U.S. Geological Survey

OPEN FILE REPORT NO. 81-354

KILAUEA VOLCANO, HAWAII: CHRONOLOGY AND MORPHOLOGY OF THE SURFICIAL LAVA FLOWS

by

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1980

KILAUEA VOLCANO, HAWAII: CHRONOLOGY AND MORPHOLOGY OF THE SURFICIAL LAVA FLOWS

A DISSERTATION

SUBMITTED TO THE DEPARTMENT OF GEOLOGY

AND THE COMMITTEE ON GRADUATE STUDIES

OF STANFORD UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

By

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December 1980

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ABSTRACT

Long-term variations in eruptive behavior occurred as Kilauea's present surface formed. These variations are revealed by geologic mapping, dating, and morphologic analysis of lava flows.

The chronology is based on the secular variation of the geomagnetic field, reconstructed from paleomagnetic measurements of lava flows dated by ^{14}C. Key flows of unknown age are dated by comparison with the history of variation, and relative ages of other flows are determined from superposition and vegetation development.

Paleomagnetic dating precision varies with time and depends upon the rate of secular variation and dispersion in the data. Typically, variation rates are about 4 deg/century, and dispersions are about 4.5 deg. Principal sources of dispersion are imprecision in the ^{14}C ages (3.0 deg), local anomalies in the geomagnetic field (2.2 deg), and primary deformations of lava flows (1.7 deg). Dating precisions are about 100 years during the past 500 years and about 250 years during the preceding millenium. Precision should be increased to a few decades by reducing the dispersion, refining the history of variation, and adding paleomagnetic intensity to the record of variation.

About 70 percent of Kilauea's surface is younger than 500 years, about 90 percent younger than 1000 years. A major hiatus in summit overflows occurred between about 1500 and 1000 years B.P. Much of Kilauea's present caldera dates from the 18th century, but an earlier caldera developed about 1500 years B.P. and later filled.

Behavior of prehistoric eruptions is revealed by the morphology of their products. Eruptions are classified on the basis of duration, which is expressed in the degree of channelization achieved by lava flows. Lava flows are classified as aa, surface-fed pahoehoe, and tube-fed pahoehoe. Flow types and vent features are used to classify eruption assemblages corresponding to various eruption types. Type A eruptions last hours to days and leave open eruptive fissures and commonly a single lava flow consisting of surface-fed pahoehoe and aa. Type B eruptions last for days to weeks and produce pyroclastic central vents and multiple flows of surface-fed pahoehoe and aa. Type C eruptions last for months to years and produce small lava shields and many flows consisting of all three types. Type D eruptions persist for decades to centuries and produce large lava shields and flow assemblages dominated by tube-fed pahoehoe. Type E eruptions last for days to weeks, and their phreatomagmatic explosions may produce craters and sheets of pyroclastic material. This classification scheme was refined during detailed mapping (1:24,000) of the Mauna Ulu region and was then applied in mapping the entire volcano (1:50,000).

Kilauea's past behavior has varied in space and time. The chief spatial variation is a decrease in typical eruption duration at increasing distances away from the summit magma reservoir. Other variations appear to be peculiar to particular localities. Changes have occurred over intervals of decades and centuries; some have been repeated and some may have occurred in evolutionary sequences. Two Type E eruptions large enough to produce extensive pyroclastic sheets have been followed by long intervals when most activity was confined to a summit caldera. Rift activity waxed as summit activity waned, and in one example the waxing sequence resembles an evolutionary progression: Rift eruptions were at first brief and widely separated in time and space but gradually became frequent along a restricted segment of the rift zone and culminated in sustained activity at one locality.

The causes of long-term eruptive variation remain undetermined. Alternative phenomenological models are characterized as evolutionary, cyclical, and steady-state; these alternatives differ greatly in their implications on long-range forecasting.

CHAPTER I

INTRODUCTION

This report deals with the long-term eruptive behavior of large shield volcanoes. It focuses in particular upon behavioral variations that occur during intervals of centuries and millenia in a volcano's stage of principal shield growth. At one end of the time scale, regional mapping has revealed much about the overall growth and degradation of shields during intervals of hundreds of thousands to millions of years. At the other end, much is known from detailed real-time observations about the character of individual eruptions persisting for hours to decades. Comparatively little is known, however, about processes significant on intermediate time scales, such as centuries to millenia. Nevertheless, variations over these intermediate time scales may be the most important for human societies making long-range assessments of volcanic hazards and geothermal-energy resources. The work reported here has focused on such long-term eruptive variations through an examination of the recent eruptive history of a single volcano as revealed in the chronology and morphology of its surficial lava flows. That volcano--Kilauea--because of its accessibility, frequent eruptions, and much previous study, is probably the Earth's premier example of a large shield volcano.

Kilauea Volcano

Kilauea is a shield volcano on the Island of Hawaii (Fig. 1) at the southeastern end of the Hawaiian archipelago (Macdonald and Abbott, 1970). It is one of the most active and best known volcanoes in the world, and much of our present knowledge of volcanism is derived from studies of it.

Kilauea has erupted frequently for a long period. According to Hawaiian oral traditions, eruptions from Kilauea "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" (Ellis, 1827, p. 194). The recent rate of magma supply is similar to the rate inferred to have built the island as a whole (Swanson, 1972), and there is no evidence of significant intervals of erosion on Kilauea, so the eruption frequency is likely to have been roughly similar during most of the volcano's span of development. Its frequent activity makes this volcano especially well suited for research on many volcanic phenomena.

Kilauea may be the most intensively studied volcano in the world. Its eruptions have been well recorded since the arrival in its vicinity of the first Christian missionaries in 1823, and continuous scientific studies of its behavior have been made since the Hawaiian Volcano Observatory was established on its caldera rim in 1912. The Observatory has become one of the world's foremost centers of volcanological research, and a wide variety of investigations by many workers have been carried out at Kilauea. These include visual observations of eruption processes, measurements of the physical properties of lava,

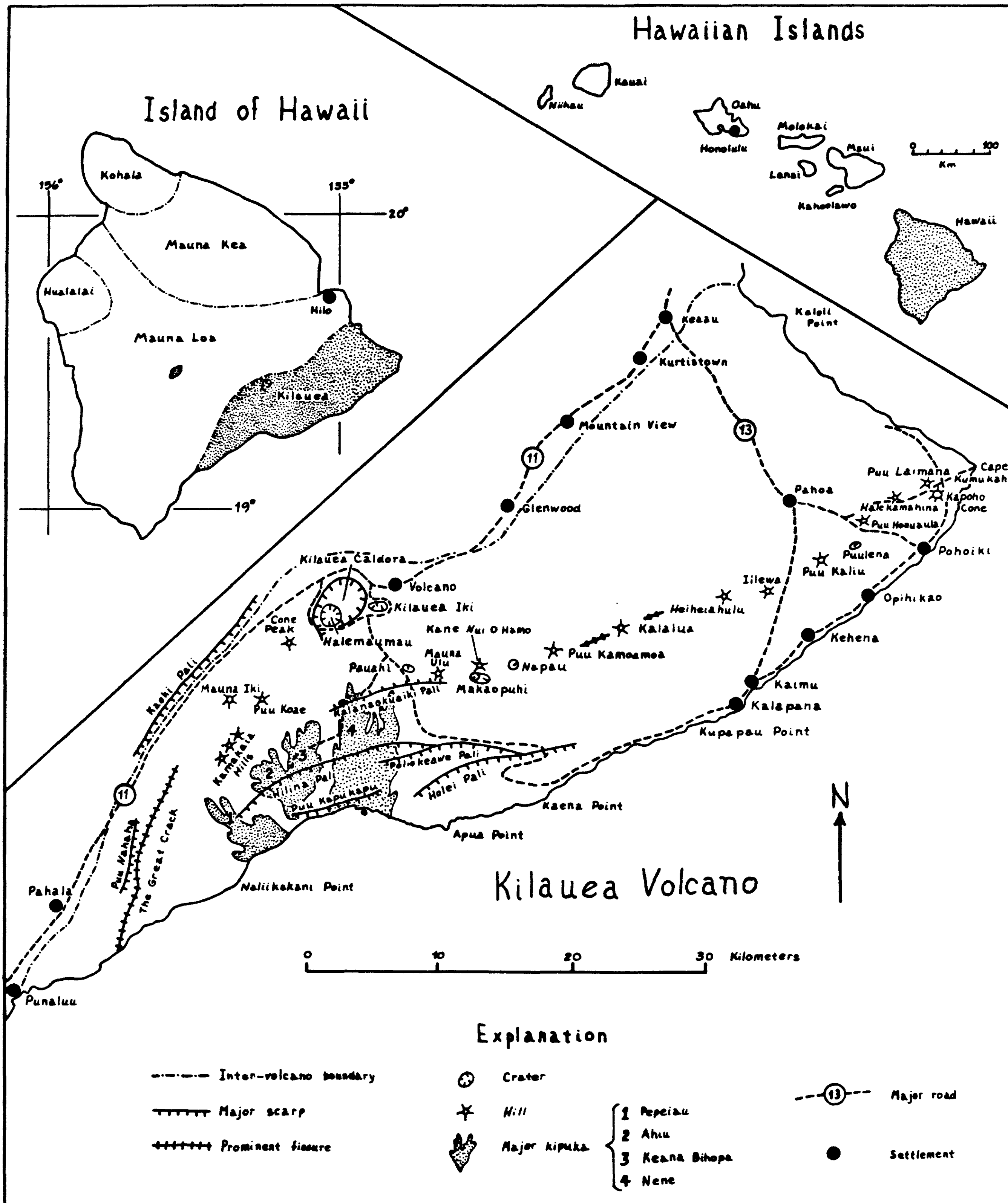


Fig. 1--Index maps showing the location and principal features of Kilauea.

geochemical and petrologic studies of magma evolution, geophysical studies of volcano dynamics and gross rock properties, and various applied studies such as investigations of volcanic hazards and geothermal resources and experiments in the control of lava flows (Macdonald, 1947, 1976; Hawaiian Volcano Observatory Staff, 1974). Many of the general approaches and particular techniques in the study of volcanism were first developed at Kilauea, and Kilauea is often used as a standard against which other volcanoes are compared. As a result, any significant advances in our understanding of Kilauea are likely to have more general applications elsewhere and to comprise significant contributions to the science of volcanology.

Statement of Thesis Problem

Despite the great amount of research done at Kilauea and the detailed record of its activity since 1823, it has become apparent recently that a gap in our understanding is posed by the lack of an eruption history prior to the Nineteenth Century. The carefully preserved oral history of the region was lost with the destruction of the Polynesian culture early in that century, and only a few scattered traditions have survived from the Polynesian period. The accumulation of knowledge had to begin anew with the development of the modern Hawaiian culture, and until recently there was little reason or means to reconstruct the earlier history. Recent advances, however, in the understanding of lava-flow morphology and dating techniques have rendered such work feasible, and the need to evaluate volcanic hazards and geothermal resources has made it desirable.

A particular barrier to the study of long-term eruption histories has been the feeling that little would be learned from such studies because the volcano's behavior has remained monotonously similar for long periods, having, in fact, no real history to reconstruct. This view arose from mapping done 25 to 50 years ago. From the geological survey of the Hawaiian Islands by H. T. Stearns and G. A. Macdonald during the 1920s to 1950s, an ideal life history of the typical shield volcano was synthesized (Fig. 2). According to this synthesis a volcano goes through several distinct stages of development during its evolution. Among these stages are a youthful shield-building period and a mature caldera stage, differing distinctly from each other. The youthful stage prior to caldera formation is regarded as an uninterrupted series of monotonously similar eruptions producing lava flows that accumulate steadily to build the shield. Caldera development comes at the end of this period when the magma supply can no longer overcome a tendency for the summit region to founder into the magma chamber (Macdonald, 1965). The presence of a caldera is taken as a sign that a volcano's principal growth is done and that stagnation has begun. According to this view Kilauea, the youngest and most active Hawaiian volcano, has entered its mature stage because it has a caldera. The caldera is thought to be young and the volcano to have only recently entered its mature stage.
It has just emerged from its long period of monotonous accumulation, and the events that preceded caldera formation were uninformative and not closely related to what is occurring now. There is thus little incentive to study its earlier history.

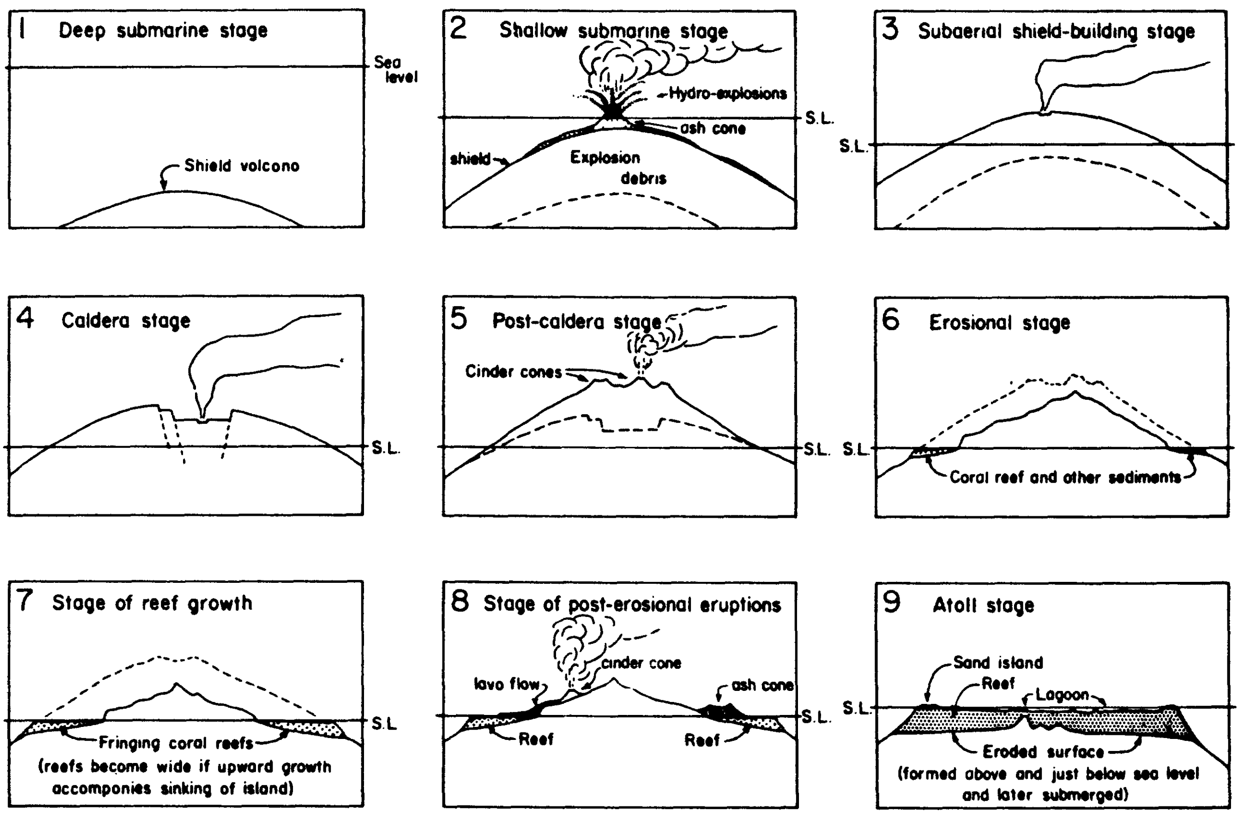


Fig. 2--Life stages of Hawaiian volcanoes, after Macdonald and Abbott (1970).

In opposition to that prevailing view, however, is the idea that Kilauea's present caldera was preceded by at least one ancient caldera that was completely filled and obliterated before the present one formed (Powers, 1947; Holcomb, 1976a, 1978). If this alternative idea is correct, the present caldera may have been preceded by many earlier ones, and it is possible that instead of passing through distinct youthful shield-building and mature caldera-forming stages the shield volcanoes undergo numerous repetitions of caldera formation and filling as they grow (Holcomb, 1976a, 1978). In this modified view of volcano evolution the presence of a caldera has no particular significance regarding the stage of development of the volcano. Events that occurred before caldera formation may occur again, and a knowledge of past history may really be useful in predicting future events.

Moreover, repeated formation of calderas may be associated with long-term changes in eruptive behavior of the volcano. If summit collapse is due to withdrawal of magma during eruptions or intrusions low on the volcano's rift zones (Richter and others, 1970), then very deep submarine events may produce profound collapse in the upper parts of the rift zones too and disrupt the highly elongated dike systems thought to transport magma laterally from the summit region (Fiske and Jackson, 1972). Caldera collapse might then be associated with temporary changes in eruptive activity in the various parts of the volcano. If caldera formation is repetitive it might be accompanied by repetitive changes in eruptive behavior at intervals of centuries, millenia, or whatever times separate the major collapses. If they occur and can be identified in the geologic record, such changes in behavior might tell us much about the internal structure and operation of the volcano, and they might lead to much better predictions of its future behavior.

The problem addressed by this research has been the nature of Kilauea's long-term behavior. I have worked toward answers to these questions: What kinds of eruptions typify Kilauea's behavior over long intervals? How widely do individual eruptions vary from the typical? Have long-term changes in behavior occurred? If changes have occurred, does the 150-year historic record characterize most of the past behavior, or is it typical of just some intervals scattered among other times of very different behavior? Or is the historic record completely atypical? If long-term changes have occurred, have they been associated with other events such as caldera collapses? Have such events occurred completely at random through time or in recognizable patterns that might lead to testable models of Kilauea's plumbing system and to long-term forecasts of future activity? What are the consequences of this information on practical affairs, such as our understanding of volcanic hazards and the development of geothermal-energy resources?

Approach and Technques, Progress, and Acknowledgements

In this research the problem of Kilauea's long-term behavior was approached from an historical point of view. The work focused upon the few thousand years during which the topmost layer of lava flows was spread over the surface of the volcano. A history for this interval was pieced together from a program of geologic mapping, age determinations, and morphologic analysis of lava flows. This history was then used as the basis for generalizations about the volcano's past and future long-term behavior. Inasmuch as some of the techniques used are themselves new, this research comprises a contribution to the methods of volcanology in addition to an increased understanding of volcanic behavior. I made a conscious effort in this work to develop new ways of investigating volcanoes and hope that it can serve as a model for similar studies elsewhere.

This project has spanned about eight years of part-time effort, from about 1972 to 1980. It began informally with a few questions that began to nag at me while I was working on the staff of the Hawaiian Volcano Observatory, and it has culminated over the past three years in a directed effort to answer these questions through my doctoral research at Stanford. I owe many people a great deal of thanks for their help and encouragement at many points along the way.

The roots of this work extend to the years 1971 to 1975 when I served on the Observatory staff. It was then that I was introduced to the problems of Hawaiian geology and immersed in observations of eruptive activity. My experiences were shared by a group of especially able and congenial colleagues that included Don Peterson, Bob Christiansen, Wendell Duffield, Bob Tilling, Charlie Zablocki, and the other members of the Observatory staff, as well as Don Swanson, Howard Powers, Gordon Macdonald, and a host of visitors passing through. The observations, ideas, and methods described here were shared with many others, and I am grateful to them all. I owe much especially to Bob Christiansen and Don Peterson for their unflagging interest in the volcano. They have always been ready with an encouraging word, penetrating question, apt observation, or sharp rejoinder whenever they were needed. Chris has had the amazing ability to

understand immediately anything I had to say, no matter how poorly it was expressed.

The existence of ancient buried calderas on Mauna Loa and Kilauea were proved to my satisfaction in 1973, and the basic problem of Kilauea's long-term behavior was well-defined by the end of 1974. From a general familiarity with Kilauea it appeared to me that the volcano might have undergone long-term changes in its eruptive behavior, and at first I saw such variations as possible tools for recognizing even earlier calderas whose existence was otherwise completely obliterated by later events. It soon became clear that long-term variations could not be useful in this way because they could arise from causes other than caldera formation. But once their existence was entertained it was equally clear that such variations could be important for other reasons, and I determined to evaluate their existence.

My first directed attempts to attack the problem were made in 1975 to 1977. In 1975 while still at the Observatory I made a series of photogeologic maps of Kilauea that served to define the particular problems involved in working out a chronology and interpreting the morphology of lava flows. At this point Jack Lockwood and Pete Lipman, newly arrived at the Observatory, provided a healthy dash of skepticism that incited me to further exertions. They doubted that lava-flow morphology could be used in the way that I proposed, and they saw no evidence from my crude maps for any changes in Kilauea's behavior. It appeared I would have to start over again from scratch, with more rigor. I recouped and then made a concerted effort to map the recent lava flows of the mauna Ulu region in some detail as a pilot study for the more extensive work I proposed to do. This preliminary mapping

seemed like an imposing bit of work at the time, and I am grateful to Patrice de St. Ours and the Beatles for helping me through the long nights needed to complete it. My first complete geologic map of Kilauea was photocompiled and field-checked in 1977, and I thank Steve Oriel and Bob Tilling for encouragement and support at this stage of the work. I am grateful also to Tim Bralower for field assistance and to Bill Della Sala, Martha Komohai, John Martin, Bill Yeoman, Bud Doty, Rick Edwards, and many other residents of Ka'u and Puna for their hospitality and information. Gordon Eaton and the HVO staff gave logistical support, and Jim Jacobi, Rick Warshauer, and Holly McEldowney provided much useful information about the flora and cultural history of the region, as well as their friendship. Robert P. Sharp and George W. Walker provided valuable comments on aeolian processes and the stratigraphy of Kilauea's south flank.

My tenure at Stanford was made possible by a tuition grant from the Piton Foundation of Denver, Colorado, and Bob Compton, Harvey Weinstein and my fellow students helped me through some of the rough parts of my return to a university campus. I am thankful to Jerry van Andel and Bob Ballard for providing an opportunity to enlarge my understanding of flow morphology through a study of submarine lava flows, and to Jon Fink, Paul Delaney, Sue Karl, and Dave Pollard for many fruitful discussions of flow morphology.

The final phase of the project was undertaken in 1978 to 1980 after I had settled on the method to be used in defining a volcano-wide chronology. Being familiar with Duane Champion's paleomagnetic work then in progress on the Snake River Plain, I enlisted the collaboration of Duane and Mike McWilliams in a study of Hawaiian geomagnetic secular variation. I am grateful to Duane and Mike for seeing this work through to its end expeditiously despite their deep involvement in other concurrent projects. The work could not have been executed without Duane's stellar performance in the field and Mike's ability to keep the magnetometer operating. I am thankful also to Lisa Kanter, Sue Karl, and Jim McGill for assistance in the field and laboratory, to Jack Lockwood and Pete Lipman for information on ^{14}C-dated lava flows and discussions of Mauna Loa stratigraphy, to Norm Banks, Dick Moore, and Mike Easton for similar information about Kilauea, to Sherm Grommé and Allan Cox for advice on paleomagnetic techniques, and to Jim and Zoe Jacobi, Paul Higashino, and John and Annette Orr for hospitality in Hawaii. Funding for this phase of the work was provided by the U.S. Geological Survey through its program for geothermal research, and logistical support was provided by Bob Decker and the staff of the Volcano Observatory. Anne Berry typed beautifully!

My sincere apology is extended everyone I have neglected to mention here by name. Above all others, I am grateful to my family--Annette, Chris, and Maui--who have put up with it all.

Previous Work

Because so much research has been done at Kilauea it is not practical to attempt a general review in this report. Instead, only a few contributions of particular pertinence to this work are summarized briefly. These include the foremost contributions to the general understanding of the volcano, the interpretation of lava-flow morphology, the determination of lava-flow chronologies, and the geologic mapping of Kilauea's surface.

Contributions to General Understanding

Kilauea was well known to the ancient Hawaiians, who interpreted its eruptions as the acts of gods and its summit sites of most frequent activity as the homes of those gods. Eruptions brought much grief to the Hawaiians, and a priesthood developed to watch for signs of activity and appease the gods. Over the centuries a large body of mythical knowledge must have accumulated about the patterns of eruptions, but nearly all of this was lost soon after Hawaii's discovery by Europeans. The mythological view of the volcano was replaced by a new edifice of understanding based on principles of Western scientific rationalism. Unfortunately, the factual basis of the ancient traditions was ignored, and a detailed oral history of the volcano apparently was not written down. Only a few traditions about specific eruptions and a spare, tantalizing outline of Kilauea's Polynesian history have survived (Westervelt, 1916).

The modern understanding of Kilauea and other Hawaiian volcanoes is based largely on observations that accumulated rapidly during the first half of the Nineteenth Century. The earliest written allusions to Kilauea were by members of the Cook expedition in 1777 who were impressed by the many lava flows of the Kau district of Hawaii and recognized their general nature but supposed the volcanic activity to be extinct (Ledyard, 1783; Beaglehole, 1967). Vancouver (1798) first recorded activity at the volcano, and Ellis (1825) made the first detailed description of Kilauea and recorded some oral accounts of previous eruptions. Other missionaries following Ellis recorded its summit activity and began to inquire into the nature of the volcano's edifice as a whole. Goodrich (1829), for example, observed that

Mauna Loa, from which Kilauea was not then differentiated, is "one huge pile of lava" that has accumulated from volcanism continuing over a long period. The first scientific studies of Kilauea were made by members of Wilkes' United States Exploring Expedition in 1840-41. J. D. Dana, the geologist of the expedition, recognized Kilauea's distinctness from Mauna Loa, the general nature of Kilauea's rift zones, the faulting of its south flank, and the repetition of growth and collapse in its summit region, and he first posed many of the fundamental problems studied down to the present day (Dana, 1849, 1890).

In the later 19th and early 20th centuries the local missionaries and many visitors continued to record Kilauea's activity, and several geologists, such as C. E. Dutton (1884), contributed further observations on the structure and history of Kilauea and its neighbors. Comprehensive reviews of knowledge about the volcano were written by Dana (1890), Brigham (1909), and Hitchcock (1909). During this period much attention was given to hypothetical large fractures in the Earth's crust thought to localize the volcanoes, to the causes of the rise of magma, and to the possible relationships between the magma sources of neighboring volcanoes.

From their regional survey of the Hawaiian Islands, H. T. Stearns and his associates derived an idealized life history for a typical Hawaiian volcano. This generalization has provided a point of departure for many special studies of recent decades. Reconnaissance efforts have been made, for example, to describe and interpret the submarine underpinnings of Kilauea (e.g. Moore and Fiske, 1969; Moore, 1971), and considerable attention has been given to the gross structure of the volcano. Fiske and Jackson (1972) discussed the role of gravitational stresses in the development of Hawaiian rift zones, and Moore (1964; Moore and Peck, 1965) drew attention to the large-scale slumping that has affected the flanks of the shields. Opposing points of view have been published on the relative importance of large-scale slumping and forceful intrusion of magma as processes responsible for the dilation of Kilauea's rift zones (Moore and Krivoy, 1969; Swanson and others, 1976). Some previous explosive eruptions from Kilauea's summit have been identified (Powers, 1948; Swanson and Christiansen, 1973), and their relationship to caldera collapses is currently under study (R. L. Christiansen, work in progress). At least one ancient filled caldera has been identified and the relationship between caldera collapse and long-term variations in eruptive behavior discussed (R. T. Holcomb, 1976b, 1978). Temporal variations in magma chemistry have also received recent study (Wright, 1971). Though Stearns' idealized life history has held up well through several decades of critical evaluation, some of the recent contributions regarding large-scale slumping, phreatomagmatic eruptions, and caldera development have suggested revisions to the general model.

Especially important contributions have been made recently regarding the ages of Hawaiian volcanoes and their significance in the global-scale tectonics of the Pacific region. Dana (1849) had recognized that some volcanoes, such as Kauai, are much older than others and suggested that the volcanoes are generally younger toward the southeastern end of the chain. This progression was generally accepted in the century following Dana's exploration, but there was considerable disagreement over the relative ages of particular volcanoes. Stearns and Macdonald (1946) first suggested a strict southeastward progression, but they believed all the volcanoes to be older than the ages now assigned. They argued, for example, that the Pololu volcanic series of Kohala, the oldest lavas on Hawaii, are of Pliocene age. Radiometric dating has confirmed the strict southeastward progression (Macdougal, 1964) but has shown that the volcanoes are much younger than was thought previously. The age of the Pololu volcanic series, for example, is less than 0.5 m.y. (Macdougal and Swanson, 1972). Wilson (1963) explained the southeastward progression in terms of the theory of global plate tectonics as arising from the northwestward movement of the Pacific lithospheric plate over a comparatively stationary source of magma in the mantle, and this interpretation has been developed, with variations, in the ensuing years (Dalrymple and others, 1973).

Geologic Mapping

The first systematic geologic mapping of Kilauea was made as a part of the U.S. Geological Survey and Hawaii Division of Hydrography study of the geology and water resources of the Hawaiian Islands, begun in 1921 (Stearns and Clark, 1930; Stearns and Macdonald, 1946). A prominent ash layer exposed at scattered localities on the south flank of Kilauea (Fig. 3) was chosen to differentiate between two mappable units, the Puna volcanic series above and the Hilina volcanic series below (Fig. 3). Most surficial rocks of Kilauea belong to the prehistoric part of the Puna volcanic series and were not differentiated further during that work, being described only in a general way in the project reports.

Later more detailed geologic maps (Fig. 4) were made of two 7.5' quadrangles that included parts of Kilauea (Peterson, 1967;

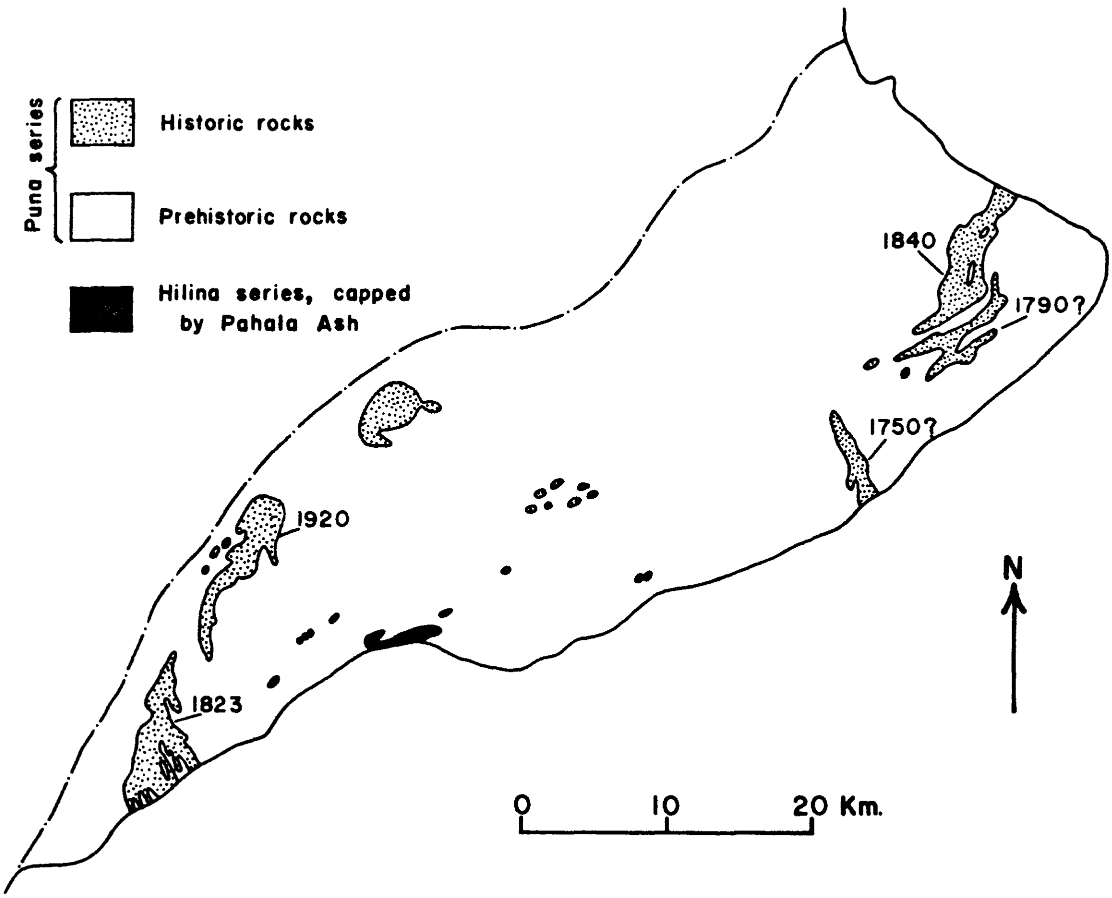


Fig. 3--Gross stratigraphy of Kilauea, reduced and simplified from Stearns and Macdonald (1946). Note the small number of historic flows and coverage by lava outside of the caldera during a long period prior to this mapping. In the short interval since this map was made, the frequency of eruptions and lava flow coverage has increased substantially. The Hilina volcanic series is exposed only in scattered parts of fault scarps of the south flank.

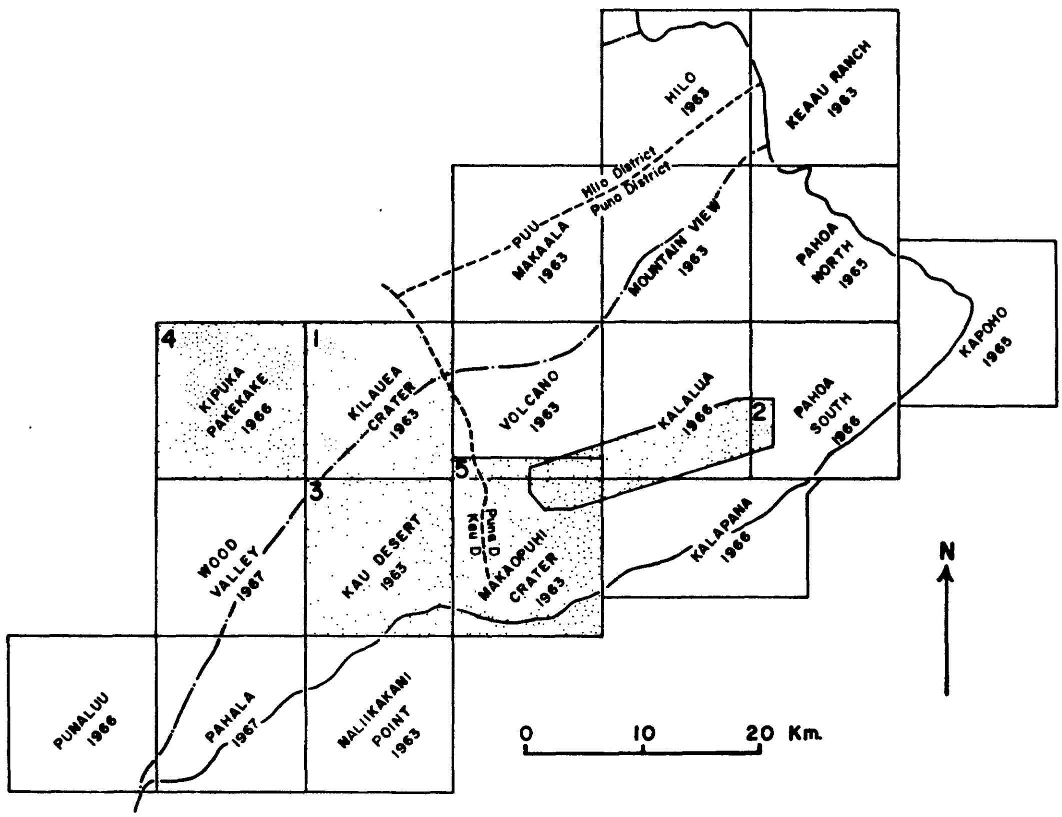


Fig. 4--Current status of topographic and geologic maps of Kilauea. Unstippled areas have topographic coverage only. Geologic maps at a scale of 1:24,000 have been published for the stippled areas:

1. Peterson, 1967
2. Moore, 1969
3. Walker, 1969
4. Macdonald, 1971
5. Holcomb, 1976

The part of Kilauea in the Kau district was included in the map of Stearns and Clark (1930) at 1:62,500, and the entire volcano was included in the map of Stearns and Macdonald (1946) at 1:125,000.

Walker, 1969). Though this mapping was done quickly, the Puna volcanic series was subdivided on a local basis and considerable detail was shown. The chief deficiency of these maps today is their lack of a volcano-wide stratigraphic framework and their failure to differentiate certain large fields of pahoehoe lava into smaller meaningful units. These deficiencies arose from the rapidity of mapping, a lack of techniques suitable for regional correlations, and a lack of understanding at that time of the significance of certain morphologic variations in lava flows.

The only other published maps of Kilauea are special-purpose maps by Moore (Moore and Koyanagi, 1969), Duffield (1975), and Holcomb (1976). Moore mapped the historic eruptions from the middle part of Kilauea's east rift zone, and from vegetation patterns in the rain forest he also inferred the distribution of latest prehistoric eruptions. Flows were not classified except by relative age, and prehistoric flows were not traced away from the rift zone onto the flanks of the volcano. Duffield mapped the central part of the Koae fault system as part of a structural analysis. The Koae structures were mapped in great detail at a scale of 1:7500, but stratigraphic units were not shown. Holcomb mapped a segment of Kilauea's upper east rift zone and south flank, giving considerable attention to the classification of rock units but dealing only with the latest historic lava flows in the area.

Lava-Flow Morphology

The morphology of basaltic lava flows, at Kilauea and elsewhere, has received much attention in the past, and a large body of literature has accumulated that deals with it. Early discussions tended to treat the morphologic variations merely as curiosities, but with the passage of time it has become apparent that these morphologic variations can reveal useful clues to the nature of basaltic lava and the eruptions producing it. As a result, considerable efforts have been made to understand the origins of various morphologic types and apply this understanding to the solution of geologic problems. The particular problems attacked, and the points of view of the attackers, have been diverse, and a resulting welter of morphologic types, processes, and controlling parameters has been described. Only a sampling of the previous work most pertinent to this particular project can be summarized here.

A primary distinction between different lava-flow types is the one first made in the scientific literature by Dutton (1884) between rough "aa" and smooth "pahoehoe." (Of course Dutton merely repeated a distinction made traditionally by the native Hawaiians, and similar distinctions had been made independently elsewhere, such as the Icelandic distinction between rough "apalhraun" and smooth "helluhruan," the German distinction between "Schollen" and "Fladen" lavas, and the Italian distinction between "lava a blocchi" and "lava a corde." The Hawaiian terms, however, have become established as the principal designations in the scientific literature.) Because pahoehoe and aa can arise from lava having the same chemical and mineralogical composition, the cause of their difference has presented a puzzle to geologists, and much effort has been expended in explaining it. (See, for example, Washington, 1923; Emerson, 1926; Jones, 1937; Macdonald, 1953, 1967; Peterson and Tilling, 1980.) There has been a consensus that most tholeiitic Hawaiian lava is erupted as pahoehoe and then can somehow undergo a transition to aa as viscosity increases with cooling. The most recent and most sophisticated treatment of the problem is by Peterson and Tilling (1980), who conclude that aa develops when a certain threshold ("transition threshold zone," or TTZ) is exceeded, the TTZ representing a critical relationship between the viscosity of the lava and the rate of shear strain forced upon it. This threshold can be exceeded in several different situations, and these different situations can give rise to morphologically distinct subtypes of aa. The particular morphology of an aa flow might then be used to infer the conditions under which the threshold was exceeded.

Different kinds of pahoehoe have been recognized as well, and the varieties have been described and pictured many times (e.g. Skeats and James, 1937; Wentworth and Macdonald, 1953; Green and Short, 1971). Numerous attempts have been made to explain the origins of particular diverse features such as flow units (Nichols, 1936), lava coils (Peck, 1966), and pahoehoe ropes (Fink and Fletcher, 1978). This kind of work has been extended to the morphologies typical of submarine lava flows, notably to the origin of pillow lavas (Moore, 1975; Moore and Lockwood, 1978) and their relationships to subaerial pahoehoe flows (Ballard and others, 1979).

In addition to topical studies of particular kinds of flows and surface features, whole new approaches to lava-flow morphology have developed in recent years, aimed at using lava flows to help solve larger problems. An example is the rapidly developing planetological point of view in which special attention is given to the features of lava flows resolvable from great distances by the imaging systems of space probes. While much of the planetological literature has been aimed only at drawing qualitative analogies between terrestrial and extraterrestrial landforms (e.g. Fielder, 1965), considerably more rigorous quantitative studies have also been made (e.g. Carr, 1974; Hulme, 1974; Moore and Schaber, 1975).

Another specialized approach is one in which the gross morphology of lava flows is considered in terms of the physical behavior of the eruptions that produced them. Examples of this approach are the work by Walker (1973) concerning the relationship between effusion rate and length of lava flows, and the observations of Swanson (1973) on the relationships between eruptive behavior and different varieties of pahoehoe. If such relationships do exist, they provide an avenue for inferring the character of prehistoric eruptions from the morphology of lava flows they produced. It is this approach to flow morphology that has been especially significant to the work reported here; of particular interest is the conclusion drawn from Kilauea's Mauna Ulu eruption that the development of lava tubes and a particular variety of "tube fed" pahoehoe results from stable effusion rates of long duration (Swanson, 1973; Peterson and Swanson, 1974). It is generalizations of this type that form the basis for interpretations of flow morphology made in this report.

Chronology

Much work has been done upon which a stratigraphic framework for Kilauea could be based. Some information has been provided by the few Polynesian traditions that have survived (Ellis, 1825). Though most of these traditions merely allude to the character of past eruptions and provide no dates for their occurrence, in a few cases the names of chiefs associated with particular lava flows have permitted estimates of their ages from Hawaiian geneologies (Macdonald, 1941).

Great improvements have been made recently in understanding the occurrences of charcoal beneath lava flows (Lockwood and Lipman, in press), and many new ^{14}C dates from Hawaii have resulted (Kelley and others, 1979; Kelley, 1979). However, few of these dates come from Kilauea; most are from Mauna Loa, where flows of many different ages have spread over ash units especially well suited for the preservation of charcoal. Though few ^{14}C dates come from Kilauea itself, the abundance of dates nearby makes it possible to use the ^{14}C method to calibrate other dating techniques.

Thermoluminescence dating has shown some promise (Berry, 1973), but attempts to use it on very young tholeiitic flows like those on the surface of Kileaua have been unsuccessful (R. J. May, 1979). Other methods depend upon rates of weathering and vegetation development on lava flows. Atkinson (1969; Atkinson and Swindale, 1974), for example, has used stages of ecosystem development and simple chemical tests of flow surfaces to estimate the ages of a few prehistoric lava flows, and Morganstein (Morganstein and Riley, 1975) has reported considerable success in dating basaltic artifacts from thicknesses of hydration rinds. The chief problems posed by these methods are the climatic factors such as temperature and rainfall that vary widely over Kilauea and can modify the rates of change in different parts of the volcano.

Another method that has been investigated elsewhere uses the secular variation in the Earth's magnetic field. This method is unaffected by local climatic factors, but because the variation does not proceed regularly at a constant rate it is necessary to construct a history of regional variation. Because it is the method chosen for this work, more detail will now be given about its past development.

Delesse (1849) noted that geologically young lava flows are permanently magnetized in directions roughly parallel to the Earth's magnetic field. Melloni (1853) showed that a piece of lava rock heated artificially to incandescence acquires a new magnetization parallel to the Earth's present field, whatever the orientation of the rock as it cools in the field. It was concluded that the magnetization of a lava flow reflects the direction of the Earth's magnetic field existing at the time in which the lava flow chilled.

Chevallier (1925) made the first attempt to trace the secular variation recorded by successive lava flows and to use this variation as a dating tool. He measured seven flows of known age and four flows of uncertain age on Mt. Etna. The magnetization directions of the two youngest flows (A.D. 1911 and 1669) agreed well with observatory measurements that had been made at those times, and the directions of magnetization of five older flows (A.D. 1566, 1444, 1381, 1329, 1284) defined a smooth variation during the few centuries immediately preceding the availability of observatory records. The declination appeared to vary periodically with a period of about 750 years, and Chevallier extrapolated the variation backward through time assuming such a periodicity. For the four flows of uncertain age he then compared their measured declinations with those expected if the flows had the ages previously attributed to them. Two flows thought to date from A.D. 1169 differed by 18 deg from the value expected, and Chevallier concluded that these flows must not date from 1169 but from earlier times. The two remaining flows gave highly discordant results but average directions that did confirm their antiquity.

Subsequent efforts were made to date lava flows using simple field measurements of magnetic declination. I know of two such efforts in the western United States. Jones (1928) measured seven flows of the Cinder Cone lava beds near Mt. Lassen in northern California, and Stearns measured 11 lava flows in Craters of the Moon National Monument in southeastern Idaho (unpubl. manuscript circa 1928, on file at the Monument headquarters). In each case declination alone was determined in the field from the deflection of a compass needle. Different flows were found to be magnetized in different directions, the Cinder Cone flows ranging through 9 deg of declination from N. 15° E. to N. 24° E. and the Craters of the Moon flows ranging from north to N. 44° E. Accepting Chevallier's periodicity in secular variation, Jones used a short record of magnetic observations from nearby Redding, California, to extrapolate a history of variation. Assuming that his field measurements accurately reflected the ancient geomagnetic field, he then used the extrapolation to infer ages for the Cinder Cone lava flows, ranging from A.D. 500 to A.D. 1846. Stearns did not attempt a similar chronology for the Craters of the Moon flows, considering the secular variation insufficiently regular to permit such extrapolation. As will be seen, he was right.

No more attempts were made, that I know of, until recently to date lava flows using secular variation, probably because of difficulties in obtaining accurate measurements and a lack of the necessary history of variations. But improvements in methods of measurement and data analysis have made the pertinent paleomagnetic techniques routine, and the development of other dating methods has made it possible to construct histories of variation. Moreover, from detailed studies of historic lava flows (Doell and Cox, 1963; Symons, 1975) we now have a much better understanding of the variability of magnetization within lava flows and the precision with which they record the geomagnetic field.

Champion (1980) has studied the secular variation in western United States during recent millenia. From paleomagnetic measurements at 111 sites on 36 dated lava flows scattered from Arizona to Washington he constructed a history of variation for this region during the past 8000 years. He also measured the magnetization at about 150 sites on approximately 50 lava flows of unknown age, mainly in Craters of the Moon, as an aid in working out the stratigraphy of lava flows. Though the magnetization was useful in distinguishing separate lava flows and correlating isolated outcrops of the same flow, it was not possible to date flows precisely, owing mainly to uncertainties in the history of secular variation arising from time gaps in the ^{14}C record. His work suggested that secular variation could be a very useful dating tool if enough independently dated lava flows were available to construct a reliable history of variation. Hawaii should provide a useful test of the method because ^{14}C dating there has recently established an especially good chronology of lava flows.

A barrier to the use of this paleomagnetic method in Hawaii has been posed by previous work suggesting that little secular variation occurred in the Hawaiian region during geologically recent time (Doell, 1969; Doell and Cox, 1965, 1971, 1972). This conclusion was based partly on paleomagnetic records obtained from intensive sampling of two thick (>100 m) stratigraphic sections, both displaying little magnetic variation from bottom to top, exposed in the caldera walls of Mauna Loa and Kilauea. The length of time represented by these stratigraphic sections was not known because none of the lava flows had been dated, but estimates of the accumulation intervals were made using generally accepted magma supply rates (Swanson, 1972) and the total volumes of lava represented by the caldera sections, assuming that comparable thicknesses of lava were added to the entire surface of the volcanoes. The time estimates obtained were on the order of 10,000 years; consequently the rates of geomagnetic secular variation were inferred to be very low.

In contrast to this view, recent paleointensity measurements and a reevaluation of the earlier data have suggested that considerable secular variation has occurred during the last 20,000 years (Coe and others, 1978). The well-defined mean virtual geomagnetic poles (VGPs) of the two caldera sections differ clearly from each other, and the VGPs of the few previously radiocarbon-dated lava flows on the flanks of the volcanoes are widely dispersed (Fig. 5). The broad distribution of VGPs suggests that secular variation has not been low during recent millenia; if so, the small dispersions of the two caldera sections must be due to rapid local accumulations of lava, at two different times, instead of low rates of secular variation.

Support for the newer interpretation comes from recent geological work indicating that the intensively sampled caldera sections on Mauna Loa and Kilauea did accumulate rapidly because they are inside of ancient buried calderas (Fig. 6; Powers, 1947; Holcomb, 1978). These sections represent the rapid filling of restricted depressions by relatively small volumes of lava instead of widespread mantling of the shields by large volumes of lava. Given the generally accepted rates of magma supply (Swanson, 1972), these flow sequences probably accumulated within several decades or a few centuries instead of the several millenia thought previously; thus the low degree of paleomagnetic variation did result from short accumulation and recording times. Suspecting that normal secular variation has occurred in Hawaii, I decided to use this variation to define a magneto-stratigraphic framework for Kilauea.

Order of Discussion

The various aspects of the work are presented here roughly in the order in which they were taken up. An exception is the discussion of lava-flow chronology, which has been split into two parts. This was done mainly to improve the narrative flow of the report. While other topics lead into each other logically, the initial paleomagnetic discussion does not fit in very well and is taken up first so that it intrudes less upon the main train of thought. A separate section on refinement of the chronology using stratigraphic information has then been added near the end of the report. This ordering has the added benefit of putting first the material least dependent on the rest and the proceding stepwise into material that is more speculative. The skeptical reader can therefore desist where he chooses with little fear of missing something important.

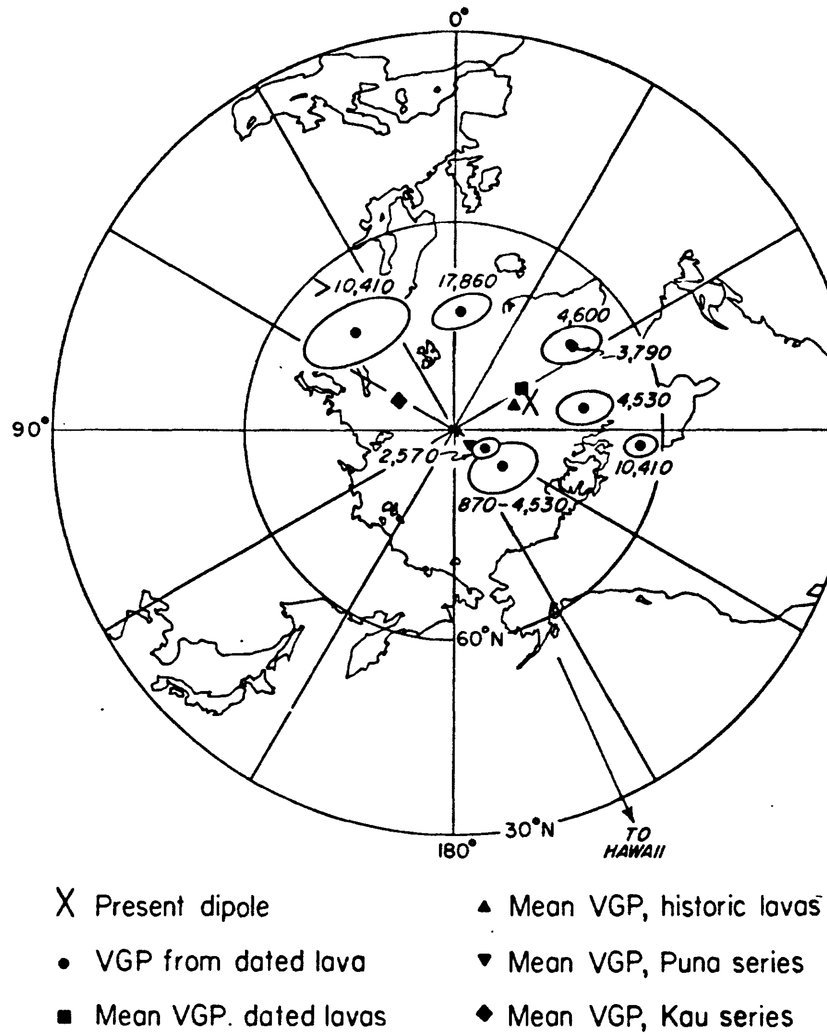
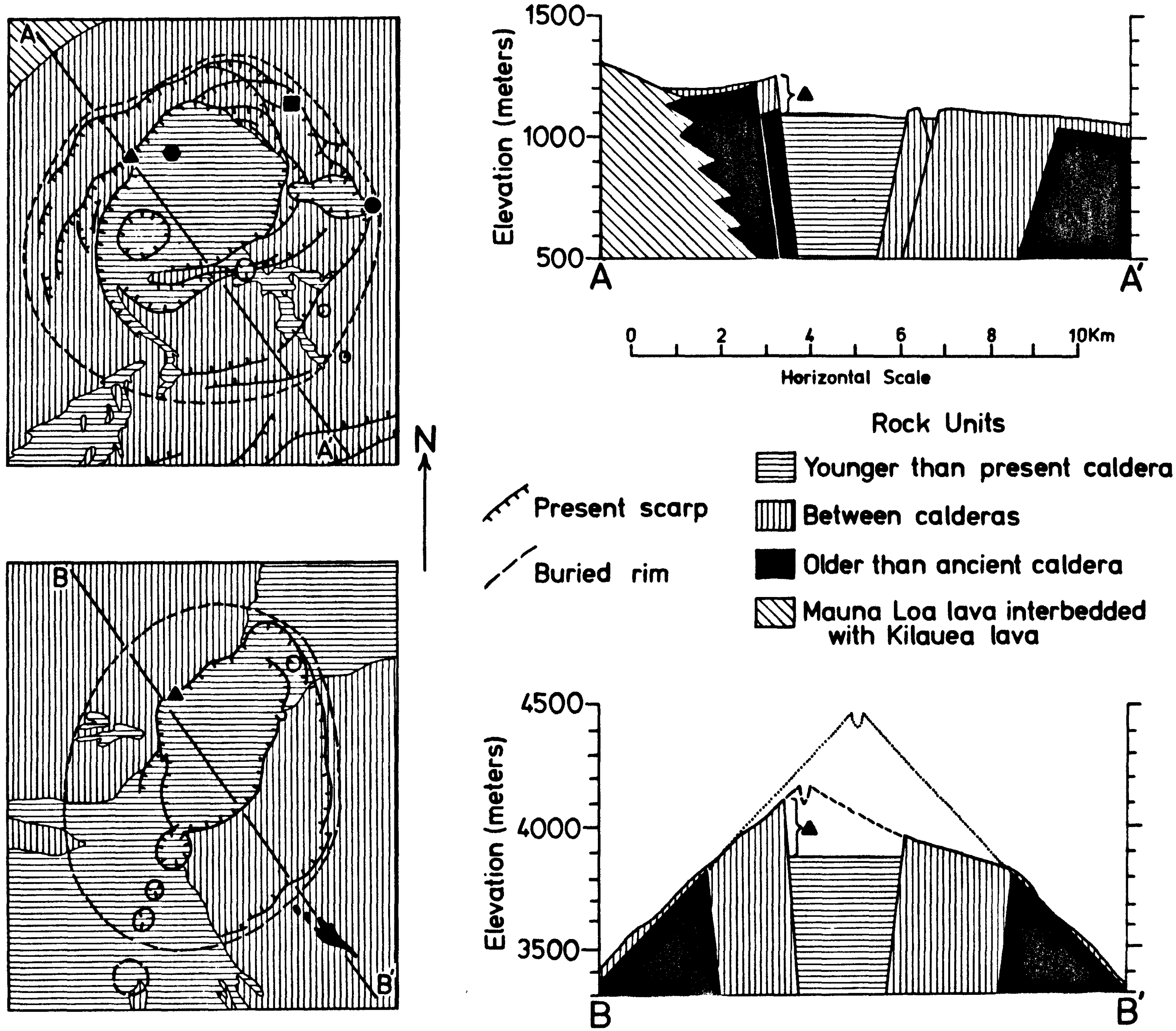


Fig. 5--Equal-area projection of a part of the northern hemisphere showing VGPs obtained by Coe and others (1978) from ^{14}C-dated Hawaiian lavas with corresponding ages in years before present ("present" being taken as A.D. 1950), the present geomagnetic dipole, and mean VGPs from Hawaiian historic, Puna series, and Kau series lavas. For the ^{14}C-dated lavas, 95 percent confidence ovals are shown; 95 percent confidence circles for the other lava series are smaller than the plotted symbols.

Fig. 6--Maps and interpretive cross-sections of Kilauea (a) and Mauna Loa (b), showing their nested calderas. The triangles show the sampling sites of Doell and Cox (1965) and Doell (1969). On the Kilauea map the small circle indicates the location of Hale O Ai-laau, the hexagon shows the former location of Lua Pele, and the square shows the inferred approximate location of the vent for the older lavas of Kilauea's north flank.



A
A'
B
B'
N
Elevation (meters)
1500
1000
500
A
A'
0
2
4
6
8
10Km
Horizontal Scale
Rock Units
Present scarp
Buried rim
Younger than present caldera
Between calderas
Older than ancient caldera
Mauna Loa lava interbedded with Kilauea lava
Elevation (meters)
4500
4000
3500
B
B'

CHAPTER II

PRELIMINARY PALEOMAGNETIC CHRONOLOGY

The purpose of this work was to devise a chronology useful for correlating lava flows on all parts of the volcano, so that the stratigraphic sequences of different areas could be integrated to derive an historical synthesis. This phase of the research was done with the collaboration of Duane Champion of the U.S. Geological Survey and Mike McWilliams of the Department of Geophysics, Stanford University.

Procedure

We used the secular variation in the geomagnetic field to date many of the surficial lava flows on Kilauea. In order to accomplish this we first defined the history of secular variation in Hawaii for the last 6000 years by measuring the directions of remanent magnetization of lava flows dated previously by the ^{14}C method. We then dated flows of unknown age by comparing their magnetization with the history of secular variation.

Field Collections

Sampling was done during two different field trips in Auguat 1978 and March 1979. Samples were collected from 67 sites on lava flows of known age. Most were along the southeastern flank of Mauna Loa between elevations of 300 and 2000 m (Fig. 7). In most cases

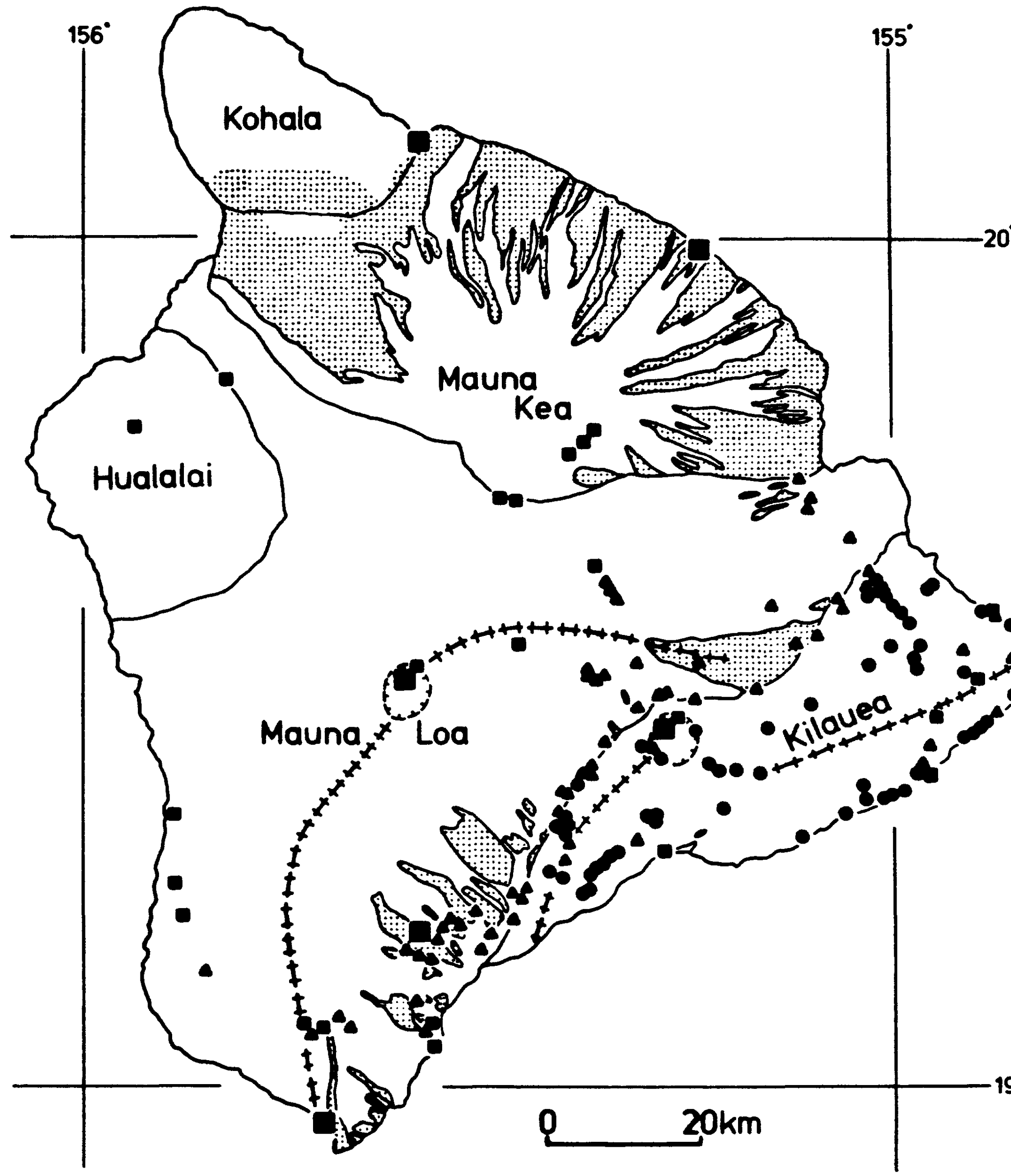


Fig. 7--Sampling locations on the Island of Hawaii. Map is adapted from Stearns and Macdonald (1946). Stippling indicates exposures of the widespread ash units from which many of the ^{14}C dates have been obtained. Cross-hatched and hatchured symbols indicate the rift zones and calderas, respectively, of Mauna Loa and Kilauea. Circles and triangles represent sampling sites of this project on lava flows of known and unknown ages, respectively. Squares represent sites sampled previously, the small squares being individual surface flows (Doell and Cox, 1963; Coe and others, 1978) and the large squares being intensively sampled stratigraphic sections (Doell and Cox, 1965; Doell, 1969, and unpublished).

the samples were taken from the exact locality where a ^{14}C sample had been collected previously; this was done to reduce the possibility of miscorrelation of lava flows between the ^{14}C and paleomagnetic sites. However, some ^{14}C sites occur on steep scarps, and in such situations local topographically related magnetic anomalies may affect the paleomagnetic results. Because of uncertainties in the results from the first sampling trip, eight sites on dated flows were resampled during the second trip. Samples were also collected from 68 sites on lava flows of unknown age. Most of these were taken from roadcuts on the flanks of Kilauea at elevations of less than 700 m. Locations of these samples were less constrained by the possibility of correlation errors and were generally collected from the most convenient outcrops. But because of uncertainties in the boundaries of some lava flows, the sites generally chosen lay near the axes of the flows as they are shown on the geologic map (Pls. 2, 3).

We drilled 12 or 24 cores from each site using a portable gasoline-powered diamond drill. At most sites the cores were taken from two or more distinct subsites within an area about 50 m in diameter. (At multiply-sampled sites a total of 24 cores was taken from as many as five subsites.) Though we took care to avoid sites where broad deformation of the flow surface was evident from the flow morphology, the subsites were chosen such that local deformations not visible in the field would be revealed as angular differences in subsite magnetic directions and minimized by averaging the subsites together. We also distributed the subsites symmetrically on either side of spatter cones where we expected that vent anomalies (Doell, 1972) might affect the results.

Almost all (1947 out of a total of 1976) of the cores were oriented with a suncompass; in the few cases where the suncompass could not be used, we used a magnetic compass and corrected for magnetic declination with a backsight or by assuming the declination measured by suncompass at an adjacent drill hole. Though only one 2.5-cm specimen was needed to obtain paleomagnetic directions from each core, most of the cores were drilled 5 to 15 cm long in order to increase the precision of orientation and provide extra specimens for intensity measurements to be made in the future.

In order to evaluate the possible effects of local magnetic anomalies we measured the declination, inclination, and intensity of the present magnetic field at most sites. Inclination was measured with a dip needle hand-held about 1.5 m above the ground, and intensity was measured with a portable proton precession magnetometer mounted on a 3-m mast. A mean site declination was obtained through averaging the declinations determined at each drill hole by subtracting suncompass directions from magnetic compass directions measured at the same points.

Laboratory Measurements

Paleomagnetic directions were measured on one specimen from each of approximately 2000 cores, using a cryogenic magnetometer. For each specimen we first measured the direction of natural remanent magnetization (NRM) and then remeasured the specimen after alternating field (AF) cleaning to a level chosen for each site. The AF cleaning field was chosen on the basis of step-demagnetization experiments performed on two pilot specimens from each site. Typically, each pilot was remeasured after cleaning at steps of 2.5, 5, 10, 15, 20, 30, and 40 milliteslas (mT); some pilots were cleaned and remeasured also at 50, 60, and 70 mT. Results of a typical demagnetization experiment are shown in Figure 8. The final cleaning field chosen for each site was the minimum peak field intensity beyond which no significant change in direction was measured, the only effect of further demagnetization being a decrease in the intensity of remanent magnetization of the rock. The remaining 10 specimens from each site were then measured before and after cleaning at this chosen peak field intensity.

The results obtained from individual cores were then used to derive a mean paleomagnetic direction for each site. Results of obviously anomalous cores were discarded if our field notes suggested that their parent blocks might have rotated or an orientation error had possibly occurred. A preliminary mean for each site was then computed, and results from cores which lay more than two angular standard deviations away from the site mean direction were discarded (Fig. 9). The remaining cores were then averaged to yield a final site mean. Mean directions for the subsites were also computed and compared for consistency using an F-test at the 95 percent level of confidence.

Data Analysis

Mean directions from dated lava flows were used to characterize the changes in magnetic inclination and declination during the past few thousand years. Mean directions from undated lava flows were compared with this record to infer the ages of their parent flows.

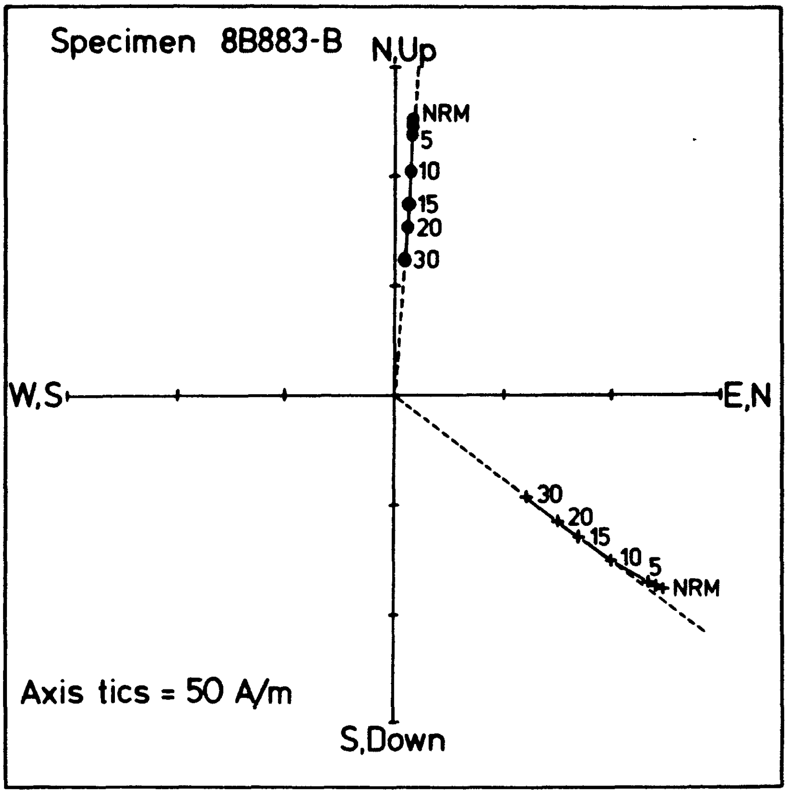
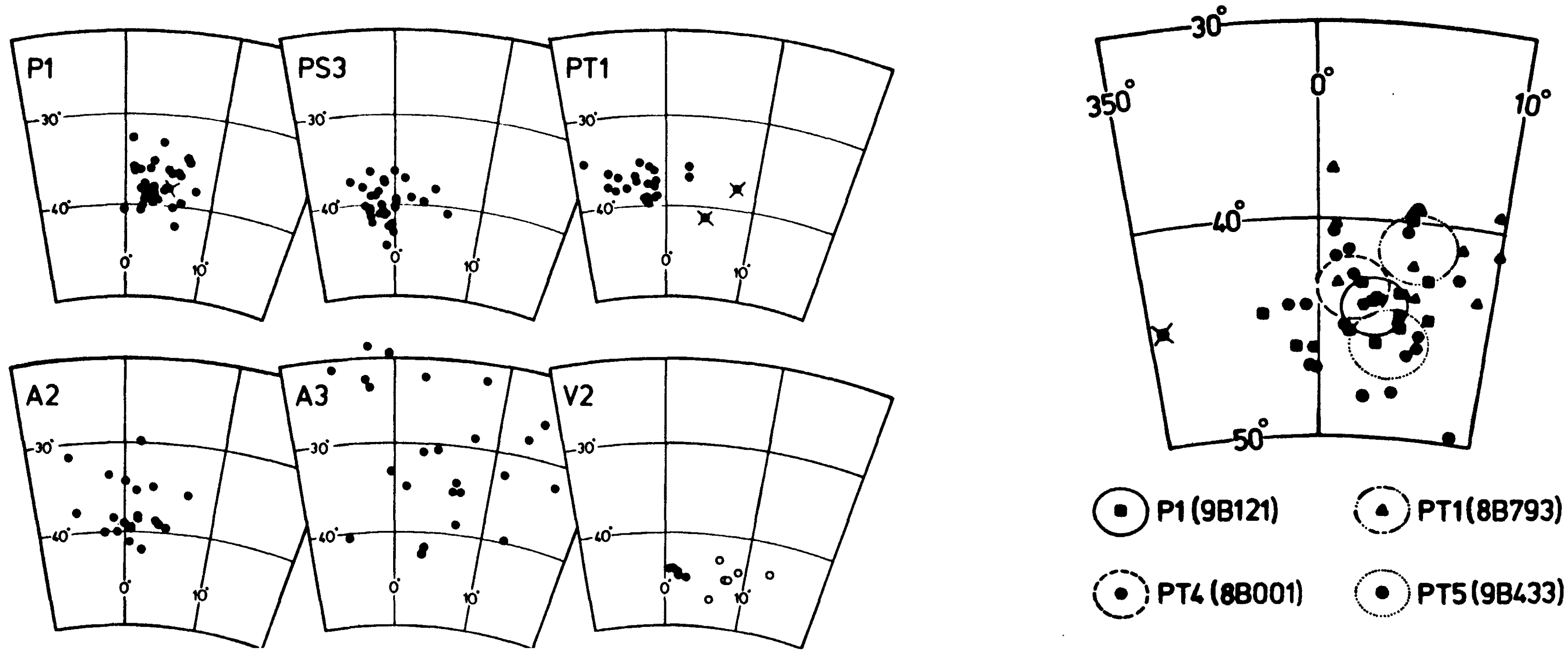


Fig. 8--Example of magnetometer system output for a cleaning experiment. Orthogonal vector plot of pilot AF demagnetization; specimen 8B883B. Circles = projection of vector endpoint upon horizontal plane; crosses = projection upon N-S vertical plane.



