Structures and Forms of Basaltic Rocks in Hawaii

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STRUCTURES AND FORMS OF BASALTIC ROCKS IN HAWAII

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ABSTRACT

The Hawaiian volcanic mountains are broad shields, built by eruption of many thousands of thin lava flows from zones of fracturing known as rift zones. Most of the summits are indented by calderas formed by collapse. Smaller collapse craters, known as pit craters, lie along some of the rift zones, and the calderas have developed at least partly by the coalescence of pit craters. Grabens lie along parts of the rift zones, and collapse of the edges of the shields has produced high fault scarps facing the ocean.

The vents are marked by spatter ramparts, spatter-and-cinder cones, and lava cones on the basaltic volcanoes. On the andesitic volcanoes the cones are mostly true cinder cones. Littoral cones, closely resembling the cinder-and-spatter cones at vents, are formed where aa flows enter the sea.

Most flows consist of several thin flow units, extruded at slightly different times, but during the same period of eruption. Near the vents the lavas are predominantly pahoehoe, but aa becomes more abundant at greater distances. Pahoehoe flows are characterized externally by smooth, hummocky, ropy, or festooned surfaces, and internally by lava tubes and nearly spherical vesicles. Tumuli, pressure ridges, pressure plateaus, and slump scarps form principally on ponded pahoehoe flows.

Aa flows are characterized by a central massive phase lying between clinkery fragmental top and bottom layers. The fragments are exceedingly irregular and spinose. Aa vesicles are less regular in outline than those of pahoehoe. The central river feeding an aa flow moves through an open channel through most of its course. Spines and accretionary lava balls are common surface features on aa flows.

Basaltic cinder-and-spatter cones consist largely of agglutinated spatter and driblet, with some cow-dung bombs, and more rarely spherical cored bombs. Reticulite and Pele's hair are formed by lava fountains. In the andesitic cones the material generally is little welded, and the bombs are generally bipolar fusiform bombs.

Ash and tuff are not abundant in Hawaii. Most of the ash is vitric magmatic debris, commonly palagonitized. Accretionary lapilli are common in it in the vicinity of Kilauea caldera. Tuff cones with broad craters are formed by explosions where hot rising lava encounters water-saturated rock. Bomb sags and vegetation molds are common in the ash in some areas.

Erosion has exposed hundreds of narrow dikes, forming dike complexes along the rift zones of several of the older volcanoes. Sills and intrusive necks and stocks are less common. Most Hawaiian eruptions are of the fissure type, and congelation of the conduit filling produces a dike.

INTRODUCTION

PURPOSE AND SCOPE

The purpose of this paper is to list and describe the physical features of basaltic rocks found in Hawaii and to discuss their origins, insofar as is practical. The features described are chiefly primary, formed in the course of the eruption and emplacement of these rocks. Even in works devoted to igneous structures (Balk, 1937) there is little systematic reference in geologic literature to the physical features of effusive or pyroclastic rocks, possibly owing to the preponderant concern of geologists with tectonic or petrographic approaches.

With little exception, the whole mass of the Hawaiian Islands consists of basaltic lavas containing small amounts of pyroclastic rocks of the same chemical composition. This paper is a synopsis of the structures and forms of such rocks, based on extensive field studies on all the major islands. The mode of treatment is systematic and only such limited reference to areal or historical findings is made as may be required for clarity. Areal and petrographic studies have been reported elsewhere, as listed in the literature cited. For additional references see the bibliography for the island of Hawaii (Macdonald, 1947).

TERMINOLOGY

Many of the features described are objects of common observation in volcanic regions and the names have been taken from the common usage of these areas. In some instances it seems best to follow usage long established in Hawaii, or most applicable to the local features. Terms such as structure, texture, and formation, are used in the general, rather than the strict stratigraphic or other geologic sense. We have not attempted to follow a strict pattern but have adopted and defined the usage that offers the clearest understanding.

ACKNOWLEDGMENTS

Geologists and other visitors have noted many of the features described and have often recognized their significance and origin. In other instances, like early workers in other fields, they have offered interpretations that have been shown by a better knowledge of the usual or normal volcanic process in Hawaii to be erroneous or exaggerated. Often the early travelers have emphasized the features

that were novel to the visitor, but have not treated them systematically or described them in the terms we now use.

James D. Dana visited Hawaii in 1840 as geologist of the U. S. Exploring Expedition and observed many volcanic features, that he vividly describes in papers and books on Hawaii (Dana, 1849, 1887, 1890), and in the successive editions of his Manual of Geology, 1863, 1875, 1880, 1895. Brigham's visit in 1868 also led to publication of his extensive observations on volcanic features (Brigham, 1868, 1887, 1909). Both Dana and Brigham came into contact with many lay observers whose observations covered the period from 1820 to 1900, and whose contributions were reported by Dana or Brigham or through their encouragement. Notable among these was the Reverend Titus Coan, who lived on the island of Hawaii from 1835 to 1882, and was the chief observer of a wealth of volcanic episodes (Coan, 1852–81).

In 1884, Dutton spent several months in Hawaii studying the volcanic terrane preparatory to mapping the Cascade Range of the Pacific Northwest for the United States Geological Survey. World-wide use by geologists of the terms *pahoehoe* and *aa* dates from Dutton's (1884) report. He made many other valuable observations at that time. W. L. Green, Sereno Bishop, C. H. Hitchcock, W. Lindgren, and W. H. Dall published important papers from 1887 to 1903.

Since 1900, studies of the geology of Hawaii, chiefly in relation to water supply, have been by the United States Geological Survey with the collaboration of the Territory of Hawaii, by the Hawaiian Sugar Planters' Association, by other agencies of the sugar and pineapple industries, and by the Honolulu Board of Water Supply. Other studies have been made under auspices of the Bishop Museum, the Hawaiian Volcano Observatory, and the University of Hawaii. The data presented in this paper, while based more particularly on work done for the Geological Survey and the Board of Water Supply, has benefited largely by access to the results of many years of discussion and exchange of observations between all the geologists of Hawaii. We are especially indebted to H. A. Powers and R. H. Finch, whose many years in Hawaii have made their criticism of this paper particularly helpful. J. Y. Nitta of the Territorial Division of Hydrography prepared the drawings for this report.

FACTORS INFLUENCING VISCOSITY AND EXPLOSIVENESS OF ERUPTING MAGMA

Hawaiian lavas range in composition from ultrabasic nepheline basalts and picrite-basalts, to trachyte verging toward rhyolite (Macdonald, 1949b). This paper deals primarily, however, with those structures occurring in rocks of a general basaltic nature. The trachytes and some of the oligoclase andesites, being more viscous and richer in gas than the basaltic lavas, build large cinder cones, steep-sided domes (tholoids), and thick flows similar to those formed by rhyolitic, dacitic, and sometimes by andesitic lavas in the continental zones of volcanism (Stearns and Macdonald, 1942, p. 173–178; 1946, p. 161, 180). These forms are not characteristic of Hawaiian volcanism.

The dominant lavas of Hawaii, from the eruption of which result the structures typical of Hawaiian volcanoes, are the olivine basalts and basalts, and the closely related picrite-basalts and basaltic andesites. Generally, the forms developed are those due to great fluidity in the erupting lava. Generally speaking, the features influencing fluidity of lava flows are chemical composition, gas content, and temperature.

The silica content of the common Hawaiian lavas ranges from about 42 percent in the picrite-basalts containing abundant phenocrysts of augite, to about 51 percent in the andesine andesites. In the melilite-nepheline basalts the silica content drops as low as 36 percent; in the common olivine basalts it averages about 48 percent. Typical chemical compositions of the common Hawaiian lavas are shown in the accompanying variation diagram (fig. 1).

The degree of explosiveness of the erupting magma does not correlate directly with the increase of silica content or with the change in proportion of any other oxide. Rather, there is a general increase in both directions from a middle point at olivine basalt. In other words, assuming that the parent magma is the olivine basalt, the explosiveness of the erupting magma increases with the degree to which differentiation has altered it from the parent magma. This is true among the augite-rich picrite-basalts as well as among the nepheline basalts, although in both there are many exceptions in which the erupting lava is not appreciably more explosive than the ordinary olivine basalt. An example of comparatively great explosiveness in erupting nepheline basalts is the large cinder cone and widespread ash showers produced by the Tantalus eruption on Oahu. Similar examples among the augite-rich picrite-basalts are large cinder cones on Haleakala and Mauna Kea. The picrite-basalts of oceanite type which lack abundant phenocrysts of augite do not share in the greater explosiveness, but closely resemble the ordinary olivine basalts in their mode of eruption. It is probable that the greater explosiveness of the erupting nepheline basalt and augite-rich picrite-basalt magma, as compared with the olivine basalt, is the result of a greater gas content, possibly coupled with somewhat lower temperature.

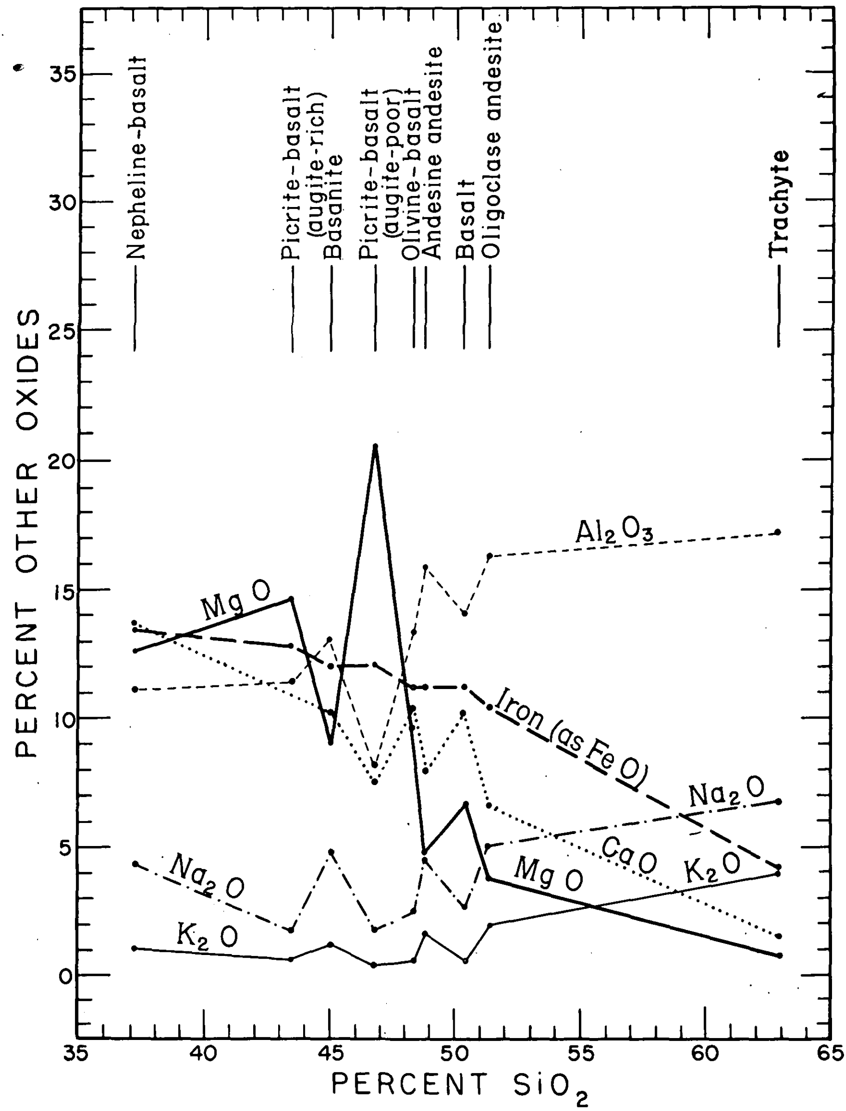

FIGURE 1.—Diagram showing composition of Hawaiian lavas.

Viscosity of the erupting magma generally increases from olivine basalt toward the more sodic members of the series. As already stated, thick lava flows and steep-sided domes are common among the andesites and trachytes. The nepheline basalts and augite-rich picrite-basalts, although they are commonly more explosive than the olivine basalt, do not show a correspondingly greater viscosity. That the greater explosiveness of those magmas was the result probably of greater gas content, not of greater viscosity, is shown by the numerous pancake or cow-dung bombs, and other ejecta expelled in a fluid state, that lie on the flanks of the cinder cones. In contrast, the bombs on the andesite cones are more generally well formed spindle bombs and other Strombolian-type ejecta, suggesting a greater viscosity of the erupting lava.

The actual gas content of erupting Hawaiian lavas has never been measured, nor is it likely that it can be measured directly in the near future. The volume percentage of gas is undoubtedly large, although the weight percentage is probably small. Explosive eruptions are rare at Hawaiian volcanoes, and in typical eruptions of olivine basalt, the gas, which is present, is liberated quietly. The only violent explosions during historic times were those of 1924 at Kilauea volcano which were of phreatic, not magmatic origin (Jaggar and Finch, 1924; Stearns, 1925). Similar phreatic explosions have occurred at other times on Kilauea volcano, on Mauna Loa, and probably on Hualalai volcano, but they are comparatively uncommon and not typical of Hawaiian volcanism. As pointed out, many eruptions of the more highly differentiated lavas, such as the augite-rich picrite-basalts and andesites, were moderately explosive, building large cinder cones, but the largest of those cones are small compared with many of the cinder cones of continental volcanoes. The common basalts of Hawaii erupt quietly, building only low spatter ramparts and diminutive spatter-and-cinder cones.

The effects of falling temperature are apparent in any basaltic flow in its gradual passage from thin fluidity through increasing viscosity to eventual immobility. It is evident, also, that as fluidity increases with gas content, the loss of gases through flow, agitation and reduction of temperature would in addition to temperature decline alone result in increased viscosity. Temperature alone is not the governing factor in the behavior of lava flows. Although the magmatic temperatures are about the same, the lava of Parícutin forms thick flows and a large cinder cone, whereas, the lava of Mauna Loa and Kilauea volcanoes form thin flows and low cinder-and-spatter cones (Zies, 1946, p. 178–189: Jaggar, 1917a, p. 397–405). The temperature of erupting basaltic lava at Hawaiian vents generally ranges from 900° to 1100° C.

MAJOR VOLCANIC STRUCTURES

GENERAL FORM AND RELATIONS

The fluid basaltic lavas of the Hawaiian Islands build broad, gently sloping cones of flat domical shape. These are commonly referred to as *domes*, and more specifically by Daly (1933) as *exogenous lava-domes*. However, the term dome is commonly used for other types of geological structures. *Volcanic dome* is restricted by Williams (1932) and others to the steep-sided accumulations of viscous lava at vents on volcanoes erupting more viscous lava. Therefore, it seems preferable to use the term *shield volcano* (*Schildvulkan* of German writers) (Rittmann, 1936) for the Hawaiian and Icelandic types of structures.

Typically, Hawaiian shield volcanoes are broad and flat in profile. The general form and dimensions of the five major volcanoes of the island of Hawaii are shown in the accompanying table (Wentworth, 1938, p. 13). The lengths and widths are measured at sea level. The actual dimensions of the base of the mountains, at the level of the surrounding ocean floor, are much greater. Thus the area covered by Mauna Loa, at the minus 15,000-foot level, is probably of the order of 5,000 square miles compared with 2,000 square miles at sea level. Some conception of the enormity of the huge mountain mass of Mauna Loa, which rises over 30,000 feet above the surrounding ocean floor, may be gained from a comparison of its volume, of the order of 10,000 cubic miles above the minus 15,000 foot-level, with that of 80 cubic miles above the 4,500 foot-level for Mount Shasta in California (Williams, 1934).

Dimensions and form of the shield volcanoes of the island of Hawaii

Name	General outline	Slope of shield surface		Length (miles)	Width (miles)	Area (square miles)	Summit altitude (feet above sea level)
		Maximum (degrees)	Minimum (degrees)				
Kohala	Elliptical	9	4	22	15	234	5, 505
Mauna Kea	do	21	5	51	25	919	13, 784
Mauna Loa	Three-pointed	11	3	75	64	2, 035	13, 680
Hualalai	Paraboloid	15	3	24	20	290	8, 251
Kilauea	Sigmoid belt	5	1	51	14	552	4, 090

The slopes of the basaltic shields generally range from about 4° to 10°. Locally, steeper slopes may result from the mantling of fault scarps or buried cinder-and-spatter cones. Thus, the steep western slope of Mauna Loa and the southern slope of Haleakala (East Maui) volcano may have resulted from the burial of a series of normal faults along which the seaward blocks have been downthrown. Such faults have been found on the flanks of both volcanoes (Stearns and Macdonald, 1942, p. 73; 1946, p. 34–42), and others may be entirely hidden by later flows. Elsewhere, steeper slopes are partly or entirely the result of a capping of andesitic or trachytic lavas erupted in a more viscous condition; or the presence of more abundant pyroclastic material, probably also resulting from an increase in viscosity or gas content, or both, accompanying some differentiation of the magma.

Owing to their characteristic mode of construction, by flows erupted from an elongate zone of fissures, the ideal form in plan of the Hawaiian shields is a more or less elongate ellipse. Departures from this ideal form arise principally from interference with the growth of the structure by neighboring mountains. Thus the three-lobed plan of Mauna Loa was caused by interference with the outward growth of the mountain by Mauna Kea on the north, Hualalai volcano on the northwest, and Kilauea volcano on the southeast. However some shields, such as West Maui, are nearly circular in plan, because of an approach to radial arrangement of the eruptive fissures, or because of more effective domination by the central vent (fig. 2).

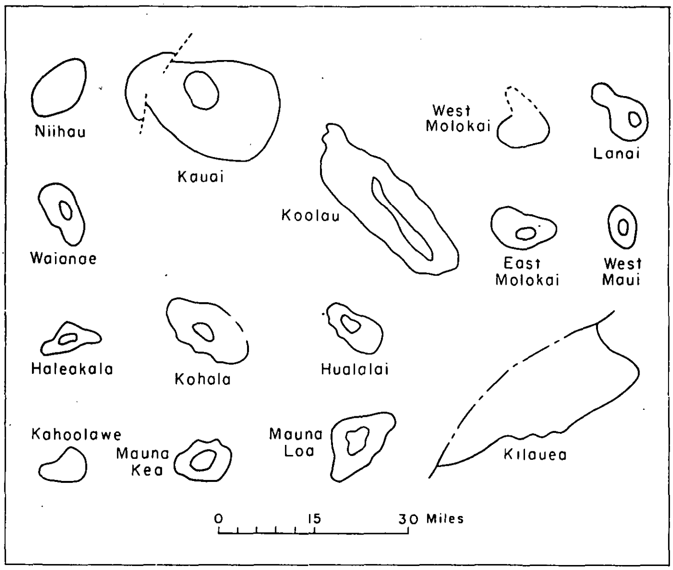

FIGURE 2.—Outlines of Hawaiian shields. The inner contour for each is 1,000 feet below supposed original summit; the second is 3,000 feet below.

