feature of rift zone. Stereo triplet prepared from frames 125–127, roll 12CC, USDA series EKL, 1965.

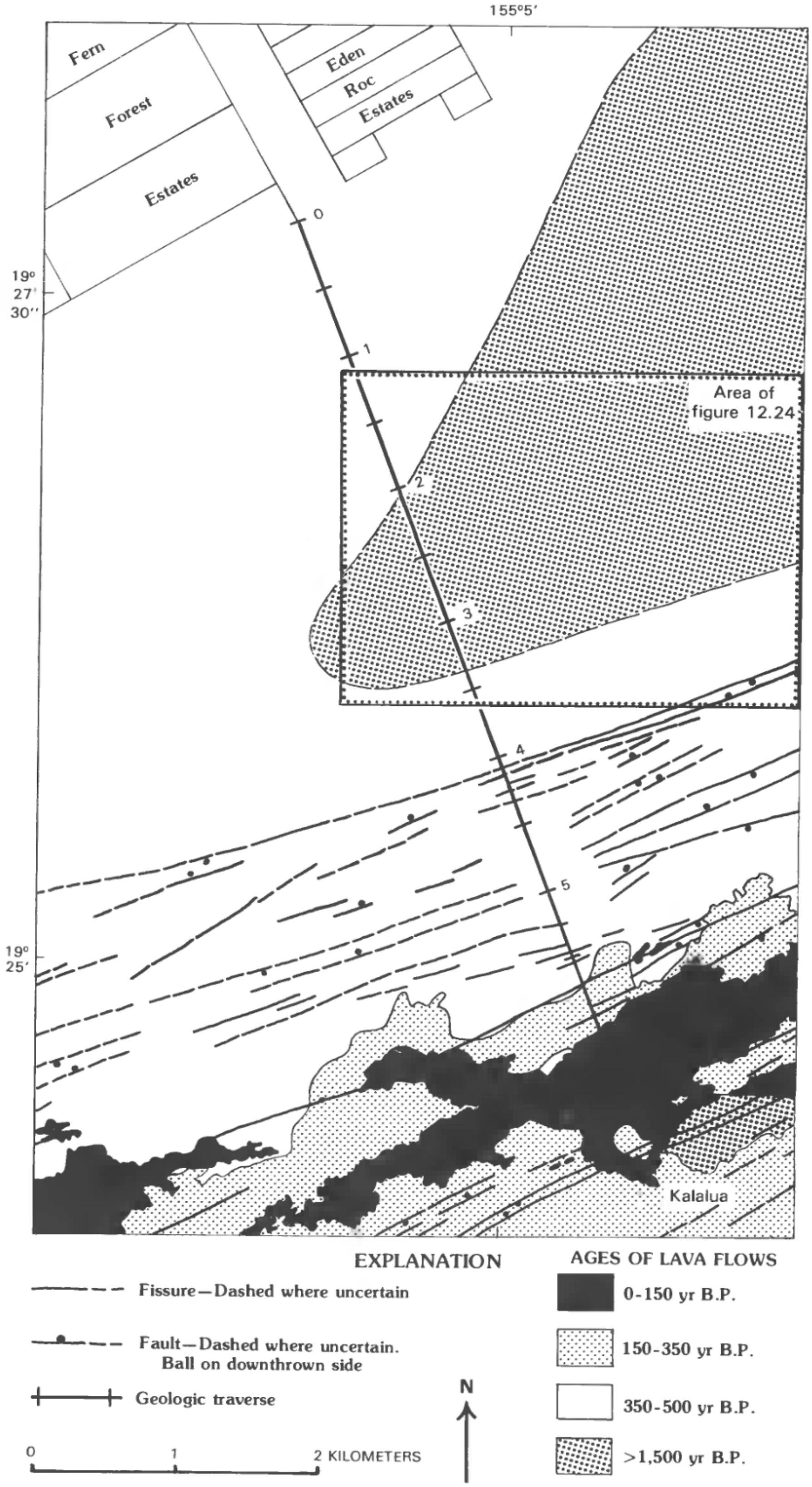


FIGURE 12.25.—Geologic map of Kilauea north flank adjacent to middle east rift zone. Contacts within area of figure 12.24 inferred from changes in rock type found along one tape-and-compass traverse through forest, indicated by heavy line marked at 0.5-km intervals.

older flows are more weathered and have a different vegetation pattern. Tree molds in the younger flows show that trees were growing on the older flows when they were flooded by the younger lava. The older flows have magnetization (8B049, 8B073, 8B217; fig. 12.11*F*, crosses) similar to those at Volcano, but they are similar also to 9B889 (fig. 12.5*J*), which is tentatively correlated with lava dated at about 3.7 ka (W–4177). They are also magnetically similar to a Mauna Loa flow (8B901) upslope from Mountain View dated at about 5.6 ka (W–3862). This magnetic direction is near that for a geocentric axial dipole; it is frequently repeated and is therefore not very diagnostic of age.

A few flows along Kilauea's rift zones are also magnetically similar. Among them is the flow above the hiatus in Pauahi Crater (9B217), which could represent an overflow from the summit. Another is the Kaliu flow (8B361 and 9B493, fig. 12.5*G*,*H*), which overlies the flows of Opihikao, but its measured magnetic dispersion is high and its age is therefore uncertain. Ash-covered pahoehoe of Waiakahiula Two (8B097, fig. 12.5*J*) above Pahoa also has this direction, as do flows of Keahialaka and Pohoiki (8B373, fig. 12.5*H*; Moore, 1981), but they could be older. A site (9B865, fig. 12.5*B*) on the lava shield of Ponohohoa Chasms also is similar, but here again the age is not constrained stratigraphically. An unnamed pyroclastic cone of the lower east rift zone, 2 km northeast of Iilewa Crater (fig. 12.5*G*), has been dated at about 900 years B.P. by ^{14}C (W–4690), but its magnetization is not known.

Tube-fed pahoehoe flows on the inland side of the lower southwest rift zone (fig. 12.5*C*) have yielded ^{14}C ages of about 900–1,000 years (W–5147, W–5211, W–5215). The source of these flows is uncertain; they could have spread down the west flank of Kilauea from a source on Mauna Loa, or they could have come from the summit of Kilauea. They may be coeval with the flows from the Observatory vent if that vent is older than the Ai-laau vent, as discussed in a later section, despite distinctly younger ^{14}C ages for the Observatory flows.

In summary, though several flows are tentatively assigned to Kilauea eruptions 750–1,000 years ago, most are equivocal. Stratigraphic uncertainty permits many to be older, and of those dated by ^{14}C, all except one could have been erupted from Mauna Loa.

KALUE FLOWS

Much of the Koae fault zone north and west of Kipuka Nene (figs. 12.18, 12.29) is surfaced by barren lava thought to have overflowed the southern caldera rim. These flows are not easily differentiated from other so-called regional pahoehoe (Walker, 1967) barren of vegetation above Hilina Pali, but they are magnetically distinct (fig. 12.11*F*, squares). Below the pali they are easily distinguished from older flows, being darker (fig. 12.32) and less green because of less weathering and less surficial cover. Between Hilina Pali and Puu Kaone they are split into four main lobes; two cascaded over the coastal cliffs to form the Kakiiwai and Kalue lava deltas, and a third forms the shoreline at Kaaha.

The magnetization of these flows is shared by others to the west (fig. 12.5*C*), including the pahoehoe of Kipuka Pepeiau (8B493), the Naliikakani flows (3R481), and the Waiwelawela flows (8B529; but site 3R421 on the Waiwelawela flows has yielded a different result). The Opihinehe flows (fig. 12.5*D*) are probably coeval. Because no lava shield of this age is known along the southwest rift zone, these extensive flows are inferred to come from the same summit source as the Kalue flows.

Similar magnetization is also shared by extensive pahoehoe seaward of the east rift zone (fig. 12.5*E*,*F*) from Kupapau to Kaena Point (8B229, 8B241, 3R157, 3R181) and beneath the eastern flows of Mauna Ulu (3R097, 3R109, 3R121, 3R133, 3R169, 3R193, 3R229). The eruption of Kane Nui o Hamo fed these flows. The size of the lava shield and large extent of its tube-fed flows suggest that this was the longest and most stable eruption of any known along either rift zone, but no other rift eruptions of similar age have been found.

The age of this group is uncertain, and because it illustrates the contradictions still existing among stratigraphic, paleomagnetic, and ^{14}C data, some details will now be given. The magnetization of this group is consistent with an age of 750–500 years, according to the preliminary chronology of Holcomb and others (1986), and the magnetically distinct Kipuka Nene flows beneath are judged from other evidence to have an age of 1.1 ka, as noted earlier. Yet charcoal from beneath one of the upper flows (3R001; fig. 12.30) in Kipuka Nene indicates an age of 1.15 ka (W–5135) for Kalue lava. The problem is compounded by two other flows in Kipuka Keana Bihopa (fig. 12.5*D*) with still different magnetizations but ^{14}C ages of 1.14 ka (W–5212) and 1.13 ka (W–3827). Though the magnetic inclinations of both latter flows (8B397, 3R025) differ from those of Kalue, their declinations are similar; they could be coeval with Kalue flows but have inclinations affected by a topographic magnetic anomaly along Hilina Pali. If so, the three ^{14}C dates would agree well in assigning an age of 1.14 ka to the Kalue flows instead of the 500–750 years adopted here. If this were true, then the magnetically distinct older flows of Kipuka Nene would have to be older than its assigned age, and possibly predate the Powers caldera.

AI-LAAU FLOWS

Much of Kilauea's north flank is covered by tube-fed flows extending northeast from the summit to the coast between Haena and Honolulu Landing. The Ainaloa, Kazumura, Old Volcano Trail, and other flows of this group are well-known for their large lava tubes. Despite high rainfall in this area, the flows are little weathered and support a juvenile forest (figs. 12.5*J*, 12.21) implying that they are young. Their vegetation was even lighter in the 19th century, eliciting comments from visitors. For example, Wilkes (1845, p. 119) observed in 1840 that "After leaving Olaa, we had no distinct path to follow; for the whole surface became a mass of lava, which retained all its metallic lustre, and appeared as if it had but just run over the ground—so small was the action of decomposition. There were only a few stunted bushes on our track." Even a critique accusing Wilkes of exaggeration (by "A.V." in the February 1, 1847, issue of a missionary journal, *The Friend*) described vegetation different from today, saying "the road from Olaa to the

A

FIGURE 12.26.—Hiatus exposed in Kilauea Iki Crater. Photographs by J.D. Griggs, December 1985. ***A***, Northeast wall of crater below Byron Ledge overlook, showing color change on face of cliff. Tree-covered recess at right is older Ai-laau part of crater. ***B***, Closer view of color change, which coincides with layer of red cinders. Debris from this layer mantles slopes below, reddening surface and supporting more plant growth than slopes above. Cinder unit is truncated at right by densely vegetated thin lava plaster on wall of Ai-laau crater; plaster may be dregs of subsided lava lake.

volcano is generally very distinct. Ohelo bushes grow much of the way, as other bushes, grass and small trees, on both sides of the road."

Of seven ^{14}C ages obtained from these lava flows (table 12.6), three that duplicate others are anomalous and are disregarded. Others range from 260 to 450 years and average 335 years B.P. They are distinctively magnetized (fig. 12.11*F*, triangles; sites 8B001, 8B061, 8B085, 8B169, 8B193, 8B421, 8B733, 8B793, 9B121, 9B133, 9B421, 9B433, 9B397, 9B673).

Ohia trees clustered along flow margins can be used to delineate individual tube-fed flows (figs. 12.5*J*, 12.21) up to elevations of about 500 m. Separate flows cannot be mapped above this; they disappear upslope into a monotonous young ohia-hapuu forest that extends to the summit region. Thurston Lava Tube and other tubes fanning eastward from the summit fed the multiple lobes distinguished at lower elevations.

The source of the flows is the eastern part of Kilauea Iki (figs. 12.5*A*, 12.33), which is an eruptive crater choked with talus. It is older than the other parts of Kilauea Iki and supports a more mature forest. It is also less deep and has lava plastered against its walls in some places. The rest of Kilauea Iki is deeper, steeper, and lacks wall plaster; it is a chain of later collapse pits. A sagged platform east of this Ai-laau vent resembles those developed above Alae and Aloi Craters after burial (Swanson and others, 1972; Holcomb and others, 1974); a buried pit crater is inferred beneath it. The presence of such a crater, filled with still-cooling lava, could explain a self-potential anomaly mapped by Zablocki (1976) in this area.

Also inferred to come from the Ai-laau vent are magnetically similar (8B109, 8B181, 9B145A) tube-fed flows extending northeast from the middle east rift zone near Kalalua to the coast around Makuu (fig. 12.5*G–J*). Initially these flows were assumed to have come from the rift zone, but no vent could be found; vents inferred by Moore and Koyanagi (1969) are younger fissures crossing the flows, while Kalalua and other pyroclastic cones are older and Puu Kahaualea is younger. Because their vegetation and magnetization are similar to those of the other flows from the Ai-laau vent, they are inferred to be of the same age and come from that same vent. If so, they must have spread east past the northeast side of Kane Nui o Hamo and along the northern part of the rift zone for several kilometers before moving northeast onto the north flank. Fissures, faults, and grabens may have prevented them from crossing the rift zone and spreading farther south. The many structures crossing them must be younger or had recurrent displacement after burial 350–500 years ago.

B

FIGURE 12.26—Continued.

The lightly vegetated Keauhou flows seaward of the upper east rift zone west of Kane Nui o Hamo (figs. 12.5*E*, 12.34, 12.35) have similar magnetization (8B541, 1B432, 3R049, 3R073, 3R085, 3R205, 3R217, 3R265, 3R325, 3R397) and ^{14}C ages (table 12.6). These flows could come from the Ai-laau vent, but they are smaller and include a more complex assemblage of flow types. They probably represent sustained, unstable eruption (table 12.1) from an upper-east-rift vent, most likely Puu Huluhulu. The spatter cone between Hiiaka and Devils Throat also has similar magnetization; this brief eruption may have preceded the sustained one (like the brief eruptions of 1968–69 that preceded the Mauna Ulu eruption of 1969–74) but a stratigraphic relationship has not been established. Some pit craters of the upper east rift zone must postdate these eruptions.

Other flank vents and flows are thought to have similar ages. Two assemblages have similar magnetization. One is the group of Kamakaiauka along the southern strand of the southwest rift zone (fig. 12.5*B*); its age assignment is tentative because only one paleomagnetic site (8B481) has been sampled from an aa flow. Another group along the lower east rift zone (fig. 12.5*H*) includes Kaholua o Kahawali (9B205) and its associated lava flows. A flow younger than Puu Kaliu but older than A.D. 1790 lava has been dated at about 500 years B.P. (W–4688), while a flow at Kehena has been dated by ^{14}C at about 450 years B.P. (W–5054). Puu Honuaula and a flow 2 km southwest of Puu Kaliu are dated at about 350 years B.P. (W–5048, W–3800).

Macdonald (1941) and Holcomb (1980a) included several other vents with Kaholua o Kahawali because the legend of Pele and Kahawali suggests that a long chain of vents erupted at the same time. But mapping by R.B. Moore (1981) has not confirmed this. Moore believes that Kaholua o Kahawali and an adjacent cone are significantly younger than Halekamahina and other nearby vents. Moore has also mapped as much older a flow having similar magnetization (8B037) east of Kapoho Crater.

One other Puna flow should be mentioned, the prominent aa flow of Makaukiu Point between Nanawale and Cape Kumukahi (fig. 12.5*H*). A ^{14}C age of 350 years B.P. (W–5088) has been obtained from charcoal beneath this flow, and chemical weathering data suggest an age of 300–350 years (Atkinson and Swindale, 1974). Moore (1981) has mapped it as one of the youngest prehistoric units in the Kapoho area because it still projects beyond the adjacent shoreline to form Makaukiu Point. However, this flow is clothed by a mature *Pandanus* forest that implies it is much older (Atkinson, 1970), and paleomagnetic data (8B973, 9B181) indicate that it and the flows beneath are older than 1.5 ka.

Dating is not yet precise enough to determine relative ages of eruptions within this interval, and it is not clear whether the rift eruptions are younger or older than the Ai-laau vent. Some Hawaiian traditions suggest a sequence: Kaholua o Kahawali and the flows seaward of Puu Huluhulu are associated with the current volcano goddess Pele (Ellis, 1827; Macdonald, 1941), while activity at Kilauea Iki is associated with Pele's predecessor, Ai-laau

A B

FIGURE 12.27.—Hiatus exposed in north wall of Pauahi Crater. Photographs by J.D. Griggs, October 1985. ***A***, Northwest wall of Pauahi, viewed from overlook shown in figure 12.23. Hiatus occurs atop yellow tephra layer. ***B***, Closeup view of yellow tephra, which is mixture of blocks and ash. This tephra may consist in part of Uwekahuna Ash Member, but because it grades laterally into coarse debris in crater of buried tephra cone nearby (fig. 12.23), at least some of it may have been ejected from local source. Organic ash is abundant atop tephra, and overlying lava flow contains many tree molds.

(Westervelt, 1916). If that chronology is correct, the rift eruptions followed the summit eruption.

OBSERVATORY FLOWS

Lightly vegetated prehistoric tube-fed flows in a band 4 km wide extend down the inland side of the southwest rift zone (fig. 12.5*B*,*C*). They are buried by Keamoku, Mauna Iki, and Cone Peak flows at elevations of 800–900 m but reappear higher up; flows with similar magnetization (1B001, 1B013, 1B025, 1B037, 1B049, 1B061, 1B073, 1B109, 1B133) form the northwest rim of the present caldera (fig. 12.5*A*) and the upper section of Uwekahuna Bluff (5 flows of 1B157; sites 145–148, Doell and Cox, 1965).

Though detailed mapping may show some of these flows to have been erupted on Mauna Loa (possibly more of the lava north of Tree Molds dated by W–3879 and W–3880), the source of at least some was a long-sustained vent located in what is now the northwest caldera near Uwekahuna Bluff. A large lava shield grew around this vent; it is well expressed west and northwest of the caldera rim by ground slopes, mappable aa lobes, and flow lineations radiating from a point about 1 km east of the Hawaiian Volcano Observatory (fig. 12.36). The crater of the Observatory vent may have extended close to Uwekahuna Bluff. Though the large shield and extensive tube-fed pahoehoe indicate that activity was long-sustained at the Observatory vent, the radiating aa lobes indicate some instability toward the end of its activity, like that observed at Mauna Ulu (Tilling and others, chapter 16; Holcomb, 1976a).

Flows of apparently similar age cover the south flank north and west of Kipuka Ahiu and extend over Hilina Pali to the coast west of Kaaha (fig. 12.5*B*,*D*). They consist of multiple units, aa flows from the southwest rift zone being interbedded with pahoehoe flows from the summit. Aa mapped by Walker (1967) as one unit from Puu Koae actually consists of two flows separated by pahoehoe from the summit (fig. 12.37). The western aa flow, traceable directly to Puu Koae, was erupted in the 18th century and lies atop the pahoehoe, while the eastern aa lobe, inferred to come from Cone Crater, lies below the pahoehoe. Another pahoehoe sheet occurs beneath the Cone Crater aa flow. The pahoehoe unit between the aa flows is distinctively picritic. Though Walker (1967) did not map the contact between the picritic unit and older pahoehoe, he did show extensive distribution of picritic basalt with separate symbols,

A

FIGURE 12.28.—Hiatus exposed in Makaopuhi Crater. ***A***, Northwest wall of crater, viewed from west rim, showing lower layer of yellow tephra separated by thin lava flows from upper layer of reddish tephra. Massive lava flows above red tephra occur in flank of Kane Nui o Hamo lava shield. Photograph by R.T. Holcomb, February 6, 1973. ***B***, Closeup view of upper tephra layer, which consists of red and green cinder beds. This layer appears to have been barren of vegetation when it was covered by lava. Photograph by R.T. Holcomb, March 24, 1974. ***C***, Closeup view of lower yellow tephra layer, which consists of blocks and ash. Large size of some blocks indicates they were ejected from local source, such as nearby pit crater ancestral to Makaopuhi. Upper part of this layer is rich in organic ash, and lava flow above it contains many molds of trees and ferns, indicating hiatus in accumulation of lava flows. Photograph by R.T. Holcomb, March 24, 1974. ***D***, Southwest wall of crater, viewed from mezzanine, showing two tephra layers and small tephra cone lower in section. Photograph by R.T. Holcomb, June 30, 1972, when lava from Mauna Ulu was cascading over crater rim to build talus-and-lava cones (Holcomb and others, 1974) against crater wall.

B

C

FIGURE 12.28.—Continued.

D

FIGURE 12.28.—Continued.

and picritic lava has been traced to the southwest rim of Kilauea caldera (T.L. Wright, oral commun., 1976), where it is the top unit beneath the Keanakakoi Ash Member. The Cone Crater aa (8B457) and the picritic unit (1B097) are magnetically similar to the Observatory flows; the older pahoehoe (8B445) is magnetically more similar to the flows of Volcano.

The Observatory flows are of uncertain age. They predate Cone Peak and other 18th-century flows of the southwest rift zone, but their age relative to Ai-laau flows is not yet certain. Vegetation is sparser on Observatory flows, but this probably arises from a rainfall contrast instead of a difference in age: annual rainfall on the north flank is 380 cm (150 in.) versus 75 cm (30 in.) on the southwest flank. Observatory flows have deeper weathering (J. Lockwood, oral commun., 1985), but because they are downwind from summit vents their weathering may have been accelerated by fumarolic acids.

Four ^{14}C ages have been obtained from Observatory flows (table 12.6), but one is anomalous. Sample W–4998 was collected within the caldera near Tree Molds (fig. 12.5*A*) and is the sample most likely contaminated by fumarolic carbon (Rubin and others, chapter 9; Chatters and others, 1969). The other three ages are similar to those for Ai-laau flows. Because the Observatory flows

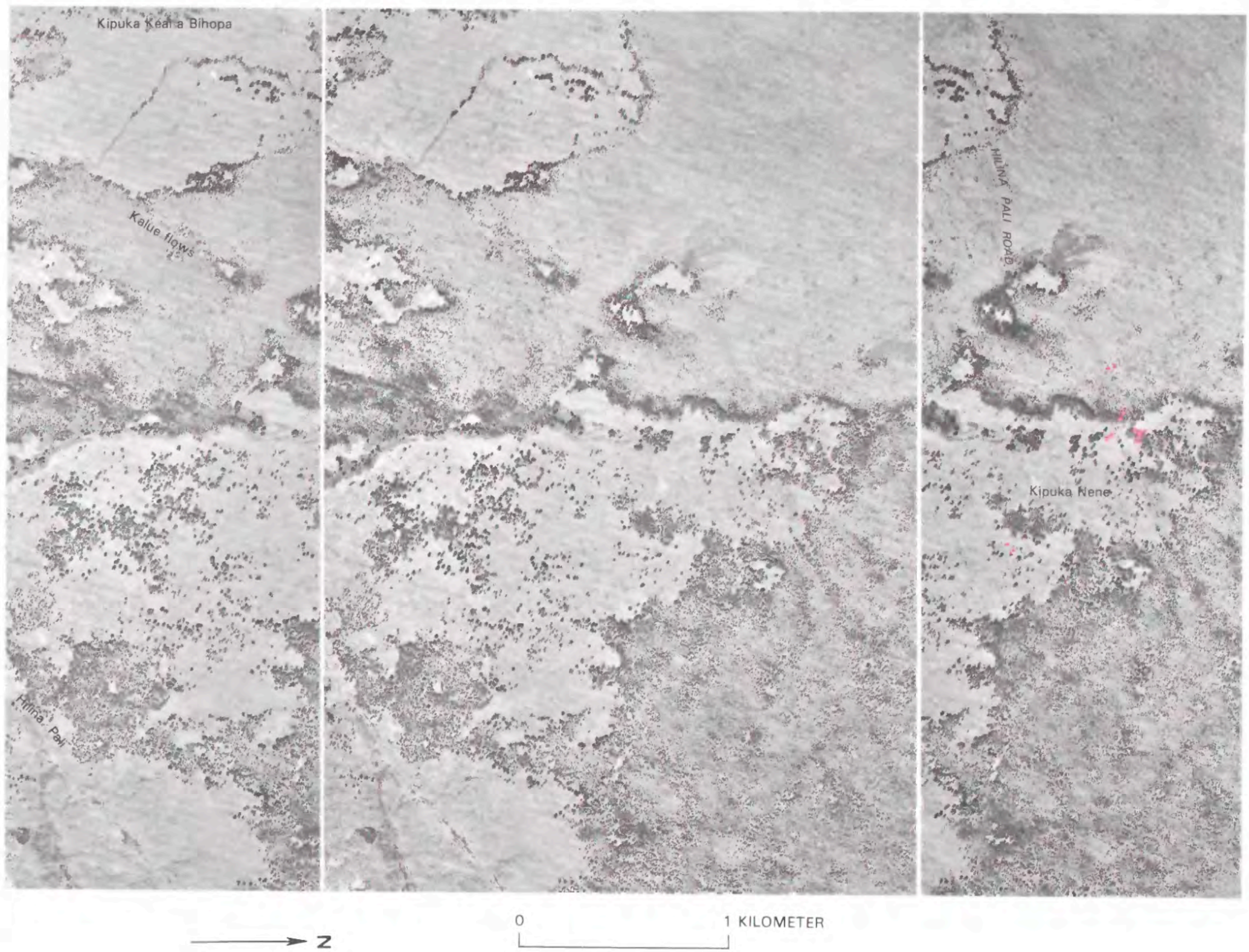


FIGURE 12.29.—Vegetation contrasts in Kipuka Nene area. Kipuka Nene and Kalue flows believed about 1,100 and 500–750 years old, respectively. Though vegetation contrasts generally seem to reflect different ages of lava flows, vegetation boundaries do not follow flow boundaries exactly, as shown in figure 12.30. Large red dot, ^{14}C sampling site; pairs of small red dots, paleomagnetic sampling sites. Stereo triplet prepared from frames 75–77, roll 14CC, USDA series EKL, 1965.