(a) (b)

Fig. 9--Examples of within-site dispersion for different sampling situations. Directions of remanent magnetization after AF cleaning are shown for individual specimens plotted on equal-area projections, each projection representing one lava flow. Superimposed crosses indicate rejected specimens. (a) Dispersion for some typical situations listed in Table 6. The sites included are classified as P1 (interiors of thin pahoehoe lobes: 8B865, 9B349), PS3 (deep interiors of surface-fed pahoehoe: 8B913, 9B457, 9B469), PT1 (surface of tube-fed pahoehoe: 8B133, 9B169), A2 (deep interior of aa: 8B613, 9B073), A3 (spines projecting into the upper clinkery zone of an aa flow: 8B613, 9B493), and V2 (highly welded pyroclastic vent edifice, closed and open circles indicating the different subsites of 8B781). (b) Dispersion from four different kinds of sampling sites on a single lava flow (the "Old Volcano Trail Flow" of the Hale O Ai-laau group along the northeast margin of Kilauea). Ovals are 95 percent confidence areas for the site means.

The general accuracy of these ages was checked by means of an estimate of the volumetric rate of eruption they would require, this rate being compared with rates obtained previously from other kinds of evidence.

Laboratory Results

Results for the sites on flows of known age are listed in Table 1 and those of unknown age in Table 2. Additional information about these sites is given in Appendices A and B. Sites for which the results are doubted are listed on Table 3. Natural remanent magnetization intensities of all sites exceeded 1 A/m (Fig. 10). Little magnetic cleaning was needed; for most sites AF demagnetization at peak fields of 10 to 30 mT was sufficient, and only a few sites struck by lightning required more than 40 mT. The dispersion at each site is low, the α_{95} (Fisher, 1953; Appendix C) generally being less than 2 deg for approximately 12 specimens. A majority of the sites have subsites with mean directions separated by less than 2 deg, which is not a significant difference at the 95 percent confidence level. Data of this quality should be adequate to define secular variation and date lava flows with some precision if there are at least a few degrees of variation per century and if the direction of remanent magnetism truly represents the actual geomagnetic field on a regional scale.

Mean directions for the sites on flows of known age during the past 6000 years are shown on Figure 11. They range through about 40 deg of inclination and 30 deg of declination, and they confirm the inference of Coe and others (1978) that significant magnetic variation has occurred during the past several thousand years.

Explanatory Notes for Tables 1 and 2

1. A long dash in place of an entry means that no measurement was made. A blank entry means that measurement results are not yet available.

2. *Site identification code.* Sites sampled in 1978 and 1979 have initial digits of 8 and 9, respectively, and the following B is a laboratory (U.S.G.S., Manlo Park) code assigned to this project. The following three digits identify individual cores. Each year the cores were numbered in the order of their collection, beginning with 1, and each site was assigned the number of its first core. Subsites that are tabulated separately are distinguished from each other by A and B. The multiple specimens cut from each core are assigned trailing letters of A,B,C,D,E,F in order from bottom (rock interior) upward to rock surface.

3. *Site locations.* North latitude and west longitude are given in degrees and minutes, to the nearest 1/100 of a minute.

4. *Field directions.* Directions are specified by declination (D) and inclination (I). The present field and the ancient paleomagnetic fields are denoted by the subscripts p and a, respectively.

5. *Paleomagnetic laboratory parameters.* Column $\tilde{H}$ indicates the peak alternating field intensity, in milliteslas (mT), chosen for AF cleaning of specimens. Column F gives the results an F-test comparison of the subsites: S and N indicate that the subsite means are or are not, respectively, significantly different at the 95 percent level of confidence, while I indicates that a preliminary comparison of subsite dispersions showed the F-test to be invalid. Column n gives the number of specimens used in computing the final site statistics, after aberrant specimens had been eliminated, and k and α_{95} indicate the site precision and dispersion, respectively.

6. *Age data.* Entries on Table 1 indicate, in most cases, the age of the lava flow in years before present (before A.D. 1950) and the U.S.G.S. laboratory (Reston) number identifying the ^{14}C determination. Dates without a laboratory number represent the year (A.D.) of eruption. Entries in Table 2 are inferred ages, in years B.P.

7. *Site type.* Explanations of the code are given in Table 6.

Table 1 : Paleomagnetic results from dated lava flows

Site	N Lat	W Long	Present D	Present I	N	F	n	k	α_{95}	Ancient D	Ancient I	Yr bp or age	Lab ID	Flow type
8B001	19 36.48	155 01.77	14.9±2.8	38.0	20	N	12	701	1.6	2.8	43.3	260±70	W-3881	PT4
8B025	19 26.61	154 51.99	10.8±1.5	39.0	20	N	11	827	1.6	8.3	37.5	ca.1790	-	PT5
8B061	19 35.42	155 00.90	5.9±3.1	39.0	10	N	11	1535	1.2	3.8	41.5	450±60	W-3941	PT4
8B301	19 22.43	154 58.01	14.4±4.0	37.0	15	N	12	552	1.8	6.3	33.6	ca.1750	-	A2
8B325	19 23.87	154 57.62	10.3±4.4	36.5	15	I	12	470	2.0	6.3	36.9	ca.1750	-	PT5
8B337	19 30.94	154 54.76	10.9±3.7	39.0	20	S	12	846	1.5	6.8	37.5	1840	-	PS2
8B385	19 18.16	155 18.34	20.4± 23	37.5	60	N	8	452	2.6	357.8	29.5	4820±90	W-3798	L,PT1
8B397	19 18.10	155 18.38	14.4±1.1	37.5	20	N	11	354	2.4	353.6	21.1	1130±60	W-3827	A4
8B409	19 18.11	155 18.37	13.7±2.8	37.5	60	N	11	796	1.6	3.6	35.9	3480±80	W-3831	L,PT1
8B421	19 28.20	155 10.22	11.8±1.9	36.5	30	I	18	872	1.2	3.0	42.5	310±70	W-4162	PT4
8B433	19 42.80	155 07.09	15.4±2.9	35.0	15	N	12	1467	1.1	4.5	33.4	4050±200	W-3803	PT1
8B541	19 20.44	155 13.41	12.7±3.9	36.5	15	N	11	1363	1.2	0.7	41.9	620±70	W-4337	PT1
8B553	19 29.25	155 23.19	8.7±2.3	38.0	30	I	24	377	1.5	357.9	37.4	910±70	W-4047	A1
8B577	19 21.90	155 23.10	10.6±2.4	35.0	20	N	12	320	2.4	4.6	38.5	4340±80	W-3844	PT3
8B589	19 19.98	155 24.34	12.0±2.0	33.0	30	I	20	1037	0.4	4.1	38.5	450±60	W-3842	PT2
8B601	19 20.04	155 24.49	14.6±2.7	36.0	30	I	23	354	1.6	1.9	32.8	2950±80	W-3841	PT2
8B613	19 26.73	155 19.12	15.5±5.3	40.5	15	S	9	515	2.3	0.6	37.8	230±60	W-3871	A2
8B625	19 27.32	155 17.60	11.4±2.9	38.0	20	N	12	1091	1.3	11.3	15.2	2190±70	W-3876	A2
8B661	19 13.43	155 27.94	15.2±1.6	37.0	20	N	12	893	1.5	4.3	24.3	1400±60	W-3858	PT4
												1470±60	W-3857	PT4
8B673	19 13.94	155 27.58	17.2±2.4	-	30	S	23	840	1.0	1.7	35.6	670±60	W-3860	PT2
8B685	19 27.06	155 14.32	11.3±2.4	38.0	15	N	11	901	1.5	4.2	37.2	730±80	W-3999	PT2
8B697	19 11.23	155 29.15	12.3±3.2	36.0	30	S	24	580	1.3	353.0	31.9	1810±80	W-3850	PT4,A2
8B709	19 11.36	155 31.70	9.2±2.6	38.3	30	N	12	547	1.9	355.3	41.2	3900±80	W-4009	A2
8B721	19 09.19	155 32.77	13.4±2.0	36.0	15	N	12	933	1.4	356.9	37.8	640±50	W-4025	A2
8B757	19 23.24	155 17.84	13.2±1.8	39.5	20	N	11	1602	1.1	8.9	39.1	1790	-	P1,PS2
8B793	19 32.71	155 05.30	12.6±2.1	37.0	15	N	12	630	1.7	5.5	41.3	260±70	W-3881	PT1
8B829	19 33.10	155 18.10	10.8±6.9	40.5	20	N	11	2162	1.0	7.2	36.4	450±60	W-3793	PS1
												420±60	W-3790	PS1
8B841	19 27.32	155 17.07	12.1±4.4	35.5	20	S	11	171	3.5	3.3	36.5	830±60	W-3879	P2,PT1
8B853	19 22.49	155 22.68	11.3±1.1	36.0	10	N	11	515	2.0	4.3	26.0	1330±70	W-3000	PT1
8B865	19 13.03	155 27.10	12.9±0.9	37.0	30	I	24	661	1.2	3.9	37.0	330±60	W-3811	P1,PT
8B877	19 12.73	155 28.16	14.0±0.8	36.0	15	N	11	559	1.9	6.6	37.0	3610±60	W-3884	PS2
8B889	19 07.07	155 34.46	9.4±4.2	38.0	10	N	11	624	1.8	11.0	15.4	2180±60	W-4015	A2
8B901	19 32.57	155 07.46	9.4±1.5	-	20	S	12	829	1.5	5.5	33.6	5650±90	W-3862	A2
8B913	19 08.28	155 33.14	12.2±2.4	39.3	20	N	9	1385	1.4	359.5	37.7	740±60	W-4012	PS3
8B925	19 04.19	155 36.91	4.7±2.3	40.5	15	N	11	530	2.0	7.4	29.7	3620±250	W-2016	PT3
												3740±250	W-856	PT3
8B937	19 09.46	155 32.58	10.2±2.1	36.5	15	N	11	873	1.5	5.9	7.0	2300±60	W-4008	A2
8B949	19 09.65	155 32.55	-	37.0	20	I	18	1328	0.9	11.2	28.0	3900±90	W-4132	PS3
9B013	19 35.85	155 08.82	6.4±2.8	36.5	20	N	11	1748	1.1	359.3	22.2	2890±70	W-4174	PS3
9B037	19 38.38	155 02.55	11.6±1.5	35.5	20	N	12	361	2.3	357.8	25.6	2890±70	W-4174	A2
9B049	19 41.06	155 06.55	7.6±6.1	36.0	20	N	11	686	1.5	359.7	18.6	1280±70	W-4343	PT2
9B061	19 38.52	155 07.64	11.1±3.9	37.0	30	N	9	777	1.8	5.4	40.0			PT3
9B073	19 21.68	155 22.85	5.1±2.0	36.0	20	N	10	819	1.7	1.3	38.5	230±60	W-3871	A2
9B085	19 35.71	155 21.37	13.9±1.9	36.5	20	N	12	411	2.1	1.9	18.9	1400±70	W-4340	PT1
9B097	19 34.86	155 21.03	14.6±2.2	38.5	20	N	9	679	2.0	0.0	17.3	1490±50	W-4357	PT1
9B109	19 33.84	155 20.64	12.3±1.6	37.5	20	N	12	401	2.2	2.2	18.2	1320±50	W-4237	PT1
9B121	19 34.80	155 83.72	10.4±2.0	-	20	N	12	906	1.4	3.2	44.2	260±70	W-3881	P1,PT
9B133	19 35.26	155 01.03	15.0±1.6	-	30	N	11	528	2.0	4.2	45.6	450±60	W-3941	PT3
9B205	19 29.81	154 52.44	5.7±1.6	-	10	S	10	1075	1.4	359.7	41.8	ca.1360	-	V1
9B253	19 29.86	155 19.10	13.2±2.4	37.8	30	N	11	1316	1.3	9.9	36.9	<200	W-4331	PT1
9B265	19 28.73	155 22.01	7.8±2.4	38.0	30	N	11	1658	1.1	6.0	40.5	580±80	W-4118	A1
9B277	19 29.16	155 23.13	11.3±4.5	36.5	70	N	11	240	3.0	354.9	15.9	1840±60	W-4116	PT1,L
9B349	19 13.03	155 27.70	11.8±2.1	37.0	30	N	11	6217	0.5	3.4	38.3	330±60	W-3811	P1,PT
9B373	19 08.87	155 30.97	5.1±2.5	37.5	30	S	11	245	2.9	355.3	31.1	3800±90	W-4152	PT3
9B409	19 17.48	155 24.13	12.4±1.9	37.0	40	S	12	361	2.3	2.8	36.6	<200	W-3937	PS1
9B433	19 34.29	155 03.57	11.8±3.0	-	20	N	11	418	1.7	4.2	46.9	269±70	W-3881	PT5
9B445	19 09.64	155 32.55	11.4±5.0	-	20	N	12	466	2.0	3.5	27.6	5160±10	W-4135	PT2
9B457	19 08.50	155 33.28	13.2±2.7	38.5	30	N	10	3134	0.9	359.1	40.5	890±60	W-4137	PS3
9B469	19 99.04	155 33.94	12.1±2.3	37.0	20	S	11	2232	1.0	358.2	41.4	740±60	W-4156	PS3
9B505	19 04.28	155 40.96	10.8±3.5	36.0	40	S	9	785	1.8	6.9	33.0	330±70	W-4238	PS2
9B517	19 03.79	155 39.56	9.7±1.9	36.5	20	N	11	1063	1.4	1.1	33.8	490±80	W-4234	A2
9B529	19 03.98	155 42.98	13.3±4.4	38.0	20	N	12	501	1.9	350.3	29.5	780±70	W-4232	A2
9B577	19 28.94	155 21.74	12.7±5.5	41.0	30	N	11	559	1.9	358.4	39.8	420±70	W-4049	A1
9B697	19 15.57	155 24.63	14.0±2.1	39.0	40	N	11	1722	1.1	4.3	38.6	210±60	W-3938	PS1
9B721	19 33.45	154 52.87	11.8±1.0	-	10	S	11	1558	1.2	4.9	40.7	1840	-	A2
9B757	19 07.79	155 50.50	15.0±2.3	37.0	25	N	11	1120	1.4	8.6	37.9	<200	W-4198	A2
9B889	19 35.04	155 01.84	11.2±1.6	37.5	30	N	11	1721	1.1	0.8	36.1	3690±70	W-4177	PT1
9B925	19 24.74	155 20.54	10.7±2.5	38.0	10	N	10	532	2.1	4.7	42.1	290±70	W-4006	PT2

Table 2 : Paleomagnetic results from undated flows

Site	N Lat	W Long	Present D	Present I	N	F	n	k	α_{95}	Ancient D	Ancient I	Inferred age	Flow type
8B013	19 25.68	154 53.12	11.1±1.8	38.5	20	I	12	1137	1.3	10.6	21.4	2000-2500	PT1
8B037	19 30.08	154 50.17	13.1±3.2	37.5	15	S	12	1744	1.0	3.3	42.8	250- 500	PT4
8B049	19 35.82	155 01.23	11.4±1.4	38.0	15	N	11	1182	1.3	1.3	32.8	500-1000	PT4
8B073	19 34.62	155 00.31	13.5±2.8	37.5	20	S	12	2047	1.0	0.5	35.1	500-1000	PT4
8B085	19 33.70	154 59.62	12.4±0.6	40.5	20	N	11	2197	1.0	3.1	42.6	250- 500	PT1
8B097	19 29.37	154 57.51	10.9±2.0	39.2	50	N	11	965	1.5	2.5	37.0	500-1000	PT1
8B109	19 29.64	154 57.74	11.6±5.0	37.0	40	N	11	1331	1.3	4.9	43.5	250- 500	PT4
8B121	19 19.72	155 16.93	9.7±1.2	38.8	50	N	11	768	1.6	357.0	39.2	500-1000	PT2
8B133	19 19.74	155 16.89	10.9±4.7	38.3	50	N	11	1475	1.2	357.5	37.9	500-1000	PT2
8B145	19 25.13	155 14.76	7.4±2.6	33.0	15	N	11	959	1.5	355.4	24.7	1500-2000	CW,PT4
8B157	19 25.13	155 14.76	9.9±0.8	33.0	20	I	12	233	3.4	359.5	35.9	500-1000	CW,PS2
8B169	19 35.01	155 00.59	16.6±3.3	37.5	30	S	11	2160	1.0	4.8	45.7	250- 500	PT4
8B181	19 30.78	154 57.76	14.0±5.9	36.8	30	S	10	1616	1.2	2.7	44.1	250- 500	PT4
8B193	19 32.96	154 58.81	14.8±2.0	41.8	30	N	12	1804	1.0	5.2	45.2	250- 500	PT4
8B205	19 30.27	154 50.17	13.7±5.2	36.0	20	N	10	548	2.1	3.9	40.2	250- 500	A2
8B217	19 34.94	155 01.77	11.5±1.4	39.0	30	N	10	1549	1.2	4.0	36.4	500-1000	PT1
8B229	19 17.56	155 06.64	12.0±1.6	37.5	30	N	10	1041	1.5	358.8	39.1	500-1000	PT1
8B241	19 19.31	155 02.88	9.9±2.1	37.5	30	N	11	779	1.6	354.8	30.6	500-1000	PT1
8B253	19 21.17	155 02.51	12.1±1.7	35.2	10	S	12	586	1.8	354.3	29.2	1500-2000	A2
8B265	19 20.56	155 00.55	8.8±2.0	36.0	15	S	12	826	1.5	358.0	14.5	1500-2000	PT3
8B277	19 20.64	155 00.37	6.5±2.1	37.8	15	S	12	1132	1.3	355.9	31.2	1500-2000	A2
8B289	19 21.04	154 59.56	13.7±2.9	38.0	20	N	11	843	1.6	355.0	30.8	1500-2000	PT2
8B313	19 22.34	154 58.07	5.2±1.9	37.5	20	N	12	1164	1.3	352.3	30.4	1500-2000	PT4
8B349	19 24.63	154 54.59	9.5±4.3	41.0	20	N	12	1214	1.2	356.0	29.8	1500-2000	PT1
8B361	19 25.50	154 53.42	11.4±3.3	38.5	30	I	12	112	4.1	6.7	34.8	ca.1000	A3
8B373	19 27.56	154 51.00	10.0±3.2	39.0	30	N	10	1050	1.5	5.0	31.3	500-1000	PT1
8B445	19 17.09	155 20.09	11.4±2.0	37.5	20	I	12	901	1.4	3.3	35.4	250- 500	PT1
8B457	19 16.88	155 20.32	16.5±4.4	38.5	20	N	10	928	1.6	5.2	39.9	250- 500	A1
8B469	19 16.56	155 20.81	12.8±3.7	37.5	20	I	11	828	1.6	4.7	34.2	500-1000	PS1
8B481	19 16.43	155 21.17	15.2±4.9	39.5	50	N	12	162	3.4	4.6	42.2	250- 500	A4
8B493	19 16.06	155 21.67	11.9±3.3	37.0	20	N	10	864	1.6	359.8	37.7	500-1000	PT1
8B505	19 14.41	155 22.33	11.5±2.4	37.5	20	S	12	861	1.5	3.9	36.1	500-1000	PT1
8B517	19 14.40	155 22.37	9.3±4.3	37.3	30	I	8	3395	1.0	8.5	37.5	0- 250	PT1
8B529	19 14.56	155 24.72	12.5±2.7	38.5	20	N	10	1990	1.1	359.7	38.5	500-1000	PT1
8B565	19 21.10	155 23.36	9.2±3.6	36.0	10	I	10	610	2.0	7.6	37.9	250- 500	PT4
8B637	19 18.23	155 25.21	10.5±2.5	40.5	15	S	12	943	1.4	5.3	39.8	250- 500	PT3
8B649	19 17.46	155 25.61	11.1±5.5	38.5	15	S	12	980	1.4	5.5	30.6	250- 500	PT3
8B733	19 24.98	155 14.47	11.9±1.2	36.0	10	N	11	1147	1.3	6.3	43.4	250- 500	PS3
8B745	19 23.67	155 18.59	15.3±3.4	38.0	15	N	9	905	1.7	5.0	42.8	250- 500	V2
8B769	19 22.82	155 17.26	13.5±2.8	38.5	20	N	9	490	2.3	4.7	34.9	0- 250	V2
8B781	19 22.75	155 14.37	9.7±2.3	38.5	15	S	12	577	1.8	4.8	44.0	250- 500	V2
8B805	19 30.73	155 00.48	8.9±0.8	39.0	15	I	12	1164	1.3	354.7	21.2	1500-2000	PT3
8B817	19 28.32	154 50.04	12.4±2.9	39.5	15	N	10	542	2.1	354.0	31.5	1500-2000	PT2
8B973	19 32.69	154 50.83	11.4±4.2	37.5	25	N	10	306	2.8	359.9	34.8	-	A3
9B145A	19 35.07	154 56.96	12.8±1.6	-	30	-	6	1384	1.8	8.4	43.4	250- 500	PT1
9B145B	19 35.02	154 57.00	12.8±1.6	-	30	-	6	877	2.4	7.5	36.1	-	PT1
9B157	19 22.25	155 10.56	12.0±2.1	-	20	I	12	513	1.9	3.3	32.5	500-1000	CW,A2
9B169	19 19.77	155 16.85	11.4±1.7	-	30	N	10	968	1.6	357.9	37.4	500-1000	PT1
9B181	19 32.88	154 51.03	13.3±2.8	39.5	20	N	11	265	2.3	355.7	25.3	-	A3
9B193	19 17.86	155 18.95	11.0±3.4	-	30	N	8	319	3.1	4.8	41.1	250- 500	PT1
9B217	19 22.94	155 13.64	13.3±5.1	-	20	N	11	419	2.2	359.3	33.9	500-1000	CW,PT4
9B229A	19 25.64	155 17.07	14.9±2.9	-	20	-	6	725	2.5	356.8	31.4	1500-2000	CW,PT4
9B229B	19 25.67	155 17.05	16.5±1.7	-	20	-	6	671	2.6	351.5	17.6	1500-2000	CW,PT4
9B241	19 22.25	155 10.56	11.0±2.3	-	30	S	12	603	1.8	355.7	36.6	500-1000	CW,PT4
9B385	19 22.47	155 13.62	13.2±2.3	-	30	S	10	290	2.4	348.8	27.2	1500-2000	CW,A2
9B397	19 26.48	155 87.98	15.6±1.8	-	20	N	11	173	3.5	5.6	45.6	250- 500	PT5,1
9B421	19 28.24	155 05.07	11.3±2.1	-	20	I	9	2277	1.1	4.5	43.3	250- 500	PT2
9B493	19 25.48	154 53.36	13.0±3.1	-	40(7)		12	97	4.4	2.6	26.5	ca.1000	A3
9B589	19 20.03	155 02.36	12.1±3.3	36.5	40	I	9	1812	1.2	356.2	37.6	500-1000	PT3
9B673	19 29.52	155 02.69	11.2±2.3	-	30	S	12	722	1.6	1.6	39.8	250- 500	PT1
9B685	19 14.93	155 25.65	8.8±3.6	38.0	30	S	70	332	2.7	347.3	30.2	-	PS4
0B709	19 29.16	154 54.55	16.6±3.8	-	30	S	11	512	2.0	1.8	41.1	250- 500	PS3
9B829	10 17.92	155 24.21	10.7±2.4	39.5	10	N	11	435	2.2	2.7	29.2	1000-1500	PS4
9B841	19 18.30	155 24.44	13.2±4.0	38.5	40	S	12	640	1.7	5.1	39.9	250- 500	PS1
9B853	19 33.68	154 53.36	12.0±2.4	-	25	I	10	532	2.1	356.4	28.4	1500-2000	PT2
9B865	19 18.28	155 24.38	11.9±1.9	-	30	N	9	2751	1.9	2.7	34.1	500-1000	PS1
9B877	10 17.92	155 24.14	12.3±2.3	-	30	N	11	947	1.5	2.1	37.6	250- 500	PT1
9B913	19 22.96	155 12.50	8.6±6.0	42.0	20(7)		9	238	3.3	2.5	46.4	250- 500	V2

Table 3

Sites for Which Results are Doubted*

Site	^{14}C age (years B.P.)	Reasons for doubt
8B385	4820 ± 90	Topographic anomaly
8B397	1130 ± 60	Topographic anomaly
8B409	3480 ± 80	Topographic anomaly
8B709	3900 ± 80	Anomalous inclination; tenuous correlation with ^{14}C site
8B841	830 ± 60 530 ± 60	Topographic anomaly; broad dispersion; conflicting dates
9B505	330 ± 70	Field evidence that date is too old
9B517	490 ± 80	Field evidence that date is too young
9B529	780 ± 70	Direction anomalous; field evidence that date is too young
9B889	3690 ± 70	Tenuous correlation with ^{14}C site
8B361	-	Wide dispersion from internal aa spines
9B493	-	Wide dispersion from internal aa spines
9B913	-	Vent anomaly; rift zone anomaly

*There are reasons for doubting some other sites as well, but these are the sites most doubted according to a numerical ranking system that we devised for comparing different sites.

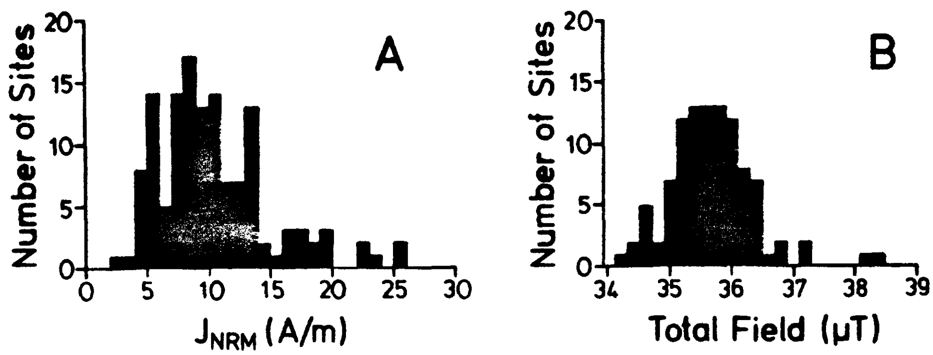


Fig. 10--Histograms of intensity measurements made in this study. (a) Mean intensity of remanent magnetization of specimens collected from the sampling sites, measured in the laboratory; (b) intensity of the present geomagnetic field at the sampling sites, measured in situ.

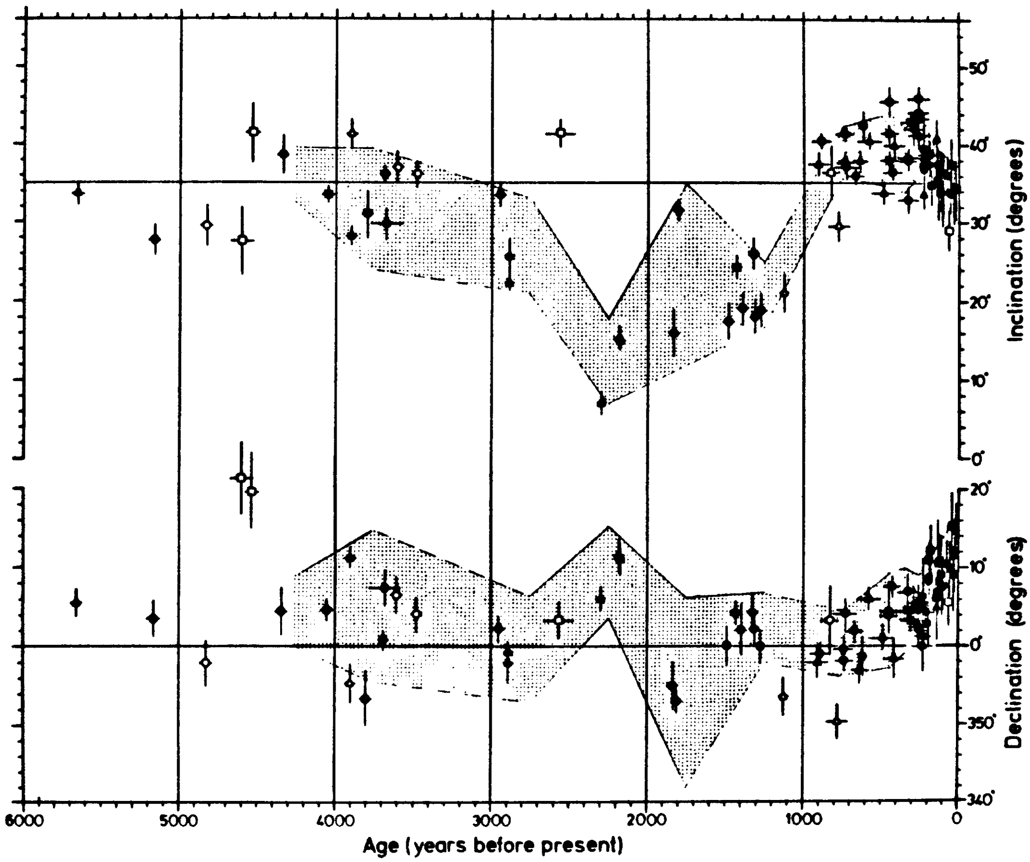


Fig. 11--Declination and inclination of remanent magnetization, after cleaning, at sites in dated flows, plotted against their ages. Circles and triangles represent pahoehoe and aa flows, respectively; squares indicate data from other workers (Doell and Cox, 1963; Coe and others, 1978). Open symbols represent data we doubt for reasons given in Table 3; we have less reason to doubt the data of the solid symbols. Error bars in directions of magnetization at individual sites are for inclination ±I and for declination ±D as defined by equations (7) and (9) of Appendix C. Error bars in age are one standard deviation in the counting statistics for the laboratory determination of ^{14}C activity. Shading indicates the area within deviations ±i and ±d, defined by equations (8) and (10), from the temporal means of Table 4.

Table 4

Means of Paleomagnetic Directions for Successive Intervals of Time*

Group I.D. number	Age (years B.P.)	N	d (deg)	i (deg)	k	Ψ_{63} (deg)	α_{95} (deg)	Variation rate (deg/century)
A. 100-year intervals								
1	0- 100	8	11.7	35.2	779	2.9	2.0	4.6
2	100- 200	13	8.3	36.9	775	2.9	1.5	4.4
3	200- 300	11	3.9	40.1	411	4.0	2.3	3.5
4	300- 400	4	4.5	38.0	360	4.3	4.8	1.7
5	400- 500	6	3.2	39.3	288	4.8	4.0	1.2
B. 500-year intervals								
6	500-1000	9	0.3	39.0	608	3.3	2.1	2.0
7	1000-1500	6	2.3	20.6	393	4.1	3.4	2.6
8	1500-2000	2	354.0	23.7	53	11.1	34.9	2.8
9	2000-2500	3	9.4	12.3	217	5.5	8.4	3.6
10	2500-3000	3	359.7	27.0	181	6.0	9.2	
11	3000-3500	0	-	-	-	-	-	1.2
12	3500-4000	4	4.6	31.7	110	7.7	8.8	1.1
13	4000-4500	2	4.5	36.0	505	3.6	11.1	0.6
14	4500-5000	0	-	-	-	-	-	
15	5000-5500	1	3.5	27.6	-	-	-	1.5
16	5500-6000	1	5.5	33.6	-	-	-	1.2

*Not included in these averages are the sites listed on Table 3 and shown by open symbols on Figure 11.

N is the number of sites used to compute the interval mean, each site given unit weight. d is the declination of the interval mean. i is the inclination of the interval mean. k is the estimated precision parameter of the interval mean. Ψ_{63} is the estimated angular standard deviation of the site means around the interval mean. α_{95} is the circle of 95 percent confidence of the interval mean. Variation rates are obtained by dividing the differences of successive interval means by the number of centuries separating them.

The data points cluster such that flows of similar age tend to have similar paleomagnetic directions. A striking example is provided by two flows located 50 km apart but indistinguishable in age (8B889, 2180 ± 60 years B.P.; and 8B625, 2190 ± 70 years B.P.) that also have indistinguishable magnetic directions distinctly different from those of all other dated flows. During the last 3000 years flows differing in age by more than a few centuries also differ significantly in their magnetic directions. It is not until 3000 to 5000 years B.P. that directions are found similar to any in the younger lava flows; radiocarbon dates W-3841 (site 8B601, 2950 ± 80 years B.P.), W-3831 (site 8B409, 3480 ± 80 years B.P.), and W-3884 (site 8B877, 3610 ± 60 years B.P.) are from flows having directions similar to some flows erupted during the last thousand years.

During this interval of 0 to 6000 years B.P. the inclination of the remanence vector describes an oscillatory variation having an amplitude of about 30 deg and apparent period of about 4000 years. Departure from the nominal inclination of about 35 deg for an axial dipole at this latitude (19.5°) is greater toward low inclinations than toward higher ones. Going backward in time from the present near-nominal value, a maximum of about 40 deg is reached about 300 years ago, beyond which 2000 years of shallowing leads to a minimum of about 10 deg about 2300 years ago. Beyond this minimum the inclination steepens for another 2000 years to a maximum of about 35 deg about 4400 years ago, and then appears to shallow again.

Declination varies in a more complex manner during this interval, with oscillations having shorter periods, smaller amplitudes, and less regularity than changes in inclination. Easterly declinations dominate over westerly. Going backward in time from the presently extreme easterly declination, during the past 1000 years the values change at a comparatively slow rate similar to that for inclination, reaching a minimum of about 0 deg about 700 years ago. Beyond 1000 years the variation is comparatively rapid and appears to consist of successive irregular oscillations having periods of about 1300 years and amplitudes of about 15 deg.

Potential usefulness of secular variation for dating lava flows is indicated by its record on Hawaii during the past 3000 years, when unique magnetic directions were recorded during different segments of time. Amplitude of the secular variation is much larger than the measurement precision, or within-site dispersion, at each sampling locality. The resolution of the method can be estimated from the rate of variation and the measurement precision. The overall rate of change appears to have varied between 0.5 and 5 deg/century, if we accept the 100-year and 500-year means of Table 4. However, the rates for the 500-year intervals are probably minimum values because the intervals are long enough for short-period variations to be averaged out. If a rate of 4 deg/century (typical of rates found by Champion and Shoemaker, 1977) is representative, and if the paleomagnetic measurement precision is 2 deg--similar to the dispersion at most sampling sites--the corresponding precision in age inferences is ±50 years. Such resolution could make the secular variation a very useful tool in dating lava flows. However, the potential resolution is degraded by a somewhat larger dispersion of magnetic directions between different sampling sites on flows thought to be of the same age.

The between-site dispersion is especially obvious where the sampling frequency is comparatively high during the last 1000 years. It is obvious during this interval that lava flows of similar age commonly differ by 6 to 10 deg in their magnetic directions. The effect on dating of this between-site dispersion is illustrated on Figure 12, where mean directions for successive intervals of time are surrounded by dispersion circles corresponding to the shaded bands of Figure 11. During the last 500 years, for example, the means of successive 100-year intervals display good serial correlation but their circles of dispersion overlap greatly--such that individual site means for flows 500 years old can scarcely be distinguished from flows of the last century at the 63 percent confidence level. In order for secular variation to achieve useful resolution as a dating tool, the sources of between-site dispersion must be identified and reduced. We will now consider in some detail the various sources of dispersion. We will focus in particular on the dispersion arising from (1) experimental errors, (2) secular variation during the averaging intervals, (3) imprecision in the ^{14}C dates, (4) local variations in the geomagnetic field, (5) deformations of lava flows after their magnetization was acquired.

Error Analysis: Sources of Between-Site Dispersion

Doell and Cox (1963) made the most detailed previous analysis of dispersion of paleomagnetic directions in similar young basalts, considering the various contributions to the total dispersion arising at several different levels. At the intraflow level they found the principal sources of dispersion to be orientation errors, ambient field variations at the time magnetization was acquired, and defor-

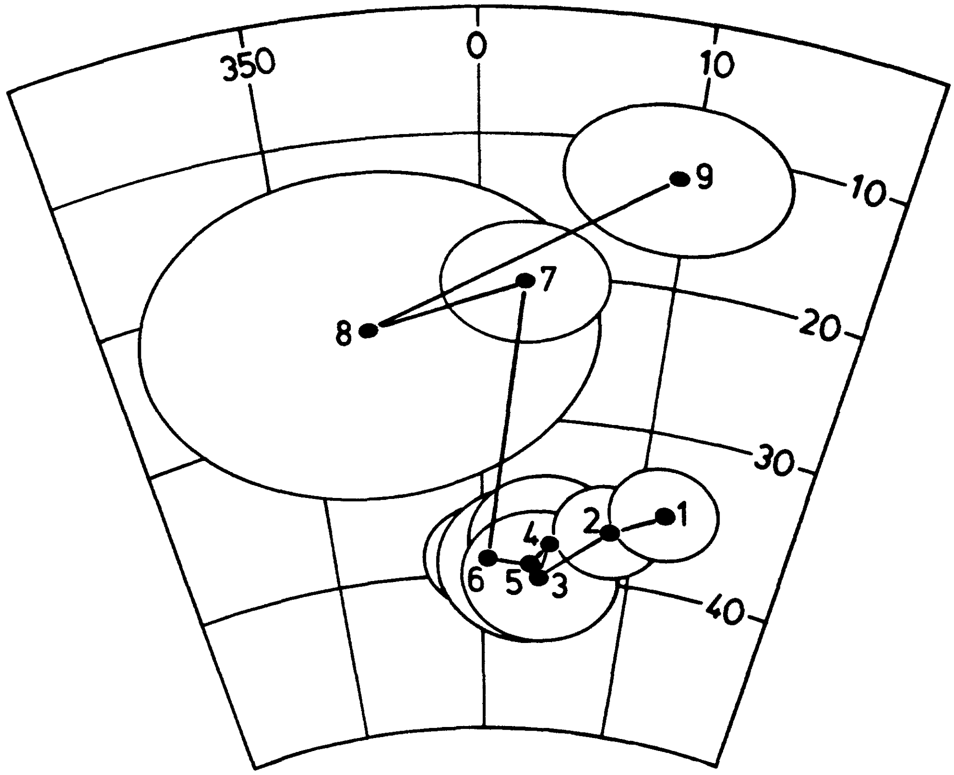


Fig. 12--Mean magnetization directions of dated flows for the intervals in Table 4 for the last 2500 years. Each oval represents one angular standard deviation from the mean for the respective interval numbered on Table 4. The relatively large oval for 1500 to 2000 years B.P. (interval 8) is due to just two values occurring in this interval, which differ by only 2 deg in declination but 16 deg in inclination. The comparatively large size of all ovals for intervals older than 500 years B.P. is due partly to the long 500-year spans they represent, during which significant secular variation occurred.

mations of the lava flows after magnetization was acquired. These results have guided the conduct of our work, especially our sampling methods where we adopted procedures aimed at reducing the dispersion encountered by Doell and Cox. For comparative purposes this discussion parallels theirs, differing mainly in excluding some sources that Doell and Cox found to be insignificant, and including the dispersion arising from uncertainties in age. The flows studied by Doell and Cox were all from the short historic period, and their ages were known accurately.

Procedure

In analyzing the dispersion we followed the procedure used by Doell and Cox, considering in turn each source of dispersion and then summing them (using the additivity of variances) and comparing the sums to the total dispersion observed. Various statistics are available for describing the dispersion and its inverse, the precision. The parameter used most commonly is the estimated precision parameter, k; an alternative is the estimated angular standard deviation, Ψ_{63}. These parameters and their relationships to each other are defined in Appendix C. In this report the dispersion is generally discussed in terms of Ψ_{63} because it is analogous to the familiar standard deviation. Shown also in parentheses are corresponding values of k because they are more commonly used in paleomagnetism and because they will allow easier comparison of our results with those of Doell and Cox (1963). We now consider in turn each source of dispersion.

Experimental Errors

In this class are the sources of dispersion arising from imprecision in specimen orientation, demagnetization, and measurement of magnetization. Because the experimental procedure is complex, the sources of error are many, and we do not present here a step-by-step analysis of our experimental error. However, the procedures used are by now fairly routine, and an initial crude estimate of the overall experimental precision can be obtained through comparison with previous work. Using generally similar procedures Doell and Cox (1963) estimated their precision parameter at the experimental level to be about 1000, equivalent to an angular standard deviation of about 2.6 deg. Our precision should be better than this because of our more accurate suncompass orientations, so we consider the values of Doell and Cox as a lower limit for our own precision.

A more realistic estimate can be obtained from the overall precision achieved at our own individual sampling sites, because the overall precision cannot exceed the experimental precision that is only one contributor to the overall value. Our within-site dispersion is low, such that the mean α_{95} for all 135 sites after filtering is 1.7 deg and its standard deviation is 0.7 deg. The larger dispersions at some sites are almost certainly due to factors other than experimental procedure and should not be used in making the estimate. For example, the large difference between subsites at the spatter cone of site 8B781 (Fig. 9a; Appendix B) is probably caused by a vent anomaly (Doell, 1972). The very large difference at site 8B385 may arise from lightning effects not entirely removed by cleaning, or it may be due to a high gradient in the ambient geomagnetic field near the brink of a high cliff at the time of cooling. The difference at 8B841 (Appendix A) also may be due to topographic effects of the steep scarp on which it is situated. Sites 8B157, 9B157, 9B217, 9B241, and 9B385 are on the faces of cliffs, and it is probable that subtle mass wastage not observed in the field has caused some blocks to rotate, yielding the relatively poor dispersions and subsite differences. Site 9B673 is in a forested area very near a mapped flow margin, and the two subsites may be from different flows. As will be discussed later, much of the dispersion observed within most other sites is probably caused by deformation after the flows were magnetized. The least dispersed site has α_{95} = 0.5 deg, k = 6217 and Ψ_{63} = 1.0 deg. This is similar to the precision typically achieved in orienting a single specimen. Even if this best site is anomalously precise, several others indicate that our measurement precision significantly exceeds values of (k = 2000) Ψ_{63} = 1.8 deg. This precision is considerably better than that achieved by Doell and Cox (1963) and is probably due to our (1) improved understanding of the nature of within-site deformations, (2) greater number of cores per site and rejection of anomalous specimens, and (3) use of a suncompass.

Secular Variation During the Averaging Intervals

Any secular variation occurring during a temporal averaging interval, such as those of Table 4, would contribute some dispersion to the data for that interval. If the mean directions of remanent magnetization accurately reflect geomagnetic field directions during successive intervals, the amount of variation can be estimated from the difference between their respective means. Such rates of variation are estimated in Table 4. During the 200 years of the historic period, for example, the paleomagnetic data suggest that the rate of variation has been about 4.5 deg/century. During a 100-year averaging interval this rate would cause a deviation of 2.25 deg (k = 1300) from the mean value. Since the total observed dispersion is 2.9 deg in the historic period, the dispersion left to account for when the secular variation is subtracted (equation (5) of Appendix C) is 1.5 deg, if experimental precision is about 1.0 deg. The dispersion due to secular variation depends upon the duration of the averaging interval, so that a 4 deg/century variation averaged over 500 years results in a 10 deg deviation (k = 66) from the mean value. This is a large dispersion, approaching the total expected from secular variation over a long interval at a place of Hawaii's latitude (Doell and Cox, 1972). In constructing a history of secular variation for dating pusposes, 500 years is too long an interval over which to average that data, and our data beyond 1000 years ago are too sparse to yield reliable averages. Where the data are too sparse to permit averaging over shorter intervals it is probably best to simply use individual site means and assume that the between-site uncertainty is similar to that of averaged intervals where data are abundant.

Imprecision in the ^{14}C Dates

Some of the between-site dispersion for prehistoric lava flows must arise from uncertainties in their ages. During the last 200 years (the historic interval) there are no significant errors in age, but beyond 200 years ago the ages are entirely dependent upon ^{14}C dates, and a jump in standard deviation (Ψ_{63}) values at that time from less than 3 deg to more than 4 deg (Table 4) suggests that a deviation of about 3 deg in the latest prehistoric interval may be due to age uncertainties. Moreover, the existence of dating errors is known in some cases where replicate dates from a single ^{14}C site differ greatly (e.g. samples W-3885 and W-4162 are from the same site, 8B421, but yield dates of 2160 ± 70 and 310 ± 70 years B.P., respectively (Kelley and others, 1979). We are quite certain that the former age is in error and have not listed it on Table 1). Moreover, as discussed later, stratigraphic relationships show that some ages must be in error by amounts larger than the error bars of Figure 11. These error bars, and the confidence intervals of Table 1, indicate merely the precision of the laboratory measurements and do not account for errors arising from sample contamination, variations in atmospheric production of ^{14}C, etc. Experience has shown that the overall precision of ^{14}C dates for the last few thousand years is probably about ±200 years instead of the ±60 years commonly attained in the laboratory measurements alone (M. Rubin, oral commun., 1978), and variations in the rate of ^{14}C production are known to cause errors on the scale of centuries (Stuiver, 1978; Bruns and others, 1980). If the rate of secular variation is 4 deg/century, an age uncertainty of ±200 years corresponds to an angular deviation of 8 deg and a precision parameter k of 100. This is larger than the deviation suggested at the end of the prehistoric interval, but the uncertainty in ^{14}C dates should increase with age such that the 3 deg value may be a lower limit. On the other hand, age uncertainties can add significantly to the total computed dispersion only when they are large relative to the lengths of the averaging intervals. If uncertain dates are constrained to be well within the limits of an averaging interval, their uncertainty adds little or nothing to the total uncertainty for that interval. Thus for the 500-year intervals of Table 4 the actual contribution due to age uncertainties should be less than the 8 deg inferred from the estimated magnitude of age uncertainty. It must be conceded that this effect is artificial and arises merely from the averaging procedure; age uncertainties certainly do contribute significantly to the dispersion as it appears on Figures 11 and 12.

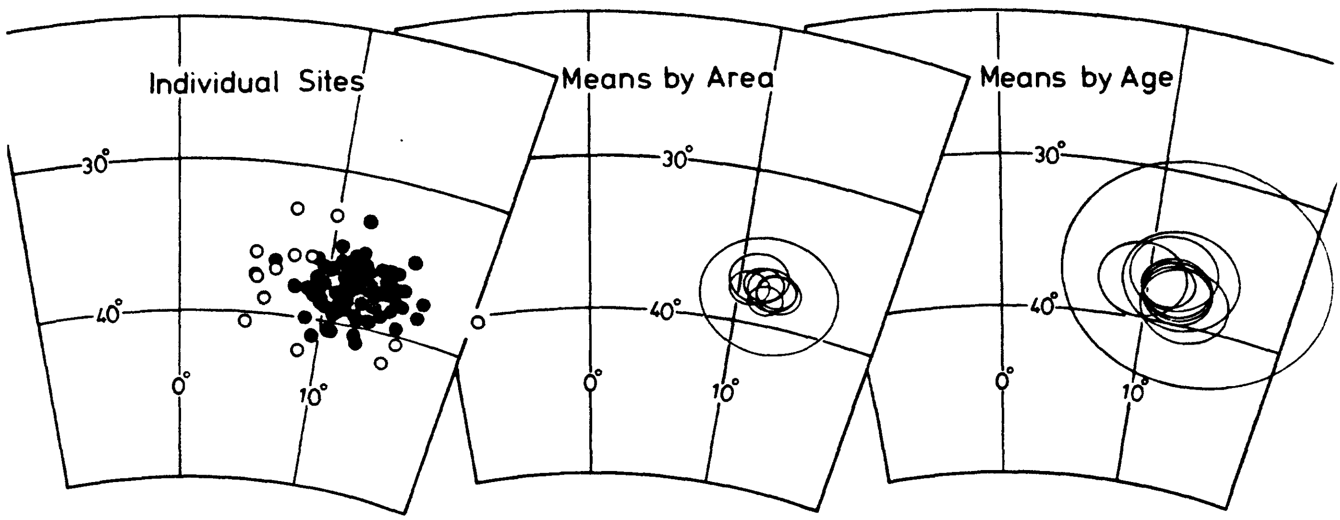
Local Anomalies in the Geomagnetic Field

Doell and Cox (1963) reasoned that local magnetic anomalies should contribute a significant component of dispersion to the total observed in paleomagnetic data. They had no data for the modern field in Hawaii but inferred its dispersion through comparison with a volcanic island in Japan, finding that local anomalies in Hawaii should cause 1 to 1.5 deg of dispersion. We tested this conclusion by measuring the present field at many of our sampling sites (Figs. 10b, 13). We did find large local anomalies at some places, such as the rims of palis. Because our sites were chosen strictly for the potential quality of their paleomagnetic results, some of them were poorly located for measuring the present field, it being affected by artificial factors like power lines, fence lines, and roadcuts. In estimating the natural dispersion in the geomagnetic field we have omitted the sites known to be affected by artificial factors. From 96 remaining sites we obtained a standard deviation of 2.2 deg (k = 1370). This is larger than the value predicted by Doell and Cox

(1963), but we believe it is an upper limit because of the crude nature of our present-field measurements. The dip needle was not mounted on a tripod, and the standard deviations of the in-site declination measurements are large from being measured very close to the ground. Our measured dispersion probably includes a large component of experimental error, and a value of 1.5 deg (k = 2916) seems a reasonable estimate of dispersion from this source. We have not corrected the paleomagnetic results for the local anomalies measured because we have found no correlation at individual sites between their deviations from means of the present field and paleofield of appropriate age (Fig. 14).

It remains possible that large regional anomalies could bias groups of measurements in addition to contributing to dispersion. However, there appear to be no significant differences in the direction of the present field for sites from different regions or on flows of different ages (Table 5, Fig. 13). Recently obtained aeromagnetic data do show that a 1000-γ anomaly about 2 km wide extends along most of Kilauea's east rift zone (C. J. Zablocki, unpubl. map). Anticipating that such an anomaly would be found, we generally avoided sites close to the east rift zone. In a few cases, however, we did sample vents (8B781, 9B913) and pit crater walls (9B157, 9B217, 9B241, 9B385) in the rift zone, and these sites may have been affected by the anomaly if it has been a persistent feature.

Another factor that could contribute significantly to the dispersion is the effect of latitude. Most sites fall within 0.4 deg, but range across 0.65 deg, of latitude. If the geomagnetic field is approximated with an axial geocentric dipole, these latitude variations



a b c

Fig. 13--Between-site dispersion in the measured directions of the present geomagnetic field. Intensity variation is shown on Figure 10b.

(a) Measurements at individual sites. Open circles represent values thought to be affected by some anomalous factor near the outcrop, such as power lines, fence lines, lightning strikes, or cliffs.

(b) Mean directions for different geographic subdivisions of Kilauea.

(c) Mean directions for lava flows of different ages. Ovals represent the area of 95 percent confidence of the means, as listed in Table 5. Large sizes of some ovals are caused by the small number of averaged values in their groups.

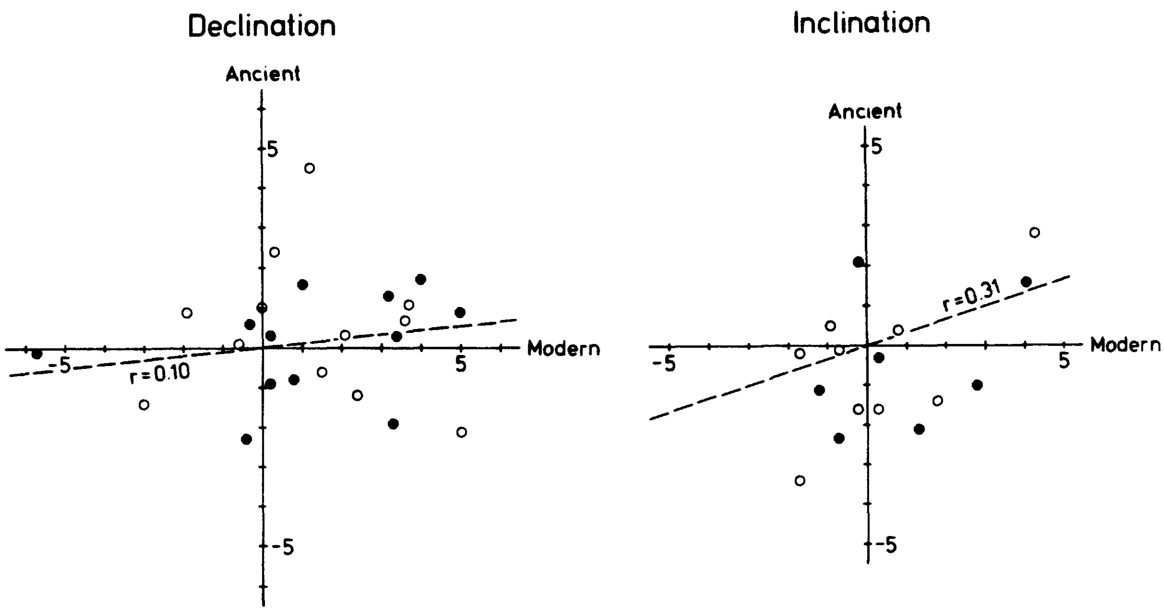


Fig. 14--Comparison of present and ancient magnetic field deviations. Deviations in declination and inclination are shown on separate diagrams. Each data point represents a sampling site on a lava flow thought to be about 400 years old. Solid circles are lava flows from the vent we call Hale O Ai-laau and are grouped together with a high degree of confidence (see Table 8 and associated discussions). Open circles represent other lava flows whose directions of magnetization indicate that they are of similar age; these are included in the group with less confidence. As a group these sites provide measures of dispersion in both the present field and the field of about 400 years B.P. Deviations (in degrees) from the modern mean are shown along the abscissa, and deviations from the ancient mean are shown along the ordinate. If the modern and ancient deviations were well correlated, they would cluster closely along lines through the origins, but they do not. Because the correlation is so poor, it would not be valid to correct the paleomagnetic data for present field anomalies.

Table 5

Means of the Modern Field for Groups of Sites Similar in Location or Age of Their Lava Flows

Group	N	d	i	α_{95}
A. Area groups				
Kilauea north flank	19	12.0	38.4	0.9
Kilauea southeast flank	17	10.8	37.8	1.0
Kilauea south flank	10	12.8	37.9	1.2
Kilauea southwest rift	13	12.3	37.6	1.3
Kilauea east rift	3	12.2	38.0	3.8
B. Age groups*				
3. Eighteenth century	10	12.0	37.9	1.8
4. Lua Pele	6	11.6	36.8	2.4
5. Hale O Ai-laau	7	12.7	38.7	2.5
7A,B. South flank	6	11.9	37.7	1.8
8A. Older, north flank	2	12.1	38.2	1.4
Dated, 500-1000 years B.P.	8	11.4	37.6	7.2
9. About 1400 years B.P.	2	13.2	36.5	3.1
10. Kulaloa	4	12.1	37.2	2.3
12. Older Kalapana	7	9.6	37.5	

*Group numbers correspond to those of Table 10, but the number of sites included in a group may differ because present-field measurements were not made or were rejected because of artificial factors.

correspond to 0.8 deg (k = 10,000) and 1.3 deg (k = 3900) of inclination, respectively. This is small in comparison with some of the other sources of dispersion, but in order to refine the precision as much as possible we will subtract it in subsequent discussion by normalizing the site directions to a common site locality at the summit of Mauna Loa (19.484° N., 204.395° E.).

Deformation of Lava Flows after Their Magnetization was Acquired

Doell and Cox (1963) believed a significant factor in between-core dispersion to be the rotation of lava blocks after cooling, but they had no way to isolate this effect from others. We have attempted to evaluate it by comparing the different degrees of dispersion observed in different kinds of lava flows. In very young flows like these the rotations should generally arise not from tectonism but from primary deformation of the flows as they solidify, their solid parts having been tilted and rotated after acquiring a remanent magnetization. Because different morphologic types of lava flows are deformed in different degrees and in different ways, their magnetic dispersions should also differ. Moreover, each kind of lava flow should display differences between its different parts, the last-cooled parts having less dispersion. We have therefore classified all of our sampling sites according to the flow type, etc., represented (Tables 1, 2; classification code given in Table 6).

Results from the various sampling situations are compared in Table 6. Despite our use of morphologic clues to minimize the effects of flow deformation, the results indicate that we were not able to eliminate them entirely, and the differences between different sampling

Table 6

Dispersion for Different Sampling Situations

Site type	Symbol	N	k_{site}	$k_{subsite}$	Ψ_{63} (deg)	Ψ_d (deg)	$\overline{SSM}$ (deg)
Interior of thin pahoehoe lobe	P1	4	2347	2113*	1.7	0	0.9
Surface of pahoehoe draped on face of a scarp	P2	1	171	249	6.2	6.0	7.2
Tube-fed pahoehoe, surface	PT1	27	1099	1315	2.4	1.7	1.3
Tube-fed pahoehoe, surface to shallow interior	PT2	13	866	1156	2.8	2.2	2.2
Tube-fed pahoehoe, shallow interior	PT3	10	813	1067	2.8	2.2	3.3
Tube-fed pahoehoe, deep interior	PT4	13	1355	1769	2.2	1.4	1.5
Tube-fed pahoehoe, near large lava tube	PT5	4	472	794	3.7	3.3	2.2
Surface-fed pahoehoe, surface	PS1	6	1411	1615	2.2	1.4	2.6
Surface-fed pahoehoe, shallow interior	PS2	3	730	1138	3.0	2.5	3.2
Surface-fed pahoehoe, deep interior	PS3	7	1641	1663	2.0	1.1	2.4
Surface-fed pahoehoe, channel	PS4	2	384	1108	4.1	3.7	5.1
Aa, channel walls or overflow	A1	4	881	1078	2.7	2.1	2.4
Aa, deep interior	A2	17	803	927	2.9	2.3	2.5
Aa, spines projecting into clinkers	A3	4	195	347	5.8	5.5	4.7
Aa, massive interior of undercut flow margin	A4	2	258	269	5.0	4.7	1.9
Vent edifice, poorly welded	V1	1	1075	944*	2.5	1.8	3.4
Vent edifice, highly welded	V2	4	553	1134	3.4	2.9	3.2
Crater wall, flow exposed in cross-section	CW	8	552	1147	3.4	2.9	4.3
Lightning-strike (erratic compass needle)	L	3	496	326*	3.6	3.2	5.2

N is the number of sites averaged in the group. k_{site} is the mean of the estimated precision parameters of the sites. $k_{subsite}$ is the mean of the estimated precision parameters of the subsites. Ψ_{63} is the mean of the estimated angular standard deviations of the sites. Ψ_d is the estimated dispersion due to deformations, obtained by subtracting 1.7 deg from Ψ_{63} according to equations (2) and (3). $\overline{SSM}$ is the mean of the separation-of-subsite-means for the sites, which are tabulated in Appendices A and B. Asterisks (*) indicate cases where $k_{site} > k_{subsite}$.

situations suggest the magnitude of dispersion arising from this source. The smallest dispersion, and presumably the least deformation, occurs in the interiors of thin (thickness < 1 m) pahoehoe lobes (Type P1). If there is little deformation at these sites and their dispersion arises strictly from experimental error and other small-scale variations, then their mean dispersion (Ψ_{63} = 1.7 deg) can be subtracted, according to equation (5) of Appendix C, from the means of other site types to yield an estimate of deformation dispersion for each type of site. The resulting estimates listed in Table 6 range from 0 to 6 deg, with 1.7 deg (k = 2270) being typical of the kinds of sites (P1, PT1, PT4, PS1, PS3) most desirable for sampling.

Some kinds of lava flows yield less dispersion than do others (Fig. 9; Table 6). (The different kinds of flows and their primary deformations are described further in Chapter III.) Pahoehoe flows have less dispersion than do aa flows. Aa flows commonly are thicker than pahoehoe flows and spread with less fluidity, apparently undergoing more deformation at low temperatures. The results suggest that only the very massive parts of their interiors should be sampled where exposed in cross-section. Apparently-rigid tabular spines projecting from the massive interior into the lower part of the clinkery zone display very large dispersions, probably due to deformation of the flow and to irregular reorientation of magnetized clinkers adjacent to the spines when they cooled. Surface-fed (Holcomb, 1976) pahoehoe flows have slightly smaller dispersion than do tube-fed (Swanson, 1973) pahoehoe flows. Tube-fed flows are commonly inflated by lava injected into their interiors, their surficial crusts being slowly broken and heaved at low temperatures. The deep interiors of both types generally give better results than their surfaces, though the surfaces can yield low dispersions when the sites are selected carefully. Interestingly, sites from shallow interiors display more dispersion than surficial sites. This probably arises from the limited areas available for sampling at these sites; they are from roadcuts where it is not possible to choose from as wide an area as is generally available on a flow surface. Where roadcuts are sampled, it appears advisable to sample as deeply within the flows as possible. It was found to be generally best to avoid lava channels and tubes, as well as lava draped over steep scarps. Highly welded pyroclastic vents have wide dispersions caused by vent anomalies. Sites on crumbly crater walls have relatively large dispersion that probably arises from detachment and rotation of the blocks comprising the crater walls. Lightning-struck sites too have large dispersion, probably because the effects of lightning were not entirely removed by cleaning.

The validity of these dispersion estimates depends upon the scale at which the deformations occur. The estimates describe dispersion within sites, but we would like to extrapolate them for use in analyzing the dispersion between sites. The validity of such extrapolation is supported by three kinds of evidence. First, in almost every kind of site, mean subsite precision is smaller than the mean site precision (Table 6), indicating that the dispersion within a site occurs over a length scale that is a large fraction of the site. Among the few cases where the subsite dispersion is larger is site type P1, where we infer deformation to be minimal. Second, the mean separation of subsite means is in most cases similar to the estimated deformation dispersion (Table 6), again indicating that the scale of deformations is large relative to the spacing of sampling sites. Third, for a few flows where more than one site was sampled, the between-site dispersions are similar to the subsite dispersions for the flows of different types (Fig. 9).

Total Error

The total error can be estimated by combining the various components according to equations (5) or (6) of Appendix C (Table 7). During the last 1000 years, for example, if we estimate, for the estimated precision parameters defined in Table 7, k_E = 6200, k_S = 2900, k_A = 730, k_M = 1370, and k_D = 2270, the total according to (6) is k_{T_o} = 330. This precision is equivalent by equation (4) of Appendix C to a total dispersion of 4.5 deg and is similar to the values for the interval 200 to 1500 years ago listed on Table 4. The components estimated can account for the total observed. Moreover, if the errors due to age uncertainties are removed, the total estimated dispersion is 2.95 deg, similar to the totals observed during the past 200 years.

The largest source of dispersion listed on Table 7 is the imprecision in ^{14}C dates, followed by local magnetic anomalies and lava-flow deformations. If the history of secular variation were well known and the rate of variation were 4 deg/century, a dispersion of 2.95 deg could yield a dating precision of about ±74 years, a value similar to the laboratory precision but better than the overall precision of ^{14}C dates. Paleomagnetic dating is thus potentially more precise than the method used to calibrate it. However, because the precision of secular variation depends upon the rate of variation, its precision

Table 7

Summary of Error Analysis

Description of error	Nature of estimate	Estimated dispersion: Quantity	Estimated dispersion: Value	Estimated precision: Quantity	Estimated precision: Value
Experimental errors (orientation, demagnetization, measurement)	Smallest within-site dispersions obtained	Ψ_E	1.0°	k_E	6200
Secular variation within averaging intervals	Rates of secular variation obtained from differences between 100-year and 500-year averaging intervals	Ψ_S	1.5° to 10°	k_S	2900 to 70
Imprecision in ^{14}C dates	Inferred from assumed age precision of 200 years and SV rate of 4 deg/century	Ψ_A	3° to 8°	k_A	730 to 100
Local anomalies in the geomagnetic field	Dispersion in the present field, from observations at 96 sampling sites	Ψ_M	2.2°	k_M	1370
Deformation of lava flows	Dispersions observed within sites for different kinds of lava flows	Ψ_D	0° to 6.0°	k_D	∞ to 180

is variable. With a dispersion of 2.95 deg the dating precisions corresponding to rates of 1 deg/century and 10 deg/century are ±300 years and ±30 years, respectively.

Reduction of Errors

The prospects are good for increasing the resolution of the method. This can be achieved by (1) reducing the dispersion unrelated to age uncertainties, (2) refining the history of secular variation, and (3) incorporating intensity of the ancient magnetic field into the program of measurements.

The angular dispersion can be reduced by reducing its separate components. Because the experimental errors are so small, the chief improvements must arise in regard to local magnetic anomalies and lava flow deformations. The latter errors can be reduced to some extent by even more careful choices of sampling sites, using the results of Table 6 as a guide. It should also be helpful to modify the sampling design so that the dispersion occurring over distances comparable to our site separations are reduced. It may be effective, for example, to use a multi-tiered sampling design in which the number of specimens per subsite is reduced and the number and spacing of subsites is increased, and to average the results with more sophisticated statistical methods such as the two-tier analysis of Watson and Irving (1957).

The history of secular variation can be refined through adding more ^{14}C dates, adding stratigraphic information to the record, and averaging the directions obtained from flows known to be of similar age. An initial attempt at such refinement is made in a following section of this report. Further refinement can come from the addition of information from other sources.

An additional improvement in resolution may be achieved by incorporating field intensity into the record of secular variation. We have not yet attempted an analysis of past field intensities because reliable laboratory experiments (Thellier and Thellier, 1959; Coe, 1967a, b; Coe and Grommé, 1973) consume much time, but there is reason to believe that intensity measurements could be very useful. From three specimens of the "Visitor Center" flow near Kilauea's present caldera (Fig. 6), Coe and others (1978) obtained from apparently high-quality measurements of the paleomagnetic field an intensity of 58,000±2900 γ, about 63 percent larger than the average value of 35,635±7 γ we obtained from 101 measurements of the present field. Coe and others (1978) assumed the age of that lava flow to be about 2500 years, in accordance with a ^{14}C date obtained nearby (W-201, Rubin and Suess, 1956). But contamination of the charcoal sample is now suspected (M. Rubin, oral commun., 1978), and much evidence now indicates that the date is far too old. The sampled flow lies within the boundary of Kilauea's ancient caldera and sits atop the section of caldera fill that is younger than 1000 years. The slope of its surface and the direction of its remanent magnetism indicate that it belongs to a group of flows (group 5 of Table 8) erupted from the Hale O Ai-laau vent (Fig. 6) at the east end of Kilauea Iki crater, and recent ^{14}C dates show that these flows are younger than 500 years. If the intensity determination is correct, the geomagnetic field in Hawaii has undergone a large change in intensity during just the past few centuries. If this change in intensity is typical, measurements of paleointensity should add a new dimension to the record of secular variation and considerably enhance its resolution as a tool for dating lava flows.

Lava Flows of Unknown Age

Because of the large dispersion obtained between sites of the same ^{14}C age it was not possible to date all of the flows of unknown age solely on the basis of their directions of remanent magnetization. It was necessary first to estimate preliminary dates using a semi-quantitative classification procedure, as discussed below. It was possible later to use stratigraphic relationships and averages from groups of flows to refine the history of secular variation, and then assign ages to the remaining flows, as discussed in Chapter V.