The major shield volcanoes of the Hawaiian Islands occur in definite groups. The five major volcanoes that comprise the island of Hawaii are united above sea level, but separated from the Maui group of volcanoes to the north by water 8,000 to 10,000 feet deep. The six volcanoes of the Maui group form the islands of Maui, Molokai, Lanai, and Kahoolawe, separated by channels 250 to 1,300 feet deep, but generally less than 900 feet deep. The Maui group is separated from the two volcanoes of the island of Oahu by water 2,300 feet deep and the Oahu group from the island of Kauai by water 9,000 to 10,000 feet deep. Water more than 2,000 feet deep separates Kauai from the Niihau mass, and a channel more than 5,000 feet deep separates the Niihau mass from the volcanic mass carrying the tuff cone of Kaula Island on its summit. Although separated from each other by moderately deep water, the islands of Kaula, Niihau, and Kauai form a fairly definite group of three major volcanoes.

Within each group the volcanoes have merged, partly by overlapping, and partly by interfingering of their lavas at the periphery of the shields. Although the order of extinction of the several volcanoes within a group can be demonstrated with more or less accuracy, there is no evidence of the order of initiation of activity. Within the Hawaii group, Mauna Kea, Hualalai volcano, Kilauea volcano, and Mauna Loa apparently were active during the same general period. The active period of Mauna Kea almost certainly commenced while the earlier Kohala was still active. In other groups also, neighboring volcanoes were probably active simultaneously during part or most of their lives. Volcanic masses such as the island of Hawaii, formed by the overlapping and interfingering of a group of shield volcanoes, may appropriately be termed *volcanic shield-clusters*.

PHYSICAL COMPOSITION OF HAWAIIAN SHIELD VOLCANOES

The Hawaiian volcanoes are composed largely of lava flows. Pyroclastic material comprises certainly less than 5 percent and probably less than 1 percent of the mass. Among the basaltic flows aa and pahoehoe types are approximately equal in abundance. Pahoehoe predominates on the upper parts of the volcanic mountains and near the rift zones. Farther downslope aa increases in abundance until it predominates. Sections in the walls of the calderas of Mauna Loa and Kilauea volcanoes (Macdonald, 1949a, p. 60, 64–65) contain respectively over 98 and 92 percent pahoehoe. At Hilina Pali, 9 miles from the center of Kilauea caldera, the lavas of the Hilina volcanic series are 76 percent pahoehoe. Of the lavas exposed in the shaft of the Olaa well, 37 miles east of the caldera of Mauna Loa and about 20 miles from the lowest recent vents on the northeast rift zone, 71 percent are aa. The lavas exposed in the Paauilo well on the northeastern flank of Mauna Kea, 17 miles from its summit, are entirely aa.

The sections in figure 3 illustrate well the composition of the Koolau shield volcano on Oahu, 4 to 5 miles from the center of the former rift zone. Wentworth and Winchell (1947, p. 62) report about 75 percent aa lava flows in 2,000 feet of core-drilled sections in the Red Hill and Honolulu areas 1 or 2 miles from the leeward coast.

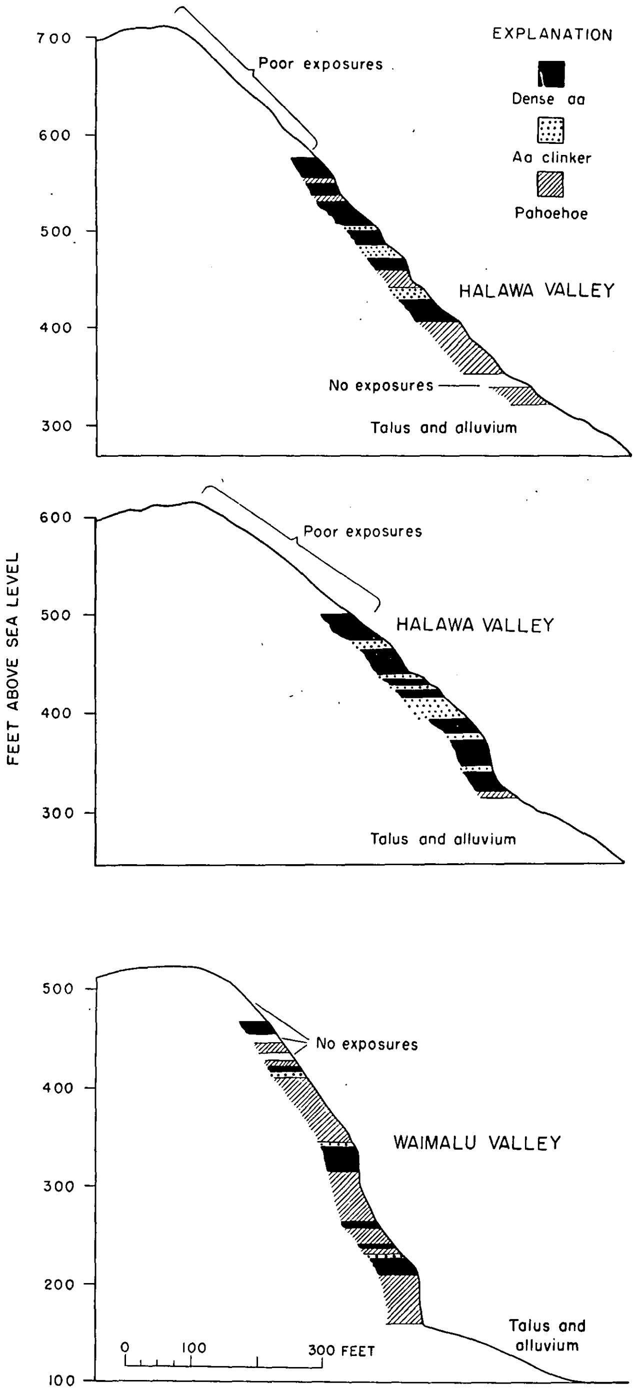

FIGURE 3.—Sections showing proportions of lava-flow types exposed in the walls of Halawa and Waimalu valleys, Oahu.

RIFT ZONES

The Hawaiian shield volcanoes have been built by innumerable fissure eruptions. The fissures are generally concentrated within certain narrow zones, known as rift zones. The rift zones range from a few hundred feet to more than 2 miles in width, and extend down the flanks from the summit of the mountain to below sea level. Typically, each volcano has two principal rift zones extending outward from the summit of the mountain. Some, such as Haleakala volcano, have a third minor rift zone, also extending outward from the summit. The two major rift zones generally meet at the summit with an angle of 130° to 180°. They may represent a single continuous straight or gently curved zone of fissuring. The third minor rift zone generally approximately bisects the external angle between the major rifts. Localization of most eruptions along the major rift zones is the cause of the common elongate shape of the shield volcanoes (fig. 4).

At the surface the rift zones are marked by lines of cinder-and-spatter cones and spatter ramparts, pit craters, lava cones, and on the active volcanoes where erosion has not appreciably modified the surface, by many open fissures (fig. 5). The fissures range in width from a few inches to about 10 feet. They frequently can be sounded, or are visible to a depth of 50 feet, and many probably are open to a much greater depth. The great irregularity of their walls and the narrowing of the fissures downward make it difficult to lower a sounding weight to any great depth. The most spectacular of these surface fissures, the Great Crack along the southwest rift zone of Kilauea volcano, extends continuously for more than 8 miles, with a width in places 30 to 40 feet and a visible depth of as much as 40 to 50 feet. The extreme widths are generally the result of local minor graben collapses. Where the walls have not been too much modified by collapse, projections on one wall commonly correspond with concavities in the opposite wall. The opening of the fissures has resulted largely from tension; there is little or no evidence of shearing movements along them.

At depth the rift zones are occupied by hundreds of nearly vertical dikes, most of which represent the feeders of the surficial eruptions (see Dike complex). In places they are so abundant that the intervening rock nearly or entirely disappears, leaving only the intrusive dike-rocks. The distension of the volcanic structure represented by these dike complexes is enormous and, although difficult to form a reliable estimate of its magnitude, it probably amounts in some places to several thousand feet.

Although most of the fissures that have given vent to lava flows are radial with respect to the mountain summit, a few are concentric.

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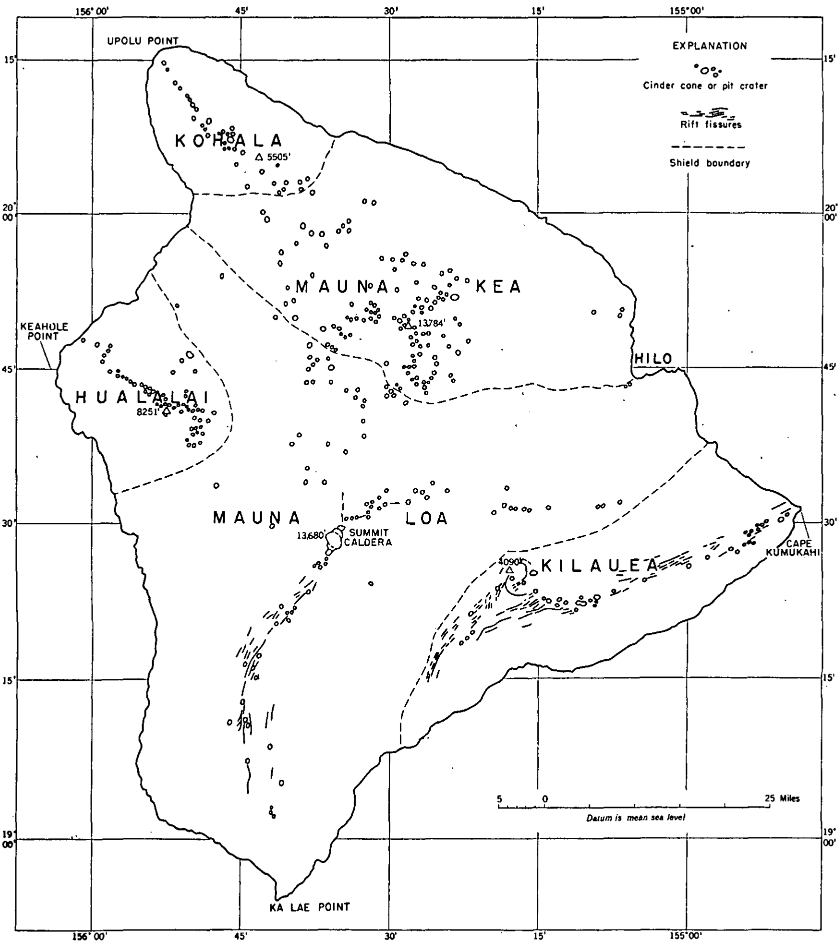

FIGURE 4.—Sketch map of island of Hawaii, showing cracks, vents, cones, and margins of the five component shields.

The concentric fissures are generally associated with a caldera, and may be faults bounding it. Lava escaping from a concentric fissure 0.7 mile southwest of the boundary of Kilauea caldera built a line of small spatter cones (Stearns and Clark, 1930, p. 52; Finch, 1942). During the 1942 eruption lava issued from concentric fissures at several places just northeast of the rim of the North Bay of Mokuaweoweo (Mauna Loa) caldera, as well as from radial fissures in the same area (Macdonald, 1945b, p. 2). On Mauna Kea, eruption occurred at the surface from radial fissures, but localization of some vents appears to be the result of intersection of the surficial radial fissures with concentric intrusions (ring-dikes?) at depth (Macdonald, 1945a, p. 210–217).

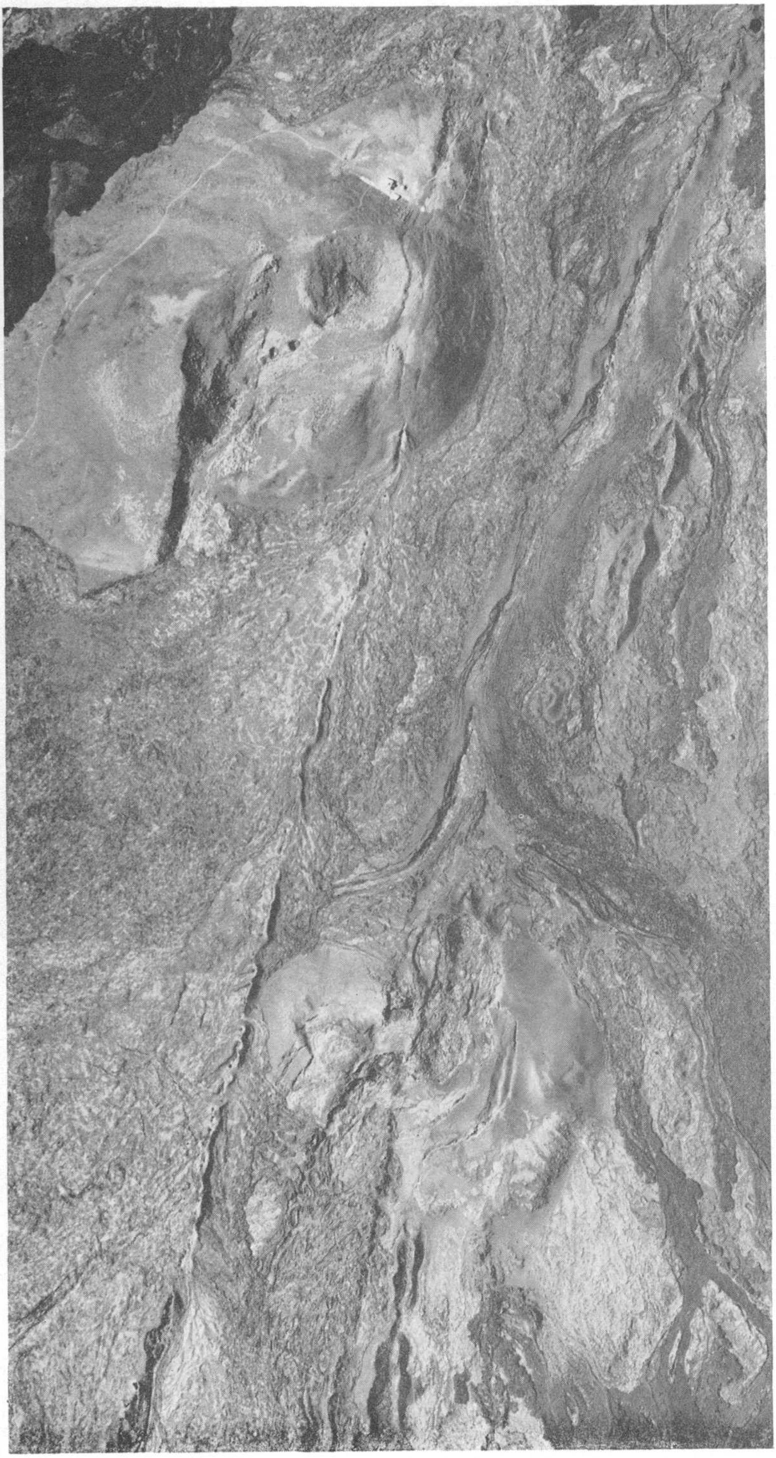

FIGURE 5.—Fissure and cones along the northeast rift zone of Mauna Loa volcano. Puu Ulaula, in the upper right corner, is a cinder cone about 0.4 mile across. The general slope of the ground surface is toward the left. Vertical air photo by 18th Air Base Photo Laboratory, Air Corps, U. S. Army.

The origin of the rift zones is uncertain. However, evidence indicates that subterranean magma pressure preceding and during eruptions somewhat exceeds the hydrostatic pressure of the overlying rocks. Both tumescence of the volcanoes preceding and during eruptions, and subsidence after eruptions, are indicated by tilting of the ground surface that is easily measurable by means of tiltmeters. Differential leveling has shown that the elevation of the mountain summit during tumescence probably amounts to several feet. Lava fountains issuing from the rifts of Mauna Loa may reach heights of several hundred feet above the ground surface, even at the summit of the mountain. During the 1949 summit eruption the fountains attained heights of at least 800 feet (Macdonald and Orr, 1950, p. 9). If the pressure in the magma exceeds the weight of the overlying rocks, the upward thrust applied in a relatively small area beneath the summit portion of the volcano may be expected to produce an opening of the overlying structure in the form of three principal radiating fracture zones. Considering the nonhomogeneous structure of the mountain, it also is expectable that two of the radiating rifts be better developed than the third. That is the pattern actually found in the rifts of most Hawaiian volcanoes, and consequently this origin of the rifts appears most probable.

Whatever may be the original cause of the rift zones, the opening of the fissures, allowing magma to rise to the surface, probably results at least partly from the tumescence of the mountain previous to eruptions that has been shown to take place at Kilauea (Jaggar, 1920, p. 201–249; Jaggar and Finch, 1929, p. 38–51). In addition there may be some tendency for the cone to split open under the influence of gravity, the sides moving downward and outward toward the ocean deeps (Williams, 1941, p. 287).

RIFT-ZONE GRABENS

Along some of the rift zones, particularly the southwest rift zone of Kilauea volcano, collapse has resulted in broad shallow grabens at the surface. There is no reliable evidence of the magnitude of the collapse, however. It may be represented in its entirety by the existing topographic depressions a few feet deep, or the subsidence may have amounted to scores or even hundreds of feet, the trough having been filled by related lava flows more or less contemporaneously with its formation.

CALDERAS

The summits of both Mauna Loa and Kilauea volcanoes are indented by calderas. Similarly, calderas appear to have existed during earlier stages of some of the other volcanoes, including the Waianae and Koolau volcanoes on Oahu, and those of East Molokai, West Maui, Lanai, Kahoolawe, and Kauai. The calderas of Kilauea and Mauna Loa are oval in outline. That of Kilauea is 2.7 miles long, 1.9 miles wide, and 490 feet deep at the highest point of the boundary cliff. Mokuaweoweo caldera, on Manua Loa, is 3.3 miles long (including the North Bay, but not the independent pit crater South Pit) and 1.6 miles wide. The boundary cliff is about 600 feet high at its highest part, but its height decreases almost to zero in North Bay (fig. 6).

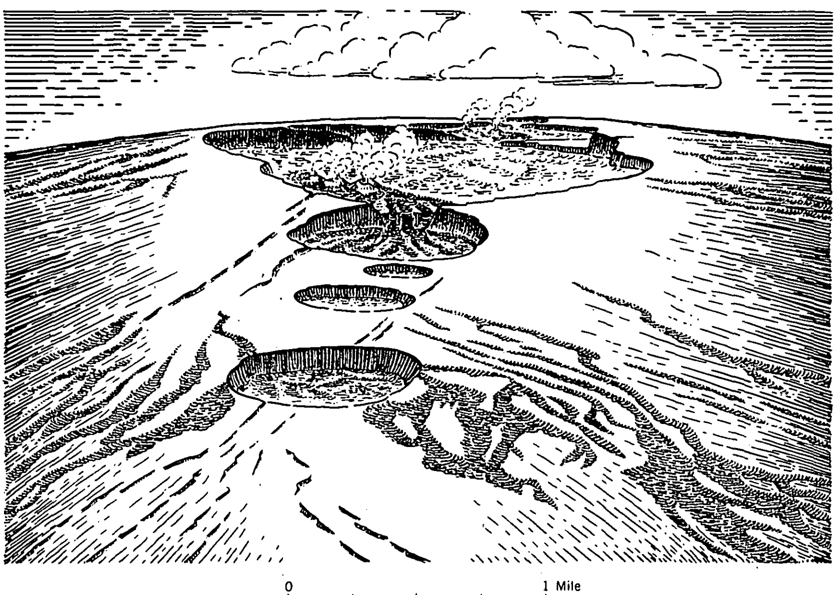

FIGURE 6.—Mokuaweoweo caldera and adjacent pit craters on the summit of Mauna Loa. View from the southwest. The large caldera is about 9,000 feet from left to right. (Drawn from photo taken by U. S. A. A. F.)