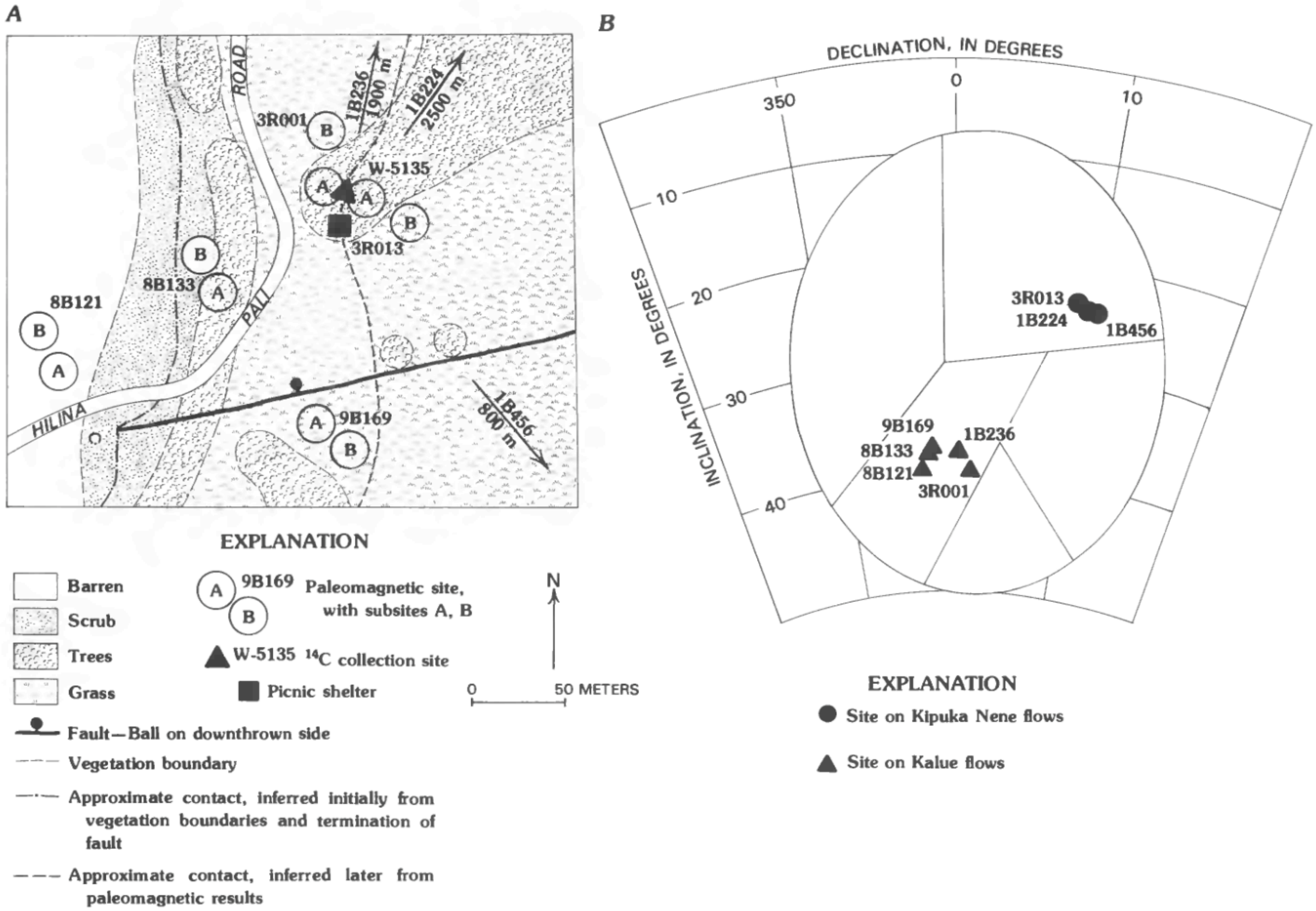


FIGURE 12.30.—Location of Kalue flow margin adjacent to Kipuka Nene. ***A***, Sketch map of Kipuka Nene picnic area, showing flow margin inferred initially and that inferred currently. Margin, traced with certainty only near picnic shelter, does not coincide exactly with vegetation boundary, causing earlier confusion about ages of Kipuka Nene and Kalue lava flows. Boundary between trees and barren lava may follow edge of thicker, inflated part of Kalue flows not easily penetrated by tree roots. Thinner marginal lobes may be penetrated easily by roots of trees but not roots of grass, and sand and soil beneath may provide water and nutrients enhancing tree growth. ***B***, Paleomagnetic results from Kipuka Nene area; Kipuka Nene and Kalue flows are magnetically distinct. Ellipse divided into fields containing sites of similar age, as defined in figure 12.11.

were sampled downwind from summit vents, their ^{14}C ages could be affected by fumarolic carbon, while samples beneath Ai-laau flows from the rainy windward flank could be contaminated by modern organisms. This suggests that the Observatory flows may be younger; but three older ages from the southwest rift zone could also represent Observatory flows (table 12.6), and they would raise the Observatory mean to more than 500 years.

The two flow groups differ magnetically (fig. 12.11*F*), the Observatory direction being intermediate between the Ai-laau and 18th century directions. However, the Observatory magnetization is not far from the axial dipole direction and alone is not diagnostic of age. Holcomb and others (1986) argued that the Observatory flows are younger than Ai-laau flows because lava in Uwekahuna Bluff beneath the Observatory flows seemed to have Ai-laau magnetization, according to the data of Doell and Cox (1965, flows 138–144) and R.R. Doell (unpublished work, flows 137I, 138A, 138B, 139A, 140A, 141A, 141B, 142A). But later sampling (1B582, 1B594, 1B606) has not confirmed the Ai-laau direction in Uwekahuna Bluff; it appears that the inferred Ai-laau samples of Doell and Cox were taken from a rotated fault block. Because the Observatory flows are magnetically not very different from the Volcano flows, they could be similar in age to the Volcano flows and thus 500 years older than judged by Holcomb and others (1986). Detailed mapping and chemical analyses should help sort out ages and sources of these various interfingered flows from Kilauea and Mauna Loa.

LATEST PREHISTORIC ERUPTIONS

Prominent widespread flows along both rift zones span a narrow range of ages. Most of them probably date from the 18th century, though some may be slightly older. This interval of frequent rift eruptions ended with a caldera collapse and explosive eruption at the summit.

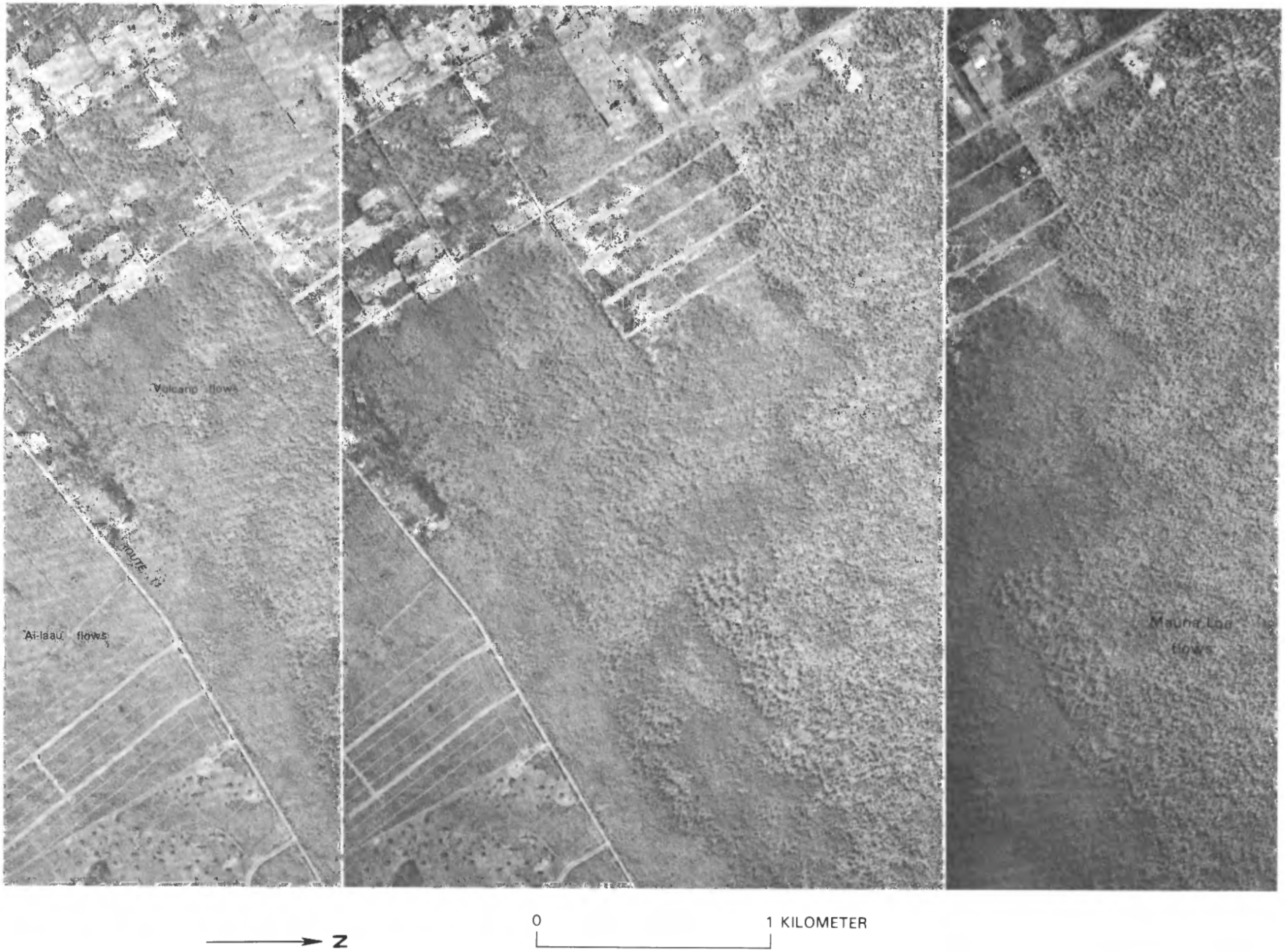


FIGURE 12.31.—Vegetation contrasts between flows of Volcano, older flows of Mauna Loa, and younger flows of Ai-laau vent. Large red dot, ^{14}C sample site; pair of smaller red dots, paleomagnetic sample site. Stereo triplet prepared from frames 183–185, roll 12CC, USDA series EKL, 1965.

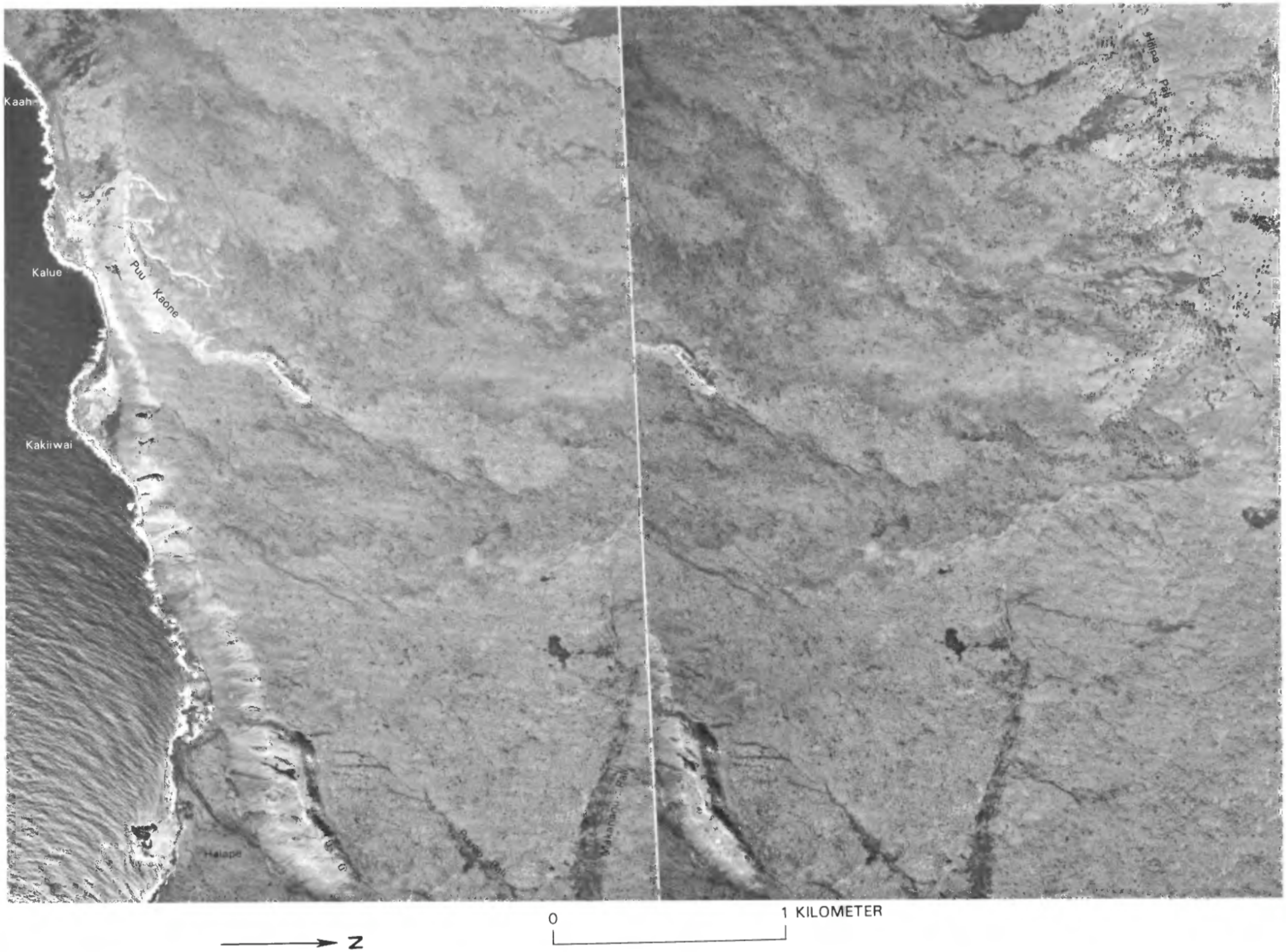


FIGURE 12.32.—Contrasting flow units in area between Hilina Pali and Puu Kaone. Two series of widespread surficial flows differ in photographic tone and surficial cover. Stereo pair prepared from frames 77, 78, roll 14CC, USDA series EKL, 1965.

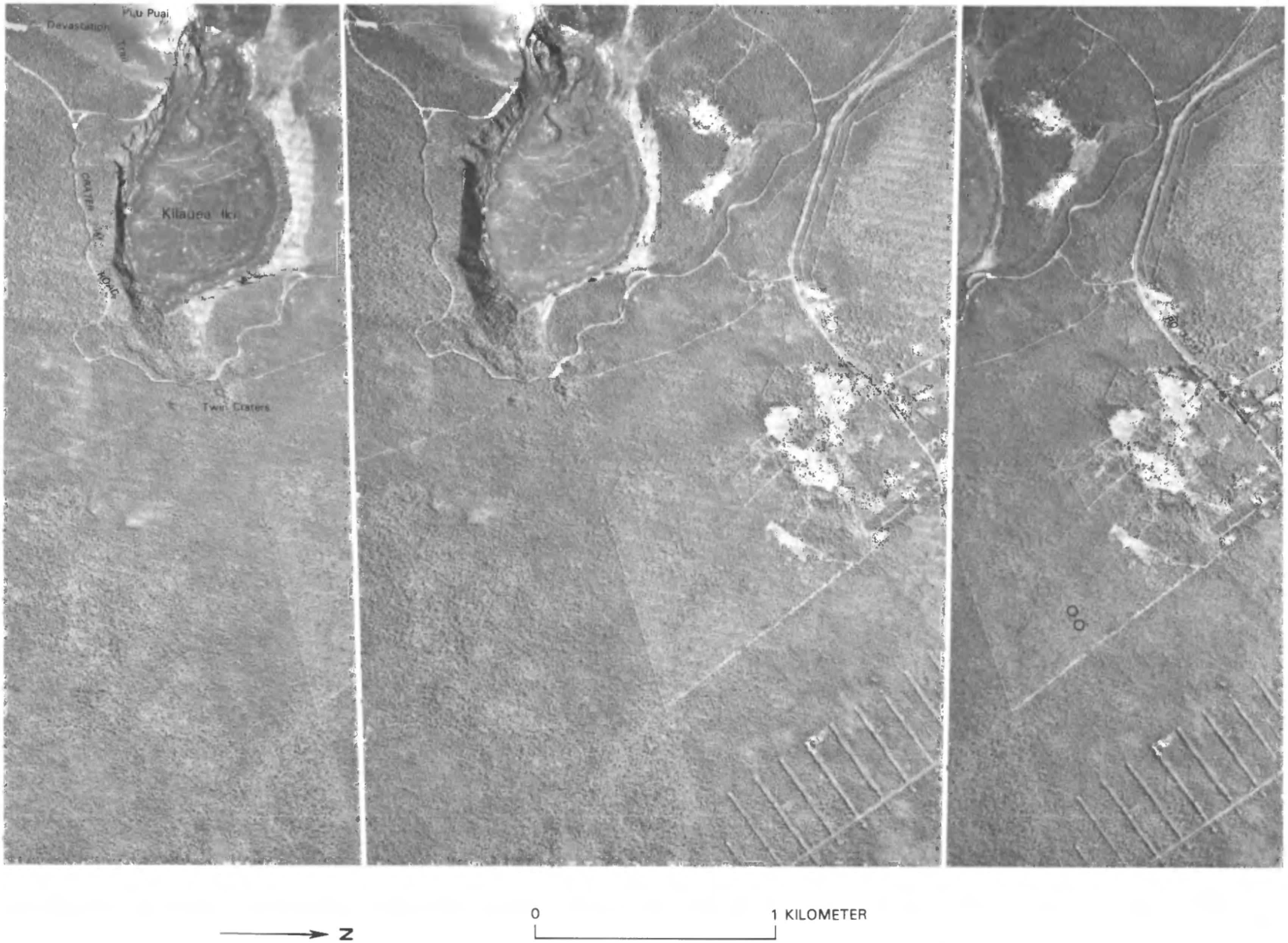


FIGURE 12.33.—Ai-laau vent and lava shield. Kilauea Iki is chain of three or four collapse structures extending eastward from inner sink of present caldera; it contains lava lake erupted in 1959. Ai-laau vent area includes east end of Kilauea Iki and small Twin Craters. Broad, shallow sag southeast of vent area is thought to overlie buried pit crater. Broad ridge with small axial pits (circled) extending northeast from vent area may represent path of major lava tube; similar ridges radiate south and southeast from broad sag, beyond this view. Paired red dots, paleomagnetic sample sites. Stereo triplet prepared from frames 185–187, roll 12CC, USDA series EKL, 1965.

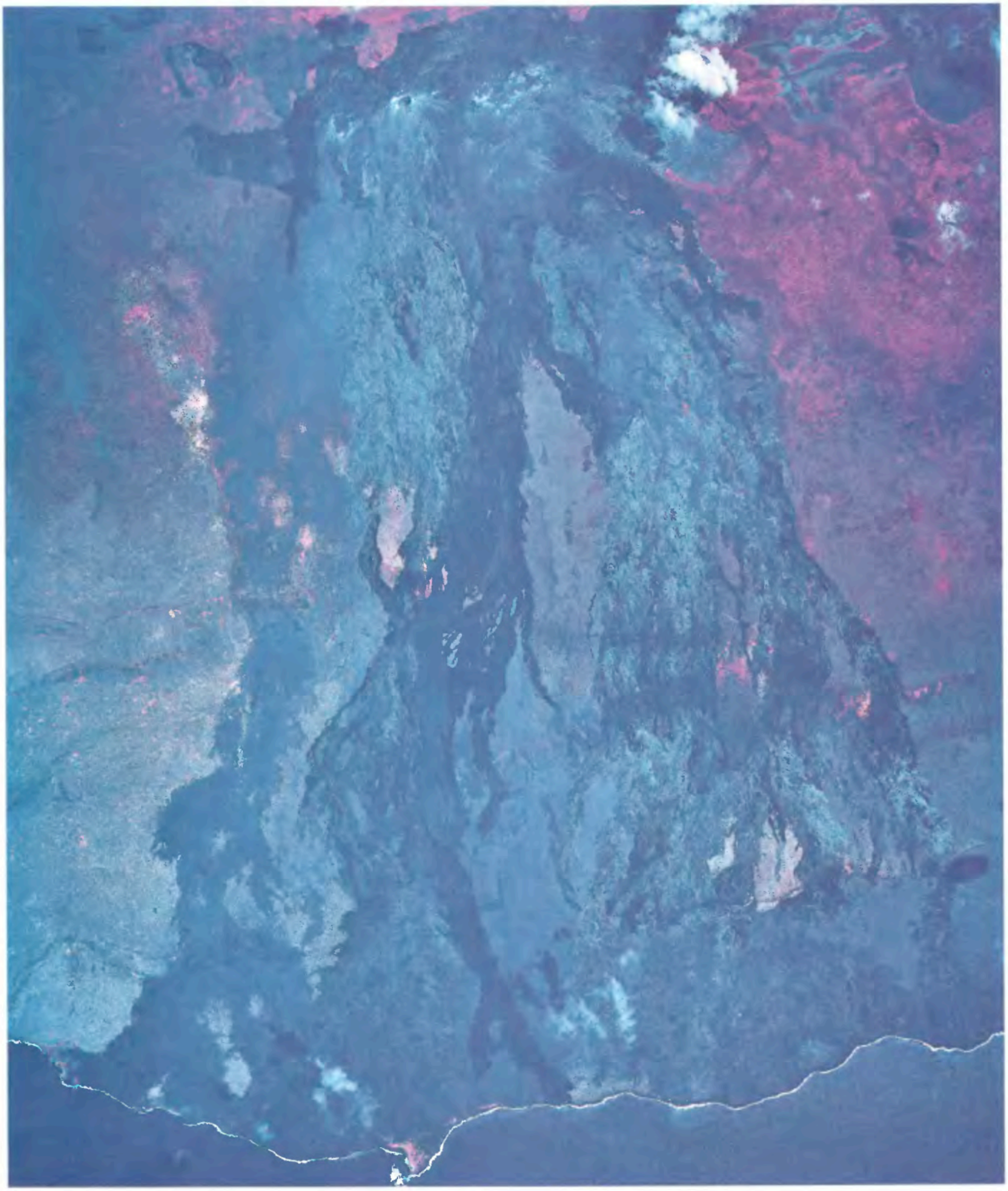


FIGURE 12.34.—Mauna Ulu region of upper east rift zone and south flank. High-altitude false-color infrared photograph showing bands of Mauna Ulu lava in center, flanked to left by Keauhou and Kipuka Nene flows, and to right by flows of Kane Nui o Hamo. Rain forest along rift zone is red; oldest grass-covered flows have very light tones. Barren lava flows are bluish gray and black. Darkest flows are aa; rest are pahoehoe. U2 photograph by NASA Ames Research Center, 1974.

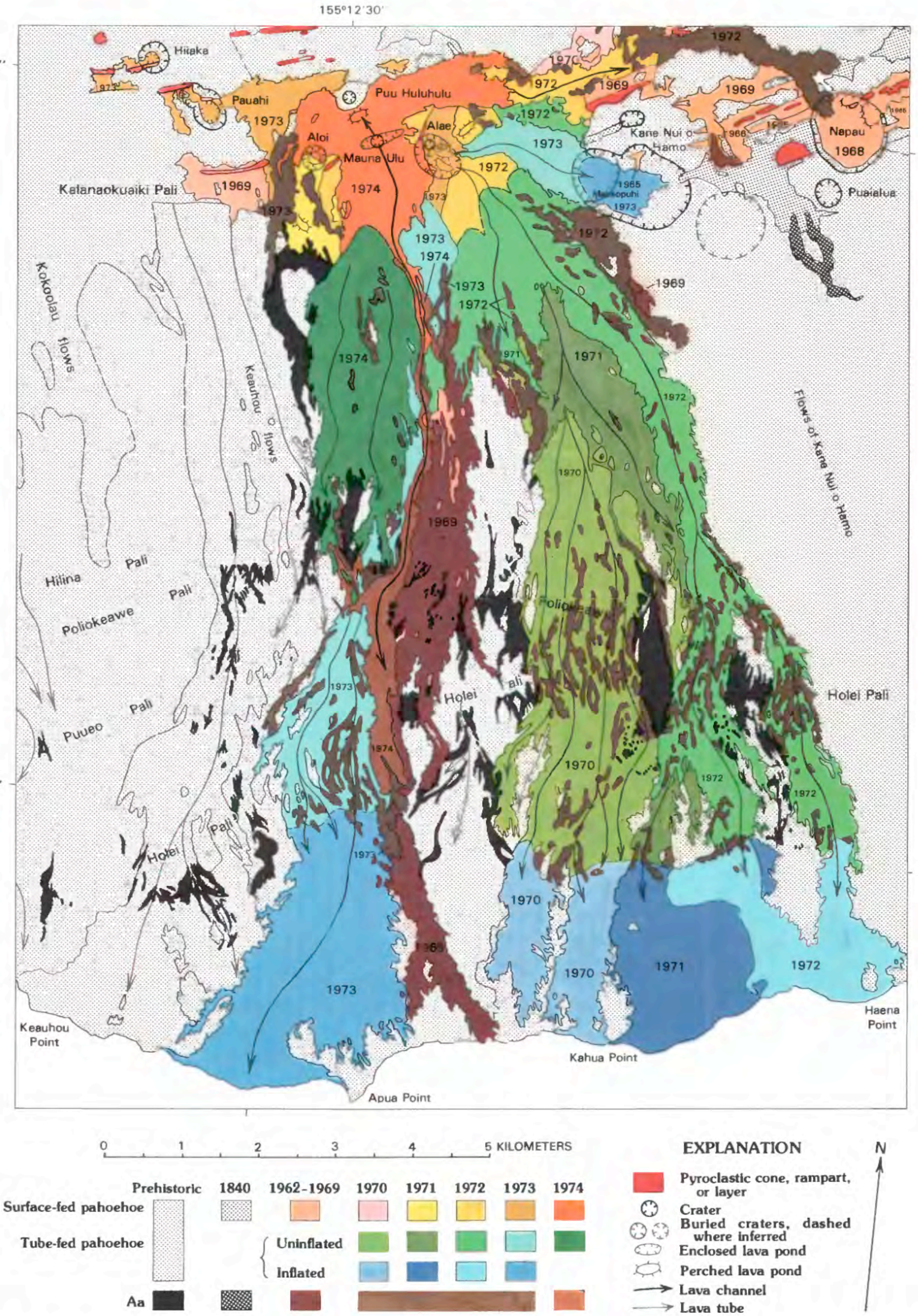


FIGURE 12.35.—Mauna Ulu region, with lava flows classified by their morphology. Shown also are boundaries between pahoehoe units of different age, as indicated on figure 12.5*E*, and eruption years of historical flows. Simplified from Holcomb (1976a, 1980a).