Initial Dating Procedure

Our preliminary dating procedure relies on the fact that flows of different age erupted during the last few thousand years tend to have different directions of remanent magnetism. First we plotted the directions of dated flows on an equal-area projection, omitting sites which were doubted (Table 3) or occurred in situations where dispersions were especially large and likely to yield imprecise results (Table 6). We found that the remaining sites of known age plot on different parts of the projection, so that the area enclosing all directions could be subdivided into fields that were almost mutually exclusive in age (Fig. 15a). We then plotted directions of unknown flows on the projection and assigned them preliminary ages according to the fields in which they fell. Because dated flows older than about 3000 years have directions similar to more recent ones, we could not use this procedure for the entire 6000-year interval encompassed by the dated flows. Instead, we considered only the last 2000 years, an interval in which magnetic directions seem to correspond to unique ages and in which most of Kilauea's surficial flows were judged (from ^{14}C determinations) to have originated. Within this 2000-year interval we assigned preliminary ages to the undated flows according to their directions of remanent magnetization.

Results

Magnetic directions for surficial lava flows of unknown age on Kilauea are shown on Figure 15b. Most of these directions fall within fields corresponding to ages of 250 to 1000 years; we assigned them preliminary ages accordingly. In some cases, however, stratigraphic evidence contradicted the magnetic directions, and we used it to overrule the directions. Examples are discussed in a later section of this report.

For comparison with our results, the directions of lava flows from the Puna series type section of Kilauea's caldera (Doell and Cox, 1965, and unpublished) and the Kau series type section of Mauna Loa's caldera (Doell, 1969) are shown in Figure 15c and 15d, respectively. The flows of the Puna series type section are similar in age to the surface flows of Kilauea despite their occurrence in a very thick stratigraphic section. This is consistent with the interpretation that they comprise a young sequence of rapidly accumulated caldera fill (Holcomb, unpubl. ms.). The flows of the Kau series type section

Fig. 15--Diagrams showing the semiquantitative method used to infer the ages of lava flows. All diagrams show declinations and inclinations plotted on equal-area projections.

(a) System of age classification based on dated flows of the last 2000 years. Symbols represent different ages: circles, younger than 250 years B.P.; triangles, 250 to 500 years B.P.; squares, 500 to 1000 years B.P.; hexagons, 1000 to 1500 years B.P.; and crosses, 1500 to 2000 years B.P. Open symbols are sites we doubt for reasons given in Table 3. The elliptical area including all values is divided into fields containing sites of similar age, with the smaller ellipse representing an area of confusion in which sites of diverse ages are clustered together. The arrows connecting consecutive fields are inferred to approximate the history of secular variation during this interval.

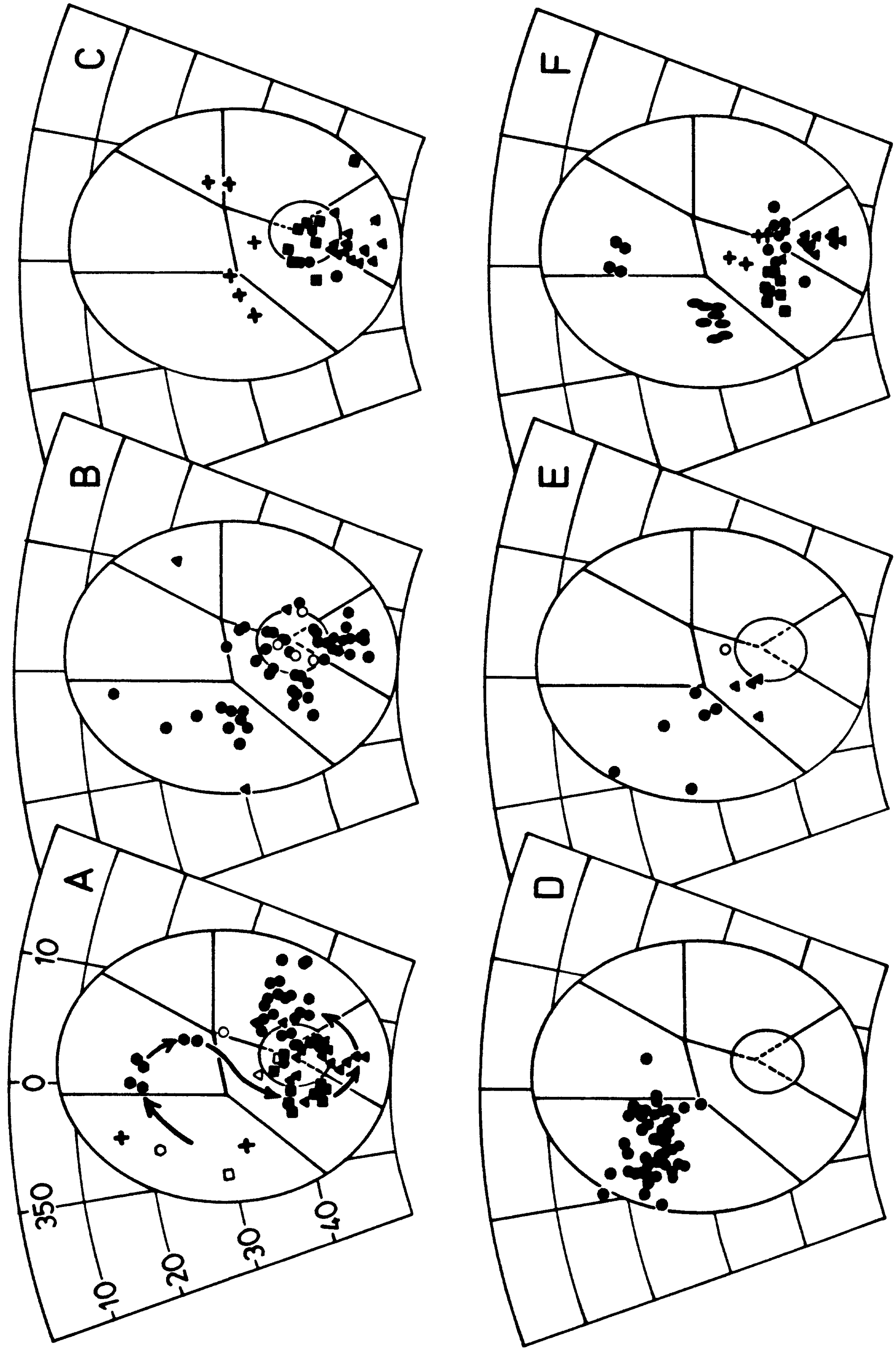
(b) Site mean directions for undated surficial lava flows of Kilauea. Circles and triangles represent pahoehoe and aa, respectively. Open symbols denote values we doubt for reasons listed in Table 3.

(c) Puna series type section, in Uwekahuna bluff of Kilauea caldera (data of Doell and Cox, 1965; Doell, unpubl.). Symbols represent sites in different parts of the section: crosses, below Uwekahuna Ash (nos. 131-133, 137C-137E); squares, lower section above hiatus above Uwekahuna Ash (nos. 134-137B, 137F-137H); triangles, middle part of section included in group 6 of Table 10; circles, upper part of section included in group 4 of Table 10.

(d) Kau series type section, in western wall of Mokuaweoweo, the caldera of Mauna Loa (data of Doell, 1969).

(e) Buried lava flows of Kilauea, exposed in the walls of the caldera and pit craters. Symbols indicate stratigraphic position: circles, below the hiatus, triangles, above the hiatus. The open circle indicates the anomalous direction of magnetization found below the hiatus in Makaopuhi crater.

(f) Some groups of surface flows thought from independent evidence to be closely similar in age. Symbols correspond to different groups listed on Table 10: circles, group 4; triangles, group 5; squares, groups 7A and 7B; crosses, group 8A; hexagons, group 10; ellipses, group 12.


A
B
C
D
E
F
10
0
350
10
20
30
40

are distinctly older, their directions corresponding to ages of approximately 1500 to 2000 years.

We also sampled a few buried lava flows in order to date an apparent hiatus in the growth of Kilauea. Flows were sampled in the walls of Kilauea caldera and the pit craters of the upper east rift zone named Kilauea Iki, Pauahi, and Makaopuhi (Fig. 15e). In each stratigraphic section is an horizon that apparently represents a significant interruption in the accumulation of lava flows. In the caldera this horizon occurs at the top of a weathered ash layer correlated with an ash layer elsewhere on which large Koa trees grew before it was covered by lava (Powers, 1948). In Kilauea Iki it lies below a layer of cinders thought to represent early fountains in a long sustained eruption that built the Hale O Ai-laau lava shield centered on the eastern end of the crater (Fig. 6). In both Pauahi and Makaopuhi it lies above a weathered fragmental layer on which a forest grew, so that tree molds were produced when the area was flooded by lava. In each case we sampled the adjacent lava flows below and above the horizon.

The results indicate that the hiatus is roughly contemporaneous at all four sites (Fig. 15e). The flows above the hiatus are all of similar age, in each case being somewhat less than 1000 years old. The flows below the horizon are of similar age in three cases out of four, being somewhat older than 1500 years. The flow below the hiatus in Makaopuhi is an exception, its magnetic direction plotting in a position corresponding to an age of about 1000 years. If that age is correct it requires a relatively brief hiatus and rapid forest growth at Makaopuhi. However, because no stratigraphic evidence bounds its age, the lava flow may be older than 2000 years, beyond the range of age in the scheme of Figure 15a. Alternatively, it is possible that the flow was thermally remagnetized as the thick pile of Kane Nui O Hamo lava shield accumulated rapidly and cooled slowly above it. With this possible exception, the hiatus is correlative at all sites and apparently spans more than 500 years from more than 1500 to less than 1000 years ago. More data will be needed to define its duration with certainty. This hiatus may correspond to the partial filling of the ancient caldera inside of which Kilauea's present caldera is nested.

Our data and interpretation can be checked crudely for consistency with other evidence by estimating the mean eruption rate they require during the 1500 years since the ancient caldera is inferred to have formed. We can estimate separately the volume of caldera fill and the volume of the subaerial carapace postdating the hiatus. If the present caldera is approximated by a cylinder 3.5 km in diameter and 150 m deep, its volume is 1.5 km^3. The ancient caldera has a rim diameter of 7.0 km, and if its depth/diameter ratio was similar to that of the present caldera before it began to fill, its volume was 30.8 km^3. The net volume of caldera fill with the present caldera subtracted is 29.4 km^3. The subaerial surface area of Kilauea is about 1500 km^2. If we approximate the subaerial part of the volcano with a right circular cone 1300 m high, it would have a basal radius of about 21.8 km at sea level. The hiatus horizon occurs at a depth within the pit craters that suggests it has been buried under about 50 m of lava in summit areas outside of the caldera. If we assume the carapace thins to zero at sea level, then its volume is 24.9 km^3.

The volume of carapace and the remaining caldera fill together is 54.9 km^3, or 46.1 km^3 if we subtract 15 percent for vesicularity. The latter volume requires a mean eruption rate for the past 1500 years of $2.6 \times 10^6\ m^3$/mo. This estimate is very crude because of several simplifying assumptions, but it is in rough agreement with estimates obtained previously for short intervals in the historic period ($2.5 \times 10^6\ m^3$/mo) by Stearns and Macdonald (1946); $3.6 \times 10^6\ m^3$/mo by Moore (1970). It is lower by a factor of three than Swanson's (1972) best estimate of $9 \times 10^6\ m^3$/mo and the rate required to explain Moore's (1970) subsidence rate for Hawaii, but this discrepancy may be due to additional volumes of lava intruded and stored underground or erupted unseen beneath sea level (Swanson, 1972). The essential point is that our data do not require an eruption rate higher than those obtained from other kinds of evidence, and our ages are therefore not unreasonable.

CHAPTER III

INTERPRETATION OF LAVA-FLOW MORPHOLOGY

The relationships between lava-flow morphology and eruptive behavior exploited in this research were generalized initially from observations of active eruptions and lava flows. From these observations it appeared that the differences between certain kinds of pahoehoe flows are especially significant for the interpretation of eruptive behavior (Swanson, 1973), and that certain slow-acting processes contribute importantly to pahoehoe morphology and thereby provide the means for distinguishing the flows that are active over different lengths of time. Duration and stability of eruption can therefore be inferred from the morphology of lava flows. These initial generalizations were checked and elaborated by means of systematic mapping of flow assemblages from eruptions of different types. This mapping demonstrated that each eruption produces an assemblage of different kinds of lava flows, and different kinds of eruptions produce different kinds of assemblages. The assemblages can be used to infer the behavior of the eruptions that produced them.

Observations of Processes and Their Products

My observations of active processes were made at Kilauea during the interval 1971 to 1975. This was a time of considerable and especially varied activity that included the second part of the sustained Mauna Ulu eruption and several brief eruptions from the summit and rift zones of Kilauea, as well as one eruption from the summit and upper northeast rift zone of Mauna Loa. The following generalized descriptions of lava flows and eruptions are synthesized from those observations and others recorded previously in the published literature.

Lava Flows

The morphology of a lava flow is influenced by many factors. Of these the most commonly discussed are the composition of the lava and its physical properties such as temperature and viscosity. But other factors are important too. Some of these are conditions of the environment into which the lava is introduced, such as the ground slope and the degree of topographic confinement of the lava flow. Others pertain to the way lava is brought to the surface--by the behavior of eruptions. Examples of behavioral factors are the rate, duration, and stability of effusion from the vent. The work reported here has been focused especially upon the duration and stability of eruptions. These factors can influence lava-flow morphology especially through the tendency for flowing lava to become more highly channelized with time. The degree of channelization determines how molten lava is delivered to the expanding front and surface of the flow, and this has a great effect on resulting flow morphology. These relationships can be illustrated by considering what may happen during the advance of a typical flow, showing how it changes in flow mechanics and morphology as it develops and continues to spread.

Initially a hot, highly fluid basalt flow emanating from a vent tends to move as a single broad sheet, spreading out thinly and uniformly (Fig. 16a), unless it is restricted to a pre-existing channel. If effusion ceases at this stage, the flow stops spreading and freezes near the vent, characteristically as a thin sheet whose surface is festooned with ropes or other wrinkles (Fig. 16b). If the wrinkled crust founders as spreading ceases, it is replaced by new crust that remains undeformed and comprises flat patches on the surface (Figs. 16c, 18a). A gas-rich flow may deflate as it chills and assume a shelly character as pieces of its crust sag onto one another (Fig. 16d; Swanson, 1973).

If the feeding is maintained past the initial stage of a few hours or less, various things can happen to the lava flow. It may be confined and ponded by the pre-existing topography, or it may become "self-ponded" behind its own spreading fronts or internal levees. Or it may continue to spread, in which case it may undergo a transition to aa or become highly channelized and develop lava tubes. Though the various ponding processes are important in some contexts, they have comparatively little significance here and will not be mentioned further. Of principal interest here are the lava flows that continue to spread away from the vent.

If the flow continues to be fed and does not become confined, it spreads farther and gradually cools, slows, and thickens, eventually undergoing a transition to aa (Fig. 17; Peterson and Tilling, 1980). During all of this time the body of the flow consists of a single molten mass in motion, and the physical processes throughout display little variation. The velocity of an infinitesimal parcel, or element, of lava is at this stage a relatively simple function of its position within the moving body.

Fig. 16--Surface-fed pahoehoe flows near their vents.

(a) Sheet of fluid pahoehoe spreading rapidly away from the Mauna Ulu vent, April 1970. The flow front is about 1 dm thick after extending less than 100 m from the base of the fountain. Pliable surficial crust is readily wrinkled and contorted after tearing by the molten lava breaking out from beneath it. Photograph by D. A. Swanson.

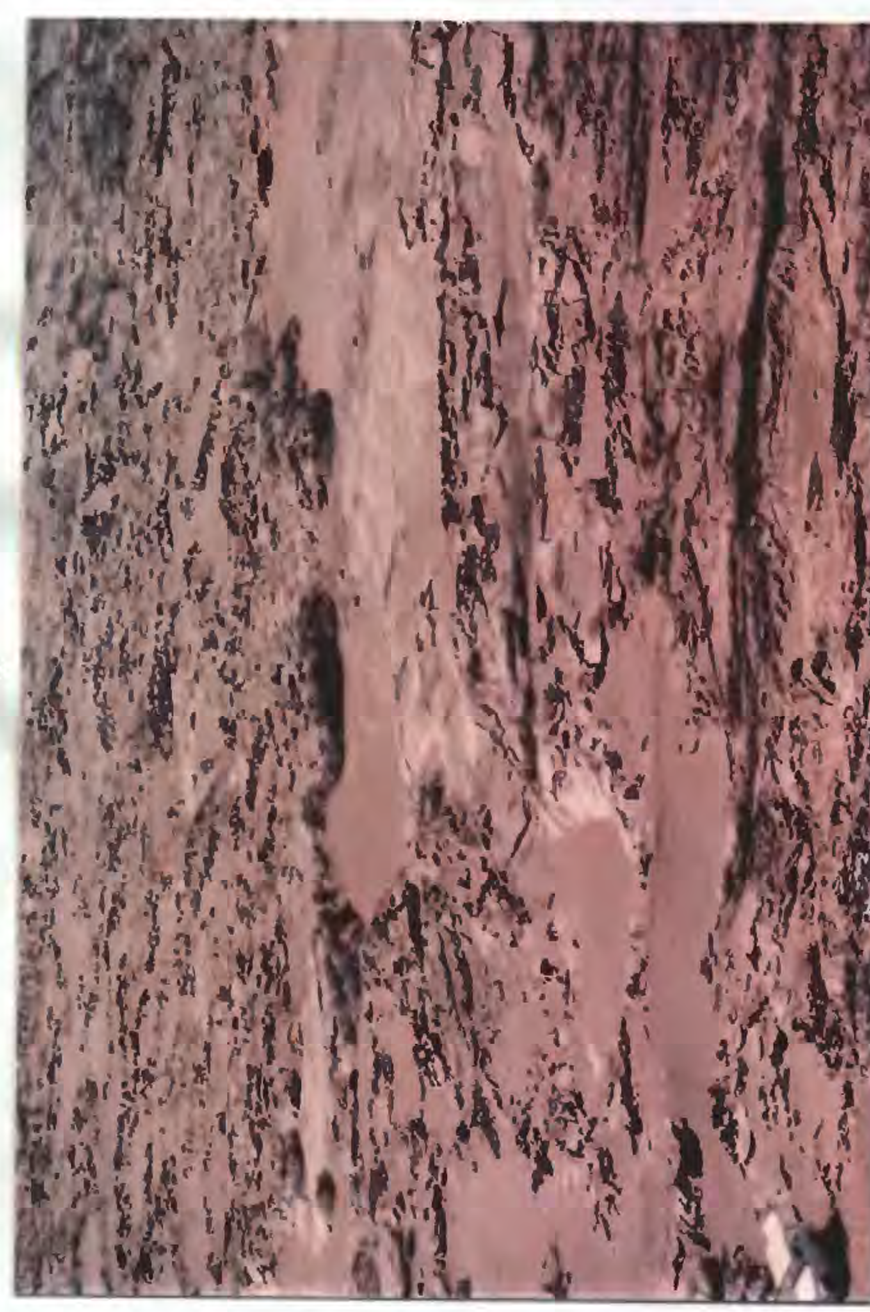
(b) Oblique aerial view of a thin sheet of surface-fed pahoehoe from the September 1971 eruption draped over prehistoric tube-fed pahoehoe, upper southwest rift of Kilauea between Cone Peak and Mauna Iki. The main lobe is a few dekameters wide and has spread less than 100 m, the eruptive vent being just out of view at the top. The flow is deflated, and its festooned crust has subsided onto the older surface. Photograph by R. T. Holcomb.

(c) Expanse of prehistoric surface-fed lava of Puu Koae, viewed from a spatter cone of the vent edifice. Flat areas are places where incipient ponding occurred and the original surface crust foundered into the underlying lava. The flow field is thinly veneered by a discontinuous layer of sand derived from the Keanakakoi Ash deposits of 1790. Photograph by R. T. Holcomb.

(d) Flow front of the August 1971 lava in Kilauea caldera. Flow is similar to those of Figures 16a and 16b, but shows close up the effects of deflation. Photograph by L. R. Kanter.

a

b



c

d

Fig. 17--Progressive thickening of flows with increasing distance from their vents. The lava of Figure 16a can be taken as an end-member for comparison. Some aa flows at Kilauea attain thicknesses much greater than any shown here.

(a) Surface-fed pahoehoe lava that has moved a few hundred meters from its vent, September 1971 eruption, southwest of Mauna Iki. Flow is advancing rapidly as small tongues that reach thicknesses of more than a meter a few meters behind their fronts. Photo by D. W. Peterson.

(b) Platy, slowly advancing front of pahoehoe flow about 1 km from the Mauna Ulu vent, January 1974. Rigid plates of wrinkled crust are tilted en masse as the movement of the pasty lava breaks and jostles them. Photo by R. W. Madden, National Geographic.

(c) Front of a thin aa flow on the south flank of Kilauea a few kilometers from its Mauna Ulu vent. Bob Tilling is using a long spatula to collect an air-quenched lava sample. Photo by R. L. Christiansen.

(d) Front of aa flow advancing through trees at the base of Holei Pali, several kilometers south of the vent at Mauna Ulu, February 1971. Photo by D. W. Peterson.

a

b

c

d

As time goes on and effusion continues, however, the flow begins to channelize as parts of it stagnate and cease to move, concentrating the flowage at first into broad bands, then narrow streams, and finally confined channels (Fig. 18). This progressive channelization seems to arise from a tendency for flow rates in adjacent parts of the flow to diverge from each other. This divergence may occur because less heat is delivered to the slower moving parts of the flow, permitting them to chill more quickly and stagnate while the faster moving parts conduct more heat, maintain high fluidity, and carry more and more of the molten lava. If so, uniform sheet flow is an unstable condition, and progressive channelization is an inevitable product of time and any initial inhomogeneities in the flow. As a result of this flowage concentration, one channel or a few anastomosing channels may develop and efficiently transport large amounts of lava to a single advancing lobe, commonly a thickened aa flow (Fig. 18d). Alternatively, a distributary pattern of channels may develop that delivers small volumes of lava to several lobes spreading separately over a broader front (Fig. 19).

Once well-developed channels have formed, they begin to roof over as lava accretes to the solidifying edges of the stream surface (Figs. 20a, b; Peterson and Swanson, 1974; Holcomb and others, 1974). The roofs thicken, and the channels gradually evolve into lava tubes (Figs. 20c, d). The flow that earlier was dynamic in the motion of its surface is now encased in a crust strong enough and cool enough to be walked upon, and it may appear solid and immobile except where views are had into the lava tubes (Fig. 21). But this apparent immobility is deceptive; the flow is still hot and fluid beneath

Fig. 18--Aerial views showing incipient channelization of short-lived lava flows.

(a) Broad lobe of lava from the eruption of September 1971, just outside Kilauea's present caldera. This flow was active for less than an hour and advanced only about 200 m, developing no significant degree of channelization except for splitting into two broad lobes. At the height of eruption the flow was ponded behind its front, with a meniscuslike profile, and its surface crust foundered and reformed a smooth secondary surface. The secondary crust was then split into large flat plates as spreading continued, and viscous lava oozing into the separations between plates produced the prominent dark bands on the final surface of the flow. Photo by D. W. Peterson.

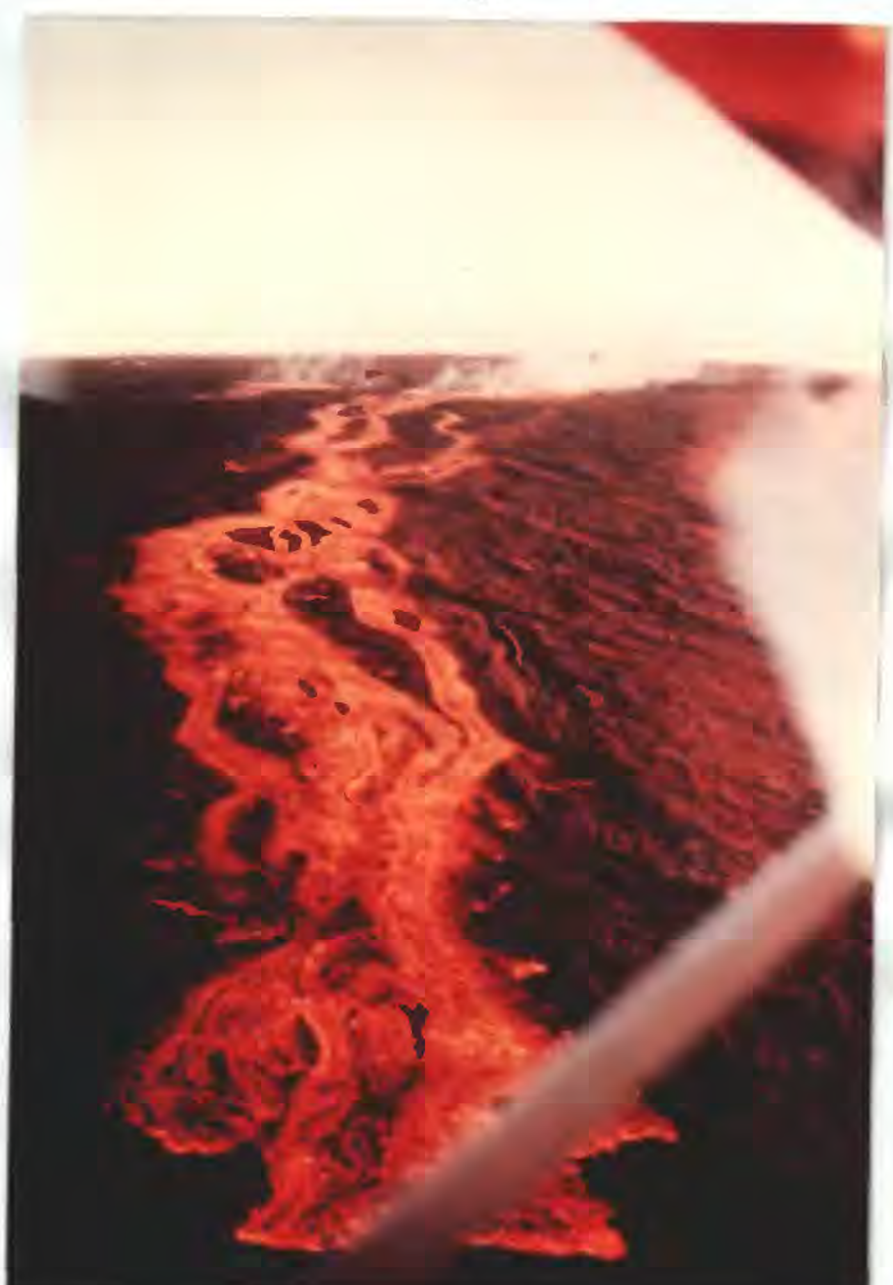
(b) Looking up Kilauea's southwest rift zone at an active pahoehoe flow of the September 1971 eruption near Mauna Iki. Within a short time the flow has extended about 1 km from its vent and is still spreading actively in all of its parts. Though a distinct channel has not developed, the flow has become highly elongate, and small lobes are branching away from it. Photo by D. W. Peterson.

(c) Aa flows extending down the northeast flank of Mauna Loa from the vicinity of Pohaku Hanalei, July 1975. Flow has become channelized into streams that are feeding separate adjacent lobes following subparallel courses down the slope. Photo by D. W. Peterson.

(d) Aa flows of the 1881 eruption, on the southeast flank of Mauna Loa. The larger flow on the right contains an axial channel several kilometers above its terminus, the channel having transported lava long after the bordering lava outside the channel had ceased movement. Smaller flow on the left does not possess a distinct channel, though marginal levees can be seen a few hundred meters above its terminus. Photo by R. T. Holcomb.

a

b



c

d

Fig. 19--Channelization of a surface-fed pahoehoe flow. Time exposure at night, showing the incipient channelization of a flow on the north flank of Mauna Ulu, January 1974. Lengths of light traces indicate relative flow rates throughout the flow. The flow is most highly channelized near its origin, where flowage has continued for the longest time. Lateral lobes higher on the slope are stagnating, while lobes at lower elevations are still developing. Each main stream is defined by two bright bands, developed at the locations of maximum shear near its margins. Between these bright bands the surface is less sheared, and surficial cooling permits the development of a surface skin that is only slightly incandescent. Photo by R. T. Holcomb.

Fig. 20--Development of lava tubes.

(a) Thin crust growing on the surface of a lava stream near Mauna Ulu, 1972. The stream is a few meters wide, and flow is from left to right. The crust grows by accretion along its leading edge where lava emerges from beneath and loses insulation. The stream is also bordered by incipient levees composed of thin tongues that overflowed the stream margin during surges. Photo by R. I. Tilling.

(b) Stream confined by levees about 1 m high, near Mauna Ulu, 1972. The levees form from overflow during periodic surges. The levee tops tend to converge inward as they grow higher, forming an arch over the stream that can develop into a lava tube. Bob Tilling is using a long-handled dipper to collect a lava sample. Photo by D. W. Peterson.

(c) Lava stream in a partially roofed channel on the eastern flank of Mauna Ulu, 1970. The stream surface has risen and fallen repeatedly, leaving records of its past levels along its banks. In the foreground is a levee similar to that of Figure 20b, while on the opposite bank are drainback features and terraces representing former levels of the stream surface. Shelves projecting across the present surface have formed by accretion more recently, and if the stream surface remains stable they may grow completely across it to form a tube. Photo by D. W. Peterson.

(d) Skylight in the thickened roof of a well-developed lava tube, southeast of Mauna Ulu, 1972. Thickening is accomplished by accretion to the roof and by overflows. Lava in the foreground displays surficial ropes and drapery produced by drainback at the end of an overflow episode. Photo by R. T. Holcomb.

a

b

c

d

Fig. 21--A tube-fed flow field east of Mauna Ulu, 1973. The stream visible through the skylight is feeding flow fronts that are actively spreading a few dilometers away, while the flow visible here around the upper reaches of the stream has stagnated. Small "toes" of pahoehoe continue to ooze from between flow units over broad expanses of the stagnant flow, however. Don Peterson is using a stainless teel rod to plumb the depth of the lava stream. Photo by R. I. Tilling.

the crust, and molten lava breaks out and flows from many places on its surface and along its front (Fig. 22a). The crust insulates the lava so that it can travel far from the vent and still arrive at the flow front with nearly the same temperature as when it was erupted.

Development of a system of distributary lava tubes induces a change in the spreading mechanism of the flow. The continuous front of the early sheet flow becomes divided into many discrete units that spread separately, and the flow becomes more lobate. If the rate of effusion from the vent remains constant--or gradually declines, which is commonly the case--the rate of delivery to any element of the front must decrease as the front expands, and the spreading rates of the individual lobes should diminish. The lobe fronts now have more time to chill, and their skins become thicker and more difficult to break. When breaks do occur, they are comparatively small, and the lava issuing from them produces small buds or flow units (Fig. 22b) that pile onto one another in clusters of flattened globules. This budding or flow-unit process begins to dominate the mechanism of advance (Nichols, 1936), and the distributary lava tubes lengthen and bifurcate through the cumulative effects of successive buddings (Macdonald, 1953; Wentworth and Macdonald, 1953; Peterson and Swanson, 1974). The flow now is highly channelized.

The progressive channelization of flow through time produces changes in the morphology of the flow. What was initially a comparatively featureless or wrinkled single sheet becomes a hummocky mass of flow units piled upon one another (Fig. 22c). These flow units may vary widely in their shapes, depending partly upon the slope on which they spread. On gentle slopes they may assume the roughly

Fig. 22--Flow units in tube-fed pahoehoe.

(a) Small stream of lava issuing from a pile of flow units near Mauna Ulu, 1972. Don Peterson has used a rock pick to collect an air-quenched lava sample. Photo by R. L. Christiansen.

(b) Lava "toe" about 0.5 m wide oozing from between slightly older flow units near Mauna Ulu, 1974. Photo by R. T. Holcomb.

(c) Mauna Ulu lava flow exposed in cross-section by a road-cut. The character of the flow changes upward from early aa to pahoehoe that subsequently spread across the aa. The pahoehoe possesses the characteristic layered structure of tube-fed lava, and typical flow units can be seen on the surface at upper left. Sue Karl is sitting in a small, terraced lava tube. Photo by L. R. Kanter.

(d) Mauna Ulu lava flows draped over Holei Pali on the south flank of Kilauea. Tube-fed pahoehoe has spread across slightly older aa, and on this steep slope the pahoehoe flow units are highly elongated. Photo by S. M. Karl.

a

b

c

d

equant shapes of thick pancakes (Fig. 22a), while on steep slopes they may be highly elongate (Fig. 22d).

As spreading continues, the body of the flow is inflated and thickened by liquid lava injected into its still-hot interior behind the slowly advancing front (Fig. 23). A flow that was initially less than 1 m thick just behind its front may thicken to 10 m or more because of this process. The degree of inflation generally increases with distance from the eruptive vent and is apparently caused by increased resistance to spreading as the distributary lava tubes become smaller and the rate of spreading slackens, permitting thicker crusts to develop around and in front of the distributaries. In addition to the overall thickening of the flow, this inflation produces characteristic landforms--such as tumuli, pressure plateaus, pressure ridges, and residual depressions above frozen, uninflated parts of the flow (Fig. 23d).

The various processes and their effects described in the paragraphs above are summarized on Figure 24. It is evident from this summary that many of the major features of lava flows result primarily from external conditions of their environment, such as the pre-existing topography or certain characteristics of their eruptions. Especially pertinent to this research are the features of pahoehoe flows resulting from channelization. Channelization is of interest because of the time required for it to develop. Sustained feeding of weeks or months is needed for highly developed distributary lava-tube systems to evolve, and this requires a degree of longevity and stability not attained in all eruptions. Any morphologic evidence of a high degree of channelization in a lava flow therefore imposes constraints on the

Fig. 23--Inflation of tube-fed pahoehoe.

(a) Aerial view of 1973 Mauna Ulu pahoehoe spread across similar prehistoric pahoehoe west of Apua Point. Inflation of the flow behind its fronts has produced a gently rolling topography of very broad low swells upon which the pattern of smaller original flow units is superimposed. Photo by R. T. Holcomb.

(b) Tube-fed pahoehoe of Mauna Ulu on the south flank of Kilauea near the site of Kealakomo. Inflation of the flow has caused its surface to buckle upward in many places, producing low whale-backed swells traversed by wide but shallow axial cracks. Lava oozing from these cracks has flowed around the bases of the swells and covered low spots in the warped surface of the inflated flow. Photo by D. W. Peterson.

(c) Tube-fed pahoehoe of Mauna Ulu along Kilauea's south coast. Some of the lava flowed into a walled enclosure and was then inflated by additional lava injected beneath the slowly thickening crust. Broken hummocks in the foreground also resulted from inflation, while ropes and toes reflect the original structure of the spreading flow front. Photo by R. T. Holcomb.

(d) Residual inflation pit in the surface of a tube-fed pahoehoe flow from Mauna Ulu, on the floor of Makaopuhi mezzanine. The site is near the south wall of Makaopuhi pit crater, where a large boulder had fallen onto the mezzanine. A small tree had grown from the top of the boulder. When the initially thin pahoehoe flow flooded the area it chilled against the boulder, and where it was chilled it could not inflate. Inflation of the rest of the flow caused it to thicken about 4 m, leaving the boulder in the center of a depression. The walls of the pit have an accordionlike structure that developed at the site of greatest differential expansion. Photo by R. T. Holcomb.

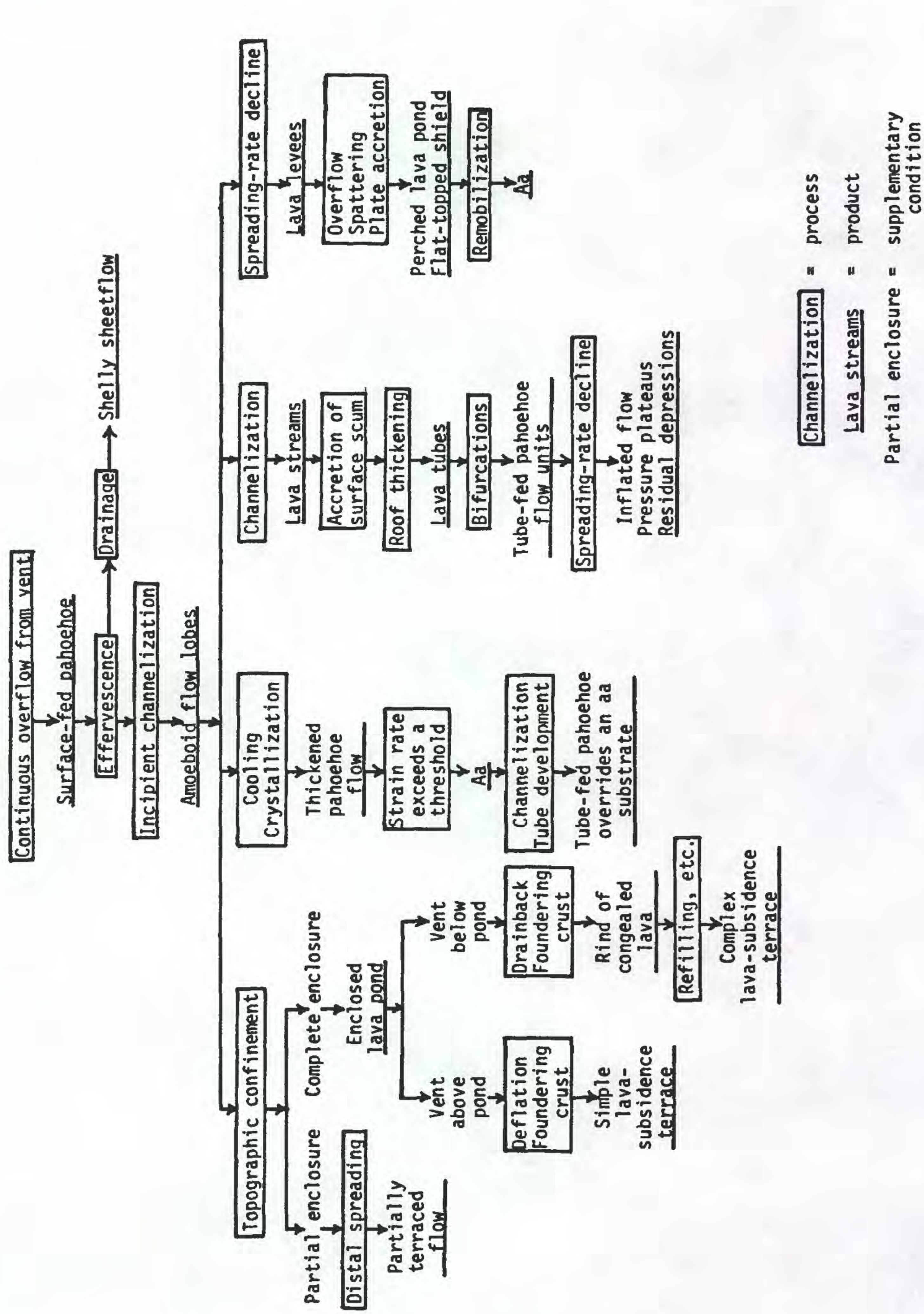
a

b

c

d

Fig. 24--Some lava-flow scenarios. Summarized here are some of the processes and environmental factors that can affect the morphology of basaltic lava flows. In order to make inferences from flow morphology about eruptive behavior it is necessary to distinguish between landforms resulting mainly from topographic accidents and those resulting mainly from the character of an eruption. Not all of the branches shown in this flow chart have proved useful in making interpretations of eruptive behavior.



Continuous overflow from vent
Surface-fed pahoehoe
Effervescence
Drainage
Shelly sheetflow
Incipient channelization
Amoeboid flow lobes
Topographic confinement
Partial enclosure
Distal spreading
Partially terraced flow
Complete enclosure
Enclosed lava pond
Vent above pond
Deflation Foundering crust
Simple lava-subsidence terrace
Vent below pond
Drainback Foundering crust
Rind of congealed lava
Refilling, etc.
Complex lava-subsidence terrace
Cooling Crystallization
Thickened pahoehoe flow
Strain rate exceeds a threshold
Aa
Channelization Tube development
Tube-fed pahoehoe overrides an aa substrate
Channelization
Lava streams
Accretion of surface scum
Roof thickening
Lava tubes
Bifurcations
Tube-fed pahoehoe flow units
Spreading-rate decline
Inflated flow
Pressure plateaus
Residual depressions
Spreading-rate decline
Lava levees
Overflow Spattering Plate accretion
Perched lava pond
Flat-topped shield
Remobilization
Aa
Channelization = process
Lava streams = product
Partial enclosure = supplementary condition

inferred character of its eruption. In order to interpret pahoehoe flows in this way it is convenient to classify them so that their differences in lava delivery are emphasized. For example, we can distinguish surface-fed pahoehoe (fed by an unchannelized sheet flow or by open channels) from tube-fed pahoehoe which, though the types are intergradational, differ enough morphologically to permit distinct spreading mechanisms to be inferred (Swanson, 1973; Holcomb, 1976). While surface-fed flows are relatively short-lived or result from widely fluctuating rates of lava supply, tube-fed flows reflect fairly constant supplies for at least a few days (Peterson and Swanson, 1974).

This view of pahoehoe flows regards their significant differences in morphology as arising from variations in flow regime and delivery pattern and ignores the effects of composition and intrinsic physical properties of the lava. It does not deny the influence of such properties--viscosity, for example, is an important control of flow regime, and chemical composition can affect viscosity and thus the mechanics and morphology of the flow--but it focuses more directly upon the relationships between flow morphology and the eruptive processes that give rise to it. Such an approach makes it possible to infer some characteristics of the eruption directly from the flow morphology.

Eruptions

Though all of the eruptions observed in 1971 through 1975, and most described previously during the historic interval of Kilauea, would be grouped together in the "Hawaiian type" of Macdonald's (1972) classification, they actually displayed considerable variation.

Different eruptions differed from each other, and single eruptions varied during their successive intervals. Most eruptions, however, were roughly similar to each other at any particular time after the onset of activity. That is, sustained eruptions in their early stages were similar to brief eruptions; their chief differences appeared later, at times after onset when the brief eruptions would have already ceased. Duration therefore is a key variable distinguishing the different kinds of eruption. Stability is also important because it seems to increase with the duration of eruption; it appears to be a function primarily of effervescence, which decreases during an eruption because the gas-rich lava is erupted first.

The simplest eruptions--which we can designate as type A--last only a few hours to a few days. Examples are the eruptions of August and October 1968 (Jackson and others, 1975) and February 1969 (Swanson and others, 1976) from Kilauea's east rift zone. Beginning from en echelon fissures a few hundred meters to several kilometers long (Fig. 25a), they build rapidly to a voluminous peak effusion rate (Fig. 25b) and then decline more slowly. These eruptions produce surface-fed pahoehoe that is ponded or undergoes transitions to aa if the flows extend a few kilometers from the vents. Commonly just one long flow, consisting of aa at its distal end, is produced by one of these eruptions. Long fissure vents are generally left open when the eruptions cease (Figs. 25c, d), and vent edifices are generally absent or small or consist chiefly of tephra.

Eruptions that are sustained for several days to a few months we can call type B. Examples are the Kilauea Iki eruption of 1959 and Kapoho eruption of 1960 (Richter and others, 1970) and the

Fig. 25--Type A eruptions and their products.

(a) Initial phase of an eruption from en echelon fissures in rain forest along the upper east rift zone of Kilauea, 1968. Sometimes just fume and minor amount of spatter is erupted, but the fume is commonly followed by lava after only a short interval. Photo by D. A. Swanson.

(b) Oblique aerial view of the August 1971 eruption in Kilauea caldera. Fountains a few dekameters high are playing from en echelon fissures and feeding a large river of lava flowing out of view in the upper left corner. Lava of this eruption formed a shallow pond along the eastern margin of the caldera, and a chain of spatter ramparts and solfataras developed along the fissures. Photo by W. A. Duffield.

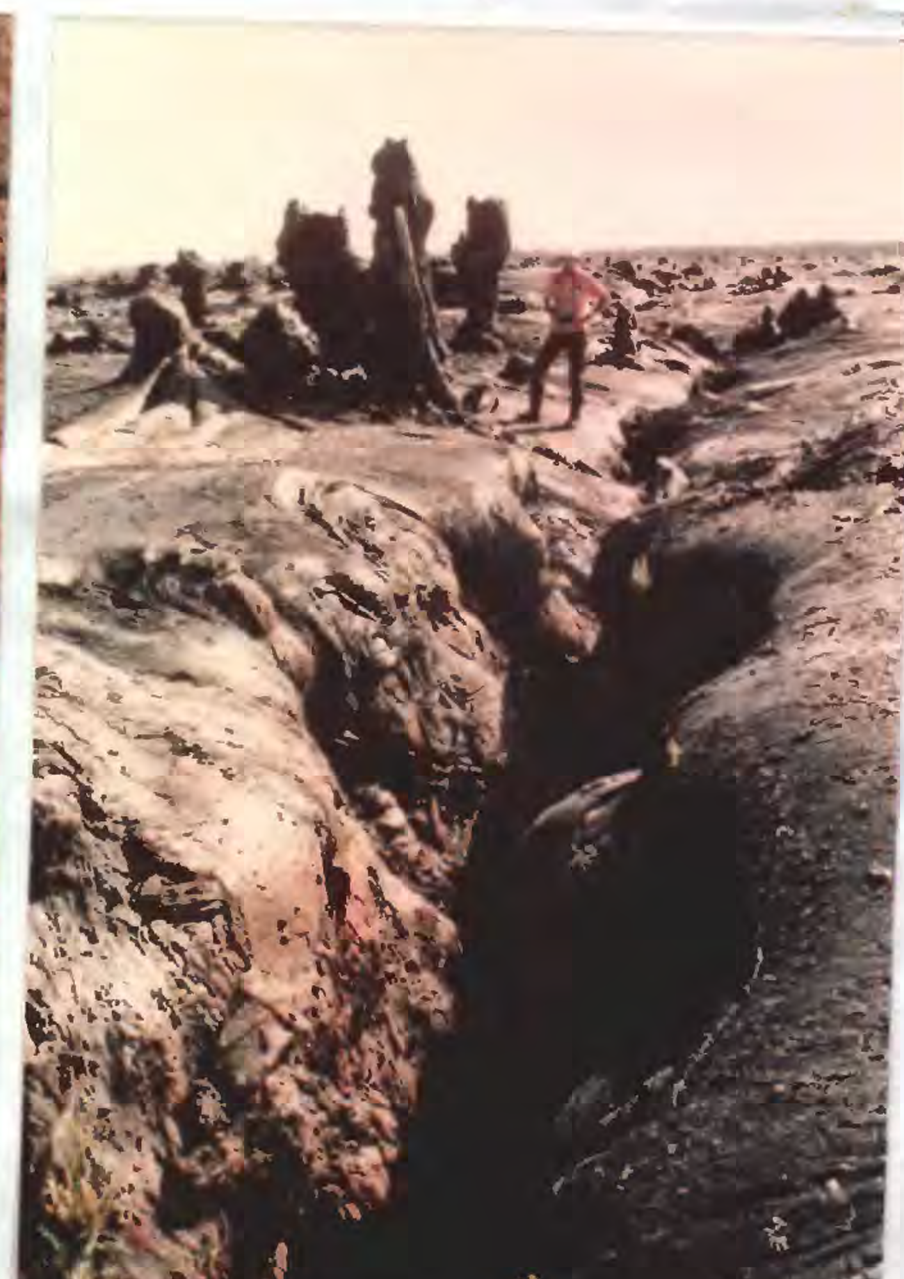
(c) High-oblique aerial view of the products of the September 1971 eruption between Cone Peak and Mauna Iki, looking downrift. The eruptive fissure gapes open, and the shelly lava along the fissure is littered with spatter ejected during the final stages of eruption. Photo by R. T. Holcomb.

(d) Eruptive fissure of November 1973, east of Pauahi. Dee Trent is standing beside tree molds that indicate the depth of lava at the height of the eruption, while the subsided flow surface displays drainback features. Photo by R. T. Holcomb.


a


b


c


d

Halemaumau eruption of 1967-68 (Kinoshita and others, 1969). These differ from the shorter eruptions in a few significant ways. First, the site of effusion becomes confined to a short segment of the initial eruptive fissure, which widens and evolves into a central vent. Second, the activity at this vent commonly becomes much more vigorous than that which preceded it, with a fountain hundreds of meters high playing above the vent (Fig. 26a). Third, changes in effusion rate may be more complex than a simple waxing and waning, with the eruption undergoing a series of vigorous eruptive phases alternating with intervals of quiescence (Figs. 26c, d). Eruptions of this type produce lava flows similar to those of type A, but because of their longer durations and multiple eruptive pulses they commonly produce greater numbers of distinct flows, and more flows are likely to undergo the transition to aa. These eruptions characteristically produce large mounds and sheets of pyroclastic material around their vents (Fig. 26b).

Still other eruptions are sustained for several months or years and display more complexities in their behavior. We can designate these as type C; the Mauna Ulu eruption of 1969-71 (Swanson and others, 1979) is an example. These eruptions begin like those of types A and B but become less vigorous and more stable as time goes on. Alternating periods of effusion and drainback occur in these eruptions, just as they do in type B eruptions, and they have been termed "gas piston cycles" by Swanson and others (1979). But those cycles occurring after the first few months commonly are less vigorous than the early pulses. The effusive phases may consist simply of quiet overflow or include small fountains, commonly dome fountains whose simple symmetrical shapes are not disrupted by effervescence (Figs. 27a, b).

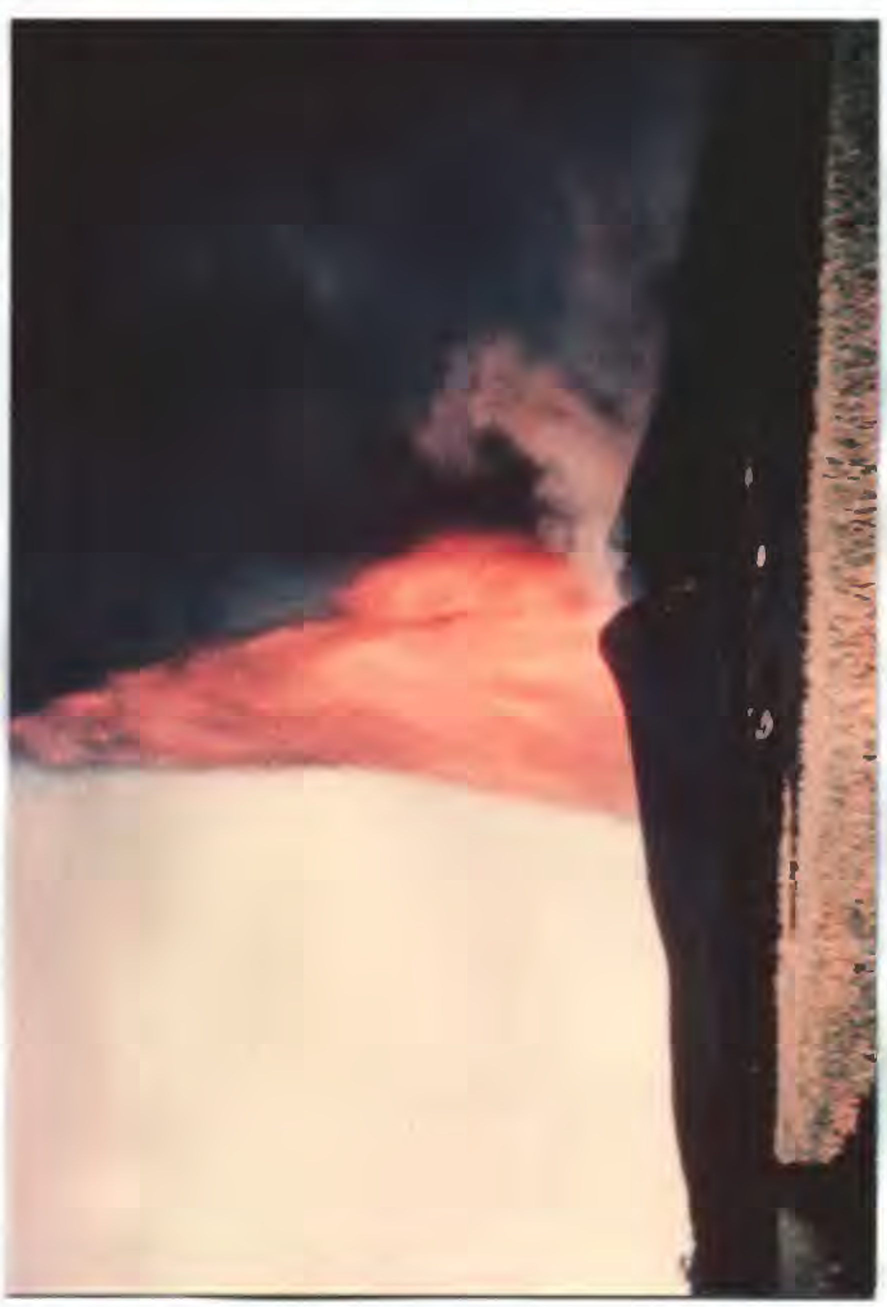
Fig. 26--Type B eruptions and their products. All photos from the files of the U.S. National Park Service.

(a) Lava fountain hundreds of meters high playing from the localized vent of the 1960 eruption at Kapoho. Fallout from the fountain is building a pyroclastic cone (Puu Laimana) and distributing a sheet of pyroclastic materials downwind. Copious lava flows are also being extruded from the vent, out of view beyond the cone.

(b) Devastation Trail, a boardwalk built across the pumice sheet of the 1959 Kilauea Iki eruption in Hawaii Volcanoes National Park. Hill in the background is Puu Puai, the pyroclastic cone of the eruption, discolored by gases emitted from the pile after the eruption ceased.

(c) The Kilauea Iki eruption of 1959, showing a lava fountain about 100 m high during one of the active phases. At such times the lava lake within the pit crater was deepened by the inflow of lava. Puu Puai is to the left of the fountain.

(d) The Kilauea Iki eruption during a period of quiescence and drainback, when the lava lake subsided. Resumption of activity would refill the lake. If the flows were not confined, an interruption such as this might cut off the lava supply to one flow and the next active phase might produce a new flow, unless channels in the previous flow carried the new lava to the same flow front.



a

b

c

d

Fig. 27--Type C eruptions and their products.

(a) Dome fountain at the eruptive vent of Mauna Ulu, phase 10 of the 1969 eruption. Fountain has the configuration typical of artesian water fountains, with a vertical column of lava rising in the center and breaking symmetrically at its top so that all lava visible to view is falling down. There is insufficient effervescence to disrupt the symmetry of the fountain, and such fountains have been observed only rarely, occurring after activity has continued for months and the most gas-rich lava has been tapped from the magma chamber. Photo by D. A. Swanson.

(b) Time exposure showing large dome fountain at Mauna Ulu in February 1974. Jet is inclined slightly toward the left so that the symmetry in Figure 27a is not preserved; lava on the left side is rising and is rimmed by a spatter rampart, while lava on the left is falling and feeding the flows overflowing the lava shield. Dome fountains and other overflows at this stage of activity are characteristically interrupted, apparently by geyserlike effervescence processes, and this interrupts the feeding of their associated lava flows. As a result, individual flows cannot extend far from the vent, and they pile up nearby to form a lava shield like the one actively growing in this picture. Photo by R. T. Holcomb.

(c) Crater-topped shield of Mauna Ulu, January 1974. At times when the shield is not actively growing its summit tends to collapse and form a crater that is filled with a lava lake when the magma column rises once again. A lake occupies the crater in this view, and continuous overflow has produced lava streams that form the prominent red streaks on the flank and carry lava away from the shield. Photo by R. T. Holcomb.

(d) Lava lakes in the summit crater of Mauna Ulu, September 1972. Scale indicated by two people standing on the left-hand rim. At such times of quiet continuous activity lava tubes can develop on the flanks of the shield and transport lava to great distances. Photo by R. T. Holcomb.


a


b


c


d

The periods of these cycles may be very short, commonly less than an hour, and the interruptions in feeding can prevent individual lava flows from spreading very far so that successive flows accumulate near the vents to form broad lava shields (Figs. 27b, c). Subsidence of the magma column in the vent may cause the summit of a shield to collapse, and continued activity may produce within the crater a lava lake (Fig. 27d) which rises and falls periodically because of effervescence. If lava tubes develop to tap the magma column from a level below the range of rise and fall, or if lava ponds develop that can serve as holding tanks on the shield flanks (Swanson and others, 1972), the outflow from the vent area can become sufficiently stable for long-lived tube systems to develop and produce broad fields of tube-fed pahoehoe. Subsequent intervals of voluminous overflow may then produce additional surface-fed pahoehoe and aa on top of the tube-fed flows, and more tube-fed lava may in turn be spread across these. The net result of such an eruption is a complex assemblage of different flow types and one or more lava shields in the vent area (Fig. 28).

Eruptions that continue for a very long time, decades or centuries, are known to occur from the observations made of the almost continuous activity at Kilauea's summit during the nineteenth century (Dana, 1890; Brigham, 1909; Hitchcock, 1909). These eruptions we can call type D, and they may display higher degrees of stability than those of type C, undergoing long periods of sustained overflow and only rare fountaining. Though the historic activity of this type was confined to Kilauea's caldera and produced no extensive flow fields, unconfined flows of such eruptions would consist dominantly of tube-fed

Fig. 28--Flow assemblage produced by a type C eruption. The view is a high-altitude vertical aerial photograph (false-color infrared) that includes an area equivalent approximately to a 7.5' quadrangle, much of the area of Plate 1. It shows the lavas of Mauna Ulu extending from Kilauea's upper east rift at the top to the south coast at the bottom, a distance of about 12 km. Rain forest is red, while the youngest lava flows are blue, gray, and black. Lightest flows are pahoehoe, while young aa flows are black. Some of the dark flows in this view are pahoehoe, such as some prominent surface-fed flows along the rift zone. A similar assemblage of lava flows apparently erupted from Puu Huluhulu somewhat less than 500 years ago underlies the Mauna Ulu lavas and includes the prominent flow at the left. U2 photograph by NASA Ames Research Center.

pahoehoe. That they also produce very large lava shields is shown by the large shield, whose summit crater is Halemaumau, now nestled within Kilauea's caldera.

A final eruption type we can designate as type E. These are the explosive eruptions, of which those of 1790 (Swanson and Christiansen, 1973) and 1924 (Jaggar and Finch, 1924) are examples. They seem to occur at long intervals (Easton, 1978) and may be caused by the sudden mixing of groundwater with magma following sudden withdrawal of the magma column (Christiansen, 1979). Eruptions of this type produce extensive deposits of ash and other pyroclastic materials around their vents.

Eruption Sequences

In the prehistoric record it may not be possible to distinguish the lava-flow assemblage produced by a single eruption, but it may be possible to identify an assemblage produced by a series of closely spaced eruptions. It may therefore be valuable to consider the assemblages produced by such sequences. The historic record is too short for many sequences of this kind to have been recorded, but they are known to occur. It has long been known, for example, that eruptions at the summits of both Kilauea and Mauna Loa are often followed by eruptions from the flanks, and flank eruptions may sometimes cause summit eruptions to cease, apparently because draining of magma from the flanks lowers the magma column beneath the summit (Dana, 1890; Richter and others, 1970). Other kinds of more complicated sequences may occur as well. A recent sequence of apparently related eruptions from Kilauea's east rift zone is a good example.

After at least 150 years of infrequent eruptions and 33 years of dormancy, when most activity was confined to the summit caldera, the subaerial part of Kilauea's east rift zone became frequently active in February-May 1955 with a series of eruptions on the lower segment between Heiheiahulu lava shield and Cape Kumukahi (Macdonald and Eaton, 1964). These were followed by eruptions from the middle (Napau Crater to Heiheiahulu) and lower parts of the rift zone in January-February 1960 and September 1961 (Richter and others, 1964, 1970). Further eruptions from the upper (Kilauea caldera to Napau) and middle parts of the rift zone occurred in December 1962, August 1963, March and December 1965, August and October 1968, and February 1969 (Moore and Krivoy, 1964; Peck and others, 1966; Fiske and Koyanagi, 1968; Wright and others, 1968; Moore and Koyanagi, 1969; Jackson and others, 1975; Swanson and others, 1976). In a first phase of this sequence (1955-63), eruptions occurred at points widely distributed along the rift zone, interspersed with eruptions at the summit; as the activity continued, however, it became concentrated primarily along an upper segment of the rift zone between Hiiaka and Napau pit craters. As the locus of eruptions contracted, the frequency of eruptions increased to intervals of a few months in 1968 and 1969. Individual eruptions in this sequence were brief, but the sequence culminated in a sustained eruption that began in May 1969 and continued, with brief interruptions, until June 1974 (Swanson and others, 1971; Tilling and others, 1973, 1975; Peterson and others, 1976). Because these eruptions followed each other in rapid succession, were isolated from previous eruptions of the rift zone by a long dormant interval, and displayed well-defined trends in frequency and character as they occurred, they can be viewed as a related sequence. The 20-year interval can in fact be viewed as a single episode of intermittent activity in one region of the volcano. The products of this episode are a long chain of vents and a complex assemblage of lava flows of closely similar age. If this assemblage were found in the geologic record it would not be possible to distinguish the individual eruptions, but the assemblage as a whole could be used to characterize the behavior of the rift zone as a whole during this interval.

Summary

The morphology of lava flows is controlled to a great degree by the character of the eruptions that produce them, with sustained, stable effusion leading to high degrees of channelization and inflation. Eruptions of different kinds, differing especially in duration and stability, produce different assemblages of lava flows and vent constructs (Table 8). Very brief eruptions produce simple assemblages of surface-fed pahoehoe and aa, while very long-sustained eruptions produce simple assemblages dominated by tube-fed pahoehoe. Eruptions of intermediate duration, several weeks to a few years, produce relatively complex assemblages of all three flow types (Fig. 28). From an assemblage of flow types it should therefore be possible to infer the nature, in particular the general duration and stability, of the eruption that produced it. Eruption sequences can produce complex assemblages that may be used to typify the character of eruptions in a locality during an interval of time even though the products of individual eruptions cannot be distinguished.

Table 8

Classification of Eruptions at Kilauea

Type	Duration	Character of effusion	Vent	Lava flows
A	Hours--days	Simple waxing and waning; small fountains	Open fissures, ramparts	Surface-fed pahoehoe and aa; single flow
B	Days--weeks	Simple waxing and waning or pulses; large fountains	Central vent, commonly pyroclastic	Surface-fed pahoehoe and aa, multiple flows
C	Months--years	Complex sequence of waxing, pulses, and waning	Small lava shields	Complex mixture
D	Decades--century ?	Dominantly slow and steady, occasionally interrupted	Large lava shield	Dominantly tube-fed pahoehoe
E	Days--weeks ?	Successive explosions	Crater	Pyroclastic sheets

Geologic Map of the Mauna Ulu Assemblage

A detailed geologic map was made of the recent lava flows of the Mauna Ulu region at a scale of 1:24,000. This mapping was intended as a pilot study for the more extensive mapping of Kilauea at a smaller scale; its specific purposes were to check with some rigor the generalizations made earlier about the relationships between flow morphology and eruption behavior, and to develop techniques for recognizing and mapping different flow types from aerial photographs. The map shows the fissures and eruptive products in the area of concentrated and sustained activity during the period of frequent eruptions beginning in 1955. The map area includes the Makaopuhi Crater 7.5' quadrangle and the southern part of the Volcano 7.5' quadrangle. The map is included as Plate I of this report and has been published as U.S. Geological Survey Map MF-811 (Holcomb, 1976).

Compilation Methods and Accuracy of the Map

The map was compiled from aerial photographs made repeatedly during the eruptions by R. M. Towill Corporation (Table 9) and from data and notes collected by the staff of the Hawaiian Volcano Observatory. Although I have traversed the area thoroughly on foot during and after the eruptions and know it intimately, I have not attempted a program of detailed field checks, spot checks having established its general accuracy.

Lava flows erupted from 1962 to 1974 are shown on the map. However, the eruptive sequence is exceedingly complex, and because of the great number of overlapping flows, not all flows could be shown. In the rifted vent area long the chain of pit craters, flows buried

Table 9

Photographs Used in Compilation of the Mauna Ulu Map

Date Flown	Flight Line No.	Frame Nos.	Approximate Scale	Flight line location and direction
5/28/72✓	5719	1-8	1:19,000	S to N, from Apua Point to Puu Huluhulu
	5736	1-9	1:11,000	E to W, from Napau to Hiiaka-Ainahou
	5737	1-7	1:18,000	S to N, from Kaena Point to Makaopuhi
	5739	6-9	1:18,000	S to N, from Kalapana Trail to Napau
	5740	1-10	1:22,000	N to S, from Makaopuhi to Apua Point
10/19/72	5809	1-12	1:16,000	S to N, from Apua Point to Makaopuhi-Alae
	5810	1-13	1:21,000	S to N, from Kahue Point to Makaopuhi-Napau
	5811	1-12	1:20,000	S to N, from Kaena Point to Napau
	5812	1-12	1:16,000	S to N, from Apua Point-Keauhou to Hiiaka-Mauna Ulu
	5813	1-5	1:19,000	S to N, from Poliokeawe Pali to Pauahi
	5814	1-8	1:21,000	W to E, from Devils Throat to Puu Kahaualea
	5815	1-13	1:12,000	E to W, from Puu Kamoamoa to Pauahi-Ainahou
2/5/73	5857	1-13	1:21,000	W to E, from Hiiaka to Iilewa-Heiheiahulu
	5858	1-12	1:9,000	E to W, from Heiheiahulu to Ainahou-Poliokeawe
	5859	1-8	1:25,000	N to S, from Mauna Ulu-Makaopuhi to Kealakomo-Apua Point
7/21/73	5926	1-7	1:12,000	W to E, from Devils Throat to Makaopuhi
12/13/73	6111	1-8	1:26,000	S to N, from Apua Point to Puu Huluhulu-Makaopuhi
	6113	1-7	1:12,000	W to E, from Devils Throat to Makaopuhi
6/1/74	6246	1-13	1:16,000	N to S, from Hiiaka-Alae to Kealakomo
	6247	1-16	1:22,000	S to N, from Apua Point to Puu Huluhulu
6/3/74	6270	1-10	1:11,000	W to E, from Pauahi to Napau
7/28/74	6356	1-9	1:19,000	NW to SE, from Bird Park to Poliokeawe Pali

*In addition to these recent photographs by Robert M. Towill Corporation (Honolulu), several older photograph series were also consulted. Most useful among these were the 1954 HAI series (1:50,000) by the U.S. Navy and the 1964-5 EKL series (1:20,000) by the U.S. Dept. of Agriculture.

✓Flight lines of this date have incomplete stereoscopy before 1970 are omitted, and buried younger flows are generalized. Elsewhere buried flows were generally omitted if they were covered before aerial photographs recorded their positions. Similarly, lava channels and lava tubes of buried flows were omitted. Buried eruptive fissures were simplified, and their indicated positions are only approximate.

On this preliminary map the temporal subdivisions of the Mauna Ulu eruption are in years. This scheme was chosen in order to depict the relative rates of eruption during successive equal increments of time. However, these subdivisions are somewhat artificial with respect to the actual events of the eruption. For example, the sheet of 1973 lava south of Mauna Ulu actually began spreading late in 1972, and the 1972 lava near Alae can be subdivided into distinct units. A different temporal classification could yield a more meaningful picture of the eruption.

The accuracy of the map is limited by temporal and spatial gaps in the photographic coverage. For example, aerial photographs were not made between 1969 and 1972. This caused uncertainties in the ages of some flows and incomplete delineations of others. Parts of two flows, the 1972 pahoehoe at Kaena Point and the 1974 aa below Holei Pali, still uncovered, were not photographed completely before they were mapped.

The base map does not properly depict present topography because the contour lines show the topography of 1963, before it was covered by new lava. The eruptions produced drastic changes: Aloi and Alae pit craters were filled completely, while Hiiaka, Pauahi, and Makaopuhi pit craters were filled partially. Large lava shields were built at Mauna Ulu and the site of Alae Crater, and smaller spatter ramparts were built around other vents. Talus-and-lava cones (Holcomb and others, 1974) accumulated against palis (cliffs), and lava deltas (Moore and others, 1973) added new land to the south coast. Ground surface was modified and generally built up by several meters in areas of new flows.

The obsolescence of the topographic base caused inaccuracies in the compilation of the geologic map. A Kail Radial Planimetric Plotter was used to transfer flow boundaries and other features from the photographs to the topographic base. The plotter's position on the base map and its scale could not be accurately established because control points shown on the base map have been obliterated by new lava flows. Moreover, the accuracy of some indicated positions is reduced because of the plotter's inherently poor resolution of high-relief features, such as steep-walled craters and precipitous palis. Though an effort was made to plot positions to within an accuracy of 20 m, some points may be 100 m off, especially near the center of the map where identifiable control points are widely spaced.