Neither of these figures for depth represents total collapse because of the unknown amount of fill to form the present floor in each caldera. The boundary cliffs slope at an average angle of 60° to 70°. The walls of the calderas comprise a series of step-fault scarps. The floors of both calderas slope outward very gently toward their peripheries. In Kilauea caldera, the high part of the floor is the remnant of the summit of a broad flat lava cone built up by overflows of Halemaumau lava lake and partly destroyed by the great collapse at Halemaumau during the 1924 explosions. In Mokuaweoweo caldera, the floor inclines outward from the apex of a gently sloping lava cone, crowned by a large cinder cone, at the source of the long-continued 1940 lava flow.

The calderas of some Hawaiian volcanoes may have been larger than those of Mauna Loa and Kilauea. Stearns (1946, p. 81–86) believed that of East Molokai to have been 4 miles long and that of

Kauai to have been some 10 miles across. There is no positive evidence that calderas ever existed on Hualalai volcano and Mauna Kea, although it is not unlikely that they did.

The caldera of Mauna Loa, and probably that of Kilauea, apparently developed at least partly by the gradual coalescence of pit craters (Stearns and Macdonald, 1946, p. 29–33). During the century and a quarter of written history in Hawaii, the calderas appear to have alternated between deepening, by collapse of the central part of the caldera, and infilling by lava flows. Williams (1941, p. 246, 286–292) places the Hawaiian calderas in a special class, called the Kilauea type. He believes that rapid effusion of lava on the flanks of the volcano or intrusion of magma as dikes or sills drains the central conduit and causes foundering at the central vent. The principal evidence for this belief is the observed collapse that accompanied the great lowerings of magma level at Halemaumau pit in Kilauea caldera. There is no doubt that collapse at Halemaumau may, at least at times, be the direct result of lowering of the magma level. However, large as was the volume of engulfment at Halemaumau during and following the 1924 explosions, it was minute compared with the total subsidence that formed the great depression of the entire caldera. More comparable in scale are the great collapses that occurred in the Kilauea caldera early in the 19th century. In 1840 the collapsed portion occupied more than half the area of the inner caldera floor (Stearns and Macdonald, 1946, p. 32). Finch (1940, p. 2; 1941, p. 1) estimated that in 1823 and 1832 the volume of the depressions formed by collapse exceeded 19 and 20 billion cubic feet respectively.

Records are too incomplete to permit more than a presumptive correlation of the collapse that took place about 1823 with the flank eruption of 1823. The collapses of 1832 and 1840 are known to have been closely associated in time with the eruptions of these years. However, during the eruption of 1832 the extrusive vents were approximately 275 feet above the caldera floor before the collapse and probably more than 1,000 feet above the floor after the collapse. It therefore appears unlikely that simple drainage by the eruption could have caused the collapse. Furthermore, the volumes of lava extruded during the 1823, 1832, and 1840 eruptions were only a small fraction (0.1 to 6 percent) of the volume of the associated collapse. Thus, allowing for considerable error in the estimates of volumes, unless the volume of magma intruded subterraneously vastly exceeded that extruded, the eruptions were totally inadequate to account for the associated collapse by drainage of magma from beneath the caldera. That the volume of intruded magma exceeded that extruded appears improbable from what is known of the relatively small proportion of intrusive material in the exposed internal structure of older Hawaiian volcanoes.

A large collapse in the caldera of Mauna Loa during the middle part of the 19th century may have been associated with one or more of the flank outflows of that volcano, but knowledge is too fragmentary to permit any definite correlation. Since that time the history of Mauna Loa caldera has been one of gradual infilling. Several large flank eruptions, including that of 1950 during which more than 600 million cubic yards of lava was liberated, have not been accompanied or followed by any collapse in the caldera.

Stearns and Macdonald (1946, p. 33), have advanced as an alternative explanation the suggestion that the Hawaiian calderas resulted from weakening of the summit area by large-scale stoping and cauldron subsidence, as in the calderas of Williams Glen Coe type. The sinking may have resulted from the greater density of the surficial rocks compared with the underlying magma, and certainly any withdrawal of the underlying magma or reduction in its pressure, for whatever cause, would greatly abet the collapse. Williams accepts stoping and melting as the primary cause of pit craters, and extends it to the early stage of formation of Hawaiian calderas. It appears most probable that the calderas of Mauna Loa and Kilauea owe their origin to a combination of the two processes.

PIT CRATERS

The term *pit crater* was proposed by Wilkes (1845, p. 180), and defined as "that description of crater of which there is no appearance whatever until one is close upon it, and which never throws out lava". These features are circular or ellipsoidal pits sunk below the gently sloping surface of the volcano and surrounded by no mound of accumulated lava. The pit craters are collapse structures that have never been filled to overflowing with molten lava. In many pit craters, however, lava flows have broken out along the walls, at the base or part way up in the talus banks that mantle the lower part of the boundary cliffs, and formed ponds of lava in their bottoms.

Many pit craters occur along the rift zones of Mauna Loa and Kilauea (fig. 7), and filled pit craters have been found on other Hawaiian volcanoes. They range in size from 100 feet or less to more than half a mile across. The largest single pit crater is Napau Crater, on the east rift zone of Kilauea volcano, which is 0.7 mile long and 0.6 mile wide. The neighboring Makaopuhi Crater is 0.9 mile long, but is in reality a double pit crater. Devil's Throat, on the east rift zone of Kilauea, when originally described was only 30 feet across at the surface, and 250 feet deep. It is remarkable in

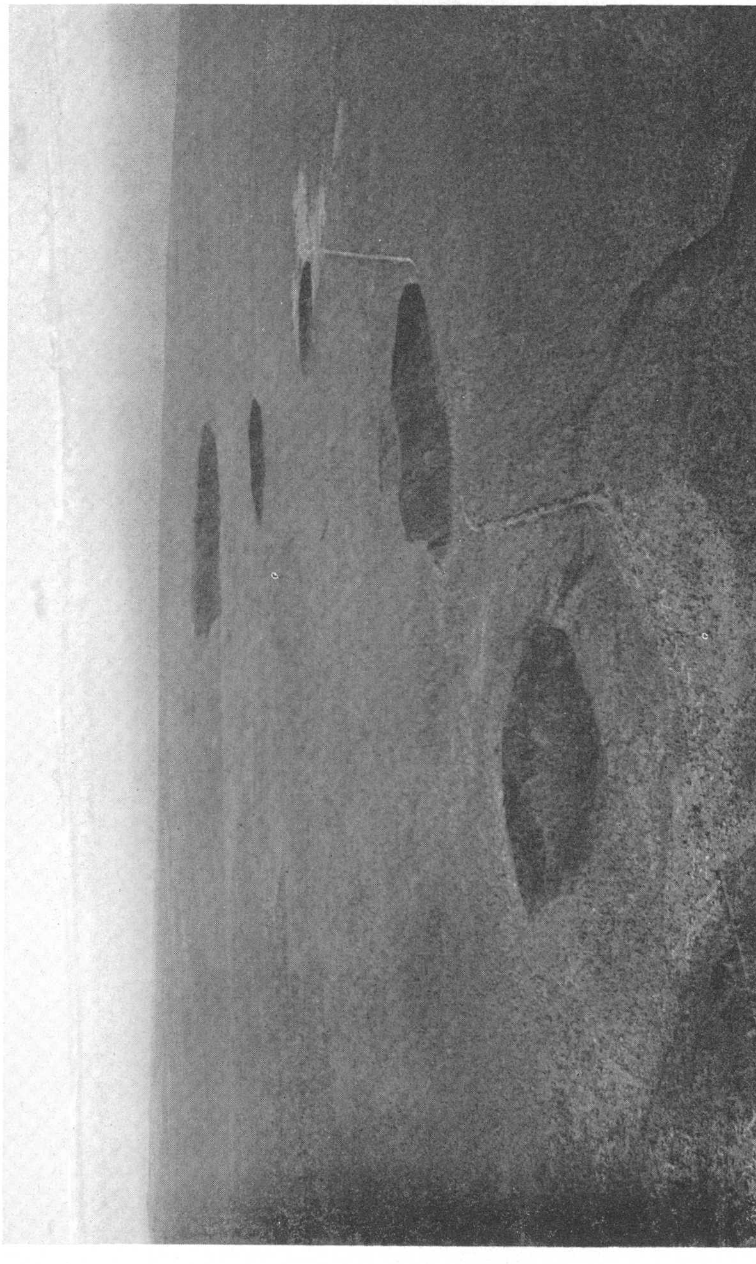

FIGURE 7.—Pit craters along the east rift zone of Kilauea volcano. Heake Crater, in the left foreground, is about 0.3 mile across. Photo by U. S. Army Air Force.

having overhanging walls, the width at the bottom being 125 feet (Stone, 1926a, p. 50). Since 1926 collapse has doubled the diameter of the opening. The pit craters range in depth from less than 50 feet to 800 feet. Except where talus banks are present, their walls are essentially vertical. Their margins are in general broad curves, but in detail they are highly irregular, with numerous angular projections and re-entrants, indicating that the actual detailed course of the boundary fractures was controlled by older joints (fig. 8).

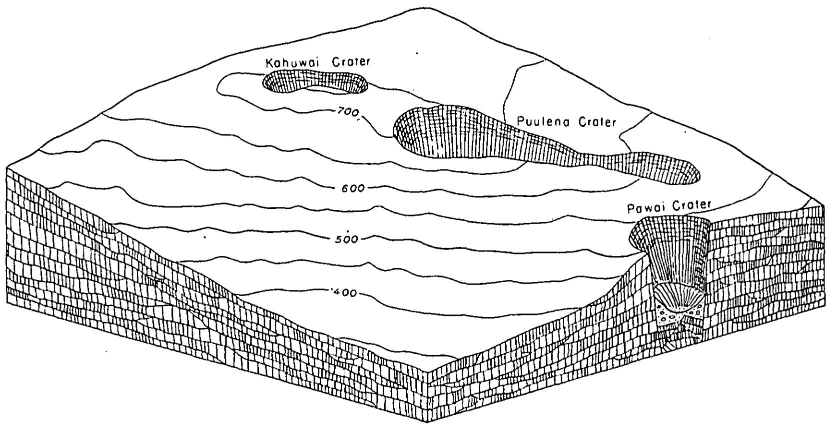

FIGURE 8.—Block diagram showing pit craters along the east rift zone of Kilauea volcano. Contour interval, 50 feet.

Pit craters undoubtedly are the result of collapse, but the immediate cause and manner of the collapse are conjectural. Wilkes (1845, p. 180) thought them to be collapsed lava tubes. Some small ones undoubtedly do originate in that way. A large lava tube is visible at the bottom of the two small pit craters near Cone Crater on the southwest rift of Kilauea, and at the bottom of a very small pit crater near the Kulani Prison road on the east slope of Mauna Loa. However, the large size of many of the pit craters precludes that origin. It is unlikely that a crater such as Makaopuhi, 1 mile long and 0.6 mile wide, could have formed by collapse into a lava tube (fig. 9).

Stearns and Clark (1930, p. 127) attribute the pit craters to "stoping and fluxing action of the magma surging at a particular place along a crack. With later subsidence of the lava, collapse occurs." Stone (1926a, p. 54) also suggests that the collapse results from the removal of support by withdrawal of underlying magma. The suggestions of Stearns and Stone are accepted by Williams (1941, p. 228). Stone believes that the collapse occurs by the sinking, not of a single block, but of many small blocks "such as occurs when a plug is drawn from the bottom of a box of loose sand and a funnel-

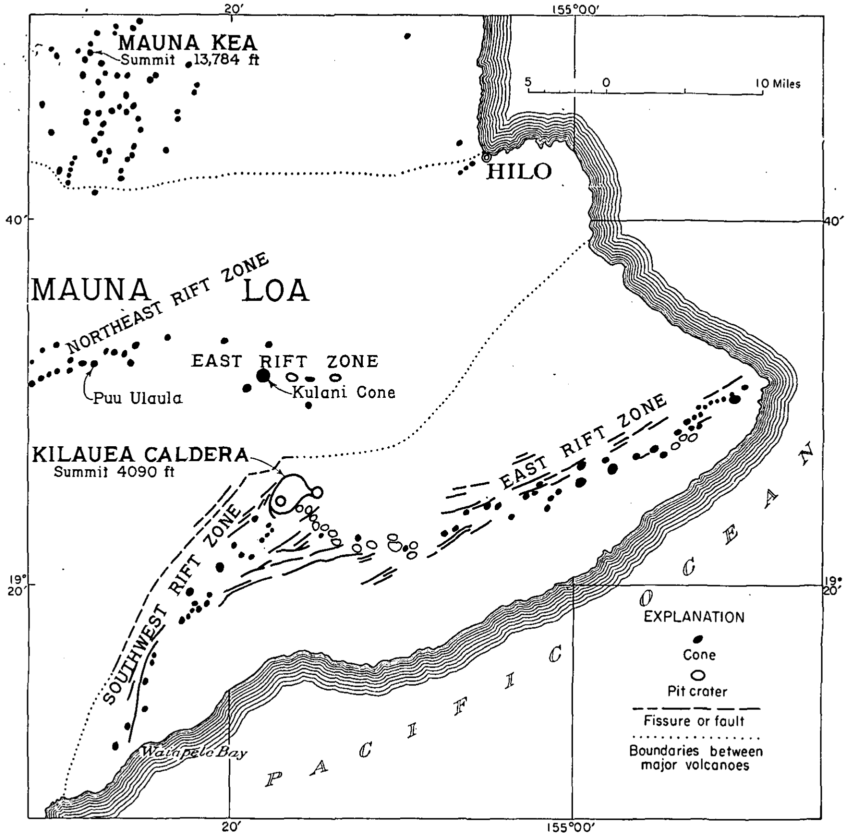

FIGURE 9.—Sketch map of Kilauea and adjacent rift zones.

shaped depression is formed," but cites no particular evidence to support his conclusion. Subsequent dilapidation of the walls has produced large banks of talus within the pit craters, but this does not prove that the pits were formed by piecemeal collapse. On the contrary, there appears to be evidence that many if not all pit craters were formed essentially by the subsidence of single cylinders of rock. Eruptions occurring within the pit craters, such as those of 1840 at Alae Crater, 1868 at Kilauea Iki, and 1922 at Makaopuhi and Napau Craters, have broken out high on the walls, as though the magma were guided to the surface by cylindrical bounding fractures. Moreover, as Stearns and Clark (1930, p. 128) pointed out, there are all gradations from pit craters to grabens. Heake Crater on Kilauea volcano is surrounded by a broad area that is subsiding en masse along concentric fault planes. In Lua Poholo, on Mauna Loa, a large block of the floor has sunk essentially intact, although much tilted (Stearns and Macdonald, 1946, pl. 18).

The shape of Devil's Throat conforms well to that deduced by Anderson (1924, p. 11–12) as the shape that should theoretically be exhibited by ring fractures resulting from the withdrawal of support by an underlying magma body. However, if the overlying roof is relatively thin in comparison to the breadth of the magma body, the part of the roof above the projectile-shaped ring fractures would be unable to support itself. There would then result a roughly cylindrical vertical-walled subsiding block, or piece-meal collapse resulting in a projectile-shaped dome of equilibrium. Following subsidence of a central block, the walls of the crater would undoubtedly to some extent tumble in under the impulse of gravity and earthquakes, building at their foot banks of talus which in some craters would coalesce at the center to form funnel-shaped depressions.

Pit craters may be enlarged by explosion (Stearns and Clark, 1930, p. 128). Phreatic explosion debris was ejected from both Alae and Puulena Craters (on the east rift zone of Kilauea volcano) in prehistoric times. However, the volume of such explosive material is small compared with that of the pit crater from which it came.

It is concluded that large pit craters are formed by collapse resulting from the withdrawal downward of the surface of underlying magma. Probably in some cases they are formed by the sinking en masse of a cylinder bounded by ring fractures approximately vertical at the surface. In others the collapse may have been piece-meal. Small pit craters may be formed in the same way, or by collapse into lava tubes.

LATERAL FAULTING

On the flanks of several Hawaiian shield volcanoes normal faults occur, dipping seaward generally at moderate angles, along which the peripheral parts of the shield are slipping downward and seaward. The best known of these are the faults of the Hilina system, on the southern slope of Kilauea volcano, and those of the Honuapo and Kaoiki systems on the southeastern side of Mauna Loa. Similar faults have been found on the western flank of Mauna Loa and on the eastern flank of West Molokai. Apparently these faults occur also on the southern flank of Haleakala volcano, and at the southwest point of the island of Lanai.

The Hilina fault system on the southern flank of Kilauea volcano is typical. It consists of a dozen or more normal faults, with subparallel en echelon arrangement. The displacement on each fault ranges from a maximum near the center to zero at the ends. The principal scarp, at Hilina Pali, reaches a height of 1,500 feet. The dip of the fault planes cannot be measured directly, but judging from the slope of the scarp it is probably about 40°. The angularity of the fault pattern suggests that the position of the faults was probably influenced by earlier joint patterns. The fault planes may flatten to become parallel with bedding planes at depth.

STRUCTURES AT PRIMARY VENTS

The common structures at vents of Hawaiian lava flows are spatter-and-cinder cones, spatter ramparts, and lava cones. True cinder cones are rare at the vents of basalt flows, but common at the vents of andesite flows. Cinder cones and tuff cones as products of exclusively pyroclastic eruptions are discussed in detail in the section on pyroclastic features.

SPATTER RAMPARTS

During the early hours of a typical Hawaiian eruption, fountains of very fluid basalt magma erupt from a fissure or fissure-zone that in some instances may attain a length of 3 or 4 miles (Schulz, 1943, p. 741; Macdonald, 1943, p. 245, 256). These fountains build low walls of coagulated spatter, known as spatter ramparts, along the eruptive fissure. Typically, a wall is built along each side of the fissure, although locally copious outwelling of lava may carry away the spatter as rapidly as it falls and prevent the building of the wall. Locally also, abundant spatter may unite the two parallel walls at their tops, forming a bridge across the fissure. The bridges may be several feet thick, and it is possible to cross the hot and still fuming fissure by means of these bridges within a few hours after the cessation of fountaining. The ramparts range in height from a few inches to 15 or 20 feet and in thickness from 1 to 10 feet. They merge into spatter cones. The ramparts are composed of coagulated and welded spatter or *agglutinate* (Tyrrell, 1931, p. 66). The forms of individual ejecta are described in the section on types of materials and fragments (p. 73).