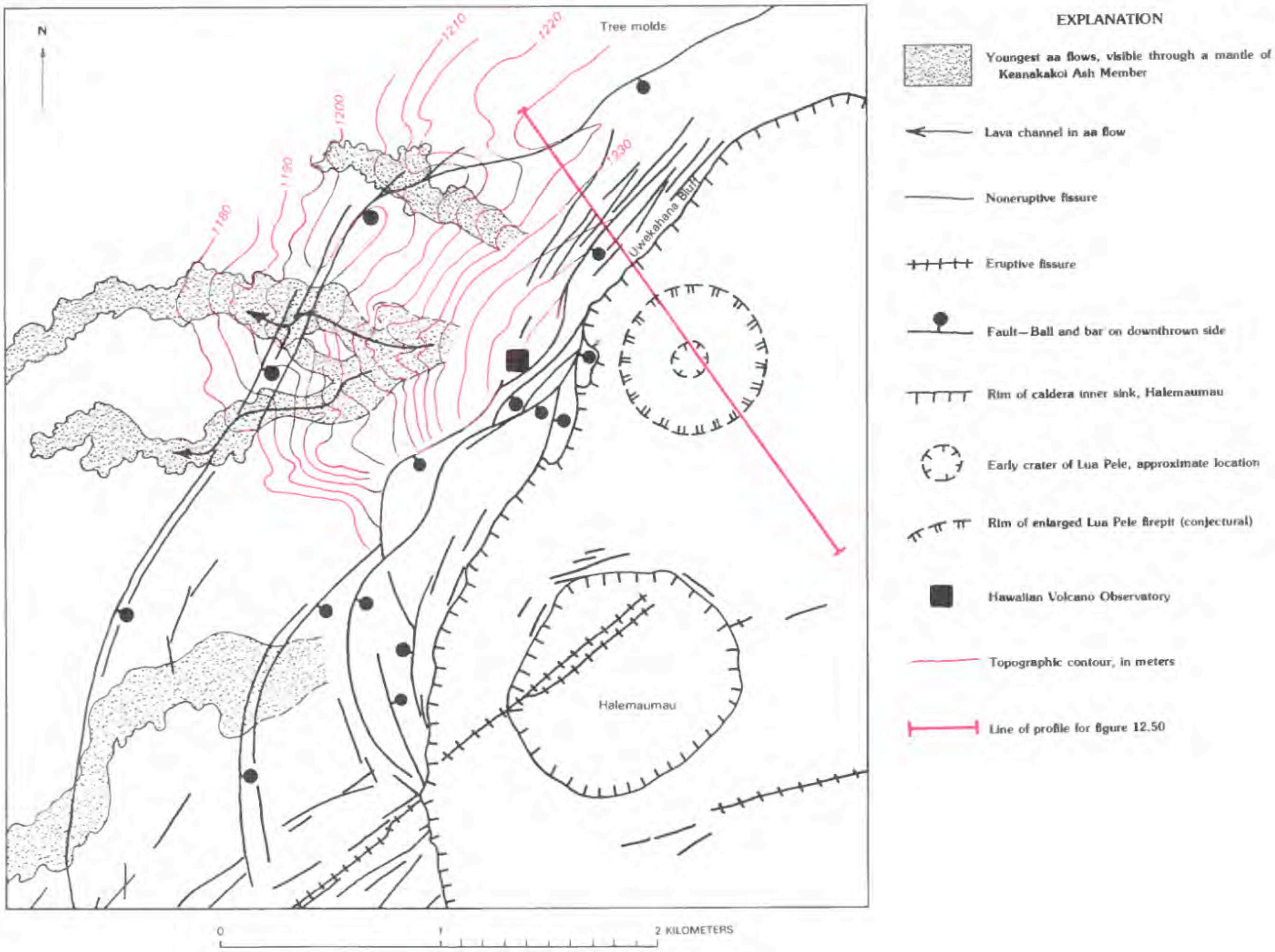


FIGURE 12.36.—Northwest sector of Kilauea caldera. Location of Observatory vent is inferred from radiating ground slopes and lava flows. Enlarged Observatory firepit is conjectural, its former existence suggested by remnants of concentric dikes on present caldera wall (fig. 12.49). Youngest aa flows and their channels (visible beneath mantle of Keanakakoi Ash Member) appear to have been deflected along fault scarp now cutting across them, indicating that displacement began before flows were erupted. This early deformation could have arisen from thermal contraction of lava filling older Powers caldera, as shown in figure 12.50.

KOKOOLAU ERUPTION

Superposition relations between Kokoolau (fig. 12.38) and surrounding lava flows are not yet clear. Holcomb (1980a) interpreted Kokoolau as a kipuka surrounded by flows from the Ai-laau vent, but paleomagnetic sites on Kokoolau (1B188, fig. 12.5*A*) and seaward flows (1B212, 3R349) extending into Kipuka Papalinamoku have shown that they are probably younger, dating from the late 17th century or early 18th century. An aa flow east of the Ahua Kamokukolau triangulation station (fig. 12.5*A*), atop Kalue lava and probably fed by a caldera-concentric vent mantled by A.D. 1790 ash south of Keanakakoi, is overlapped by pahoehoe on its east side (Peterson, 1967, and written commun., 1966). The younger pahoehoe is thought to come from Kokoolau; if so, Kokoolau is not only younger than the Kalue lava but also younger than at least one of the concentric vents. Kokoolau probably belongs to an extensive assemblage from the 17th and 18th centuries that extends the length of the east rift zone.

VEGETATION PATTERNS OF THE MIDDLE EAST RIFT ZONE

One reason for the age uncertainty of Kokoolau is a coincidental vegetation boundary caused by orographic rainfall variation. The rest of the east rift zone extends through an area of high rainfall and rapid forest growth, making it possible to differentiate lava flows using vegetation patterns (Atkinson, 1970). The latest prehistoric flows downrift from Kokoolau can be recognized from their distinctive vegetation. Although in rainy areas they are densely overgrown, their vegetal structure and floristic composition indicate that they are considerably younger than neighboring flows, including those from the Ai-laau vent (fig. 12.39).

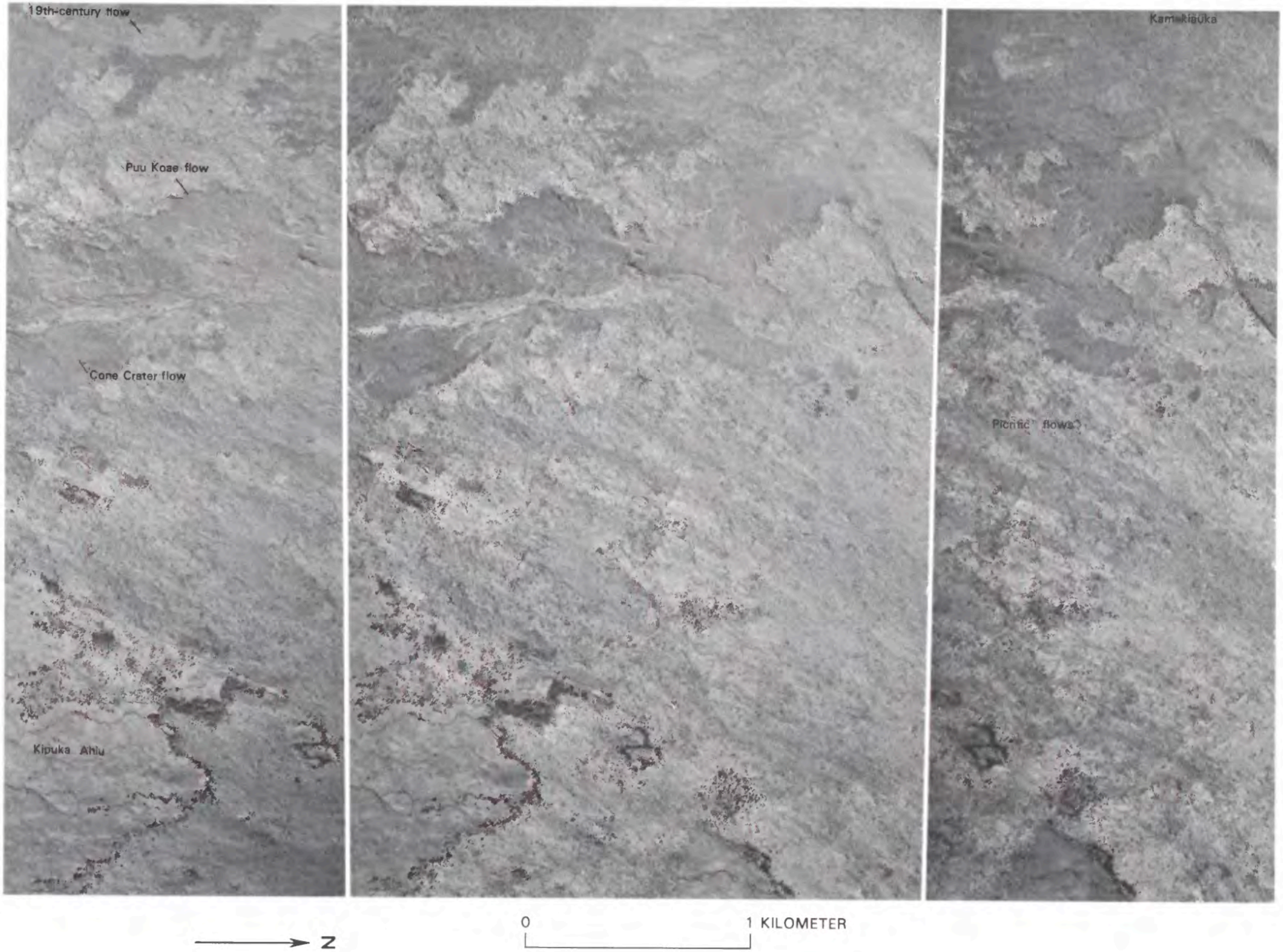


FIGURE 12.37.—Overlapping flows between Kamakaia and Kipuka Ahiu. Aa flows of two ages are present, with sheets of tube-fed pahoehoe between and beneath them. Both pahoehoe units inferred to originate from summit, upper aa from Puu Koae, lower aa from Cone Crater and chain of spatter ramparts to northeast (now covered by lava of 1974). Tonal stripes trending north-northeast to south-southwest at right represent variations in sand cover; dark bands contain more sand. Stereo triplet prepared from frames 201–203, roll 12CC, USDA series EKL, 1965.

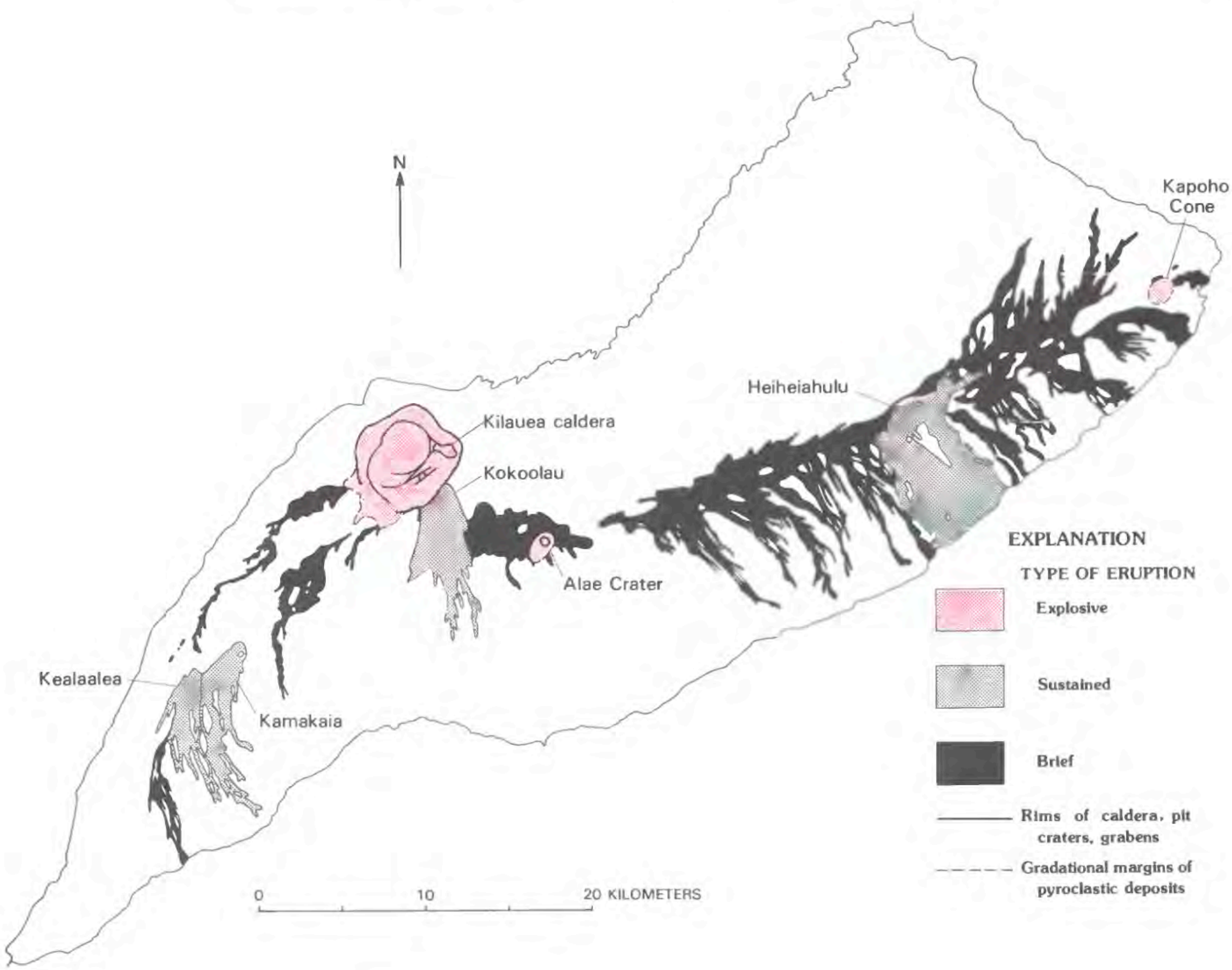


FIGURE 12.38.—Kokoolau and eruption products of 18th century.

Older flows display on aerial photographs a relatively coarse forest grain owing to greater spacing and crown heights of trees. Vegetation patterns have hectometer-scale patchiness, unrelated to flow morphology. When viewed on the ground, large ohia lehua trees (*Metrosideros polymorpha*) of older forests commonly are seen to be epiphytically rooted, indicating that they are not the first generation of trees on the flows. Older flows have more floral diversity; kukui trees (candlenut: *Aleurites moluccana*) are especially common in older forests at lower elevations and are easily detectable because of their high albedo. The younger flows possess a finer vegetation grain arising from close spacing of young trees, and the patchiness of the forest on them is closely related to flow margins and other features of the flow morphology.

Most of the younger flows date from the 18th century, though some could be slightly older. They are distinctly older than flows of 1840, which are also densely vegetated but with plants that are shorter and more closely spaced (fig. 12.39). Though they must be prehistoric, their ^{14}C ages are consistently less than 200 years B.P. (W–359, W–2970, W–3467, W–3468, W–4638, W–4639, W–4644, W–4689).

An 18th century age is indicated also by 19th-century accounts showing that the flows were then much less overgrown than now. Members of the United States Exploring Expedition in 1840–41 were able to walk the length of the middle east rift zone from Napau to Pahoa in a single day, traversing "old lava plains * * * covered with stunted shrubs" (Wilkes, 1845; see especially p. 181–183, 216). A similar trip in 1975 required two days of arduous travel through heavy forest, despite some barren areas of 20th-century lava. When Wilkes passed by the north side of Heiheiahulu lava shield (which he called "Kalalua") he could see that it was a volcanic cone surfaced by streams of pahoehoe even though he had no time to examine it at close range. Today the shield is so densely carpeted with small trees and uluhe (*Dicranopteris linearis*, a species of false staghorn fern) that its nature cannot be determined without climbing

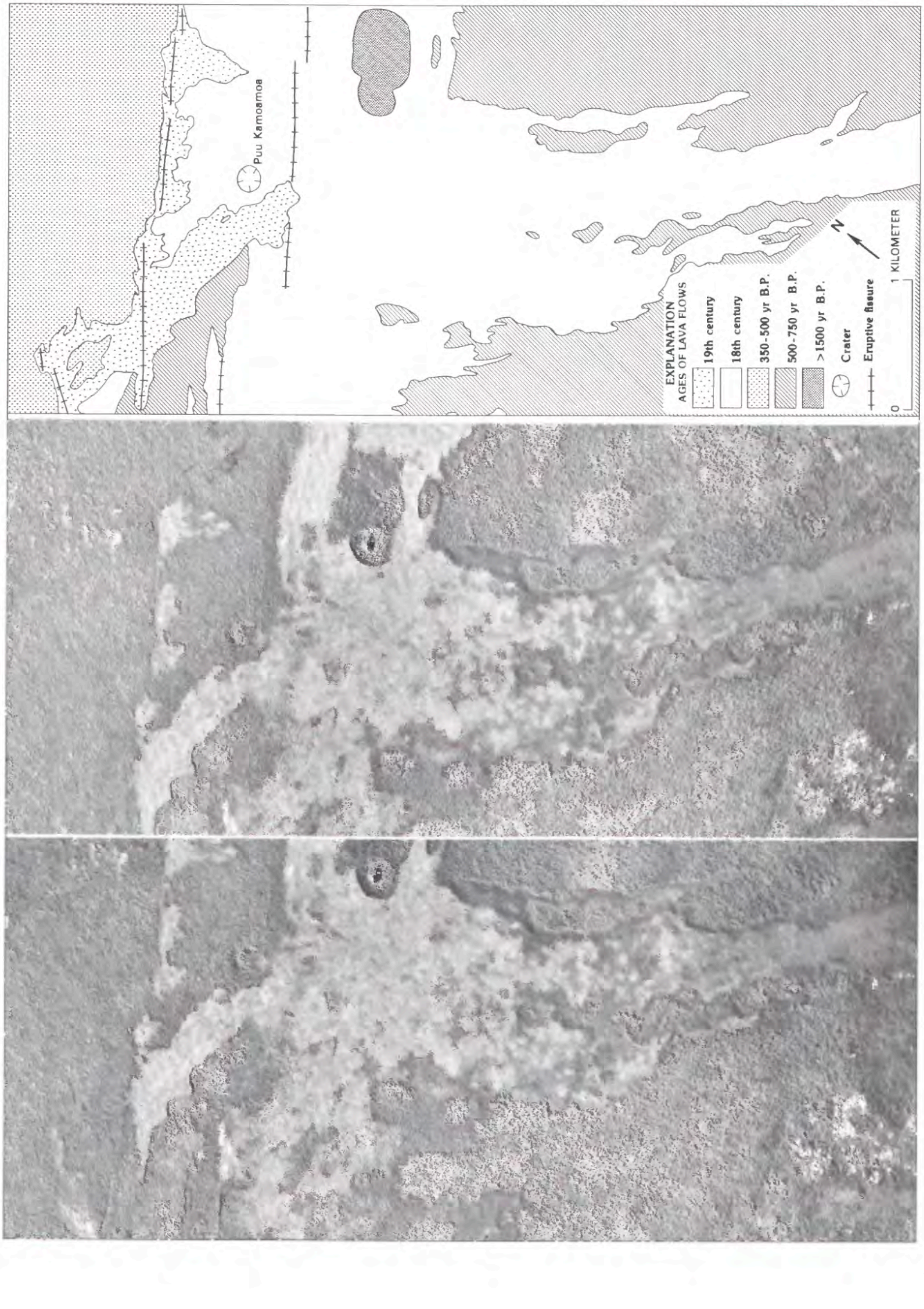


FIGURE 12.39.—Vegetation contrasts near Puu Kamoamoa before extensive flooding by 20th-century lava. All flows visible here are densely vegetated, and their forest patterns vary with age and surface morphology. Most trees are ohia, but light-toned ones in lower left are kukui on flow-mantled fault scarp. Where trees are small on young flows, unshaded understory is composed largely of uluhe; where trees are large, understory is generally dominated by hapuu. Stereo pair prepared from photographs 019, 020, roll 14, U.S. Navy series HAI, 1954.

its flank; in fact, the vegetation is so dense that Heiheiahulu and some smaller cones mentioned by Wilkes cannot even be seen from most places along the rift zone. Because of their vegetal sparsity then and dense vegetation now, most flows along the middle east rift zone must have been quite young when traversed in 1840.

In an earlier interpretation of these vegetation patterns, Moore and Koyanagi (1969) differentiated "late prehistoric" flows (older than about 300 years) from "very late prehistoric" flows older than 1840. However, the vegetation contrasts they used to differentiate the two groups arise from differences in flow morphology instead of age. This is demonstrated by vegetation patterns seaward of Heiheialulu lava shield, inland from Kaimu (fig. 12.40). Here oral history establishes the age, and ranges of climate and flow morphology reveal various rates of forest development for different conditions of rainfall and substrate.

HEIHEIAHULU ERUPTION, CIRCA A.D. 1750

In 1823 Ellis (1827) was told in Kaimu that "the district * * * was overflowed [by lava] in the days of Arapai." Because the reign of Alapai ["Arapai"] was less than a century earlier (approximately 1730–54, according to Hitchcock, 1911) this report should be reliable. Macdonald (1941) supposed the eruption of circa 1750 to be represented by a barren aa flow along the coast about 1 km east of Kaimu (fig. 12.41). Macdonald could not trace this flow directly to its source because it disappears into thick forest, but extrapolation upslope showed that its probable source was Heiheiahulu (Stearns and Macdonald, 1946).

Stratigraphic relations at the shoreline demonstrate that this flow is not the youngest one. Its eastern margin is overlain by pahoehoe of a lava delta (Moore and others, 1973) covering 3 km of shoreline eastward past the Moana Hauae triangulation station and Waipuku Point (figs. 12.41, 12.42). This delta was fed by a lava tube traceable to the upper flank of Heiheiahulu (fig. 12.43). Other tubes and channels radiate from Heiheiahulu; the shield and its flows comprise a diverse assemblage similar to that of Mauna Ulu. The Kaimu district was overflowed not by a single flow but by many, and by analogy with Mauna Ulu this 18th-century eruption was sustained for several months or a few years.

Though all of the Heiheiahulu flows are closely similar in age, their vegetation is highly diverse, varying with flow morphology and climate. The dominant trees on all flows are young ohia (*Metrosideros polymorpha*), but the flows vary widely in the size and spacing of their trees and the character of their understories. In a narrow relatively warm and dry band along the coast, the vegetation is light on all flows but is more dense on tube-fed pahoehoe than on aa. Aa is colonized only by scattered ohia and lichen, while adjacent pahoehoe has thickets of shrubs and grasses as well as more numerous ohia. The contrast is probably caused by differences in water retention; pahoehoe is less permeable and rainwater remains on it longer than on aa. Though vegetation is much more dense in wetter and cooler areas at higher elevations inland, vegetal contrast remains high between flow types. Ohia trees are taller and more closely spaced on aa flows than on pahoehoe. The broader spaces between trees on pahoehoe are generally overgrown by thick tangles of uluhe. Aa probably provides better substrate for trees where rainfall is abundant. Transitions in the vegetal cover on a single flow correspond to morphologic transitions, so that although Heiheiahulu lavas are densely forested, it is still possible to map morphologic transitions from vegetation patterns visible on aerial photographs. Trees grow faster along margins of flows than in their centers, probably because thinner margins are more easily penetrated by roots. Where flows are thick they commonly possess massive interiors that may prevent roots from reaching nutrients and moisture beneath the lava.

These vegetation patterns can be used to identify 18th-century flows along most of the east rift zone. Similar relations of vegetation to flow morphology and climate have been found on the 1868 flow of Mauna Loa (Juvik, 1976).

OTHER ERUPTIONS FROM THE EAST RIFT ZONE

A few flows have been included with the 18th-century group despite evidence that they may be somewhat older. On some flows the vegetation is slightly different, the ohia trees being taller and more widely spaced and giving the forest a coarser grain when viewed on aerial photographs. Some of these flows may be contemporaneous with the Observatory flows, but this is not yet certain; some of the flows differ for reasons other than age. An example just southeast of Napau (fig. 12.44) has a vegetation pattern coarser than most 18th-century flows, but ^{14}C samples W–3468 and W–3469 suggest an age younger than 200 years. This flow consists of surface-fed pahoehoe generally less than 1 m thick, penetrated by tree molds from which many of the present trees grow. These conditions may have permitted more diversity and rapid growth; if so, they prevent fine age distinctions based on vegetation differences.

Some age uncertainties arise from early historical descriptions. For example, the pahoehoe of Malama-Ki Forest Reserve, comprising the coastline between Lililoa and Mackenzie State Park (fig. 12.45), is included in the 18th-century group even though Ellis' (1827, p. 201, 205) account seems to preclude such an age. Ellis was told on passing through Malama that the area inland was inundated by an eruption in about A.D. 1790, but he observed that the coastal tract where he traveled "was covered with soil, and smiling with verdure." He was told later at the village of Pualaa that an eruption near the time of Cook's visit inundated much country along the lower east rift zone but was arrested by the contiguous hills of Kaliu, Malama (Kahuwai-Puulena), and Honuaula. Macdonald (1941) inferred from these accounts that the flows of circa 1790 were confined to the region north of Puu Kaliu and Malama, but aerial photographs show that Macdonald's fissure vent extending from Kaliu to Malama fed flows to the south as well as to the north. The two reports given to Ellis could have referred to two different eruptions in the late 18th century, so that the one confined north of the Kaliu-Malama complex differs from the one sending flows into the lower Malama district, resolving the apparent contradiction. But Ellis' implication that coastal Malama was not flooded is clearly inconsistent with the flow distribution shown on figure 12.45. More faith is placed here in the vegetation and flow morphology than in Ellis' inference. An 18th-century age for the Malama flow is also consistent with its direction of remanent magnetization (site 8B025). Ellis' verdant coastline may front another part of Malama, or

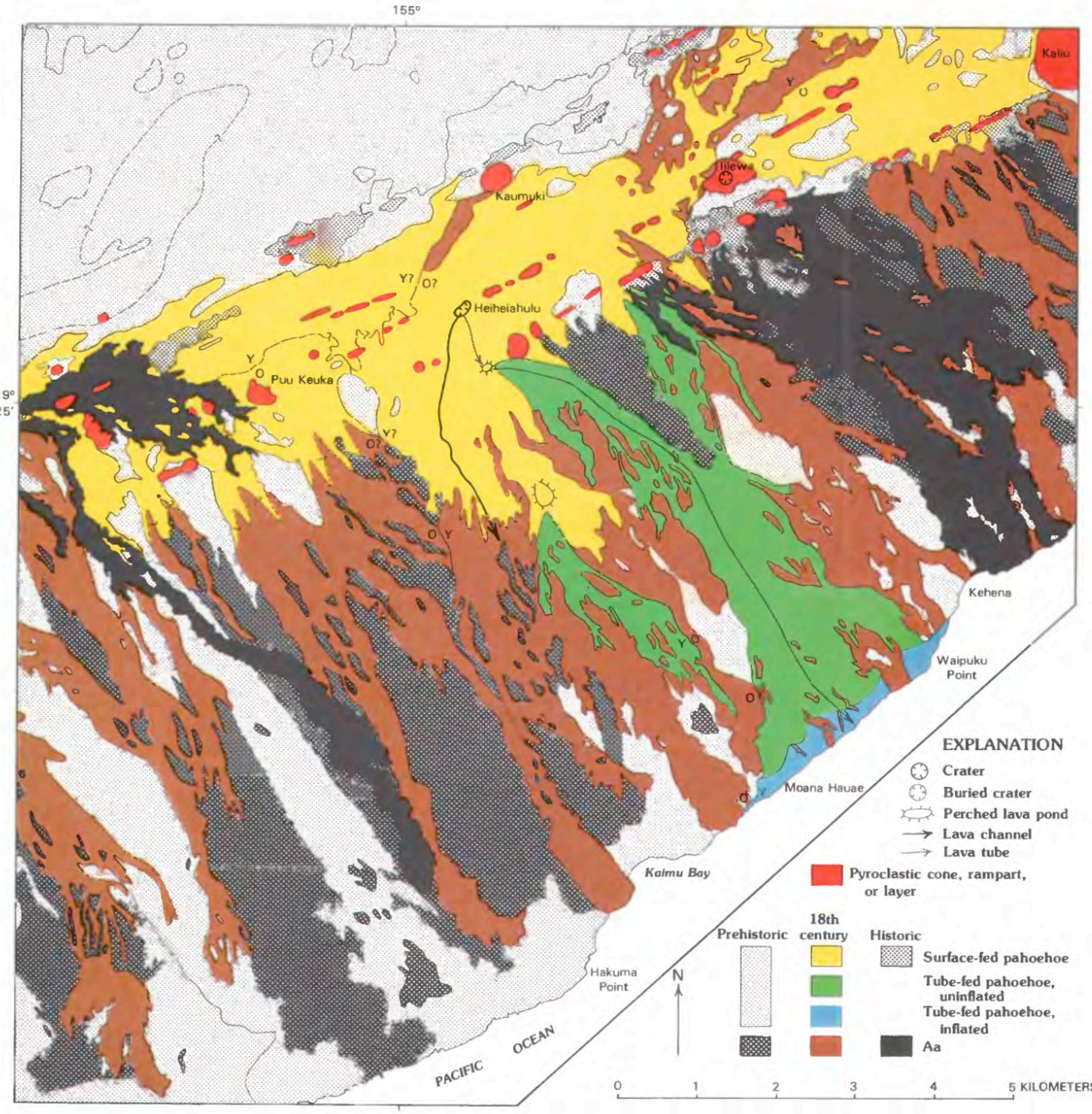


FIGURE 12.40.—Lava flows of circa 1750 eruption of Heiheiahulu, classified by their morphology. Relative ages indicated at some contacts: Y, younger; O, older; queried where uncertain.