Lava Flow Types

An initial attempt was made to classify lava flows strictly according to Swanson's (1973) classification, but it failed because it was not possible to distinguish some kinds of pahoehoe on aerial photographs. Swanson recognized three major types of pahoehoe lava produced by the Mauna Ulu eruption: (1) shelly, (2) fountain fed, and (3) tube fed. Though the first two types are associated with different kinds of eruptive behavior, they could not be distinguished reliably on photographs and were classed together in this work as "surface-fed" pahoehoe, the term emphasizing their difference from the more highly channelized tube-fed pahoehoe. As discussed above, surface-fed pahoehoe may undergo transitions to aa or tube-fed pahoehoe, and lava of one type may be covered by lava of another type only slightly later in the spreading of a flow. As a result, the different categories are not only intergradational, but their boundaries, when distinct, may be extremely intricate. The map is generalized to a degree that is appropriate to its scale and as a result depicts merely the broad major trends that characterized successive eruptive stages.

Lava-type designations on the map are based on the morphology and reflectivity of the lava flows evident on aerial photographs. The appearance of a flow varies with the scale at which it is viewed. For simplicity in this report, however, the effects of viewing scale are ignored, and features of the flows are generally described in terms of their absolute dimensions.

Aa flows (Fig. 18d) tend to be long and thick relative to their width, and have relatively high surface relief (more than 2 m), on a dekameter scale (that is, over horizontal distance of tens of meters). They are characterized by such hectometer-scale features (over horizontal distances of hundreds of meters) as longitudinal ridges and large lava channels, commonly anastomosing, in their upper parts, and transverse ridges resembling glacier ogives (Thorarinsson, 1953) in their distal parts.

Surface-fed pahoehoe flows (Fig. 16) are relatively thin and widespread--sheetlike--near the vents, and numerous successive flows may accumulate to build broad lava shields in the vent areas. The flows contain numerous large and small open lava channels and longitudinal ribs on dekameter and hectometer scales. The familiar ropy structures occur at centimeter to meter scales and are generally not visible on aerial photographs. Lava ponds are common; their surfaces are nearly flat on an hectometer scale and are composed of a polygonal pattern of dekameter-sized plates bowed slightly upward and separated by shallow cracks, resembling large cobblestones on the photographs. Ponds in older depressions, such as Hiiaka and Pauahi pit craters, generally subside after they form and leave lava-subsidence terraces chilled to their confining walls (Holcomb, 1973). Other ponds are enclosed by contemporaneous lava levees and perched above the surrounding surface (Holcomb and others, 1974). Subsidence of perched ponds commonly produces shallow depressions atop small ventless lava shields.

Tube-fed pahoehoe flows (Fig. 23a) are broad and thin, with broadly dendritic patterns, feathering out from low, broad ridges marking the master lava tube systems. In the upper parts of the flows, large lava tubes that have undergone partial collapse occur and can be recognized by chains of hornitos, skylights, and small rootless lava flows. The lower parts of the flows are thickened by inflation, and tumuli and pressure plateaus are numerous on dekameter to kilometer scales.

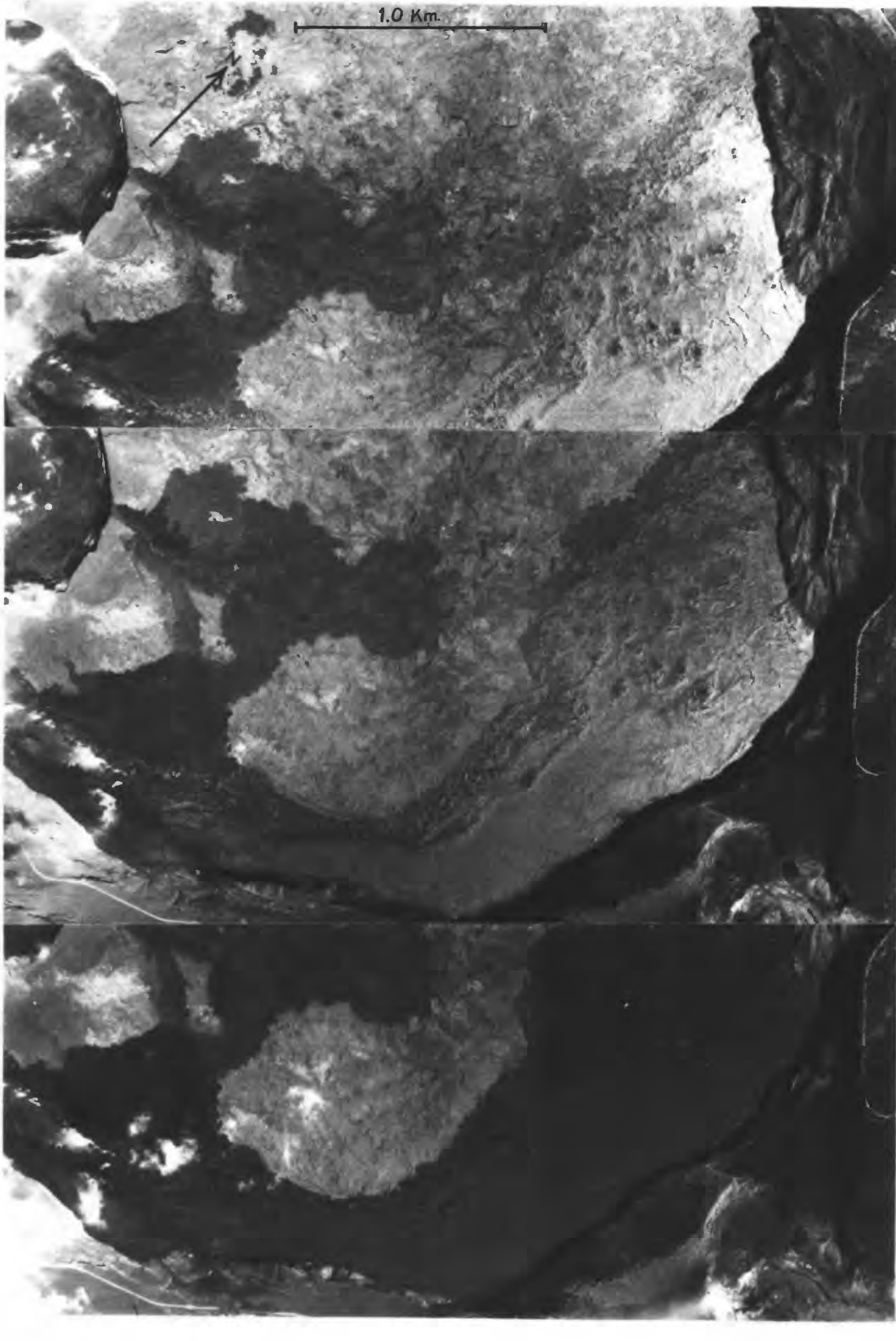
Fresh aa flows have low albedos, apparently due to their millimeter-scale surface roughness and their paucity of glass. Fresh pahoehoe flows have generally higher albedos, apparently due to their glassy skins and comparative millimeter-scale smoothness.

However, while the fresh aa flows are uniformly dark, fresh pahoehoe flows exhibit a great range of albedoes depending upon the phase angles through which they are viewed (Fig. 29). Because of their peculiar photometric phase functions, pahoehoe flows in some circumstances can appear very dark and be misinterpreted as aa; this problem was minimized by studying most flows on several photographs made under contrasting illuminations.

Some tube-fed pahoehoe flows are dark on all photographs, apparently because they are unusually rough on a millimeter scale. These flows, termed "spiny pahoehoe" by Peterson and Tilling (1980), may be mistaken for aa, but stereoscopic examination reveals tumuli and other dekameter- to hectometer-scale features characteristic of tube-fed flows. This type of lava appears to be one of the transitional forms between pahoehoe and aa. A good example is the 1972 pahoehoe lying between the sites of Alae and Makaopuhi craters, southwest of Makaopuhi and east-southeast of Alae (Fig. 30).

Further complications are caused by transitions between the various flow types. Transitions are of several types and may occur over distances from a few meters to a kilometer. In this map albedo was used as the sole criterion to distinguish pahoehoe (light) from aa (dark) in their transition zones. Mapping on the ground could yield a different pattern, but mapping criteria suited for aerial photographs are probably preferable because the photographs are so convenient to use. The transition between surface-fed pahoehoe and tube-fed pahoehoe is much more subtle than the pahoehoe-aa transition and can be defined only on the basis of hectometer-scale flow features such as the presence of a well-developed master tube system and medial

Fig. 29--Variation of pahoehoe reflectivity with phase angle. This stereo triplet prepared from R. M. Towill Corp. photographs 6356-2,3,4 (August 27, 1974) shows lava flows not in the Mauna Ulu area but within Kilauea's caldera where the phenomenon is especially well displayed. The prominent dark flows in the northeastern member of the triplet are the lava flows of August 14, 1971, and July 19, 1974, ponded in the eastern part of the caldera, and the lava flow of 1954 extending eastward from the rim of Halemaumau. The lighter-toned flows were erupted in the 19th century and are weathered. The younger flows, especially those of 1971 and 1974, display a pronounced variation in reflectivity from member to member of the triplet, owing to changes in phase angle, while the older flows do not.


1.0 Km.
N

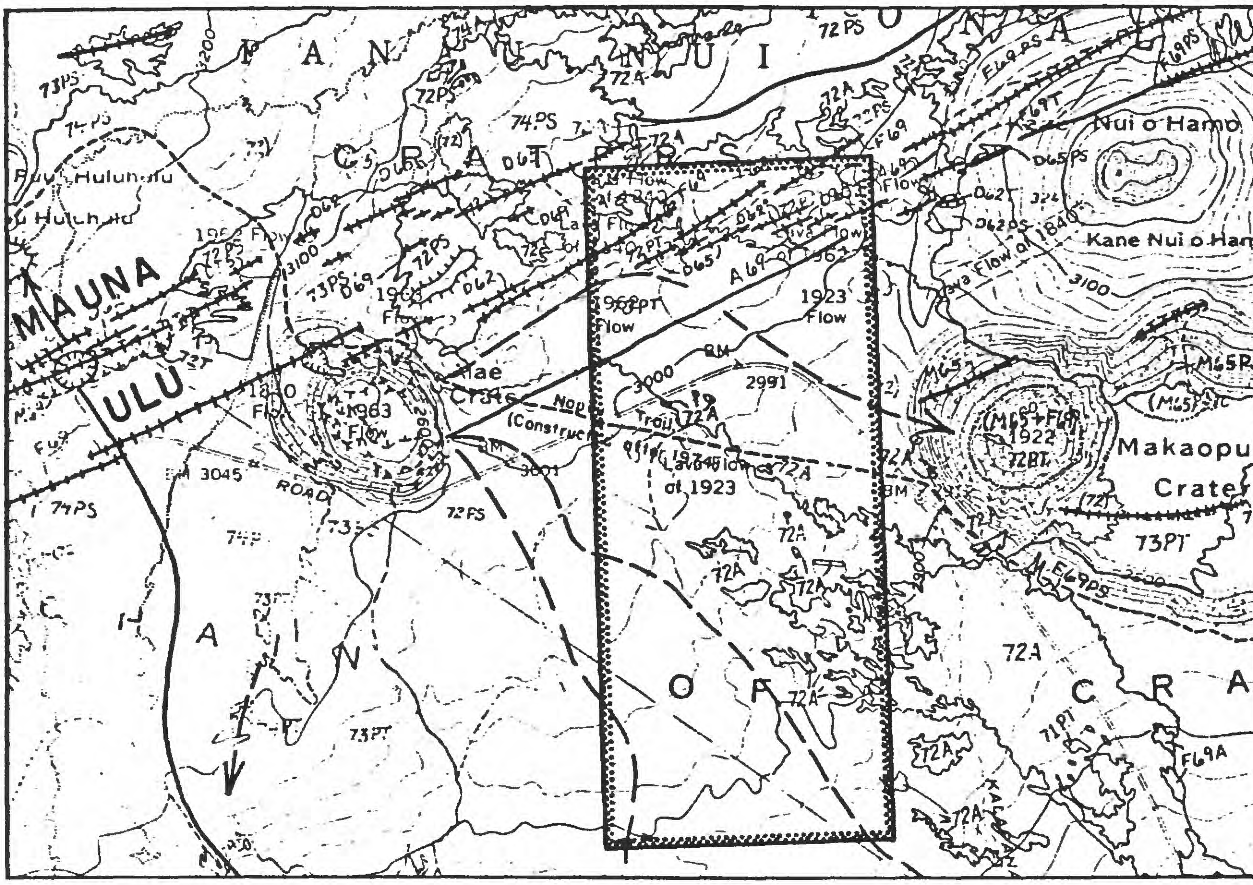
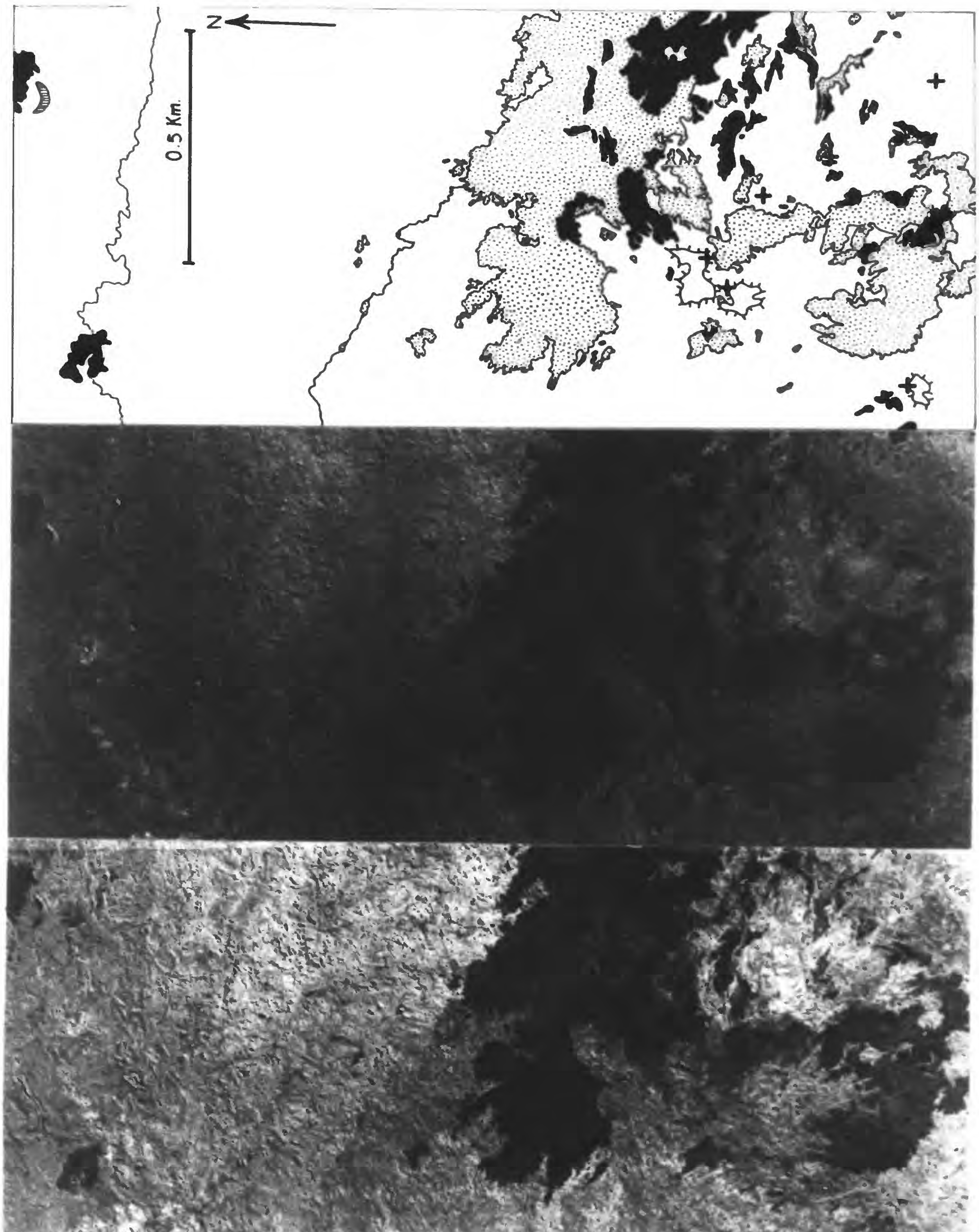


Fig. 30--Lava flows west of Makaopuhi Crater. The index map above, made from a part of Plate 1, indicates the area shown in the stereo pair and geologic sketch map. Black areas on the sketch map are aa flows, and the small crescent-shaped edifice in the northeastern corner is a kipuka of 1969 spatter not yet covered by younger lava flows. White areas are tube-fed pahoehoe and include a band of 1973 lava in the northern half between bands of 1972 lava along the northern edge and in the southern half of the scene. Stippled areas of the map are spiny pahoehoe, a transitional flow type having lava tubes and tumuli but a very rough, nonglassy surface. Note that the aa and spiny pahoehoe are uniformly gray while the tone of the tube-fed pahoehoe differs dramatically in the two photographs.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0.5 Km.

ridge. Differences between the two pahoehoe flow types are not apparent on photographs, at least in the transition zones; therefore the dashed contacts shown are gradational and somewhat arbitrary.

Mapping criteria for older lava flows must differ in some respects from those for young flows because the albedo contrasts disappear with increasing age. Pahoehoe flows darken to a uniform gray as their glassy skins are dulled by weathering and as lichen and plants begin to cover them. Aa flows tend to lighten with age for the same reasons, so that the photometric properties of the different flow types converge with age. The mapping of older flows requires more reliance on their differences in morphology at dekameter- and larger scales. But in compensation for the loss of photometric criteria, older flows of different types display differences in their vegetal covers, as is discussed in the next chapter.

Conclusions

Broad temporal trends in the morphology of lava flows and landforms are evident on the map; they reflect rather well the eruptive history of the area and confirm the initial generalizations regarding the relationships between flow morphology and eruptive behavior. The brief but voluminous initial eruptions of the series and the early stages of the sustained Mauna Ulu eruption produced surface-fed pahoehoe that generally ponded or underwent transitions to aa. Long fissure vents were generally left gaping when the eruptions ceased, and vent edifices are generally absent or small and consist chiefly of tephra. Later, more continuous eruption at Mauna Ulu produced broad fields of tube-fed pahoehoe that partly covers earlier lavas and eruptive fissures.

Fluctuations in lava supply later produced additional surface-fed pahoehoe that accumulated around the vents to form broad lava shields and occasionally underwent transitions to aa. Because changes in lava flow and vent morphology reflect changes in eruption mode, the same mapping techniques used here may be applied to prehistoric lava flows to help characterize eruption modes at various times in the past.

CHAPTER IV

GEOLOGIC MAP OF KILAUEA

The methods developed in mapping Mauna Ulu were adapted for use in mapping Kilauea as a whole at a scale of 1:50,000. That map is the central product of the research project and is included as Plates 2 and 3 of this report.

General Description

The map shows the entire subaerial portion of Kilauea and includes parts (in some cases very small parts) of 17 7.5' quadrangles (Fig. 5). Mapping was performed primarily on aerial photographs using standard methods of photogeology, supplemented by spot field checks of the photograph analysis. Map units were classified by age according to the scheme outlined in Chapter II and by type according to procedures discussed in Chapter III.

Character of the Mapped Region

The area included is about 80 km long, averages about 20 km wide, and includes about 1500 km^2. It is topographically simple, consisting of a long, domelike ridge sloping gently, in most places, from sea level to a summit elevation of 4000 ft (Fig. 31). It is climatically and botanically diverse, with significantly large portions ranging from tropical rain forest to barren desert (Figs. 32, 33), through the orographic effect of the long, high ridge standing in the path

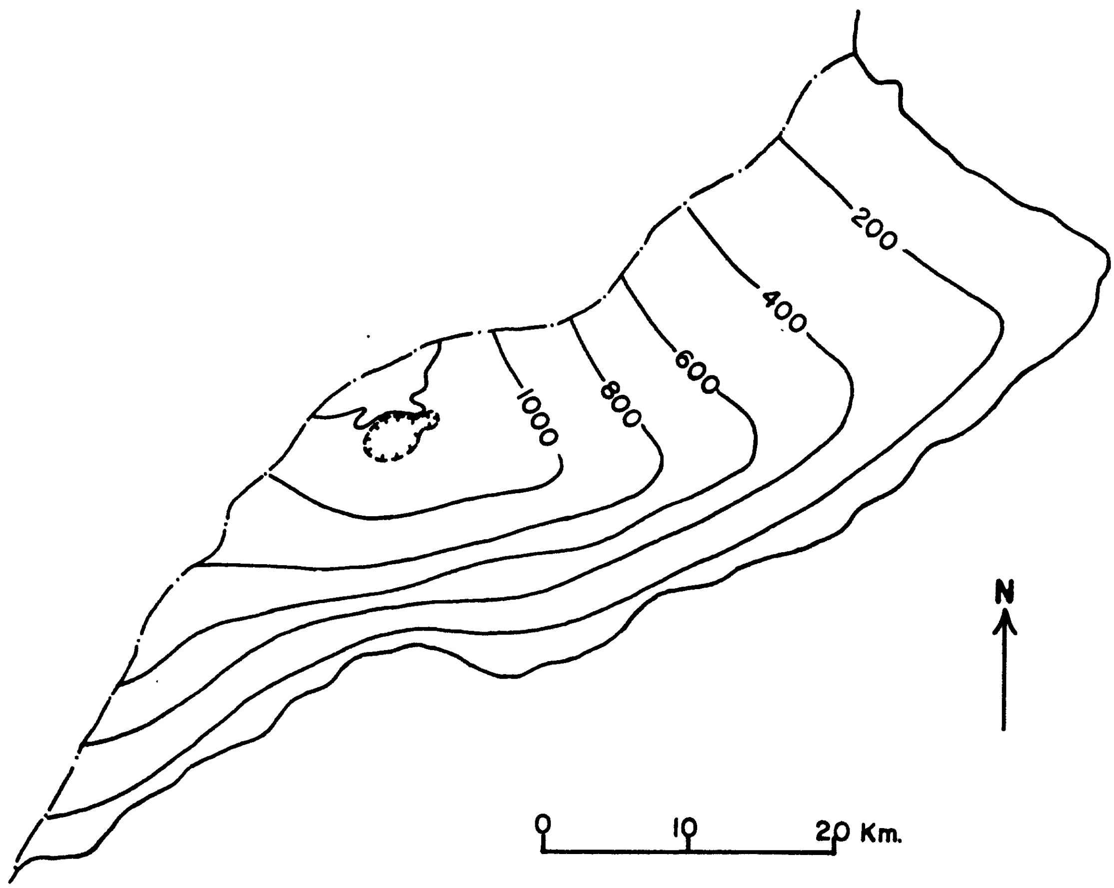


Fig. 31--Topography of Kilauea. Contour interval is 200 m.

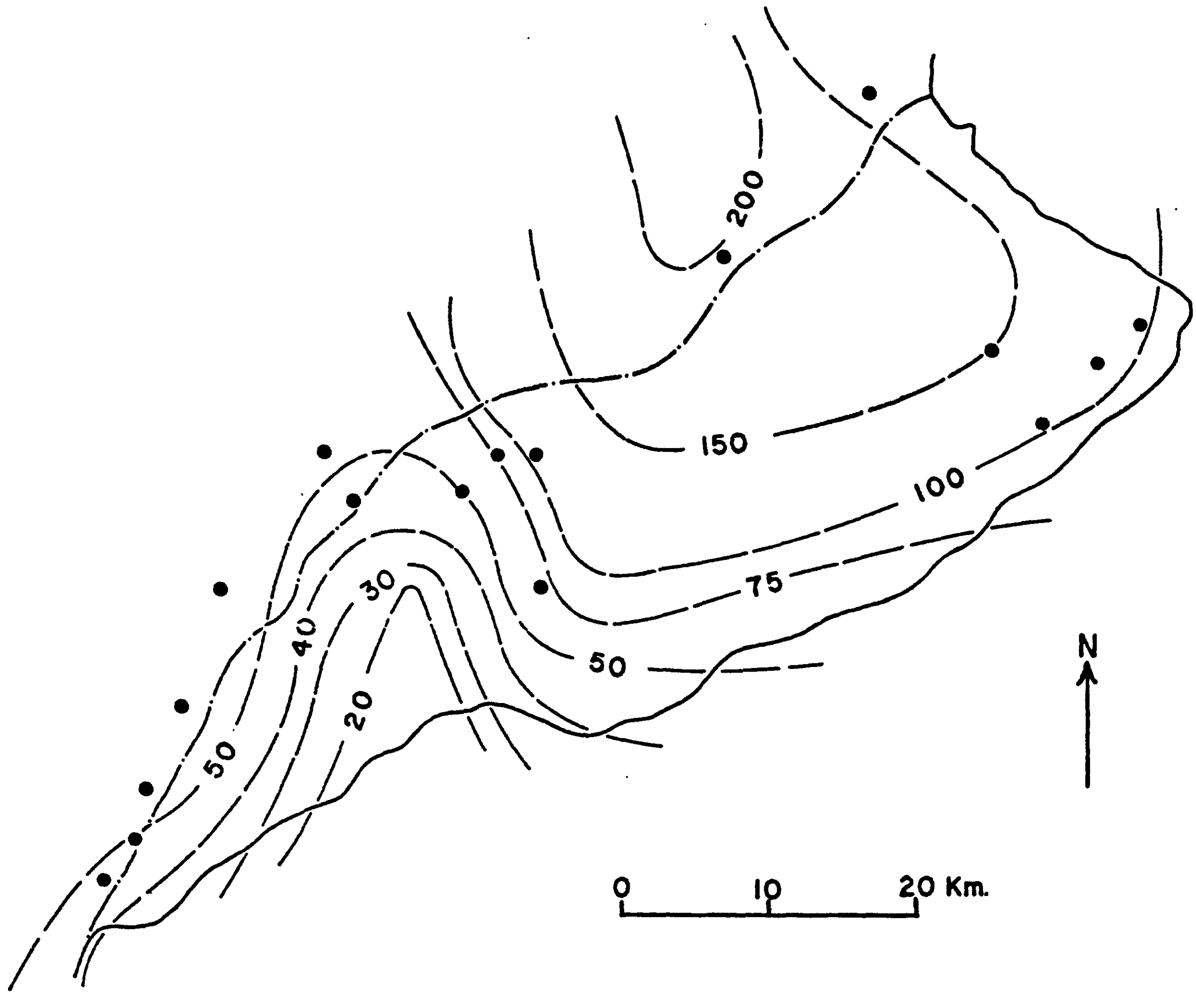
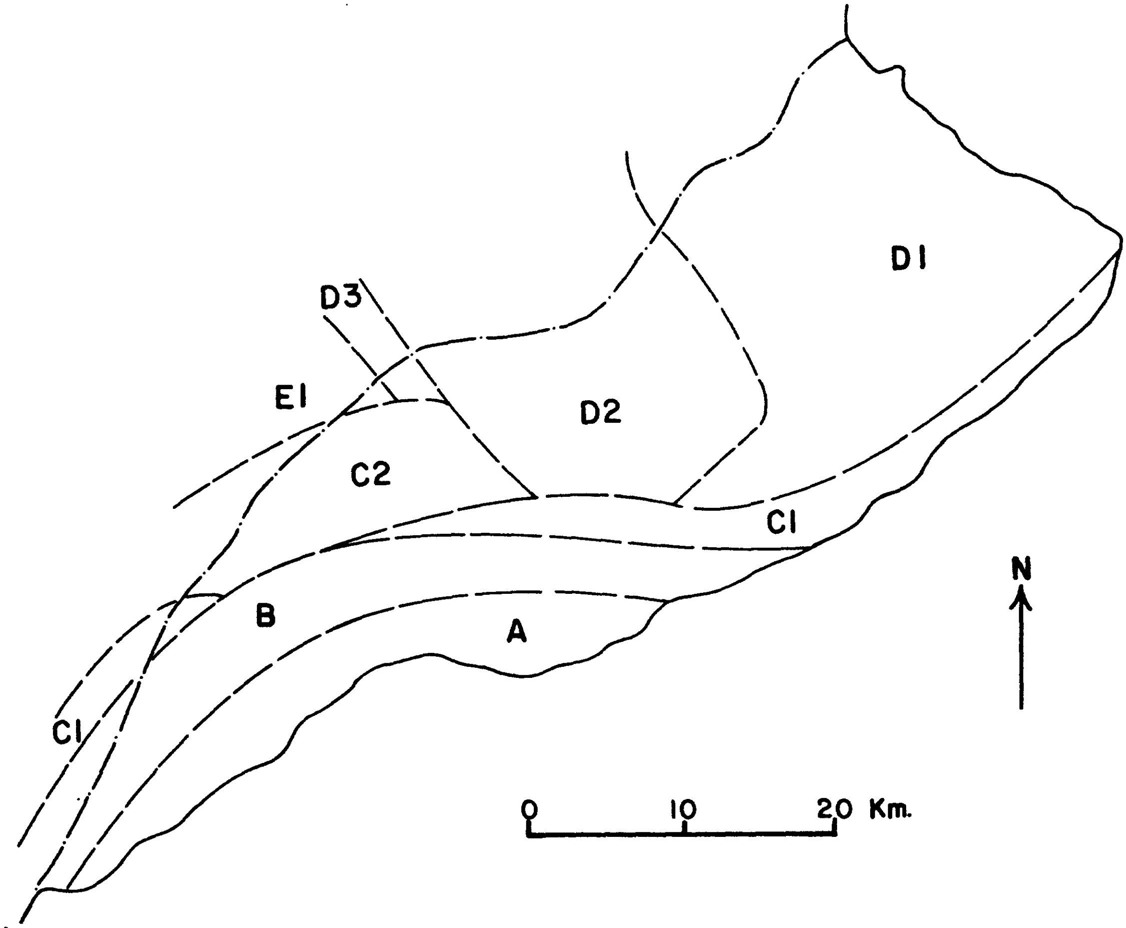


Fig. 32--Rainfall of Kilauea, after Taliaferro (1959).



Vegetation Zone	Approximate Yearly Rainfall (inches)	Approximate Altitude Limit (feet)	Characteristics of the Vegetation: Natural Cover	Characteristics of the Vegetation: Typical Plants
Zone A	20	1000	Xerophytic shrub with a coastal fringe of trees	Algaroba, koahaole, swollen fingergrass, feather fingergrass, piligrass, bristly foxtail
Zone B	20-40	3000	Xerophytic shrub with some trees in the upper part	Lantana, koahaole, klu, cactus, uhaloa, ilima, falsemallow, Natal redtop, piligrass, native panicums, kakonakona
Zone C				
Low phase (C1)	40-60	2500	Mixed open forest and shrubs	Koahaole, guava, lantana, Spanish clover, Bermudagrass, kukaipuaa, pilipiliula
High phase (C2)		2500-4000	Mixed open forest	Bermudagrass, Spanish clover, wild geranium, bristly-fruited mallow, plantain, rattail
Zone D				
Low phase (D1)		1500	Shrub and closed forest	Guava, sensitive plant, Boston fern, Hilograss, ricegrass, basketgrass, honohono, staghorn fern
Middle phase (D2)	60	Variable	Closed forest	Ohio lehue, tree fern, staghorn fern
High phase (D3)		4000-7000	Open forest	Koa, pukamole, sheepgrass, mountain pili, rattail, alapaio fern, tree fern
Zone E				
Low phase (E1)	50	4000-7000	Open forest and shrub	Koa, mamani, heu pueo, mountain pili, large Hawaiian lovegrass, kalamaloa, sweet vernalgrass, bracken fern, alapaio fern, Kentucky bleugrass

Fig. 33--Climatic zones of Kilauea, after Ripperton and Hosaka (1942).

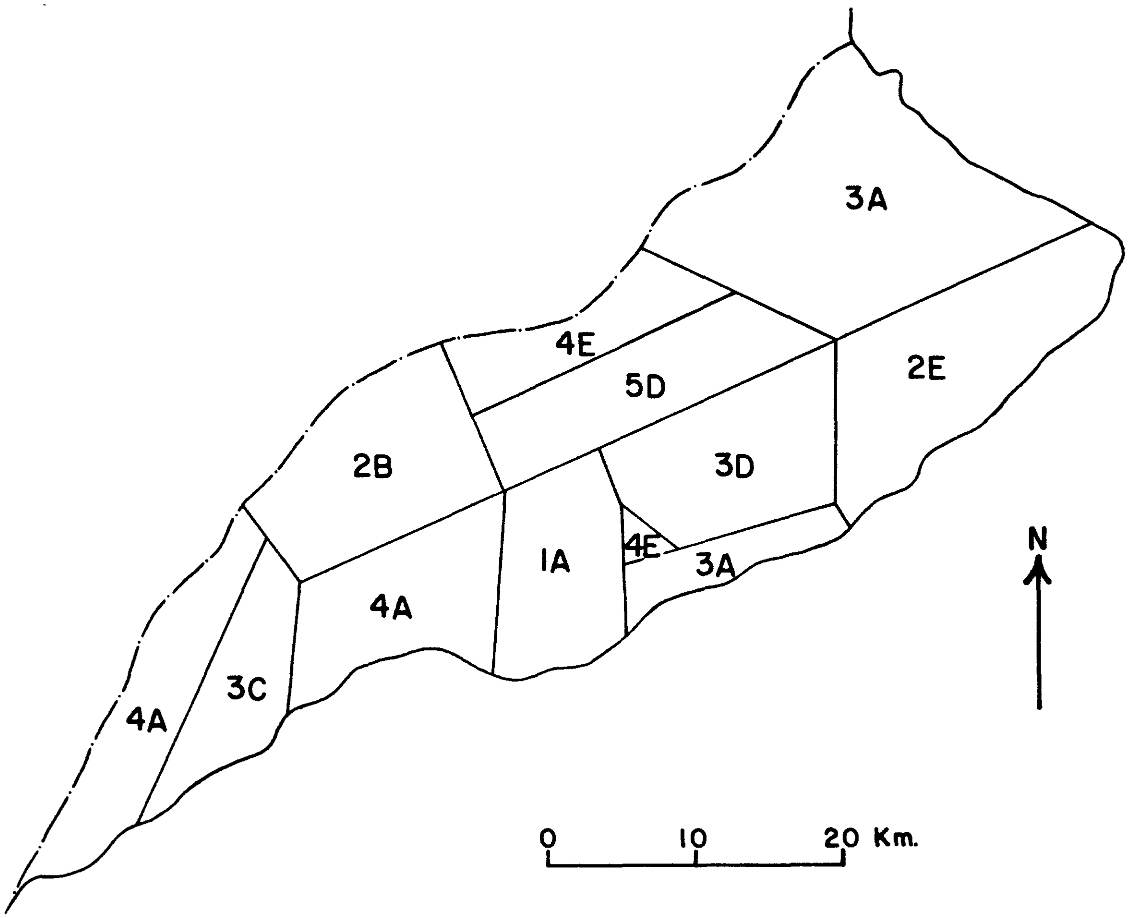
of nearly constant tradewinds. Though primary roads provide good access to all the major parts of the volcano, a sparsity of roads and nearly impenetrable rain forest render some localities near the east rift zone nearly inaccessible, and a lack of secondary roads in desert areas seaward of the southwest rift zone make it difficult to field check this area in detail very rapidly.

Because of the large area included and difficult access into some portions, the map represents a detailed reconnaissance study and not a definitive treatment of the volcano's geology. The degree of mapping confidence varies considerably from place to place, depending upon differences in compilation methods, lava flow types and ages, plant cover, and accessibility. Different factors are dominant in limiting the confidence in different regions of the map (Fig. 34). Some particular problems will be discussed in a following section of this chapter, but it will be useful first to describe the general methods used in making the map.

Compilation Methods and Dimensional Accuracy

The map was compiled from previous geologic maps, prominent flow boundaries shown on some topographic maps, and my own analysis of aerial photographs and two months of field checking.

A variety of aerial photographs was used in the mapping. Kilauea probably has more complete coverage of aerial photographs of different types at different scales under different conditions of illumination than almost any other area in the world, making it ideally suited for photogeologic work of this kind. The principal set of photographs used were those of the EKL series made by the U.S. Department of



General degree of confidence		Main factor limiting confidence	
1	Very good	A	Adjacent pahoehoe flows have inherently obscure contacts
2	Relatively good	B	Tephra obscures relationships between underlying units
3	Average	C	Vegetal sparsity on non-adjacent flows obscures chronology based on plant succession
4	Relatively poor	D	Rain forest obscures geology
5	Very poor	E	Human forest modification obscures plant succession

Fig. 34--Relative mapping confidence for different regions of Kilauea. In all areas the younger units are mapped with more confidence than the older ones. Ages, especially, of older flows are more uncertain, as discussed in Chapters II and V. The degree of confidence is also indicated on the geologic map (Pls. 2, 3) by dashing of the contacts and structures.

Agriculture in 1964-65 at a scale of approximately 1:24,000. Also relied upon heavily for broader-scale relationships were the HAI series made by the U.S. Navy in 1954 at a scale of approximately 1:60,000. These sets were supplemented by photographs of several other series showing small areas of Kilauea at scales generally between 1:10,000 and 1:20,000 all in standard 9 in. x 9 in. black-and-white vertical format. A few high-altitude false-color infrared photographs by NASA at scales smaller than 1:100,000 were consulted for a few specific problems. Two recent series of photographs, one in color at a scale of about 1:20,000 and one in black-and-white at about 1:40,000 were not used because they were not available to me.

Mapping was done directly on the EKL series photographs, transferred to 1:24,000 topographic maps, and then compiled onto the 1:50,000 base map by use of a pantograph. Because of the scale reduction the initial transfer of geology from photographs to topographic maps could be done by tracing and sketching without use of a plotter and little loss of accuracy at the final scale.

Following compilation of the final scale, the map was then field checked and modified. Because of the large area and difficult access to some regions, the field work was limited to spot checks at especially critical or representative localities. Particular attention was given to the mapping of lava-flow margins in heavily vegetated areas where the contacts are based on vegetation boundaries. Flow types and vent locations were checked where feasible in forested areas, and a special effort was made to check the locations of major lava tube systems through local inquiries about the locations of tube skylights, which are generally invisible on aerial photographs of vegetated areas. Rock specimens were also collected systematically from all parts of the volcano. These specimens include small samples from flow surfaces for measurements of photometric properties and thickness of hydration rinds, and larger hand specimens for evaluating correlations and petrographic variations within lava flows and for future chemical studies. When this field work was finished and a stratigraphic framework had been established from the chronologic studies, the photogeology was then revised to produce the final reconnaissance map.

Historic flows erupted since 1962 from the summit, southwest rift zone, and upper east rift zone were mapped using posteruptive photographs and a Kail Radial Planimetric Plotter. They were reduced for this map from an original plotting scale of 1:24,000 and are considered accurate. The Mauna Ulu region of the upper east rift zone and south flank is mapped with more confidence than any other part of the volcano (Fig. 34).

Historic flows prior to 1965 and some prominent prehistoric flows, especially from the southwest rift zone, were shown on the 1:24,000 topographic maps made during the 1960s. Their mapped outlines were checked, corrected, and commonly made more detailed and then reduced for this map. They too are considered accurate, though more extensive field checking could correct many details. Flows erupted since 1965 from the middle east rift zone were not plotted accurately but merely sketched from aerial photographs. Though their general positions are well known, the details of their contacts are inaccurate. Exceptions are the products of the September 1977 eruption, which are shown as mapped by R. B. Moore (1978) and assumed to be highly accurate.

The geology of the Kilauea Crater and Kau Desert quadrangles was adapted from the maps of Peterson (1967) and Walker (1969). These maps were checked, minor changes made, and details added or deleted before reduction onto this map, and this work is also considered accurate. However, I have tried to subdivide the sheets of tube-fed pahoehoe, and because this is difficult the overall mapping confidence is reduced, especially in the Kau Desert quadrangle. This problem will be discussed in more detail later in the report.

The remainder of the map is based solely on reconnaissance work and is generally less accurate. Contacts were sketched by hand from aerial photographs onto 1:24,000 topographic maps and then reduced. Contacts should be fairly accurate where they coincide with prominent vegetation boundaries shown on the topographic maps; elsewhere they may have large errors.

Structures

Because of the focus of this research on eruptive history, the mapping emphasized the delineation of stratigraphic units produced by eruptions. Though structures are shown on the map, they have been given less attention than the stratigraphic units. Especially cursory attention was given to structures on the flanks of the volcano that are presumably related less directly to eruptive processes. Structures can be useful, however, in revealing stratigraphic relationships of some lava flows. If, for example, one lava flow is broken by through-going faults while an adjacent flow is not, the first flow predates the faulting while the second postdates it and is younger than the first. Good examples occur in the highly fractured area inland of Wahaula Visitor Center along the southeastern coast of Kilauea (Fig. 35). The aa flow of Wahaula Heiau has been depressed by a broad graben inland from the visitor center, and this graben is filled by the pahoehoe flows that surround the aa. The aa flow predates the graben while the pahoehoe postdates it. The structure serves a useful stratigraphic function and is mapped. Similarly, it has been useful to infer the probable buried extensions of some structures in order to illustrate the inferred stratigraphic relationships of flows. But because the structures themselves were not the primary focus of the research, relatively little effort was made to field check or otherwise test rigorously the existence of inferred structures that are buried and not visible on aerial photographs. Because many of the structures shown on the map are highly interpretive, less confidence is placed on them than on the stratigraphic units.

Some structures observed directly on the photographs are also locally uncertain. Many small fractures are probably longer than shown because their extensions are not visible on the photographs. Many minor faults may be mapped as fissures, and other structures omitted entirely, for the same reason. Some structures shown in densely forested areas may be illusions due to aligned tree shadows and other artifacts of the illumination.

Classification of Rock Units

Rock units are classified in three ways: by flow types, by eruption types, and by age. A three-part code is used to designate units on the map. The first part of the code, a number, describes the age, the second part, a capital letter, denotes the assemblage type, and the third part, one or two lower-case letters, indicates the type of flow or pyroclastic deposit. If a particular rock unit is not differentiated in one of these ways, the appropriate part of the code is omitted. For historic flows the year (A.D.) of eruption may also be indicated separately from the three-part code.

Age designations are based on various criteria. Eruptions since 1823 are generally documented well enough that their absolute ages are well known. A few small Nineteenth Century eruptions may have escaped observation, however, especially along the middle east rift zone where there appear to be more patches of very young forested lava than are accounted for by the outbreaks recorded in 1840. Absolute ages of a few earlier eruptions are estimated from oral traditions. Ages for the rest of the flows are inferred from other kinds of evidence. Relative ages in restricted localities are determined most reliably from superposition relationships between the lava flows and, in some cases, structures. Relative ages of two flows in contact are commonly indicated on the map by "Y" (younger) and "O" (older) on opposite sides of the contact. When two nearby flows of the same type are not in contact, their relative ages are judged from their differences in albedo and vegetal cover. These local criteria could not be used to reconstruct a volcano-wide stratigraphic sequence because the lenticularity of lava flows prevents them from being in contact with flows from diverse regions, and because large climatic variations cause variations in weathering and plant growth that rule out simple widespread relationships between these factors and the ages of flows. As discussed elsewhere in this report, the method used for making regional correlations of stratigraphic sequences is based on the secular variation in the geomagnetic field. Because there are too many different lava flows for all to be dated by this method, the ages inferred for many flows rest on local stratigraphy, and where the ages of the sequences are poorly bounded the ages of individual members are highly uncertain. These uncertainties are indicated by question marks in parentheses after the age symbols.

Flow types are classified as in Plate 1, the main categories being surface-fed pahoehoe, aa, and tube-fed pahoehoe. Though the flow types are the same as in Plate 1, some criteria used in recognizing them are different. Weathering of older flows tends to suppress their photometric contrasts so that more reliance must be placed on larger-scale morphology. Vegetation differences must be used in heavily forested areas of the Mauna Ulu map. A few rock types are shown which do not appear in the area of the Mauna Ulu map. For example, deposits of phreatomagmatic explosion debris are mapped at the summit and along the rift zones, and the deposits of wind, water, and landslides are shown in various area.

Eruption assemblages are classified by their duration and behavior as indicated by the assemblages of their products. In order to classify a flow by eruption type it is commonly necessary to identify it as belonging to a recognizable assemblage, but this is not always possible. For example, though it is assumed that tube-fed pahoehoe is always produced by eruptions of at least moderately long duration, aa flows can result from various eruption types. If a vent or flow assemblage associated with the aa flow cannot be identified, the eruption type remains unknown. As a result the eruption type is not differentiated for many of the flows.

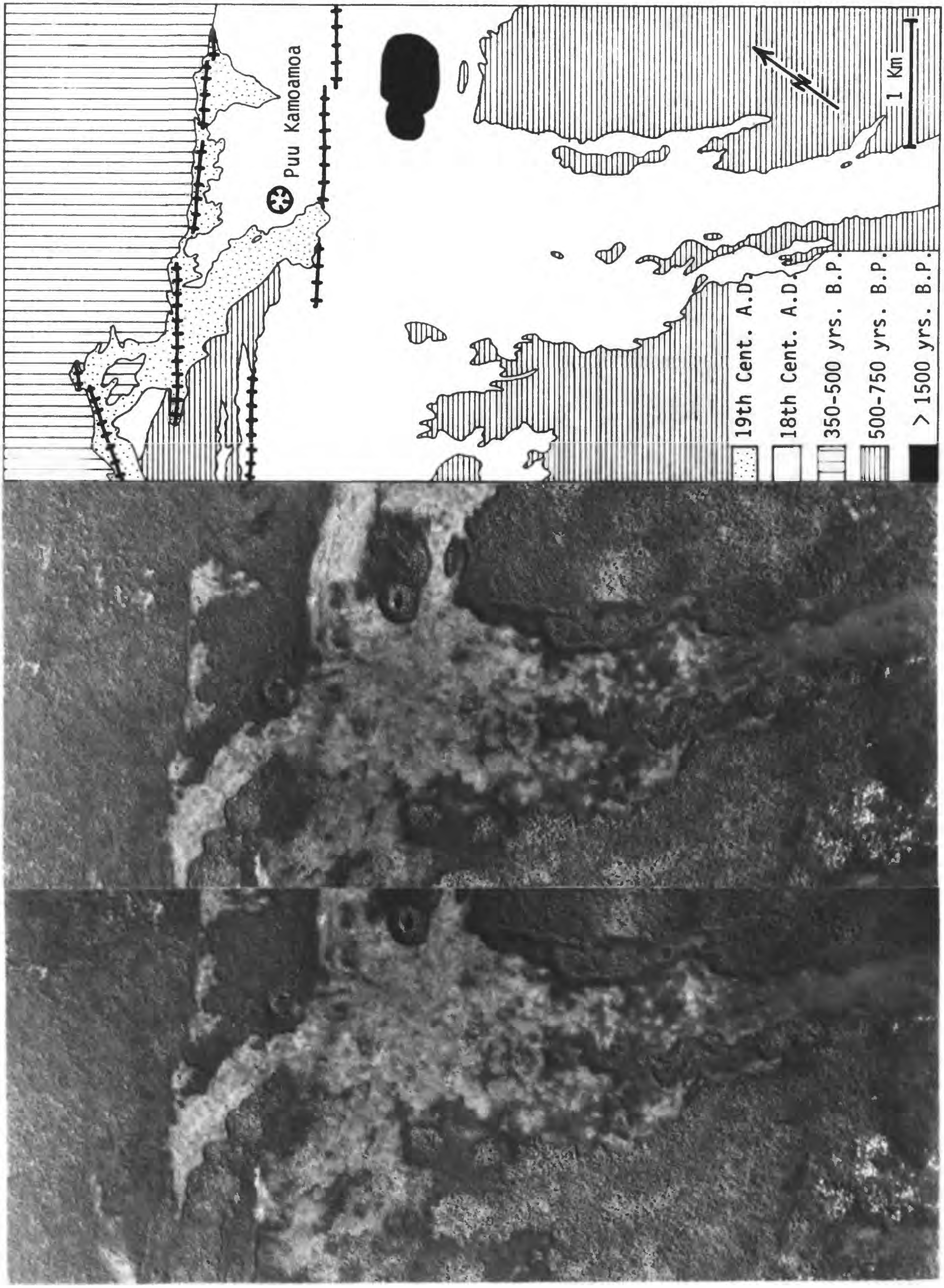
Some Specific Problems

Some particular problems encountered in the mapping merit special comment. These will be discussed in a geographic order beginning on the east rift zone and progressing around the volcano in a counter-clockwise direction.

Latest Prehistoric Eruptions of the East Rift Zone

A prominent group of widespread flows along Kilauea's east rift zone appears to span a narrow range of ages and probably dates from the Eighteenth Century. These flows are distinctively vegetated. Although in general they are densely overgrown, the vegetation structure and floristic composition indicate that they are considerably younger than most neighboring flows (Fig. 35). Older nearby flows display a relatively coarse forest grain when viewed on aerial photographs, caused by both the greater heights reached by the crowns of trees above the forest understory dominated by hapuu (*Cibotium*) and other tree ferns, and a greater tree spacing than in younger forests. The flora of older forests is more diverse, and the vegetation pattern commonly displays a hectometer-scale patchiness unrelated to mappable flow boundaries. Candlenut, or kukui, trees (*Aleurites moluccana*) are especially diagnostic of older forests at lower elevations and are easily recognizable on aerial photographs because of their high albedo. When viewed on the ground, large ohia lehua trees (*Metrosideros polymorpha*) of older forests commonly are seen to be epiphytically rooted, indicating that these individuals are not among the first generation of trees on these flows. Eighteenth Century flows possess a finer vegetation grain arising from close spacing of young

Fig. 35--Puu Kamoamoa region of Kilauea's middle east rift zone. Location of the area is shown on Figure 40. The stereo pair illustrates vegetation contrasts on lava flows of units 2, 3, 5, 6, and 9 of Plates 2 and 3. This pair was made from photographs 019 and 020 of roll 14, U.S. Navy series HAI of 1954. The photographs were made before this area was extensively flooded by the Twentieth Century flows shown on Plates 2 and 3, and all units visible here are carpeted by dense vegetation. Vegetation patterns vary with both the age of lava flows and the location upon a lava flow. Most trees are ohia, but the very light-toned trees in the lower left corner are kukui growing on a flow-mantled fault scarp. Where trees are small on young flows the unshaded understory is composed largely of uluhe, but where trees are large the understory is generally dominated by hapuu.


Puu Kamoamoa
1 Km
19th Cent. A.D.
18th Cent. A.D.
350-500 yrs. B.P.
500-750 yrs. B.P.
> 1500 yrs. B.P.

trees, and their patchiness is closely related to flow boundaries or other features of the flow morphology. They are recognizably older than the flows of 1840, which are also densely vegetated but with plants that are significantly more crowded and of lower stature. Though they must be prehistoric, some are younger than 200 years, according to the ^{14}C dates obtained from them (Kelley and others, 1979).

Youthfulness of these prehistoric flows along the middle east rift zone is indicated also by Nineteenth Century accounts suggesting that they 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 the vicinity of Napau to the vicinity of Pahoa in a single day, traversing "old lava-plains. . . covered with stunted shrubs" (Wilkes, 1845; see especially p. 181-183, 216). A similar trip led by R. Holcomb and J. Jacobi in November 1975 required two days of arduous travel along the rift zone now heavily forested except for those parts covered by Twentieth Century lava flows. When Wilkes (1845, p. 182-183) passed by the north side of Heiheiahulu lava shield (called "Kalalua" by Wilkes) 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 forested that its nature could not be determined without climbing its flank; in fact, the forest is so dense and high that Heiheiahulu and some smaller cones mentioned by Wilkes cannot even be seen from most places more than a few meters away from them. Because of their vegetation sparsity then, and dense vegetation now, most of the flows along the middle east rift zone must have been quite young when traversed in 1840.

Especially good keys to the interpretation of vegetation patterns occur on the south side of Heiheiahulu lava shield inland from Kaimu. Here the oral history establishes the ages of the flows, while a wide range of flow morphologies and climates indicate the general rates of forest development under different conditions of climate and forest substrate.

When Ellis (1827) passed through Kaimu in 1823 he was told by the Hawaiians living there that "the district. . .was overflowed [by lava] in the days of Arapai [Alapai, who reigned during the approximate interval 1730-54, according to C. H. Hitchcock (1911), citing W. D. Alexander as his source]." Since Alapai had ruled less than a century earlier, this eruption must have occurred not long before, and its report has been considered reliable. In trying to identify this eruption of ca. A.D. 1750, Macdonald (1941) supposed it to be represented by an aa flow that is especially barren of vegetation where it covers a few hundred meters of the shoreline about 1 km east of Kaimu (Fig. 36). Macdonald could not trace this flow directly to its source because it disappears into thick forest, but extrapolation of the flow straight upslope to the rift zone showed that its probable source was Heiheiahulu (Stearns and Macdonald, 1946).

Stratigraphic relations at the shoreline, however, 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 a 3 km stretch of shoreline to the east past Moana Hauae and Waipuku Point (Figs. 36, 37, 38). This delta was fed by a lava tube whose

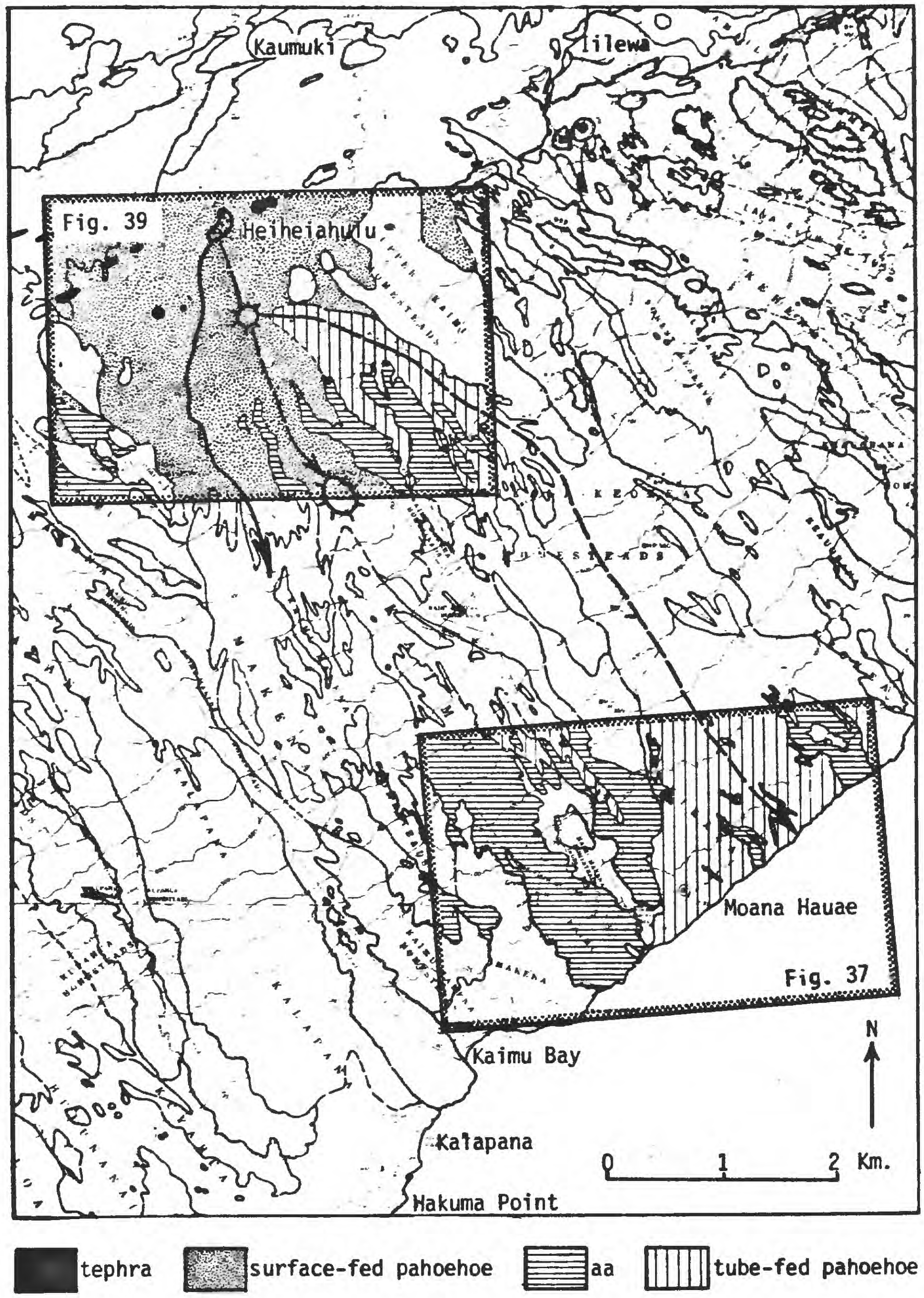


Fig. 36--Index map for Figures 37 and 39 in the Kaimu region. It is adapted from Plate 3, and only the Eighteenth Century lava flows (unit 3) are shaded. Especially prominent lava tubes and channels are delineated.

Fig. 37--Coastal lava flows between Kaimu Bay and Waipuku Point. The prominent dark flow in the western half of the stereo triplet is the one designated as the ca. 1750 flow by Macdonald (1941), but flow morphology and superposition relationships indicate that many of the other flows are of similar age, all having been erupted at Heiheiahulu. Eighteenth Century aa flows are very dark on the photographs and are colonized mainly by ohia trees whose spacing decreases with increasing elevation inland. Eighteenth Century tube-fed pahoehoe flows have gray tones and comparatively fine textures on the photographs, being overgrown with shrubs and grasses between small ohia trees. Older flows are more densely vegetated, with scattered large trees being prominent. The numerous trees having a distinctively globular shape are mango, while the very light-toned trees are kukui. Arrow near bottom indicates the small cove whose northeast edge is shown in Figure 38b. Paired dots are paleomagnetic collection sites, each dot representing a subsite. These sites are identified on Plate 3. Illustration was prepared from photographs 47, 48, and 49 of roll 12CC by the U.S. Department of Agriculture series EKL of 1965.

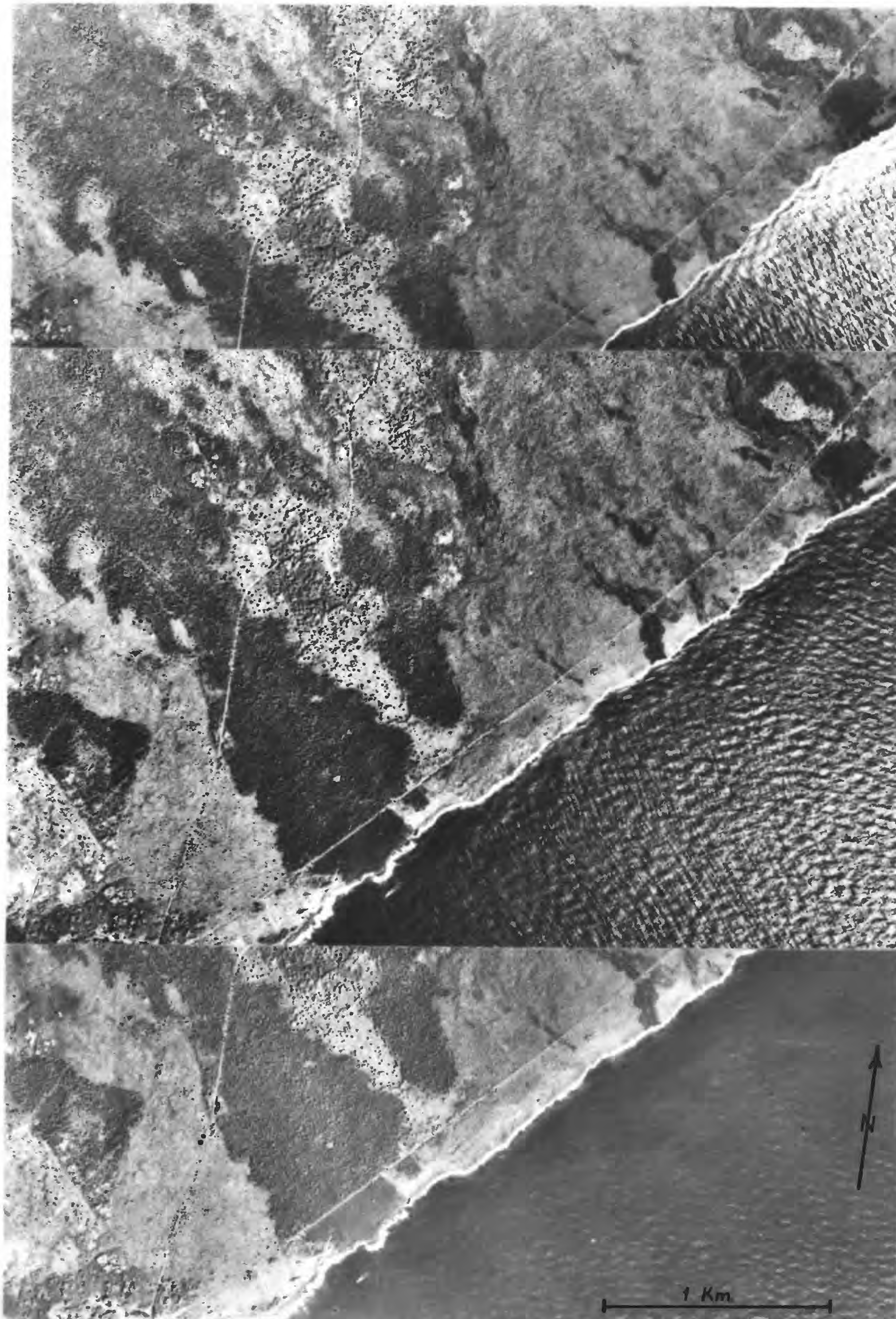

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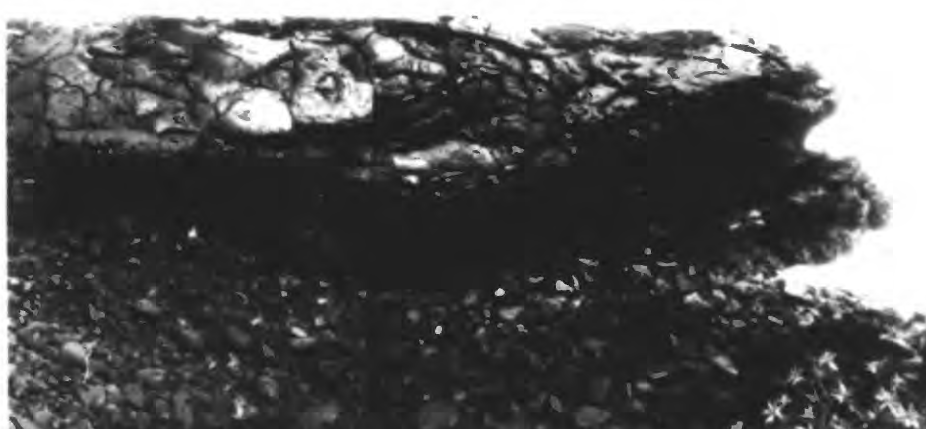
Fig. 38--Stratigraphic relationship of "1750" flows at the shoreline. Photographs by J. P. Lockwood.

(a) Oblique aerial view showing Macdonald's ca. 1750 flow on the left and the tube-fed pahoehoe flow of the Moana Hauae-Waipuku Point lava delta on the right. A narrow, light-toned "horn" of pahoehoe extends along the shoreline from the delta to the front of the aa flow. Such horns are characteristic of pahoehoe deltas (see the delta of A.D. 1973 shown on Pl. 1) and typically form where the lava spreads laterally along a beach while the advance of its front is retarded by surf.

(b) View looking seaward from the top of the aa flow where it is in contact with the pahoehoe flow. Marine erosion has removed the clinkery surface of the aa flow near the shoreline producing the small cove indicated on Figure 37 (extending to the right of this view) and revealing the contact between the two flows. The contact is located at the position of the rock hammer visible near the left side of the picture. The pahoehoe is younger than the aa and is molded around the aa clinkers beneath it.

a

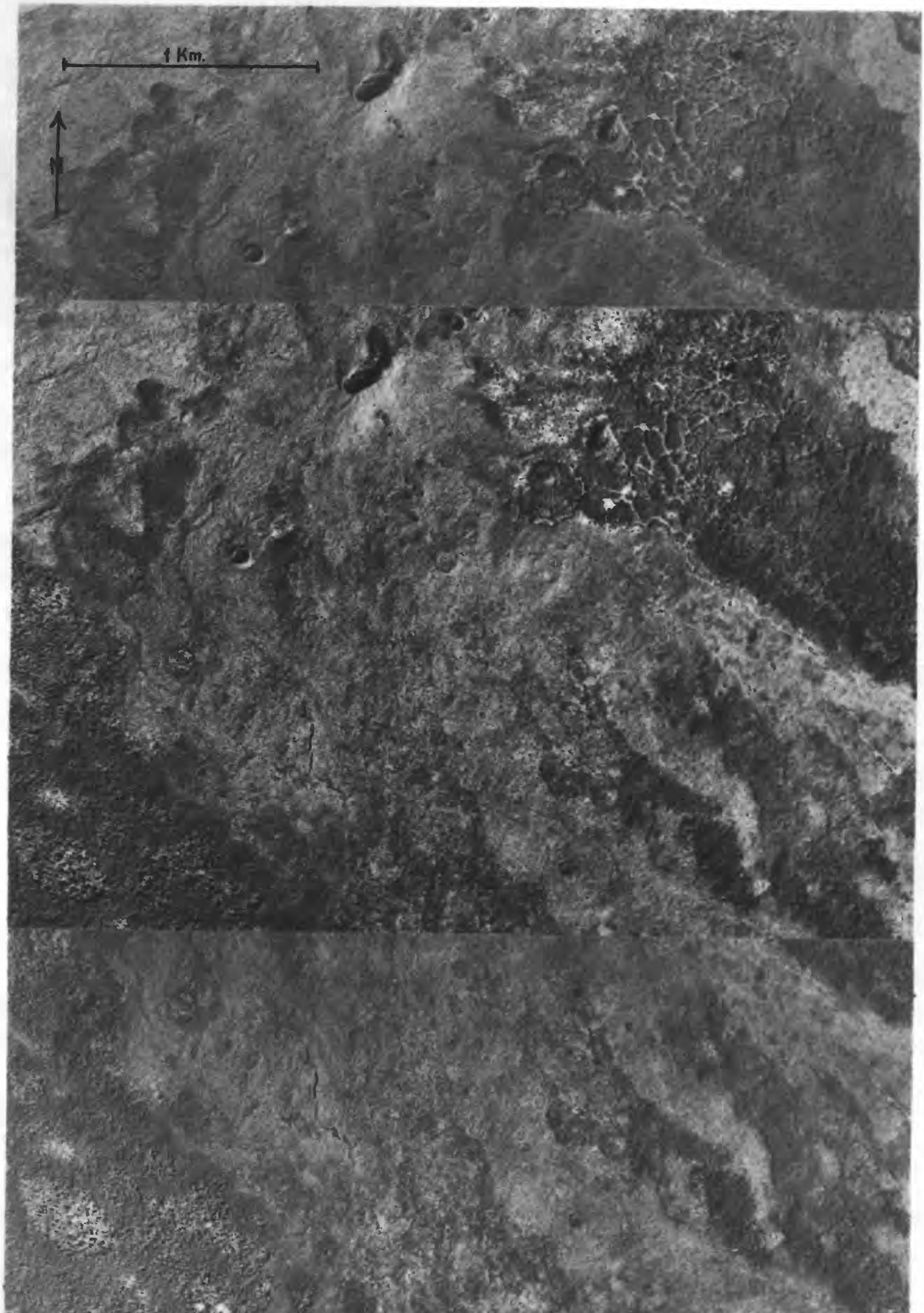


b

course can be traced to the upper flank of Heiheiahulu (Figs. 36, 39). Several other large tubes and channels radiate from Heiheiahulu, and the shield and its flows comprise a diverse assemblage remarkably similar to that of Mauna Ulu. The Kaimu district was not overflowed by a single flow but by many, and by analogy with Mauna Ulu this eruption of the Eighteenth Century was sustained for several months or a few years.

Though the Heiheiahulu flows are all of similar age, their vegetation cover is highly diverse, varying with flow morphology and climate. The dominant trees on all flows are young ohia lehua (*Metrosideros polymorpha*), but the flows vary widely in the size and spacing of their trees and the characters of their understories. In a relatively warm and dry narrow band along the coast, the vegetation is comparatively light on all flows but is more dense on tube-fed pahoehoe flows than on aa flows. Aa flows are colonized only by scattered ohia trees and lichen, while adjacent pahoehoe flows are covered by thickets of shrubs and grasses as well as comparatively numerous ohia. The contrast is probably caused by differences in the water retention of aa and pahoehoe, pahoehoe surfaces being better sealed so that rainwater cannot drain away as easily but is channeled into puddles that allow rapid establishment of plants. In relatively wet and cool areas inland at higher elevations the vegetation is much more dense, but the vegetation contrast between flow types remains high. Ohia trees are taller and more closely spaced on aa flows than on pahoehoe. The relatively broad spaces between trees on pahoehoe are generally overgrown by thick tangles of uluhe (*Dicranopteris linearis*, a species of false staghorn fern of the family *Gleicheniaceae*). Rugged aa surfaces

Fig. 39--Seaward flank of the Heiheiahulu lava shield. Shown in this stereo triplet are the headward ends of the ca. 1750 flows of Figure 37. Aa flows are expressed on the photographs by the darker tones of dense stands of ohia, while pahoehoe flows have the lighter tones of uluhe thickets growing between relatively widely spaced ohia. The illustration was prepared from photographs 55, 56, and 57 of roll 12CC of the EKL series by the U.S. Department of Agriculture, 1965.