SPATTER-AND-CINDER CONES

After a few hours of eruption the activity typically becomes restricted to a short stretch of the fissure, about a quarter of a mile in length. Lava fountains continue for days or weeks, and a *spatter-and-cinder cone* is built (Macdonald, 1943, p. 247, 256). The great bulk of the material comprising the cone is fluid spatter, the glassy skins of which adhere to form agglutinate (fig. 10). True cinder and Strombolian bombs also may be present and there generally is some pumice and Pele's hair. Small driblet flows are common on the cone flanks. The resulting cone is commonly elongate and seldom more than 50 feet high. The summit of the cone is indented by pits that mark the sites of the principal lava fountains. During activity, a lava river generally issues at the lower end of the cone, and that end of the

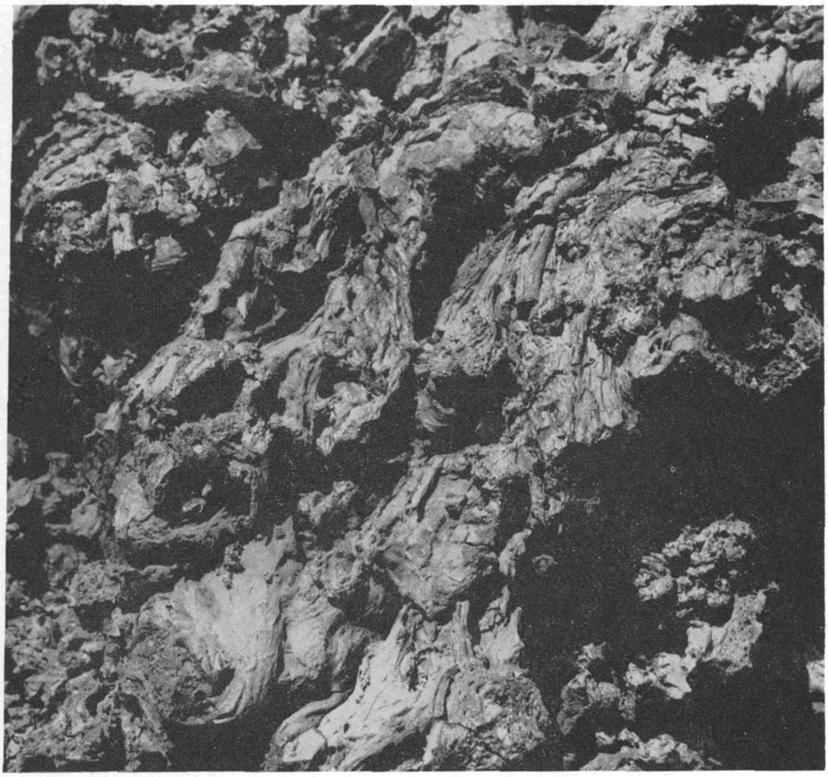

FIGURE 10.—Detail of driblet lava in road-cut outcrop, Chain of Craters road, Hawaii. Width shown is about 24 inches. Photo by C. K. Wentworth.

cone remains partly or entirely open, the cinder and spatter falling there is carried away on the surface of the lava flow. The sides of the cones generally slope at an angle approximating the angle of repose of loose debris, that is about 30°, but some cones are much steeper because of the large proportion of agglutinate. Small steep-sided cones composed very largely of spatter are common on the rift zones of Hualalai volcano.

CINDER CONES

True cinder cones are rarely formed during eruptions of olivine basalt and basalt in Hawaii, but examples are known on both Mauna Loa and Kilauea volcanoes. They are usually larger and more symmetrical than the spatter-and-cinder cones described above. The cone formed in the caldera of Mauna Loa during the 1940 eruption is about 250 feet high, 700 to 1,200 feet across at the base, and quite symmetrical. In its top is a deep crater, breached by a shallow notch toward the north. It is composed largely of typical cinder (fig. 11).

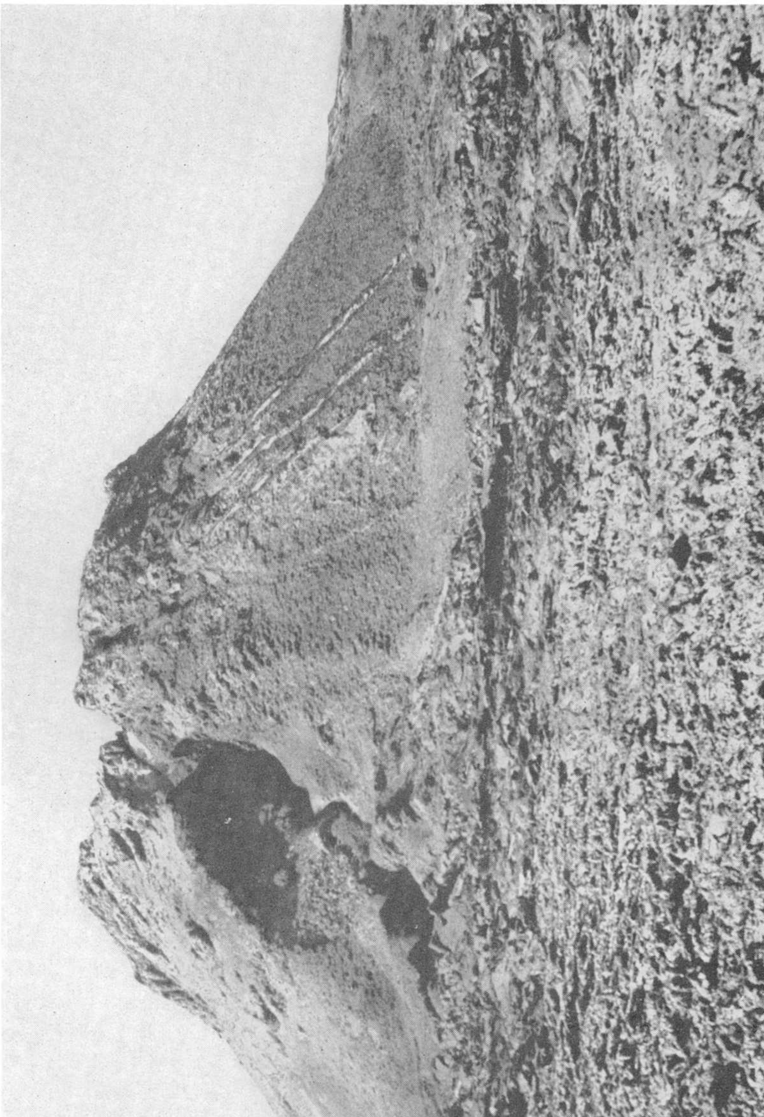

FIGURE 11.—The cinder cone of the 1940 eruption in Mokuaweoweo caldera, Mauna Loa, seen from the south. The large fissure was formed during the 1949 eruption, when lava rose in the crater of the cone and abundant spatter veneered the rim of the cone and formed the small rootless flows visible on the right flank. The cone is about 200 feet high. Hawaii National Park photo by J. B. Orr.

True cinder cones are characteristic of the vents of flows of andesite and augite-rich picrite-basalt and are abundant on the flanks of Mauna Kea, and Haleakala, where they range to several hundred feet in height, and almost a mile across at the base. The cones are commonly asymmetrical, built higher on the side which was downwind during the eruption, commonly southwest. Some have well preserved bowl-shaped craters but many vent cones are breached, usually on the downhill side, either through removal of falling ejecta by concurrent lava streams or by subsequent burrowing of a lava flow.

The cones are composed largely of scoria from half an inch to an inch across, together with some larger fragments from 8 to 12 inches in diameter. Some contain abundant finer lapilli and ash, but others do not. More commonly in andesitic cones spindle-shaped bombs are found whereas pancake, or cow-dung type bombs are characteristic of augite-rich picrite-basalt cinder cones of Hawaii. Where the later ejecta are more spattery than the earlier, a layer of agglutinate may form around the crater rim. Because it is more resistant than the cinder layers it will stand out with the appearance of a ruff on slightly eroded cones. In Hawaii these cones commonly bear the native name "Pohaku o Hanalei", which means "wreath of stones".

LAVA CONES

Lava cones are built around some vents. These cones are miniature shield volcanoes composed largely of lava flows with very little pyroclastic material. Excellent examples of these are Maunaiki, the broad low cone at the vent of the 1920 lava flow on the southwest rift zone of Kilauea volcano, Kane Nui o Hamo and Heiheiahulu on the east rift zone, as well as Kaimuki in Honolulu. These lava cones generally range in width from half a mile to 1.5 miles, and in height from 100 to 350 feet. Their sides slope at an average angle of 2° to 5°. They are formed largely by fissure eruption, but at the summit some have small craters formed principally by collapse. Thus Heiheiahulu cone contains a crater about 200 feet wide and 30 feet deep. An unusually large crater, 1,000 feet wide and 207 feet deep, with nearly vertical walls, indents the summit of Kane Nui o Hamo. This crater was the result of collapse caused by lava draining back into the conduit at the end of the eruption. The floor of Kilauea caldera is largely occupied by a gently sloping lava cone with the collapse crater Halemaumau at its apex.

Rarely the lava cones are steep sided. The small lava cone formed during the late stages of the 1949 eruption of Mauna Loa (Macdonald and Finch, 1949) by repeated overflow of a small lava pond is about 100 feet high and 300 feet across at the base. Its sides slope at an average angle of about 35°.

LAVA RINGS

The lava ring is a very specialized structure that sometimes develops around the margin of an active lava lake (Daly, 1914, p. 135). This feature is a wall of spatter built up by the ejecta from the many small lava fountains that play on the lake surface. It is similar in structure and general nature to the ramparts formed along erupting fissures. Lava rings range from a few inches to several feet in height. At times they may act as dikes to hold the liquid lava of the lake at a level slightly higher than the surrounding surface. In August 1892 the Halemaumau lava lake is reported to have been enclosed in a narrow wall, with the lake surface about 40 feet above the surrounding floor (Dodge, 1893). A beautifully developed but lower ring was present in 1894 (fig. 12). A similar but still lower ring was formed around a small lava pond during the 1934 eruption of Kilauea (Jaggar, 1934a, p. 1–2; 1934b, p. 1).

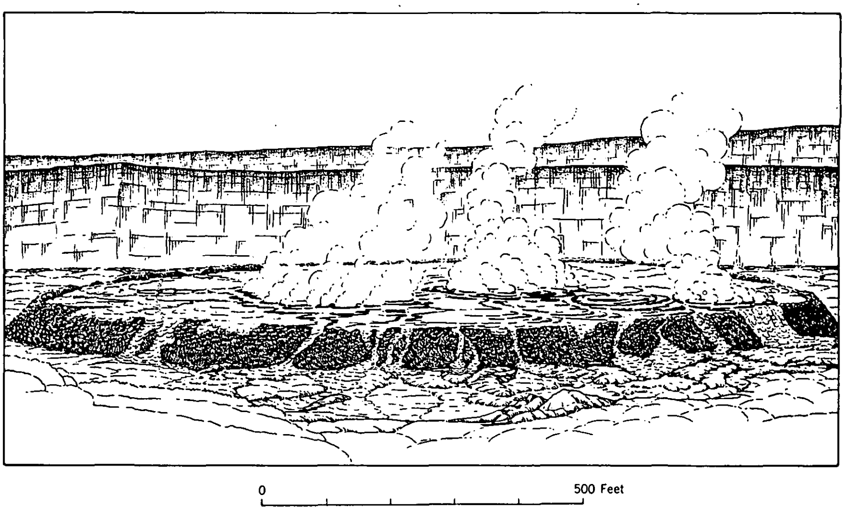

FIGURE 12.—Lava ring at Halemaumau, Kilauea, in March 1894 (after Brigham). The lava lake stood about 40 feet above its surroundings, and was about 1,200 feet in greatest diameter.

ROOTLESS VENTS

The term "rootless vent" is applied to vents not directly associated with the conduits that brought the magma to the surface from the deep-seated magma reservoir. Three varieties of rootless vents have been observed in Hawaii. One variety includes the hornitos and small accumulations of lava overflow on the surface of pahoehoe flows, fed through openings in the flow crust from liquid lava in an underlying tube. Hornitos are discussed on page 52.

The second variety occurs on a much larger scale, and produces major outflows of lava at a considerable distance, sometimes several miles, from the true vents of other flows of the same eruption. It apparently results from the lava entering tubes in older pahoehoe, and flowing long distances underground before it breaks through to the surface. In 1935, the primary vents were located along fissures on the northeast rift zone of Mauna Loa above an altitude of 11,700 feet and were marked by rows of lava fountains. The lava flow originating at those vents extended 9 miles down the northern slope of the mountain. At two places near the source fountains streams of lava plunged into an open fissure and a small pit crater (Jaggar, 1935, p. 3). A week after the commencement of the eruption near the summit, lava broke out at a point 5 miles from the rift zone vents, at an altitude of 8,800 feet. This vent on the northern slope of Mauna Loa, was far off the course of the northeast rift zone. This fact alone is not significant, as other scattered vents on the northern slope are on fissures that spread out from the upper part of the rift zone. It is, however, significant when coupled with the facts that the lava issued from a tubelike opening in older pahoehoe, and that the strong fountain activity characteristic of Mauna Loa vents was lacking. It is believed that the lava flowed underground for 5 miles, through one or more old lava tubes, before it broke through to the surface to form the rootless vent at an altitude of 8,800 feet.

In 1942, the principal fountaining vents were situated at an altitude of 9,200 feet, on the northeast rift zone of Mauna Loa. Within 2 days after the outbreak at 9,200 feet, another vent opened 3 miles farther east-northeast, at an altitude of 7,800 feet. The locality is on the northeast rift zone, but the lava issued from somewhat arcuate cracks that trended northwesterly, approximately at right angles to the fissures of the rift zone. This lower vent exhibited none of the characteristics of the usual vents on Mauna Loa. The lava issued quietly from beneath the toe of an older aa flow that overlies a still older brown pahoehoe. Fume was liberated in much less volume than at the vent at 9,200 feet, and apparently no lava fountains were present. Only a very small amount of dense spatter was formed, and the lava was denser and much poorer in gas than that at the higher sources. This lower outbreak probably represents lava draining through an older pahoehoe tube that intersected the eruption fissure at some point higher up the mountain (Macdonald, 1943, p. 246). The gas-poor nature of the lava at this lower, rootless vent probably resulted partly from gas loss at the lava fountains of the primary vents, and partly from progressive loss of gas as it flowed through the subterranean tube.

The third type of rootless vent is the littoral cone, discussed in the following section.

LITTORAL CONES

Where an aa lava flow enters the sea there commonly occurs a series of steam explosions that hurl into the air large amounts of ash, lapilli, and small bombs. The debris is derived entirely from the new lava. Accumulation of this debris on the stagnant top of the flow results in a littoral cone (Wentworth, 1938, p. 22) that in many ways resembles the cinder-and-spatter cones at vents. So far as known, the cones are built exclusively by aa flows. The heated interior portion of a pahoehoe flow is largely protected from the water by its poorly conducting glassy crust, whereas the open clinkery surface of an aa flow permits easy access of the water to the hot inner portion (Macdonald, 1944a, p. 181).

Littoral cones reach heights up to 300 feet and diameters up to half a mile. They are commonly double, a hillock developing on each side of the flowing lava river, while the debris falling on the river itself is carried away. The cones lack craters, and are generally better bedded than typical cinder cones. They consist largely of vitric ash of sand and silt grades, enclosing irregular lapilli and bombs up to 2 feet across. Many of the bombs show ribbon and spindle shapes. The matrix differs, however, from that typical of cinder cones built by lava fountains at primary vents. The latter is highly inflated, many of the lapilli are pumice, and the small ash fragments show the typical arcuate shard outlines resulting from fragmentation of pumiceous material. In contrast, the small fragments of the littoral cones are dense or only moderately vesicular. The shards are angular and the arcuate forms are absent or comparatively rare. On the surfaces of some of the littoral cones there are scattered angular blocks of lava resembling those typical of vulcanian explosion (Finch, R. H., personal communication). The differences result from the fact that the gases accompanying lava fountains at vents are of internal origin, the lava undergoing active inflation during the explosions, whereas the steam that atomizes the liquid lava in the littoral explosions is of external origin (Macdonald, 1949a, p. 72).

MARGINAL EXPLOSION CRATERS

Lava flows entering the wet jungle cause many minor explosions by generation of steam from the underlying swampy soil and distillation of combustible gases from inundated vegetation. The odor of marsh gas is often distinct near the flow boundary. Explosion craters 3 to 20 feet across and 2 to 5 feet deep have been observed at the flow margin and as much as 200 or 300 feet distant from it. Blocks of rock as much as a foot in diameter are scattered around the craters for a distance of 15 or 20 feet. The explosions apparently result from the combustion of hydrocarbon gases accumulated in lava tubes in the underlying older pahoehoe (Jaggar, 1917c, p. 274; 1926, p. 37).

FUMAROLES

An extended discussion of fumaroles is not warranted here. Hawaiian fumaroles are of both primary and secondary (rootless) types (Lacroix, 1906, p. 650). The primary fumaroles issue from cracks in and near the calderas or along the rift zones, and are continuous for long periods of time. Those at Kilauea caldera have been active continuously since the first visits by Caucasians, in 1823. The liberated gases are largely water vapor, derived principally by the heating of ground water, but include also magmatic gases presumably rising from underlying magma reservoirs or slowly cooling intrusives. Alteration of the rocks by fumarolic gases has been described elsewhere (Macdonald, 1944c, p. 496–505).

Secondary or rootless fumaroles are short-lived gas vents that exist on the surface of lava flows only while the flow is still hot and liberating gas. The gas is derived largely from the underlying lava, but at least in some cases is partly steam from underlying wet ground and volatiles distilled from vegetation burned by the flow. A typical secondary fumarole observed on the 1942 lava flow 7 miles below the vents and 2 days after the flow ceased moving, consisted of a hot glowing area liberating a small amount of sulfurous fumes, and encrusted with a thin deposit of sulfur. This fumarole was situated at the edge of one of the aa channels, a common location for secondary fumaroles.

LAVA FLOWS

GENERAL FEATURES

DIMENSIONS

The basaltic lava flows of the Hawaiian volcanoes vary greatly in all dimensions. On the flanks of the volcano, where they can spread freely, they range in thickness from a few inches to 40 or 50 feet, averaging about 5 feet near the mountain summit and 20 feet near the shoreline (Stearns and Macdonald, 1946, p. 28). The increase in thickness on the lower slopes is largely the result of decreasing temperature and gas content, with concomitant increase in viscosity. It is accompanied by a general transformation in the prevalent type of lava flow, from pahoehoe to aa, pahoehoe flows averaging considerably thinner than those of aa. Where they are ponded on the floors of the calderas, or in craters or other depressions, or where the slopes are very low as in the saddles between the mountains, the thickness is greatly increased. Some flows ponded in pit craters or calderas have thicknesses of 200 feet and more.