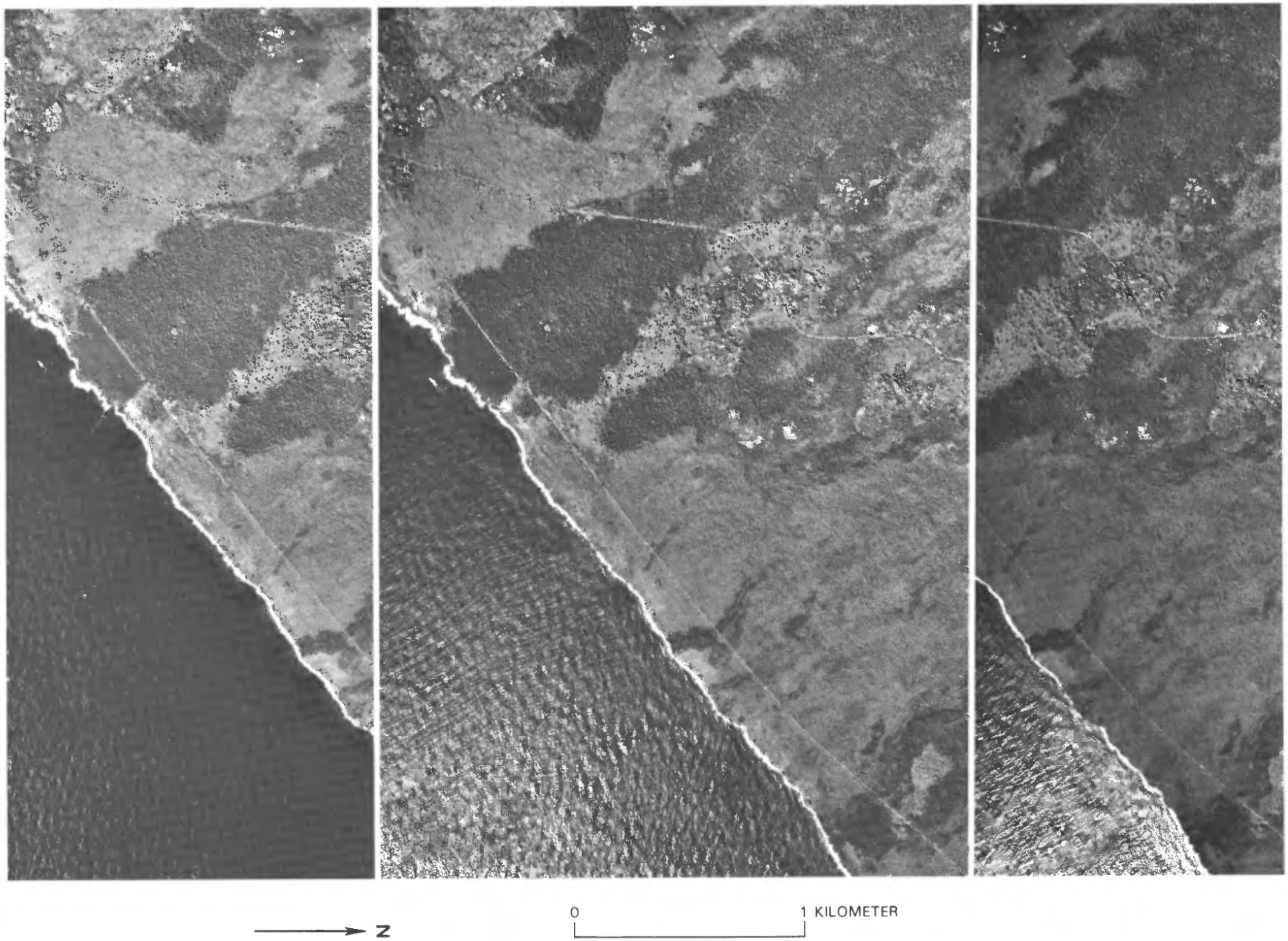


FIGURE 12.41.—Coastal flows between Kaimu and Waipuku Point. Prominent dark flow was only one designated as circa 1750 by Macdonald (1941), but flow morphology and superposition relations indicate that many other flows are of similar age and also erupted at Heiheiahulu. Spacing of ohia on 18th-century aa decreases with increasing elevation inland. Dark-gray, fine-textured tube-fed flows of 18th century are sparsely overgrown with shrubs and grasses between small ohia. Light-toned older flows are densely vegetated, with scattered large trees being prominent. Distinctive globular trees are mango; very light trees are kukui. Arrow indicates small cove whose northeast edge is shown in figure 12.42B. Pairs of red dots are paleomagnetic sample sites, each dot representing a subsite. Stereo triplet prepared from photographs 47–49, roll 12CC, USDA series EKL, 1965.

A

B

FIGURE 12.42.—Stratigraphic relation of circa 1750 flows at shoreline. ***A***, Oblique aerial view showing circa 1750 flow of Macdonald (1941) on left and tube-fed flow of Moana Hauae/Waipuku Point lava delta on right. Narrow, light-toned horn of pahoehoe extends along shoreline from delta to front of aa flow. Horns typically form when surf retards spreading of delta front but permits lava to spread along shore. Photograph by J.P. Lockwood, June 1974. ***B***, Seaward view from atop aa flow in contact with pahoehoe delta. Marine erosion has removed clinkery top of aa flow, producing small cove indicated on figure 12.41, which extends to right of this view. Rock hammer at left (circled) is on contact between flows. Pahoehoe is molded around underlying clinkers. Photograph by J.P. Lockwood, June 1976.

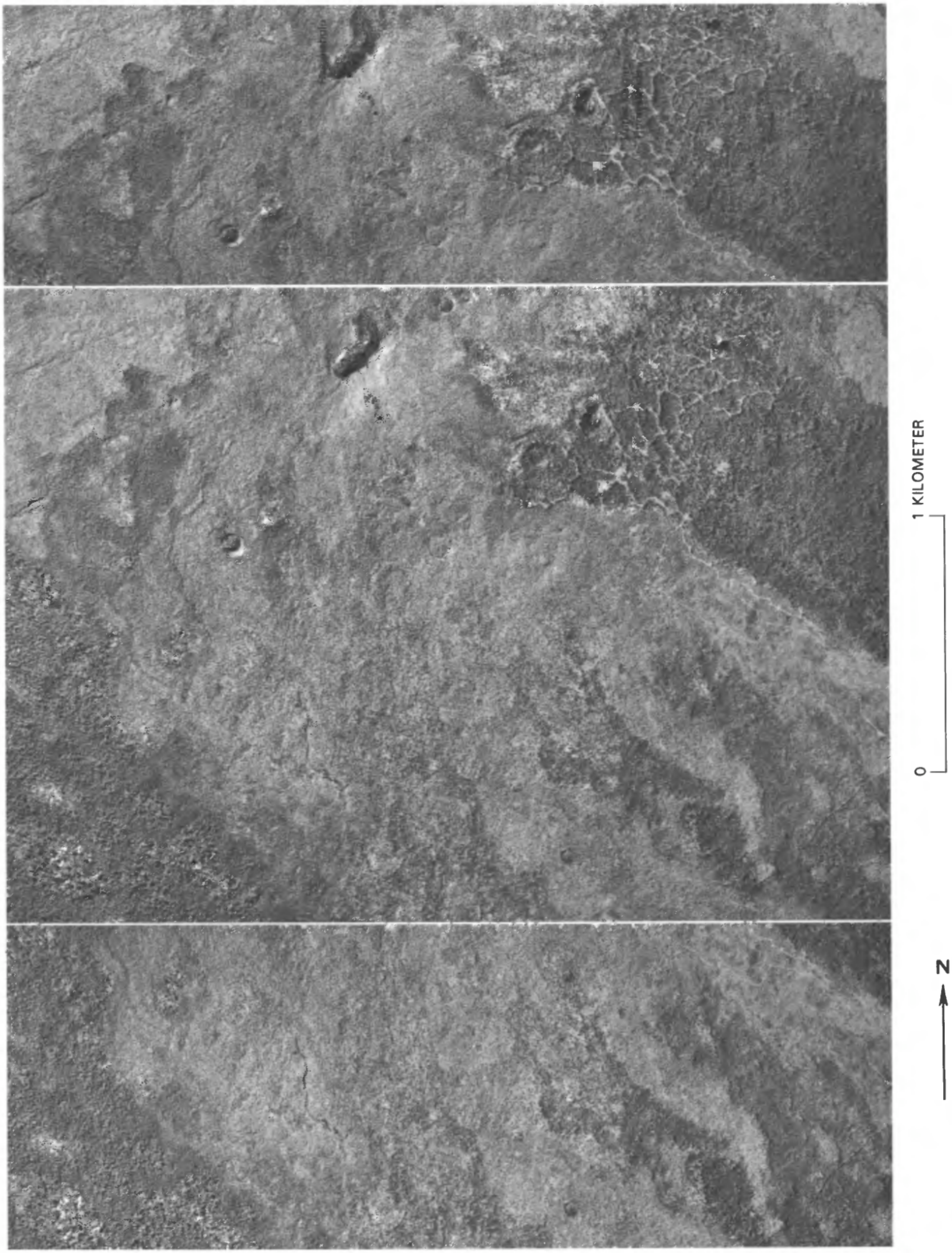


FIGURE 12.43.—Seaward flank of Heiheiahulu. Dark-toned aa supports dense ohia forest, while pahoehoe is covered by uluhe thickets and more widely spaced ohia. Stereo triplet prepared from photographs 55–57, roll 12CC, USDA series EKL, 1965.

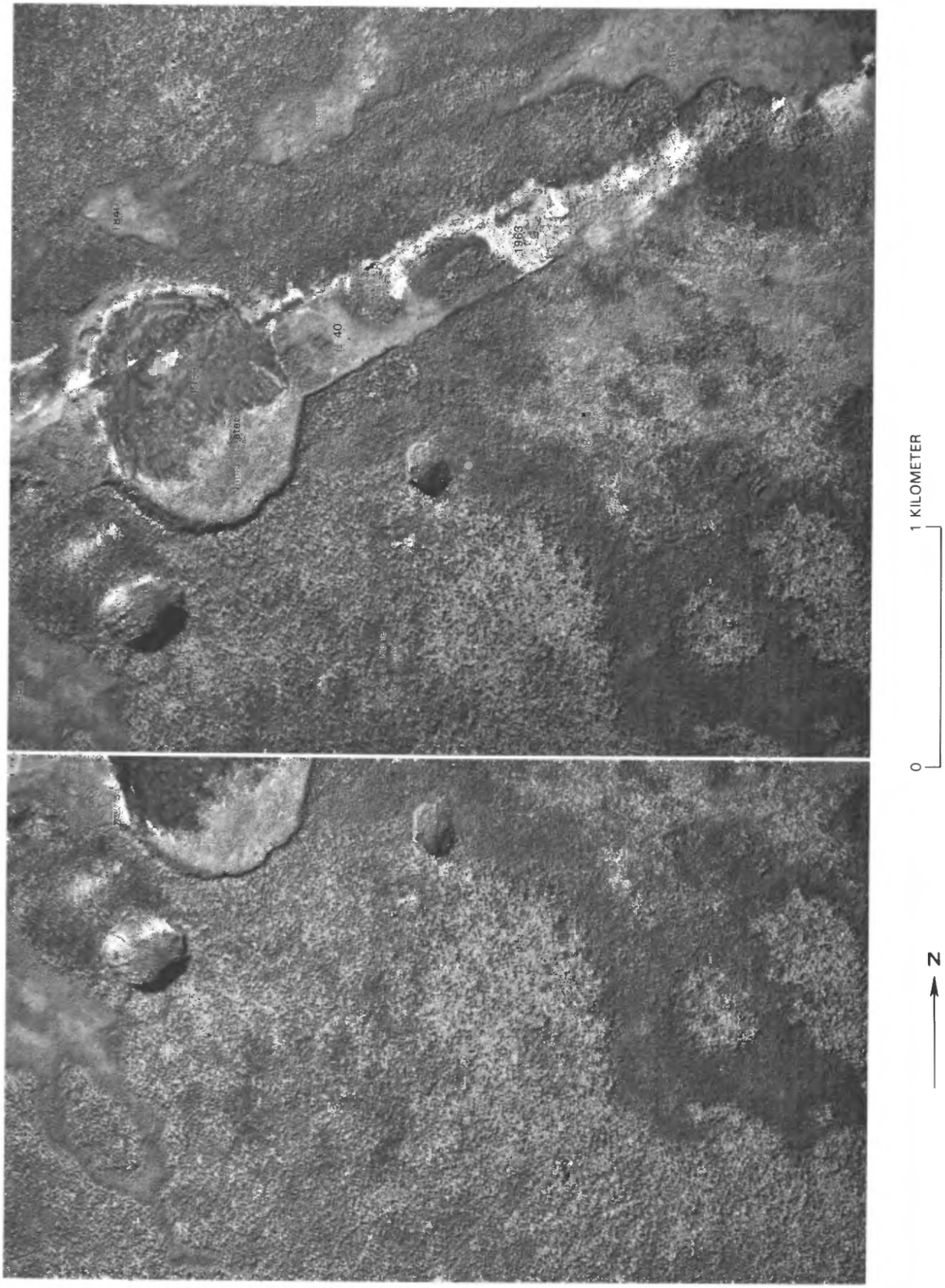


FIGURE 12.44.—Young lava flows near Napau, with years of eruption indicated. Large red dot is ^{14}C sampling site, where ages of less than 200 yr have been obtained from charred roots beneath flow. Stereo pair prepared from photographs 142, 143, roll 12CC, USDA series EKL, 1965.

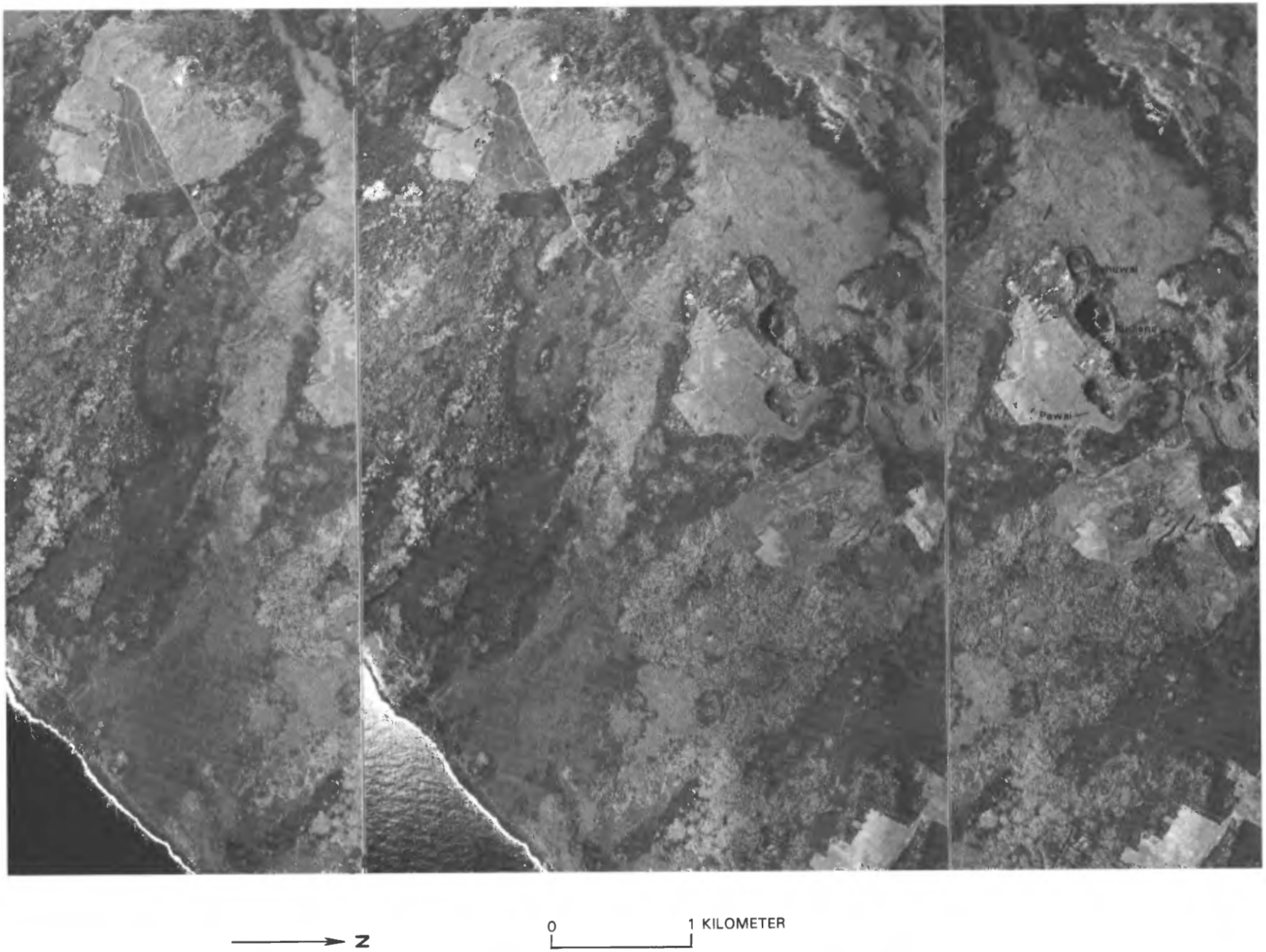


FIGURE 12.45.—Late prehistoric Malama flows, erupted from fissure extending east-northeast from Kaliu past Kahuwai and Puulena. Macdonald (1941) attributed flows inland of fissure to eruption of circa 1790, but their vegetation and morphology show that seaward flows are coeval. Open fissures and spatter ramparts occur together with a tube system; evidently criteria of table 12.1 can be contradictory in some cases. Holcomb (1980b) used vegetation differences to assign 17th-century age to flow east of Pawai Crater, but R.B. Moore (1985) has shown it to be from same eruption of circa 1790. Large red dot, ^{14}C sample site; pair of small red dots, paleomagnetic sample site. Stereo triplet prepared from photographs 128–130, roll 23, U.S. Navy series HAI, 1954.

vegetation may have been reestablished quickly along the coast. Kaliu, Malama, and Honuaula could have dammed a flood of lava and yet permitted some tongues to flow through the gaps between them.

The most recent activity in Kapoho Crater (fig. 12.46) is of uncertain age but probably occurred in the early 18th century or 17th century. An age significantly earlier than A.D. 1800 seems required by the account of Ellis (1827), who in 1823 recognized the volcanic nature of the tuff cone and questioned local residents about its last eruption. Though tradition described it as a seat of volcanism, the people living there could give no specific information about the last eruption, which suggests that it had occurred long before. There had certainly been enough time for thick vegetation to grow, because Ellis described the tuff cone as "overhung with trees, and clothed with herbage" (Ellis, 1827, p. 205–206). On the other hand, the aa flow extending east from the cone (fig. 12.47) is magnetized (8B205) in a direction similar to the Observatory flows, and a ^{14}C age of less than 200 years B.P. (W–2970) has been obtained from charcoal beneath a thick pyroclastic layer within the cone. Given the uncertainty in the ^{14}C and paleomagnetic ages, a single eruption could have produced both the flow and pyroclastics a century or so before Ellis' visit.

The morphologies of flows and vents indicate that all of these latest prehistoric eruptions, except for those of Kokoolau and Heiheiahulu, and perhaps the one of circa 1790, had high discharges and short durations. Though the flows typically extend several kilometers from their fissure vents and terminate as aa lobes, they are remarkably free of mappable lava channels.

ERUPTIONS FROM THE SOUTHWEST RIFT ZONE

The 18th century saw frequent and sustained eruptions from the southwest rift zone as well as the east rift zone, with eruptions occurring from all of its active parts.

Brief eruptions were widespread (fig. 12.5*B*). A vigorous one from the northern strand produced the Cone Peak ramparts (8B745) and flows that extended nearly to Kamakaia. Subdued eruptions near the end of the same strand built small shields and lava pads (9B841), similar to those of 1868, inland from Kamakaia; some of the pads overlap the Cone Peak aa flow. Vigorous eruption from the central strand produced Puu Koae and other spatter cones and aa flows extending to about 1 km from Hilina Pali.

Another brief eruption occurred from the lower segment about 1.3 km east of Puu Nahaha and 600 m east of the upper end of the Keaiwa flow of 1823 (fig. 12.5*C*). Lava flows from this eruption reached the sea between Kapaoo Point and Waiwelawela Point. They are more weathered than the overlying Keaiwa flow and have been dated by ^{14}C at about 200 years B.P. (W–3938, W–4452). The Red Cones and their aa flows, which also overlie these flows, are undated, but they too are overlapped by the Keaiwa flow. Both the Red Cones and the earlier unnamed flows probably date from the 18th century. Their eruptive fissures appear to have extended through Yellow Cone from the southern strand of the upper segment, but they cannot be traced far uprift because they are buried by other 18th-century lava flows of sustained eruptions.

The late prehistoric lava commonly termed the Kamooalii flow (see Stearns, 1926) consists of two assemblages of similar age from different strands of the rift zone. A sustained eruption from the central strand built a lava shield at Puu Kou and Kealaalea Hills (fig. 12.5*B*), and a complex flow assemblage extending seaward across the Kau Trail and past the west side of Puu Ahi (fig. 12.5*C*). The eastern part of the Kamooalii flow is another complex assemblage fed by vents of the southern strand, including Kamakaia and Kamakaiawaena (fig. 12.48). Kamakaia flows overlap those of Kealaalea. Magnetization of Kealaalea (9B409) and Kamakaia (8B517) flows is consistent with an 18th-century age, and the Kealaalea flows have been dated by ^{14}C as younger than 200 years B.P. (W–3937). Both flow assemblages probably represent sustained, unstable eruptions during the 18th century.

Yellow Cone is a small kipuka of pyroclastic material protruding through the flank of the Kealaalea shield (fig. 12.5*B*). It may predate the 18th century; no young flows have been found seaward of it beneath the flows of Kealaalea. While the lavas of Yellow Cone, Red Cones, Kamakaia, Kamakaiawaena, and Kamakaiauka along the southern strand of the southwest rift zone all have differentiated compositions, the analyzed flows from the Great Crack and central strand of the upper southwest rift do not (Wright and Fiske, 1971).

FIGURE 12.46.—Kapoho Crater, looking northeast from distance of about 1 km. Photograph by R.T. Holcomb, 1977.