1 Km.
N

may provide a better substrate for tree roots where rainfall is sufficient to permit rapid growth. Transitions in the vegetation cover on a single flow correspond roughly to transitions in the morphology of the flow, so that although Heiheiahulu lavas are densely carpeted, it is still possible to map crudely the morphologic transition using the vegetation patterns visible on aerial photographs. (The transitions mapped on Plates 2 and 3 may not correspond exactly to the transitions shown on Plate 1, however, because of the different criteria used.) The forest has grown faster along the margins of flows than in their centers, probably because the flows are thinner at their margins and are more easily penetrated by tree roots. Where flows are thick they commonly possess massive interiors that may prevent roots from reaching nutrients and moisture beneath the lava.

These principles of vegetation development, that I first recognized on the Heiheiahulu flows, were used to delineate Eighteenth Century lava flows extending the length of the east rift zone. (It should be noted, however, that similar inferences of the relationships between aa/pahoehoe flow morphology and climate were made independently and earlier by J. O. Juvik (1972) on the basis of quantitative vegetation data from the Mauna Loa lava flow of 1868.) My map differs from J. G. Moore's map of the middle east rift zone (Moore and Koyanagi, 1969) in showing fewer late prehistoric units. Moore differentiated late prehistoric flows (older than about 300 years) from very late prehistoric flows older than 1840, but I have lumped these groups together. The Heiheiahulu vegetation patterns show that the vegetation contrasts used by Moore to differentiate the flows arise not from differences in age but from differences in flow morphology.

On the map a few flows are included with this Eighteenth Century group despite some evidence that they may be older. In some cases it is the vegetation which is slightly different, the ohia trees being less numerous and more widely spaced but taller, giving a coarser grain to the vegetation pattern as viewed on aerial photographs. Such flows may be somewhat older than other members of the group, but these flows are few in number, and until quantitative data are gathered on the rates of forest development (and climatic variations from place to place) it is not possible to say whether the age difference is significant. In some cases the differences in forest morphology apparently have causes other than age. An example is the flow immediately southeast of Napau (Figs. 40, 41). This flow has a comparatively coarse vegetation pattern, but ^{14}C samples W-3468 and W-3469 suggest that it is younger than 200 years (Kelley and others, 1979). This flow is very thin, generally less than 1 m thick, and it is penetrated by many large tree molds from which many of the present trees grow. The peculiar character of this flow apparently favored a comparatively early and rapid reforestation of its surface.

Apparent contradictions regarding the ages of a few other flows arise purely from early historic accounts. For example, the pahoehoe flow of Malama Ki Forest Reserve, comprising the coastline between Lililoa and Mackenzie State Park (Figs. 42, 43), is included in the Eighteenth Century group even though Ellis' (1827, p. 201, 205) description seems to preclude such an age. Ellis was told on passing through Malama that the inland part of the district was inundated by

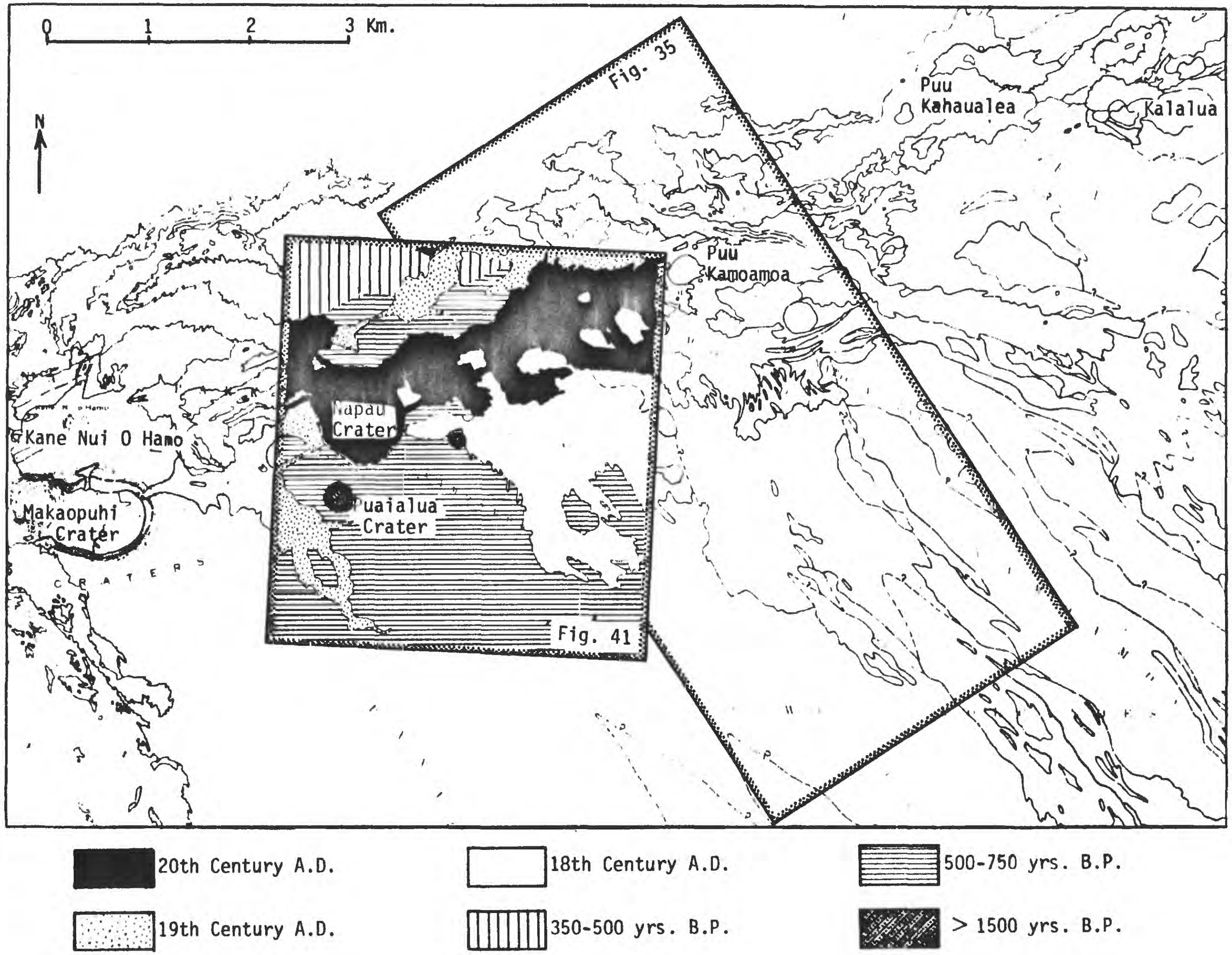
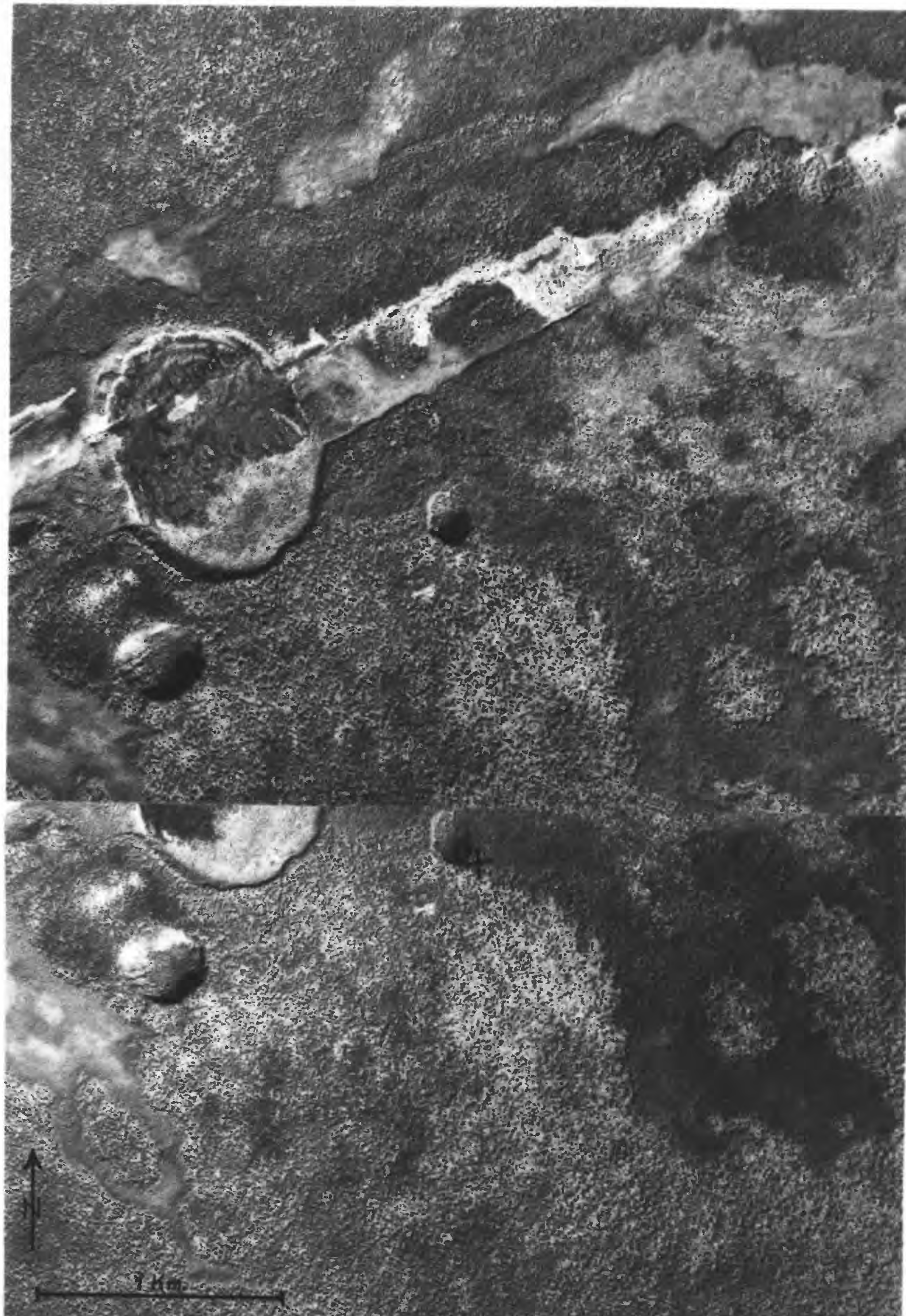


Fig. 40--Index map of the middle east rift zone between Makaopuhi Crater and Kalalua. Outlined are the areas shown in Figures 35 and 41.

Fig. 41--Lava flows east of Napau. Stereo pair prepared from photographs 142 and 143 of roll 12CC, series EKL by the U.S. Department of Agriculture, 1965. The young prehistoric flows south of the graben and east of Napau are believed to date from the Eighteenth Century A.D., even though some lobes possess ohia trees larger than those found on many flows of that age. Radiocarbon dates of less than 200 years B.P. have been obtained from charred roots beneath this flow at the location indicated by the crossed dot. Some fresh Twentieth Century flows are shown in this view, but more eruptions have occurred in this area since the photographs were made (compare with Fig. 40).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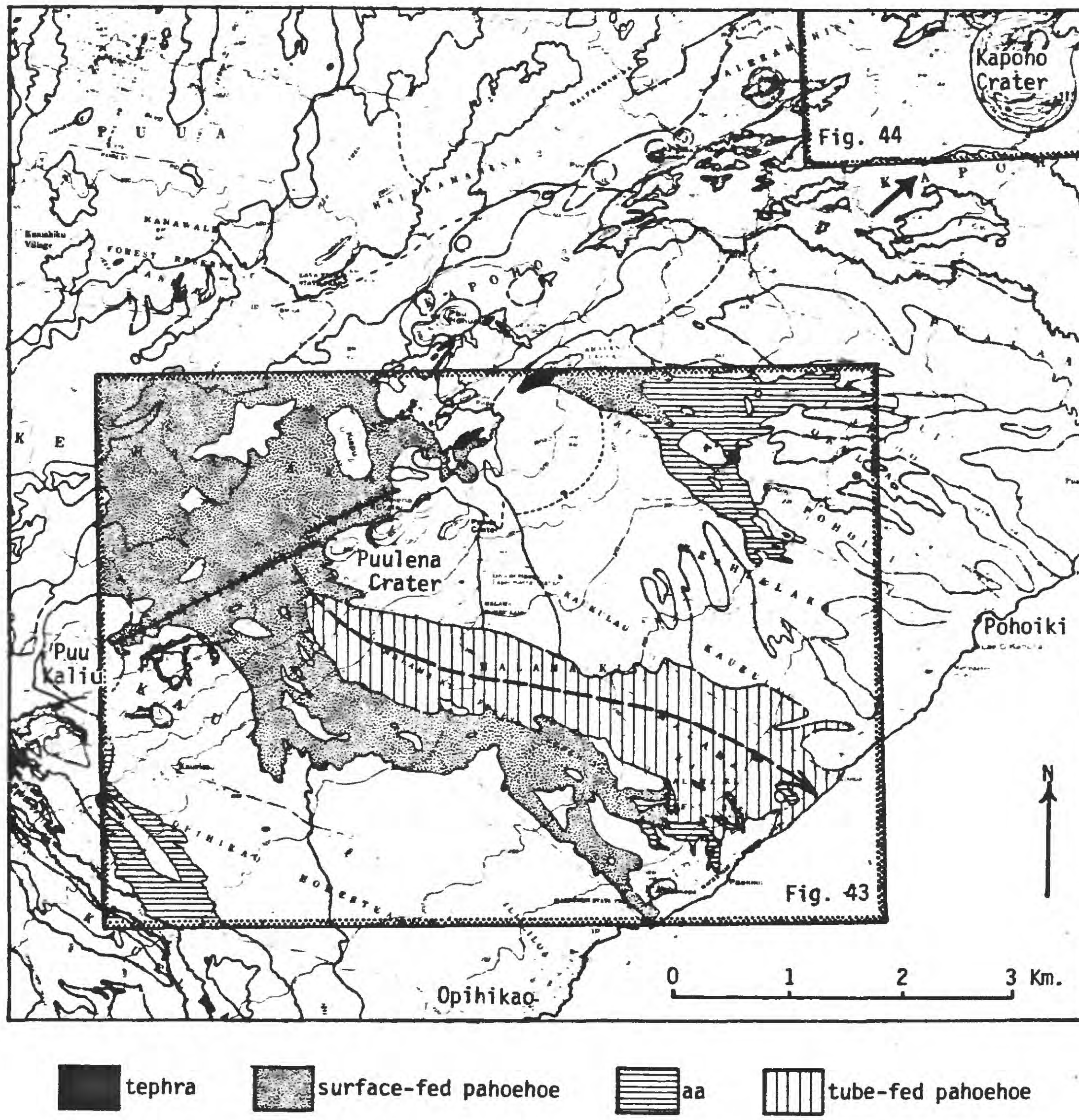


Fig. 42--Index map of the lower east rift zone between Kaliu and Kapoho Crater. Shown are the locations of Figures 43 and 44. Shading patterns indicate the various types of flows thought to date from the Eighteenth Century A.D. The arrow near the upper right corner indicates the viewpoint and view direction of the panorama at the top of Figure 44.

Fig. 43--Lava flows of the Malama vicinity. A prominent group of lava flows was erupted from a fissure extending from Kaliu past the north side of Kakiwai and Puulena craters. Macdonald (1941) included parts of these flows landward of the fissure in the flow of ca. 1790 mentioned by Ellis (1827), but he did not include the parts extending seaward from the rift zone. The morphology of the flows, especially a prominent lava tube traceable to the vent area, indicate that these seaward parts should be included and that these flows did reach the sea, contrary to Ellis' remarks. There is some uncertainty in the classification of this lava flow assemblage; the vent area is characterized by open fissures and spatter ramparts typical of type A assemblages, but the tube-fed flow is characteristic of type C or type D assemblages. It is designated as type A because of the vent character even though the tube-fed flow is inconsistent with this classification. Evidently the scheme outlined in Chapter III cannot be applied strictly in all cases. Some other flows in this area, such as the one extending southward past the east side of the Pawai crater, have been assigned on Plate 3 to the Seventeenth Century, but this was done with considerable uncertainty; they too may date from the Eighteenth Century. The paired dots near the coast at lower right designate a paleomagnetic collection site. This stereo triplet was prepared from photographs 128, 129, and 130 of roll 23, series HAI by the U.S. Navy, 1954.


N

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 Pualaa village 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 (Puulena), and Honuaula. Macdonald (1941) inferred from these accounts that the lavas of about 1790 were confined to the region north of 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 Eighteenth Century, so that the one confined north of the Kaliu-Malama complex is different than 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 43. In mapping this flow I placed more faith in the patterns of vegetation and flow morphology than in Ellis' inference, trusting that his verdant coastline fronts another part of Malama or that vegetation was reestablished quickly along the coast. (It should also be noted that the Hawaiian account given to Ellis could be essentially correct in stating that Kaliu, Malama, and Honuaulu dammed a flood of lava, but these hills could still permit some tongues to flow through the gaps between them.) An Eighteenth Century age for this flow is also consistent with its direction of remanent magnetization (site 8B025).

Age uncertainties may account for a peculiar pattern of ages along the rift zone. Though few Seventeenth Century flows are shown along most of the rift zone, several are shown along its lower segment. Moreover, Eighteenth Century flows that are widespread elsewhere are not shown along the rift below Puu Honuaula. Some of the flows indicated as Seventeenth Century may actually belong to the Eighteenth Century, and vice versa. Quantitative studies of forest morphology, or other precise dating methods, may resolve these uncertainties.

The morphology of flows and vents indicate that all of these latest prehistoric eruptions, except for that of Heiheiahulu, and perhaps the one of ca. 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.

Pyroclastic Deposits of the Lower East Rift Zone

The east rift zone below Heiheiahulu contains several large pyroclastic vents, and sheets of ash blanket several kipukas now cultivated for sugar cane on both sides of the rift zone. Ash layers of several different ages appear to be present, and they afford an opportunity to define a detailed stratigraphy for this area by means of tephrochronology. Such detailed field studies were not possible in this project, but future work is warranted because of the rapid population growth of this area and the threat of further eruptions. The possible complexity of the record can be illustrated by considering the age of the Kapoho Crater tuff cone, an especially prominent vent complex whose pyroclastic deposits appear to have a variety of ages.

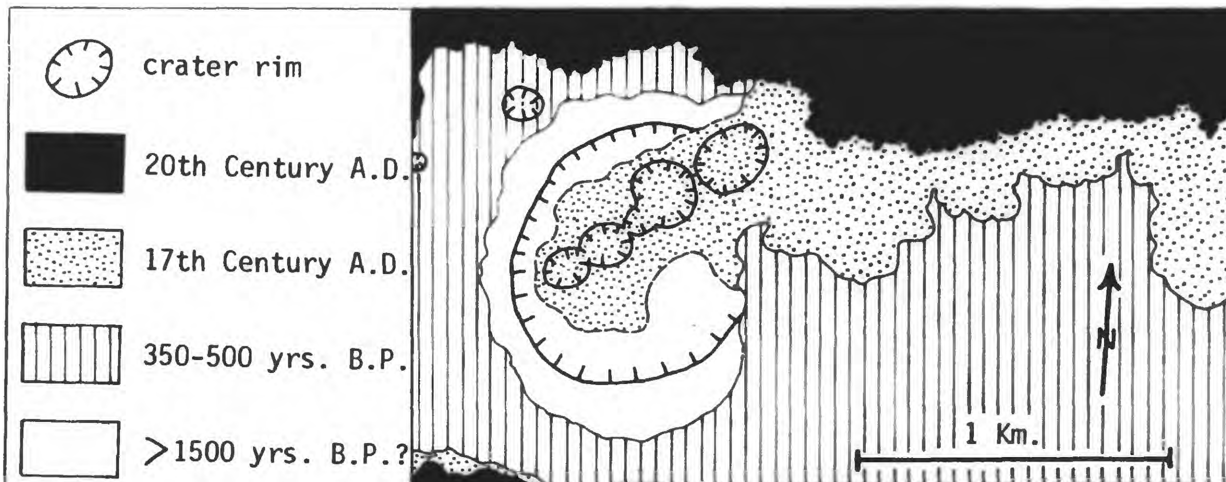
The most recent activity in Kapoho Crater is of uncertain age but probably occurred in the Seventeenth Century A.D. A date significantly earlier than A.D. 1800 is indicated by the account of Ellis (1827), who in 1823 recognized its volcanic nature and questioned the Hawaiians living there about its last eruption. Though Hawaiian traditions 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 a long time 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." On the other hand, the aa flow extending through the gap in the east side of the cone (Fig. 44) is magnetized in a direction typical of the Seventeenth Century (paleomagnetic site 8B205), and a ^{14}C date of less than 200 years B.P. was obtained from charcoal sample W-2970 beneath a pyroclastic layer within the cone (Kelley and others, 1979). Given the uncertainties in both the radiocarbon and paleomagnetic dating methods, a single eruption may have produced both the flow and the pyroclastics a century or so before Ellis' visit.

But earlier eruptions also occurred in Kapoho Crater. The Hawaiians questioned by Ellis (1827) said that the crater was "one of the places from which the volcanic goddess threw rocks and lava after Kahavari, for refusing his papa, or sledge, when playing horua," a well-known account of an eruption attributed to about A.D. 1350 (Westervelt, 1916; Macdonald, 1941). (This age is only slightly inconsistent with an age of 350 to 500 years B.P. inferred from paleomagnetic site 9B205 on Kaholua o Kahawali.) Moreover, strati-

Fig. 44--Kapoho Crater. At the top is a panoramic view looking northeastward from the area indicated on Figure 42, and below it are a geologic sketch map and stereo pair prepared from photographs 4 and 5 of roll 12CC, series EKL, by the U.S. Department of Agriculture, 1965. The tuff cone is incomplete, possessing a gap on its eastern side through which a thick prehistoric aa flow extends eastward 1 mile to the present shoreline. This aa flow appears to have been erupted during the Seventeenth Century A.D., and it sits atop pahoehoe flows that have a direction of magnetization consistent with an age of 350 to 500 years B.P. (Paired dots on the stereo pair indicate the paleomagnetic sampling sites.)

Both lava flows are veneered by ash distributed around the tuff cone, suggesting that the pyroclastics postdate the flows, but the aa flow must be younger than the cone if it has extended through a gap in the cone, and the sharp break-in-slope around the outer base of the cone suggests that the cone protrudes through the pahoehoe flows and predates them as well. (If the cone postdated the pahoehoe flows, it should possess a concave profile feathering out smoothly onto the flows.) An answer to this dilemma is suggested by a radiocarbon date of less than 200 years B.P. obtained from a charred log excavated from beneath an ash layer on the interior slope of the tuff cone. (The charcoal sample site is indicated by a crossed dot on the stereo pair.) Both the aa flow and its veneer of ash may have been erupted during the Seventeenth Century from the chain of craters within the cone, while the bulk of the cone is older than the pahoehoe flows. At least one of the interior craters, the one containing Green Lake, is rimmed by ash deposits having cross-beds and antidune structures typical of the base surge deposits of phreatomagmatic eruptions. Ellis (1827) described within Kapoho Crater "a smaller circle of hills, equally verdant, and ornamented with trees" which may have comprised an inner tuff ring around the chain of interior craters. (An inner circle of hills is not now definable as a morphologic feature, and it may have been destroyed by quarrying.) The aa flow and young ash deposits around the chain of craters may be products of different stages of a single eruption. The younger ash was considered too thin to map in most places and is shown on Plate 3 only where it is thick within Kapoho Crater.

The age of the tuff cone itself is difficult to estimate because it appears to predate all other units, but if the charred log represents a forest growing on the cone when the younger ash was erupted, the cone must predate the ash by a significant interval. The prominent gulleys of the outer slope of the cone (which Ellis described as having "deep indented sides" in 1823) may also arise from considerable age, and such an age is also probable if the eastern gap of the cone represents the former presence of a shoreline there and its subsequent eastward migration by means of lava-flow accretion. The age of the cone is therefore estimated, with considerable uncertainty, as greater than 1500 years B.P.


crater rim
20th Century A.D.
17th Century A.D.
350-500 yrs. B.P.
>1500 yrs. B.P.?
1 Km.
N

graphic and morphologic evidence suggest that the bulk of the tuff cone is considerably older than 500 years B.P. (Fig. 44). Three or more different ash sheets of distinctly different ages may have been deposited by eruptions from Kapoho Crater; if so, they should be useful for defining relative ages of other nearby eruptions. If more pyroclastic layers have been produced by other vents in the vicinity, a very detailed stratigraphic sequence may be worked out.

The abundance of pyroclastics along this stretch of the rift zone could have various causes related to the volcano's long-term behavior. Three possibilities are especially pertinent to the focus of this work. First, this area could have been less flooded by lava than other areas because eruptions were less extensive here, with unflooded patches accumulating ashy veneers from several different eruptions. Second, the eruptions here could be more vigorous ash producers because of changes in magma composition during its transport along the rift zone. Third, the eruptions here could be more vigorous because the surface elevation is low and close to the water table, with rapid near-surface mixing of cool water and hot magma producing phreatomagmatic explosions. Such hypotheses cannot be judged well with the field evidence now available; this evidence is sufficient only to suggest that the abundance of pyroclastic material varies along the rift zone. This problem should be given further attention during future detailed studies of rift-zone behavior.

Structural Pattern of the East Rift Zone

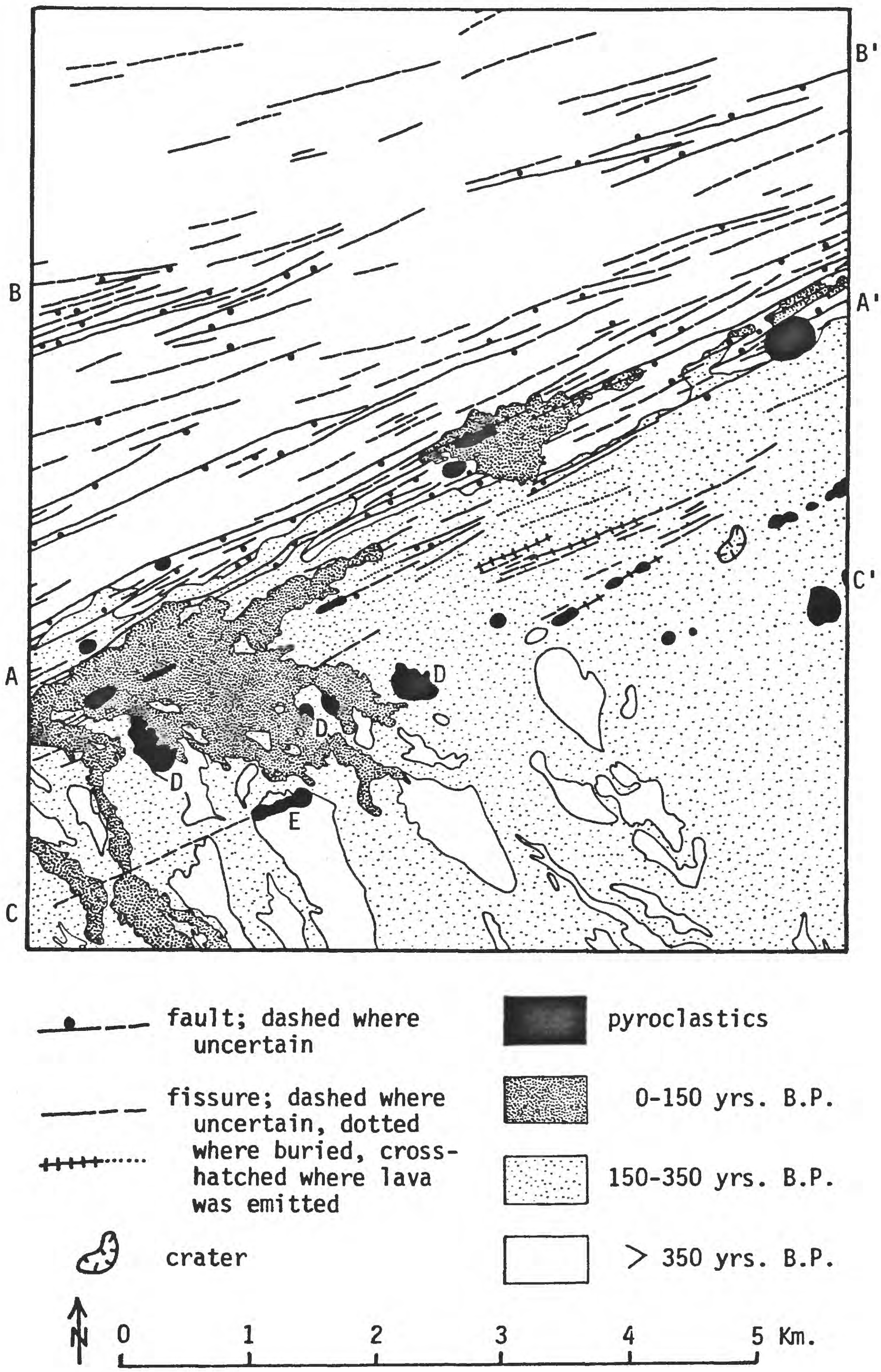
The geologic map reveals a structural pattern for the east rift zone somewhat different than has generally been visualized in the past.

The rift zone is more straight and regular and generally wider than is commonly thought. Previous misconceptions have apparently arisen from the briefness of the interval of historic rift behavior and from irregularities in the distribution of Eighteenth Century lava flows, which selectively blanketed and concealed some parts of the rift zone.

Examples of these misconceptions occur in the lower east rift zone, where kinks are often shown in maps (e.g., Skokan, 1974; Furomoto, 1976) of a narrow rift zone. The kinks follow offsets in recent eruptive fissures. But older eruptive fissures follow paths that are very different, and kinks in the rift zone as a whole cannot be inferred from offsets of just a few young fissures. The 1840 and 1955 fissures, for example, are subparallel but separated by as much as 3.5 km of relatively unbroken ground flooded by Eighteenth Century lava. Offsets in the line of 1955 fissures do not reflect the structure of the rift zone as a whole.

Another misconception is the idea that the middle east rift zone has migrated seaward in recent times (Swanson and others, 1976). A wide band of prominent structures borders the recent eruptive fissures to the north but not to the south (Fig. 45). It has been inferred from this pattern that active rifting now occurs near the southern margin of the middle east rift zone and that the locus of rifting has therefore migrated southward. But the map shows that some older structures do exist south of the recently active zone of rifting. Some ancient large spatter cones, for example, lie more than 1 km seaward of Kalalua (which itself is an ancient vent south of the recent fissures) in alignment with the 1955 fissures further east, and buried faults are expressed by lineations and areas of ponded lava.

Fig. 45--Middle east rift zone west of Heiheiahulu. The map shows contrasts in the numbers of eruptive vents and surficial fissures north and south of the most recently active part of the rift zone between A and A'. The northern limit of the rift zone is indicated approximately by B-B' along which the northernmost definitely mappable fissures occur; the possible fissures shown north of B-B' are inferred from faint lineations in the rain forest and may be imaginary. The southern limit of the rift zone is thought to lie along C-C', where the southernmost pyroclastic cones occur. If these limits are correct, the most recently active part of the rift zone is its axis, and the two halves of the rift zone differ strikingly from each other in appearance and recent behavior. The northern half is densely fissured but contains no eruptive vents, while the southern half is comparatively unfissured but contains many eruptive vents. Low hills at points D are indicated with much uncertainty as pyroclastic, but a field check showed that the hills at point E are definitely pyroclastic. The sparsity of surficial fissures south of A-A' is thought to arise from widespread burial of fissures by lava flows during the Eighteenth Century. The broken surficial lavas north of A-A' are thought to be 350 to 500 years old, and the fissures must be younger. If the visible fissures represent an interval of dilation of the entire rift zone, with their southern counterparts now buried, this dilation must have occurred before the Eighteenth Century flows were erupted. Therefore an episode of considerable dilation may have occurred between 150 and 500 years ago, but neither the age nor the amount of dilation is tightly constrained by the evidence now available.


B'
B
A'
A
C'
C
D
D
D
D
E
fault; dashed where uncertain
fissure; dashed where uncertain, dotted where buried, cross-hatched where lava was emitted
crater
pyroclastics
0-150 yrs. B.P.
150-350 yrs. B.P.
> 350 yrs. B.P.
N
0
1
2
3
4
5 Km.

The middle east rift is much wider than previously thought, and the recent rifting is along its axis. The southern part has been obscured because the Eighteenth Century lava flows were erupted slightly south of the topographic crest of the rift zone and accordingly flowed southward, selectively flooding the southern part of the rift zone.

The upper east rift zone too has been considered a narrow feature, but because the geologic map shows the rift zone elsewhere to be 3 to 4 km wide, this segment is shown on Figure 46 as wide also. If this is an accurate portrayal, the pronounced bend in the recently active part of the upper east rift zone--a feature exciting much curiosity in the past--is no longer prominent in the east rift zone as a whole. The bend may arise merely from a recent localization of activity along the southern boundary of this segment of the rift zone, perhaps because magma has recently found easy access from the rift zone into faults of the Koae system splaying out westward toward the southwest rift zone. If such intrusions from the upper east rift zone into the Koae fault system, inferred from seismic and geodetic data to have occurred recently (Unger and Koyanagi, 1979), have occurred for a long time in the past they could result in a gradual <u>westward</u> migration or expansion of the east rift zone (and development of the prominent bend in the active zone) instead of the southward migration inferred previously.

These observations of the location and regularity of the east rift zone are supported, generally but not entirely, by a recently compiled aeromagnetic map (C. J. Zablocki, unpubl.). The map shows a large magnetic anomaly, presumably caused by dikes or ponded flows that have accumulated for a long time, extending straight down the

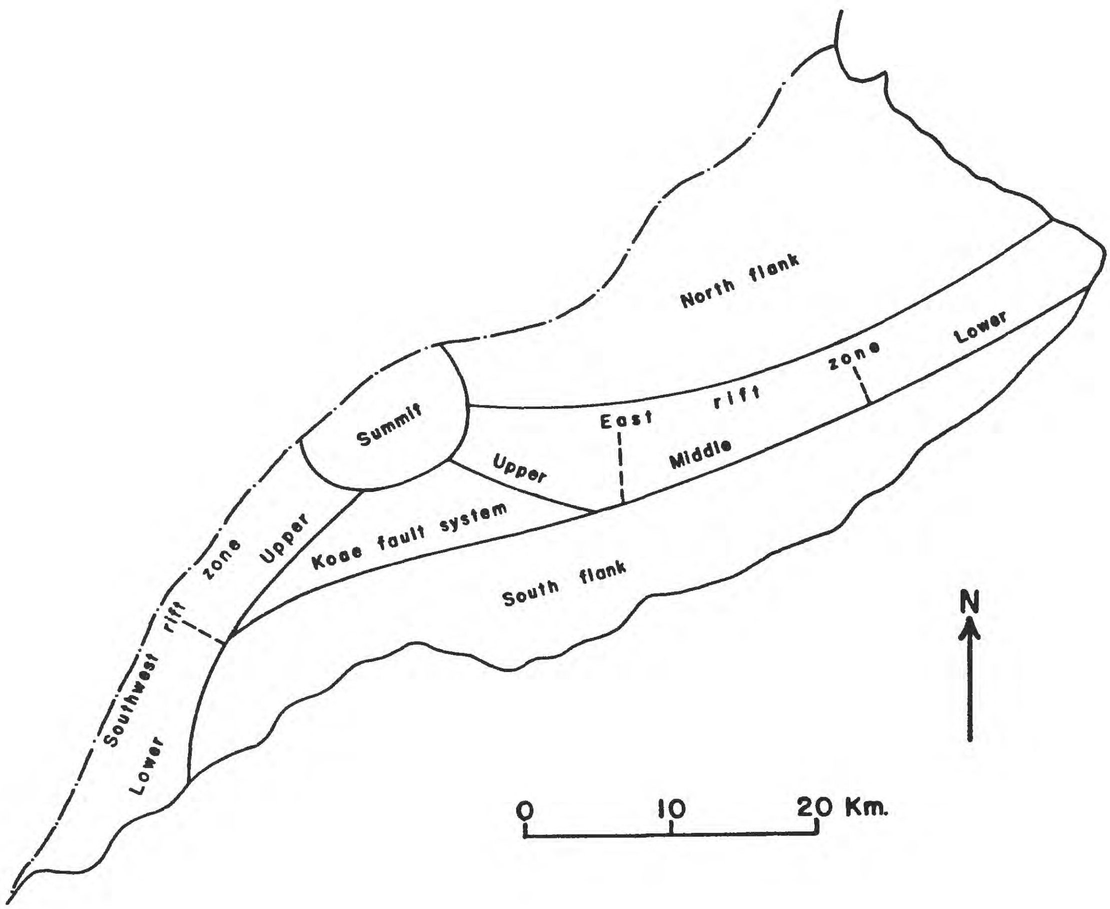


Fig. 46--Structural subdivisions of Kilauea. Modified after a similar map by Swanson, Duffield, and Fiske (1976). Summit structures are arranged mainly in an annular pattern and are downthrown toward the caldera. Faults of the Koae system are also downthrown northward toward the caldera, while faults (Hilina fault system) of the south flank are mainly displaced downward to the south. The upper east rift zone is dominated by pit craters aligned along the volcano's dominant conduit system, and the middle and lower parts of the east rift zone are marked by close-spaced parallel fissures, faults, graben, and linear chains of vents. The southwest rift zone is similar to the east rift zone, but its surface lacks large pit craters and appears to be affected more greatly by broad-scale subsidence, the upper part being a very broad and shallow sag or graben structure and the lower part a locus of seaward subsidence. The only part of Kilauea's surface unbroken by recent structures is the north flank, but the lava flows here may merely be draped across inactive lower parts of Mauna Loa's east rift zone.

center of the wide zone of the middle and lower east rift, not to the north of the recently active zone as would be expected if the rift has migrated southward. In the upper east rift zone, however, the anomaly follows the curve of the narrow chain of craters--not the center of a broad rift as shown on Figure 46.

North-flank Lava Flows from Hale o Ai-laau

Much of Kilauea's north flank is blanketed by a group of tube-fed pahoehoe flows extending east-northeast from the summit region through the subdivisions south and east of Mountain View to the coast around Kaloli Point. All flows of the group appear to be of similar age and younger than some kipukas (discussed in a following section) along the north side of the middle east rift zone, cutting across them and supporting a comparatively patchy and juvenile forest. Their youthfulness is accentuated by the fact that their vegetation was apparently even lighter in the Nineteenth Century, eliciting frequent comments from visitors about their lack of forest (e.g., Hitchcock, 1911, p. 160-161). Wilkes (1845, p. 119), for example, 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." (That this description may be somewhat exaggerated, however, is indicated by the following quotation in a vitriolic critique, by "A. V." in the February 1, 1847, issue of The Friend, of Wilkes' report: "the road from Olaa to the 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. The smooth lava, when it is not covered with sod, has been trodden so much, that it is grooved out and worn away in many places. The path is nearly as distinct as a turnpike, the greatest part of the way." Maybe Wilkes turned off the pike.)

Despite the general lack of thick forest on these flows, scattered patches of ohia trees occur on them and can be used, between elevations of about 50 and 500 m, to delineate individual tube-fed flows of the group (Figs. 47, 48). Large ohia tend to be clustered together on certain parts of the flows, especially along their margins and axial lava tubes. Trees grow along the tubes, and especially around breakdowns of their roofs, perhaps because their roots can penetrate into the tubes to obtain moisture collecting on their ceilings, walls, and floors. Cave organisms may also provide nutrients for the trees. Trees probably grow on the thin flow margins for similar reasons, taking moisture and nutrients that accumulate along the underside of the flows.

Individual flow lobes cannot be mapped above elevations of about 500 m, disappearing upslope into a monotonous young ohia-hapuu forest. The climate above this elevation may promote a faster growth of forest all over the flows, concealing their boundaries. Or the flows upslope may be less inflated and thinner, permitting tree roots to penetrate to their bottom surfaces everywhere.

The forest above 500 m extends with little variation (except for an irregular band along the former Glenwood-Makaopuhi trail that was logged early in this century) to the summit region on the east side of Kilauea caldera. This region is capped by a large satellitic

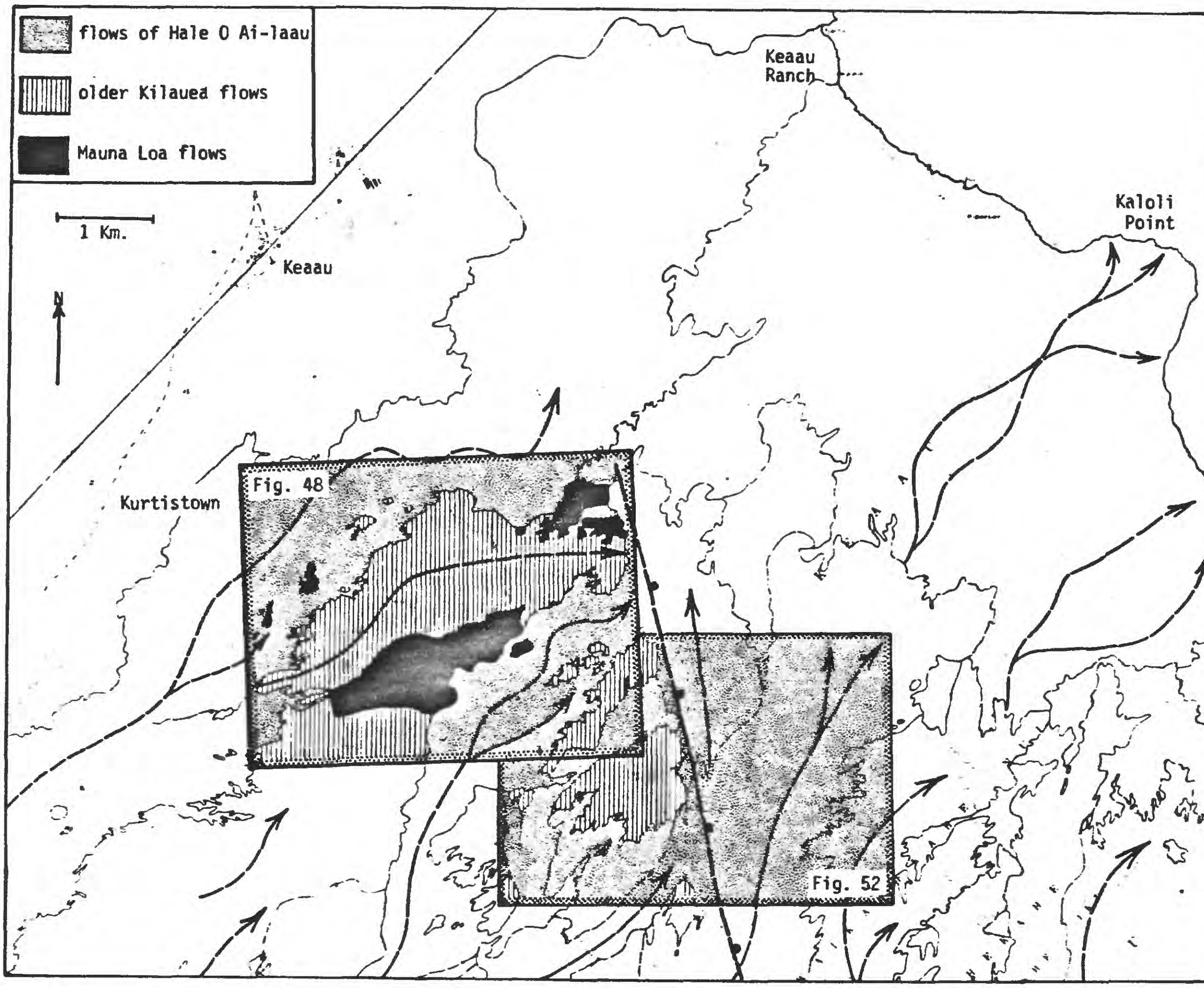
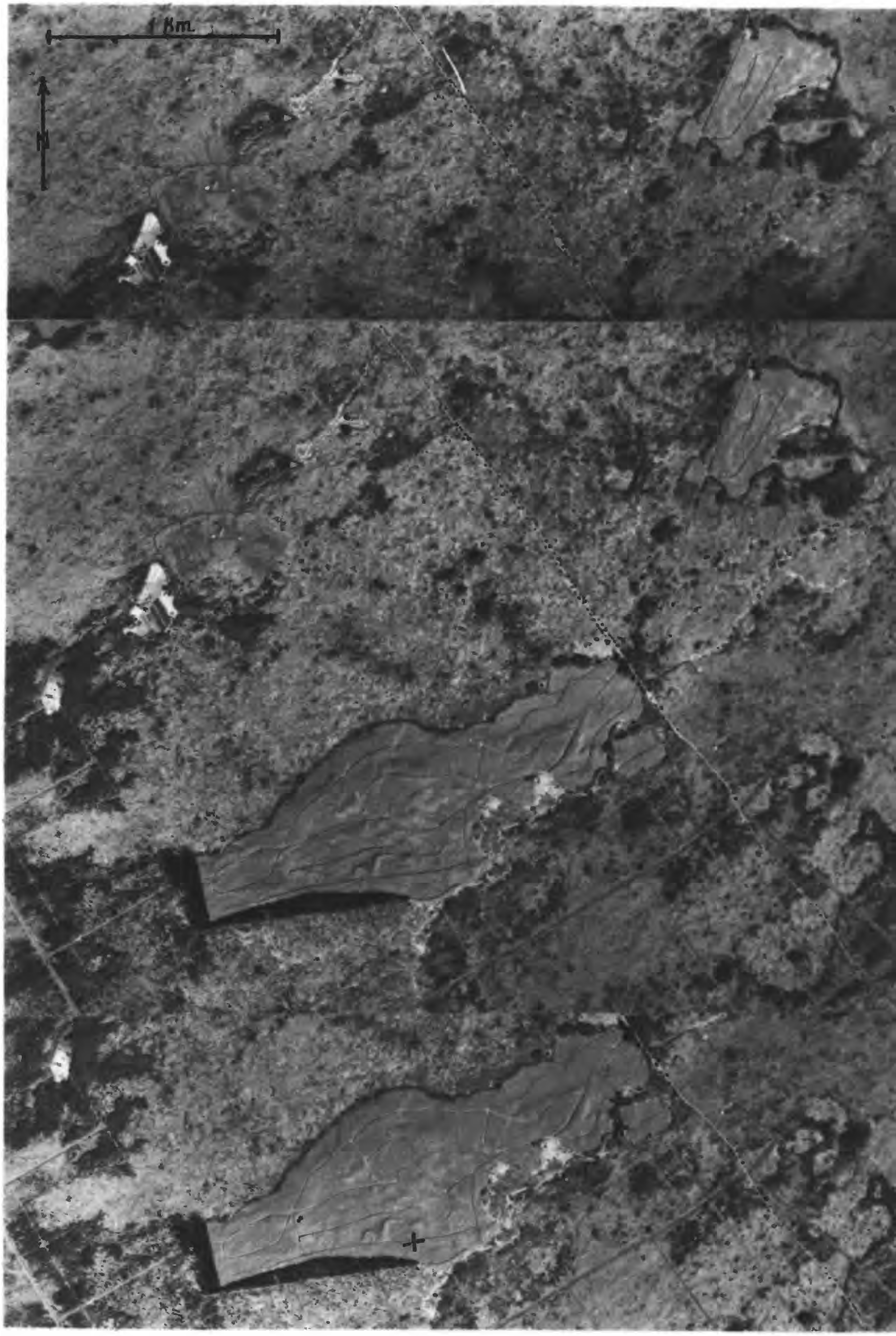


Fig. 47--Index map for Figures 48 and 52, southeast of Keaau.

Fig. 48--Lava flows southeast of Keaau. Stereo triplet was prepared from photographs 81, 82, and 83 of roll 12CC, series EKL by the U.S. Department of Agriculture, 1965. Truck farms and fields of sugar cane occupy the older ash-covered flows of Mauna Loa, while the Kilauea flows are uncultivated. Two groups of Kilauea flows can be distinguished, differing from each other in age. The older flows possess a subtle pattern of gray splotches, probably owing to vegetal variations, that is absent on the younger flows, and older flows possess a characteristic pattern of incipient drainage channels cut into their surfaces. Though contacts between the two flow groups are difficult to observe in the field, owing to the dense vegetal cover, they are expressed on the aerial photographs by changes in gray tone and by clusters of ohia trees atop the younger flows near their margins. The accuracy of the mapped contacts has been confirmed in a few places by field checks, and the difference in age of the two flow groups has been confirmed by means of geomagnetic secular variation. Paired dots indicate paleomagnetic sampling sites, and crossed dots are ^{14}C sampling sites. Some of the small clumps of ohia along the axes of the younger flows are known to occur above lava tubes. The thick stand of trees bordering the southern and western sides of the largest cane field is an artificial planting of Norfolk pines and other trees.


1 Km
N

lava shield centered on the east end of Kilauea Iki crater, and large lava tubes (including Thurston lava tube) extending eastward down its flank apparently fed the lobes mapped at lower elevations. The shield and flows together are inferred to be the products of a long-sustained, stable eruption of type D.

The apparent vent area for the flows is the east end of Kilauea Iki, which is a complex elongate crater extending eastward from the caldera (Fig. 49). The easternmost part of the crater, where the Kilauea Iki trail descends from the Thurston Lava Tube parking lot to the crater floor, appears older than the other parts, its slopes supporting a more mature forest. This part also differs in morphology, being less deep and having lava plastered against its walls in a few places. It is interpreted as the principal site of eruption, the drained eruptive crater now choked with bouldery talus of the lava shield. The remainder of Kilauea Iki is deeper, steeper, and lacks any sign of wall plaster; it is interpreted as a chain of later collapse pits along a large conduit that fed magma to the vent from a shallow magma chamber beneath the present caldera. For reasons given in Chapter 5, the vent area at the east end of Kilauea Iki is referred to as Hale o Ai-laau.

The summit of the lava shield is complicated somewhat by a broad, sagged platform developed on its surface just east of Hale o Ai-laau (Fig. 49). The sagged platform is similar to those developed at various times above the site of Alae pit crater after it was filled (Swanson and others, 1972; Holcomb and others, 1974), and a large pit crater is inferred to lie buried beneath it. The presence of such a crater, filled with ponded, still-cooling lava, could explain the

Fig. 49--Hale o Ai-laau. Stereo triplet constructed from frames 185, 186, and 187 of roll 12CC, series EKL of the U.S. Department of Agriculture, 1965. The elongated crater Kilauea Iki is a chain of three or four different collapse structures extending eastward from the present caldera. The crater contains a lava lake erupted in 1959; note the change in photographic tone of the lake surface from frame to frame. Hale o Ai-laau is the vent area including the east end of Kilauea Iki and the smaller collapse pits surrounding the parking lot for Thurston lava tube. The vent area occupies the summit of a large satellitic lava shield whose tube-fed lava flows cover much of Kilauea's north flank. A broad, shallow sag occupies the platform southeast of the vent area; this sagged platform is thought to overlie a large buried pit crater. A broad ridge extending northeastward from the vent area appears to have small pits (circled) along its crest and may represent the path of a major lava tube. Similar ridges radiate southward and southeastward from the platform outside of this view. Paired dots are paleomagnetic sample sites.

self-potential anomaly mapped by Zablocki (1976) in this area. Similar morphologic evidence has been used to infer, with much uncertainty, on Plates 2 and 3 the presence of other prehistoric pit craters buried beneath the surface of the east rift zone.

The total extent of lava flows from Hale o Ai-laau is uncertain. Besides the flows of the recently developed land subdivisions south of Glenwood and Keaau, three other flow groups of similar age could be derived from the same vent. These groups include (1) a thick accumulation in the summit region comprising the walls of the present caldera; (2) a band of flows extending southward of the upper east rift zone between Ainahou and Kane Nui o Hamo to the coast between Keauhou Landing and Kealakomo; and (3) a band of flows extending northeastward from the middle east rift zone in the vicinity of Kalalua to the northeast coast around Makuu. All of these flows share the distinctively high-inclination (steeper than 40 deg) direction of magnetization of the flows from Hale o Ai-laau. Each group of flows poses a unique problem of interpretation.

The summit group is problematic because although it is thicker than 100 m in the region of the present caldera, no correlative flows have been found beyond the summit to the southwest. Apparently the flows from Hale o Ai-laau were able to spread widely only to the east and south, while something prevented their spreading to the west. As discussed elsewhere, the barrier to westward spreading probably was an ancient caldera present in the summit region when Hale o Ai-laau was active. The vent was located along the eastern margin of this large ancient caldera, and much of the lava accumulated within the caldera, largely filling it. But as the lava shield grew around the vent it eventually overtopped the eastern rim caldera rim so that flows could spread eastward down the north flank of Kilauea.

The southerly band of flows could also come from Hale o Ai-laau, but on Plate 2 these flows are interpreted differently. They are smaller, individually, than those of the north flank, and they comprise a more complex assemblage of flow types. They are interpreted as a type C assemblage from a vent along the upper east rift zone, probably Puu Huluhulu. These flows are associated in Hawaiian traditions with a conflict between Pele and her lover Kamapua'a, the "pig-man," while the north-flank flows are probably associated with Pele's predecessor, Ai-laau, as discussed in Chapter 5. If the chronology of the traditions is correct, the band of flows south of Puu Huluhulu is at least slightly younger than those of Hale o Ai-laau even though their directions of magnetization are similar.

The third group of flows, appearing superficially to come from the middle east rift zone, is assigned to Hale o Ai-laau on Plate 3. There is considerable uncertainty in this judgment, and I mapped them initially as flows of the east rift zone, but I now believe the chances are good that they do belong to Hale o Ai-laau. I assigned them initially to the rift zone with considerable uneasiness because although they appear to be large tube-fed flows normally expected to occur in a type D assemblage, there was no large vent complex associated with them along the middle east rift zone. The vents inferred for them by Moore (Moore and Koyanagi, 1969) are simply younger fissures that cut across the flows near the margin of the rift zone. Kalalua is the only large vent edifice in the area, but its vegetation cover suggested that it was much older. Moreover, it is a large pyroclastic accumulation downslope from which the thick aa flows of Kaunaloa and Kapaahu extend southward to the coast at Kii, together comprising a typical type B assemblage. Paleomagnetic measurements showed that these aa flows are older than 1500 years, while the tube-fed flows have directions of magnetization similar to the much younger flows from Hale o Ai-laau. The possibility that a former vent edifice along the middle east rift zone subsided and was covered by younger flows can be ruled out because such an edifice would have to lie south of the rift axis. If such an edifice were present, some of its lava should have flowed southward, but neither paleomagnetic measurements nor vegetation analysis has revealed such flows. Because their magnetization directions and vegetation patterns are similar to the other flows from Hale o Ai-laau, I have assigned these flows to that group also. If this assignment is correct, these flows must have spread along the northern part of the rift zone for several kilometers without crossing it before moving northeastward onto the eastern part of the north flank. Graben structures and north-facing fault scarps may have prevented these flows from crossing the rift zone and spreading farther south. If the northern half of the rift zone was flooded extensively by flows of this age, the numerous faults must be younger than 350 to 500 years. It is possible, however, that most of these structures are older and have merely experienced recurrent displacement since the flows spread across them. The inferred youthfulness of flows upon the northern half of the rift zone may explain the lack of vents observed there (Fig. 45), with older vents being buried. The existence of buried vents and older structures may be evaluated by means of detailed fieldwork in this area, especially through examination of fissure walls. If the structures are old but eruptive vents are absent, the lack of eruptions poses a problem for the behavior of the rift zone.

Older Flows of the North Flank

The young flows from Hale o Ai-laau are not the only group that flowed from the summit region over the north flank. They were preceded by an older group distinguishable in kipukas between the younger lobes below elevations of about 400 m (Figs. 47, 48). The surfaces of these older flows are more highly weathered, and they are sufficiently older to have had trees growing on them before they were covered by the flows from Hale o Ai-laau because tree molds have been found near the edges of the latter flows in contact with the former. The older flows are recognizable on aerial photographs by the fluvial drainage systems developed upon them. Dendritic patterns of shallow gullies extend downslope along these flows, but the gullies terminate sharply at contacts with the younger flows. Vegetation patterns are slightly different on the older flows as well. For example, trees in the clusters commonly are larger on the older flows, and individual ohia of moderate size are scattered widely all over the flow surfaces. These older flows are similar morphologically to the younger ones, consisting of tube-fed pahoehoe with large axial tubes and gradients parallel to those of the younger flows. Though the present evidence cannot exclude a Mauna Loa source for these flows, a Kilauea origin seems most likely.

Several cultivated kipukas of even older flows occur between elevations of 50 and 200 m within 1 to 3 km of Kilauea's margin southeast of Keaau. These flows are covered with ash deposits and consist mainly of picritic aa flows similar to those on the nearby slopes of Mauna Loa. They are interpreted as Mauna Loa flows which underlie the surface of much of Kilauea's north flank at shallow depths. It appears that only two distinct groups of flows from Kilauea's summit have spread a thin sheet across the east flank of Mauna Loa near Keaau.

A third class of older flows, perhaps intermediate in age between the other two groups, exists on the north flank adjacent to the middle east rift zone. This region between the axis of the rift zone and subdivisions south of Mountain View, the area designated as "5D" on Figure 34, is the most poorly known region on Kilauea owing to its thick vegetation cover and lack of roads. Though large rift structures are prominent on aerial photographs of the southern boundary of this area, the forest is so monotonous that few rock units can be differentiated from photographic study (Fig. 50), and the forest is so thick that field work is difficult. However, some flows older than Hale o Ai-laau are known to exist here. Paleomagnetic site 8B805 shows that at least some of the north-flank flows in Ainaloa subdivision are older than 1500 years B.P., and a single traverse across the north flank to the rift zone at Kilauea (Fig. 51) showed that rocks different from those of Hale o Ai-laau are present. The flows between 2.2 and 3.3 km along the traverse are distinctive, possessing a "pimply" surface owing to abundant large (4-6 mm diameter) olivine phenocrysts embedded in their surficial glass, and they also contain numerous thin laths of plagioclase 7 to 10 mm long. Hydration rinds of these rocks are unusually thick compared with most surficial flows of Kilauea

Fig. 50--The monotonous forest along the north side of the middle east rift zone. Stereo triplet was prepared from frames 125, 126, and 127 of roll 12CC, series EKL by the U.S. Department of Agriculture, 1965. The location of this area is indicated on Figure 51. Aerial photographs could not be used to map lava-flow boundaries with any confidence in this area, but a single traverse on the ground showed that major boundaries must be present (Fig. 51). Some prominent rift structures are visible in the southeastern corner, and a subtle, broad swell, elongated east-northeast near the center of this view, may be an ancient feature of the rift zone.

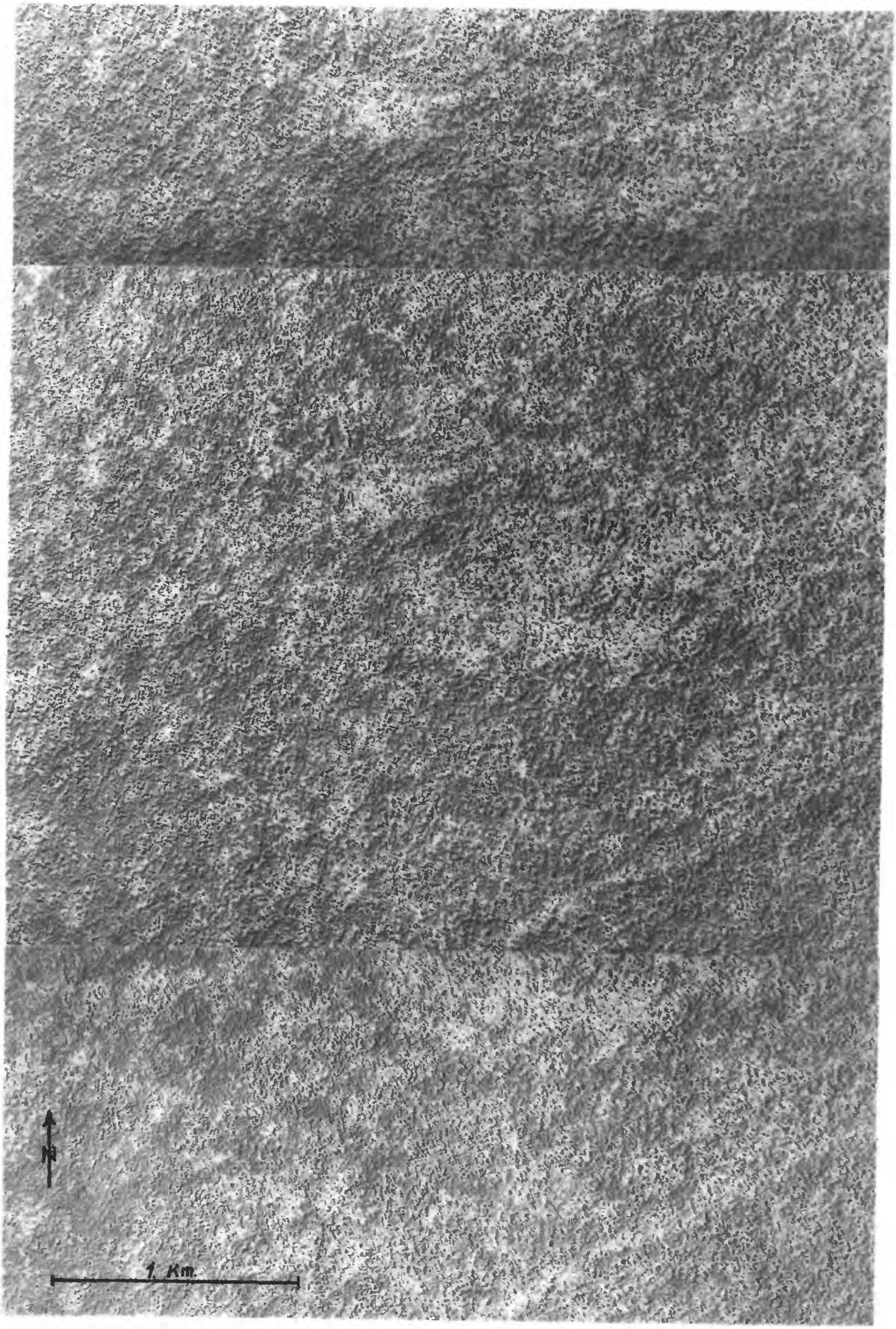
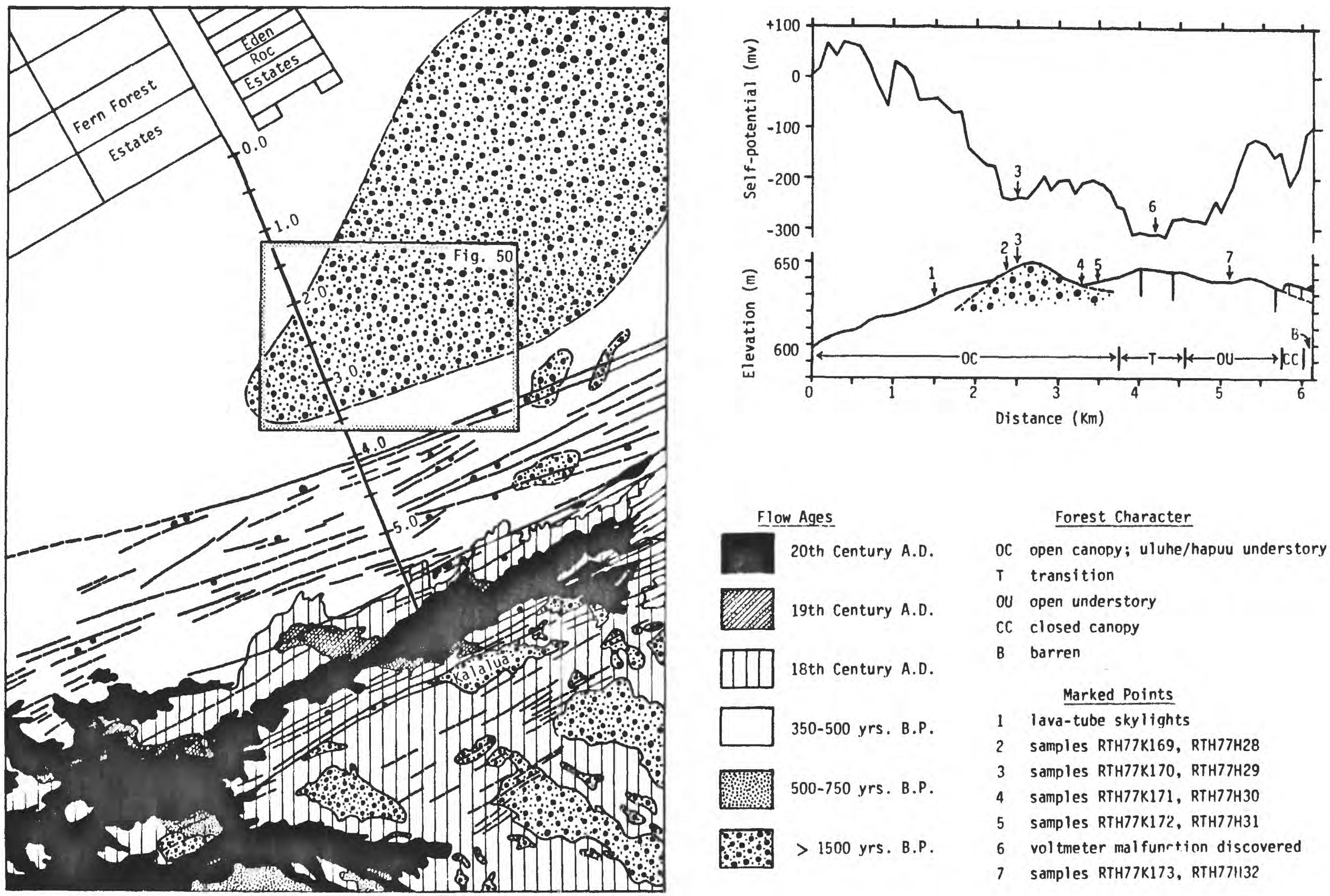

N
1 Km.

Fig. 51--Geologic map and cross-section of the north flank adjacent to the middle east rift zone. Shown on the cross-section are results obtained from a single traverse through the forest along the line of profile marked in 0.5 km segments on the map. Data and samples collected along the traverse included rock specimens, descriptions of forest character, and measurements of self-potentials at 100-m spacings using techniques described by Zablocki (1976). Self-potentials southeast of point 6 are considered unreliable because of erratic behavior of the voltmeter. The faults and fissures shown on the map are those inferred from aerial photographs, while the three vertical lines extending downward from the topographic profile represent the only three structures observed on the ground. Many structures could have escaped notice on the ground because of thick ground cover and limited "vistas."