The lengths of flows also vary greatly. Some flows travel only a few feet. Thus the lava of 1868 along the southwest rift zone of Kilauea volcano in places hardly flowed away from the feeding fissure, and at other places only reached to within a few feet of the surface level at the fissure. Other flows travel many miles from their vents. The 1880 lava flow of Mauna Loa (fig. 13) reached a point in the

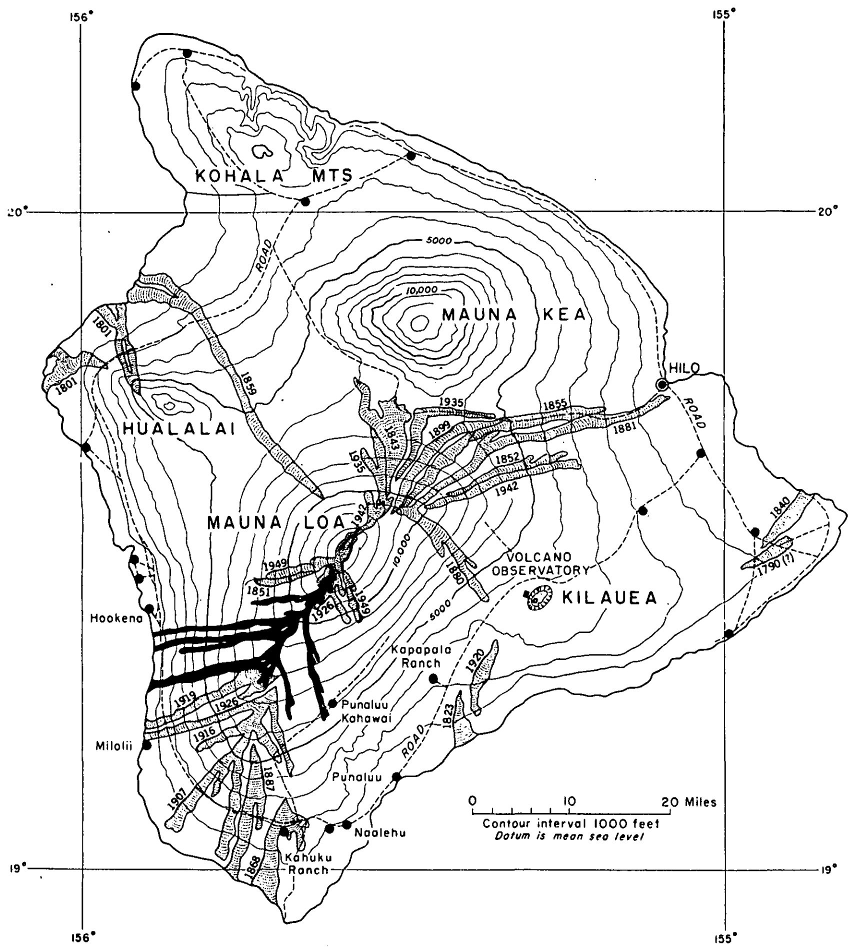

FIGURE 13.—Map of Hawaii showing historic lava flows. The 1950 flows of Mauna Loa are shown in solid black. Older historic flows are stippled.

outskirts of the city of Hilo, 30 miles from its source. In 1859, the lava flow entered the ocean more than 31 miles from its vents, and continued for an unknown distance below sea level.

The breadth of lava flows ranges from a few feet, or at the very upper end of source fissures sometimes even less than a foot, to several miles. Where it spread in the saddle between Mauna Loa and Mauna Kea, the 1843 lava flow is nearly 3 miles wide. On slopes where they flow freely, however, the flows are seldom more than 1.5 miles wide, and average between 0.5 and 1 mile.

The volume of lava extruded during a single eruption ranges from a few to several hundred million cubic meters. The range in length, average width, area, and approximate volume of historic lava flows of Mauna Loa is shown in the accompanying table. Prehistoric flows apparently did not differ appreciably from the historic flows. For the flows that entered the sea, the dimensions given are those of the part of the flow above sea level.

Historic flank flows of Mauna Loa and Kilauea

[Asterisk (*) denotes flows that reached the sea]

Date	Length [a] above sea-level (miles)	Approximate average width (miles)	Area [b] above sea-level (square miles)	Approximate volume [c] above sea-level (million cubic yards)
Mauna Loa				
1843	13.5	1.5	20.2	250
1851	10.0	.5	6.9	90
1852	13.8	.6	11.0	140
1855	[c] 20.0	.5	12.2	150
1859	*31.7	.8	32.7	600
1868	*11.1	.5	9.1	190
1880–81	30.2	.5	24.0	300
1887	*15.0	.7	11.3	300
1899	15.0	.9	16.2	200
1907	13.6	.4	8.1	100
1916	7.5	.3	6.6	80
1919	*11.8	.3	9.2	350
1926	*13.2	.5	13.4	150
1935	16.8	.5	13.8	160
1942	15.7	.6	10.6	100
1950	*14.8	.5	35.6	491
Kilauea				
1790 (?)	5.6	0.3	3.0	38
1823	*6.3	.4	3.9	15
1840	*6.9	.7	6.6	281
1919–20	7.1	.5	5.0	62
1922	.4	.1	.04	.3
1923	.1	.2	.2	.1

[a] Where the flow had more than one branch, the length given is that of the longest branch.
[b] Data on area and volume from Stearns and Macdonald, 1946, p. 69, 111.
[c] The upper end of the 1855 lava flow has been lost in the complex of recent flows along the northeast rift zone. The figures given are for the part of the flow below where it is overlapped by the 1880 lava.

ATTITUDES OF LAVA FLOWS

The attitudes of lava flows are governed largely by the conformation of the underlying terrane. Owing to the fluidity of the prevailing lava types, the slopes of large volcanic accumulations in Hawaii are usually gentle, and accordingly the newly erupted lava beds on the flanks of the volcanoes have gentle dips. Wherever the flow is ponded its attitude becomes essentially horizontal. On the other hand, where lava flows have poured down the sides of cinder cones or over fault scarps or sea cliffs, the dips increase to approximately equal the underlying slopes. Flows on the flanks of cinder cones dip as much as 35°. Those which pour over cliffs commonly form a veneer adhering to the cliff face, with dips in some places approaching the vertical.

FLOW UNITS

Many lava flows of the Hawaiian volcanoes comprise two or more parts poured one over the other during the course of a single eruption. For these nearly contemporaneous subdivisions of flows Nichols (1936) proposed the name *flow units*. In Hawaii, the flow units commonly range from a few inches to about 10 feet in thickness. Their extent is variable, ranging from local gushes that move a few feet over an earlier surface of the same major flow, to sheets that flow for thousands of feet or even miles partly or entirely over earlier lava of the same eruption. Repeated flow units occur in both aa and pahoehoe, but are seen most commonly in pahoehoe. In some sections, scores of pahoehoe units, none more than 2 to 4 inches thick, aggregate 10 or 20 feet in thickness. In some instances a later flow unit of pahoehoe may move over an earlier flow unit of aa, or vice versa. In prehistoric lavas it is commonly difficult or impossible to ascertain whether successive beds of similar lava, without intervening soil, are merely different flow units of the same major flow, or independent flows extruded during different eruptions.

CLASSIFICATION OF FLOWS

The common types of lava flows in Hawaii are pahoehoe and aa. Although these two forms are intergradational, they are characteristically distinct. *Pahoehoe* may be defined as the variety typified by a smooth, billowy, or ropy surface, and *aa* as that typified by a rough, jagged, spinose, clinkery surface. Not only the surfaces, but in general the internal structures of pahoehoe and aa flows are distinct, and the mode of advance of the two types is quite different. They are discussed in detail in the following paragraphs. The terms dermolith and aphrolith have been proposed for the two types by Jaggar (1917a), but have not been generally accepted. A third type, *block lava*, resembles aa in the fragmental character of the flow surface, but differs in that the fragments are not spinose and clinkery but are relatively smooth angular blocks (Finch, 1933b, p. 769–770). It is intergradational with true aa. Block lava is rare in Hawaii, but occurs in some flows of andesite (fig. 3).

PAHOEHOE

GENERAL FEATURES

Pahoehoe lava flows are characterized by a smooth, hummocky, ropy, or entraillike surface, and the presence of lava tubes. After the initial burst of lava the top becomes crusted over by congealed rock, and the advancing fluid lava entirely fills the resulting lava tubes. The large tube divides into many smaller ones, each of which feeds a lobe of lava along the advancing flow front. The entire front advances by the protrusion of successive lobate toes, somewhat in the manner of a moving amoeba. Large tubes may be several tens of feet in diameter, but are commonly not more than 10 or 15 feet. The smaller tubes are generally 1 to 3 feet across. Lava may congeal in the tube, the position of the tube being marked only by the concentric arrangement of vesicles; or the fluid lava may drain away, leaving the tube partly or entirely empty. In cross section a flow unit often consists of a large number of small, filled tubes. The ellipsoidal shape of the tubes and the way in which they are packed together give the outcrop on superficial examination the appearance of pillow lava (Stearns and Macdonald, 1942, p. 24–25). Flows of pahoehoe are commonly a succession of flow units, from a foot to 15 or 20 feet in thickness. Each flow unit represents a separate period of lava spreading, a few hours, days, or weeks apart, during the same eruption.

Thin pahoehoe flows, and the upper parts of thick flows, are characterized by very abundant vesicles making the rock almost spongy. Extremely gas-rich flows, especially in the summit region of Mauna Loa, develop a layer from less than 1 inch to about 2 inches thick, of typical basaltic pumice (Finch, Powers, and Macdonald, 1948). The lower and middle parts of thick flows, which remain fluid long enough to lose much of their gas, are dense. The vesicles of pahoehoe are typically spherical or spheroidal, composed of clusters of spheroids or moderately distorted spheroids. Their outlines are smooth, regular curves, as contrasted with the typically very irregular outlines of aa vesicles (fig. 14). Although this difference in vesicle shape does not always hold true, and gradations in vesicle shape from aa to pahoehoe are recognized it is nevertheless so general that it constitutes a very useful criterion for the recognition of aa and pahoehoe in cross section or in hand specimen.

At the surface of pahoehoe flow units there is generally a glassy skin, ranging from a mere film to a layer an inch or more thick. The glassy crusts weather more readily than the rest of the rock, and in cross sections of old lavas the flow tops are commonly marked by undulating bands of red or yellow. In detail the surfaces of pahoehoe flows may be smooth, or pockmarked by innumerable broken blisters.

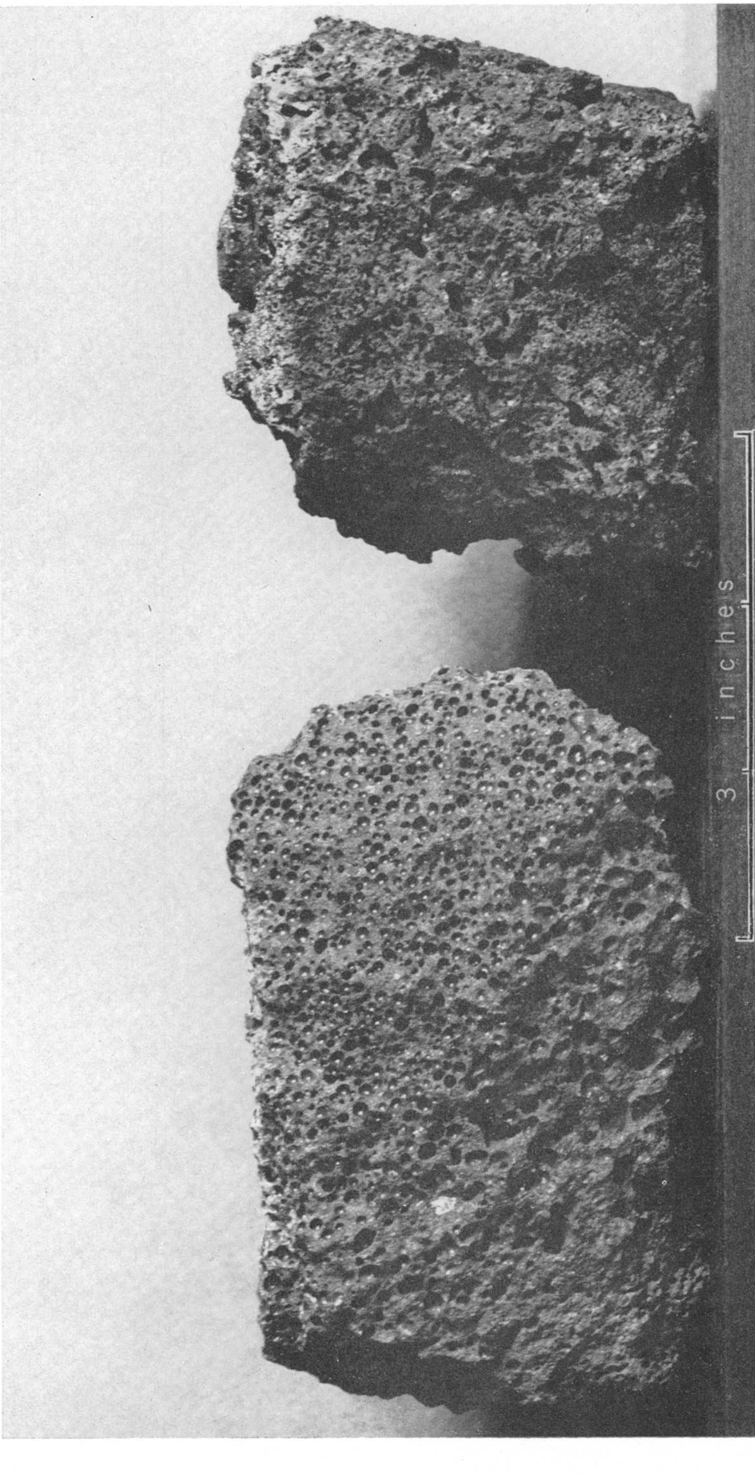

FIGURE 14.—Typical pahoehoe vesicles (left) contrasted with typical aa vesicles (right). Note the great irregularity of the aa vesicles as compared with the regular spheroids in the pahoehoe. Photo by G. A. Macdonald.

Most commonly, however, they are covered with innumerable tiny spicules and spines produced by the escape of gas from the lava surface, each bubble dragging with it a filmaent of the enclosing liquid. The liquid dragged upward by the escaping bubble quickly chills, sometimes leaving a small upright spine a millimeter or more high. The resultant minutely spinose surface feels exceedingly rough to the hands. This type of pahoehoe surface has been termed *shark-skin pahoehoe* by T. A. Jaggar and his associates at the Hawaiian Volcano Observatory (fig. 15). It generally is developed where quick chilling of the flow surface, as by heavy rain, has formed a tachylite crust.

More commonly the filaments carried upward by the escaping gas bubbles bend partly or entirely over before they freeze to immobility. Most of the threads fall back onto the flow surface, and commonly are alined in the direction of flowage. The surface of this type of pahoehoe has a lacy or filamented appearance, and the flows may be termed *filamented pahoehoe* (fig. 16). It is the commonest type of pahoehoe surface, and generally is superimposed on the ropy, hummocky, or entraillike forms.

On a larger scale, many pahoehoe surfaces are marked by a series of small cordlike ridges, commonly alined parallel to the direction of flow (figs. 17 and 18). These small cords, usually an inch or less in diameter, may be superimposed on still larger ropelike convolutions of the crust. This type of surface may be termed *corded pahoehoe*. Less commonly, liquid lava flowing beneath the plastic crust drags it into ropy festoons, which are convex in the direction of motion. This type of surface is best termed *festooned pahoehoe*. These ropy or festooned surfaces are often considered characteristic of pahoehoe flows, but actually such surfaces are comparatively limited in their distribution. Still another type of pahoehoe surface consists of innumerable small contorted toes of pahoehoe, intricately jumbled together, and generally associated with festooned surfaces. It is usually found on the flanks of minor vents or rootless vents such as hornitos and ruptured tumuli. Its entraillike appearance has been noted by several writers, and may be appropriately termed *entrail pahoehoe* (fig. 19).

In a broad sense, a field of pahoehoe is generally irregular and hummocky. Some of the hummocks are typical tumuli (p. 45). Others are broad swells and ridges, that range from less than 1 foot to more than 10 feet in height (fig. 20). When viewed from a distance and especially from the air the hummocks and ridges sometimes have a wrinkled and draped appearance that has given rise to the term *elephant-hide pahoehoe* (Stearns and Macdonald, 1946, p. 20).

FIGURE 15.—Sharkskin pahoehoe, surface of lava flow of 1919, Kilauea caldera. Photo by G. A. Macdonald.

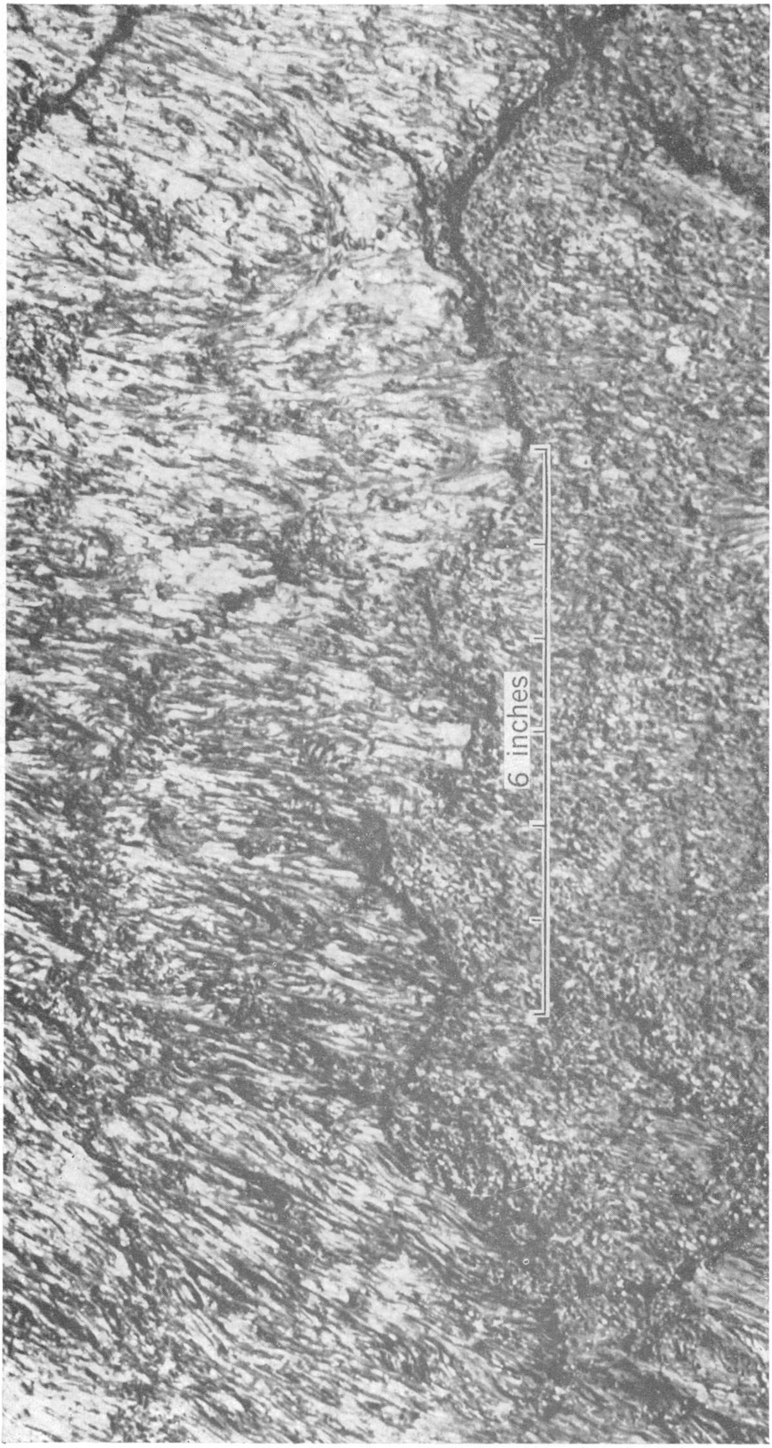

FIGURE 16.—Filamented pahoehoe, surface of lava flow of 1919, Kilauea caldera. Photo by G. A. Macdonald.