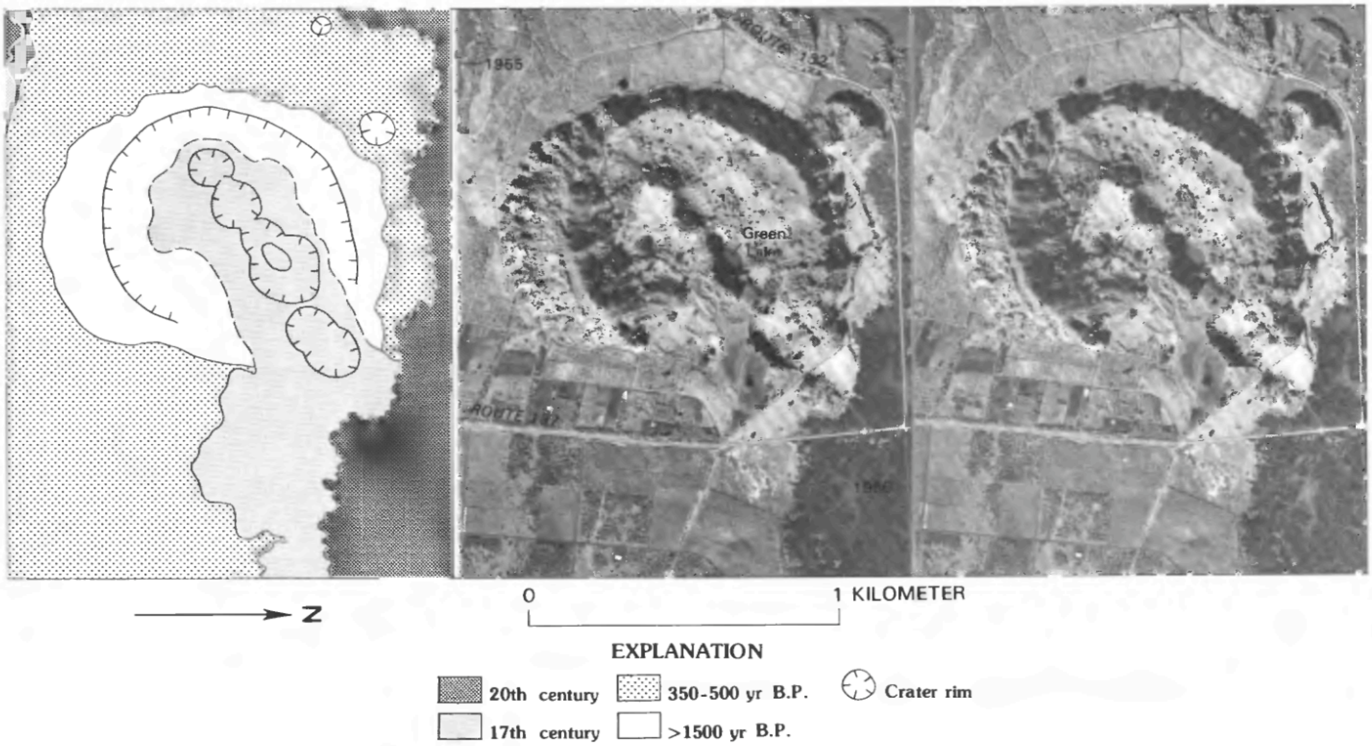


FIGURE 12.47.—Vertical view of Kapoho Crater. Tuff cone is incomplete, possessing gap on its eastern side through which thick prehistoric aa flow extends east about 1.5 km to present shoreline. This aa flow probably was erupted during 17th century and sits atop pahoehoe flows that have direction of magnetization consistent with age of 350–500 yr B.P. (pairs of small red dots, paleomagnetic sample sites). Both flows veneered by ash distributed around tuff cone, suggesting that pyroclastics postdate flows, but aa flow must be younger than cone if it has extended through gap in cone, and sharp break in slope around outer base of cone suggests that cone protrudes through pahoehoe flows and predates them as well. A ^{14}C age of less than 200 yr B.P. was obtained from charred log beneath ash on interior slope of tuff cone (large red dot). Both aa flow and its ash veneer may have been erupted during 17th century from chain of craters within cone, while bulk of cone is older than pahoehoe flows. Crater containing Green Lake is thickly rimmed by ash. Ellis (1827, p. 206) described within Kapoho Crater "a smaller circle of hills, equally verdant, and ornamented with trees" that may have comprised an inner tuff ring (not now definable as morphologic feature, possibly destroyed by quarrying). Aa flow and young ash deposits around chain of craters may be products of single eruption.

The compositions of the 18th-century flows beneath Red Cones, and of flows from other seaward vents such as the Lava Plastered Cones, are not known.

In summary, the latest prehistoric interval saw from the northern strand of the upper southwest rift zone a brief but vigorous eruption at Cone Peak followed by brief, less vigorous eruptions farther downrift. The central strand saw brief, vigorous eruption at Puu Koae and sustained, unstable eruption at Kealaalea, with their sequence not yet known. The southern strand saw a vigorous brief eruption east of Puu Nahaha followed by a smaller eruption of Red Cones and sustained eruption at Kamakaia farther uprift.

THE MODERN CALDERA

The age of the modern caldera and the timing of collapse with respect to the explosive eruption of A.D. 1790 are not yet known. There still remains much room for alternative sequences and mechanisms.

Much—maybe all—of the collapse preceded the explosive eruption, because all of the 1790 ash now exposed is draped unbroken across the modern caldera faults surrounding the inner sink (Christiansen, 1979). Within the sink, the so-called sand spit between Keanakakoi and Halemaumau and the deeply subsided blocks adjacent to Uwekahuna Bluff and Waldron Ledge also are draped by the ash. However, higher caldera walls in several places lack ashy plaster and may have seen local collapse following ash deposition. It remains possible that most of the collapse occurred only a short time (hours or days) before the onset of explosive eruption. It also remains possible that much collapse occurred within the inner sink during, or even following, the explosive eruption without continued displacement along the outer caldera structures.

Alternatively, the inner sink could have reached essentially its present diameter sometime earlier than 1790. Incipient smaller scale collapse probably did begin earlier, with alternating rise and fall of the magma column. Many dikes and other intrusive bodies are exposed along the north wall of the modern caldera (Powers, 1916); those rising high through the stratigraphic section must postdate the Observatory vent (Casadevall and Dzurisin, chapter 14). Some dikes appear to follow structures bounding the inner sink of the modern caldera: Some occurrences thought by Powers to be intru-

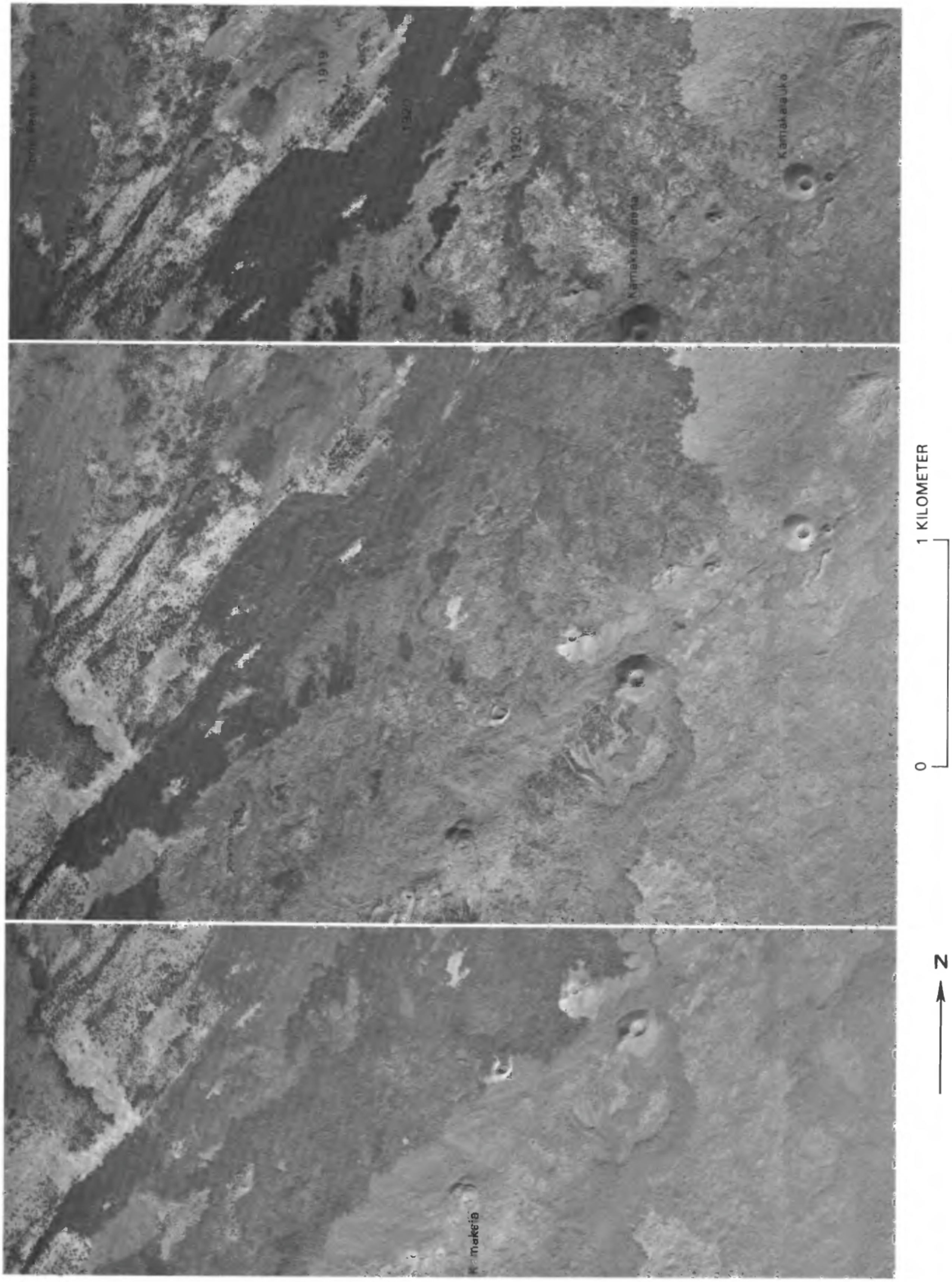


FIGURE 12.48.—Kamakaia Hills. Red dot indicates approximate viewpoint for figure 12.17. Stereo triplet prepared from frames 41–43, roll 5CC, USDA series EKL, 1965.

sions within the truncated stratigraphic section are actually veneer a few meters thick adhering to the caldera wall (fig. 12.49). These probably are remnants of dikes intruded along older fissures concentric to the Observatory vent. Some thinner dikes seem to extend irregularly into the wall away from these thicker concentric dikes instead of rising vertically through fissures radial to the caldera. The concentric fissures may have formed when the magma column subsided to produce an enlarged Observatory pit like Halemaumau, and dikes may have been intruded along these fissures later when the magma column rose again. The column could have oscillated several times, and successive collapses could have enlarged the sink to nearly its present size long before the climactic explosive eruption in 1790. (It was suggested by de St. Ours, 1979, that multiple collapses occurred at different centers; see also, de St. Ours, 1982.) An active lava lake may have been present much of the time in this sink; reticulite at the base of the Keanakakoi Ash Member shows that high lava fountains occurred near the summit sometime before the 1790 explosions (Decker and Christiansen, 1984). A hypothetical sequence showing the enlargement of an Observatory firepit followed by a larger scale collapse to form the present inner caldera sink is sketched in figure 12.50. This sequence was drawn assuming a 17th-century age for the Observatory flows, but other ages and other sequences are possible.

FIGURE 12.49.—Part of north caldera wall of Kilauea, showing light-toned rectangular rock body that Powers (1916) interpreted as sill-like intrusion projecting into cliff face. Close inspection has shown instead that it adheres like plaster on cliff face. Cliff and trees on its rim are 120 m and 10 m high, respectively. Steam in foreground rises through lava flows of 1919. Photograph by J.D. Griggs, May 1979.

Stratigraphic constraints on the age of the northwest part of the inner caldera sink turn largely on the age of the Observatory lava shield. Much of the caldera here must have developed after the Observatory shield ceased to grow, because much of the shield was engulfed by the collapse of the inner sink. If the Observatory flows do date from the 17th century, they constrain caldera development to the late 17th century and 18th century. But if the Observatory flows are older than 700 years, the caldera could have begun to grow long before the 18th century.

Neither is the age of caldera formation well constrained to the south. A few eruptions from fissures concentric to the caldera probably occurred after extensive collapse in the summit region. One flow from a concentric fissure southwest of the caldera and having 18th-century magnetization (8B757) occurs between layers of the Keanakakoi Ash Member and must date from 1790. Others predate the ash by unknown amounts; magnetization of one (8B769) south-southwest of the caldera implies that it could date from the 17th century, but its large within-site dispersion (4.7°) permits it to be a century younger. An aa flow east of the Ahua Kamokukolau triangulation station was probably fed by a concentric vent south of Keanakakoi; as discussed earlier, the east side of this flow is overlapped by pahoehoe probably from Kokoolau. Two of these flows from caldera-concentric vents were deflected by preexisting Koae fault scarps and then broken by recurrent displacements on those scarps.

PIT CRATERS OF THE UPPER EAST RIFT ZONE

Subsidence and dilation of both rift zones also occurred during the past few centuries, but the timing of these events with respect to summit collapse is not yet known. Especially prominent are several pit craters of the upper east rift zone. Some craters probably collapsed in the 18th century, though a few show signs of complex development that began earlier. Makaopuhi and Alae illustrate the complexity especially well.

The coarse ejecta exposed in the wall of Makaopuhi (fig. 12.28C) indicate that an earlier pit existed at or near the site of the present one. The present crater consists of two parts indenting the flank of Kane Nui o Hamo (figs. 12.51, 12.52; see Aramaki and Moore, 1969, fig. 7). The eastern pit may be older than 500 years; it was partly filled by a thick lava lake followed by four thinner flows (Stone, 1925). The lowermost of these flows sent dikes down into columnar joints of the lake far enough to suggest that the lake cooled for at least a few decades before it was covered (Moore and Evans, 1967). The uppermost flow may have been erupted from the southwest crater wall; its surface slopes slightly (0.3°) away from

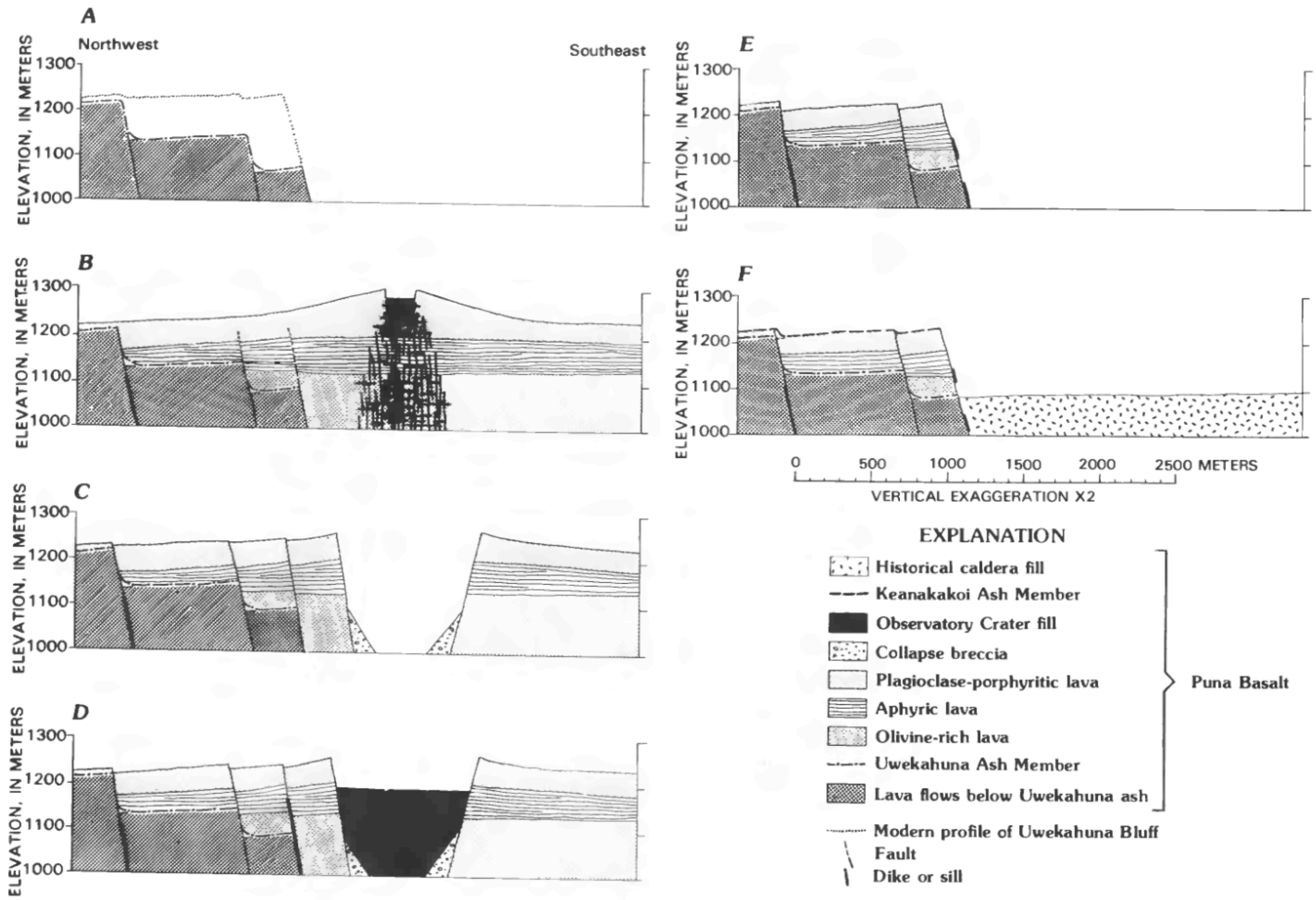


FIGURE 12.50.—Cross sections showing possible developmental sequence for Uwekahuna Bluff, assuming that Observatory shield ceased to grow during 17th century. Line of profile shown on figure 12.36. ***A***, About 1,500 years ago. Powers caldera mantled by Uwekahuna Ash Member. Profile of modern caldera shown for comparison. ***B***, About 300 years ago. Powers caldera filled by flows of three successive groups (Casadevall and Dzurisin, chapter 13). Lower fill broken by differential thermal contraction above buried fault scarps. Dikes and sills surround magma column beneath Observatory lava shield, and dikes intrude along some peripheral caldera faults. ***C***, About 275 years ago. Drainage of magma has produced enlarged firepit. Continued contraction of caldera fill has broken surficial lava flows, forming low scarps above buried faults. ***D***, About 250 years ago. Magma has risen again into firepit and has fed dikes along fractures around pit. ***E***, About 200 years ago. Inner sink rejuvenated by caldera collapse, and dike remnants adhere to its wall. ***F***, Present time. Modern caldera mantled by Keanakakoi Ash Member and partially filled by historical lava flows.

lava drapery and spatter along a fissure in the wall. Lava also issued from a fissure on the crater floor to form small pads atop the upper flow. Another collapse then produced a western pit with the older crater fill forming a mezzanine on its eastern side. The age of the western pit is not known; though it is prehistoric, it must be fairly young. Vegetation on the earlier mezzanine is similar to that developed elsewhere on lava flows of the 18th century.

Alae also was a compound crater (figs. 12.53, 12.54). It appears on aerial photographs that the older pit postdates Puu Huluhulu and the flows of Keauhou; it may therefore be younger than 350 years. The crater was partly filled by a lava lake capped by thinner flows, and then a new collapse formed an inner pit bordered by a western mezzanine. Phreatic explosions from the inner pit deposited a layer of lapilli 15 cm thick on the crater rim and ejected blocks up to 1 m in diameter, some of them to nearly 1 km west of the crater (Stearns and Clark, 1930, p. 143). The debris was partly covered by lava that extruded from a fissure on the northwest rim and flowed into the crater. This lava was overlaid by additional ejecta, possibly from the caldera eruption of 1790, which in turn was overlapped by more lava in 1840 that flowed across the mezzanine into the inner pit. On aerial photographs, the vegetation on a part of Alae mezzanine appears similar to that of 18th-century flows elsewhere, but this cannot be confirmed; the inner pit was floored by a new lava lake in 1963 (Peck and others, 1966), and the entire crater was buried in 1969–71 (Swanson and others, 1972).

Pauahi and Hiiaka are compound craters too (figs. 12.55, 12.56). Before it was buried in 1973, a small lava lake in the central pit of Pauahi supported vegetation typical of 18th-century age, while the lightly vegetated walls of the west pit appeared fresher. The outer compartment of Hiiaka is a sag instead of a sharp-rimmed

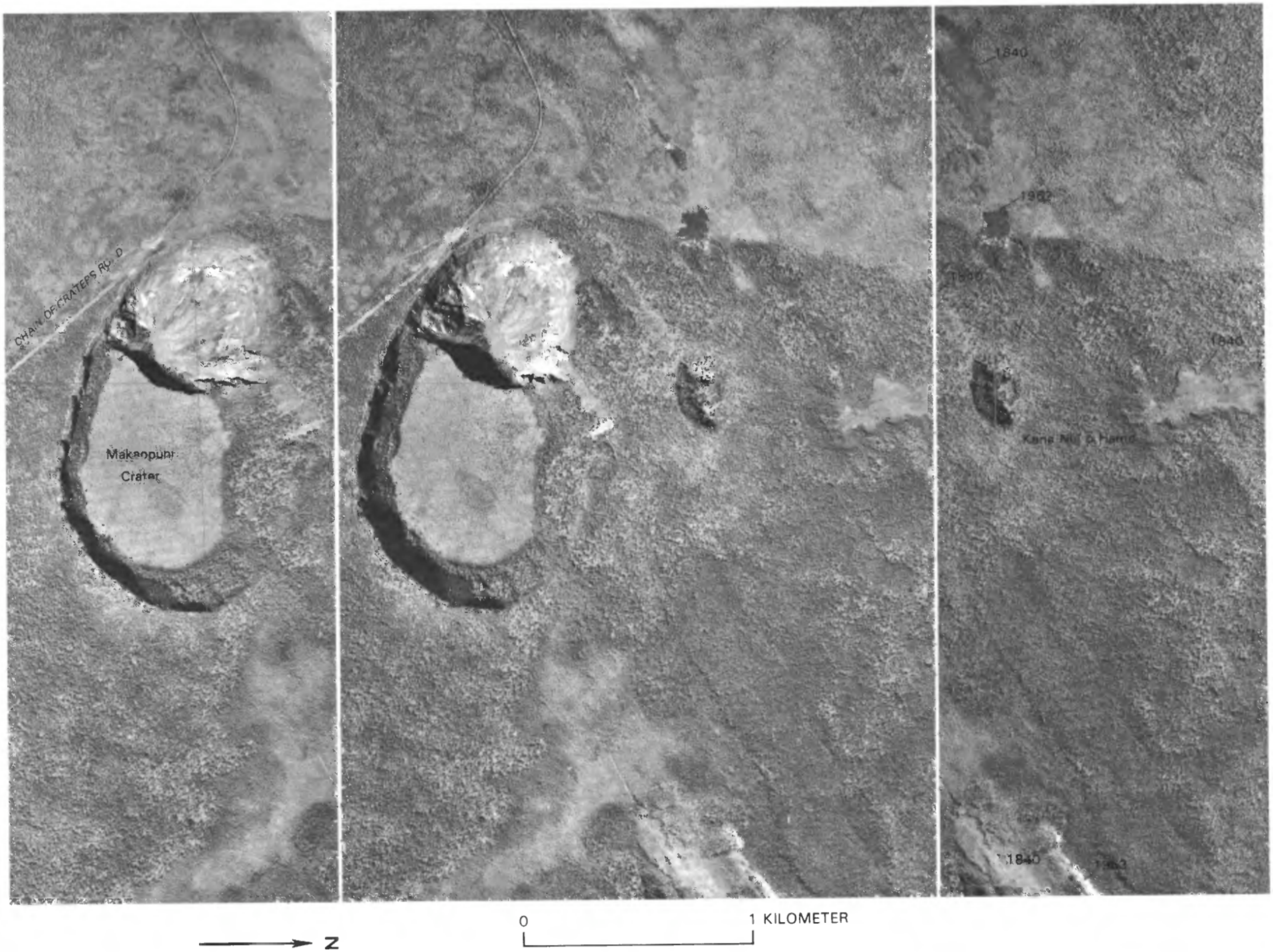


FIGURE 12.51.—Makaopuhi Crater area before much of it was covered by 20th-century lava flows. West pit of Makaopuhi in this view contains very small flat floor of ponded lava erupted in 1922; west pit was later filled and western part of mezzanine covered during eruptions from 1965 to 1974. Red dots, paleomagnetic sample sites above and below yellow tephra layer. Also shown in red are lines of profile for figure 12.52. Ovate, slightly darker area on eastern mezzanine is prehistoric lava pad extruded from fissure extending northeast across mezzanine. Northeast-trending lineament west of this pad is another fissure from which another pad was extruded in August 1972 (fig. 12.52). Stereo triplet prepared from frames 159–161, roll 12CC, USDA series EKL, 1965.

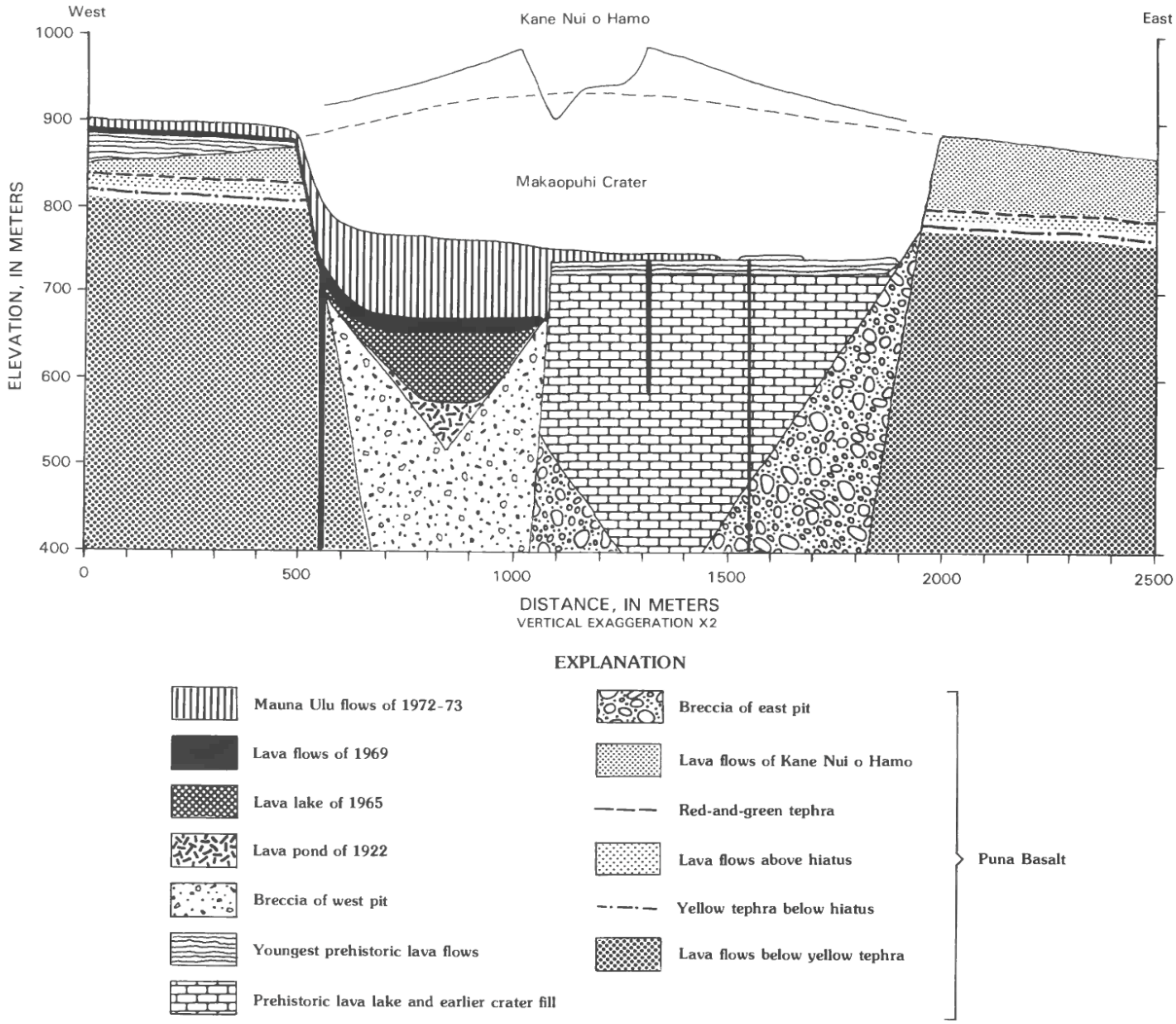


FIGURE 12.52.—Cross section of Makaopuhi Crater, along longer red line of figure 12.51. Also shown are inferred precollapse profile (dashed line) along this section, and present profile (solid line) across crater of Kane Nui o Hamo lava shield 800 m to the north (shorter red line of figure 12.51). Thick vertical lines are dikes that fed prehistoric lava pad on mezzanine (east; see fig. 12.51), eruptions of 1922 and 1965 (west), and eruption on mezzanine in August 1972 (center). Dike of 1972 is shown as rootless because it was probably fed laterally by Mauna Ulu lava ponded in west pit (Tilling and others, chapter 16).

crater (figs. 12.55, 12.56). Stearns and Clark (1930, p. 128) attributed the sagging to subsidence of an intact block preceding collapse of the inner pit, but other interpretations are possible. In the alternative shown in figure 12.56, the sag developed by thermal contraction of lava filling a buried crater, similar to the sag now developed at Alae. A buried crater of this sort could be a source of tephra now exposed in the wall of Pauahi (fig. 12.27).