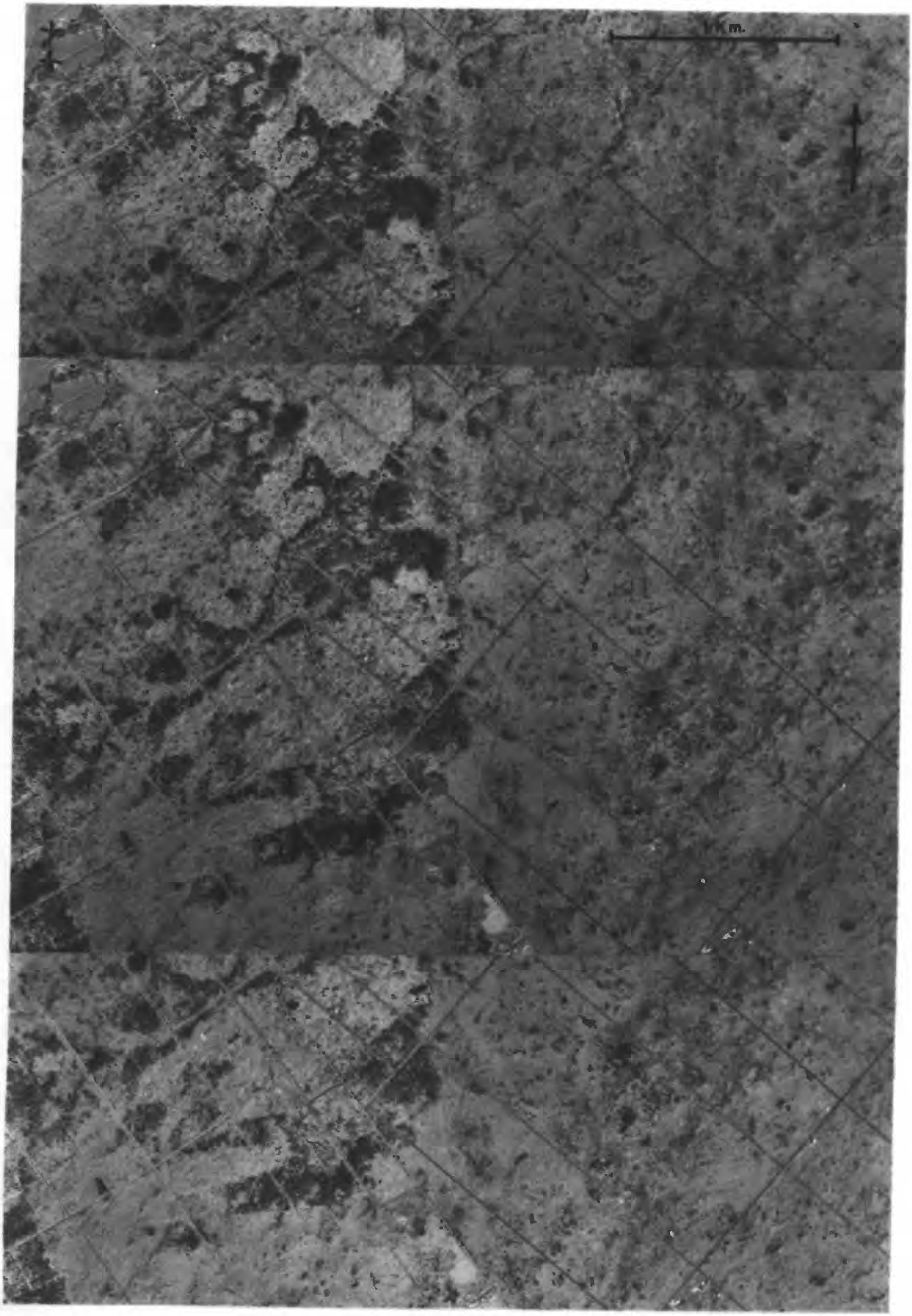

Fern Forest
Estates
Eden
Roc
Estates
0.0
1.0
2.0
3.0
4.0
5.0
Fig. 50
Kalalua
Self-potential (mv)
+100
0
-100
-200
-300
Elevation (m)
650
600
Distance (Km)
0
1
2
3
4
5
6
OC
T
OU
CC
B
Flow Ages
20th Century A.D.
19th Century A.D.
18th Century A.D.
350-500 yrs. B.P.
500-750 yrs. B.P.
> 1500 yrs. B.P.
Forest Character
OC open canopy; uluhe/hapuu understory
T transition
OU open understory
CC closed canopy
B barren
Marked Points
1 lava-tube skylights
2 samples RTH77K169, RTH77H28
3 samples RTH77K170, RTH77H29
4 samples RTH77K171, RTH77H30
5 samples RTH77K172, RTH77H31
6 voltmeter malfunction discovered
7 samples RTH77K173, RTH77H32

(J. G. Moore, oral commun., 1978); probably these flows are comparatively old. On the assumption that flows of diverse ages exist in this region of the north flank, some subtle variations in the vegetation pattern were used to differentiate flows thought to belong to Hale o Ai-laau from flows probably older than 1500 years. But little confidence is placed in the mapped pattern, and more field work will be needed to improve the knowledge of this area.

Structure of the North Flank

The north flank appears to be remarkably free of surficial structures, though ancient inactive structures of both Kilauea and Mauna Loa may lie buried beneath the surface. Only one possible large structure is shown on the geologic map, and even this one is indicated with great uncertainty. Its presence is inferred tentatively from a sudden change in surface gradient, flow morphology, and mapped rock units. It is a linear feature subparallel to the present coastline, about 5 km inland from Kaloli Point, extending about N. 15° W. from the intersection of Paradise Drive with Highway 13, at elevations averaging about 60 m. Several kipukas in the youngest flows are truncated along this line (Fig. 52), and no kipukas of Mauna Loa lava occur seaward of it. The average surface slope decreases sharply across it from about 1.6 deg inland to about 1.0 deg seaward. The flows from Hale o Ai-laau broaden abruptly seaward of this line and assume an "elephant-hide" texture (Stearns and Macdonald, 1946, Pl. 11B) and other features indicating significant degrees of inflation. Boundaries between these thickened lobes are obscure and are mapped with considerable uncertainty; the flows are interpreted as a band

Fig. 52--A topographic and geologic discontinuity southeast of Keaau. Stereo triplet made from frames 64, 65, and 66 of roll 12CC, series EKL by the U.S. Department of Agriculture, 1965. A sharp change in vegetation patterns extends north-south across the center of the view and corresponds to a lava-flow boundary. To the east are the younger flows from Hale o Ai-laau, highly inflated on a comparatively flat coastal plain, while to the west older flows are exposed in northeastward-elongated kipukas between less inflated lobes of young lava extending down a steeper slope to the coastal plain. The discontinuity may reflect a buried fault and/or shoreline, or it may simply represent the edge of a large lava fan accumulated near the coast. Highway 13 is recognizable as the paved road with mango trees planted at regular intervals along its edges. Paired dots are paleomagnetic sample sites, and crossed dots are ^{14}C sample sites.


1 km.

of roughly contemporaneous lobes coalescing on a low plain seaward of the discontinuity. The discontinuity may be a normal fault, dropped down to the east, or it may be an old shoreline. If it was a shoreline, it must have been a cliff several tens of meters high. It could have been a simple wave-cut cliff; if so, considerable time would have been needed for erosion before the younger flows accreted against the shoreline. If the discontinuity arose from faulting, however, little time would be needed for it to develop. Alternatively, it could represent neither fault nor shoreline but simply the edge of a very broad, flat cone of lava banked against older, steeper slopes. Such a cone could develop from several causes; for example, a rise in sea level could have raised a "baselevel" to which the subaerial slope of this stable area may have been adjusted.

Some Complications in the Summit Region

Kilauea's summit has been mapped in considerable detail by Peterson (1967), and little new information is shown on Plate 2. Nevertheless, some complications are present which were not shown on Peterson's map, and because they have considerable significance in the interpretation of Kilauea's recent history they will be summarized here. Some of these complications have been discussed previously in published literature; others have received no previous comment. They relate mainly to the locations of the principal eruptive vents before the collapse of Kilauea's present caldera, and to the existence and location of an ancient caldera that preceded the present one.

The details of the summit geology are difficult to unravel because a thick ash blanket of the 1790 phreatomagmatic eruption (Christiansen,

1979) obscures the morphology of underlying lava flows. Nevertheless, enough clues can be found to infer the locations of the earlier caldera and some eruptive vents.

There was at least one other important eruptive center in the summit region besides Hale o Ai-laau. Ground slopes and mappable aa lobes and flow lineations west and northwest of the caldera radiate from a point near the northwest wall of the caldera (Uwekahuna Bluff) a short distance east of the Hawaiian Volcano Observatory (Fig. 53). This point is inferred to be an eruptive center north of the most recent locus of activity at Halemaumau, and as discussed in Chapter V it is younger than Hale o Ai-laau. For reasons given in Chapter V, it will be referred to hereafter as "Lua Pele." The crater may have been located very close to Uwekahuna Bluff; a part of the bluff may have also been a part of the earlier crater wall. Some of the features interpreted previously as intrusions exposed in, or protruding out of, the caldera wall (Powers, 1916) are in reality plastered against the wall. They could be remnants of a lake in the eruptive crater, or they could be remnants of dikes intruded into a former concentric fissure that developed into the present caldera wall. Though the size of the Lua Pele shield and its extensive field of tube-fed pahoehoe (described in the next section) indicate that activity was long sustained at this vent, the radiating aa lobes indicate the existence of some instability toward the end of eruption, like that observed at Mauna Ulu (Holcomb, 1976).

Kilauea's caldera has a complex structure and history. It consists of two parts. First is an inner sink that has undergone profound collapse and is now floored by historic lava. The sink is

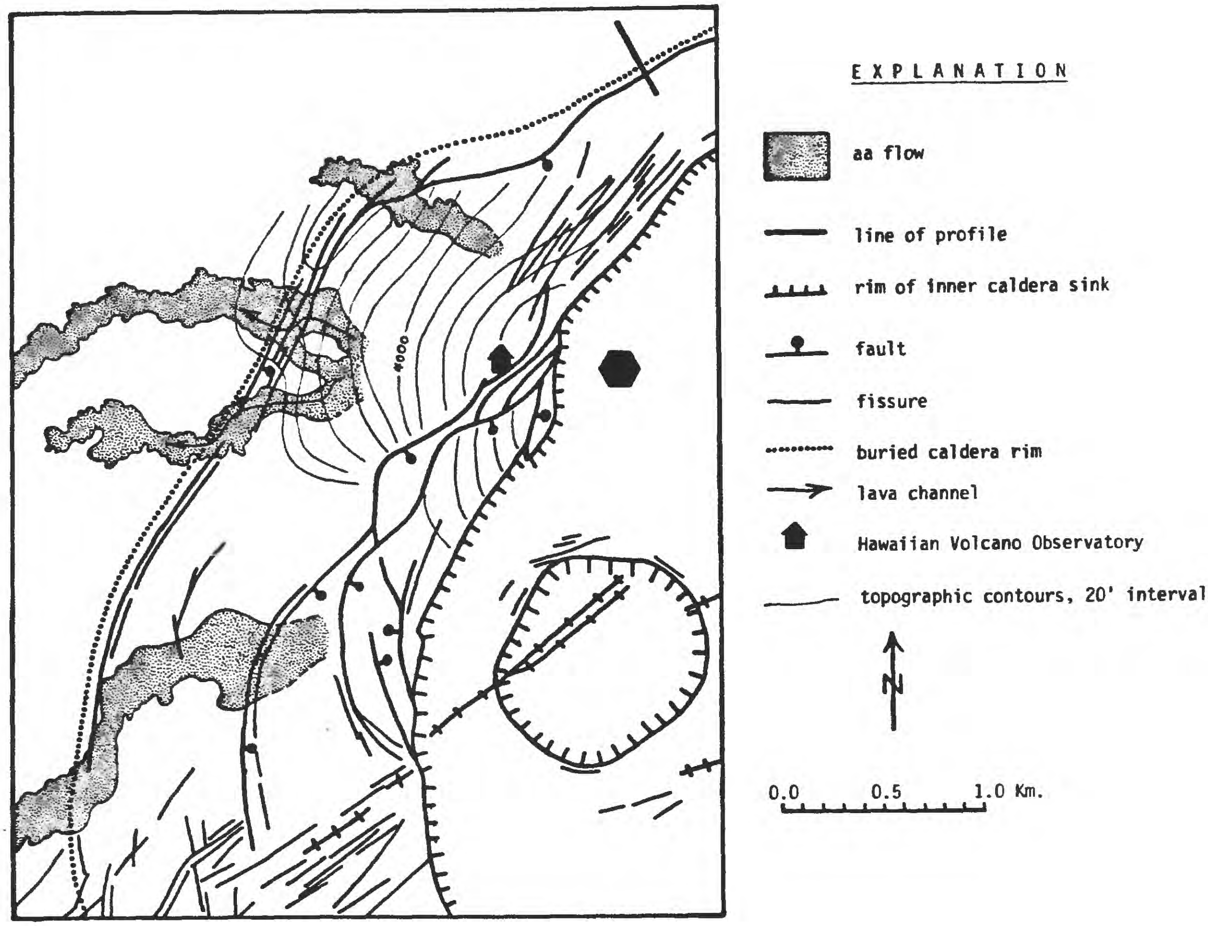


Fig. 53--Northwestern sector of Kilauea's caldera. The map shows some features used to infer the approximate location of "Lua Pele," indicated by the hexagon near the rim of the present caldera. Ground slopes (indicated by generalized topographic contours) and lava flows radiate from this area, which is north of Halemaumau. The map patterns of the youngest aa flows suggest that they may have been deflected by a scarp ancestral to the fault that now cuts across them, indicating that the deformation had begun before, and continued after, these flows were erupted. This structure therefore predates the formation of the present caldera, which postdates Lua Pele, and it is thought to lie just inboard of an ancient caldera rim, developing from thermal contraction of the lava filling the ancient caldera. Shown in the upper right corner is the line of profile for the diagrammatic cross-section of Figure 54.

surrounded by a less collapsed annulus in which anastomosing subconcentric fractures bound arcuate blocks that are stepped downward toward the central sink. All major displacements on these step faults occurred before deposition of the Keanakakoi Ash in 1790 (Christiansen, 1979), but it has been inferred that collapse was episodic and proceeded in successive steps above discrete centers (St. Ours, 1979).

The present caldera is nested within an older prehistoric caldera that was filled and buried before the present one developed. Existence of this ancestral caldera was first inferred by Powers (1948) from the great elevation differences between separate exposures of the Uwekahuna Ash. The principle exposures are in the base of Uwekahuna Bluff at elevations of about 1100 m, but Powers correlated these with an ash at Tree Molds less than 1 km away outside the present caldera at an elevation of about 1220 m (Doerr, 1933). In order to attain such a relief the ash must have been draped across a pre-existing caldera or must have been offset by caldera collapses after it was deposited. In either interpretation the ash exposed in Uwekahuna Bluff caps a fault block that subsided about 120 m in an old caldera, the actual fault displacement depending upon the unknown dip of the ash bed. Though he recognized the existence of an ancestral caldera, Powers did not infer its area or the exact location of its rim.

The location and shape of the ancient caldera are inferred on Plate 2. The buried rim is inferred in the Tree Molds area with a fair degree of confidence but elsewhere with much less certainty. The inference at Tree Molds is based on a truncation of the ash deposit. The ash may be examined by climbing to the bottom of the largest tree mold, about 2.5 m in diameter and 6 m deep. The ash here ranges up to about 1 m thick, and by comparison with the exposure in Uwekahuna Bluff, Powers inferred that the ash here was deeply eroded before it was covered by the surficial lava flow. Though the ash was eroded, the distribution of tree molds presumably rooted in it indicates that it still comprised an extensive layer when buried. Yet the ash layer crops out nowhere in the face of the outermost caldera fault just a few dekameters away (Fig. 54); the ash layer must be truncated between the tree molds and the fault so that it is not exposed. Truncation is inferred to arise from the presence of the buried caldera rim, and the outer caldera fault is inferred, by analogy with a similar fault around Mauna Loa's caldera, to have originated close to, but in front of, the ancient caldera wall due to differential thermal contraction of the lavas filling the caldera (R. T. Holcomb, unpubl. manuscript). If this interpretation is correct, it constrains the location of the ancient caldera rim in this area to within a few dekameters. If the outermost fault has the same origin everywhere it can be used to locate the old caldera rim through half of its perimeter from Hale o Ai-laau past Tree Molds to the vicinity of Cone Peak. A small amount of support may be given to this interpretation by apparent deflections in lava flow paths along the arc between Tree Molds and Cone Peak. If the outer fault was caused by thermal contraction it should have begun developing while the old caldera was still being filled, while the magma column was still high before subsiding to initiate the principal development of the present caldera. That this fault did develop at an early time is suggested by the morphology of the youngest mappable lava flows from Lua Pele, which appear to have been deflected along the fault scarp (Fig. 53). However, this

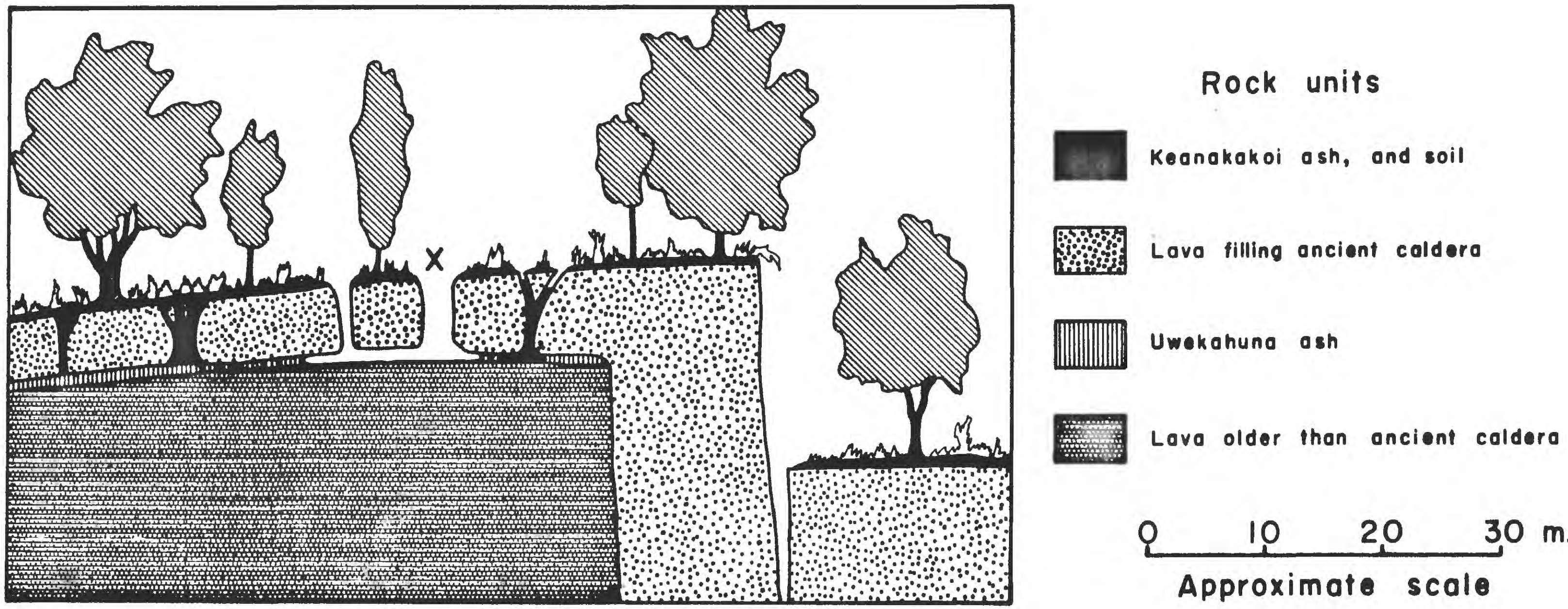


Fig. 54--Diagrammatic cross-section showing the buried rim of Kilauea's ancient caldera. It is inferred to lie buried only a few meters below the present ground surface a short distance south of the Tree Molds area of Hawaii Volcanoes National Park.

bit of evidence is considered tenuous. The southern perimeter of the ancestral caldera is inferred with much uncertainty because it is not possible to distinguish an outermost caldera fault from the faults of the Koae system. The rim is inferred to lie outside the concentric vents about 2 km south-southwest of the present caldera, and pass near the triangulation station at Ahua Kamokukolau. It is not known whether Puhimau Crater is inside or outside the old caldera. The stratigraphic section exposed in Puhimau should be useful in this regard, but it was not examined because of the difficulty in climbing into the crater. If the ancient caldera is delineated properly, its diameter is about twice that of the present inner sink.

Little information is available about the interior configuration of the ancient caldera. Only one deep exploratory hole has been drilled within its perimeter (Keller and others, 1979), and too little core was collected from the hole to construct a stratigraphic column at that point. However, the caldera was not everywhere a deep sink because the Uwekahuna Ash and older rocks are exposed in the wall of the present caldera about 1 km inside the perimeter of the ancient caldera and only a little more than 100 m lower than its rim. A bench at least 1 km wide must have lain along the northwestern perimeter of the caldera; that this bench was probably broken by faults is suggested by the considerable relief between different outcrops of the Uwekahuna Ash observed in the present caldera wall (Powers, 1948). More information about the ancient caldera may be revealed by detailed mapping by T. Casadeval and D. Dzurisin of the present caldera wall, now in progress.

The age of the ancient caldera is not well constrained by the data now available, but it appears to have developed sometime between 1500 and 750 years B.P. The lava flows beneath the Uwekahuna Ash possess directions of magnetization consistent with ages of 1500 to 2000 years B.P., while the oldest dated flow thought to have overflowed the caldera rim is about 750 years old (radiocarbon sample W-3999; Kelley and others, 1979). Because the caldera probably formed soon after the uppermost flows beneath the Uwekahuna Ash, and because a long time probably elapsed before the caldera could overflow, the age of the caldera is probably much closer to 1500 than to 750 years. Until better chronologic information becomes available, the age of this caldera may be estimated as approximately 1500 years. As discussed in Chapter V, paleomagnetic data require that the present caldera be younger than the Seventeenth Century A.D., and if the Keanakakoi Ash dates from soon after caldera formation this collapse must have occurred in about A.D. 1790 (Christiansen, 1979). It therefore appears that the two most recent collapses producing large calderas and widespread ash deposits were separated in time by about 1000 to 1500 years. Several smaller collapse episodes may have occurred between these two, however; a hypothetical sequence of such events is given in Chapter V.

Tube-fed Flows on the Inland Side of the Southwest Rift Zone

A band of lightly vegetated tube-fed pahoehoe flows, about 4 km wide, extends down the inland flank of the southwest rift zone. They are similar morphologically to the flows from Hale o Ai-laau but differ greatly in their vegetation patterns, presumably because of scarcer rainfall (Fig. 55). The source of these flows is somewhat uncertain but probably is Lua Pele. The source does not lie along the rift zone itself because the ground slopes and flow directions do not radiate from rift-zone vents but are subparallel to the rift and tend to converge slightly downslope with the zone of younger vents. Some of the lobes, in fact, appear to extend obliquely across the rift zone. Some of these appear to be continuous with similar sheets of tube-fed pahoehoe mantling a part of the seaward flank upslope from Kipuka Ahiu and reaching the sea between Naliikakani Point and Kaaha. The flows disappear upslope beneath younger Keamoku, Mauna Iki, and Puu Koae flows at elevations of about 800 to 900 m, but similar flows higher up can be traced to the northwestern part of the caldera rim. As discussed in Chapter V, these flows all possess directions of remanent magnetism similar to the uppermost flows in Uwekahuna Bluff, and they are probably of closely similar age. Though it remains possible that some of these flows may have emanated from a source on Mauna Loa's northeast rift zone, flowing onto Kilauea in the Keauhou Ranch-Kipuka Puaulu area, their most probable source is Lua Pele.

As shown on Plate 3 and discussed in Chapter V, all of these flows are inferred to date from the Seventeenth Century A.D. However, from his detailed mapping east of Pahala, now in progress, N. G. Banks believes that flows of several ages can be differentiated in this group (written commun., 1980). Preliminary radiocarbon dates suggest that some of these flows are considerably older than 1000 years while others are younger than 400 years. Evidently, considerable field work will be needed to differentiate the various lava flows in this area.
The problems involved in distinguishing different sheets of tube-fed

Fig. 55--Lower southwest rift of Kilauea. This picture is a part of frame 029 of roll 14, series HAI by the U.S. Navy, 1954. In the upper left corner is the town of Pahala on the cultivated flank of Mauna Loa, and in the lower right half is an assemblage of prominent dark flows erupted from the Great Crack in 1823. Most of the area between the Great Crack and the flank of Mauna Loa is covered by barren tube-fed pahoehoe, most of which is mapped on Plate 3 as Seventeenth Century flows from Lua Pele. Fieldwork by N. G. Banks, however, indicates that several units of disparate ages are present. The prominent tonal boundaries generally do not seem to correspond to mappable flow boundaries but appear to represent patchy variations in the surficial cover. Some artificial variations in the cover, along the left edge of this view, have arisen from flooding by cane trash from the Pahala sugar mill.

pahoehoe are discussed further in the following section dealing with Kilauea's south flank.

Structural Pattern and Behavior of the Southwest Rift Zone

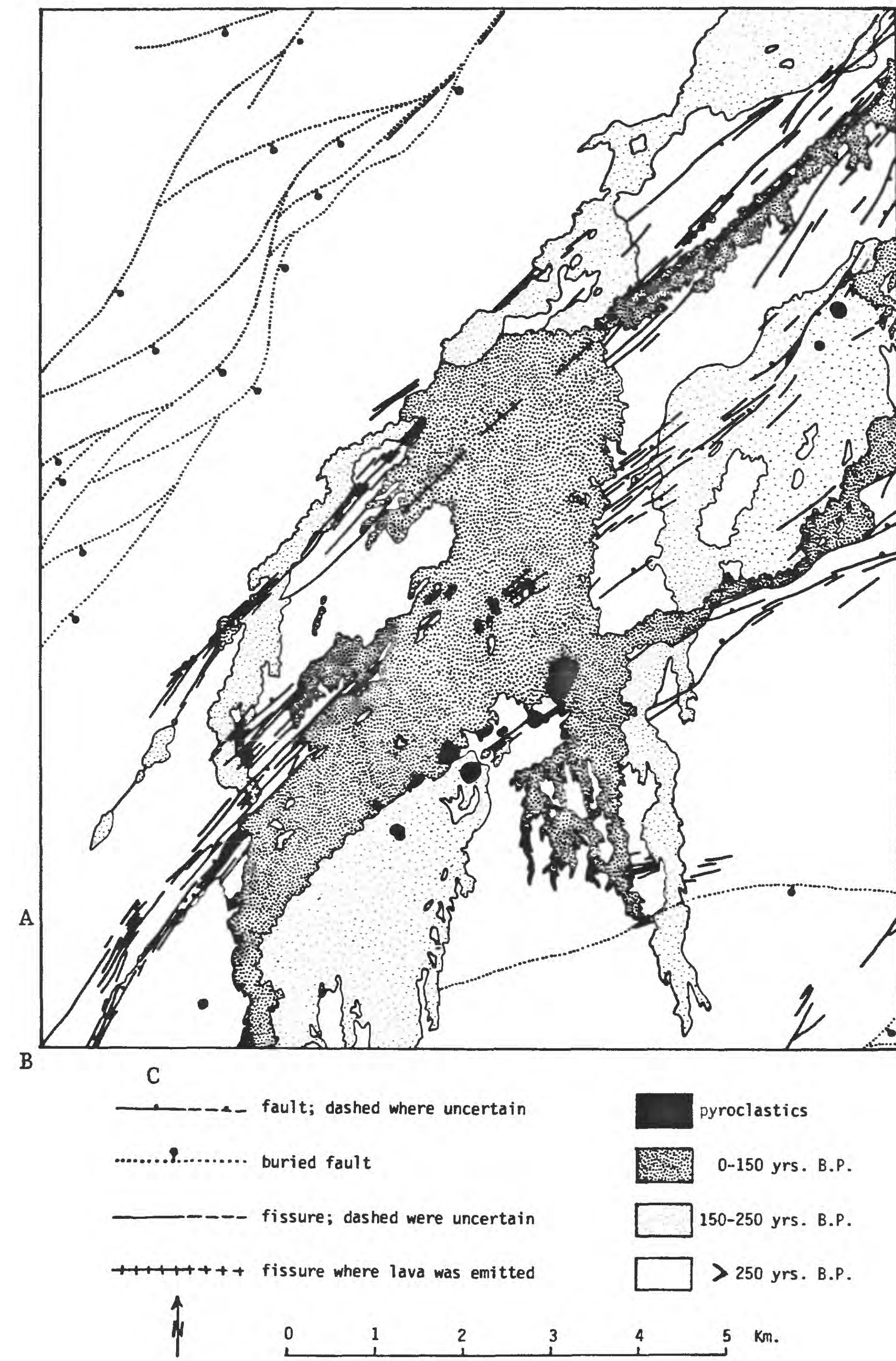
The southwest rift zone displays considerable complexity in surficial structure and eruption products. Its subaerial stretch consists of two segments joined together at an elevation of about 700 m where the Koae fault system intersects the rift zone. The rift zone also makes a gradual 35 deg bend in this area, with the upper segment trending about S. 50° W. and the lower segment about S. 15° W. The two segments differ considerably in their structural patterns and apparent behavior.

The lower segment possesses a relatively narrow zone of currently active rifting about 1 km wide, dominated by the Great Crack. Fault displacements are dominantly downward to the southeast, toward the sea. Much of the seaward subsidence has occurred along faults bordering the northwest side of the recently active zone; some blocks landward of these faults, such as Puu Nahaha, stand tens of meters above the recently active zone and have escaped draping by the young flows erupted along the active fissures (though they are draped by the tube-fed flows from the summit region). A seaward migration of eruptive activity may have occurred here; while all of the vents seaward of the faults appear young, the only vents observed inland from the prominent faults are older than 1000 years. However, some vents only slightly older than about 250 years B.P. could be concealed beneath the wide band of flows from Lua Pele. A prominent fissure along the Kilauea-Mauna Loa boundary about 1 km southeast of Pahala may be one of the oldest Kilauea vents still exposed at the surface; a radiocarbon date of 3610 ± 60 years B.P. has been obtained from a thin lava flow that issued from it (sample W3884 of Kelley and others, 1979). However, it is not clear that this fissure is a true eruptive vent; a surficial lava flow from either Kilauea or Mauna Loa could have flowed into it further upslope and then overflowed its rim.

In the upper rift segment, the zone of active rifting flares from a width of about 1 km in the southwest to more than 3 km in the northeast. In contrast to the lower segment, it appears to behave as a broad graben or shallow sag; this sagged character is especially apparent to an observer looking from the vicinity of Cone Peak across the rift zone toward the Koae fault system. This segment of the rift zone is split into three distinct strands, converging downrift, that are expressed by bands of close-spaced fractures breaking through the sheet of late prehistoric tube-fed flows (Fig. 56). The strands differ in the chemistry and morphology of their vents and lava flows.

The northern strand passes through Mauna Iki and Cone Peak to Halemaumau. This strand is the most active one of the historic period, and it has commonly been viewed as _the_ southwest rift. In addition to the Mauna Iki lava shield, its eruptive features include the fissures of April 1868 and September-October 1971, as well as a chain of small lava shields and lava pads farther downrift. The eruptions here seem to be generally less vigorous than those of the other strands, involving only small fountains and producing little pyroclastic material. The historic eruptions from this strand have been observed to follow very shortly after more vigorous or sustained activity at the summit, and lava feeding the eruption of Mauna Iki (1919-20) was reportedly

Fig. 56--Structure of the southwest rift zone between Yellow Cone and Puu Koae. Individual features are identified on Plate 3 and Figure 57. The band of buried faults in the upper left corner is a part of Mauna Loa's Kaoiki fault system; the conventionally recognized boundary between Mauna Loa and Kilauea runs along the base of the lowermost fault. Faults of Kilauea's Hilina system trend east-west just below the bottom right corner of this view. Between these two major fault systems the upper southwest rift zone flares northeastward toward Kilauea's summit region. Surficial ground breakage and eruptive vents are concentrated into three strands: northern (A-A'), middle (B-B'), and southern (C-C'). The southern strand passes eastward into the southernmost faults of the Koae system, while the northern strand--the "southwest rift" proper--extends into Halemaumau. The central strand passes directly from the center of tumescence south of the present caldera into the lower segment of the rift zone. Much of the surficial ground breakage has occurred since the Seventeenth Century, when a large part of this region was covered by flows from Lua Pele.


A'
B'
C'
A
B
C
fault; dashed where uncertain
buried fault
fissure; dashed were uncertain
fissure where lava was emitted
pyroclastics
0-150 yrs. B.P.
150-250 yrs. B.P.
> 250 yrs. B.P.
N
0
1
2
3
4
5
Km.

seen to drain directly from the summit along the rift fissures at very shallow depths (Jaggar, 1947, p. 137-140, Pl. 37). Lavas erupted from this strand have olivine-controlled chemical compositions similar to lavas erupted at the summit (Wright, 1971).

The middle strand passes directly from the active band of the lower southwest rift through Puu Koae and Cone Crater to the currently dominant center of summit tumescence south of the present caldera. Historic eruptions from this strand include one of 1919-20 and another of July 1974. It appears that eruptions from this strand have generally been vigorous and brief, producing aa flows and spatter cones but little tube-fed pahoehoe. Chemical compositions are similar to those of summit flows (Wright, 1971).

The southern strand passes through Yellow Cone and the Kamakaia Hills (Figs. 57, 58) into the southern faults (e.g., Kalanaokuaiki Pali) of the Koae fault system. No historic eruptions have occurred along this strand, but the prehistoric eruptions appear to have included examples of all three types A, B, and C. These eruptions have been distinctive in commonly producing cinder cones and viscous lava flows of unusually differentiated compositions (Wright, 1971; Wright and Fiske, 1971) and morphology (Fig. 59).

The differences between these strands of the upper southwest rift zone comprise an intriguing problem deserving more study. They may arise from differences in the subterranean connections between the different strands and the principal magma reservoir. A possible plumbing configuration may include the following features:

1. The central strand connects most directly with the subsurface reservoir. Eruptions from this strand tap directly magma that has

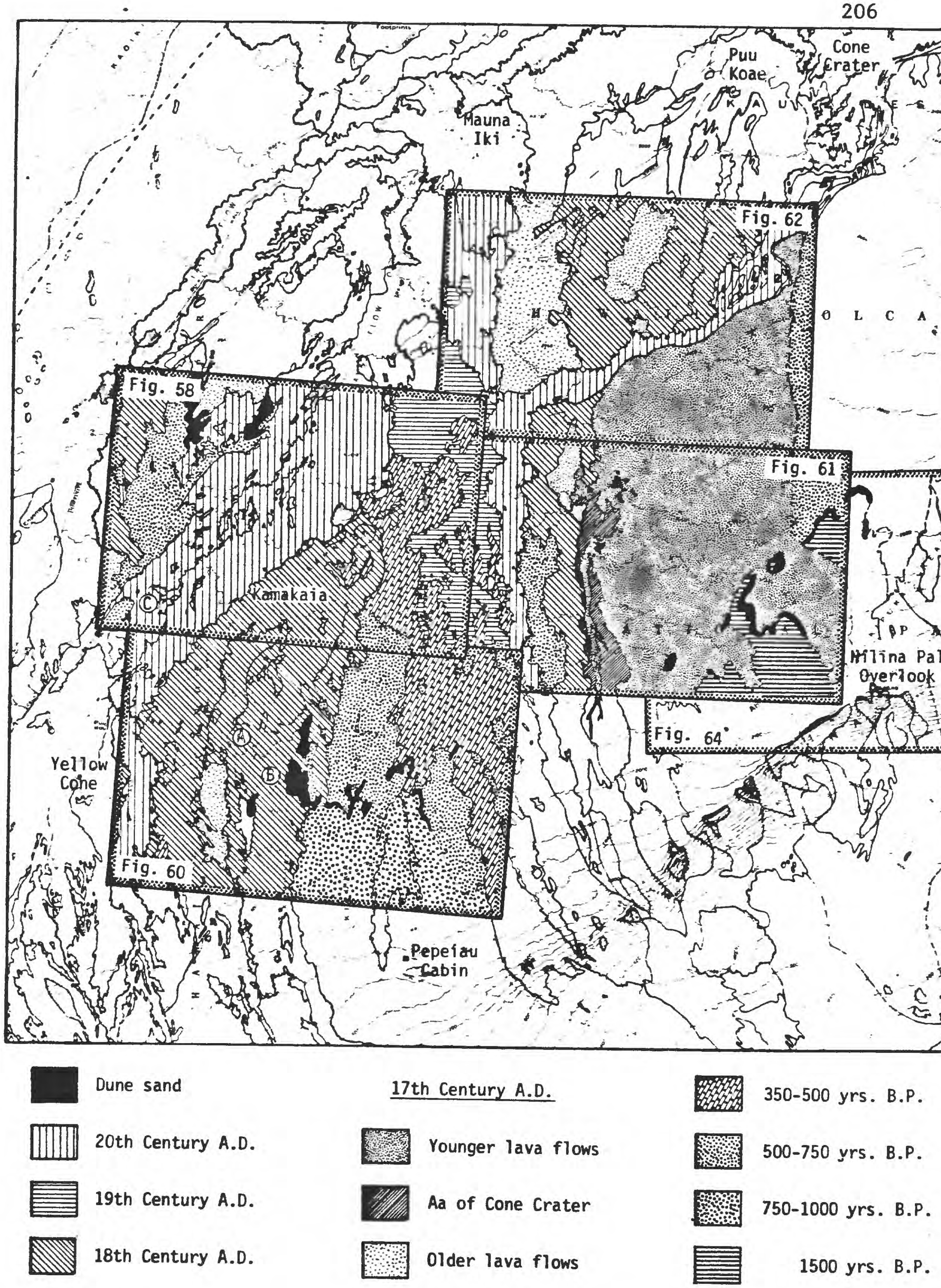


Fig. 57--Index map of the upper southwest rift zone between Yellow Cone and Puu Koae. The area shown is similar to that shown in Figure 56 but is centered somewhat to the southeast. The lava flows of the Seventeenth Century A.D. are differentiated into three different age groups on this map.

Fig. 58--The Kamakaia Hills. Stereo triplet was prepared from frames 41, 42, and 43 of roll 5CC, series EKL by the U.S. Department of Agriculture, 1965. The dot indicates the approximate viewpoint for Figure 59. Much of the lava in this area is veneered discontinuously by aeolian sands derived from the Keanakakaoi Ash, brought here from the summit by prevailing northeast tradewinds. The flows of 1919-20 display complex relationships with these deposits, having chilled against and on top of dunes and then been undercut, as the sand beneath was blown away, and veneered by more sand from dunes migrating onto them from the northeast. These complexities are especially well displayed to ground observers by the small lava shield of 1919-20 southwest of Mauna Iki, at the top of this view, left of center. They are also inferred to exist near the lower left corner of this view, where a prominent tonal anomaly is visible (point C of Fig. 57). This anomaly consists of a sharp-edged, light-toned band crossing the dark aa flows of Mauna Iki. The characteristic aa "ogives" (Thorarinsson, 1953) and gross morphology of the flow are unchanged across this band, and high spots within the band are dark. The tonal anomaly is inferred to be caused by a veneer of sand continuous enough to alter the photometric properties of the flow surface but too thin to obscure its gross morphology. A depression floored by light-toned older pahoehoe at the northeast end of the band is interpreted as the site of a large sand dune against and around which the aa flowed. Subsequent deflation of the dune produced a depression at its site and spread the band of sand across the flow.


N
1 Km.

Fig. 59--Unusual eruption products of the Kamakaia Hills.

(a) General view, looking northeast from the vicinity of the dot on Figure 58, showing in the background one of the cinder cones (Kamakaiawaena), found only in this area of Kilauea, and in the foreground one of the peculiar near-vent lava flows.

(b) Closer view, looking westward, of the same flow front shown in Figure 59a. Scale is indicated by the aerial photo case, about 10 in. square, perched on the day pack. The flow front consists of thick, cylindrical, toothpaste-like 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.

a

b

resided in the plumbing system only a short time and has changed very little through differentiation or loss of volatiles. It is highly charged with gas that produces vigorous eruptions, but there is no store of magma higher than the vents to sustain eruptions long after the gas-charged fraction has been tapped from the top of the reservoir.

2. The northern strand is connected to the main reservoir only indirectly via a very shallow plumbing system near Halemaumau. Lava erupted from this strand has not resided at shallow depths long enough to undergo very much chemical differentiation but has lost a large part of its gases through summit eruptions or fumaroles. The reduced volatile content results in less vigorous eruptions along this strand, but eruptions may sometimes be sustained for months or more when much degassed but still molten lava is stored at high levels within the caldera, which acts as a shallow holding tank.

3. The southern strand possesses only a tenuous connection to the principal magma reservoir. The lava erupted from this strand has resided for long intervals in the shallow plumbing system after leaving the principal reservoir, permitting it to undergo substantially more differentiation than lava from the other two strands.

4. While magma passes with relative ease along each of the strands, it is very difficult for magma to pass across the rift zone from one strand to the other. The strands may be separated by relatively impervious tabular blocks consisting of dikes and/or relatively unbroken slices of the volcanic edifice.

5. Magma may move eastward, instead of westward, into the southern strand from the middle strand at their intersection southwest of the

Kamakaia Hills. This "backing up" of magma into the west end of the Koae fault system may be analogous to intrusions observed recently from the upper east rift zone into the east end of the Koae system (Unger and Koyanagi, 1979).

Whatever the particular plumbing configuration, it does appear that systematic spatial variations in eruptive behavior occur along the rift zone, and these must be considered before temporal variations can be completely identified and understood.

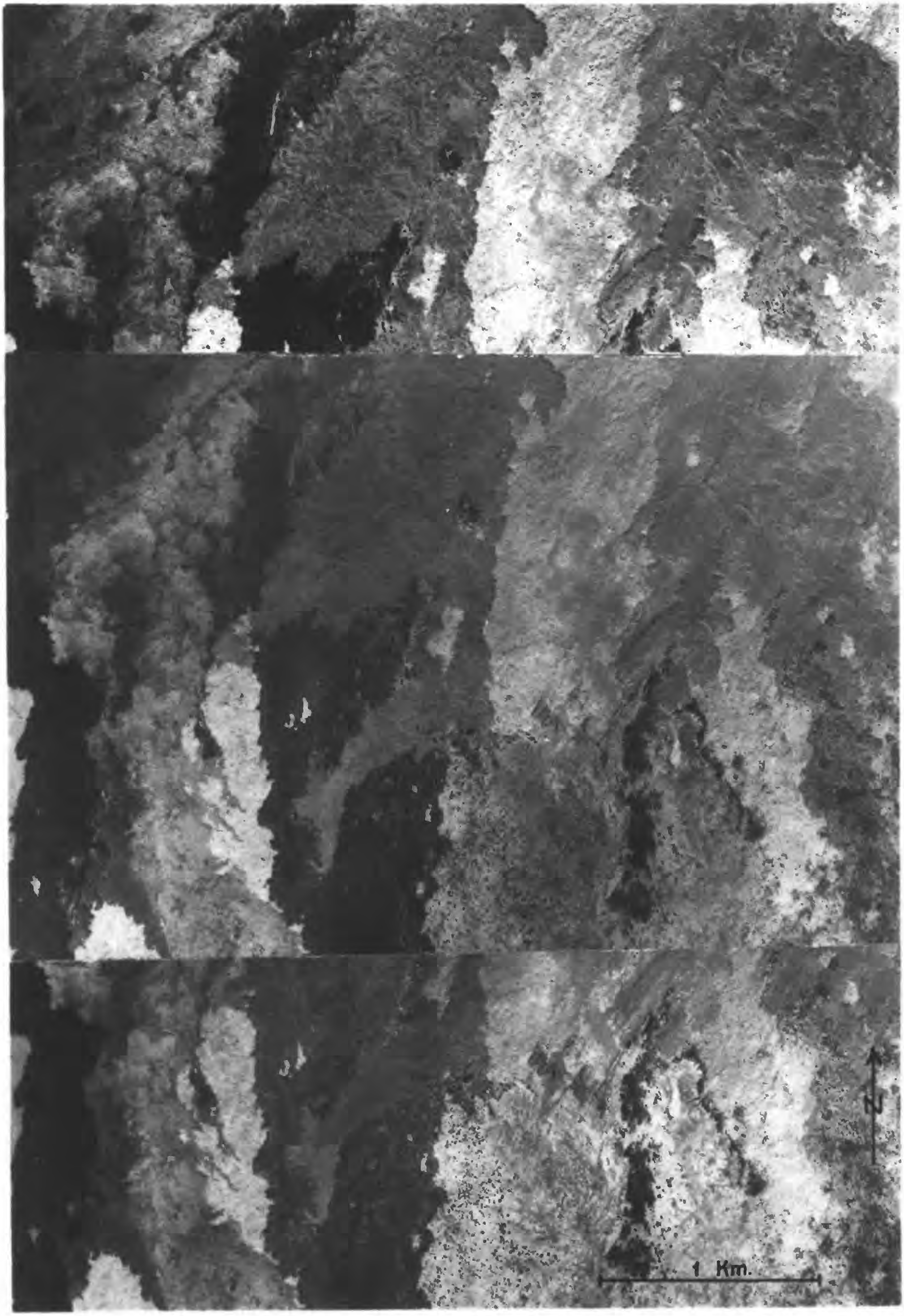
Some Aeolian Features of the Kamakaia Region

Kilauea's south and southwest flanks are partially veneered by surficial deposits derived from pyroclastic materials erupted in the summit region. An overview of these deposits has been presented by Dzurisin and others (1980), and a comprehensive description is not given here. However, the interpretation of these deposits is critical to the understanding of surficial stratigraphy on Kilauea's south flank, and some treatment of them is necessary for a discussion of the stratigraphic problems. Stratigraphic questions arise frequently from the variations in surficial cover observed from place to place, but the amount of cover depends upon several factors besides the ages of surficial lava flows. The Kamakaia region provides a good introduction to these problems because it displays little ambiguity in the relative ages of many surficial flows, and variations in cover unrelated to age are easily identified.

Variations in surficial cover are displayed especially well between Kamakaia and Pepeiau cabin (Fig. 60), where two kinds of variation are prominent. The first is related to the meter-scale roughness of

Fig. 60--Aeolian deposits between Kamakaia and Pepeiau cabin. Stereo triplet was prepared from frames 42, 43, and 44 of roll 5CC, series EKL by the U.S. Department of Agriculture, 1965. Much sand veneers some lava flows in this area and is presumably derived from the Keanakakoi Ash to the northeast. The aeolian deposits include two prominent sheets (at locations A, B of Fig. 57), with sharp boundaries, producing tonal anomalies similar to the one shown on Figure 58. These sheets display albedo variations from frame to frame, with neither of them forming a tonal anomaly against their underlying aa flows on the south frame but displaying prominent anomalies on the other frames.

Considerable variation in the amount of surficial cover can be seen from place to place. Some of the variation is related to the meter-scale surface roughness of lava flows, the rougher aa and surface-fed pahoehoe flows having more sand than the smoother tube-fed pahoehoe flows, even though many of the rougher flows are younger. Evidently the rougher flows are more efficient traps of aeolian material. Other variations in surficial cover may be related primarily to age: Both aa and tube-fed pahoehoe of Kipuka Pepeiau in the lower right-hand part of this view are veneered thickly by surficial deposits and vegetation, with prominent sand dunes occurring along some boundaries between the "kipuka" and comparatively barren lava flows. An important problem of Kilauea's south flank is whether these boundaries represent contacts between lava flows of different age or instead arise from differential stripping of a formerly continuous sheet of surficial material.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surficial lava flows, with smoother tube-fed pahoehoe possessing less cover than rougher aa and surface-fed pahoehoe. The second variation is more problematic, being related to either the age of lava flows or some process of stripping or deposition.

Variations related to surface roughness are especially well shown in the upper central part of the stereo triplet of Figure 60, where older tube-fed flows are barren and younger aa flows downwind are thickly veneered by sand. The sand sheets at A and B of Figure 57 display strong tonal variations from frame to frame of Figure 60, similar to variations noted on Figure 58, and are inferred to consist of glass young enough to be unweathered and untarnished (Appendix D gives a rationale for this compositional interpretation) and derived probably from the Keanakakoi Ash. Though it had to travel across the pahoehoe in order to reach its present site, very little sand is on the pahoehoe now, and the sharp boundary of the sand deposit coincides with the margin of the aa flows. Evidently some factor differing between aa and pahoehoe affects the accumulation of sand; the most obvious factor to consider is surface roughness. Aa flows may trap more sand because their rougher surfaces more effectively impede the saltation of sand grains.

Other variations in surficial cover shown in Figure 60 display no obvious relationships to flow morphology. Both the thickly veneered aa of Kipuka Pepeiau and the barren expanse to its north contain aa and pahoehoe flows varying widely in their surface roughness; yet the boundary between these two areas displays little spatial correlation with the pattern of flow types. The boundary is sharp in most places, even when it separates areas differing very little in flow morphology, and it generally coincides with a narrow band of sand dunes whose map pattern (Fig. 57; Pl. 2) is not likely to arise from burial of rough-surfaced patches. These features suggest that the sharp contrast in this area is not related to surface roughness of the lava flows. It must arise instead from other causes, among which three possibilities are considered in the following section. According to these alternatives, the contrast arises from (1) differences in the age of lava flows, with more surficial material on the older flows; (2) differential stripping of a sheet of surficial material formerly continuous upwind of the sand dunes; or (3) differential deposition of surficial material downwind of the sand dunes. Alternatives (2) and (3) could involve very different interpretations of lava-flow stratigraphy than alternative (1), and a good understanding of Kilauea's south flank must rest on the proper choice among these alternatives. The alternative interpretations are discussed further in the following section, which focuses on the number of mappable pahoehoe sheets on Kilauea's south flank. The features displayed in Figure 60 are used merely to introduce the problem.

One area obviously affected by aeolian processes is about 3 km east-northeast of Kamakaia, in the center of Figure 61. Prominent stripes on the ground surface in this area are alined parallel to the dominant wind direction, and the dark stripes begin upwind at the edge of Kalanaokuaiki Pali segments where the fault is expressed as an inclined ramp instead of a cliff (Fig. 62). The stripes are interpreted as depositional phenomena, the dark stripes composed of small pockets of aeolian material blown up the ramps from fluvial deposits along the base of the pali. The fluvial deposits visible

Fig. 61--Aeolian striping and lava-flow stratigraphy between Kamakaia and Kipuka Ahiu. Stereo triplet was prepared from frames 201, 202, and 203 of roll 12CC in the EKL series. The prominent tonal stripes trending NNE-SSW on the barren pahoehoe flows in the upper right part of this view represent variations in sand cover, the dark bands containing more sand. An intermediate source of this sand is shown on Figure 62. Overlap relationships between several different flows, including barren tube-fed flows of two different ages, are visible in the west half of the view. The prominent aa flows were mapped by Walker (1969) as a single unit erupted from Puu Koae, but the photographs show that two different flows are present, the western flow overlapping the eastern one as well as tube-fed pahoehoe that also overlies the older aa flow. The older aa in turn overlies some of the barren pahoehoe, so two units each of pahoehoe and aa are inferred to be present. However, the contact between the pahoehoe sheets in most places is not mappable from aerial photographs. In the interpretation offered here, both pahoehoe units are inferred to originate from Lua Pele while the aa flows are from type B vents of the middle strand of the upper southwest rift, the upper aa coming from Puu Koae and the lower aa (including a large lava fan at the base of Hilina Pali, shown on Pl. 2) from Cone Crater.

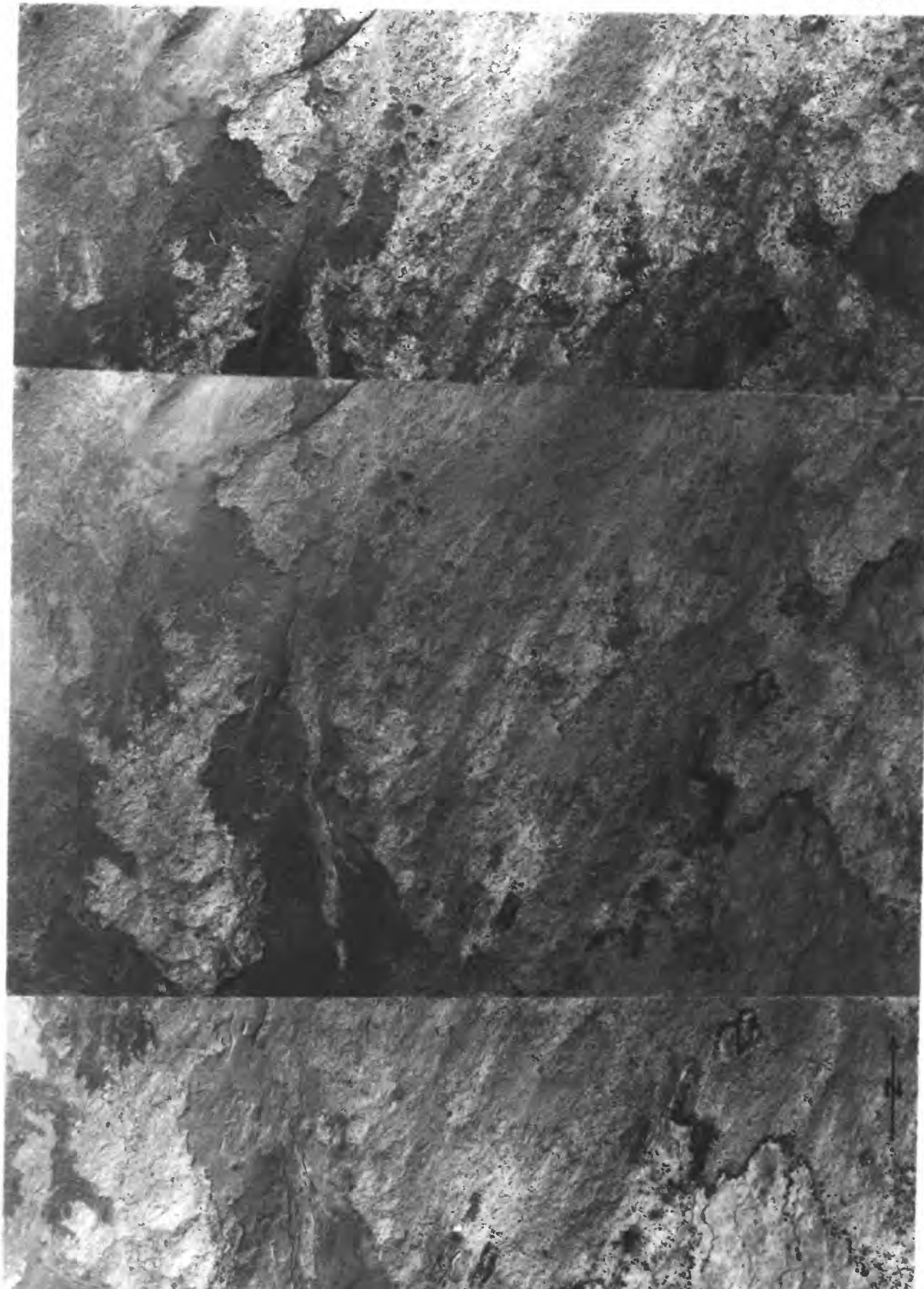
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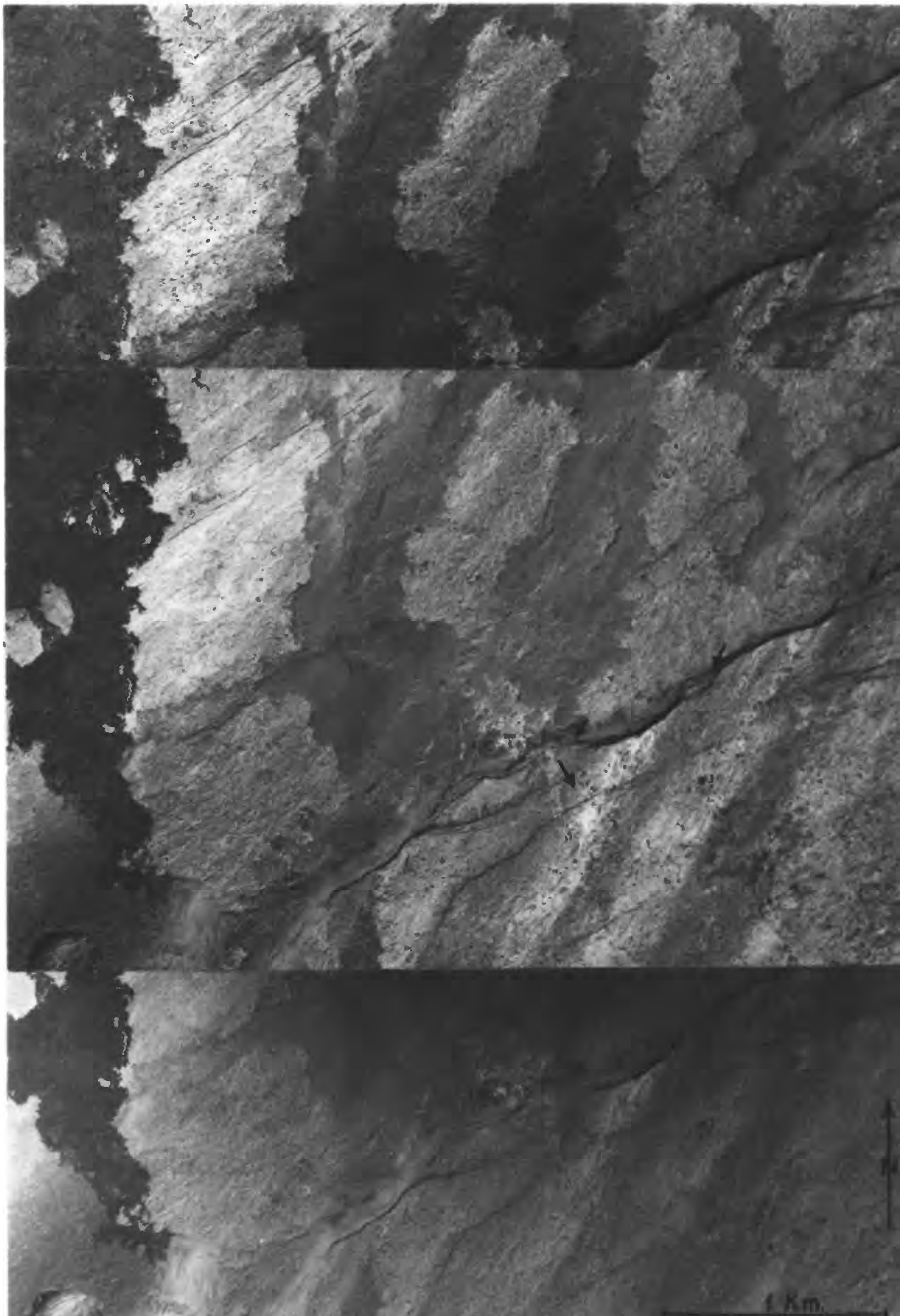
Fig. 62--Relationships of lava flows and aeolian striping to the western Koae fault system. Stereo triplet was prepared from frames 202, 203, and 204 of roll 12CC, series EKL. The prominent north-facing fault scarp is the westward extension of Kalanaokuaiki Pali, along which the lava flow of July 1974 spread after these photographs were made (Pl. 2). The aeolian stripes originate at places along the fault where the scarp is an inclined ramp instead of a vertical wall. The sand sources for the dark stripes are inferred to be the deposits of fluvial sediment along the base of the scarp, brought there from the blanket of Keanakakoi Ash upslope by intermittent floods of water. The sand so deposited is able to climb the scarp only where it is a ramp. Though much of the fault displacement seems to postdate the eruption of Puu Koae, the path of the Puu Koae aa flow suggests that it was deflected southwestward by a small scarp along the site of the present fault. Moreover, a tongue of pahoehoe (indicated by the arrow) may have flowed through an especially low gap in this ancestral scarp. A small scarp had therefore developed only shortly after the pahoehoe sheets from Lua Pele were spread across this area.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in Figure 62 were covered by the lava flow of December 31, 1974, that spread along the base of the pali; yet a field check in 1977 indicated that the pockets of windblown material in the dark stripes were not being stripped away after their source was cut off. This casts some doubt on the current effectiveness of wind in stripping away previously deposited surficial deposits. However, the three-year interval between the cutting off of the inferred supply and observed persistence of the stripes may have been too short for a significant change to occur. It will be interesting to see what happens in the coming years.

Tube-Fed Pahoehoe Sheets of the South Flank

An important stratigraphic problem of Kilauea is the number of significantly different surficial pahoehoe sheets on the flank south of the summit region (Fig. 63). It is an important problem because this region is one of the few where slopes permit only lava flows from the summit to spread over its surface. This region therefore should preserve one of the least ambiguous records of eruptive activity at or near the summit, uncluttered by events along the rift zones. In order to decipher this record it is necessary to learn how many distinct sheets of lava cover the south flank, how much time is represented by each sheet, and how frequent and how long were the intervals when lava from the summit did not spread onto this flank. Unfortunately this problem is a difficult one, turning on the nature of surficial deposits, and it could not be resolved by the work reported here. The evidence available, which is largely photographic, is conflicting and ambiguous, and a definitive solution must await

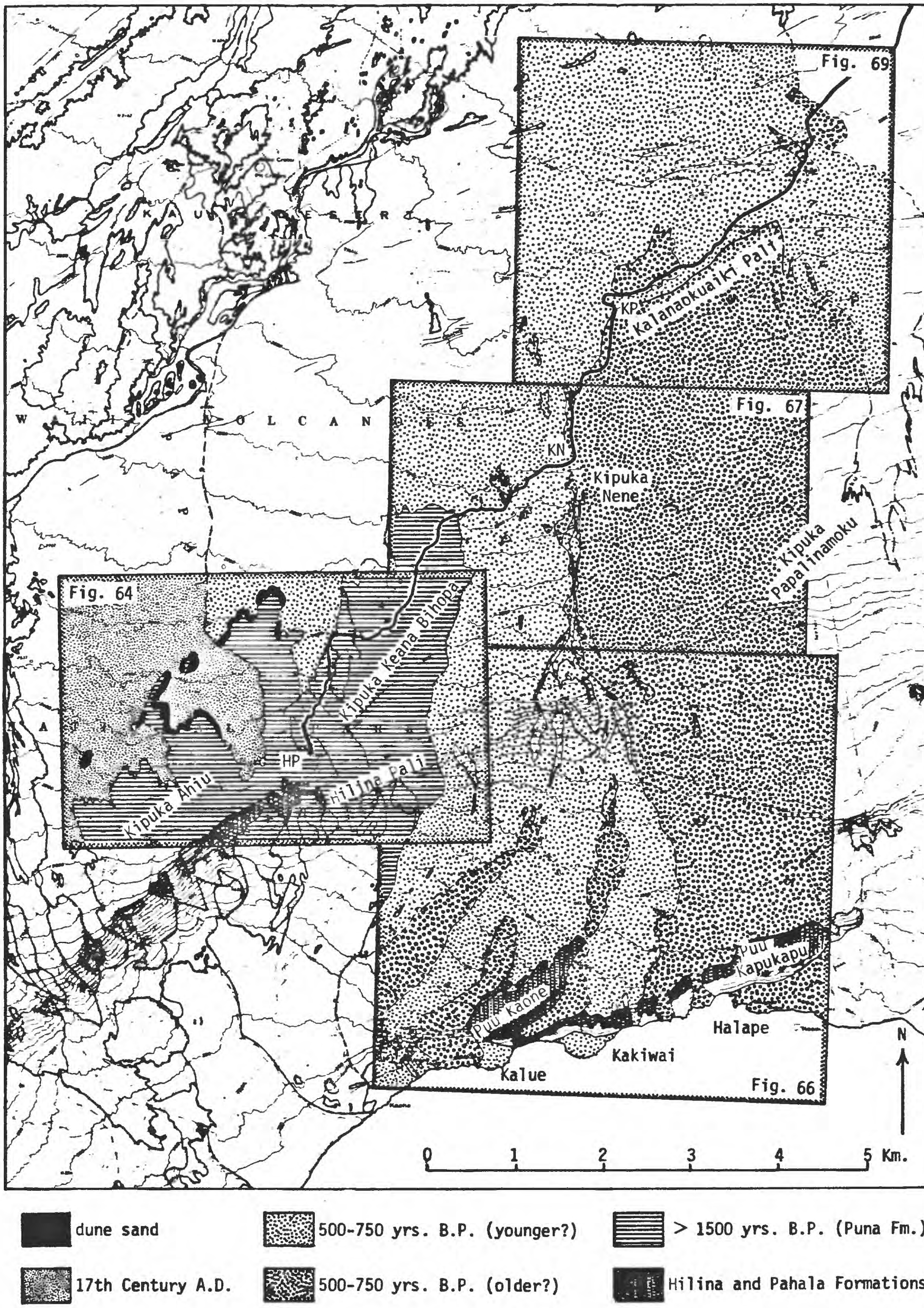


Fig. 63--Index map of a part of Kilauea's south flank, showing some of the sheets of tube-fed pahoehoe differentiated in this work. HP is the Hilina Pali overlook and picnic shelter at the end of the Hilina Pali Road, and KN is the area shown in detail on the sketch map of Figure 68.

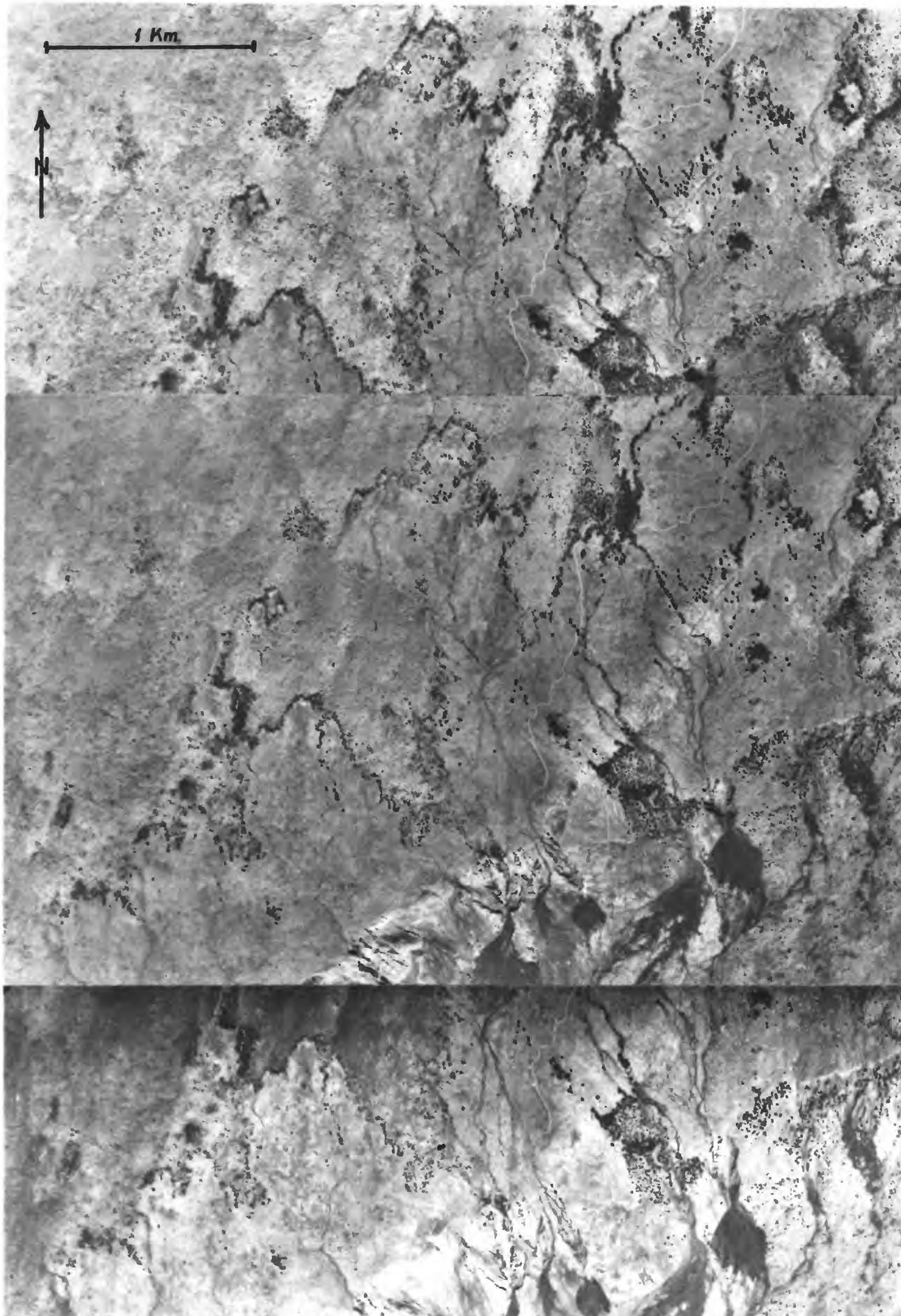
more extensive fieldwork. The discussion that follows merely summarizes the available evidence and outlines the rationale behind the provisional interpretation offered on Plate 2.

As an introduction to the problem, we can note first some clear evidence that not all of the lava on the south flank is of the same age. This is demonstrated along the western edge of the region, where tube-fed pahoehoe flows from the summit are interbedded with aa flows erupted from the upper southwest rift zone (Figs. 57, 61). The band of aa mapped by Walker (1969) as a single unit from Puu Koae actually consists of two different flows separated stratigraphically by a sheet of summit pahoehoe. The western lobe, traceable directly to the Puu Koae vent complex, lies atop this pahoehoe, while the eastern lobe inferred to come from the Cone Crater vent complex lies below it. The intervening pahoehoe is a distinctively picritic flow (indicated by a separate symbol on Walker's map but with its margins not drawn) that on the ground has been traced to the western rim of Kilauea's caldera, where it crops out at the top of a stratigraphic section erupted at or near Lua Pele (T. L. Wright, oral commun., 1976). Evidently the eruptions at Cone Crater and Puu Koae were separated by an interval of eruption at the summit. Though the picrite must be younger than morphologically similar pahoehoe beneath the aa of Cone Crater, the contact between the two pahoehoe sheets cannot be traced on the aerial photographs. The evidence, however, for the existence of at least two different pahoehoe sheets is clear in this locality. The evidence for other sheets to the east (Fig. 63) is more ambiguous.

Contrasting patterns shown on aerial photographs upslope from Hilina Pali (Fig. 64) suggest the presence of several surficial units differing distinctly in their ages, and the existence of such units was suspected at least as long ago as the early 1960s (T. L. Wright, oral commun., 1976). The patterns reflect vegetation contrasts arising from differences in the amount of ash and soil veneering different parts of the south flank. The surficial veneer is thickest in Kipuka Ahiu and Kipuka Keana Bihopa, less on Kipuka Pepeiau, Kipuka Nene, and Kipuka Papalinamoku, and absent on areas surrounding these kipukas. As shown already on Figure 60, boundaries between the different areas are generally sharp. Barren patches bounding the kipukas have lobate outlines that are elongated downslope (Fig. 64) and resemble the generalized outlines of young flows spread across older ash-veneered lavas of the kipukas. If this interpretation is correct, the different patterns arise from significant differences in the ages of the lava flows such that older flows have accumulated thicker veneers of surficial material.