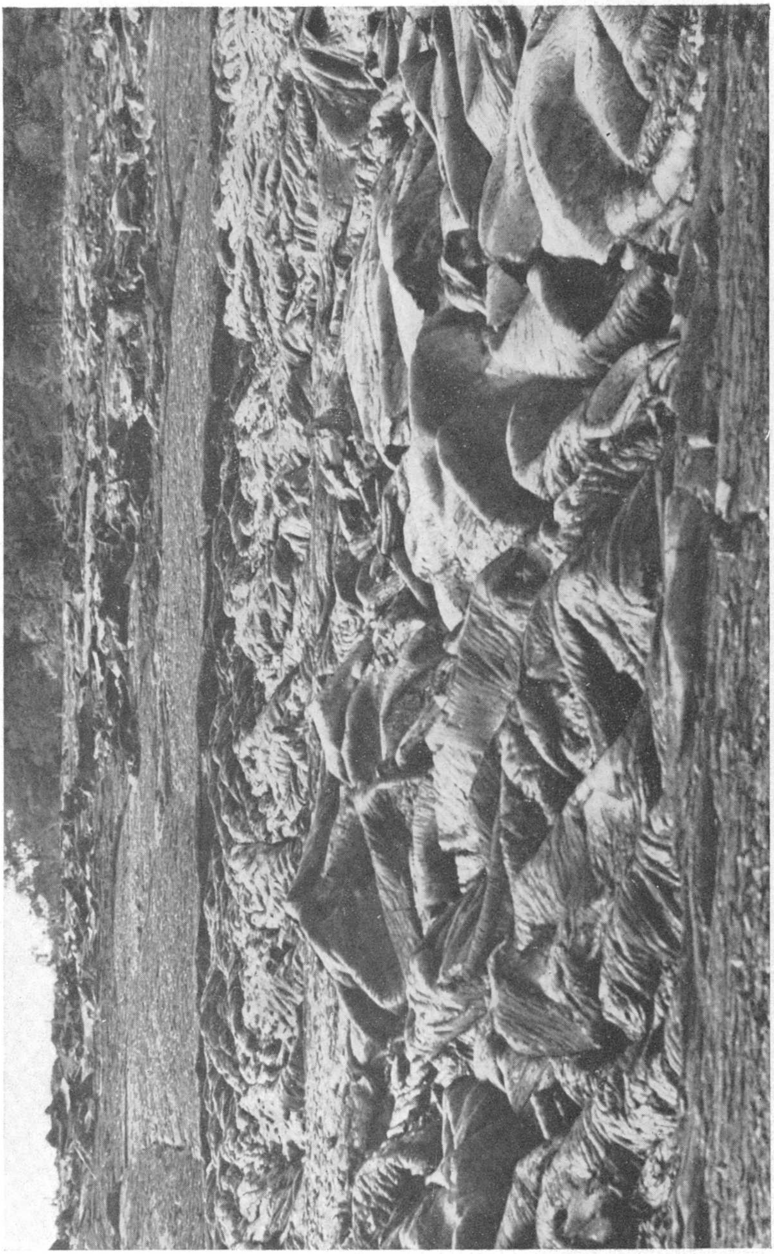

FIGURE 17.—Surface of pahoehoe lave flow, 1935 eruption of Mauna Loa, near Humuula, showing ropy, contorted bands with intervening bands of undisturbed early crust. Width of near band of disturbed crust about 30 feet. Flow from right to left. Photo by C. K. Wentworth.

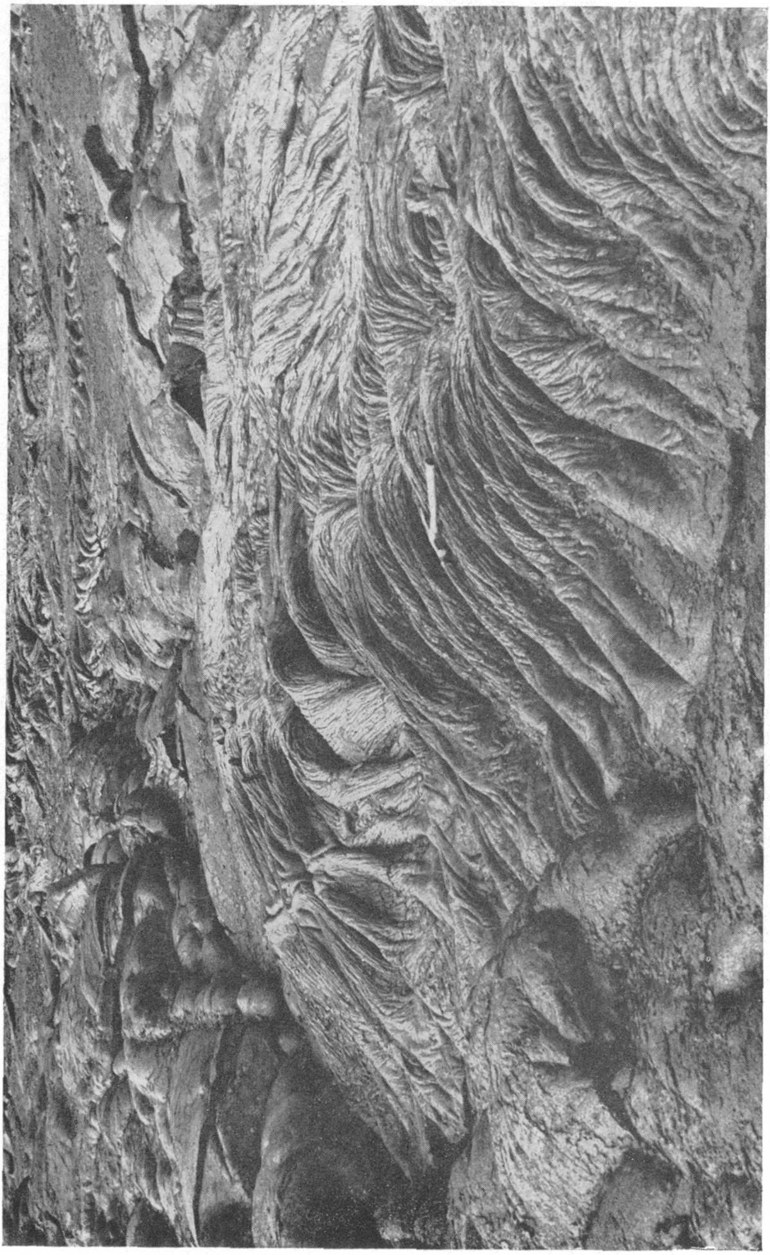

FIGURE 18.—Detail of surface of 1935 Mauna Loa flow, near Humuula. Motion from right to left. Photo by C. K. Wentworth.

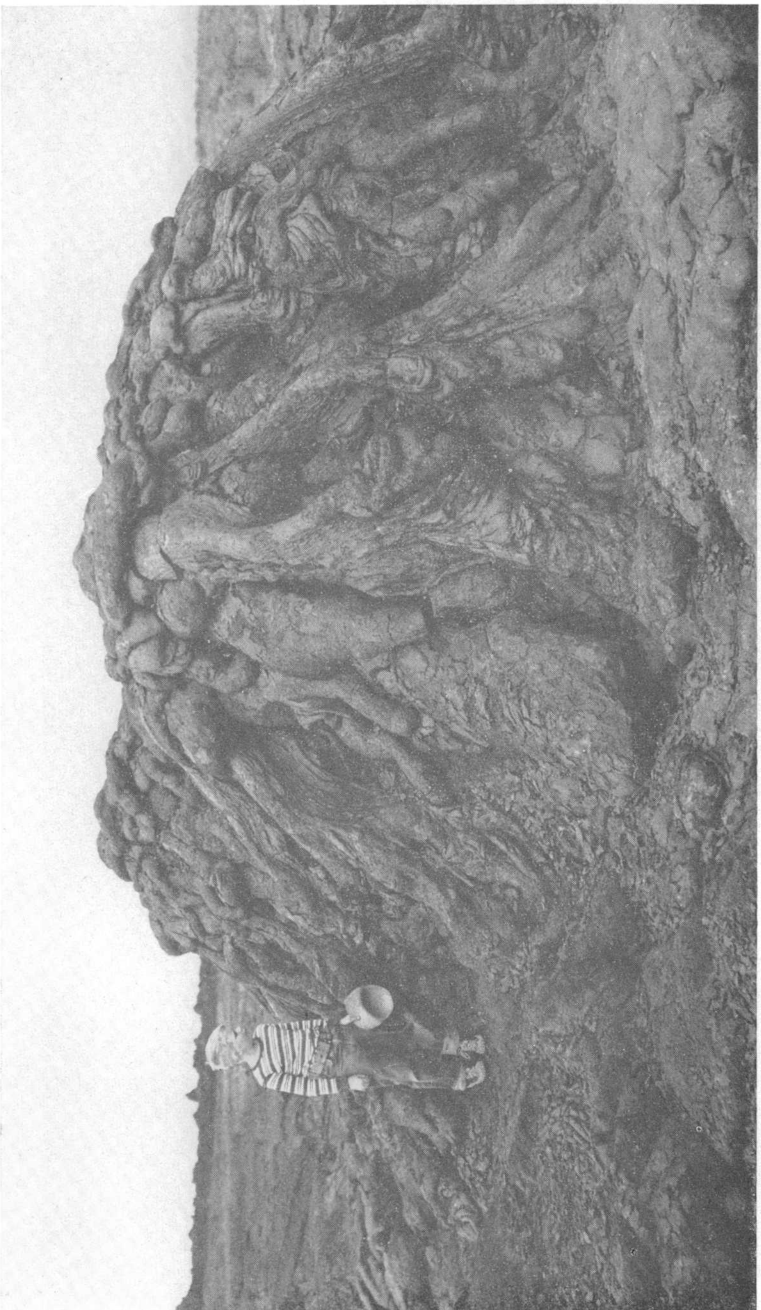

FIGURE 19.—Entrail pahoehoe on flank of small tumulus on 1920 lava flow of Kilauea. Photo by G. A. Macdonald.

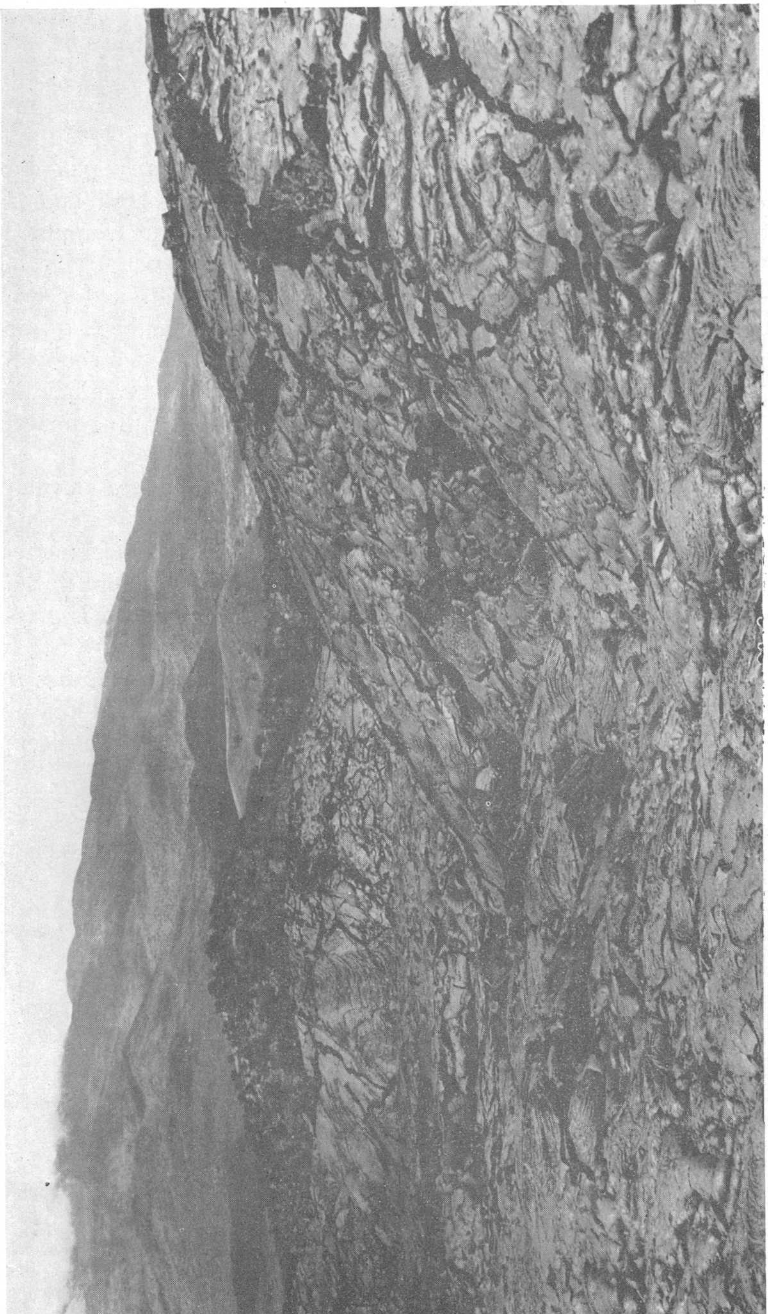

FIGURE 20.—Surface of 1843 Mauna Loa lava flow, southwest of Humuula, view to northward, with Mauna Kea slope and cinder cones in distance. This flow is marked by tumuli and intervening collapse depressions on a large scale. Tumulus at right is 25 feet high. Photo by C. K. Wentworth.

On some pahoehoe flows, draining of the liquid from beneath a thin crust, followed apparently by some movement of the flow as a whole, has resulted in fracturing of the crust and tilting and heaping of the fragments. The fragments of crust are plates, 1 to 4 or 5 feet in length and width, and 2 to 6 or 8 inches thick. Their upper surfaces exhibit the minor features characteristic of any pahoehoe flow, but their lower surfaces are exceedingly rough and spinose. The plates are tilted, jumbled, or imbricated, in a manner similar to the plates of ice in an ice pack. This type of pahoehoe surface has been described from several other localities, including the McCartys flow in New Mexico (Nichols, 1938, p. 601–603). It has been termed slab-lava by Jones (1943, p. 267), and block-fields of pahoehoe by Cotton (1944, p. 125). Because it is more slablike than blocklike, it is suggested that the name *slab pahoehoe* be used for this form of lava.

The rare variety known as *arborescent* or *dendritic lava* develops along fractures in the crust of both pahoehoe and aa flows close to the condition of transition from one to the other. It is formed at points where the crust sags leaving one side of the crack higher than the other (Stearns and Macdonald, 1946, p. 80). The lava is glassy but apparently otherwise entirely normal in composition, covered by a red oxidized shell less than 1 millimeter in thickness. Its beautifully dendritic character is shown in figure 21. The exact reasons for its formation and mode of development are obscure, but it ap-

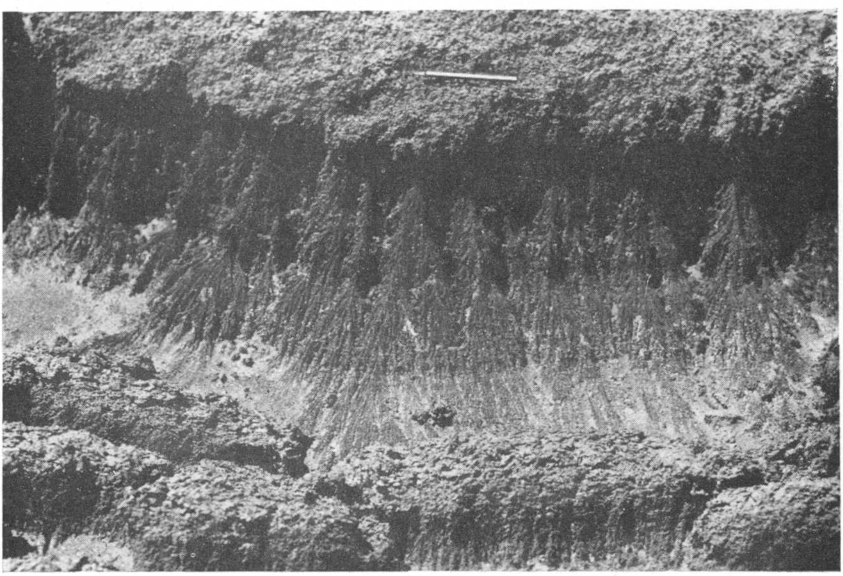

FIGURE 21.—Dendritic lava, on a small scarp in the 1920 flow of Kilauea. The scale is shown by the pencil. Photo by G. A. Macdonald.

pears likely that it is genetically related to the spinose and sproutlike development, of equally obscure origin, that typifies the surface of some aa flows.

Near some vents, especially on the upper slopes of Mauna Loa, floods of gas-rich pahoehoe have developed a plexus of small tubes and blisters. Some were originally filled with fluid lava that drained away, but others apparently were never entirely filled with liquid but were inflated by gas pressure (Macdonald, 1943, p. 249). The crust above these small tubes and blisters ranges from about 2 inches to 1 foot in thickness. It usually will not support the weight of a man and when crossing these lava fields a person repeatedly undergoes the startling and unpleasant experience of falling through the crust into the openings beneath, a distance of 1 to 4 or 5 feet. This type of lava has been termed *shelly pahoehoe* (Jones, 1943, p. 265–268).