The complex histories of several pit craters, and the coarse ejecta exposed in the walls of some, indicate that they have long been sites of repeated collapse and phreatic explosion. Nodes in the plumbing system may occur at these places, developed where Koae faults intersect the rift zone. Such nodes could form reservoirs for producing differentiated and hybrid magmas along the rift zone (Wright and Fiske, 1971; Swanson and others, 1976b, p. 28).

Though they are prehistoric, several of the simple craters and younger pits of the compound craters must be very young. They could have formed at the same time as a caldera collapse in or before 1790, all of them resulting from one drainage event lower along the

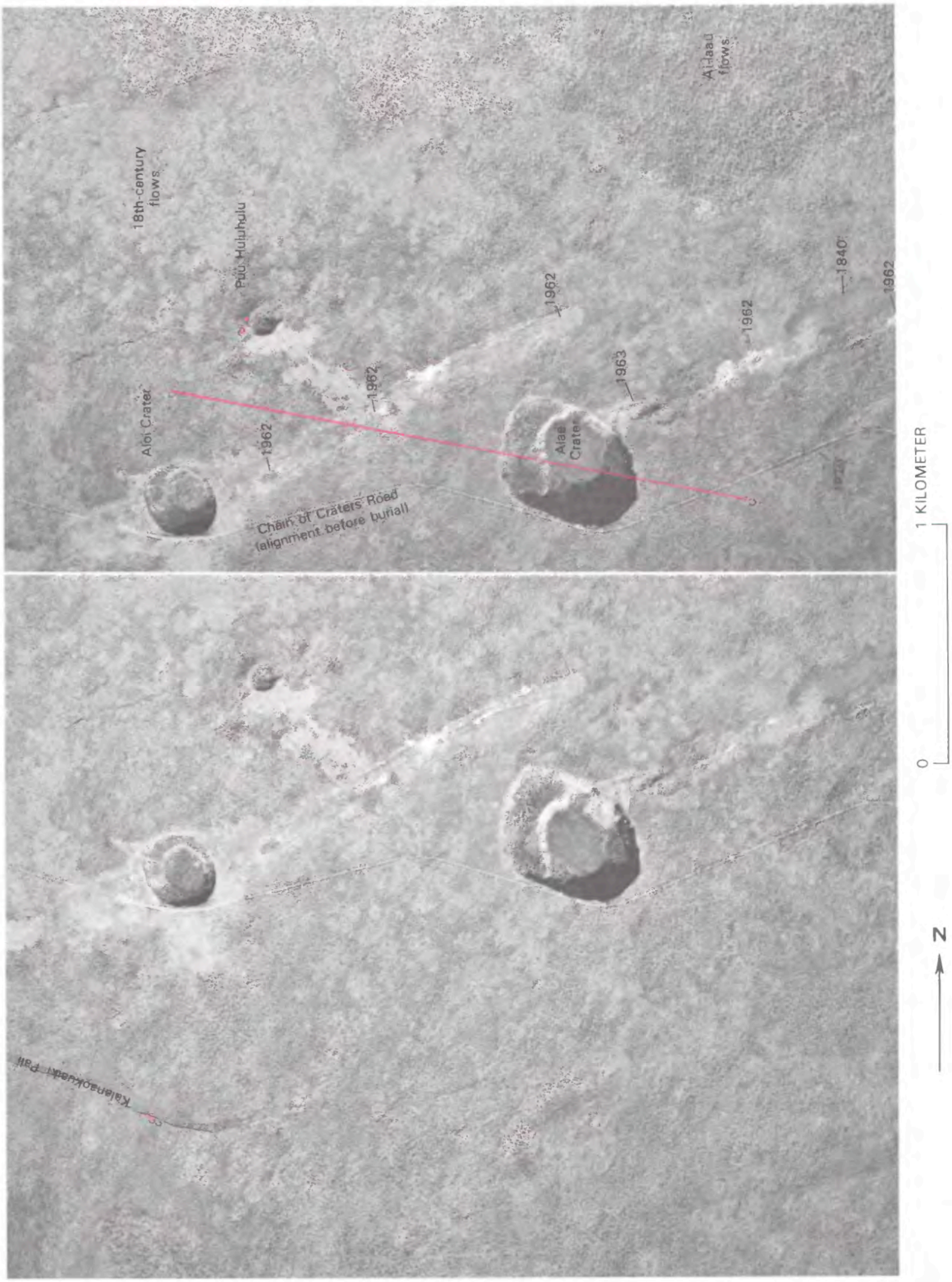


FIGURE 12.53.—Alae Crater, Aloi Crater, and Puu Huluhulu before craters were buried by growth of Mauna Ulu. Red dots, paleomagnetic sampling sites. Also shown in red is line of profile for figure 12.54. Stereo pair prepared from frames 174 and 175, roll 12CC, USDA series EKL, 1965.

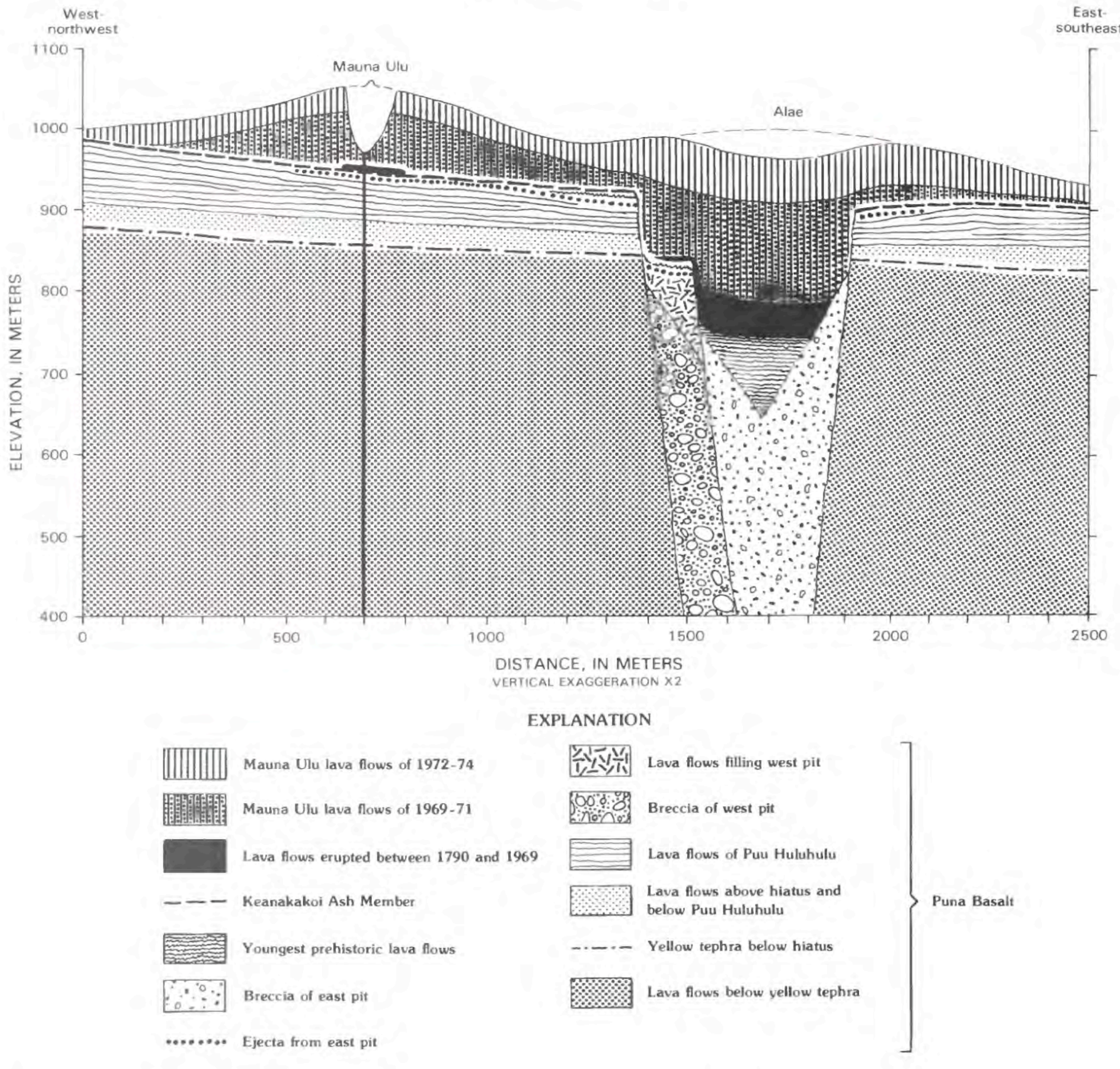


FIGURE 12.54.—Cross section of Mauna Ulu and buried Alae Crater, along line shown on figure 12.53. Dashed lines show profiles before crater formation on Mauna Ulu and sagging of lava shield above Alae Crater. Thick vertical line represents dike that fed Mauna Ulu. Hiatus and yellow tephra layer correlative with Uwekahuna Ash Member are inferred from their known occurrence in Makaopuhi Crater to east and Pauahi Crater to west. Thin layers of prehistoric ejecta and lava on rim of Alae are inferred from description by Stearns and Clark (1930); their thickness is exaggerated in this illustration.

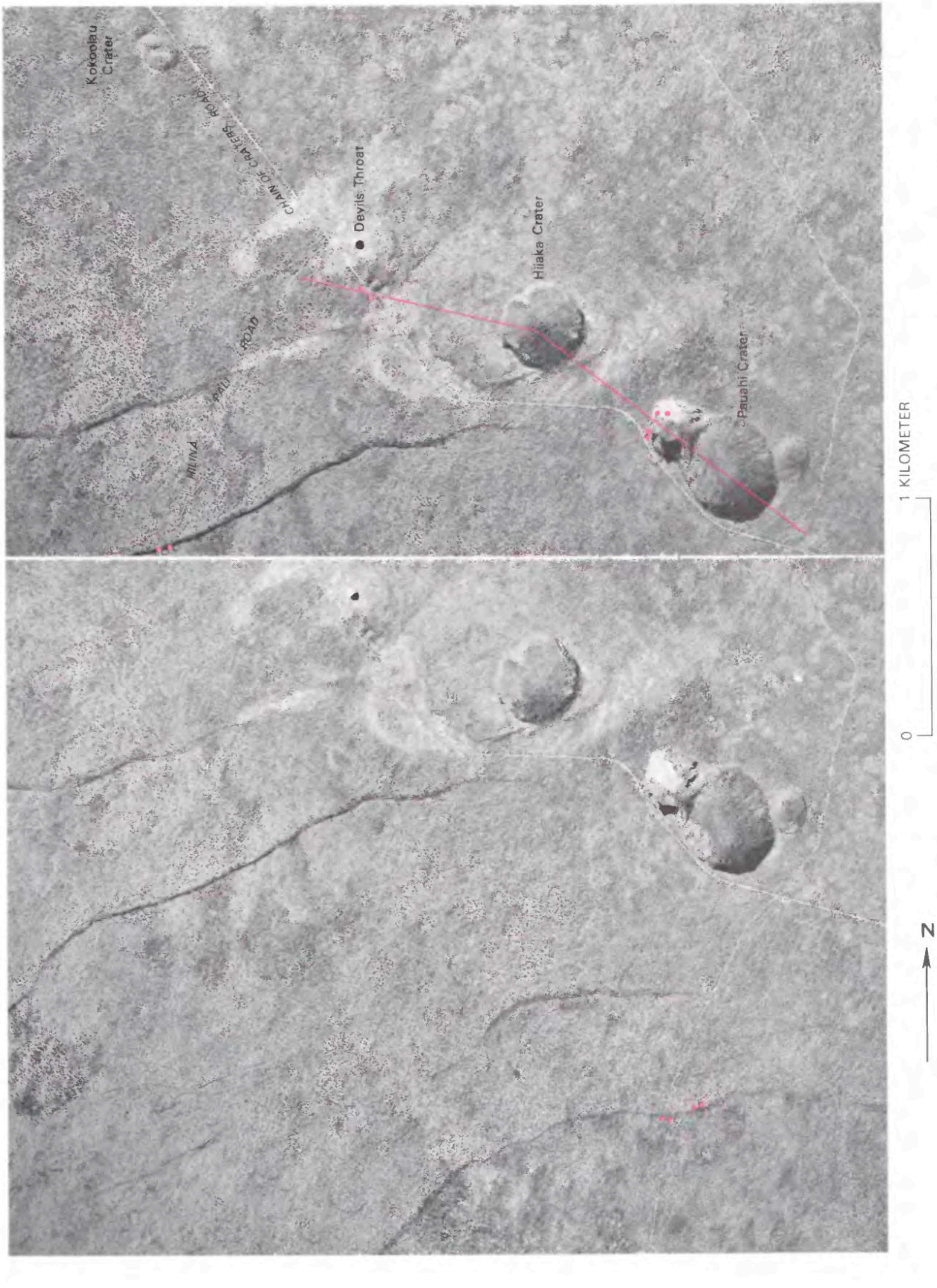


FIGURE 12.55.—Pauahi and Hiiaka before these craters were partly filled by lava during 1968–79. Larger central pit of Pauahi was floored by prehistoric lava lake. Pairs of red dots, paleomagnetic sample sites. Also shown in red is line of profile for figure 12.56. Stereo pair prepared from frames 188 and 189, roll 12CC, USDA series EKL, 1965.

east rift zone, but this has not been proved. Similar pits may form in the future, especially near sites of sustained eruption such as Mauna Ulu and Puu Oo.

SUMMIT ERUPTION OF A.D. 1790

Except for thin deposits of older and younger basaltic pumice at its base and top, the Keanakakoi Ash Member was produced by a series of explosions in 1790 (Decker and Christiansen, 1984). This eruption was still remembered well when Europeans first visited Kilauea in 1823, and it was notable for wiping out a detachment of Keoua's Puna army (Swanson and Christiansen, 1973). Deposited in quick succession were well-sorted vitric ash, less well sorted lithic-vitric ash, a local lava flow from a circumferential fissure, and poorly sorted lithic ash and blocks. Hawaiian accounts suggest that the main explosive phase continued for two or three days. The explosions were probably caused by rapid lowering of the summit magma column and entrance of subsurface water into the emptying magma conduits. Lowering of the magma column may have been associated with the voluminous eruptions of circa 1790 low on the subaerial east rift zone, but the relative timing of the summit and rift events has not been established.

It appears that the two most recent episodes of large caldera collapse and ash eruption were separated in time by about 1,500 years. Several smaller collapses and explosive eruptions could have occurred between them but have not yet been recognized.

AFTERMATH OF THE 1790 ERUPTION

More than 30 years passed between the eruption of 1790 and Ellis' visit in 1823. Little is known about this interval, but at some point eruptive activity had resumed at the summit, within the inner sink of the modern caldera. During this interval, lava fountains probably produced the golden pumice at the top of the Keanakakoi Ash Member (Sharp and others, chapter 15). By the time of Ellis' visit, the inner sink had filled with lava to within 160 m of the

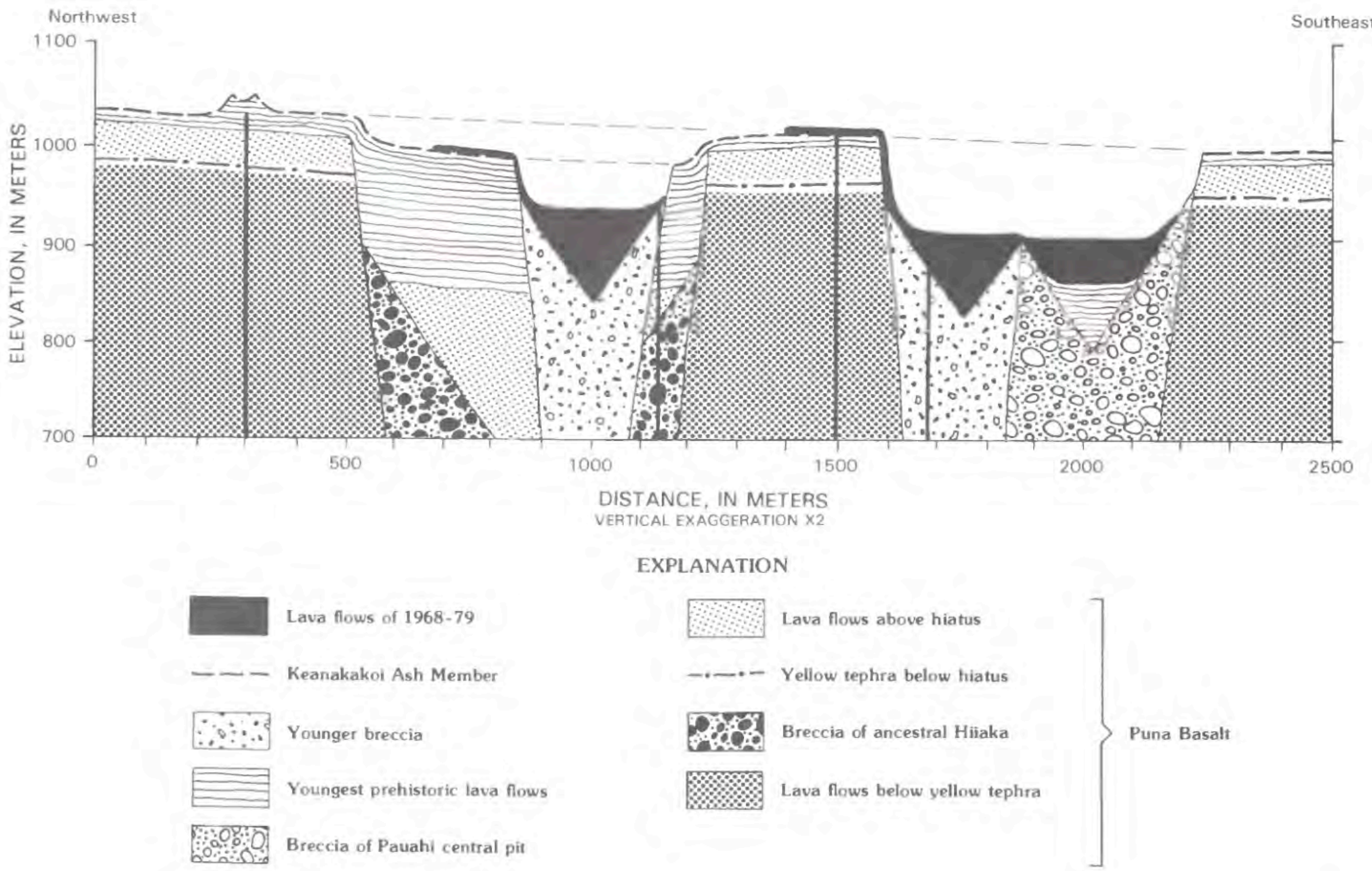


FIGURE 12.56.—Cross section through Pauahi, Hiiaka, and unnamed spatter cone near Devils Throat, along red line shown in figure 12.55. Ash and hiatus exposed in west wall of Pauahi have not been found in Hiiaka, where they are inferred to be hidden behind crater fill. Hiiaka is interpreted here as complex crater formed by two collapses, with earlier crater rim buried by prehistoric lava flows that sagged from thermal contraction. This has not been proved, however; other interpretations are possible. Ash and debris exposed in west wall of Pauahi may consist partly of Uwekahuna Ash Member ejected from Powers caldera, and partly of material ejected from local source such as older crater of Hiiaka. Dashed lines show profiles before sagging and collapse. Thick vertical lines represent dikes that fed younger lava flows.

northern rim, and then subsided again to leave a congealed terrace called the Black Ledge. This subsidence probably occurred during the southwest rift eruption of 1823, shortly before Ellis' visit. No other flank eruptions have been definitely tied to this interval, though some of the 18th-century flows may have been erupted then. Ellis' Hawaiian guides told him that several places had been overflowed by lava since the explosions of 1790. Other activity had occurred too, including a memorable earthquake and ground cracking at Kaimu.

HAWAIIAN TRADITIONS

Much of the Polynesian oral history has been lost, and many surviving fragments are contradictory, ambiguous, or unspecific. Some accounts still preserved, however, provide provocative comparisons with geologic information.

ELLIS' GENERAL ACCOUNT

The most authoritative summary was recorded in 1823 by Ellis (1827, p. 171–172) on the caldera rim. This history was given by Ellis' Hawaiian guides, according to whom Kilauea

> had been burning from time immemorial, or, to use their own words, 'mai ka po mai,' from chaos till now, * * * and had overflowed some part of the country during the reign of every king that had governed Hawaii: that in earlier ages it used to boil up, overflow its banks, and inundate the adjacent country—but that, for many kings' reigns past, it had kept below the level of the surrounding plain, continually extending its surface and increasing its depth, and occasionally throwing up, with violent explosion, huge rocks or red-hot stones. These eruptions, they said, were always accompanied by dreadful earthquakes, loud claps of thunder, with vivid and quick-succeeding lightning. No great explosion, they added, had taken place since the days of Keoua [1790]; but many places near the sea had since been overflowed, on which occasions they supposed Pele went by a road underground from her house in the crater to the shore.

Confirmation of the story was provided to Ellis (1827, p. 194) a few days later at Kaimu, along the southern coast of Puna, where

> the evenings we spent with the people of the place in conversation on various subjects, but principally respecting the volcano which we had recently visited. They corroborated the accounts we had before heard, by telling us it had been burning from time immemorial, and added, that eruptions from it had taken place during every king's reign, whose name was preserved in tradition, or song, from Akea, first king of the island, down to the present monarch.

This account is especially valuable because it is the earliest one known and was taken from local informants at Kilauea. As a result, it is the one least likely to have been distorted by distance, time, or Western preconceptions. But much uncertainty remains in its interpretation. It is difficult to say how much of it is a simple summary of witnessed events and how much is interpretation by Ellis of what was said to him or by Hawaiians of phenomena observed by them.

Especially troublesome is the possibility of Hawaiian interpretation, because evidence indicates that other traditions do include geologic inferences from the natural record. The Hawaiian account of Pele's successive homes agrees well with the progression of island volcanism, even though the sequence could not have been witnessed directly. Unless the agreement between fact and legend is coincidental, the legend must rest on inferences from nature by Hawaiians. If traditions could include inferences about the history of the archipelago they could also include inferences about the history of Kilauea.

Despite this uncertainty, however, Ellis' acount merits serious consideration. Hawaiians were probably living on Kilauea throughout the millenium in which most surficial lava flows were erupted, and they should have seen the eruptions. Widespread consistency in genealogies suggest that oral traditions can be very precise. It is worthwhile to compare Ellis' account with modern information.

Agreement between tradition and geologic information appears generally to be good. Tradition agrees well with the other evidence in stating that Kilauea had been active for a long time, had had frequent eruptions, had undergone a change in behavior from frequent overflows to summit confinement, and had had explosive eruptions.

Ellis' account is more specific than the other evidence in at least four ways. First, Ellis states that eruptions were so frequent as to occur during every king's reign, while the geologic record could permit dormant intervals of several decades or more. Second, Ellis says that the caldera developed gradually over some extended interval, while the geologic record permits sudden caldera development shortly before the explosive eruption of 1790. Third, Ellis says that explosive eruptions had occurred more than once and at intervals, while the geologic information requires no explosive eruptions between those of the Uwekahuna Ash Member (probably pre-Polynesian) and the Keanakakoi Ash Member in A.D. 1790 (Christiansen, 1979). Fourth, Ellis' account states that many coastal areas (on more than one occasion?) had been overflowed by lava since 1790, while the geologic evidence requires no such eruptions between 1790 and 1823. (Several flows in Puna and a few along the southwest rift zone could date from this interval, but the evidence available also permits them to be older.)

There are no definite contradictions between Ellis' account and currently available geologic evidence, but potential conflicts exist, especially in regard to the timing of the last summit overflows. While the tradition states explicitly that the summit had not overflowed "for many kings' reigns past," the paleomagnetic evidence indicates that such overflows had occurred as recently as the 17th century or even the early 18th century, within 100–150 years of Ellis' visit. This seems a rather short interval to include the reigns of many kings, and in fact Kalakaua's (1888, p. 31) history lists the reigns of only five kings of Hawaii between A.D. 1685 and 1824. Despite this potential disagreement and the uncertain derivation of Ellis' account, however, there are few concrete reasons to doubt the veracity of the tradition, and it appears to have potential value in supplying information not yet available from other kinds of evidence.

WESTERVELT'S EMBELLISHMENTS

Other traditions seem less reliable. Some cited by Westervelt (1916) give many details not included in Ellis' account. For example, Westervelt describes specific changes in the focus of summit eruptions, and particular explosive eruptions, not mentioned by Ellis. According to Westervelt (1916, p. 1–3):

> When Pele came to the island Hawaii, seeking a permanent home, she found another god of fire already in possession of the territory. Ai-laau was known and feared by all the people. *Ai* means 'the one who eats or devours.' *Laau* means 'tree' or a 'forest.'

Ai-laau was, therefore, the fire-god devouring forests. Time and again he laid the districts of south Hawaii desolate by the lava he poured out from his fire-pits.

* * * * *

He lived, the legends say, for a long time in a very ancient part of Kilauea, on the large island of Hawaii, now separated by a narrow ledge from the great crater and called Kilauea-iki (Little Kilauea). This seems to be the first and greatest of a number of craters extending in a line from the great lake of fire in Kilauea to the seacoast many miles away * * *.

After a time, Ai-laau left these pit craters and went into the great crater and was said to be living there when Pele came to the seashore far below.