Despite the suggestiveness of the photograph patterns, Walker (1969) did not differentiate the kipukas on his geologic map, finding no flow contacts or other field evidence that the sharp pattern boundaries correspond to lava-flow margins. He grouped most of the flows together as a "regional pahoehoe" unit and attributed the differences in surficial cover to differential stripping. According to this interpretation, the lava flows are of similar age and were formerly blanketed by ash correlative with the Keanakakoi Ash around the present caldera. The ash was stripped away by aeolian processes and redeposited in places downwind. The barren areas have been

Fig. 64--Contrasting vegetation patterns developed on lava flows between the Hilina and Koae fault systems. These patterns were believed by Walker (1969) to arise from incomplete stripping of a formerly continuous sheet of surficial material. but they are interpreted here to reflect the general distribution of lava flows having different ages. Stripping or nondeposition of surficial material, however, seems necessary to explain many of the small isolated bare patches within the kipukas. The stereo triplet was prepared from frames 4, 5, and 6 of roll 5CC, series EKL by the U.S. Department of Agriculture. Paired dots on the lower member of the triplet indicate paleomagnetic sampling sites.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completely stripped of ash, and the areas of thickest ash are those where ash was redeposited. The kipukas containing intermediate thickness (Pepeiau, Nene, Papalinamoku) are relatively untouched and saw neither stripping nor redeposition. The sharpness of kipuka boundaries arises, in this interpretation, from the nature of the stripping process, most of it occurring along a narrow band of sand dunes encroaching onto the kipukas (G. W. Walker, oral commun., 1977). As the dunes move into the kipukas they engulf and kill the trees and grass (Fig. 65). When the ash is then exposed along the trailing edges of the dunes it is no longer protected by vegetation and is stripped away. Some of the fine particles carried downwind are trapped in the thick grass of the kipukas and are added to the ash cover. Coarser particles are incorporated into the dunes, and as they come to rest at the base of the slip faces they engulf more vegetation in front of the dunes.

I do not think this explanation is adequate, for several reasons. First, the prevailing winds are from the northeast (and are paralleled in some barren areas by the surficial striping shown in Figs. 61, 62), but the barren patches between kipukas are elongated north-south, oblique to the wind but parallel to the ground slope. Wind alone cannot account for this pattern, and if stripping did occur it must have involved other accessory agents such as running water. Second, dunes are not present everywhere along the kipuka boundaries. In particular, the migrating dune hypothesis cannot explain the sharp boundaries on the downwind sides of some kipukas (Fig. 64). Here again some accessory erosive process would be required to completely explain the pattern. Third, in most places where dunes are present, the trees

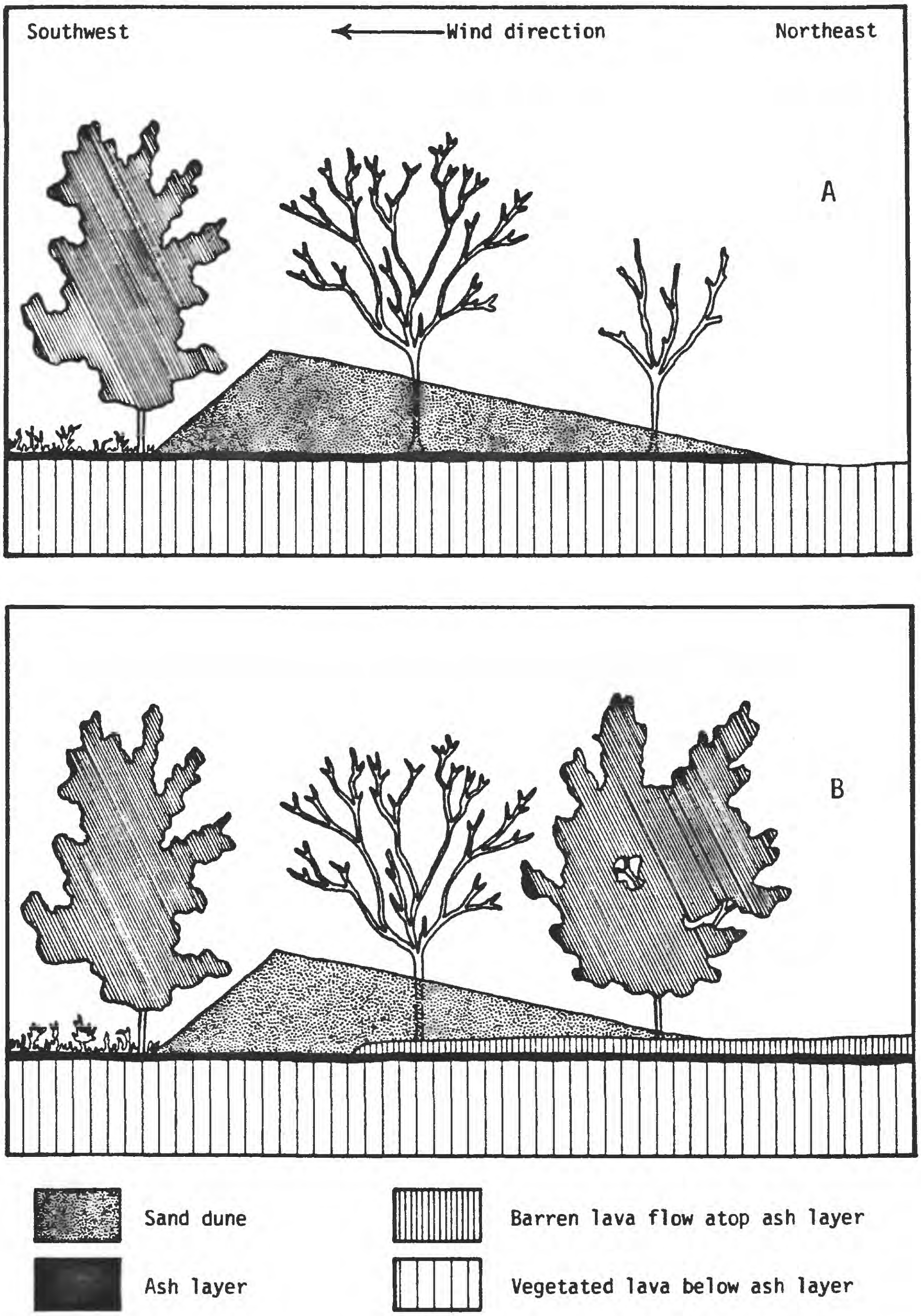

Fig. 65--Diagrammatic cross-section of a sand dune along the northeastern boundary of Kipuka Ahiu, showing alternative interpretations of the dune. (A) Interpretation preferred by G. Walker, in which the dune is migrating from northeast to southwest and an ash layer is being stripped from the lava to windward of the dune because the vegetation that anchored the ash formerly has been killed by the dune. (B) Interpretation, suggested in this report, in which the dune is stationary and has accumulated in a wind shadow produced by trees growing along the margin of a thin lava flow overlying an ash layer.

tend to be clustered upwind of the dunes instead of downwind, as can be seen from close stereoscopic inspection of Figure 64. According to the migrating dune hypothesis the trees now to the windward should have been killed by the dunes and most of the living trees should be clustered along the fronts of the dunes. Fourth, repeated aerial photography during the past few decades indicates that present rates of dune migration are too small to have stripped a swath as wide as the one present in the time available. (The barren swath averages about 6 km wide downwind of the Keanakakoi Ash blanket, which was produced less than 200 years ago. This requires a 30 m/yr rate of dune migration and more than 500 m of net migration since the Navy's HAI series photographs were made in 1954. But comparison of these with more recent photographs reveals no detectable advance of the dunes during that interval.) If the barren swath did develop behind migrating dunes, the migration would have to have been much more rapid in earlier times than it is now. Fifth, the Keanakakoi Ash thins downwind owing to its original depositional pattern, and not from subsequent stripping. This is shown by individual layers within the ash sheet that feather out toward its present edge (Powers, 1948), indicating a depositional thinning; stripping would remove the upper layers entirely while leaving lower layers intact. Sixth, fieldwork by R. P. Sharp and D. Dzurisin shows that a thin ash layer of Keanakakoi Ash lies <u>within</u> the surficial strata of Kipuka Keana Bihopa and not at its base (R. P. Sharp, written commun., 1980). This indicates that much of the surficial cover of the kipuka predates the ash from which it was supposed to have been stripped. Seventh, paleomagnetic sites 8B445 and 9B193 indicate that their barren lava flows really are much younger than surficial flows of Kipuka Ahiu and Kipuka Keana Bihopa dated by both ^{14}C and secular variation. In my judgement, the weight of the evidence argues against both the ability of aeolian stripping alone to produce the observed patterns and the likelihood that any other stripping process did produce the pattern. The evidence does not deny, however, that some stripping has occurred; in fact, some stripping or nondeposition seems required to explain the many small barren patches within the kipukas (Fig. 64).

As shown on Figure 63 and Plate 2, I have used the photograph patterns to differentiate the vegetated flows of Kipuka Ahiu and Kipuka Keana Bihopa from the barren flows surrounding them, because I believe the weight of the evidence favors the existence of at least two different units within the "regional pahoehoe" of this area. The mapped contacts, however, are highly uncertain in many places and highly generalized everywhere. The contacts shown in many places along vegetation boundaries probably have not been found on the ground because they are concealed by sand, ash, soil, and vegetation. In particular, many of the dunes may conceal contacts along lava-flow boundaries because these boundaries could produce conditions favorable for sand accumulation (Fig. 65). According to this interpretation the sand dunes are not migrating but are stationary and have developed in wind shadows alee of trees growing near the margins of barren flows. The ohia trees cluster along the flow margins because their roots can penetrate through the thin margins into ash and other surficial material buried beneath them, this buried material retaining water longer than the exposed surficial deposits. The trees form natural windbreaks behind which sand accumulates and conceals the edges of the lava flows.

Though I have differentiated the flows of Kipukas Ahiu and Keana Bihopa from their barren neighbors with a fairly high degree of confidence, further subdivision of the younger flows is made with much less certainty. Some further subdivision seems warranted by the paleomagnetic results from sites 8B121, 8B133, and 9B169, which differ considerably from the paleomagnetic directions at sites 8B445 and 9B193. I have accordingly sketched a contact across the barren swath northward from Kipuka Ahiu, separating unit 4 (Seventeenth Century A.D.) from unit 6 (500-750 yrs B.P.). The actual location of the inferred contact is highly uncertain.

Conflicting evidence makes it especially difficult to differentiate flow units in the area east and northeast of Kipuka Keana Bihopa. Various pieces of evidence suggest that two units should be differentiated here, but paleomagnetic evidence seems to contradict this, suggesting that the two units do not differ significantly in their ages. This area will now be discussed in more detail.

The best evidence for flows of different ages east of Kipuka Keana Bihopa is shown in Figure 66 between Hilina Pali and Puu Kaone. Tonal contrasts on the photographs suggest that two groups of flows are present, lobes of dark-toned younger lava having spread across a sheet of light-toned older flows. This contrast is apparent also on the ground, especially from viewpoints on the rim of Hilina Pali, where the light-toned flows are seen to have a greener hue, owing to a more dense carpet of vegetation upon them. Inspection on the ground indicates also that low spots on the vegetated flows possess more

Fig. 66--Contrasting flow units in the area between Hilina Pali and Puu Kaone. Two series of the widespread surficial flows can be differentiated on the basis of photographic tone and surficial cover. The stereo pair was constructed from frames 77 and 78 of roll 14CC, series EKL by the U.S. Department of Agriculture.


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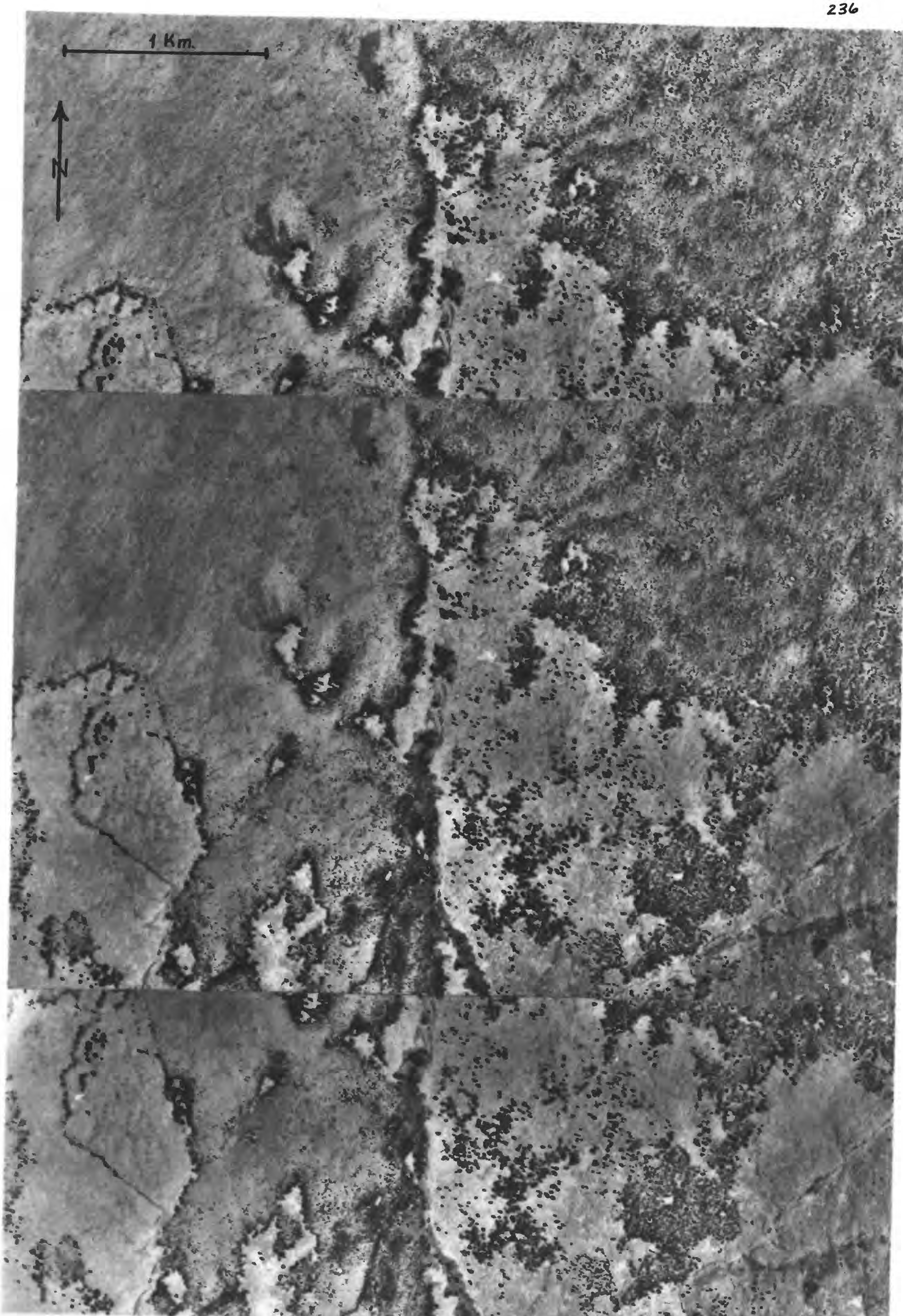
surficial deposits than do the darker flows. Walker (1969) differentiated the two groups of flows on his map, but he mapped the younger set only up to the rim of Hilina Pali, losing the contacts in a barren area he believed to arise from stripping of surficial material. However, this band of barren lava extending between Kipuka Nene and Kipuka Keana Bihopa toward the pali coincides well with the younger flows below the pali, and the entire band seems to me a good candidate for the upslope extension of the younger flows, as I have shown on Figure 63 and Plate 2. If this inference is correct, the older flows below the pali should be correlative with those of Kipuka Nene and Kipuka Papalinamoku.

Support for such a differentiation of flow units is lent by structural and morphologic evidence along the Hilina Pali Road near Kipuka Nene campground and the roadway across Kalanaokuaiki Pali. At the former site is a good example of an apparent flow boundary coinciding with a vegetation boundary (Figs. 67, 68). The flow boundary may be seen about 100 m west of the Kipuka Nene picnic shelter, along the seaward side of the road where it emerges from the trees of the kipuka onto the barren swath to the west. A small monoclinal fault--traceable for about 2 km across Kipuka Nene and shown on Plate 2 and the map by Stearns and Macdonald (1946) but not by Walker (1969)--terminates abruptly at the edge of the kipuka. A thin sheet of pahoehoe wrapping around the fault terminus is undisturbed while the lava beneath this sheet is warped and broken by the fault. The margin of the younger, unbroken flow can be traced distinctly through the vegetation for only a few dekameters, but enough is visible to show that its path is deflected by the fault scarp,

Fig. 67--Vegetation contrasts of the Kipuka Nene region inland from Hilina Pali. Paired dots indicate paleomagnetic sampling sites in the vicinity of Kipuka Nene campground. The stereo triplet was prepared from frames 75, 76, and 77 of roll 14CC, series EKL by the U.S. Department of Agriculture.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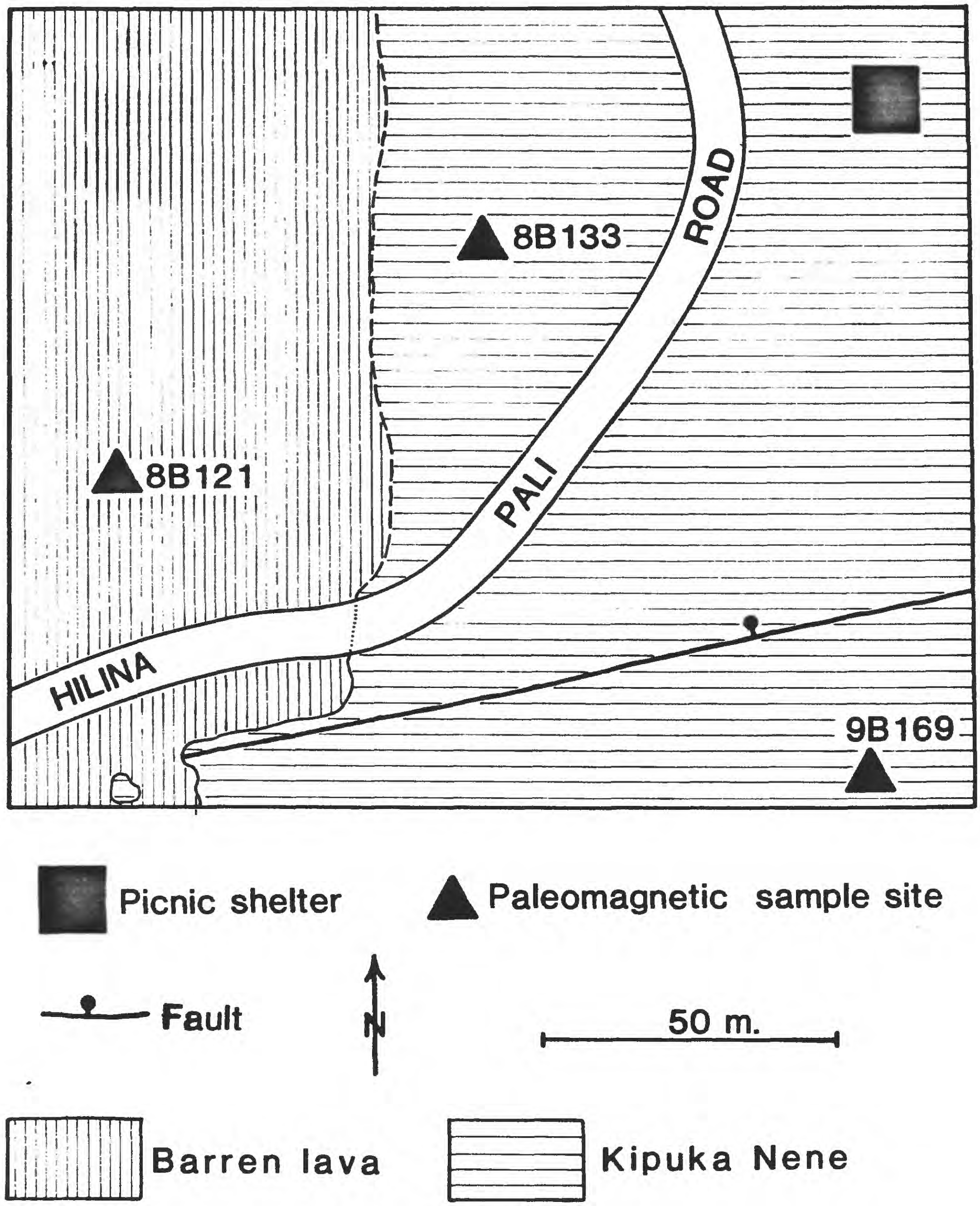

Fig. 68--Sketch map of the area surrounding the Kipuka Nene campground, showing how the termination of a low monoclinal fault coincides with a sharp vegetation boundary interpreted as the boundary between lava flows differing in ash cover and possibly differing in age.

the flow spreading farther eastward along the northern, downthrown, side of the fault. The vegetated flows of the kipuka are inferred to predate the fault and the barren flows to postdate it, the vegetated and barren flows therefore differing in age by an amount sufficient for the faulting to occur. Similarly, the barren flows are inferred to postdate some of the displacement on Kalanaokuaiki Pali because they seem to have been ponded against the fault scarp (Fig. 69), while the vegetated flows of Kipuka Nene are inferred to predate the scarp. Much evidence therefore indicates that the two groups of flows differ significantly in their ages as well as in their vegetation patterns.

But this age difference is not supported by the paleomagnetic data. In 1978 paleomagnetic samples were collected from sites 8B121 and 8B133 on what I judged to be the younger and older flows, respectively, expecting to confirm their age difference. But the directions of remanent magnetization at these two sites are not significantly different. Thinking we had mistakenly collected from the younger flow at site 8B133, in 1979 we collected again from site 9B169, which is on the upthrown side of the Kipuka Nene fault where there can be little ambiguity about the relative age of flow and fault (Fig. 68). But the remanent magnetization at this site is practically identical to that of 8B133. Unless site 8B121 is mistakenly located on older flows--an unlikely possibility--the barren and vegetated flows are magnetically indistinguishable.

Three alternative interpretations are possible for the Kipuka Nene region. First, Walker (1969) is correct, and both flows are of identical age, the barren flows having been stripped of ash and

Fig. 69--Contrasting vegetation patterns near the intersection of the Hilina Pali Road with Kalanaokuaiki Pali. The barren flows are interpreted to postdate much of the fault displacement while the tree-covered flows are thought to predate it. The pattern of polygonal plates (arrow) at the base of the cliff is characteristic of ponded lava flows, and the barren flow is inferred to have been ponded against the incipient fault scarp. The stereo pair was prepared from frames 74 and 75 of roll 14CC, series EKL of the U.S. Department of Agriculture.


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and vegetation. The field relations suggesting separate flows predating and postdating the fault are merely coincidental in some way and have no geologic significance. Second, the barren and vegetated flows do differ significantly in age, and their magnetic similarity is coincidental. Third, the interpretation of two distinct flows predating and postdating an interval of faulting and accumulation of surficial material is correct, but this interval is very short. The surficial material, for example, could have been produced by early high fountains of the Kane Nui O Hano eruption--which appears to be of similar age because its flows are magnetized (site 8B229) in the same direction--occurring between two close-spaced periods of sustained summit activity. The fault may represent an episode of flank deformation in response to these eruptions, much as the earthquake of November 29, 1975, is thought to have occurred in response to the activity at Mauna Ulu (Swanson and others, 1976; Tilling and others, 1976). A definitive judgement of these hypotheses is not yet possible with the data available, but I favor the third one out of reluctance to contradict either my own field evidence or the magnetic data. Even if this problem is useful for nothing else, it illustrates the difficulty of mapping in young basaltic terranes such as this.

In summary, the weight of the evidence suggests that two or more separate sheets of tube-fed pahoehoe can be differentiated on Kilauea's south flank. Five such units are differentiated on Plate 2; these include:

1. Unit 4 (Seventeenth Century A.D.) from the vicinity of Lua Pele, in the area north of Kipuka Ahiu. Cone Crater flows interbedded within this unit indicate that it can be subdivided further

into at least two components, the uppermost being a distinctively picritic flow.

2. Unit 5 (350-500 yrs B.P.), from either Hale O Ai-laau or a vent on the upper east rift zone such as Puu Huluhulu, that extends southward along the eastern boundary of the former Ainahou Ranch to the coast at Keauhou Landing. This unit was not discussed above, but its presence is displayed clearly on aerial photographs and its age is indicated by paleomagnetic site 8B541, the two ^{14}C samples (W-4184, W-4337) from beneath it yielding widely disparate ages.

3. Unit 6 (500-750 yrs B.P.), from an unknown vent perhaps in the vicinity of the present Halemaumau, whose barren flows include the lobes extending between Kipukas Nene and Keana Bihopa to the sea around Puu Kaone.

4. Unit 6' (500-750 yrs B.P.?), also from an unknown vent perhaps in the vicinity of Keanakakoi, that covers Kipukas Nene and Papalinamoku and much of the Keauhou ahupua'a seaward of Kalanaokuaiki Pali. Though this unit is magnetically indistinguishable from unit 6, considerable evidence of other kinds suggests that it may be significantly older.

5. Unit 9 (older than 1500 yrs B.P.), from summit vents that probably predated the formation of the ancient caldera, comprising the surficial flows of Kipukas Ahiu and Keana Bihopa.

Further studies of the surficial deposits, remanent magnetization, and lava-flow petrography may permit several more units to be differentiated in the future. Such work may prove especially valuable in providing a stratigraphic framework against which it may be possible to work out the history of recurrent displacements on faults of the Hilina system.

Structures of the South Flank

As noted previously, little attention was devoted to structure in the field checks for this map. But if the structures shown are generally correct, the faulting of the south flank is related to other structures of Kilauea somewhat more intimately than has generally been recognized.

The most prominent faults of the south flank--those of Hilina, Poliokeawe, and Holei palis, Puu Kapukapu, etc--are concentrated in the seaward part of the flank. This has led to a distinction between a faulted seaward part of the flank (called the Hilina fault system) and an unfaulted inland part separating this fault system from the other structural elements of Kilauea (Fig. 3 of Swanson and others, 1976).

This map suggests, however, that south-flank faulting is more extensive and grades into the other structural elements. Buried faults, inferred from steepened slopes, can be traced very close to the southwest rift zone without turning seaward as would be expected for a slump structure independent of the rift zone. The only westernmost fault of the south flank that can be seen to turn seaward, past Mahuka Bay, does so very close to the rift zone and parallels the zone. The faults farther inland fade out beneath younger lava flows; if they do not die out as structures or intersect the rift zone, they must turn seaward very close to it and parallel it also. More likely they intersect or follow it. Faults are also present in the inland part of the south flank between Hilina and Kalanaokuaiki palis. An example is the fault that passes near the Kipuka Nene campground. This fault is downthrown to the north while a buried fault inferred nearby to the south is downthrown to the south and is traced into faults of the Hilina system. The Koae and Hilina fault systems do not appear to be isolated from each other by an intervening unbroken block but are immediately adjacent and may grade into each other. The Hilina faults may also grade into the middle part of the east rift zone. As discussed earlier, the rift zone extends farther southward than recognized previously, and the zone of south-flank faulting probably extends farther northward as well. Few discrete faults are inferred in the inland part of the south flank adjacent to the middle east rift zone, but this is probably caused by the thick forest cover and mantle of young lava flows. The steepness of the flank here suggests that old faults are buried by the surficial flows. In summary, it appears that the faulting of the south flank is not isolated from other structural elements of Kilauea but grades into them. Its superficial isolation is an illusion caused by the restricted distribution of just the most recent displacements in a recurrent series. No large unfaulted block of Kilauea exists seaward of the rift zones; instead the entire superstructure of the volcano may be a densely and complexly fractured pile of basalt.

It should be cautioned, however, that these observations are only preliminary inferences because relatively little effort has been expended in checking the inferred faults. A special effort focused on the mapping of Kilauea's structural pattern will be needed to test these inferences. Such work may be very valuable in deciphering

Kilauea's history, and it may reveal a long-continuing intimate interplay between the volcano's eruptions and the displacement of its south flank.

CHAPTER V

GEOLOGIC HISTORY

The results obtained from paleomagnetic measurements, analysis of lava-flow morphology, and regional geologic mapping can be synthesized to produce a history for Kilauea during the past few thousand years. Such a history is presented here. Discussed first is the history of geomagnetic secular variation, followed by Kilauea's recent geologic history and a review of Hawaiian oral traditions about the volcano.

Refined History of Geomagnetic Secular Variation

In order to improve the resolution of the paleomagnetic dating tool and evaluate physical models of the geomagnetic field, it is necessary to refine the history of secular variation. Though much refinement would require the collection of more data, some improvement can be accomplished with the data now available.

I have attempted an initial refinement by averaging together in groups some of the paleomagnetic sites and ordering the groups according to their ages. In order to accomplish this refinement I had to make two kinds of judgements: (1) decide which sites were of similar age and should therefore be included together in a group; (2) decide what is the correct chronological order for the various groups. I used three kinds of evidence in making each judgement, some kinds of evidence having priority over others. In deciding which sites to use in the averages I used, in order of their priority, (1) independent geological evidence (stratigraphic position, origin from the same vent, similarity of weathering, erosion, and vegetation development) of similar age; (2) similar ^{14}C dates; and (3) similar directions of magnetization. The criteria used to order the averaged groups were (1) stratigraphic evidence from superposition relationships; (2) average ^{14}C dates; and (3) a principle of simplicity (Occam's razor) calling for the simplest history of variation that can be inferred, in the absence of other evidence. I favored stratigraphy and other geologic evidence over the ^{14}C dates because of the large errors believed to occur in the ^{14}C dates. Whenever possible I avoided using the direction of magnetization itself as a criterion for including sites because this practice would introduce an element of circularity into arguments about the ages of flows subsequently dated with reference to the refined history of variation. In the cases where I have used this criterion, I call attention to it explicitly in the discussion that follows, so that such circularity can be avoided. According to the principle of simplicity in ordering the groups, I have simply chosen the order which yields the simplest path of variation, reasoning that this path is more probable than the more complicated alternatives.

The results of my preliminary refinement procedure are presented in Table 10 and Figure 70. The various averaged groups are listed on Table 10 in an order extending backward from the historic interval, where the record of SV is comparatively well-defined, to about 3000 years ago, where the paleomagnetic directions are more poorly

Table 10

Groups of Flows Thought to Have Similar Ages[1]

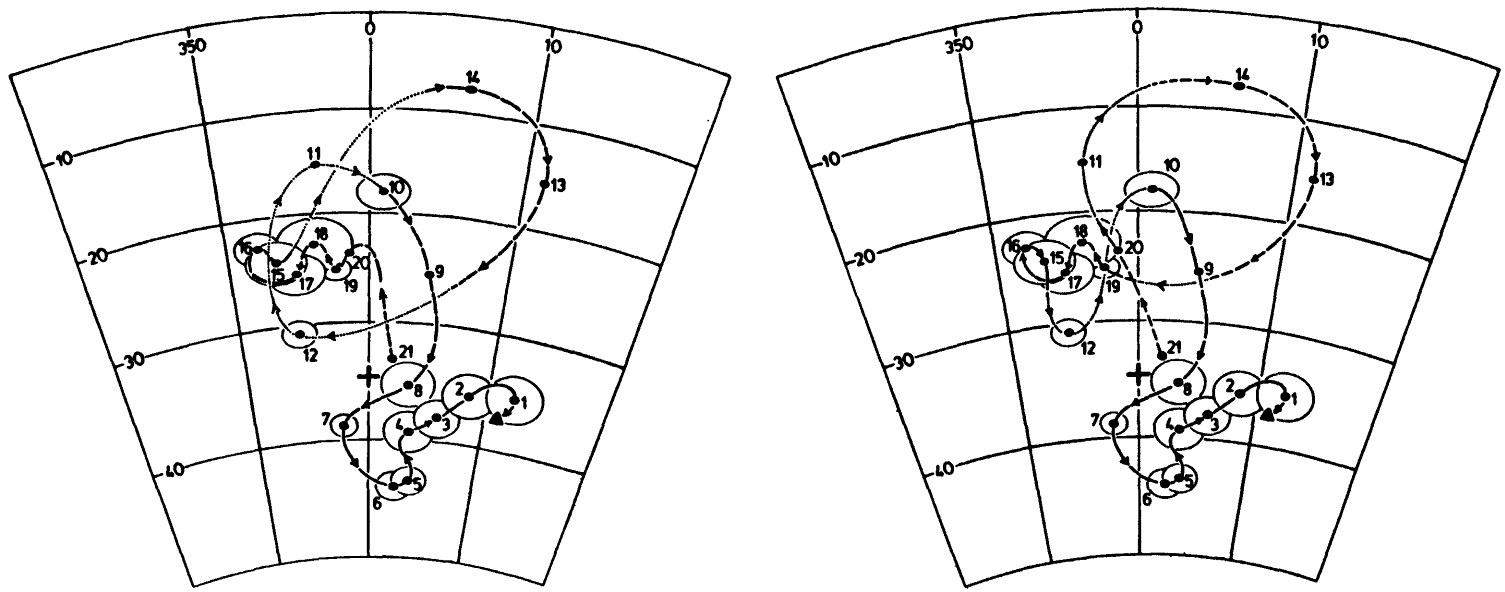
Group no.	Group name	Included sites	N	D	I	α_{95}	Mean age[4]	No. of dates
1	Twentieth Century	1907[2],1926[3],1935[2],1940[3],1950[3],1955[2],1960	7	12.3	35.4	2.0	11	7
2	Nineteenth Century	1800[2],1840[2],9B721,8B337,1843[2],1852[3],1859[3],1868[2], 1881[3]	9	8.5	35.8	1.8	103	9
3	Eighteenth Century	8B025,8B301,8B757,9B409,8B517,9B697,9B757,9B073, 8B613,8B325,1750[2],1790[2]	12	6.0	37.9	1.6	195	8
4	Lua Pele	8B589,8B865,8B565,8B637,8B649,9B877, and flows 145,146,147,148 of Doell and Cox (1965)	10	3.6	39.3	1.7	390	2
5	Hale O Ai-laau	9B673,8B001,8B061,8B421,8B793,9B133,9B433,8B085, 8B169,8B193,9B397,9B421	12	3.9	43.4	1.2	305	4
6	Middle Puna Series	Flows 1371 to 144 of Doell and Cox (1965 and unpubl.)	15	2.5	43.9	1.2	-	-
7	About 500-750 yrs B.P.	Three groups of flows, listed below, avgd tog	15	357.8	38.8	0.9	723	6
7A	Kipuka Nene flows	8B121,8B133,9B169,8B529,8B493	(5)	(358.4)	(38.4)	(1.2)	-	-
7B	Kane Nui O Hamo flows	8B229,9B241,8B241,9B589	(4)	(356.4)	(38.5)	(2.2)	-	-
7C	^{14}C flows	8B553,8B721,8B913,9B457,9B469,9B577	(6)	(358.3)	(39.4)	(1.6)	(723)	(6)
7D	Variable olivine flow	8B913,9B457,9B469	(3)	(358.9)	(40.3)	(3.1)	(790)	(3)
8	About 750-1000 yrs B.P.	Two groups of lows, listed below, avgd tog	8	3.3	35.3	1.8	697	3
8A	Older Kilauea north flank	8B049,8B073,8B217,8B685	(4)	(2.5)	(35.3)	(2.8)	(730)	(1)
8B	Other flows of similar direction	8B841,9B865,8B373,8B505	(4)	(4.0)	(35.4)	(3.3)	(680)	(2)
9	Young M.L. south flank	8B661,8B853	2	4.3	25.5	3.3	1400	3
10	Kaleloa	9B049,9B085,9B097,9B109	4	0.9	18.1	1.6	1373	4
11	Kulaho-Queens Bath	8B265,9B277	2	356.5	15.4	6.9	1840	1
12	Older Kalapana flows	8B253,8B277,8B289,8B313,8B349,8B817,9B853,8B697	8	354.6	30.7	1.2	1810	1
13	"2185 yrs B.P."	8B625,8B889	2	11.2	15.7	2.1	2185	2
14	"2300 yrs B.P."	8B937	1	5.9	7.6	-	2300	1
15	Kau Series, E	Flows 44-54 of Doell (1969)	11	353.4	24.2	2.0	-	-
16	Kau Series, D	Flows 33-43 of Doell (1969)	11	352.2	22.8	1.5	-	-
17	Kau Series, C	Flows 22-32 of Doell (1969)	11	354.8	25.4	1.8	-	-
18	Kau Series, B	Flows 11-21 of Doell (1969)	11	356.1	22.8	2.4	-	-
19	Kau Series, A	Flows 1-10 of Doell (1969)	10	357.6	25.2	1.0	-	-
20	[illegible]	9B037,9B013	2	358.6	23.7	8.0	2890	1
21	Ainapo Gulch	8B601	1	1.9	33.1	-	2950	1

[1] The site directions used to compute these means were normalized to a common site at the summit of Mauna Loa, the benchmark at 19.484° N., 204.395° E. whose elevation is indicated as 13,661 ft on the U.S. Geological Survey's Mauna Loa 7.5-min topographic quadrangle map.

[2] Results of these sites were reported by Cox and Doell (1963).

[3] Results of these sites were reported by Coe, Gromme, and Mankinen (1978).

[4] Zero age is taken as A.D. 1950. Because the historic interval is about 200 years long, those ^{14}C dates of <200 years are taken as 200 years. Where multiple dates are available for a single flow, we averaged all dates except the few we believe to be obviously wrong by very large amounts.



a b

Fig. 70--Refined history of secular variation during the past 2500 years, derived by integrating stratigraphic information with the record of ^{14}C-dated lava flows, and averaging flows of similar age. Mean directions of magnetization and their ovals of 95 percent confidence are shown for the numbered groups of Table 10. The triangle represents the mean of the present field, and the cross represents the nominal field direction for a location of Hawaii's latitude. The curved line drawn through successive means represents the inferred path of secular variation. Two alternative histories are shown. (a) The preferred version, in which the Kau series is assigned to the interval 2300 to 2900 years B.P. (b) An alternative in which the Kau series is assigned to the interval 1500 to 2000 years B.P. but group 11 is assigned to the older interval.

defined by comparatively sparse data. The resulting history of variation is shown graphically on Figure 70. Considerable uncertainty still remains in this history, and some of the uncertainty is described in the detailed discussion that follows.

Historic Interval

This interval is comparatively well known because there is virtually no uncertainty in the ages of lava flows belonging to it. Paleomagnetic sites of this interval were classified into three age groups belonging to the 20th, 19th, and 18th centuries A.D. (groups 1, 2, 3 of Table 10). Ages of the 19th and 20th century flows are documented very well, generally to the nearest day. Ages of 18th century flows are known from oral accounts only to within about the nearest decade, but these flows can still be assigned to that century with a high degree of confidence.

The chief uncertainties in this interval arise from primary deformations of the sampled lava flows, partly because many of the flows erupted in this interval are aa, frequently having large angular dispersions and partly because many of the averaged sites were sampled previously by other workers for whom less knowledge of the primary deformations was available. I could have reduced the uncertainty ovals for this interval by selecting only the sites believed to be little deformed, but I elected not to do this for fear of biasing the averages. I did omit the aa flow of 1919 (Coe and others, 1978), however, because its mean paleomagnetic direction seemed obviously aberrant. A better knowledge of secular variation during this interval could be obtained from further sampling of the historically erupted lava flows.

Latest Prehistoric Interval

This interval extending from about 250 years B.P. to about 500 years B.P. (groups 4, 5, 6 of Table 10) illustrates some of the problems encountered in trying to construct a history of secular variation. Within this interval of time two groups of lava flows differing in age can be identified, but their relative ages are uncertain because of conflicting evidence. In particular, their ^{14}C dates do not agree with their apparent stratigraphic sequence.

Dated lava flows of this interval belong to two groups: the group of tube-fed pahoehoe flows from Hale O Ai-laau on the north flank of Kilauea (group 5 of Table 10), and the group from Lua Pele on the west flank of Kilauea (six sites of group 4 on Table 10). As discussed in Chapter IV, flows within each group are of similar age, but because of strong climatic contrasts between these two flanks of Kilauea the relative ages of the two different groups cannot be judged from this kind of evidence. The two groups cannot be of the same age because their paleomagnetic directions are clearly different (Table 10, Fig. 70). Though their ranges of ^{14}C dates overlap considerably and suggest that the age difference is not large, the dates of group 4 average about 100 years older than those for group 5. Because the two vents are in close proximity, their relative ages should be revealed by superposition relationships. Their surficial contact has not been found because of a cover of thick surficial ash and dense vegetation, but the buried contact should be exposed in the walls of the present caldera.

The paleomagnetic data of Doell and Cox (1965 and unpubl.) show that the uppermost to middle flows exposed in Uwekahuna bluff (Fig. 6) have directions of magnetization similar to those of these two surficial groups (Fig. 15b, c). The four uppermost flows (nos. 145-148) above a thin tuff layer (R. R. Doell, unpubl. field notes in files of the U.S. Geological Survey, Menlo Park, Calif.) have directions generally similar to, but slightly steeper than, the surficial flows extending southwestward from Lua Pele. Because at least some of the uppermost flows in Uwekahuna bluff must be similar in age to the surficial Lua Pele flows truncated by the caldera, I have included these upper four flows in group 4 even though they increase its dispersion and reduce its contrast with group 5. The next 15 flows (group 6 of Table 10) in Uwekahuna bluff, below Doell's tuff layer, have distinctly steeper paleomagnetic inclinations quite similar to those of group 5, suggesting that they too are from Hale O Ai-laau. Their mean declination, however, is slightly more westerly than that of group 5, suggesting that they may differ in age very slightly. Thus the upper flows in Uwekahuna bluff fall into two groups corresponding roughly to the two surficial groups, but their sequence contradicts the averaged ^{14}C dates.

I have chosen to accept the stratigraphic evidence instead of the ^{14}C dates, partly because of the small number of dates and their wide ranges, and partly because the stratigraphic interpretation involves a simpler history of secular variation. The simplest explanation of the various paleomagnetic directions is that Doell's tuff layer is at the contact between flows from the two vents, with Hale O Ai-laau being slightly older. As the flows from this vent accumulated, first in the ancient caldera and later on the north flank of the volcano, the direction of the geomagnetic field changed first toward more easterly declinations and then toward more shallow inclinations. Continued shallowing and a shift toward more easterly declinations occurred during the accumulation of Lua Pele flows and led smoothly into the directions recorded during the second half of the 18th century.

If the rates of secular variation in this prehistoric interval were similar to those of the historic interval, we can estimate the ages of groups 4, 5, and 6 from their positions along the path of variation. Group 4 would immediately precede the 18th century flows of A.D. 1750-1790 and would average about 300 years old. Group 5 flows would average about 400 years old, and the lowest flow of group 6 (no. 1371 of Doell and Cox, unpubl.) in Uwekahuna bluff would be about 500 years. According to this interpretation the ages of Lua Pele and Hale O Ai-laau are just the reverse of their respective ^{14}C dates listed in Table 10.

Interval of 500 to 1000 Years B.P.

Two other distinct groups of lava flows can be distinguished with ages of less than 1000 years B.P. (groups 7, 8 of Table 10). One of these groups covers large areas of Kilauea's south flank and is probably about 750 years old, perhaps somewhat less. The other group is exposed less extensively on the northeast flank and is probably somewhat older.

The first group is composed largely of flows erupted from Kilauea's summit region onto the south flank areas of Kipuka Nene and Kipuka Pepeiau (group 7A of Table 10; equivalent to groups 6 and 6' of Pl. 2). As discussed in Chapter IV, some members of the group are mantled by ash and vegetation, while others are quite barren, suggesting that they may differ in age. However, because their directions of remanent magnetization are so similar they are considered to be paleomagnetically indistinguishable and are averaged together as group 7A. Moreover, according to the preferred interpretation of these flows, both groups are contemporaneous with another group of flows (group 7B of Table 10) comprising the Kane Nui O Hamo lava shield and covering extensive tracts of the south flank along Kilauea's upper east rift zone. All three groups of flows, 7B and the two of 7A, share a distinctive direction of magnetization and are likely to be closely similar in age, whatever the nature of their specific interrelationships. The age of this group is not known directly from any ^{14}C dates, but its direction of magnetization is shared by six dated sites on Mauna Loa whose mean ^{14}C age is 723 years B.P. (group 7C of Table 10). In order to define a point on the SV path, I combined all of the data from groups 7A, 7B, and 7C to produce the overall mean of group 7. This grouping introduces an element of circularity into the logic of the refinement procedure. In order to avoid this circularity, an alternative group, 7D, could be used. This group includes only three separately dated sites known with some confidence from geologic evidence independent of their magnetization to be on the same "Kipuka Nene" flow of Mauna Loa's south flank (P. W. Lipman, unpubl. mapping). This alternate group provides a similar mean direction within a much larger oval of uncertainty.

The last group of lava flows younger than 1000 years includes most of the surficial flows in the community of Volcano a few kilometers northeast of Kilauea's caldera, and most of the kipukas at lower elevations on Kilauea's north flank (group 8A of Table 10; equivalent to age group 7 of Pl. 2). These flows are grouped together with some uncertainty because they are exposed only in isolated outcrops, and elevation-related climatic differences prevent the correlation of high and low outcrops on the basis of vegetation similarities. Nevertheless, the members of the group exposed low on Kilauea's north flank do share similarities in vegetation growth and a distinctive pattern of incipient fluvial drainage channels, and their widespread distribution and surface slopes indicate that they are the unburied remnants of an extensive group erupted from the summit region before the north flank was flooded by the younger group from Hale O Ai-laau. The summit flows of Volcano share a similar stratigraphic position, and all members of the group have similar directions of magnetization. One ^{14}C sample (W-3999) from Volcano has been dated at 730 ± 80 years B.P. In computing an average I also included, with somewhat more uncertainty, four other flows of group 8B having similar directions of magnetization and ^{14}C ages. If group 8B is omitted from the average, the mean direction of group 8A alone is similar to that of group 8, but with a larger uncertainty oval.

Though the magnetization directions of groups 7 and 8 are distinctly different, their relative ages are uncertain. The ^{14}C dates taken alone suggest that group 7 is slightly older, but the difference is not great and I have no stratigraphic evidence bearing on this particular question. However, group 7 differs less than group 8 from groups 5 and 6, while group 8 is more similar to groups 9 and 10 that are older than 1000 years. So I have inferred group 7 to be younger than group 8 because this interpretation involves a simpler history of secular variation, shown on Figure 70. In the absence of definitive age data, I have taken 750 years B. P. as the tentative boundary between these two groups of lava flows, assigning group 7 to the interval 500 to 750 years B.P. and group 8 to the interval 750 to 1000 years B.P. Other undated flows with paleomagnetic directions plotting in the interval 500 to 1000 years B.P. of Figure 15b have likewise been assigned to these shorter intervals (500-750, 750-1000 years B.P.) as listed on Table 2.

Interval of 1000 to 1500 Years B.P.

Six of the paleomagnetic sites are dated by ^{14}C as belonging to this interval of time (Fig. 15a), and these sites fall into two groups. Two of the sites (group 9 of Table 10) are from Mauna Loa's southeast flank and are from extensive pahoehoe flows erupted in the summit region after that volcano's ancient caldera had been filled but before its present caldera had developed. The four remaining sites (Fig. 15f; group 10 of Table 10) belong to the widespread "Kulaloa" flows on Mauna Loa's east flank (J. P. Lockwood, unpubl. mapping). The two groups differ by several degrees in their mean directions of magnetization, while the sites within each group are in good agreement. If the mean directions of magnetization are not affected significantly by local magnetic anomalies, they both represent discrete points along the regional path of secular variation, and if the rate of variation was similar to historic rates, their angular difference represents a difference in time of a few hundred years. But the mean ^{14}C dates for groups 9 and 10 are virtually identical, and I have no stratigraphic information bearing on their relative age. Here again I have placed them in the sequence yielding the simplest path of variation.

Interval of 1500 to 3000 Years B.P.

In the interval beyond 1500 years B.P. the paleomagnetic data become increasingly sparse. Fewer ^{14}C dates are available for averaging, and because larger expanses of the flows are buried by younger flows their stratigraphic relationships are less clear As a result, the inferred path of secular variation is less certain and it becomes increasingly difficult to choose between alternate interpretations of the data. The most noteworthy uncertainties in this time interval concern several groups of sites having westerly declinations; I will therefore deal with the other sites first only briefly and then discuss these westerly sites in more detail.

The three sites dated by ^{14}C as belonging to the interval 2000 to 2500 years B.P. are characterized by easterly declinations and very low inclinations. Two of these sites are closely similar in both their ^{14}C ages and their directions of magnetization; they are averaged together as group 13 of Table 10. The third site differs somewhat in its age and magnetization, and it is tabulated separately as the single member of group 14. These groups are shown on Figure 70 in the sequence indicated by their ^{14}C dates.

Three sites dated by ^{14}C as slightly younger than 3000 years B.P. have declinations close to due north and inclinations somewhat lower than the average value of about 36 deg. Two of the sites occur on the very large Panaewa flow of Mauna Loa's east flank (J. P. Lockwood, unpubl. mapping) and are averaged together as group 20 of Table 10. The magnetization direction of the third site differs by about 10 deg, and this site is treated separately as group 21. The ^{14}C dates for the two groups are not significantly different, and their true relative ages are unknown. They have been placed in the sequence requiring a simpler history of variation leading to the low inclinations of groups 14 and 13. The exact path followed toward these low inclinations, however, is highly uncertain, as discussed below.

I have distinguished three different groups of sites with westerly declinations. These are group 11 with a mean inclination of about 15 deg, the Kau series (groups 15-19) with inclinations of 22 to 26 deg, and group 12 with a mean inclination of about 31 deg. According to the preliminary dating procedure of Figure 15, a and b, all of these sites could have ages of 1500 to 2000 years B.P., but in most cases there is little stratigraphic evidence to limit their ages; many could be older. In particular, it is possible that some sites could belong to the interval 2300 to 2900 years B.P. between groups 14 and 20. The nature of SV path linking these sites is highly uncertain, and I have shown two of the possible alternatives on Figure 70.

Two sites dated by ^{14}C at 1800 to 1850 years B.P. have westerly declinations but inclinations differing by 15 deg, requiring either rapid secular variation in this short interval or significant errors in ^{14}C dates and/or directions of magnetization. One of the dated sites (8B697) has the steeper (about 31 deg) inclination similar to several of the older lava flows of Kilauea's southeast flank--which among themselves have similar vegetation patterns and are likely to be of similar age. I have averaged these sites together as group 12. The other dated site (9B277) is magnetically similar to still another site (8B265) from Kilauea's south flank that appears to be of similar age to those of group 12 except for having a considerably more shallow inclination. I have averaged these two sites together as group 11. Since the two ^{14}C dates are similar and all of the undated flows are stratigraphically similar to each other, the simplest interpretation would have all members of groups 11 and 12 belonging to the interval 1500 to 2000 years B.P. but differing in age enough to record a 15 deg change in inclination, as I have shown on Figure 70a. However, there is no independent evidence tying the dated members to the undated members of the group, and it remains possible that at least some of these sites are on older flows as shown on Figure 70b.

A more difficult and more significant problem concerns the age of the Kau series in Mokuaweoweo. Those flows all appear to be of similar age. No ash layer or other stratigraphic indication is known of a time break in the section, and the magnetization directions of the lava flows form a single cluster (Fig. 15d). Moreover, mean directions of five successive parts of the section display a simple progression (Fig. 70), consistent with an accumulation during a single interval in which a small amount of secular variation occurred. No ^{14}C dates are available to date any part of the series directly. The magnetization directions are consistent with an age of 1500 to 2000 years B.P., but no stratigraphic evidence is known that can rule out a greater age. The top of the series includes the lava flows that spilled out of the ancient caldera to mantle Mauna Loa's north flank, and these surficial flows have been correlated with similar flows on Mauna Loa's southeast flank that have been dated as somewhat younger than 1500 years B.P. (P. W. Lipman, unpubl. mapping). If the surficial flows northwest and southeast of Mauna Loa's caldera are roughly correlative, the Kau series should be as close as possible to 1500 years B.P. But if these flows are correlative, their magnetization directions should also be similar, and they are not. The declination of group 15 at the top of the Kau series is much more westerly, differing by 11 deg from the declination of group 9 on Mauna Loa's southeast flank. This suggests that a significant time break separates the two groups of flows (unless large local anomalies have affected the directions of magnetization, and there is no evidence of this currently available). That such a time break may exist is supported by evidence that two groups of lava flows differing in age have overflowed the southern rim of Mauna Loa's ancient caldera (R. T. Holcomb, unpubl. mapping). If a significant time break does exist, there is no particular reason to limit its duration to a few hundred years, and the age of the Kau series is not then well constrained to the interval 1500 to 2000 years B.P. In fact, the westerly progression in declination observed in the Kau series cannot be fitted simply into the SV path defined by groups 11 and 12, which display little difference in declination but a large difference in inclination. If all of these groups do belong to the interval 1500 to 2000 years B.P., they require a complex history of secular variation during that interval. My preferred interpretation on Figure 70a assigns the Kau series to the interval 2300 to 2900 years B.P.

Summary

A refined history of secular variation is shown on Figure 70. Because of the difficulties in sorting out the data older than 1500 years B.P., two alternative paths are shown. The differences between these paths arise from different sequencing of the groups of Table 10 in the interval 1500 to 2900 years B.P. Each alternative contradicts some piece of evidence, and uncertainty in both versions is high. Other alternatives are also possible.

It should be emphasized that this initial refinement procedure is inadequate in at least two ways. First, no attempt has been made to evaluate rigorously the effects of magnetic anomalies occurring over length scales of several kilometers. Though Figure 13 shows that the present magnetic field does not vary significantly compared with the total variation in the paleomagnetic data, systematic variations of several degrees may still exist between different regions. Since each of the groups of flows averaged in Table 10 typically is restricted to one part of the volcano, its mean direction of magnetization may be biased by a local anomaly, producing artificial differences between the temporal groups of Table 10. For example, the mean inclination of the present field differs by 2 deg at sampling sites for the Lua Pele and Hale O Ai-laau groups, and the large dispersion in the present field for both groups permits the real difference to be larger (Table 5). Therefore some of the difference between the paleomagnetic inclinations of these groups (Table 10) may be caused by spatial, instead of temporal, variations. This problem must be addressed before any great confidence can be placed in the details of the SV history.

A second problem with Figure 70 is the circular reasoning used at some points in its derivation. Though I tried to average together on Table 10 only those sites for which there was independent geological evidence of similar age, in a few cases, such as group 11, I averaged sites whose only evidence of contemporaneity is their similarity in direction of magnetization. This practice can be justified to some extent if we can assume that the measured directions do accurately reflect the geomagnetic field existing at some unknown time and that all of the similarly magnetized sites belong to a common interval in which the same direction was not likely to have been recorded more than once. However, we generally cannot be confident of these assumptions, and the validity of such groupings must always be doubted. Moreover, even when they are correctly grouped, this procedure is likely to ignore other sites that should have been included but were not because their directions of magnetization differed, leading to artificially small ovals of uncertainty around their means that may really depart significantly from the true value.

Each of these defects in the refinement procedure can result in significant errors in the path of Figure 70, which must be regarded still as only an approximation. Much of the complexity shown in the path may arise from artificial causes. In addition, some of the complexity probably arises from the SV path passing directly through the mean value for each group. But the uncertainties in these means permit simpler, and probably more realistic, paths to be generalized from the data. A generalized version of Figure 70a is shown in Figure 71a. This version represents my currently most confident representation of the SV history in Hawaii during the last 3000 years.

Shown for comparison in Figure 71b is a similar path for the interval 3000 to 6000 years B.P. The data for this interval, however, are very scanty and include some significant contradictions, making this path highly uncertain. If this tentative record is in any way accurate, it suggests that the secular variation of 3000 to 6000 years B.P. differed from the subsequent behavior in two ways. First, there are no intervals of very low inclination less than 20 deg, with the path of variation departing relatively little from the nominal value of 36 deg for an axial dipole. Second, the rates of secular variation are comparatively low. With such low rates and little difference between successive intervals, the secular variation may prove to be much less useful for dating lava flows erupted during this interval than during the last 3000 years. The apparent lack of character in this interval, however, may be due primarily to the sparsity of data; future work may reveal that much more variation did occur during this interval.

Because of the uncertainties in this history of variation, future work may result in major revisions. But though I have emphasized its uncertainties, I believe that this history is useful in presenting a specific target upon which future work can be focused. Its stated points of weakness provide easily identifiable subjects for work aimed at revision.

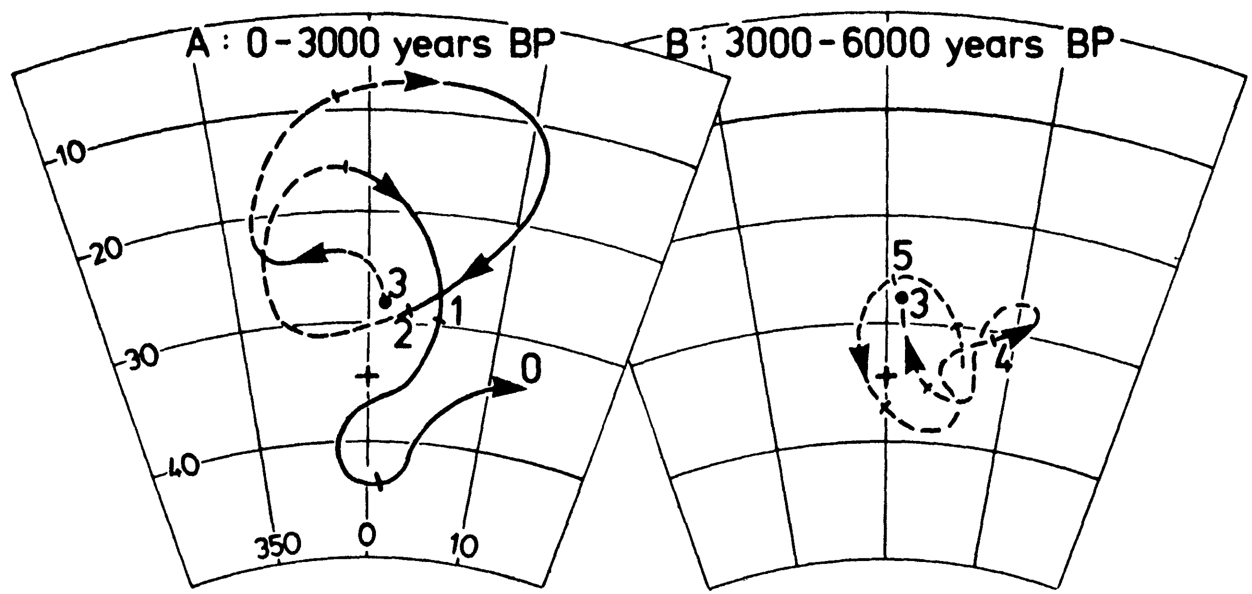


Fig. 71--Generalized history of Hawaiian secular variation during the past 6000 years. Continuity of the SV path indicates relative confidence in different segments. Tics are shown at approximate 500-year intervals, and the numbers indicate thousands of years before present.

Kilauea's Recent History, from Geologic Studies

Kilauea's recent history, as inferred from geologic evidence, is discussed here in two parts. First the age of the volcano's surface and its rate of surface renewal are summarized. Then a history of eruptions and summit collapse is presented.

Kilauea's Rate of Surface Renewal

The age assignments made on Plates 2 and 3 are summarized on Figure 72. Surface areas of different ages were measured by planimeter on a larger-scale (approximately 1:200,000) version of this map, and the results indicate that about 70 percent of Kilauea's surface is younger than 500 years, about 90 percent younger than 1000 years (Table 11; Fig. 73). This is younger than had been expected. When the mapping project was first planned in 1975 it was imagined that a large part of Kilauea's surface was 5000 to 10,000 years old (roughly an order of magnitude older than the results indicate), largely because of the 2570-year ^{14}C date on the Keanakakoi Ash near the rim of Kilauea's present caldera (Rubin and Suess, 1956). If the Keanakakoi Ash were the youngest rock unit in the summit region outside the caldera, and if its lower part were that old, then the caldera itself must be an old feature (because the ash is draped unbroken across the caldera faults); and the lava flows truncated by the caldera would be older still. And since vegetation patterns revealed clear age differences between different lava flows predating the caldera, many of the pre-caldera flows must be appreciably older than 2500 years. It was therefore puzzling when radiocarbon dates obtained during the late 1970s included few ages older than 1000 years. These dates

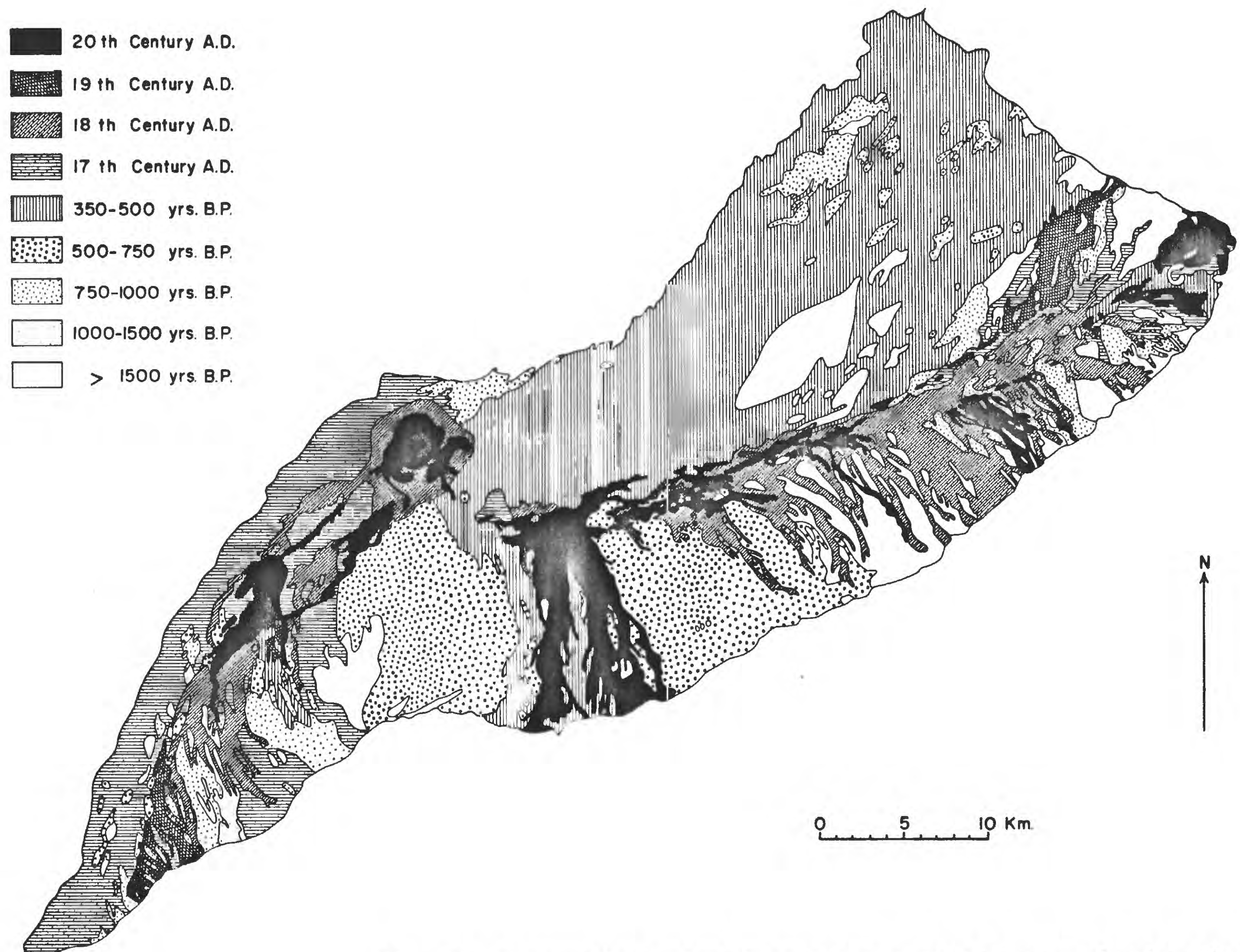


Fig. 72--Generalized stratigraphic map of Kilauea, showing the approximate ages of its surficial lava flows.

Table 11

Age of Kilauea's Surface*

Age group (Pls. 2, 3)	Age (yrs B.P.)	Area (km^2)	Cumulative area (km^2)	% of total area	Cumulative % of total area
1	0- 50	139	139	9.7	9.7
2	50- 150	33	172	2.3	12.0
3	150- 250	169	341	11.7	23.7
4	250- 350	183	524	12.7	36.4
5	350- 500	448	972	31.1	67.5
6	500- 750	209	1181	14.5	82.0
7	750-1000	105	1286	7.3	89.3
8	1000-1500	6	1292	0.4	89.7
9	>1500	148	1440**	10.3	100.0

*Measurements made by planimeter on a generalized map reduced to a scale of 1:195,000.

**A separate measurement of Kilauea's total area gave a result of 1448 km^2, and the 8 km^2 missed in the increments represents an error of 0.6 percent.

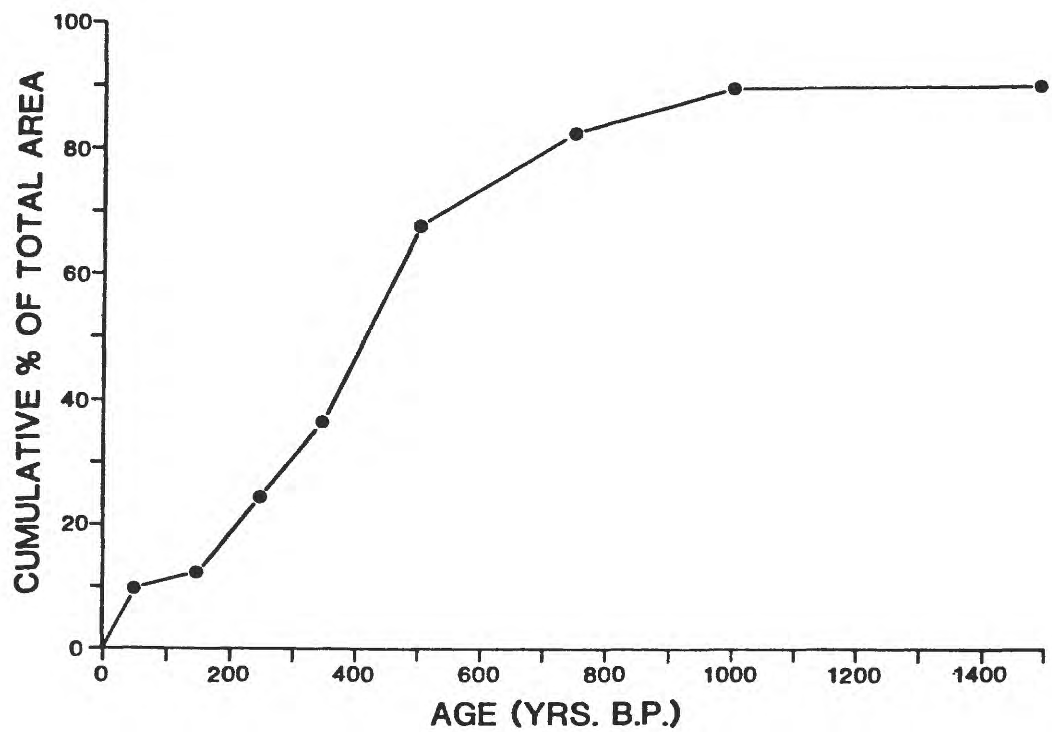


Fig. 73--Age of Kilauea's surface, a graphical presentation of the data in Table 11. Considerable variation is shown in the rate of coverage, the intervals 0-100 and 400-600 years B.P. having high rates, and the intervals 100-200 and 1000-1500 years B.P. having low rates. Rates for the earlier intervals, however, are artificially low and arise partly from later coverage of the older flows by younger lava.

suggested that Kilauea's surface was younger than had been expected, and when the paleomagnetic work was planned in 1978 it was anticipated that a majority of surface flows would be found younger than perhaps 2000 to 4000 years. The results show that the surface is younger even than this.

Though Kilauea's surface appears to be much younger than was anticipated, its youthfulness is not inconsistent with other information available about Kilauea's rate of growth. For example, if we assume Swanson's (1972) best estimate of Kilauea's magma supply rate during recent decades of 9×10^6 m^3/mo, and if we assume that the mean thickness of lava flows is 2 m, we find a rate of surface coverage of 54,000 km^2/1000 yrs, 36 times the rate needed to cover Kilauea's 1500 km^2 subaerial surface during such an interval. This potential rate of coverage is a maximum value because it includes no corrections for the overlapping of lava flows and coverage of the submarine slopes of Kilauea. Despite these omissions, however, the magma supply rate appears completely adequate to explain the rate of surface renewal graphed on Figure 73. And as discussed at the end of Chapter II, the same magma supply rate also seems adequate to fill the ancient caldera and accumulate the thickness of lava observed above the summit-region hiatus of 1000 to 1500 years ago.