PAHOEHOE CHANNELS AND TUBES

During early stages of the eruption, and sometimes near the vent during later stages, the pahoehoe river flows in an open channel. As it leaves the vent, the surface of the river is largely incandescent, of yellowish orange to red. Thin lead-gray crusts quickly form and are borne along on the moving river, repeatedly fracturing, sometimes turning on edge and sinking, and continually reforming. Drag of the crust at the edges of the river results in the formation of ropy festoons convex downstream. Occasional overflows build up low levees of congealed lava along the river margins. Spatter from the river often forms a thin veneer on the levee, particularly near the vent.

A short distance below the vent, the pahoehoe river commonly starts to develop a continuous roof, resulting in a typical lava tube, through which the river moves during most of the duration of the eruption and for most of the length of the flow. The main tube forms a myriad of distributary tubes that feed the active front and margins of the flow. Tubes form in two ways: by the chilling of a skin around protruded pahoehoe toes, and by the crusting over of the main lava river (fig. 22). The toes form by the breaking open of the crusted front of the flow, permitting the escape of "a new tongue, which emerges as a rounded bulk encased in a newly formed skin" (Jaggar, 1930, p. 2). This skin is plastic at first, stretching as the toe elongates. It is possible to poke a stick into the end of the toe, releasing liquid lava from within, or even to cause the liquid to spurt from the end by jumping on the top of the toe. The crust quickly thickens, forming a rigid shell over the still fluid interior, and repeated outbursts lengthen the toe and develop a small tube.

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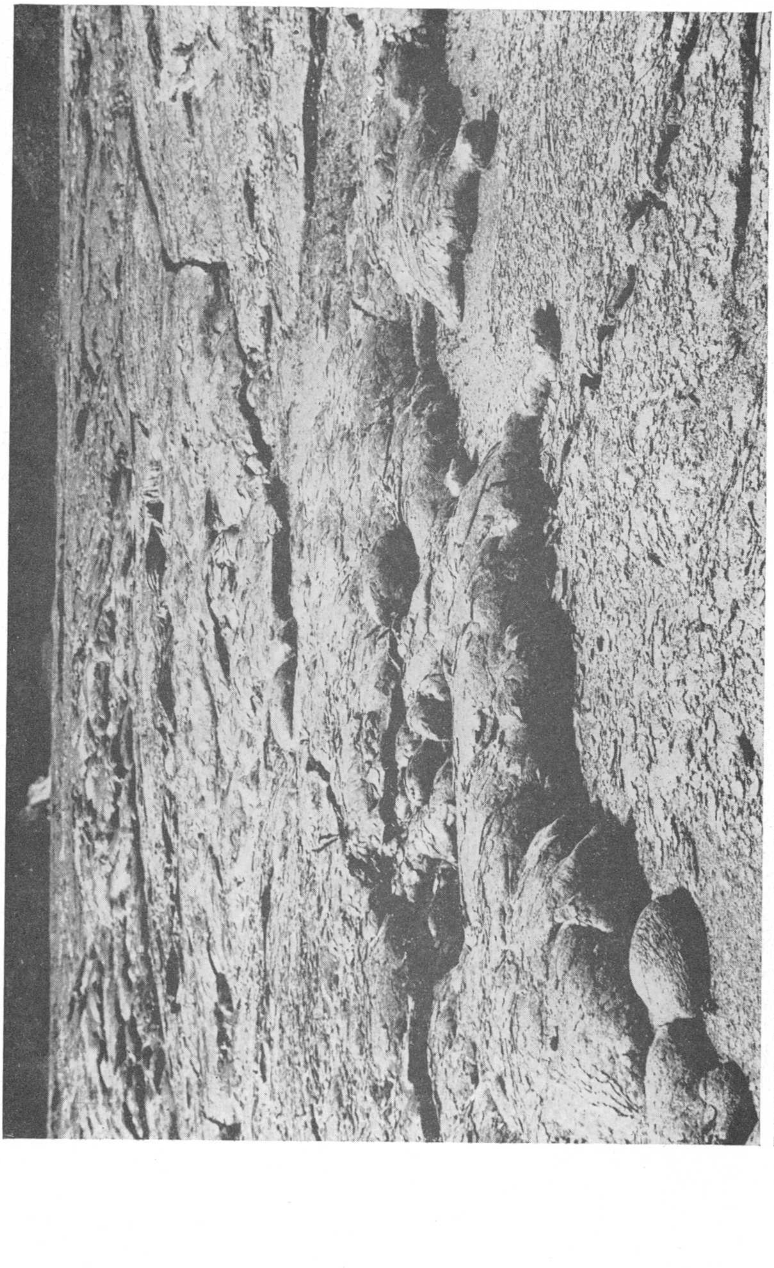

FIGURE 22.—Pahoehoe flow on floor of Kilauea caldera, showing typical pahoehoe toes at the edge of a flow unit averaging about 2 feet thick. Photo by G. A. Macdonald.

The main tube is formed by crusting over of the main lava river. The crust is at first thin and unstable, repeatedly breaking up and floating downstream. Eventually, however, floating crusts form a jam across the river, more crusts pile against the jam, and a permanent roof is established that is gradually extended upstream. This process was witnessed during the 1935 eruption of Mauna Loa by H. T. Stearns (personal communication), and again during the 1942 eruption by Macdonald. Once the crust is established, it thickens downward as the lava congeals against its under side.

At the end of an eruption the tubes may remain filled with congealed lava (fig. 23), or the lava may drain away partly or entirely, leaving an open tunnel. The superficial resemblance of cross sections of small filled lava tubes to pillow lavas (fig. 24) has already been mentioned. Open tubes range in diameter from less than 1 foot to 50 feet, or more in extreme cases. In Hawaii they seldom exceed 20 feet. The larger tubes may extend for miles, but seldom if ever are they unbroken, even during the eruption. Typically each tube has a series of openings in its roof, where a permanent roof either failed to form or was broken. Through these openings, during the eruption, the stream of molten lava can be seen below. Drained tubes commonly exhibit a series of shorelines left on their walls as the level of the lava dropped during closing stages of the eruption. The floor is generally the congealed essentially flat surface of the dwindled lava stream, and commonly this very last lava in the tube congealed as aa. The walls and roof of the tube are commonly veneered with spatter and glazed by gas fusion, and hung with stalactites. Larger tubes in old lava formations often have their floors cluttered by piles of blocks fallen from the roof, both floor and roof being convex upward. The walls of most large lava tubes are composed of several thin flow units. These are formed by repeated overflows of the lava river before it crusts over to form the roof of the tube. Several thin flow units commonly are visible in the roof of the tube also, and are formed by repeated small overflows from the openings in the tube roof.

TUMULI AND PRESSURE RIDGES

Tumuli (fig. 25) (also known as pressure domes or schollendomes) are common on pahoehoe flows that have been ponded in depressions or poured out on very gentle slopes. Tumuli are domical upbowings of the flow surface, typically elliptical in plan, and grading into much elongated structures that are best termed pressure ridges. Tumuli in Hawaii range from 1 or 2 to 10 or 15 feet in height, 10 to 30 feet in width, and in length up to three or four times their width. Extremely large examples, such as those of the Stony Rises near Lake

FIGURE 23.—Section of filled lava tube, Makapuu Head, Oahu. Vertical dimension about 14 feet. Photo by C. K. Wentworth.

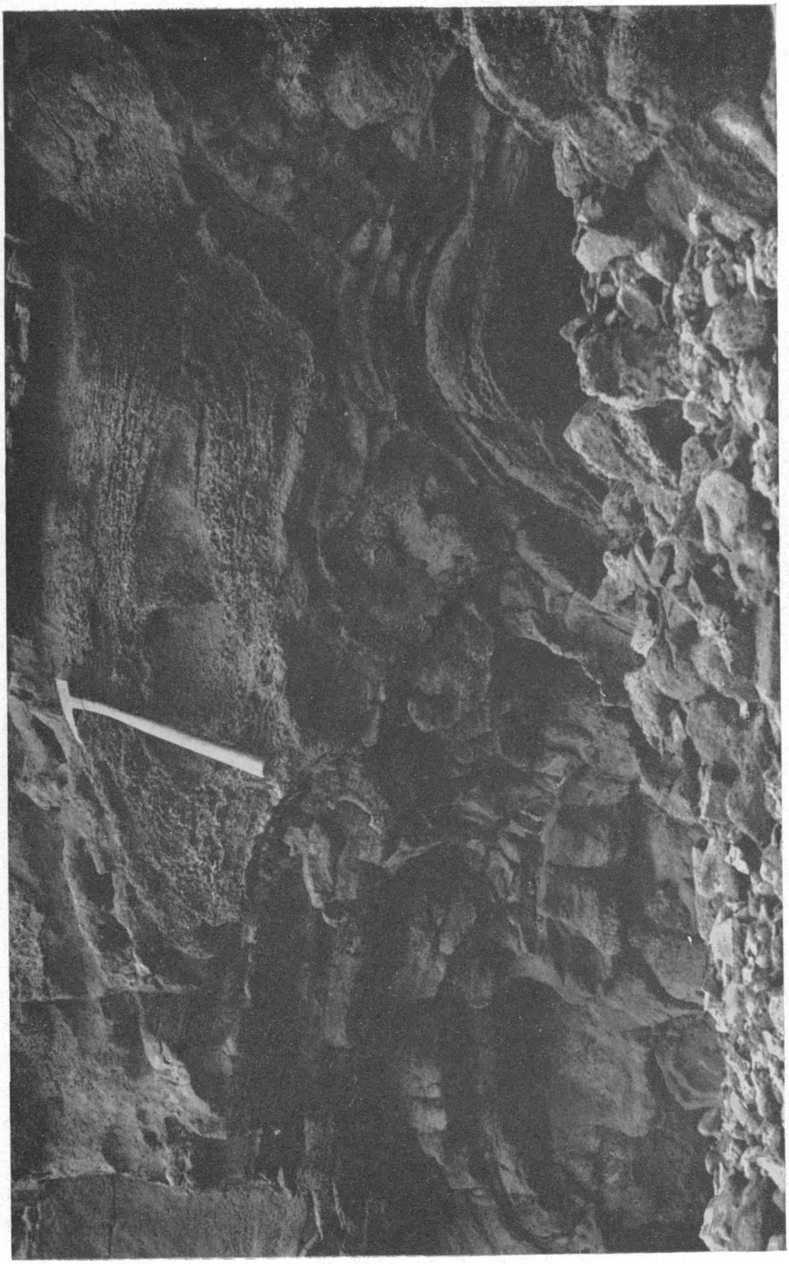

FIGURE 24.—Section of pahoehoe lava flows, Makapuu Head, Oahu. Photo by C. K. Wentworth.

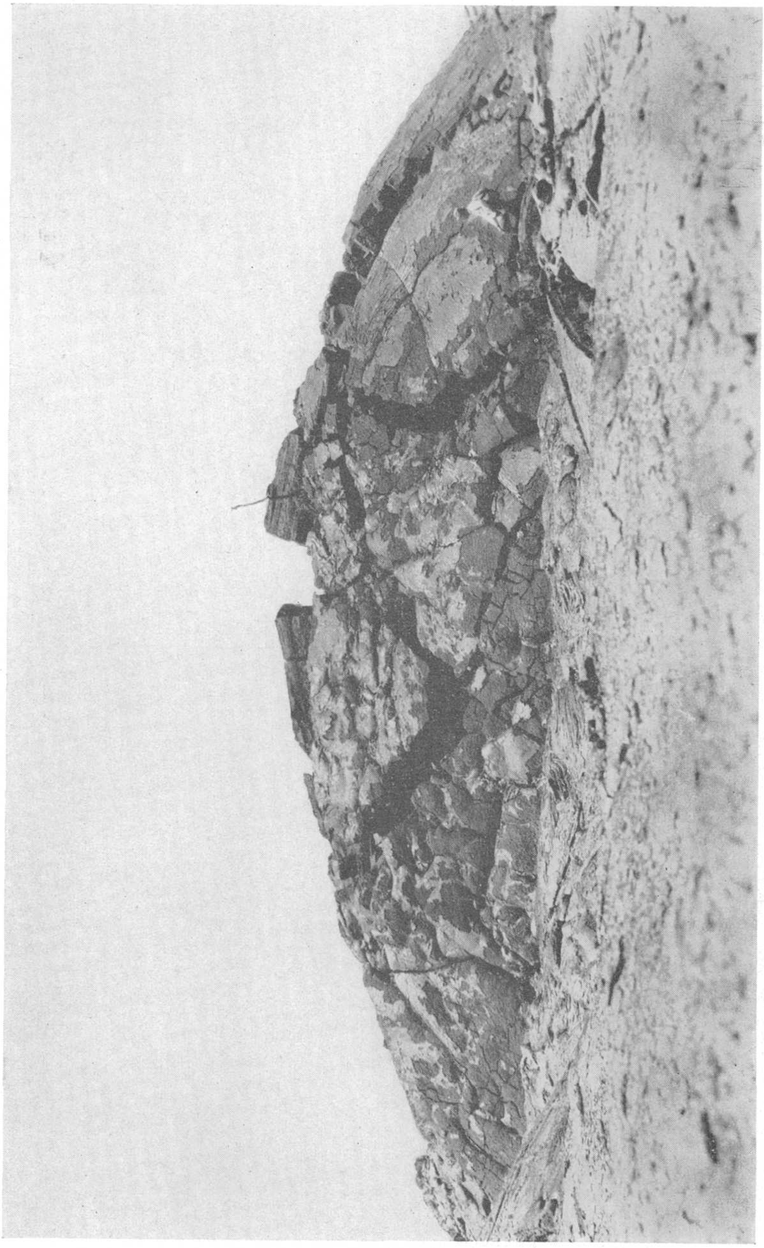

FIGURE 25.—Tumulus near Maunaiki, Kilauea. Height about 15 feet. Photo by C. K. Wentworth.

Corangamite in Western Victoria (Skeets and James, 1937, p. 245–278), are not found in Hawaii. Tumuli are generally cracked open along the summit, the crack paralleling the long axis of the dome. In some instances the crack extends to a depth of several feet, and it is possible to climb down into it to examine the structure of the flow. Other less regular cracks extend down the flanks. On tumuli with a subcircular ground plan the cracks may be disposed radially from the summit. Commonly, a little viscous lava has been squeezed up from the deeper parts of the flow partly filling the cracks and forming driblets on the flanks of the tumulus.

Pressure ridges generally resemble tumuli except in their greater elongation. In Hawaii their height seldom exceeds 15 feet although Schulz has recorded some 30 feet high formed in the caldera of Mauna Loa during the eruption of 1940 (Schulz, 1943, p. 745). Commonly they are fractured to a much greater degree than tumuli, and some examples are elongate heaps of crust blocks, tilted, jumbled, and overturned. Some resemble asymmetrical anticlines, with one gently dipping limb and the other limb steep or even overturned.

Dana (1887, p. 356) and others have explained tumuli as great blisters raised by the pressure of gas in the flow. Careful examination of many tumuli in the field indicates, however, that they are not formed in that way. Tumuli are usually not hollow, like blisters, although in some an open space is left when lava drains out. Some certainly were formed by hydrostatic pressure of the underlying fluid lava lifting the congealed crust after the manner of a laccolith (Daly, 1914, p. 135). Some also may have been formed by differential collapse of the flow crust owing to the draining away of the underlying fluid portion (Skeets and James, 1937). However, many of them, particularly those of highly elongate form, and the great majority of pressure ridges, apparently were formed by the horizontal thrusting and buckling of the flow crust caused by the pressure of fluid lava. Such buckling was actually observed in Mokuaweoweo caldera during the eruption of 1940 (Waesche, 1940, p. 8). The small open space beneath the crust in some tumuli is probably the result of upbuckling of the crust under horizontal compression.

PRESSURE PLATEAUS

Pressure plateaus are broad areas of lava, generally pahoehoe, that have been bodily elevated by the intrusion of new fluid lava into the lower, still uncongealed part of the flow without the addition of any new lava at the surface. They are, therefore, generally formed on thick ponded flows, in which the lower parts may remain fluid for many weeks. The amount of uplift may range from less than a foot to 15 or 20 feet. During the 1940 eruption of Mauna Loa the solidified lava surface in the North Bay of the caldera was raised as a pressure plateau 15 feet above its original position at the southern edge of the bay (nearest the source fountains) and 2 to 3 feet at its northern edge (Schulz, 1943, p. 745–746). The edge of the pressure plateau was not at the caldera walls, rather a narrow moat or a broader area of unelevated lava generally lay between the edge of the plateau and the wall of the caldera. The limit of intrusion, and consequent elevation, was probably determined by the extent of congelation of the interior of the flow. Even where the flow was thick, chilling of the lava against the confining wall would have resulted in congelation of the entire thickness of the lava for a few feet from the wall.

Pressure plateaus are generally associated with pressure ridges, and indeed the spectacular pressure ridges in the 1940 lava of Mauna Loa were probably largely the result of the intrusion of the new lava that caused the pressure plateaus. According to Schulz, each plateau was bordered on all sides by a pressure ridge of small height.

Similar sill-like shallow intrusions into slightly older lavas of the same eruption have been described at Parícutin. There during February and March 1945, the surfaces of the Zapicho flow of late 1943 and the San Juan flow of 1944 were raised and arched as much as 60 feet by subsurface intrusions (Krauskopf and Williams, 1946, p. 406), and during August 1944 the solidified surface of a flow ponded in an old crater was elevated 30 to 40 feet in a similar manner (Bullard, 1947, p. 437).

SLUMP SCARPS

Lava flows ponded in depressions, and those that have flowed down valleys, commonly exhibit along their margins low inward-facing cliffs, formed by subsidence of the general flow surface. These cliffs are known as slump scarps (Finch, 1933a, p. 647–649). Similar "high-lava" marks left by subsidence of the lava stream after flood stage are found around the sides of hills that had been surrounded by lava flows.