In one of the Pele stories is the following literal translation of the account of her taking Kilauea:

'When Pele came to the island Hawaii, she first stopped at a place called Ke-ahi-a-laka in the district of Puna. From this place she began her inland journey toward the mountains. As she passed on her way there grew within her an intense desire to go at once and see Ai-laau, the god to whom Kilauea belonged, and find a resting place with him as the end of her journey. She came up, but Ai-laau was not in his home. Of a truth he had made himself thoroughly lost. He had vanished because he knew that this one coming toward him was Pele. He had seen her toiling down by the sea at Ke-ahi-a-laka. Trembling dread and heavy fear overpowered him. He ran away and was entirely lost. When Pele came to that pit she laid out the plan for her abiding home, beginning at once to dig up the foundations. She dug day and night and found that this place fulfilled all her desires. Therefore, she fastened herself tight to Hawaii for all time'

Elsewhere in this book, after quoting Ellis' account presented above, Westervelt (1916, p. 191–192) states that

When the crater was 'boiling up, overflowing its banks, and inundating the adjacent territory,' as the natives said, it poured out lava which became solid rock. As it went westward, the character of its overflow changed, becoming explosive, hurling out cinders and ashes instead of boiling lava, so that all the land, especially toward the south and west, is covered with volcanic ash.

Westervelt's account can be interpreted in many ways, one of which is the following: Long ago much of Kilauea was forested (because of a hiatus in summit overflows?), but then frequent overflows from the summit destroyed more and more of the forest. For a long time the eruptions were focused in the vicinity of Kilauea Iki, but eventually the site of eruption shifted to the west, somewhere within the perimeter of the present caldera. Eventually a series of eruptions occurred along the east rift zone, the site of eruption progressing uprift from the coast. As these eruptions occurred, the summit was shaken by tremors and a summit pool of lava drained away, leaving behind an empty, growing crater. Following a series of explosive eruptions, lava returned to the enlarged crater, which became a new site of long-sustained activity.

This account is highly provocative, and it is tempting to relate particular events of the tradition to events inferred from geologic evidence. However, this would be dangerous because the reliability of Westervelt's account is highly uncertain, for several reasons.

First, Westervelt cites no sources, though comments elsewhere in his book suggest that he had consulted Hawaiian-language newpapers of the late 19th century in Honolulu. With the sources unknown, there is no way to judge their reliability.

It appears that some material is Westervelt's own synthesis of several different accounts, and there is a strong possibility that his own preconceptions were incorporated. For example, the westward shift in the focus of summit volcanism may not have come from tradition but from his own understanding of summit events. A few decades earlier Dutton (1884, p. 121) had used geologic evidence to infer such a shift of the eruptive focus.

Westervelt's accounts could have been earlier degraded by Hawaiian storytellers, especially if his sources were newspaper accounts from the late 19th century in Honolulu, a time and locale far removed from the Kilauea of pre-Western influence. During the disintegration of Polynesian society following Captain Cook's arrival, an apparently well-preserved oral history was adulterated and partly lost. It is possible, for example, that the westward shift in eruptive activity really was mentioned by Westervelt's sources, but that these sources themselves were influenced by Dutton's interpretation.

Finally, Westervelt's account is inconsistent with traditions given elsewhere. Other sources, for example, describe Pele's arrival in very different ways and make no mention at all of Ai-laau. Until the ancestry of Westervelt's account can be established and evaluated, it can be given little credence. This is also true of many other provocative traditions.

SOME OTHER TRADITIONS

Though specific details of most traditions cannot be taken as literal truth, some traditions probably allude to real eruptions, especially those traditions Ellis recorded as associated with specific lava flows. Examples are the late prehistoric Keauhou flows west of Kealakomo (associated with a legendary conflict between Pele and Kamapua'a; Ellis, 1827,p. 183), the vent and flows of Kaholua o Kahawali (tied to the legend of Kahawali; Ellis, 1827, p. 207–210), and a flow formerly forming Cape Kumukahi (associated with Pele's rejection by the Puna Chief Kumu-kahi; Westervelt, 1916, p. 27–28). Some traditions state a time in history for a particular lava flow, for example, that Pele's action occurred during the reign of a particular king whose dates have been inferred from well-kept genealogies. Such statements could provide especially valuable checks on the geologic evidence, but even here confusion can arise.

An example of possible contradition in the most authentic traditions concerns the age of Puu Huluhulu (fig. 12.57), which paleomagnetic evidence suggests is 350 to 500 years (9B913). Seaward of Puu Huluhulu and of similar age are the Keauhou lava flows. Ellis (1827, p. 183) notes this flood of lava as dating from Pele's struggle with Kamapua'a, which Kalakaua (1888, p. 140) attributes approximately to the year A.D. 1200 in the reign of Kamaiole. But Ellis' comments elsewhere (p. 182) suggest a different age for Puu Huluhulu:

Within a few miles of Kirauea, we passed three or four high and extinct craters. One of them, Keanakakoi, the natives told us, sent forth, in the days of Riroa, king of Hawaii about fourteen generations back, most of the lava over which we were travelling. The sides of these craters were generally covered with verdure, while the brown irregular-shaped rocks on their indented summits frowned like the battlements of an ancient castle in ruins.

The crater of Liloa's reign cannot be the pit now known as Keanakakoi because Ellis (1827, p. 179) had earlier clearly stated that the only deep crater he saw besides the caldera was Kilauea Iki; he saw no others, though his guides said there were many in the

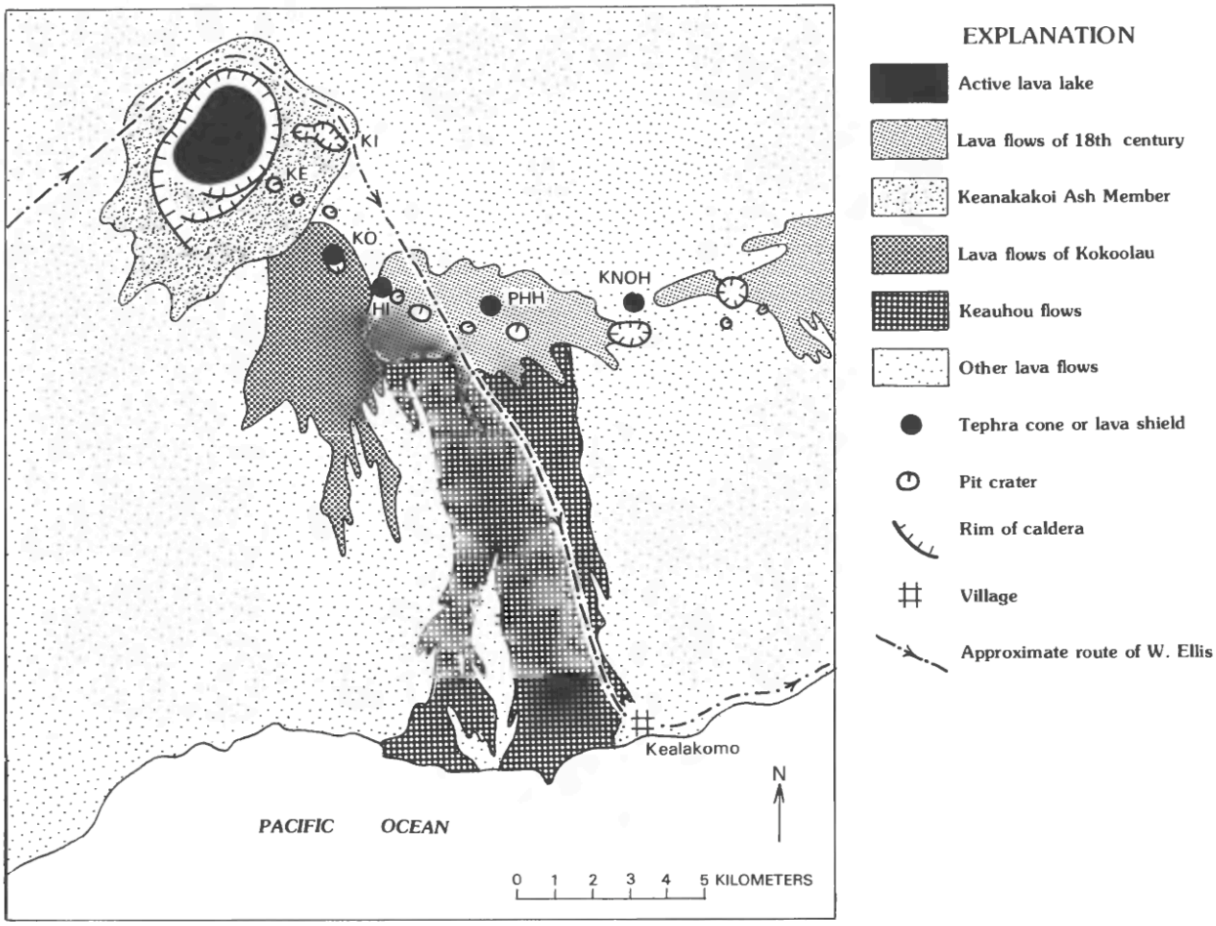


FIGURE 12.57.—Approximate route and features probably observed by William Ellis on his trek from Kilauea caldera to Kealakomo in 1823. He saw "three or four high and extinct craters" but no "deep" craters besides Kilauea Iki, though he was told that others were nearby (Ellis, 1827, p. 179, 182). Geographic features: KI, Kilauea Iki; KE, Keanakakoi; KO, Kokoolau; HI, Hiiaka; PHH, Puu Huluhulu; KNOH, Kane Nui o Hamo.

neighborhood. Moreover, Ellis described this and some other craters as high-standing edifices. Along the route that Ellis travelled from the caldera to the coast are three such features: Kokoolau, Puu Huluhulu, and the spatter cone near Devils Throat. Ellis would also have seen Kane Nui o Hamo in the distance.

If Puu Huluhulu was the crater at issue it would contradict Ellis' other comments because Liloa's reign occurred long after the inferred time of conflict between Pele and Kamapua'a. According to Kalakaua's (1888) chronology Liloa preceded Liholiho (reigning during Ellis' visit of 1823) by 14 reigns, while Kamaiole preceded Liloa by another eight reigns. Kalakaua believed Kamaiole to have reigned around A.D. 1200 and Liloa around A.D. 1475. While Liloa's reign falls into the range indicated by the paleomagnetic data (350–500 years B.P.), Kamaiole's reign does not. If Puu Huluhulu is the source of flows tied to Kamapua'a, the two traditions are in conflict. Moreover, Kane Nui o Hamo should not be the active vent of Liloa's reign because it is clearly older than Puu Huluhulu.

Other interpretatiouns are possible. The Pele-Kamapua'a tradition could refer to Kane Nui o Hamo, whose lava flows have a paleomagnetic direction consistent with the dates assigned to Kamaiole's reign. Ellis clearly stated, however, that the Pele-Kamapua'a conflict was associated with the young, dark lava flows west of Kealakomo (the Keauhou flows), and these flows could not have come from Kane Nui o Hamo; the flows from Kane Nui o Hamo are the older ones upon which Kealakomo sat.

Another alternative would have Kokoolau as the vent of Liloa's reign and Puu Huluhulu the older source of the Kamapua'a flows. This would preserve the chronology implied by the traditions; but then both Kokoolau and Puu Huluhulu would be older than expected from their paleomagnetic data, unless the reigns were briefer than believed by Kalakaua.

From the discussion above it should be clear that caution must be used in extracting eruption history from the traditions. In fact, the most useful comparisons between traditions and geologic information may proceed in the opposite direction, the geologic data providing a firmer base for reconstructing the social history.

HISTORICAL ERUPTIONS

The historical activity of Kilauea has been reviewed in detail several times previously (Dana, 1890; Brigham, 1909; Hitchcock, 1909; Stearns and Clark, 1930; Stearns and Macdonald, 1946; Macdonald and Abbott, 1970). Only a brief summary is given here.

LONG-SUSTAINED SUMMIT ERUPTIONS, 1823–1924

Though brief references to Hawaiian volcanism were recorded in the late 18th century (Ledyard, 1783; Beaglehole, 1967; Vancouver, 1798; A. Menzies, in Hitchcock, 1909), the historical record really began with Ellis' (1827) description of Kilauea in 1823. At that time a sustained eruption was in progress, and most of the inner sink was occupied by an active lava lake standing about 270 m below the north rim. About 90 m above the lake surface was the Black Ledge a terrace of freshly congealed lava thought to represent the level reached by caldera filling a short time before. The caldera floor probably had subsided in the spring of 1823, when a brief but voluminous eruption from the Great Crack flooded the western south flank with lava (the Keaiwa flow, which reached the sea from Kapaoo Point to Waiapele Bay). The subsidence of the caldera floor apparently did not generate large explosions at the summit, though small phreatic explosions deposited tephra at two places along the Great Crack (Stearns, 1926).

Continued activity after 1823 refilled the caldera to a level about 15 m above the Black Ledge by 1832, when a small eruption occurred on Byron Ledge and the caldera floor subsided again, this time about 300 m (Goodrich, 1833). Filling then recommenced, and in 1834 the caldera was much the way it had been in 1823, with an inner pit 113 m deep surrounded by a black ledge (Douglas, 1905). Continued activity filled the pit and apparently overflowed the black ledge so that it was no longer visible late in 1838 (Strzelecki, 1845). At this time the activity had become confined to 5 lava lakes, the largest of them called Hau-mau-mau in the southwestern part of the caldera on the site of the pit crater now called Halemaumau.

Vigorous summit activity in the spring of 1840 was followed by another subsidence of the caldera floor and a rapid series of brief eruptions along the east rift zone. The last eruption from the lower east rift zone was especially voluminous and sent surface-fed lava flows northeastward from the vicinity of Pahoa to the coast at Nanawale (Coan, 1841). Shortly afterward Kilauea was visited and described by members of the United States Exploring Expedition (Wilkes, 1845; Dana, 1849). The subsided inner sink at this time was about 100 m deep and was surrounded by a new black ledge about 480 m wide rising to about 180 m below the western caldera rim. By 1846 the inner basin had filled again (Dana, 1850), and by 1848 a lava shield at the site of Halemaumau had grown nearly as high as the lowest part of the caldera rim (Coan, 1851).

The next subsidence of the caldera floor occurred in 1868, when large earthquakes shook the southern part of Hawaii and simultaneous eruptions occurred from Mauna Loa and Kilauea (Coan, 1868). One Kilauea outbreak produced a chain of small lava pads near the distal end of the northern strand of the upper southwest rift zone. Another small eruption from Byron Ledge fed a lava flow that ponded on the floor of Kilauea Iki. An area about 1,900 m wide on the central caldera floor sagged about 100 m, and a deeper conical pit about 900 m wide and about 200 m deep developed at its southwest end at Halemaumau (Hitchcock, 1909). The pit again filled, and by 1874 a lava shield at Halemaumau had once again grown to about the elevation of the southern caldera rim (Coan, 1874). Minor subsidences in and around Halemaumau occurred again in 1879, 1886, 1891, and 1894 (Hitchcock, 1909). None of those episodes was associated with known eruptions from the rift zones, though some undated post-1790 flows south of Mauna Iki (fig. 12.5*B*; Holcomb, 1980b) could have been erupted at one of those times.

The subsidence of 1894 was followed by 13 years of dormancy and very subdued, episodic activity within the pit of Halemaumau (Hitchcock, 1909). In 1908 the activity once again became more vigorous, and it was nearly continuous until 1924, with minor subsidences of the lava column occurring in 1916, 1919, 1922, and 1923 (Jaggar, 1947). The 1919 subsidence was followed by the 1919–20 eruption of Mauna Iki along the southwest rift, the first sustained eruption along either rift zone during the historical interval and probably the first since the Heiheiahulu eruption of circa 1750. The 1922 subsidence was associated with small eruptions from Makaopuhi to Napau, and the 1923 event was followed by another small eruption between Makaopuhi and Alae. The summit activity once again built a broad lava shield that occupied the entire inner sink of the modern caldera, with Halemaumau at its summit.

INTERMITTENT SUMMIT AND FLANK ERUPTIONS, 1924–1968

The century-long interval of nearly continuous activity in the caldera ended in 1924 (Jaggar and Finch, 1924; Stearns, 1925). In the spring of that year an 80-m drop of the magma column was followed by a swarm of earthquakes that migrated from the summit along the east rift zone past Kapoho. Though much ground deformation developed near Kapoho, a subaerial eruption did not occur; a submarine eruption may have occurred somewhere beyond Cape Kumukahi. Renewed subsidence of the magma column at Halemaumau was then followed by 17 days of repeated phreatic explosions and collapse of the caldera floor around Halemaumau.

Lava returned to Halemaumau shortly after the 1924 explosions ceased, but instead of being sustained the activity was now episodic. A series of seven brief eruptions in the next 10 years (Jaggar, 1947) reduced the depth of Halemaumau from 390 to 150 m, and then no eruptions occurred for 18 years, from 1934 to 1952. Sustained eruption from June to November of 1952 filled Halemaumau with another 120 m of lava. A brief eruption in May–June 1954 added 6 m of lava in Halemaumau and a thin lava flow on the caldera floor to the east (Macdonald, 1955).

Then, after at least 150 years of infrequent eruption and 33 years of no eruption, the subaerial part of Kilauea's east rift zone resumed frequent activity in February–May 1955 with a series of eruptions along its lower segment (fig. 12.58*A*; Macdonald and Eaton, 1964). These were followed by a sustained eruption in Kilauea Iki in 1959 and then by eruptions from the middle and lower segments of the east rift zone in January–February 1960 (fig. 12.58*B*; Richter and others, 1970). Brief eruptions at Halemaumau in February–March 1961 were followed by a series of outbreaks at 13 places along the middle and lower east rift zone in September 1961 (Richter and others, 1964), and further eruptions from the upper and middle east rift zone occurred in December 1962, August 1963, and March and December 1965 (fig. 12.58*C*; Moore and Krivoy, 1964; Peck and others, 1966; Fiske and Koyanagi, 1968; Wright and others, 1968). A sustained eruption then occurred in Halemaumau from November 1967 to

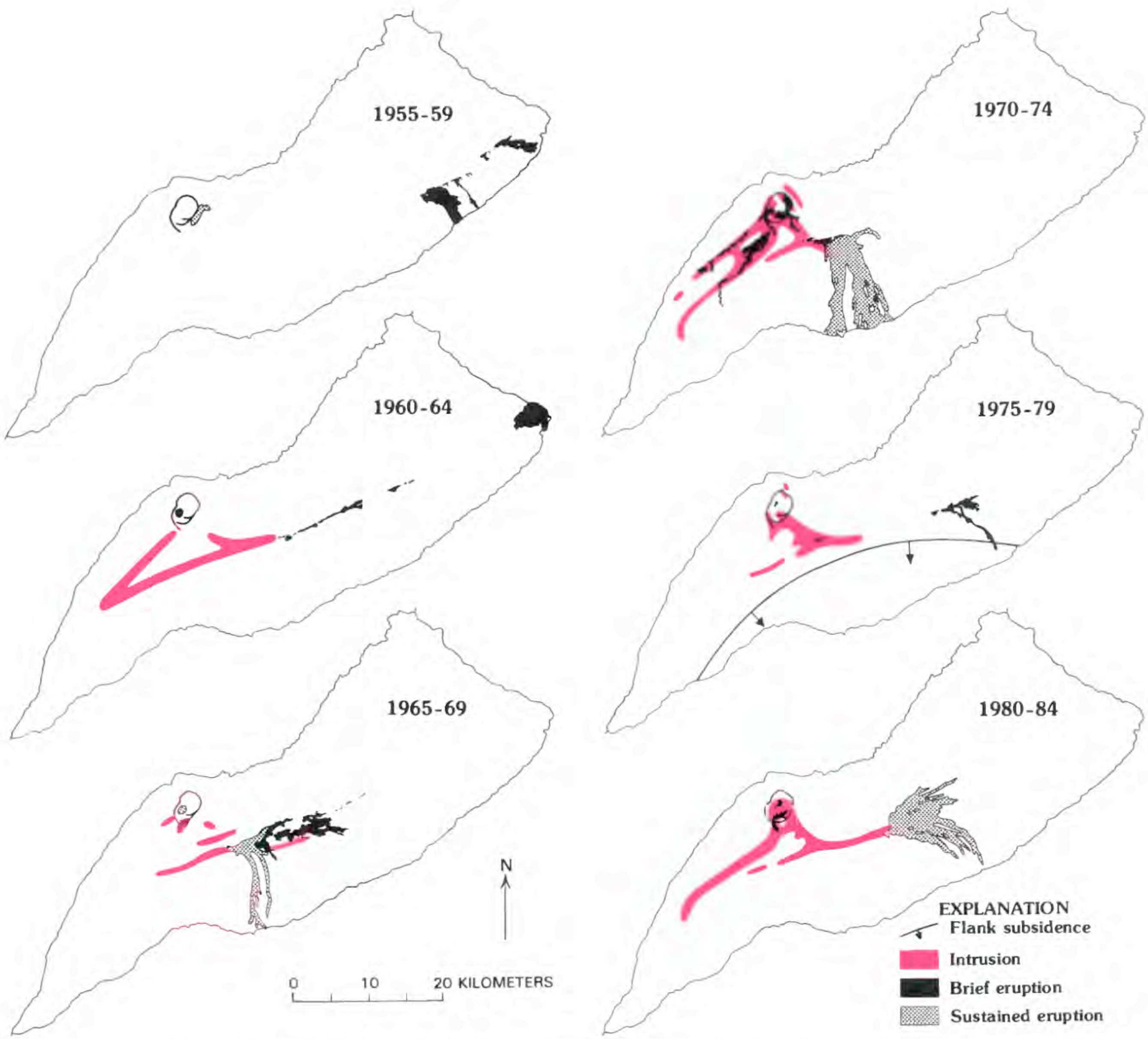


FIGURE 12.58.—Lava flows and intrusions during the interval 1955–1984 at Kilauea. Intrusions since 1962 are inferred from locations of shallow earthquake swarms compiled by Klein and others (chapter 43).

July 1968 (Kinoshita and others, 1969). This was the last sustained eruption in the summit region; sustained activity since then has occurred only along the east rift zone.

FREQUENT AND SUSTAINED FLANK ERUPTIONS, 1968–1985

The 1967–68 summit eruption was followed by a succession of brief eruptions from the upper and middle east rift zone in August and October 1968, and February 1969 (Moore and Koyanagi, 1969; Jackson and others, 1975; Swanson and others, 1976b). While the flank eruptions of 1955–1963 were widely distributed along the east rift zone and interspersed with sustained eruptions at the summit, the 1968–69 eruptions were concentrated along a short segment of the rift zone between Hiiaka and Napau pit craters. As the locus of eruptions contracted, the intervals between eruption decreased to a few months. The sequence culminated in a sustained eruption that began in May 1969 and continued, with brief interruptions, until June 1974, building the lava shield of Mauna Ulu (figs. 12.34, 12.35, 12.58*D*; Swanson and others, 1979; Tilling and others, chapter 16). An interruption in the second half of 1971 saw two brief eruptions from the summit and northern strand of the upper southwest rift zone (Duffield and others, 1982). Other interruptions saw brief eruptions higher up the east rift zone in May and November 1973 (Tilling and others, chapter 16). The final cessation of activity at Mauna Ulu in June 1974 was followed by brief eruptions from the summit and middle strand of the upper southwest rift zone in July, September, and December 1974.

A magnitude 7.2 earthquake and subsidence along the south coast on November 29, 1975 (fig. 12.58*E*; Tilling and others, 1976) was followed by episodes of summit deflation and rift intrusion in June, July, and August 1976 and February 1977 (Dzurisin and others, 1980) and then a brief eruption from the middle east rift zone in September 1977 (Moore and others, 1980). An intrusion of magma into the upper east rift zone in May 1979 was followed by a brief eruption at Pauahi and vicinity in November 1979, and five more intrusive episodes along the upper east rift zone in March (two episodes), August, October, and November 1980 (Dzurisin and others, 1984; Banks and others, 1981). Activity then shifted to the southwest rift zone, with intrusive episodes occurring there in January and August 1981 and June 1982. Brief eruptions occurred at the summit in April and September 1982 (Banks and others, 1983).

Following the 1982 summit eruptions, activity shifted once again to the east rift zone. An intrusion into the upper east rift zone in December 1982 was followed in January 1983 by an eruption near Puu Kahaualea on the middle east rift zone. That eruption was sustained, building a vent edifice called Puu Oo (Wolfe and others, chapter 17); it still continues at this writing in March 1986.

SUMMARY OF ERUPTIVE HISTORY

Kilauea saw subaerial shield growth punctuated by large explosions 100,000–10,000 years ago (Hilina Basalt and Pahala Ash); long-sustained summit eruptions and briefer rift eruptions 10,000–2,000 years ago (scattered kipukas); sustained eruptions from the summit and rift zones 2,000–1,500 years ago; caldera collapse and filling 1,500–1,100 years ago (Uwekahuna Ash Member of the Puna Basalt and hiatus); extensive caldera overflows and numerous rift eruptions, with no patterns of summit-flank interrelation yet discerned, 1,000–350 years ago (Volcano, Kalue, Ai-laau flows); sustained summit activity followed by extensive rift eruptions accompanying caldera collapse, followed by summit explosion, 350–200 years ago (Observatory flows, Keanakakoi Ash Member of Puna Basalt); and long-sustained summit eruption followed by frequent rift eruptions during the last 200 years (historical records).

The recent eruption history is summarized in figure 12.59. About 1,500 years ago the Powers caldera developed, truncating lava flows assigned paleomagnetically to the interval 2,000–1,500 years B.P. The Uwekahuna Ash Member was draped onto the rim and step faults of the caldera. Little is known about Kilauea's eruptions of about 1,500–1,100 years B.P.; only a few flows along the rift zones are known from this interval, and the summit region was remarkably devoid of eruptions outside the Powers caldera. Unless the magma supply was cut off during this interval, most of the eruptive activity must have been confined to the caldera and to submarine parts of the volcano. The Powers caldera began to overflow about 1,200–1,100 years ago and continued to do so intermittently until the 18th century. These overflows covered much of Kilauea's surface. The overflows on different flanks have different ages, indicating that activity was concentrated on one side of the summit for a few decades or centuries and then shifted to another side to cover a different sector. Progressive time relations between summit activity and rift activity are not yet resolved during this interval.

Such progressions do appear beginning about 500–350 years ago. Although paleomagnetic dating does not yet resolve a summit-rift progression at that time, traditions cited by Westervelt (1916) suggest that long-lived activity at the Ai-laau vent was followed by rift eruptions and summit collapse, which were in turn followed by sustained activity at the Observatory vent.

The Observatory activity was followed by many brief eruptions and a few sustained eruptions along both rift zones, especially the east rift zone. This flurry of flank eruptions must have been accompanied by growth of the modern caldera, much of which postdates the Observatory shield. Caldera collapse climaxed with phreatomagmatic eruption of the Keanakakoi Ash Member in A.D. 1790.

Following the 1790 eruption, Kilauea's behavior changed again, and for more than a century almost all subaerial activity was confined to the caldera. During this interval, only two large flank eruptions are known, in 1823 and 1840, wheras activity within the caldera was sustained almost continuously.