Kilauea's Eruption History

Kilauea's recent eruption history, as compiled from geologic evidence and the 200-year historic record, is summarized in Figures 74 and 75. Figure 74 displays clearly some century-scale variations in

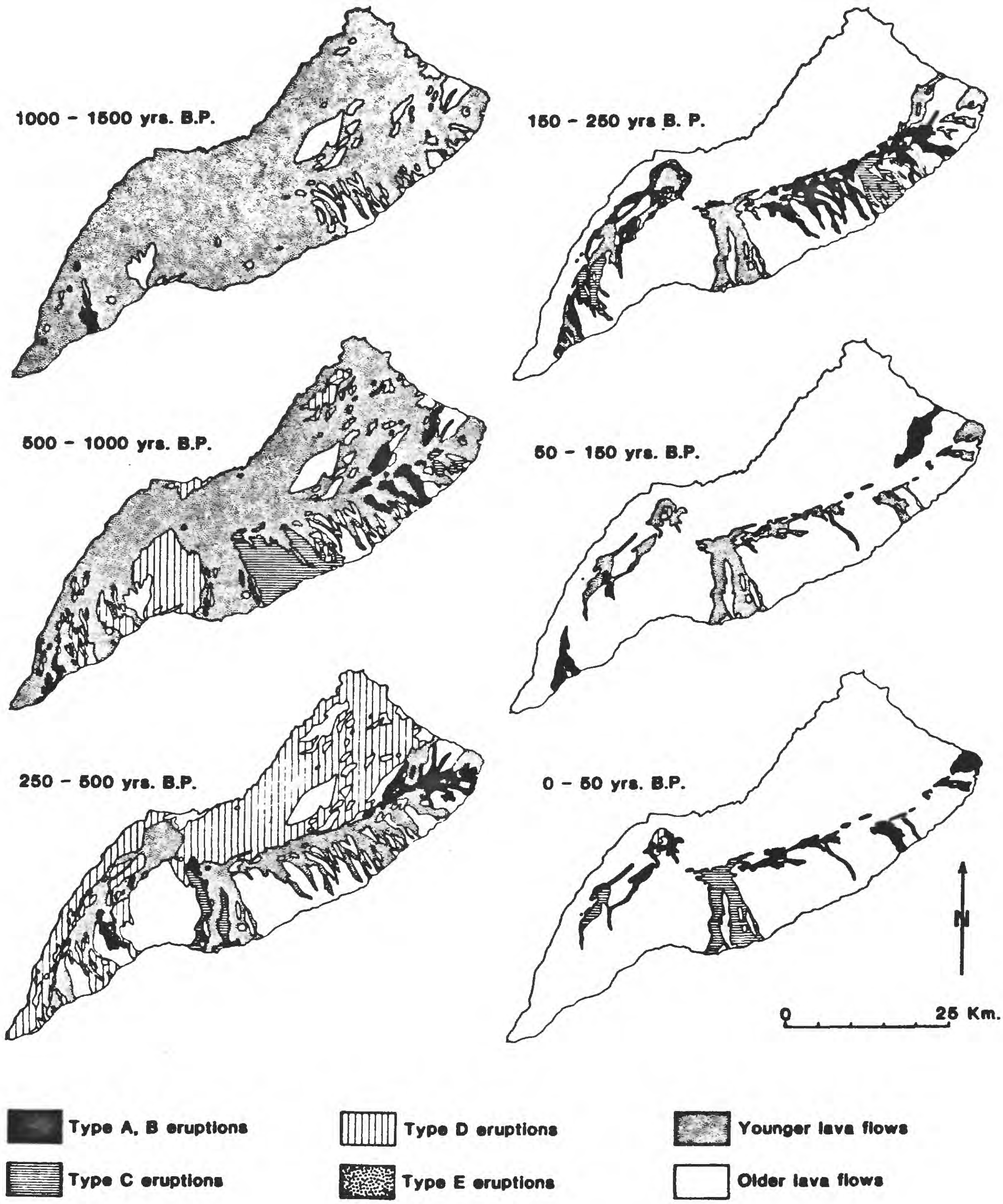
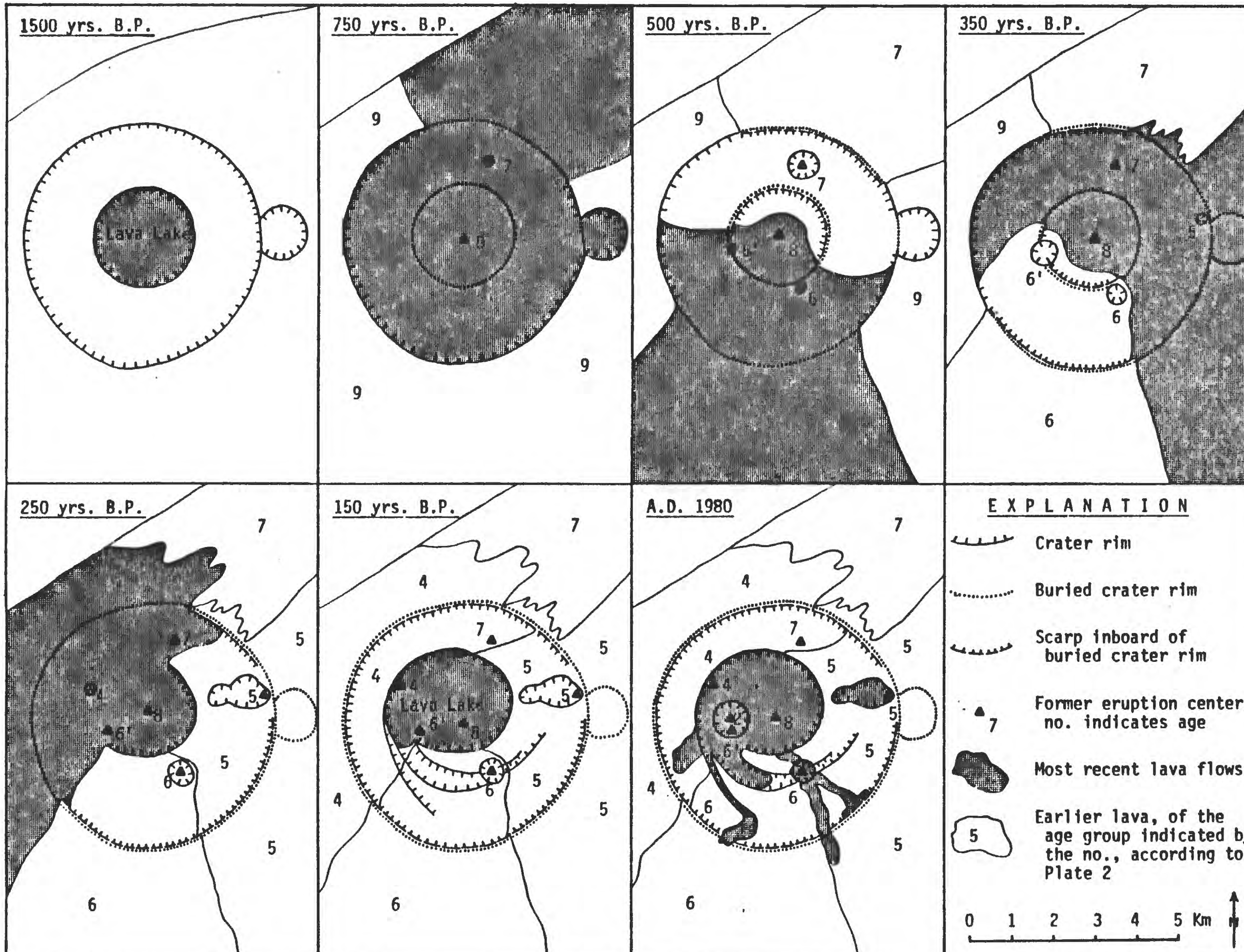


Fig. 74--Summary of Kilauea's eruption history during the last 1500 years. Successive geologic sketch maps are generalized from information given on Plates 2 and 3.

Fig. 75--Kilauea's summit region during the last 1500 years. Shown here is a series of geologic sketch maps for successive times. Omitted for simplicity in these cartoons are the extensive deposits of Uwekahuna Ash (about 1500 years B.P.) and Keanakakoi Ash (about 200 years B.P.) that mask the lava flows beneath them. This sequence of views shows the gradual filling of an ancient caldera whose ghostly presence is revealed by modern scarps inboard of the ancient caldera rim, the modern scarps arising from thermal contraction of the caldera fill. Filling of the ancient caldera, and burial of its rim, is inferred to have occurred in stages as the locus of activity shifted from place to place around the summit. Eruption centers 4 (Lua Pele) and 5 (Hale O Ai-laau) are well-expressed in the present topography of the volcano, but the locations of the other centers are highly conjectural, being inferred merely from the distribution of their lava flows over the flanks of the volcano. The patterns of flooding and collapse within the caldera are also highly speculative, and they are intended to serve merely as preliminary hypotheses for testing in future detailed studies.


1500 yrs. B.P.
Lava Lake
750 yrs. B.P.
500 yrs. B.P.
350 yrs. B.P.
250 yrs. B.P.
150 yrs. B.P.
Lava Lake
A.D. 1980
EXPLANATION
Crater rim
Buried crater rim
Scarp inboard of buried crater rim
Former eruption center, no. indicates age
Most recent lava flows
Earlier lava, of the age group indicated by the no., according to Plate 2
0 1 2 3 4 5 Km

behavior, and Figures 74 and 75 together reveal a correlation between events occurring on the rift zones and those occurring at the summit.

On the basis of work reported here, little can be said about Kilauea's history prior to about 1500 years ago. The tube-fed pahoehoe flows of Kipuka Ahiu and Kipuka Keana Bihopa indicate that sustained eruptions had occurred at the summit, and the work by Easton (1978) on the older lavas of Kilauea's south flank shows that intervals of lava-flow accumulation had long alternated with intervals of ash accumulation. It is possible that over a long period a succession of calderas had occupied the summit, each of them in its turn developing and then filling (Holcomb, 1976b).

Sometime around 1500 years ago a new caldera developed on Kilauea, truncating lava flows dated paleomagnetically as belonging to the interval 1500 to 2000 years B.P. Little is known about the geometry of this caldera except for the general location of its outer scarp and the existence of a broad, step-faulted terrace on its northern side and an inner sink somewhere southeast of the present Uwekahuna bluff. The Uwekahuna Ash was draped onto the rim and step faults of the caldera, and it may have originated from phreatomagmatic eruptions caused by caldera collapse.

Very little is known about Kilauea's eruptions during the long interval between about 1500 and about 1000 years B.P. Paleomagnetic data have revealed only one lava-flow assemblage on the southwest rift zone erupted during this interval. The apparent sparsity of eruptions may be partly an artifact of the extensive coverage by younger lava flows, with older flows of this interval concealed. However, the hiatus discovered in the walls of several pit craters indicates that

this interval was remarkably devoid of eruptions in the summit region outside the ancient caldera. Unless the magma supply were cut off during this interval, much of the eruptive activity must have been confined to the caldera and/or submarine parts of the volcano.
An hiatus in lava flow accumulation on the south flank could have coincided with the comparatively thick accumulation of surficial material on Kipukas Ahui and Keana Bihopa. A large aa flow in Kipuka Keana Bihopa has been dated by ^{14}C at 1130 ± 60 years B.P. (sample W-3827), but the data from paleomagnetic site 8B397 are more consistent with an age for this flow of 1500 to 2000 years B.P. (Table 2).
If the ^{14}C date is correct, it indicates that by about 1100 years ago the ancient caldera had filled enough for lava to overflow its southern rim, unless a brief type A or B eruption occurred south of the caldera. Whether or not any lava spilled over the south rim of the ancient caldera prior to 1000 years ago, much lava from the summit region was spread over Kilauea's south flank during the interval 1000 to 500 years B.P. Much of this lava consisted of tube-fed pahoehoe from two or three eruptive centers near the summit and from Kane Nui O Hamo on the lower part of Kilauea's upper east rift zone. Dating imprecision does not yet permit any progressions in summit/rift-zone activity to be resolved during this 500-year interval.

The interval 500 to 250 years B.P. continued to see considerable activity at the summit, with long-sustained eruptions occurring at Hale O Ai-laau and Lua Pele. But these vents spread lava mainly over the inland flanks of Kilauea. A few brief eruptions are known along the rift zones as well as a type C eruption from a vent (possibly Puu Huluhulu or Kokoolau) on the upper east rift zone. But most of the activity in this interval seems to have been confined to the summit, its lava flows flooding large areas of the north and southwest flanks.

The interval 250 to 150 years B.P. saw marked changes in Kilauea's eruptive behavior. No long-sustained summit eruptions occurred during this interval; instead many brief eruptions occurred along the rift zones. Especially noteworthy are extensive assemblages of types A and B along the middle and lower east rift zone and type C eruptions at Heiheiahulu and Kamakaia. This flurry of flank eruptions must have been accompanied by the development of Kilauea's present caldera (much of which must postdate the Lua Pele vent of the 17th century), and it climaxed with the phreatomagmatic eruption that produced the Keanakakoi Ash in A.D. 1790.

Following the 1790 eruption, Kilauea's behavior changed again, and for more than a century almost all of the volcano's subaerial activity was confined to the new summit caldera. Only two large flank eruptions, those of 1823 and 1840, are known to have occurred, while the activity within the caldera was sustained almost continuously.

Kilauea's famous 19th century pattern of continuous summit activity ceased abruptly in 1924, apparently following a shallow submarine eruption from the east rift zone that coincided with summit collapse. Since that time, summit eruptions have been infrequent and relatively brief, while eruptions from the rift zones have become more frequent and more sustained, reaching a climax with the Mauna Ulu eruption of 1969-1974. A large earthquake and subsidence of Kilauea's south flank in 1975 appears to have induced changes in eruptive behavior

(Hawaiian Volcano Observatory, unpubl. data), but it is still too early to tell if these changes have long-term significance.

In summary, Kilauea's behavior has been characterized by long-sustained eruptions from the summit and brief eruptions from the rift zones. 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. Frequent rift activity probably has been accompanied by collapse at the summit, and summit collapse has been associated with phreatomagmatic eruption. Events following explosive eruptions, however, have followed no definite 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.

Hawaiian Traditions

It appears that some information about Kilauea's eruption history can be extracted from Hawaiian oral traditions. Though much of the oral history has been lost and many of the surviving fragments are self-contradictory, ambiguous, or unspecific, the information still preserved provides provocative comparisons with the history derived from geologic data. An exhaustive review and analysis of the traditions would constitute a major research project in its own right, involving, for example, retranslations into English of traditions transcribed in the Hawaiian language, and it cannot be attempted here. A brief summary of the traditions currently available is appropriate, and given now is a general Hawaiian description of Kilauea's history, followed by traditions about a few specific eruptions.

The most authoritative general account of Kilauea known is the one recorded in 1823 by Ellis (1827, p. 171-172) on the rim of Kilauea's caldera. This history was given to Ellis by his 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 under ground from her house in the crater to the shore.

Confirmation of this story was provided to Ellis a few days later at Kaimu, 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 (Ellis, 1827, p. 194).

This account could be especially valuable because it is the earliest known and was taken from local informants at Kilauea. As a result, it is the account least likely to have been distorted by distance, time, or Western preconceptions. Nevertheless, there remains considerable uncertainty in its interpretation. It is difficult to say how much of it is really a straightforward summary of witnessed events and how much is an interpretation, either by Ellis of the words said to him, or by the Hawaiians of the physical evidence displayed before them. Especially troublesome is the possibility of interpretive inferences by the Hawaiians themselves, because there is some evidence that other traditions do incorporate geological inferences from the natural record. It is often pointed out, for example, that the Hawaiian account of Pele's succession of homes in the Hawaiian Islands agrees well with the actual progression in volcanism, even though that progression had occurred long before the Hawaiians could have witnessed it directly. Unless the agreement between fact and legend is pure coincidence, the legend must rest on inferences made from nature by the Hawaiians. And if the traditions could incorporate geologic inferences about the overall history of the archipelago they could also include inferences about the specific history of Kilauea, gleaned by the Hawaiians from observable stratigraphic relationships. Despite this uncertainty, however, the likelihood of Ellis' account being really a summary of witnessed events is high enough to merit serious consideration. After all, Hawaiians were probably living on Kilauea throughout the millenium in which most of its surficial lava flows were erupted. They should have seen the eruptions of this interval, and we know from widespread consistency in their geneologies that their oral traditions could be very precise. If, then, we accept Ellis' account at face value, how does it compare with the presumably independent geological information?

Agreement appears generally to be good between the tradition and the geologic information. Some differences, however, suggest that the tradition may tell some things not yet available from geologic evidence. 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 stating that: (1) 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; (2) the caldera developed gradually over some extended interval, while the geologic record permits a sudden development of the caldera sometime before the explosive eruption of 1790; (3) explosive eruptions had occurred more than once, at intervals, while the geologic information reveals no explosive eruptions occurring between those of the Uwekahuna Ash (Probably pre-Polynesian) and the Keanakakoi Ash of 1790 (Christiansen, 1979); and (4) 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 permits them to be older.) There are no outright contradictions between Ellis' account and the geologic evidence. However, potential conflicts exist at a few points, 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, perhaps even the early 18th century A.D. within 100 to 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 some information not yet available from other kinds of evidence.

Other sources of information about Hawaiian traditions appear to be less reliable. Examples are several traditions cited by Westervelt (1916). These traditions give many details about the summit region not included in the account by Ellis. For example, Westervelt describes specific changes in the focus of 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 devoirs." 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, among which is the following example. Long ago much of Kilauea was forested (because of a hiatus in summit overflows?), and 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 the 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 for this account, though from comments elsewhere in his book it seems possible that his sources were articles published in Hawaiian-language newspapers of Honolulu during the late 19th century. With the sources unknown, there is no way to judge their reliability. Second, it appears that some of the material is Westervelt's own synthesis of several different accounts, and there is a strong possibility that some of his own preconceptions were incorporated into the resulting product. For example, the westward shift in the focus of summit volcanism that he mentions may not have come from the traditions themselves but from his own understanding of summit events. A few decades before Westervelt's account was published Dutton (1884, p. 121) had already inferred such a shift of the eruptive focus, from geologic evidence. Third, there is a possibility that the accounts used by Westervelt had already been considerably degraded by Hawaiian storytellers, especially if the sources are Honolulu newspaper accounts of the late 19th century, a locale and time far removed from the Kilauea of pre-Western influence. During the disintegration of Polynesian society following Cook's arrival, an apparently well-developed body of oral history was partly lost and adulterated. 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. Fourth, this account by Westervelt 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 very little credence. This is true also of many other provocative traditions.

Despite the uncertainties in Westervelt's account, I have used it in assigning names to prominent features of Kilauea's summit. Thus I have called the late prehistoric vent in Kilauea Iki "Hale o Ai-Laau" (house of Ai-laau) and have termed the sustained prehistoric vent near Uwekahuna Bluff "Lua Pele" (Pele's pit), these names being consistent with the westward shift in activity that paleomagnetic evidence indicates occurred sometime around A.D. 1600. The timing of this inferred shift, however, is later than some traditions permit, and previous use of "Lua Pele" for other summit features may lead to confusion in the future. Despite these points against such names, I used them as provisional names here because I felt that some names were needed for clarity of presentation, and these were the best currently available.

Even though the specific details of most traditions cannot be interpreted as literally true, it seems likely that at least some of the traditions do allude to real eruptions. This is true especially of traditions recorded by Ellis as having specific lava flows associated with them. Thus, the late prehistoric flows reaching the coast west of Kealakomo are associated with the legendary conflict between Pele and Kamapua'a (Ellis, 1827, p. 183), the flows and chain of vents including Halekamahina are tied to the legend of Kahawali (Ellis, 1827, p. 207-210), and a flow formerly comprising the easternmost point of Puna (the 17th century aa flow extending eastward from the gap in Kapoho Cone?) resulted from Pele's rejection by the Puna Chief Kumu-kahi (Westervelt, 1916, p. 27-28). In some cases a tradition states 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 geneologies. Such statements could provide especially valuable checks on the geologic evidence, but even here confusion can arise.

An example of possible contradiction in the most authentic traditions concerns the age of Puu Huluhulu, which paleomagnetic evidence suggests is 350 to 500 years. (Paleomagnetic site 9B913 itself cannot be trusted because of possibly large errors arising from a vent anomaly and a rift-zone anomaly, but Puu Huluhulu seems a likely source of a late prehistoric type C assemblage of lava flows reaching the coast between Kealakomo and Keauhou Landing, and paleomagnetic site 8B541 assigns one of these flows to the same interval.) 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 time A.D. 1200 in the reign of Kamaiole, the usurper. 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" described cannot be the pit crater adjacent to Kilauea's caldera now known as Keanakakoi because earlier Ellis (1827, p. 179) had 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 neighborhood. Moreover, Ellis described his "Keanakakoi" as a high-standing edifice, features such as spatter cones apparently being included in his concept of "crater." There are three such features along the route he must have traveled from the caldera to the coast: Kokoolau, Puu Huluhulu, and an unnamed spatter cone near Devils Throat. One of these must have been his Keanakakoi, and if it is Puu Huluhulu there is a possibility of conflict with his other comments because the reign of Liloa occurred long after the inferred time of conflict between Pele and Kamapua'a. According to Kalakaua's 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 350 to 500 years B.P. age indicated by the paleomagnetic data, Kamaiole's reign does not. If the geologic interpretation of Plate 2 is correct, the two traditions concerning the age of Puu Huluhulu are in conflict. But other interpretations are possible. Instead of being the relatively old kipuka shown on Plate 2, Kokoolau may really be the source of much of the younger lava, including the flow of paleomagnetic site 8B541; and Puu Huluhulu may be an older source for the Kamapua'a flows. Or the Pele-Kamapua'a conflict may really describe the eruption at Kane Nui O Hamo, whose lava flows have a paleomagnetic age consistent with the dates assigned to Kamaiole's reign. Further geologic data such as chemical analyses may be useful in the future to tie some of the lava flows to their proper vents.

From the foregoing discussion it should be clear that much caution must be used in attempts to extract geologic information from the Hawaiian traditions. In fact, the most useful comparisons between the traditions and geologic data in the future may proceed in the opposite direction: the geologic data may provide a firmer base on which to reconstruct the social history.

CHAPTER VI

DISCUSSION

From the work described here, conclusions can be drawn about both the behavior of Kilauea and the methods I have used to study it. Uncertainties in these conclusions, and speculations stemming from them, point to avenues for further study.

Summary and Conclusions

This report has dealt with the long-term behavior of Kilauea Volcano, focusing upon behavioral variations that occur over intervals of centuries and millenia. The problem has been approached from an historical point of view; long-term variations in behavior were defined during the interval when Kilauea's present surface was produced. A history for this interval was synthesized from a program of geologic mapping, age determinations, and morphologic analysis of lava flows.

The chronology of eruptions was established primarily from paleomagnetic measurements. A history of geomagnetic secular variation for Hawaii was defined by measuring the directions of remanent magnetization of lava flows dated previously by the ^{14}C method. Key flows of unknown age were dated by comparing their magnetization with the history of secular variation. Relative ages of other flows were then determined using principles of superposition and vegetation development.

Geomagnetic secular variation proved to be a useful tool in dating the young lava flows of Kilauea, and it appears to have considerable potential for further refinement and extended application. The history of secular variation becomes more uncertain with age but is defined fairly well for the last 1000 to 2000 years. During this interval the rate of variation between successive averaged intervals is typically about 4 deg/century. Dating precision is about 100 years for the last 500 years and about 250 years for the preceding millenium; further refinements may result in precisions of a few decades.

Together the chronologic studies and geologic mapping indicate that Kilauea's surface is very young: about 70 percent is younger than 500 years, and about 90 percent is younger than 1000 years. A major hiatus in summit overflows occurred between about 1500 and 1000 years B.P. Much of Kilauea's present caldera dates from the 18th century, but it was preceded by at least one earlier caldera that developed about 1500 years B.P. and was later filled.

Behavior of the eruptions was inferred from the morphology of their products, observations of historic eruptions having shown that different kinds produce different assemblages of products. Duration and stability are the chief behavioral features distinguishing different eruptions; they are expressed in the degree of channelization achieved by lava flows, channelization being a time-dependent phenomenon. The surficial lava-flow assemblages of Kilauea were classified by eruption type, and patterns of eruption type were defined in time and space. The results indicate that this kind of morphologic analysis can yield much useful information about eruptive behavior and may therefore be used with profit elsewhere.

Different parts of Kilauea have differed characteristically from each other in eruptive behavior. The most notable difference is between the summit and rift zones, with all of the type D assemblages being confined to summit vents. Moreover, the type C assemblages are more numerous and extensive along the upper parts of the rift zones than along their lower parts. Evidently the duration and stability of eruptions have been greater in the summit region and have decreased along the rift zones, as distance increased from the magma reservoir beneath the summit. In contrast, the number of type B vents appears to increase with distance from the summit; this is especially obvious along the east rift zone, where the frequency of pyroclastic central vents is much higher below elevations of 500 m than it is above. The briefest eruptions, of type A, have occurred all along the rift zones as well as at the summit, on the average displaying 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 Kamakaia Hills and other individual strands of the southwest rift zone.

Different intervals of Kilauea's history too 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 eruptions. Some changes have been repeated at long intervals, and some of them may have occurred in evolutionary sequences. Two phreatomagmatic 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 historic 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.

Speculations

At this point I would like to go beyond the conclusions of the report and speculate a little about the causes of eruptive variation. The causes of variation will be an important topic of future research; if they can be identified they might be used to make better predictions of Kilauea's future behavior.

Many hypotheses could be devised to explain Kilauea's behavioral variations. Hypotheses could be conceived in different ways too, depending on the predilections of their authors. For example, hypotheses could be conceptualized directly from fundamental principles of mechanics or chemistry, or combinations thereof. I prefer to think in terms of simple phenomenological models, visualizing different spatial configurations and temporal sequences that can be extrapolated beyond the range of previous direct experience and then tested by further observations. These phenomenological models differ from theoretical models generated by geomechanics and other specialists because they are simply empirical generalizations and not constructed from fundamental principles. Theoretical models could be used to investigate or rationalize whatever phenomenological models seem most promising.

Many models could be visualized for Kilauea, and they could be classified in various ways. For example, we could distinguish between evolutionary models, cyclical models, and steady-state models. The different types of models would differ in their utility for predicting future behavior.

A cyclical model for Kilauea is shown in Figure 76. It is based on the hypothesis that eruption patterns reflect the amount and continuity of magma stored in the summit and rift zones. I have tried to visualize possible changes in the volcano's plumbing system parallel to the changes observed in eruptive behavior. The basic features of the model are changes in the amount of magma stored in different parts of the edifice, with the principal storage shifting between the summit and rift zones as successive calderas form and fill. Caldera collapse could arise from changes in the magmatic plumbing and also cause changes in the plumbing, acting as a feedback mechanism of an oscillatory system. The oscillations could be driven by a complex interplay between hydrostatic forces, friction, and thermally induced changes of state in the different parts of the system. Kilauea's history between about 1500 and 200 years B.P. could represent one cycle, and its history since 200 years B.P. could represent another, the volcano's current state corresponding to stage 2 or stage 3 of the model. Extrapolation could lead us to predict more flank eruptions, eruptions lower on the rift zones, fewer summit eruptions, and more summit collapses in the years ahead. If this occurs, geothermal energy reserves and hazards from lava flows should increase along the

Fig. 76--A cyclical model for Kilauea's behavior. Longitudinal profiles of a rift zone show five stages in the cycle. The cycle could represent a dynamic equilibrium between hydrostatic, thermal, and frictional factors.

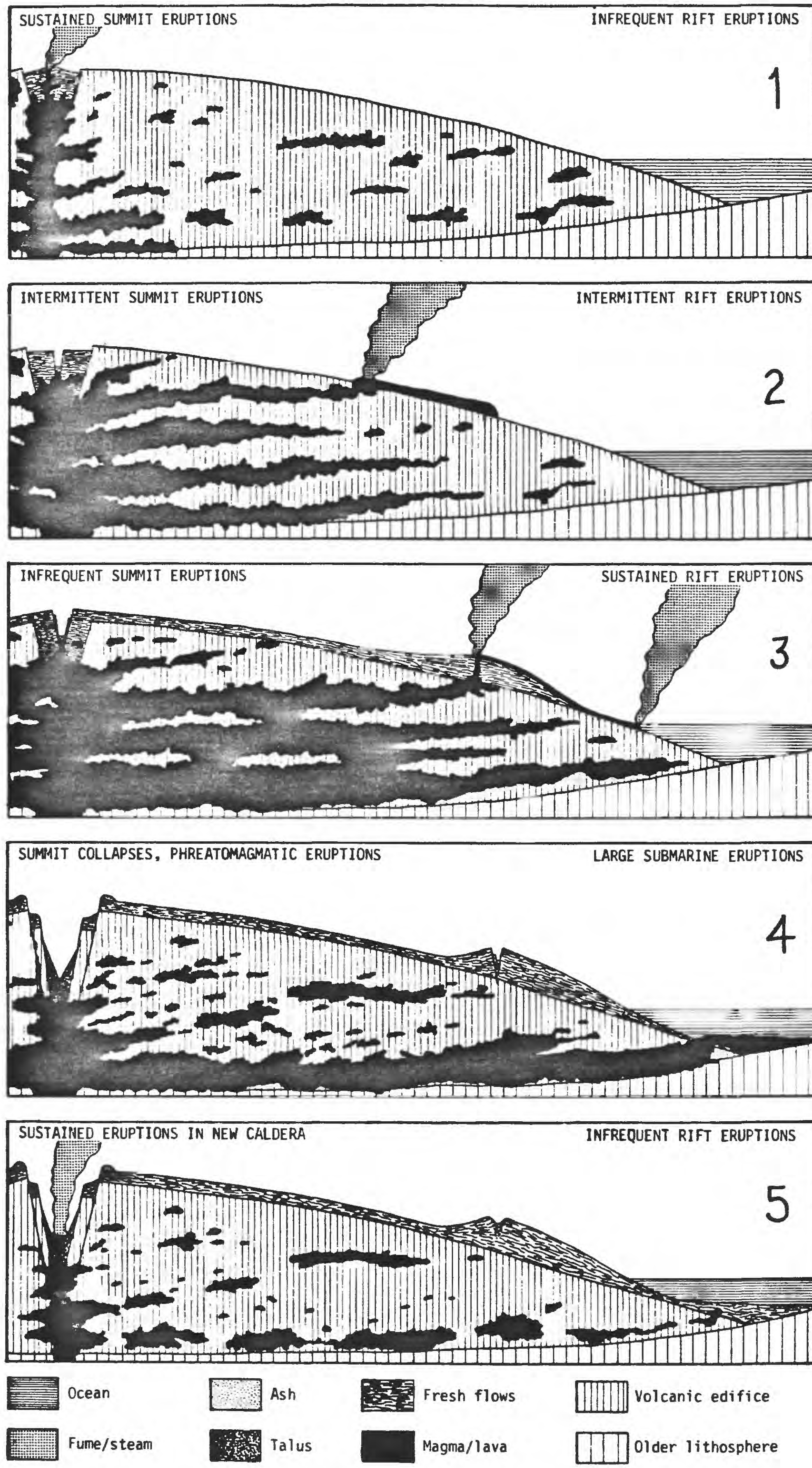
Stage 1. Eruptions are long sustained and restricted to a summit caldera, gradually filling it so that most magma in the system is stored beneath the summit. As the magma column rises, however, dikes are injected laterally under an increasing head and penetrate into the rift zones.

Stage 2. Summit eruptions are less sustained and rift eruptions are more frequent as more of the incoming magma is diverted into the rift zones.

Stage 3. Better continuity is developed in the plumbing system of the rift zone, and it is able to sustain eruptions for longer intervals at greater distances from the summit. As more lava is erupted at lower elevations, the magma column subsides beneath the summit, and the caldera-filling lava slowly cools.

Stage 4. Voluminous eruptions from the rift zones drain magma from the upper parts of the edifice, and collapse ensues. Collapse at the summit rejuvenates the caldera, and collapse along the rift zones destroys the continuity of their plumbing systems.

Stage 5. Magma rising from a deep source beneath the summit now finds its easiest escape into the newly deepened caldera; activity is once again sustained within the caldera, and continuity is lost in the rift plumbing as the dikes solidify.


SUSTAINED SUMMIT ERUPTIONS
INFREQUENT RIFT ERUPTIONS
1
INTERMITTENT SUMMIT ERUPTIONS
INTERMITTENT RIFT ERUPTIONS
2
INFREQUENT SUMMIT ERUPTIONS
SUSTAINED RIFT ERUPTIONS
3
SUMMIT COLLAPSES, PHREATOMAGMATIC ERUPTIONS
LARGE SUBMARINE ERUPTIONS
4
SUSTAINED ERUPTIONS IN NEW CALDERA
INFREQUENT RIFT ERUPTIONS
5
Ocean
Ash
Fresh flows
Volcanic edifice
Fume/steam
Talus
Magma/lava
Older lithosphere

rift zones, and hazards from collapse and phreatomagmatic eruptions should increase at the summit. Eventually, however, sustained activity should return to the summit, and hazards on the rift zones should decrease. Kilauea's brief historic record alone would lead to unrealistic assessments of the volcano's hazards and geothermal energy resources. It was a model of this type that I used as a principal working hypothesis in conducting this work; I was able to carry the project to completion in the faith that evolutionary changes probably do occur and can be used as predictive tools. But this faith may be groundless; other models could exclude the possibility of long-range forecasts.

A very different forecasting situation might arise from steady-state models of Kilauea. Such a model could be represented by stage 3, alone, of Figure 76, with a lot of magma always stored throughout the edifice. 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. Eruptions of any type could occur from any part of the system at any time. If a random model like this best described the volcano's behavior, it might not be possible to predict long-term changes using the previous history.

Alternative models could be constructed by blending the two outlined above. A model could be envisioned, for example, that is mainly steady-state but admits a small degree of evolutionary change following especially profound perturbations such as major caldera collapses.

In such a case, some predictive success might be achieved at certain times even though the overall degree of predictability remained very low.

Still other models could be fundamentally cyclical but rendered complex by the effects of additional factors. For example, the simple model of Figure 76 ignores the volcano's flank deformation. It has been suggested that magma storage in the rift zones is controlled to a large degree by recurrent slumping of Kilauea's south flank (Moore and Krivoy, 1964). More recently it has been concluded from detailed studies that flank deformation is a purely passive response to forceful intrusion of magma into the rift zones (Swanson and others, 1976), but this conclusion was based only on observations of the past century. If long-term eruptive changes occur, however, it is possible also that long-term changes in flank deformation occur also, with some intervals dominated by forceful intrusion/passive deformation and other intervals of active slumping/permissive intrusion, the true state of the edifice being a delicate equilibrium that can be perturbed in either direction. As a parallel to the "caldera" cycle of Figure 76, a "slumping cycle" could be visualized in which the volcano's plumbing system and seaward flank alternate in active and passive roles, switching roles when certain frictional and spatial thresholds are exceeded. "Slumping cycles" could be forced to oscillate in rhythm with "caldera cycles," or they could behave independently. If, for example, episodes of rapid slumping occurred more frequently than episodes of caldera collapse, with each perturbation followed by evolution of the plumbing system, very complicated but possibly predictable harmonic patterns of eruption might ensue.

Suggestions for Further Study

I hope this report is a useful contribution to the literature of volcanology. It should be obvious, however, that much work remains to be done. As in much research, a few questions have been answered while many more have been opened up. Several different lines of work could profit from more attention in the coming years.

First, improvements can be made in the methods of analysis, including the use of secular variation as a dating tool, the use of lava-flow morphology to infer the character of eruptions, and the use of photographs to interpret the geology of complex volcanic regions. Second, more can be learned about the aerial geology of Kilauea, including especially the past configurations of calderas and eruptive vents in the summit region, the stratigraphy of the south flank, the location and history of faults belonging to the Hilina system, and the geology of the volcano's submarine flanks. Third, more can be learned about Kilauea's past behavior--especially the causes of its variations--from refinements in the chronology and morphologic analysis of eruption, from studies of chemical and mineralogical variations in the lavas, and from theoretical studies of eruption mechanisms. Fourth, work of the kind described here could be extended to other volcanoes and used as the basis for comparisons and refinement of our general understanding of volcanism.

Secular variation can be improved as a dating tool in at least three different ways. First, the sources of between-site dispersion in remanent magnetization can be reduced through changes in experimental procedure and analysis, especially changes in sampling design.

Second, the history of secular variation can be refined by means of additional stratigraphic work and ^{14}C calibration. Third, paleo-intensity can be added as another measured variable in the magnetic record.

The interpretation of lava-flow morphology can be improved through field studies of morphology, observations of active flows, and theoretical models of flow behavior. Particular lava-flow processes can be better described and modeled; among these are the processes of channelization, deflation, inflation, ponding, and levee development. Efforts can be made to describe and interpret these processes quantitatively, and other processes having interpretive value can probably be identified. The system of eruption/assemblage classification can be improved so that dilemmas of the kind mentioned on page 158 can be resolved. The system may also be expanded to include the morphologic variations related primarily to physical and chemical properties of lavas at eruption.

The photogeologic methods can be improved by obtaining more ground-truth information on the morphology possessed by lava flows, structures, and vegetation on the scales expressed in aerial photo-graphs. The transitions between flow types can be better defined, and additional flow types probably can be differentiated. The variations in lava-flow reflectivity caused by differences in illumina-tion/viewing geometry, flow type, and flow age can be better described and understood. The relationships of vegetation pattern to flow morphology, flow age, climate, and human activities can all be described in much more detail and on a quantitative basis, and the causes of other vegetal variations can be determined. The photographic clues used here for inferring buried and small unburied faults can be tested and further elaborated.

Though the summit region of Kilauea has been given much attention in the past, there is much yet to learn. The size, shape, and internal configuration of the ancestral caldera, and the history of its filling can be delineated from drilling and geophysical soundings as well as paleomagnetic and stratigraphic studies of the present caldera walls and upper flanks of the volcano. Much may still be learned about the development of the present caldera too, building on the stratigraphic work by Christiansen (1979) and structural analysis of St. Ours (1979).

The stratigraphy of Kilauea's south flank can probably be unravelled much better by means of ground-based field studies. Such work might also include laboratory analyses of petrography, chemistry, and remanent magnetization as well as field descriptions of the surficial deposits.

The most important large-scale problem of Kilauea's aerial geology may be the history and nature of the Hilina fault system. It seems likely that no realistic model of Kilauea's behavior can be achieved until the history of this fault system is understood. The entire evolution of Kilauea may have been determined largely by the Hilina system and possibly antecedent Kaoiki fault system (Holcomb, 1976b). It seems likely too that anything learned about the Hilina system can be applied to our general understanding of not just large shield volcanoes but also other features, such as continental shelves, where large gravitational structures are known to exist. This problem can be approached in many ways, including field studies of the history of faulting, seismic and geodetic observations of the present state and behavior of the faults, and theoretical studies of the stress systems leading to recurrent movements. It will be especially important to learn if all displacements have occurred in small increments like that of November 30, 1975, or if in the past very large, catastrophic displacements have occurred. This question may be approached by study of the relationships between individual fault scarps and the lava flows cut by them and draped over them. Improved dating techniques may resolve temporal sequences useful in judging the cause/effect relationships between faulting and volcanism over long intervals.

Despite the considerable uncertainty still existing about much of Kilauea's subaerial geology, the amount known seems exquisite in its detail compared with what is known about the volcano's submarine flanks. The entire submarine edifice could be remapped bathymetrically using new surveying technology (multi-narrow beam sonar). Types and ages of lava flows could be delineated by use of side-looking sonar, deep-towed camera systems, and dredging. Areas deserving special attention are the submarine extensions of both rift zones and the submarine blocks displaced by the Hilina fault system.

In order to determine the causes of eruptive variations it will be helpful to refine the chronology so that sequences of a few decades or several years can be resolved. Sequences of particular importance are those of (1) the 17th and 18th centuries, that produced extensive assemblages of types A and B and the type C assemblage of Heiheiahulu along the east rift zone; (2), 750 to 500 years B.P., that produced type D summit assemblages possibly bracketing the type C assemblage of Kane Nui o Hamo; and (3), 1500 to 750 years B.P., that produced various assemblages along the east rift zone. For each group it will be helpful to establish relative ages of the members and see how they are clustered or otherwise distributed in time and space. Among the chronological methods likely to be useful are magnetic secular variation, quantitative descriptions of vegetation development, and cultural clues. Among the latter, in addition to oral traditions, are the overlapping patterns of pre-Western political subdivisions, which frequently correspond to lava-flow assemblages. If the ages of these subdivisions can be established from the oral political history, they may help establish precise ages of lava flows because the losers in feudal conflicts were generally pushed onto the most barren and undesirable lands.

Petrologic studies may be useful in generating and testing models for the state and behavior of Kilauea's magma plumbing system. Variations in chemistry and mineralogy are known to occur (Wright, 1971), but the knowledge of prehistoric variations is very scanty. Before long-term changes can be defined, however, it will be necessary to learn the amount of variation occurring within single lava flows and flow assemblages. An extensive rock collection made during this mapping project could be used to determine the variations both within and between prehistoric lava flows.

Theoretical studies of the physics of intrusion and eruption should be helpful too in testing models of Kilauea's long-term eruptive behavior. Such work might include considerations of the gross shapes of dikes and flow patterns within them, the degree of hydraulic continuity and amount of friction to be expected in the plumbing between widely separated parts of the volcano, the cooling rates of dikes and country rock surrounding them, and the mechanisms by which long-sustained eruptions become established, achieve stability, and eventually shut off. Delaney's (1980) theoretical work on the physics of dike systems could be used as a starting point for such studies.

Finally, detailed studies of the kind attempted here at Kilauea may be attempted also at other basaltic volcanoes. The most straightforward application of methods and ideas would be on other Hawaiian volcanoes and large shield volcanoes elsewhere, such as the Galapagos Islands and Reunion, which are generally similar to Kilauea but differ to some degree in morphology, structure, and historic eruptive behavior. Similar work may also be done, however, on other volcanic systems that superficially appear very different from Kilauea but may have underlying similarities. Examples are the large subaerial and submarine rift systems of lithospheric spreading centers. The magmatic plumbing systems within segments of these rift zones may behave in ways that are analogous to those of Kilauea's rift zones, with spatial and temporal variations in eruptive behavior arising from shallow lateral transport of magma away from discrete centers of intrusion. It is conceivable too that useful information may be gleaned about the eruption of flood-basalt systems by means of detailed comparisons with Kilauea's behavior. Useful comparisons may be made also with extraterrestrial volcanoes. It is known, for example, that large volcanic shields and rifts occur on both the Moon and Mars, and much may be learned about these volcanoes from photographic studies similar to the one described here.

A P P E N D I C E S

APPENDIX A

DATED LAVA FLOWS--SUPPLEMENTARY INFORMATION FOR PALEOMAGNETIC SITES

SITE IDENTIFICATION		SITE LOCATION				
Number	Name	7.5' Quadrangle	Description	Elev. (ft)	J_{NRM} (A/m)	SSM (deg)
8B001	Girl Scout service center	Mountain View	Both sides Hwy 13, 2.4 km SE of Keaau	345	9.3±5.2	0.6
8B025	Malama Ki triangulation station, "1790"	Kapaha	Around and mauka of trig station	97	7.2±3.8	2.1
8B061	Waipahoehoe Bridge	Mountain View	In stream bed, A on mauka and B on makai side of bridge	290	8.2±2.4	1.0
8B301	Kaimu quarry aa of "1750"	Kalapana	Kapoha side Hwy 13, 1 km mauka of Kaimu	100	12.2±3.0	1.9
8B325	Moana Hauae flow of "1750" at BM 486'	Pahoa South	By benchmark at 486' along Hwy 13, 4 km mauka of Kaimu	480	13.8±5.2	4.2
8B337	Nanawale Estates 1840: Kehau at Pahoa	Pahoa North	Both side, Kehau Road on makai side of intersection	390	5.8±2.1	4.1
8B385	Pali-rim, lightning-struck window	Kau Desert	Streambed near pali rim, window through flow of 8B409	2300	-	9.8
8B397	Pali-rim, aa	Kau Desert	Pali rim 550 m NE of Hilina Pali picnic shelter	2300	8.3±4.4	0.7
8B409	Pali-rim, youngest pahoehoe	Kau Desert	Rim of landslide scar, east of younger aa	2300	5.8±2.3	0.6
8B421	Wung Ranch quarry	Volcano	Quarry walls on both sides of road toward house	2600	6.6±1.4	-
8B433	De Silva school	Hilo	Across street from school, to the west (mauka)	500	16.2±4.9	1.1
8B541	Kaapue a flow near Ainahau parking lot	Makaopuhi Crater	Along Ainahau fenceline, about 150 m east of parking lot	2770	13.2±4.3	1.0
8B553	Aa lobe of Bates triangulation station	Kipuka Pakekake	Mauna Loa Road, 1.3 km below end, road cut in aa lobe	6340	17.4±6.0	-
8B577	Halfway House	Wood Valley	Thin undercut flow in shallow gully, about 200 m mauka of house	2960	9.4±6.0	3.3
8B589	Peter Lee ash pit	Wood Valley	Mauka side of Peter Lee Road, flow surface and ash-pit wall	2600	7.4±6.5	-
8B601	Ainapa gulch	Wood Valley	Head of gulch, both surface and undercut edge of draped flow	2610	8.2±6.0	-
8B613	Youngest Keamaku (kkk), Kipuka Ki	Kilauea Crater	Massive outcrop in roadcut on east edge of Kipuka	4200	14.7±9.4	5.5
8B625	Kaoiki aa, pk, Keauhou Ranch	Kilauea Crater	Both sides of roadcut in massive aa on face of Keoiki Pali	4100	7.5±3.1	1.6
8B661	Kaalaala Gulch	Pahala	Mauka side of Kaalaala Bridge, in gulch	1175	5.0±4.4	1.6
8B673	Kaalaala tributary	Pahala	Flow surface and wall of shallow gulch, mauka of Hwy 11	1305	9.8±5.3	-
8B685	Reeser backyard	Volcano	Between house and water tank	3730	7.9±6.3	1.5
8B697	Moaula Gulch	Pahala	West side of gulch, about 100 m upstream from Moaula Bridge	440	13.8±6.1	-
8B709	Punaluu flow in cane field	Punaluu	Massive outcrop on mauka side of road, SW rim of gulch	1600	6.0±1.8	2.6
8B721	Big-olivine flow on Ninole flow	Punaluu	Small quarry on mauka side of haulage road, SW of intersection	1130	10 ±3.8	1.8
8B757	Keanakakoi interbed	Kilauea Crater	Flow and rampart, both sides of fissure vent concentric to caldera	3550	4.3±1.6	1.1
8B793	Komahai frontage	Mountain View	Both sides of Puhala St., about 100 m makai of Lehua intersection	1360	7.8±2.2	1.0
8B829	Kulani junkyard	Kulani	100 m east of equipment barns	5170	18.5±3.1	0.7
8B841	Kaoiki drapery, llm, Keauhou Ranch	Kilauea Crater	On face of pali, halfway up, about 700 m east of 8B625	4100	13.6±7.4	7.2
8B853	Tilling site	Wood Valley	Between Peter Lee Road and base of Kaoiki Pali, by fence	2995	11.0±3.0	1.6
8B865	Macadamia orchard, upstream	Pahala	Thin flow capping east bank of stream channel	1115	4.8±3.0	-
8B877	Pahala fissure flow	Pahala	In SW bank of Paauau Gulch, about 20 m makai of gate	570	4.9±9.3	0.4
8B889	"Big-olivine" in cinder pit	Naalehu	Quarry walls, about 1 km SE of Kaalaiki landing strip	1680	10.1±5.6	1.9
8B901	Kapua Road aa flow	Mountain View	Roadcut on mauka side Hwy 11	1730	6.4±2.1	3.5
8B913	Kipuka Nene variable olivine, plunge pools	Punaluu	SW rim of Hilea Gulch, in trees just above meadow	1000	9.5±5.5	1.6
8B925	Kau baseyard, Waiohinu	Naalehu	Roadcut on baseyard street corner	1095	18.4±3.7	2.0
8B937	Ninole flow, lost knife	Punaluu	Both sides of road, 150 m NE of prominent aa channel	1175	8.5±7.2	0.6
8B949	Mosquitoes, upper flow	Punaluu	Bed of Ninole Gulch, makai side of road; 4 subsites	1220	8.4±3.2	-
9B013	Stainback Hwy near Olaa Flume Road	Puu Makaala	Mauka side of Stainback Hwy, .95 km mauka North Kulani Road	1835	13.0±3.9	1.8
9B037	Panaewa flow, Allied Aggregates quarry	Hilo	Quarry walls, 0.8 km mauka of Hwy 11, on south side of north pit	330	8.1±5.5	3.6
9B049	S. Ho branch of 3.2 flow, makai	Hilo	Rodrigues frontage on bend of Kupulau Rd into Kaweilaui St.	560	7.9±5.2	1.9
9B061	"Kulaloa branch of 3.2 flow"	Piihonua	Near Kulaloa Rd at Ainaloa Rd, on mauka side of man-made channel	1105	13.6±3.1	3.4
9B073	Youngest Keamaku (kkk), at terminus	Wood Valley	Hwy 11 roadcut, mauka side 50 and 150 m from terminus	2915	9.3±3.8	3.0
9B085	1942 branch of 3.2 flow	Kulani	Powerline road, makai side	2900	12.8±7.2	3.8
9B097	S. Ho branch of 3.2 flow, mauka	Kulani	Powerline road, near pole 68, makai side	6055	19.1±4.6	1.8
9B109	Kulaloa branch of 3.2 flow	Kulani	Powerline road, near poles 83 and 84, in road bed	6180	16.7±6.6	3.6
9B121	Old Volcano Trail flow at Kuauli Road	Mountain View	Both sides of Kueuli Road, flow margin in gully along SE edge cane field	790	5.2±4.2	1.4
9B133	Waipahoehoe Gulch, mauka	Mountain View	Undercut NW edge of flow in lava-filled gully between cane fields	310	4.6±2.9	2.9
9B205	Kaholua o Kahawali	Kapoho	Aa flow and welded spatter in quarry walls of tephra cone	480	10.5±3.8	3.4
9B253	Easternmost Keamoku flow (pk)	Kilauea Crater	Puu Oo Trail, both sides of road	5060	19.3±4.5	1.5
9B265	Keamoku (kkl) channel, Strip Road	Kilauea Crater	Both east and west levees of big channel in aa flow mauka side of road	5630	12.9±2.4	1.5
9B277	Kipuka Kulalio	Kipuka Pakekaka	Mauka side of Mauna Loa Road, 1 km from end of road	6240	12.5±4.6	2.8
9B349	Macadamai orchard, downstream	Pahala	Thin flow capping east bank of west branch of gully, 100 m below split	1100	3.8±2.8	0.1
9B373	Punaluu flow, Hwy 11	Punaluu	Roadcut on mauka side Hwy 11, due north of Puehu	250	13.6±5.8	5.5
9B409	Kaalaalea flows, near big perched pond	Wood Valley	Feather edge of flows on rim of older fissure where not a fault	2155	7.5±4.7	6.3
9B433	Zynel frontage	Mountain View	Flow surface between road and stone wall, 5647 9th Street	800	2.0±1.4	0.2
9B445	Mosquitoes again, lower flow	Punaluu	Bed of Ninole Gulch, below ash exposed in plunge pool	1180	15.2±4.2	0.6
9B457	Kipuka Nene variable olivine, middle	Punaluu	Bed of Hilea Gulch, along lava tube makai of bridge	1250	10.6±2.0	0.5
9B469	Kipuka Nene variable olivine, upper	Punaluu	Bed of Hilea Gulch, mauka of plunge pool	1550	5.2±1.5	2.1
9B505	Puu o Lokuana	Kahuku Ranch	Quarry: NW wall and W side of north entrance, by gate	2270	5.2±4.2	5.2
9B517	Kapuoa	Kahuku Ranch	Roadcut, mauka side Hwy 11, 0.7 km E of South Point Rd	1930	10.5±3.0	0.5
9B529	Kahuenaha	Kahuku Ranch	Roadcuts, both sides Hwy 11, 2.5 km W of Kahuku Ranch mailboxes	1970	11.7±5.5	1.5
9B577	Park boundary channel	Kilauea Crater	Walls of channel in aa flow, 400 m NE of bend in Mauna Loa Road	5630	22.0±8.9	3.6
9B697	Fern molds	Wood Valley	Subsided flow surface, both sides of fissure	1740	14.6±3.1	2.6
9B721	Honolulu Landing 1840	Pahoa North	Roadcut a few hundred m SE of Honolulu Landing	45	4.2±1.4	3.3
9B757	Manuka flow	Papa	Roadcut, makai side Hwy 11 at Kau-South Kona boundary	1650	5.7±1.8	1.5
9B889	Puna Sugar Field 20	Mountain View	Shallow streambed in cane field, about 50 m makai of cane road	455	5.9±4.4	0.4
9B925	Kipuka Maunaiu	Kilauea Crater	SW rim of gully near base of pali; subsites above and below fence	3590	12.6±9.1	4.1

SSM is the separation of the subsite mean directions of magnetization.

APPENDIX B

UNDATED LAVA FLOWS--SUPPLEMENTARY INFORMATION FOR PALEOMAGNETIC SITES

SITE IDENTIFICATION		SITE LOCATION				
Number	Name	7.5' Quadrangle	Description	Elev. (ft)	J_{NRM} (A/m)	SSM (deg)
8B013	Opihikao	Pahoa South	Tidal zone makai of Hwy 137, 300 m west of intersection	5	5.0±3.4	0.8
8B037	Pahoehoe ESE of Kapoho Cone	Kapoho	Both sides of Hwy 137, 500 m south of Beachlots Rd	50	8.9±3.3	2.0
8B049	Gullied flow SE of Keaau dump	Mountain View	Mauka side Hwy 13, 4 km SE of Keaau	330	5.6±2.0	0.2
8B073	Tumulus in gullied flow SE of Keaau	Mountain View	Roadcuts on both sides Hwy 13, in tumulus	345	9.0±2.7	1.7
8B085	Kalali Point flow	Pahoa North	Flow surface on makai side, Hwy 13, 150 m NW of Paradise Drive	410	13.6±2.5	1.3
8B097	Cone field above Pahoa	Pahoa South	Scraped flow surface on both sides of road	755	4.2±1.1	0.4
8B109	Pahoa rubbish dump	Pahoa South	Near base of section exit ramp	735	13.3±4.7	0.6
8B121	Barren flow west of Kipuka Nene	Kau Desert	Surface, 10-30 m mauka of road; holes covered with small rocks	2915	11.8±7.3	2.4
8B133	Kipuka Nene, mauka of fault	Kau Desert	Surface, 20-40 m mauka of road, among sparse trees	2920	7.2±1.4	1.2
8B145	Kilauea Iki, below red cinder layer	Volcano	East wall above head of talus cone, to north	3670	13.0±4.1	2.6
8B157	Kilauea Iki, above red cinder layer	Volcano	East wall, north of head of talus cone	3680	10.1±4.2	5.8
8B169	Flow of Waipahoehoe Bridge	Mountain View	Both sides Hwy 13, near Poheku Street	330	8.3±2.4	2.0
8B181	Younger Halona flow	Pahoa North	Roadcuts on both sides Hwy 13, 700 m SE of Pahoa airstrip	600	6.7±1.5	2.4
8B193	Younger Ainaloa flow	Pahoa North	Makai side of Hwy 13 between Ilima and Makuu Streets	470	10.3±4.5	1.6
8B205	Aa flow from Kapoho Cone	Kapoho	Both sides Hwy 137, ramp onto flow, 150 m south of Beachlots Rd	60	10.6±2.8	2.7
8B217	Field 20 regrowth	Mountain View	South edge of Field 20, bare drainage makai of young trees	465	8.9±4.2	1.5
8B229	Puuloa flows	Kalapana	Mauka side Chain of Craters Road, by BM-HVO 79, 46' elevation	45	10.0±4.5	1.6
8B241	Kamoamoa	Kalapana	Mauka side Chain of Craters Road, by BM-HVO 84, 34' elevation	35	9.4±5.6	1.4
8B253	Faulted aa of Wahaula	Kalapana	Puna Gardens, roadcut on west side of road on steep segment	360	7.0±1.5	3.8
8B265	Queens Bath flow	Kalapana	Roadcuts, both sides Hwy 13, 1 km east of Queens Bath	45	9.0±2.9	5.0
8B277	Kauneloa aa flow	Kalapana	Roadcuts, both sides Hwy 13, 1.3 km east of Queens Bath	70	7.6±2.7	2.8
8B289	Kupahua pahoehoe flow	Kalapana	Both sides of old blacktop road, makai of graben	50	9.6±6.2	2.2
8B313	Old Kaimu pahoehoe	Kalapana	Roadcuts, west side Hwy 13, 0.7 km above Kaimu	90	8.1±1.6	1.1
8B349	Kukuihale	Pahoa South	Makai of Hwy 137, near Hilo-37-milepost	20	25.3±3.0	0.1
8B361	Deep coves in Kaliu flow	Pahoa South	Spines and blocks in coastal cliff NE of Kalipa Point	15	22.4±3.0	7.8
8B373	Pahoiki	Kapoho	Both sides Hwy 137, 600 m SW of intersection	30	9.1±3.8	2.4
8B445	Barren flow west of Kipuka Ahiu	Kau Desert	About 20 m makai of trail, 3 km west of Hilina Pali picnic shelter	1930	13.4±2.3	0.4
8B457	Aa flow of Cone Crater ?	Kau Desert	Both sides of trail	1875	19.6±5.7	2.2
8B469	Kipuka in Kamakaisuka lobes	Kau Desert	Flat area with sheetwash, 20-40 m makai of trail	1720	13.9±3.7	0.7
8B481	Kamakaisuka flow	Kau Desert	West edge of flow, undercut in gully, 1.2 km east of Pepeiau cabin	1780	25.5±7.9	3.0
8S493	Kipuka Pepeiau	Kau Desert	Pahoehoe surface about 100 m SE of Pepeiau cabin	1680	9.5±3.8	1.6
8B505	Pahoehoe below Kamakaia flow	Naliikakani Point	North side of Kau Trail, along fenceline	880	8.4±5.7	3.5
8S517	Kamakaia flow	Naliikakani Point	South side of Kau Trail, along fenceline	880	4.0±2.0	1.5
8B529	Junction, Kau and Kuse trails	Pahala	At broad bend in trail, east of the Red Cone flow	1460	5.1±1.4	0.6
8B565	Peter Lee connection	Wood Valley	Roadcut mauka side Hwy 11, at spur road to Halfway House	2825	9.6±2.3	2.9
8B637	Mauka Panahohoa pit	Wood Valley	Both sides Hwy 11 at 2770' elevation	2770	11.2±2.7	3.5
8B649	Above broad curve	Wood Valley	Both sides Hwy 11 at 2160' elevation	2760	8.6±3.7	3.0
8B733	Thurston lava tube	Volcano	Roadcut along east side Crater Rim Road, south of parking lot	3915	8.6±5.2	2.1
8B745	Cone Peak	Kilauea Crater	Around mauka end of trig. station crater, inner wall and rim	3630	10.4±6.1	2.5
8B769	Concentric vent under Keanakakoi Ash	Kilauea Crater	Makai side of spatter rampart, at west end in head of little gully	3440	8.2±7.6	1.8
8B781	Devils Throat tephra cone	Volcano	Roadcut, NE side of road, both flanks of cone	3380	11.1±3.7	5.4
8B805	Baxton Frontage, Ainaloa	Mountain View	Roadcut, north side of Ainaloa Drive, mauka of Plumeria Dr.	880	7.2±2.1	1.0
8B817	Kalea cemetery	Kapoho	Tide zone and clearing, east side of Kalea	5	11.8±1.3	3.1
8B973	Older Orr flow	Kapoho	Spines in tide zone, 100 m NW of Kalaemanu Point	5	14.7±3.7	3.4
9B145A	Younger Halona flow	Pahoa North	SE side of Makuu Drive, 10-20 m mauka of 9th Street	95	8.5±2.4	-
9B145B	Older Halona flow	Pahoa North	SE side of Makuu Drive, makai of 10th Street	95	13.1±3.1	-
9B157	Makaopuhi, below forest horizon	Makaopuhi Crater	NW wall, near top of talus cone, both sides of cone	2380	10.3±3.5	4.0
9B169	Kipuka Nene, makai of fault	Kau Desert	Among grass and shrubs about 20 m west of trail and 20 m from fault	2900	7.5±1.2	2.7
9B181	Younger Orr flow	Kapoho	Cliff and tide zone north of beach, Leanui Point	5	7.2±2.9	3.5
9B193	Disappearing goad exclosure	Kau Desert	About 100 m mauka of trail, 700 m west of Hilina Pali picnic shelter	2300	4.8±2.0	5.1
9B217	Pauahi, above forest horizon	Makaopuhi Crater	West wall, in pond, and NW wall near east edge 1973 drapery	3000	7.3±2.4	3.5
9B229A	Kilauea Caldera, below Uwekahuna Ash	Kilauea Crater	West subsite, below laccolith	3600	5.1±1.0	-
9B229B	Kilauea Caldera, below Uwekahuna Ash	Kilauea Crater	East subsite, below east edge of laccolith	3600	5.0±1.6	-
9B241	Makaopuhi, above forest horizon	Makaopuhi Crater	NW wall, near top of talus cone, both sides of cone	2400	11.5±2.1	4.7
9B385	Pauahi, below forest horizon	Makaopuhi Crater	NW wall, extending east from east edge of 1973 drapery	2980	9.2±3.5	5.4
9B397	Campbell Estate	Volcano	Around lava-tube breakdown at end of overgrown bulldozed scar	2480	8.3±4.0	2.2
9B421	Eden Roc Estates	Kalalua	Ohia Ave. at Punani Place; and Palainui Ave. at Maniai Circle	1880	10.3±5.4	1.6
9B493	Rusty truck, Kaliu flow	Pahoa South	Aa spines in tide zone near NE edge of flow	10	12.0±3.6	13.2
9B589	Wahaula pahoehoe	Kalapana	SW corner of Puna Gardens, west side of road at Kalapana Trail	50	10.7±5.7	4.0
9B673	Wilhite back lot	Kalalua	Forest edge by old trucks; and near base of large tree in forest	1250	16.8±4.5	4.9
9B685	Puu Nahaha	Pahala	Levee mauka of jeep trail, near base of scarp	1600	17.1±7.0	6.2
9B709	Old ridge by Lava Tree State Park	Pahoa South	South side Hwy 132, by BM at 677' elevation	680	13.7±3.4	6.2
9B829	Kipuka levees near Kealaalea	Wood Valley	Both sides of leveed channel along Park boundary fence	2365	10.8±4.1	3.9
9B841	Prehistoric paternoster pad	Wood Valley	Down rift from jeep trail, mauka side of small shield	2360	23.1±3.6	5.0
9B853	Older pahoehoe of Hawaiian Beaches	Pahoa North	Both sides of Pepie Street (Puna Trail) at Kune Street	70	8.0±2.8	3.4
9B865	Ponohohoa Chasms	Wood Valley	Subsites along jeep trail bending around small shield	2360	17.8±4.3	0.4
9B877	Fenceline	Wood Valley	Park boundary at 2300' elevation, uprift from jeep trail	2300	6.6±6.9	2.7
9B913	Puu Huluhulu	Makaopuhi Crater	Triangulation station, and along switchbacks below summit	3400	5.3±3.4	-

SSM is the separation of the subsite mean directions of magnetization.

Appendix C

Paleomagnetic Notation and Statistics

The various statistics used in paleomagnetism have been published in diverse places, with different workers using different notations and different quantities whose interrelationships are often unclear. Moreover, the same statistics may be applied to data at several different levels, examples of these levels being specimens, cores, subsites, sites, and groups of sites. Reviewed here are the notation and statistics used in this report.

Sampling Levels

In this report the magnetic data are generally discussed at two different levels, sites and groups of sites. (Some subsite data are tabulated in Appendices A and B and are mentioned briefly in the text, but they do not appear in contexts where confusion is likely to arise. This level is therefore ignored in the remarks that follow.) In order to avoid confusion it is useful to employ different notations for some of the statistics used at two different levels. A mean direction of magnetization is expressed in terms of two components, declination and inclination. In this report the capital letters D and I denote declination and inclination, respectively, of the mean direction within a site (e.g. in Tables 1 and 2). The lower case letters d and i are used similarly to denote the mean direction of a group of sites, grouped on the basis of age or location (e.g. Tables 4, 5, and 6).

Dispersion statistics--including the quantities k, α_{95}, and Ψ_{63}--are not distinguished by levels in this report. This requires some alertness in the reader, but it preserves simplicity in the notation. Dispersion statistics used at different levels generally appear in different parts of the text, and the appropriate level in each case should be apparent from the context.

<u>Dispersion Statistics</u>

Most of the statistics used today stem from a paper by Fisher (1953), who considered the distribution of errors over the surface of a unit sphere, that distribution in which the frequency density is proportional to

$$e^{\kappa \cos \theta}$$

where θ is the angular displacement from the true position (at which $\theta = 0$ and the density is a maximum, if κ is positive) and κ is a "precision parameter." Fisher derived an estimator of κ which in this report is called the "estimated precision parameter, k, defined by

$$k = \frac{N - 1}{N - R} \simeq \kappa \qquad (1)$$

where N is the number of unit vectors in the distribution and R is the magnitude of their vector sum.

Fisher showed that the true mean direction of the sample population of N directions lies within a circular cone about the resultant vector R with semi-angle α at probability level (1 - P), for k > 3, where

$$\cos \alpha_{(1-P)} = 1 - \frac{N - R}{R} \quad \frac{1}{P}^{1/(N-1)} - 1 \ . \qquad (2)$$

From this comes the commonly used statistic, α_{95}, which is used to estimate the accuracy of a sample mean. It is defined as the case where P = 0.05 and can be visualized as a circle of 95 percent confidence of the mean projected onto the unit sphere. This statistic is analogous to an interval representing approximately two standard errors of the mean.

A measure of the observed dispersion about the mean is the angular standard deviation, which Cox (1970) showed could be well approximated by

$$\sigma = \left(\frac{2}{\kappa}\right)^{1/2} \quad (3)$$

where σ is in radians. Substituting k for κ and converting from radians to degrees gives the quantity

$$\Psi_{63} = \frac{81}{\sqrt{k}} \quad (4)$$

which is the well-known equation given in the textbooks by Irving (1964) and McElhinny (1973).

Analysis of Dispersion

Dispersions are analyzed by using the additivity of variances, expressed approximately by

$$\sigma_T = (\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \ldots)^{1/2} \quad (5)$$

where σ_T is the observed total dispersion and σ_1, σ_2, σ_3, ... are the dispersions due to various sources. (It would be prefereable to use the symbol Ψ_{63} in (5), but this would involve a complicated and confusing notation.) Alternatively, using (5) and (3),

$$\frac{1}{k_T} = \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} + \ldots \quad (6)$$

where k_T is the observed total estimated precision parameter and k_1, k_2, k_3, ..., are the estimated precision parameters corresponding to the various sources of dispersion.

Errors in Inclination and Declination

A special problem arises when the dispersion is resolved into components of inclination and declination, as on Figure 11 of this report. Errors in inclination are equal to the corresponding errors in the resultant vector; thus on Figure 11 the confidence interval of the mean inclination at the site level is

$$\pm I = \pm\alpha_{95} \tag{7}$$

and the standard deviation of inclinations at the temporal-group level is

$$\pm i = \pm\Psi_{63}. \tag{8}$$

Errors in declination are dependent upon the mean inclination, such that on Figure 11 the confidence interval of the mean declination at the site level is

$$\pm D = \pm\sin^{-1} \frac{\sin \alpha_{95}}{\cos I} \tag{9}$$

and the standard deviation of declinations at the temporal-group level is

$$\pm d = \pm\sin^{-1} \frac{\sin \Psi_{63}}{\cos I} \ . \tag{10}$$

Equations (9) and (10) describe the azimuths, relative to the mean declination, D or d, of the vertical planes tangent to the cones defined by α_{95} and Ψ_{63}, respectively.

Appendix D

Reflectivity of Sand Sheets in the Kamakaia Region

The sand is inferred to consist of unweathered glass because of its optical properties. Like glassy-surfaced pahoehoe flows, these sand sheets appear to have an unusual photometric phase function, displaying a striking albedo variation with phase angle. Reflections are specular instead of diffuse. Specular reflection requires that the irregularities of the reflecting surface be small relative to the wavelength of reflected light.

Much recent work has focused on the scattering of radar by natural materials such as sands and gravels (e.g., Beckman and Spizzichino, 1963; Schaber and others, 1976), and we may argue by analogy to that work. According to the Rayleigh criterion, a surface is "radar smooth" and will reflect an incident wave specularly in one direction if

$$h < \frac{\lambda}{8 \sin \gamma}$$

where

h = height of surface irregularities

λ = wavelength

γ = grazing angle.

If we apply this criterion to the visible spectrum, where λ is 0.4 to 0.7 µm, we find that h must be less than 0.5 µm for the grazing angles normally found in aerial photographs (45-90 deg).

The reflecting surfaces of the sand sheets must therefore be very smooth, and the materials on Kilauea most likely to be so smooth are glasses. Much sand in the Kau Desert region is known to consist of Pele's hair and other glassy materials.

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