Kilauea's famous 19th-century pattern of continuous summit activity ceased in 1924, possibly following a submarine eruption from the east rift zone that coincided with summit collapse. Since then summit eruptions have been infrequent and relatively brief, while eruptions from the rift zones have become more frequent and more sustained.

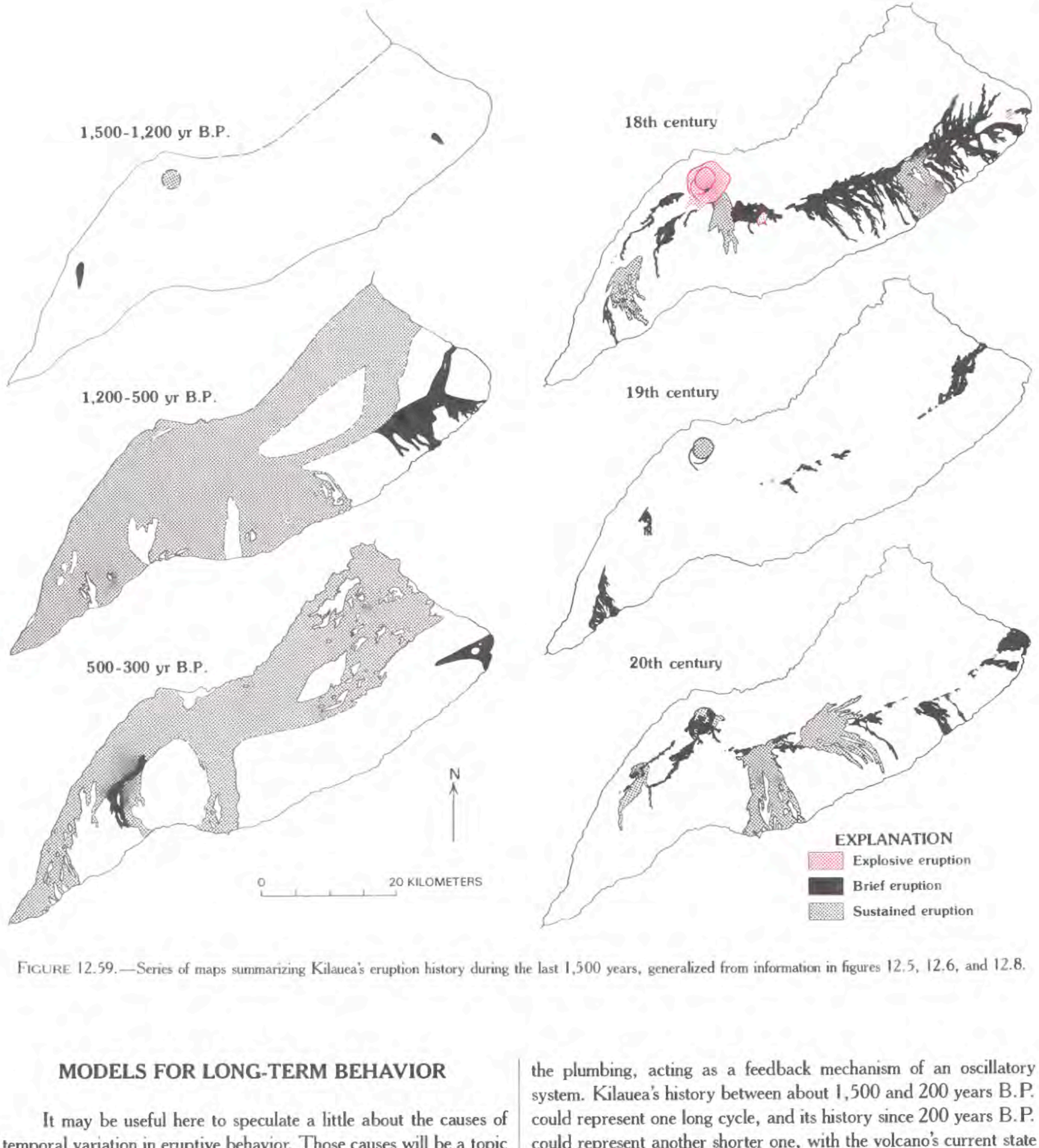


FIGURE 12.59.—Series of maps summarizing Kilauea's eruption history during the last 1,500 years, generalized from information in figures 12.5, 12.6, and 12.8.

MODELS FOR LONG-TERM BEHAVIOR

It may be useful here to speculate a little about the causes of temporal variation in eruptive behavior. Those causes will be a topic of future research because they may lead to better eruption forecasts.

Many models can be visualized, and they can be classified in various ways. For example, we can distinguish evolutionary, cyclical, and steady-state models differing in their forecasting utility.

A cyclical model is shown in figure 12.60. This caldera-dominated model features shifts in magma storage as successive calderas form and fill. In this model caldera collapse arises from changes in magma plumbing, and collapse in turn causes changes in the plumbing, acting as a feedback mechanism of an oscillatory system. Kilauea's history between about 1,500 and 200 years B.P. could represent one long cycle, and its history since 200 years B.P. could represent another shorter one, with the volcano's current state corresponding to stage 2 or stage 3 of the model (fig. 12.60).

Another cyclical model is shown in figure 12.61. This slumping-dominated model focuses on Kilauea's unbuttressed south flank, which the caldera model ignores. Eruptive behavior in this model responds to changes in magma storage arising from flank deformation. It was suggested more than 20 years ago that magma storage in the rift zones is controlled by recurrent slumping of the south flank (Moore and Krivoy, 1964). Later it was concluded from the timing

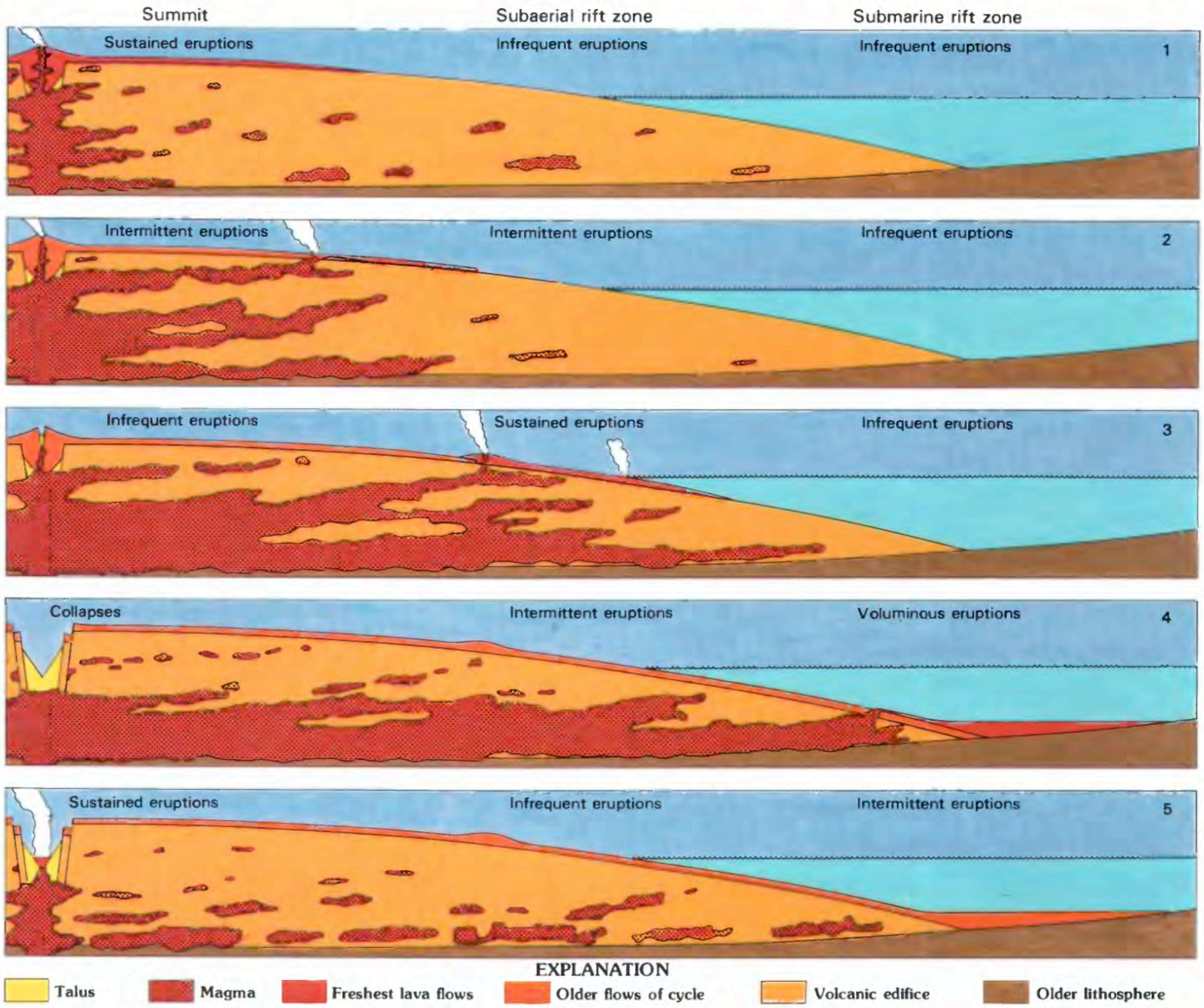


FIGURE 12.60.—Cyclical model for long-term behavior of Kilauea, based on repeated episodes of caldera collapse and filling. Schematic longitudinal profiles of rift zone show five stages in cycle, which could represent dynamic equilibrium between hydrostatic, thermal, and frictional factors. **Stage 1.** Eruptions are long-sustained and restricted to caldera, filling it so that most magma is stored beneath summit. As magma column rises, however, dikes are injected laterally under increasing head and penetrate into rift zones. **Stage 2.** Summit eruptions are less sustained and rift eruptions more frequent as more magma is diverted into rift zones. **Stage 3.** As better continuity is developed in plumbing of rift zone, longer eruptions occur farther from summit. As lava is erupted at lower elevations, magma column subsides beneath summit, and caldera-filling lava slowly cools. **Stage 4.** Voluminous eruptions from rift zones drain magma from upper parts of edifice, and collapse ensues. Collapse at summit rejuvenates caldera, and collapse along rift zones reduces continuity of their plumbing systems. **Stage 5.** Magma rising from deep beneath summit now finds its easiest escape into newly deepened caldera; activity is once again sustained within caldera, and continuity is further reduced in rift plumbing system as dikes solidify.

of flank deformation that slumping is a passive response to forceful intrusion of magma into the rift zones (Swanson and others, 1976a). But that conclusion was based on observations of just the past century; long-term changes in flank behavior might accompany long-term changes in eruptive behavior. Some intervals might be dominated by forceful intrusion and passive deformation and other intervals by active slumping and permissive intrusion. The true state of the edifice might be a quasi-equilibrium perturbable in either direction, with feedback mechanisms forcing an oscillation.

Still other models could be fundamentally cyclical but made complex from the interplay of various mechanisms. For example, slumping cycles and caldera cycles could both operate, independently or in rhythm. If episodes of slumping occurred more often than episodes of caldera collapse, with each perturbation disrupting the

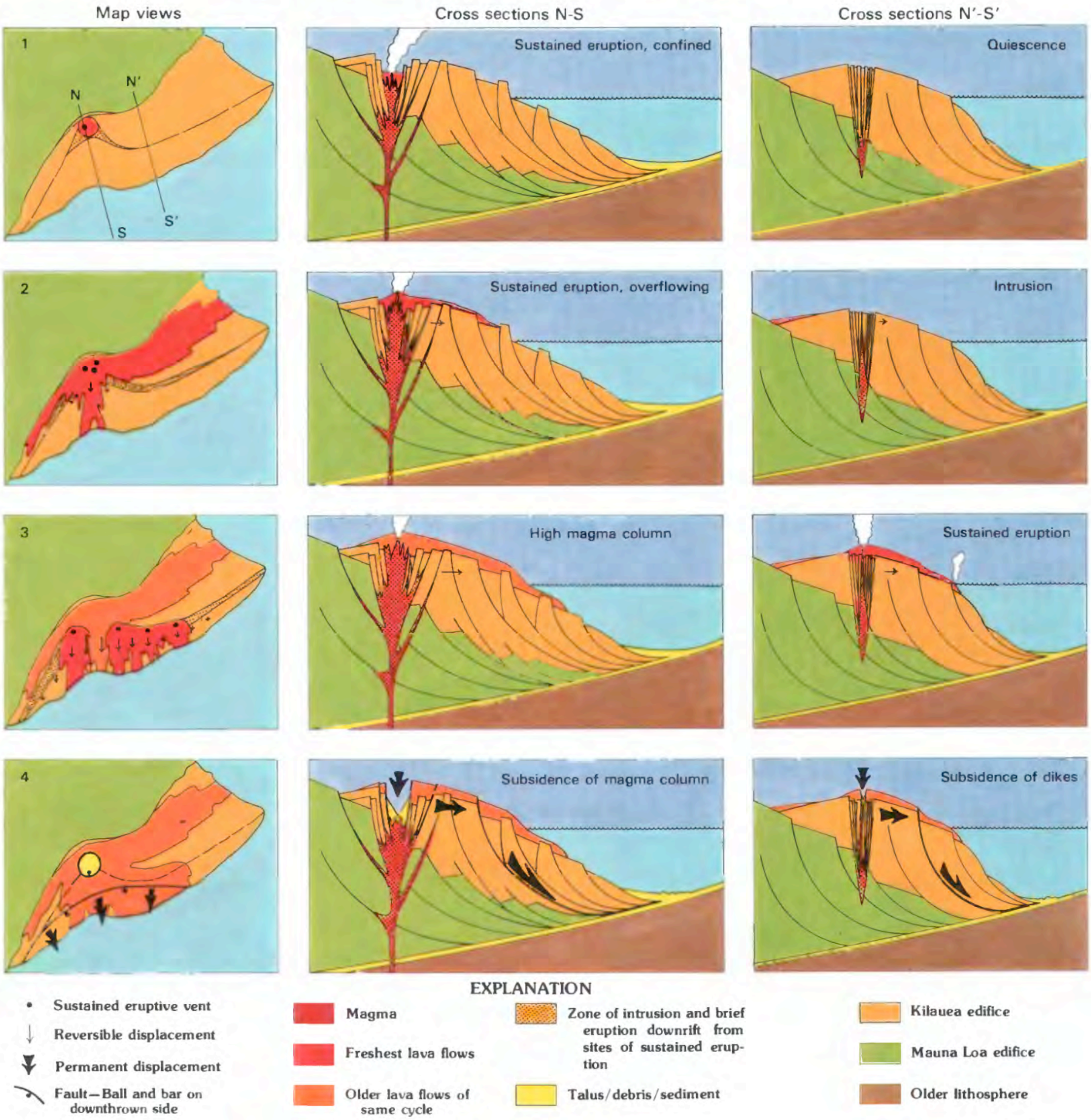


FIGURE 12.61.—Cyclical model based on seaward displacement of south flank. Schematic maps and transverse cross sections show four stages in cycle. Slumping cycles of this sort could occur over intervals as short as a few years, and they might be superimposed on long-term caldera cycles. Slumping episodes might sometimes induce caldera subsidence. Slippage might be concentrated within a layer of oceanic sediment several hundred meters thick beneath the volcano, as suggested by Nakamura (1982). **Stage 1.** Volcanic edifice is in repose as magma column rises passively to fill summit reservoir. **Stage 2.** Summit magma column rises high and overflows. Magma is forcefully intruded under rising head into rift zones, and south flank is displaced. Much of this flank deformation can be reversed if magma withdraws. **Stage 3.** Continued intrusion initiates sustained eruptions along rift zones and displaces south flank further. Flank is made increasingly unstable by steepening its slope and loading its surface, but permanent displacement does not occur until frictional threshold is overcome. **Stage 4.** Oversteepening and loading of flank by extrusion and forceful intrusion overcome sliding resistance, and permanent slumping displacement occurs along flank faults. Lateral expansion of magma reservoir causes summit magma column to subside, and head loss causes magma also to subside far out along rift zones. Magma pressure drops rapidly and stops driving permanent displacement, but slumping continues until frictional resistance overcomes inertia of sliding block. Magma resumes passive filling of space made available by slumping episode.

plumbing system and followed by evolutionary reintegration of the plumbing system, very complicated but possibly predictable harmonic patterns of eruption might ensue.

Cyclical models imply the possibility of long-range forecasts, but steady-state or stochastic models do not. By itself, stage 3 of figure 12.60 could represent such a model, with much magma always stored throughout a plumbing system that is never seriously disrupted. Eruptions of any type could occur from any part of the system at any time. In this model there would be no systematic evolution of the plumbing system over decades or centuries; instead, the variations in eruptive behavior would arise merely from chance developments such as the times when individual dikes happened to intersect the surface. If a model like this best described the volcano's behavior, it might not be possible to predict long-term changes using the previous history.

Alternative noncyclical models could blend evolutionary processes with random events. Random behavior might be superimposed upon, or reset, evolutionary progressions, and evolutionary behavior might characterize some intervals but not others. For example, the magma plumbing system might respond in a predictable, evolutionary way to a major submarine eruption or flank subsidence not caused by feedback mechanisms within the system. Although major perturbations would remain unpredictable, evolutionary trends following them might permit forecasts of long-term behavior between them. That is, we might be able to forecast long intervals of dominantly summit activity versus long intervals of dominantly rift activity. Predictive success would be achieved much of the time even though major perturbations remained unpredictable.

CONCLUSIONS

Kilauea's surface is about 10 times younger than was thought previously (table 12.2); 70 percent is younger than 500 years, 90 percent younger than 1,100 years. A major hiatus in summit overflows occurred between about 1,500 and 1,100 years ago. Much of the present caldera dates from the 18th century, but it was preceded by at least one earlier caldera that developed about 1,500 years B.P. and was later filled.

The various subdivisions of Kilauea are covered by lava flows of different types (table 12.3) produced by eruptions of different kinds from different parts of the magma plumbing system (table 12.4). Kilauea's surface is dominated by tube-fed pahoehoe (67 percent), while surface-fed pahoehoe (14 percent) is mainly limited to near vents along the rift zones, and aa (16 percent) occurs mainly on the south flank seaward of the rift zones. Surface coverage has been dominated by tube-fed lava flows from long-sustained eruptions at the summit; 51 percent of the volcano's surface still consists of such lava even though summit overflows have not occurred for the last 200 years. About 30 percent of Kilauea was covered by lava from just one long eruption at the Ai-laau vent a few hundred years ago. Surface coverage by brief eruptions is minor (22 percent), despite the high frequency of such eruptions in recent decades.

Different parts of Kilauea have differed in eruptive behavior. The most notable difference is between the summit and rift zones, with most long-sustained eruptions occurring at summit vents. Sustained unstable eruptions are more numerous along the upper parts of the rift zones than along their lower parts. Pyroclastic central vents are more common along the lower parts of the rift zones, especially below elevations of 500 m. The briefest fissure eruptions have occurred all along the rift zones and at the summit, displaying on average no obvious affinity for any part of the volcano. During particular decades or centuries, however, they have been concentrated in restricted regions. Other spatial variations appear to have been characteristic of particular localities, such as the southern strand of the southwest rift zone.

Different intervals of Kilauea's history have been dominated by different eruptive behaviors. Behavioral changes have occurred over intervals of decades and centuries. The changes include variations in both frequency and type of eruption. Some changes have been repeated at long intervals, and some may have occurred in evolutionary sequences. Two explosive eruptions large enough to produce extensive pyroclastic sheets seem to have been followed by intervals longer than a century in which most eruptive activity was confined to a summit caldera. While the caldera slowly filled, vegetation became well established on the volcano's flanks. Rift activity waxed as summit activity waned, and in the recent historical example the waxing sequence resembles an evolutionary progression: rift eruptions were at first brief and widely separated in space and time, but gradually they became frequent along a restricted segment of the rift zone and culminated in sustained activity at one locality.

During the past 500 years, when the eruptive pattern can best be defined, there has been a repeated pattern of sympathetic behavior between the summit and rift zones. Little flank activity has occurred when summit activity was sustained, and sustained summit activity has ceased when there was much activity on the rift zones. Rift activity has been accompanied by subsidence at the summit, and large summit collapses have been followed by phreatomagmatic eruption. Events following explosive eruptions, however, have displayed no consistent pattern. The large explosive eruption of 1790 was preceded by much rift activity and followed by much summit activity, but the smaller eruption of 1924 was preceded by much summit activity and followed by little such activity. The current rift activity resembles that which occurred in the 18th century before the explosive eruption of 1790.

TABLE 12.1.—*Classification of Kilauea eruptions*

[Types of lava flow: PS, surface-fed pahoehoe; PT, tube-fed pahoehoe; A, aa]

Type	Duration	Character of effusion	Vents	Lava flows
Brief, fissure	Hours to days	Simple waxing, waning; small fountains.	Open fissures, ramparts.	Few; PS and A.
Brief, localized	Days to weeks	Simple waxing, waning or pulses; large fountains.	Pyroclastic cones, mounds.	Several; PS and A.
Sustained, unstable	Months to years	Complex sequence; waxing, pulses, waning.	Small shields.	Many; PS, PT, and A.
Sustained, stable	Decades to centuries	Mainly slow, steady; some interruptions.	Large shield.	Many; mainly PT.
Explosive	Days to weeks	Successive explosions.	Crater.	Few or none.

TABLE 12.2.—*Age distribution of Kilauea's surface*

[Areas measured by digitizer on a generalized map at scale of 1:50,000]

Age (yr B.P.)	Area (km²)	Area (percent)	Cumulative area (km²)	Cumulative area (percent)
0–50	146.5	10.1	146.5	10.1
50–150	38.2	2.6	184.7	12.7
150–250	168.2	11.6	352.9	24.3
250–350	167.6	11.5	520.5	35.8
350–500	454.5	31.3	975.0	67.1
500–750	190.6	13.1	1,165.6	80.2
750–1,000	89.6	6.2	1,255.3	86.4
1,000–1,500	50.4	3.5	1,395.6	89.9
>1,500	146.0	10.1	[1]1,451.6	100.0

[1]A separate measurement of total area on the same map gave 1,451.0 km².

TABLE 12.3.—*Distribution of lava types on Kilauea's subaerial surface*

[Areas measured by digitizer on a generalized map at scale of 1:50,000. Types of lava: PS, surface-fed pahoehoe; PT, tube-fed pahoehoe; A, aa: T, pyroclastics; ML, all types erupted from Mauna Loa]

Structural subdivision	Area (km²)	Area Percent of Kilauea	Lava type	Area (km²)	Area Percent of subdivision
Summit	51.6	3.6	PS	19.4	37.5
			PT	5.0	9.6
			A	1.5	3.0
			T	18.3	35.6
			ML	7.4	14.3
Koae fault system	65.7	4.5	PS	7.8	11.9
			PT	51.1	77.7
			A	6.3	9.6
			T	.5	.8
Upper southwest rift zone	88.4	6.1	PS	21.3	24.1
			PT	46.6	52.7
			A	7.5	8.5
			T	1.1	1.2
			ML	11.9	13.5
Lower southwest rift zone	91.5	6.3	PS	13.8	15.1
			PT	64.0	69.9
			A	13.7	15.0
Upper east rift zone	55.1	3.8	PS	20.9	38.0
			PT	31.2	56.6
			A	2.8	5.0
			T	.2	.4
Middle east rift zone	91.5	6.3	PS	36.7	40.1
			PT	42.8	46.8
			A	10.7	11.7
			T	1.2	1.4
Lower east rift zone	81.8	5.7	PS	43.0	52.5
			PT	8.1	9.9
			A	25.9	31.7
			T	4.9	5.9
North flank	445.7	30.8	PS	19.1	4.3
			PT	403.4	90.5
			A	21.4	4.8
			ML	1.8	.4
South flank	475.9	32.9	PS	17.4	3.7
			PT	316.9	66.6
			A	141.1	29.6
			T	.6	.1
Total subaerial Kilauea	[1]1,447.3	100.0	PS	199.4	13.8
			PT	969.1	67.0
			A	230.9	16.0
			T	26.8	1.9
			ML	21.1	1.5

[1]A separate measurement of total area on the same map gave 1,447.9 km².

TABLE 12.4.—*Distribution of lava on Kilauea's surface from different types of eruption*

[Areas measured by digitizer on a generalized map at scale of 1:50,000]

Location of vents	Brief (km²)	Brief (percent)	Sustained, stable (km²)	Sustained, stable (percent)	Sustained, unstable (km²)	Sustained, unstable (percent)	Explosive (km²)	Explosive (percent)	Total (km²)	Total (percent)
Summit	10.2	0.7	732.9	50.6	0	0	18.5	1.3	761.6	52.6
Upper southwest rift zone	35.8	2.5	0	0	34.0	2.3	0	0	69.8	4.8
Lower southwest rift zone	28.0	1.9	0	0	0	0	.0	.0	28.0	1.9
Upper east rift zone	7.5	.5	0	0	183.3	12.6	0	0	190.8	13.1
Middle east rift zone	93.9	6.5	0	0	100.2	6.9	0	0	194.1	13.4
Lower east rift zone	154.5	10.7	0	0	25.0	1.7	.0	.0	179.5	12.4
Mauna Loa	-----	----	-----	----	-----	----	----	---	21.3	1.5
Undetermined	-----	----	-----	----	-----	----	----	---	2.6	.2
Total	329.9	22.8	732.9	50.6	342.5	23.5	18.5	1.3	[1]1,449.4	99.9

[1]A separate measurement of total area on the same map gave 1,450.4 km².

TABLE 12.5.—*Paleomagnetic results from lava flows in the Kipuka Nene area of Kilauea*

[D and I are respectively, mean declination and inclination, in degrees, of remanent magnetization in 12 specimens from each site. α_{95} is circle of 95-percent confidence around the mean direction]

Site	D	I	α_{95}
Kalue flows			
1B224	9.5	24.6	1.7
1B456	10.2	24.6	1.8
3R013	8.7	24.1	2.6
Kipuka Nene flows			
8B121	357.0	39.2	1.6
8B133	357.5	37.9	1.2
9B169	357.9	37.4	1.6
3R001	1.9	39.2	2.1

TABLE 12.6.—*^{14}C ages of material related to the Ai-laau and Observatory vents*

Source of flow	Sample	Age (yr B.P.)
Ai-laau vent	[1]W–4449	<200
	[2]W–4573	<200
	W–3881	260±70
	W–4162	310±70
	W–4661	320±70
	W–3941	450±60
	[2]W–3885	2,160±70
Probably Puu Huluhulu	W–4184	<200
	W–5110	230±60
	W–4337	620±70
Observatory vent	W–4470	310±70
	W–3811	330±60
	W–3852	450±60
	[3]W–4998	960±60
Possibly Observatory vent	W–4404	530±70
	W–5218	550±70
	W–3860	670±60

[1]Same prehistoric flow as W–3941; disregarded.
[2]Same prehistoric flow as W–4162; disregarded.
[3]Anomalous, possibly contaminated by fumaroles.

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