The subsidence is probably in small part the result of decrease in volume of the lava owing to cooling and loss of gas. In many of the flows occupying valleys it is largely due to draining away of fluid lava from beneath the congealed crust, as the still fluid lower part of the lava continues down the valley (fig. 26). Even in flows that apparently were confined in craters and other depressions, it seems that some sort of drainage of the underlying liquid portions of the lava must have taken place. Using Daly's estimates of the coefficients of expansion of crystalline and vitreous basalt, Schulz (1943, p. 743) calculated that the decrease in volume owing to cooling of the 1940 lava in the North Bay of Mauna Loa should not have exceeded about 2.45 percent. The volume decrease necessary to produce the observed

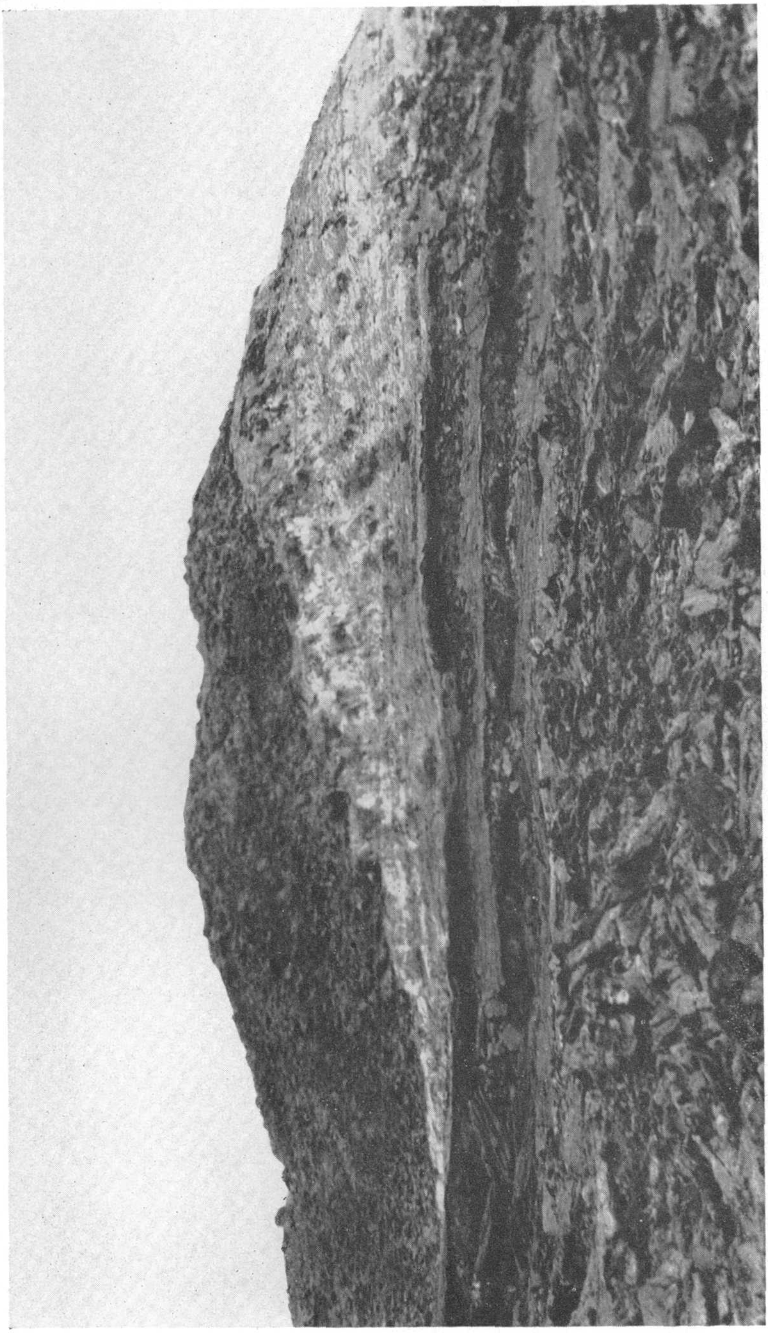

FIGURE 26.—Successive high-lava marks on 50-foot cone east of Pahala on Kilauea slope. Photo by C. K. Wentworth.

slump scarps would have been nearly 18 percent. Allowing for volume decrease as a result of loss of gas, it is unlikely that cooling and gas liberation alone can account for the decrease in volume. Many flows confined in depressions, and even many of those in valleys, do not develop slump scarps. Yet the loss of heat and volatiles by those flows must be of comparable magnitude with the flows that develop slump scarps. It is probable that where prominent slump scarps are present on flows ponded in craters or calderas, there has been some drainage of the fluid lower part of the flow back into the source vents or other fissures.

LAVA BLISTERS

The surfaces of pahoehoe flows commonly exhibit small blisters formed by gas bubbles puffing up the still viscous flow crust. Ballooning crusts frequently have been observed on pahoehoe rivers near the vents, where the lava is losing large volumes of gas. The gas-inflated toes in the gas-rich shelly pahoehoe of the early stages of Mauna Loa eruptions have been described at the end of the section on general features. Blisters are present on all types of pahoehoe, but are most conspicuous on the type with a relatively smooth tachylite crust. They range in diameter from less than an inch to about 3 feet, and in height to about 2 feet. The shell ranges in thickness from about 1 millimeter to 2 centimeters. Blisters up to 10 feet in diameter have been observed forming and bursting with minor explosions on aa flows at Parícutin (Bullard, 1947, p. 438).

Domical eminences as much as 30 feet high and 60 feet across on a pahoehoe flow at Byaduk, Western Victoria, have been interpreted by Skeats and James (1937, p. 273–275) as huge blisters formed by steam generated where the lava overflowed marshy ground. Nothing approaching this size has been observed in Hawaii. The hollowness of the mounds at Byaduk has not been demonstrated, and from the descriptions, it appears not impossible that these structures are actually nearly circular tumuli.

HORNITOS

Hornitos, also known as driblet spires and driblet cones, are small mounds of spatter built at rootless vents on the backs of lava flows. The typical hornito is a rounded, more or less beehive-shaped mound (fig. 27), whereas the typical driblet spire is a thin column or spine. Both may conveniently be included under the general designation of hornitos. Both commonly have an open pipe at the center, although the pipe may be clogged or sealed over by the last ejecta. They are built by the gradual accumulation of clots of lava ejected through an opening in the roof of an underlying lava tube. In Hawaii most of the

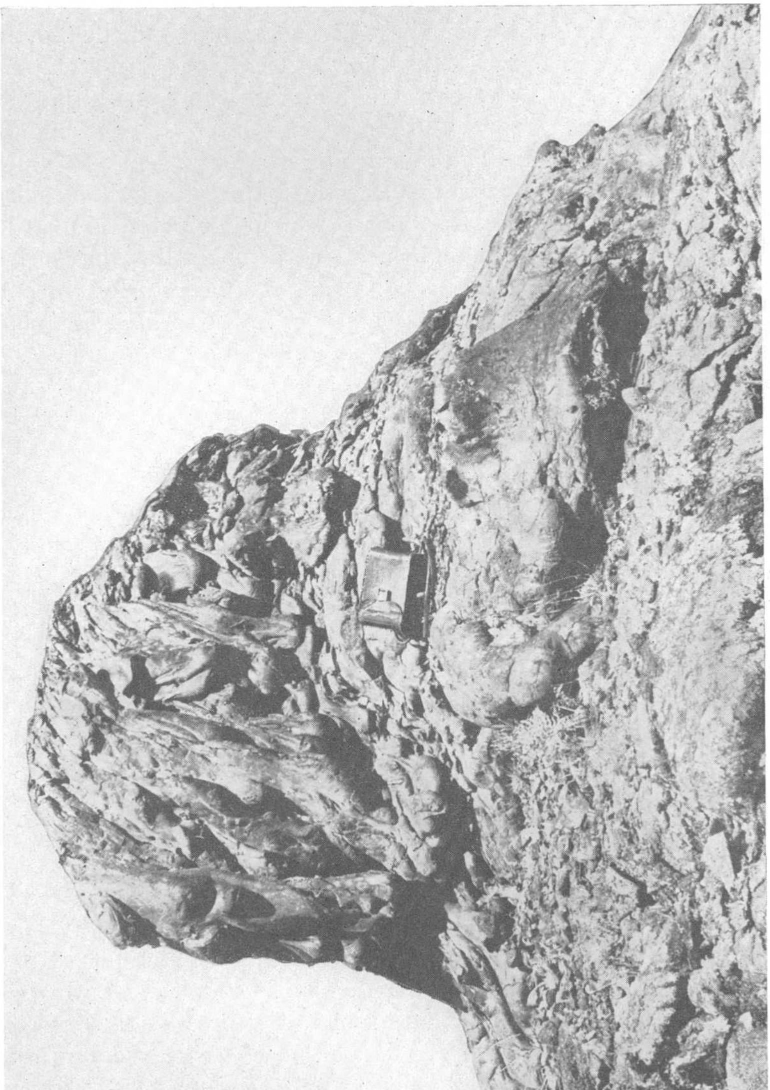

FIGURE 27.—Hornito on 1919 lava flow. Kilauea caldera. Photo by G. A. Macdonald.

ejecta are still partly fluid when they hit the ground, and the mounds are composed of agglutinate. In other parts of the world some are composed of scoria or ash, and are built by secondary (rootless) fumaroles.

In Hawaii, typical hornitos range from less than 2 feet to about 6 feet in height, and up to about 10 feet in diameter. Driblet spires range from less than 1 foot to about 2 feet in diameter, and up to about 12 feet in height, although most of them are less than 6 feet high. Bullard (1947, p. 442) has used the term hornito for cones as much as 50 feet high, apparently built over eruptive fissures, but it seems preferable to use the terms "spatter cone", "volcanello", or "vulcancito" for such structures, reserving *hornito* for the small mounds built at rootless vents.

LAVA STALACTITES AND STALAGMITES

Lava stalactites are two different types. One type forms simply by the dripping of fluid lava from the roof and walls of a lava tube or open lava river where, for any reason, the level of the fluid in the conduit falls, or in tubes or on the walls of spatter cones where spatter is flung against the roof or walls. Such stalactites generally resemble icicles, although they may be much more irregular. They commonly attain lengths of 6 to 12 inches, and rarely as much as 3 feet. Only seldom are they accompanied by stalagmites, and when stalagmites are present they generally are poorly developed.

The second type of lava stalactite is formed by gas-heating of the roof of a lava tube or the inner walls of a cone (Jaggar, 1931, p. 1–3). The intense heat, at temperatures up to about 1,200° C., fuses the exposed surfaces to a vitreous glaze that is sufficiently fluid to trickle, forming stalactites. The latter are typically very slender, attaining lengths as great as 4 feet (Stearns and Clark, 1930, p. 114) with a thickness of only ¼ to ½ inch. Some are fairly regular smooth rods, but many resemble slender elongate bunches of grapes, or contorted worms. Others are icicle shaped. Jaggar has observed them forming on the yellow-hot incandescent walls of tubes and spatter cones, and in grottoes at the wall of lava lake in Halemaumau Crater. While they are still glowing hot, they are sufficiently plastic to sway freely in blasts of gas.

In lava tubes, drip from the stalactites to the floor builds up lava stalagmites. The latter are mounds of agglutinated droplets, from 1 or 2 inches to 1 foot high, and 1 to 4 inches in diameter. Their position directly under the stalactites shows that the drip must have occurred after the lava stream comprising the floor of the tube stopped moving.

SHARK-TOOTH PROJECTIONS

At breaks in pahoehoe crust where one side has pulled away, the viscous lava may be dragged out into pointed projections resembling flattened icicles. They were found by Schulz (1943, p. 743–745) in the 1940 lava of Mauna Loa, on the underside of the remnant shelf that adhered to the caldera wall when the general flow surface slumped away from it. There the still plastic material on the underside of the crust had been pulled into projections as much as 10 inches long, tapering to hairlike points. They were termed "pulled stalactites" by Schulz, but because they were not formed by drip the name appears inappropriate. Similar projections along cracks in the 1823 lava flow of Kilauea were termed "shark teeth-slickensides" by Stearns (1926, p. 343). Those in lavas of Ascension Island (Daly, 1925, p. 21) and the McCartys basalt of New Mexico (Nichols, 1939c, p. 188–194) have been called "shark's-tooth projections," and that name is adopted here. Examples as large as those in the 1940 lava are rare, but small ones are fairly common.

LAVA TREE MOLDS

Pahoehoe lava surrounding the trunk of a tree is chilled against it, preserving a mold of the trunk and sometimes of branches. The tree itself burns, leaving an upright tubular opening in the lava. The mold is often sufficiently perfect to preserve the impression of the checks in the charred wood, and rarely details of the bark. Draining away of the lower portion of the flow may result in a lowering of the surrounding flow surface, leaving the lava that congealed against the tree standing in relief above the flow surface (fig. 28). These projecting hollow columns have also been called lava tree casts (Finch, 1931, p. 1–3) or simply lava trees. The tree molds may have any diameter, up to that of the largest tree trunk. Tree molds reach heights as much as 15 feet above the surrounding lava surface. The shell of lava surrounding the internal tube is generally 4 inches to 1 foot in thickness.

Similar structures have been found in many parts of the world. Those in Craters of the Moon National Monument, Idaho, were first termed by Stearns (1924 p. 370) "lava mortars", and believed to have originated by the accumulation of spatter around minor vents. He later recognized them to be lava tree molds (Stearns, 1928, p. 29–31).

SQUEEZE-UPS

Many flows, both of pahoehoe and aa, exhibit dikelike autointrusions of fluid matter from the lower part of the flow into fractures in the crust. Many of these reach the surface. In pahoehoe flows

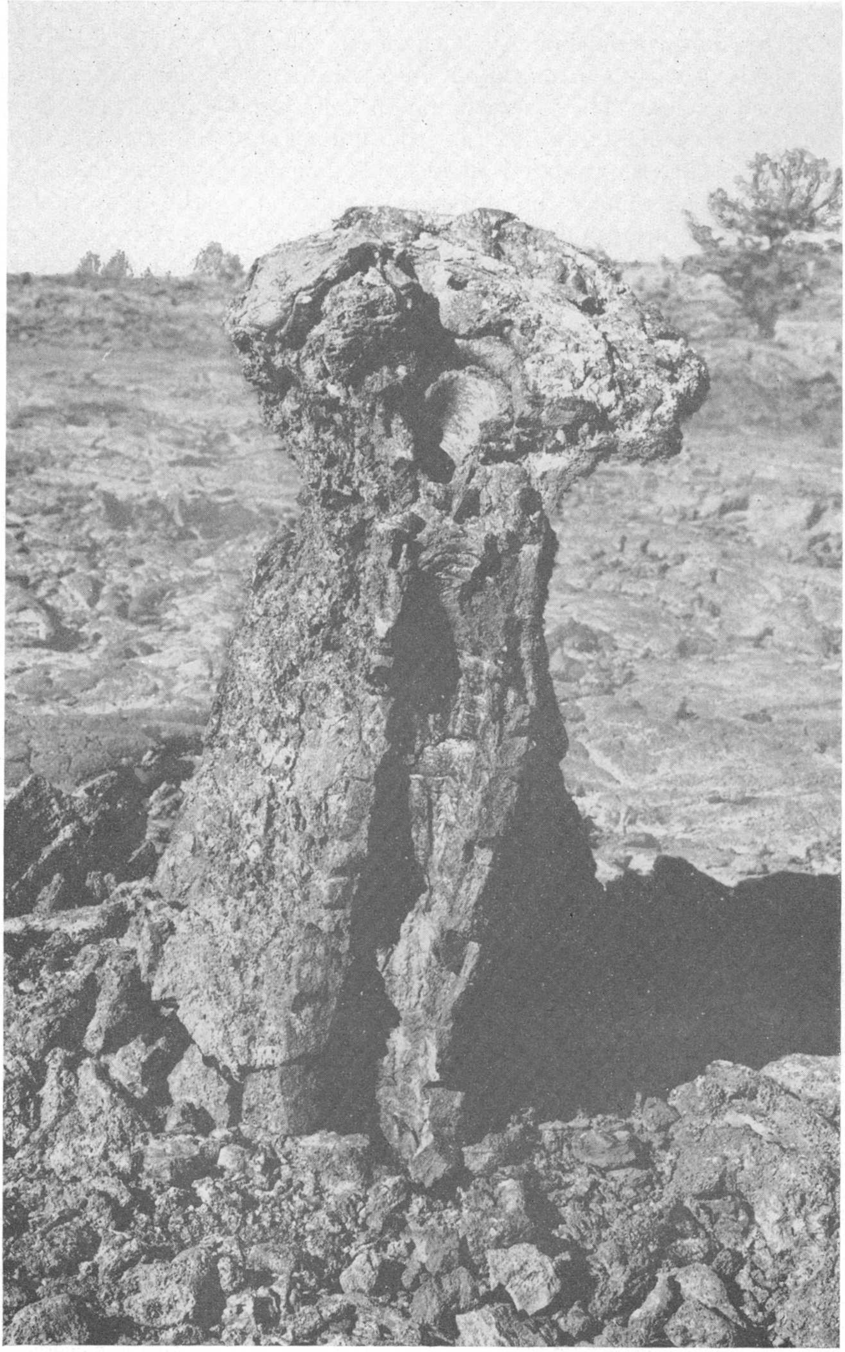

FIGURE 28.—Tree mold, 1823 lava flow of Kilauea volcano. The mold is about 4 feet high. Hawaii National Park photo by D. H. Hubbard.

some reach the surface in moderately fluid condition, and spread out as pahoehoe toes for a few inches or a few feet on the flow surface. These are the "bulbous squeeze-ups" (Nichols, 1939b, p. 421–423). Others, of more viscous nature, rise as wedges into the fissures or project a few inches to a foot or two above the surface (fig. 29). These are Nichols' "linear squeeze-ups" (1939b, p. 423). Many of them are grooved on the sides (see below). They grade into the spines that occur on a few aa flows. Closely similar in origin but on a smaller scale, are the so-called "barnacle stalactites" that are found occasionally on the walls of lava tubes, formed by squeezing of viscous lava through cracks in the tube wall (Jaggar, 1931, p. 3). Also related to the "bulbous squeeze-ups" in origin, but formed by still more fluid lava, are the "lily-blossom" forms that result where very liquid pahoehoe wells up through a hole in the roof of a lava tube, spreads out a few feet, and then partly drains back into the tube (Stearns and Macdonald, 1946, p. 80, pl. 26). This leaves a broad, nearly flat, smooth subcircular disc, with a funnellike depression in the center.

GROOVED LAVA

Wherever moderately to highly viscous but still plastic lava, either aa or pahoehoe, moves past an irregular edge or surface of more rigid lava or other rock, or is rubbed by such rigid rock moving past it, the grooves and striations formed in the plastic lava may become preserved (fig. 30). The striations resemble glacial striations or slickensides on a fault surface, but generally may be distinguished from those by the minutely rough, granular, or spinose character of the surface. Small shark-tooth projections commonly are present. "The grooves vary from mere scratches up to marks an inch deep. They may be straight, or the whole series may be slightly curved" (Nichols, 1938, p. 604).

The grooves may develop on the under side of the crust blocks in slab pahoehoe, where the still plastic under side of the block is pushed across a more rigid jagged edge or upper surface. These grooves are very common on the sides of linear squeeze-ups, on spines that develop on some flows of aa and block lava, and the still more numerous and much larger spines characteristic of viscous domes (tholoids).

AA

GENERAL FEATURES

Aa lava flows are characterized by exceedingly rough, jagged, clinkery surfaces. Much of the surface is covered, to a depth of several feet, with loose fragments of clinker. Not all the jagged spinose surface material is loose clinker, however. As Jaggar (1930, p. 3) has pointed out, many of the jagged boulderlike masses "are

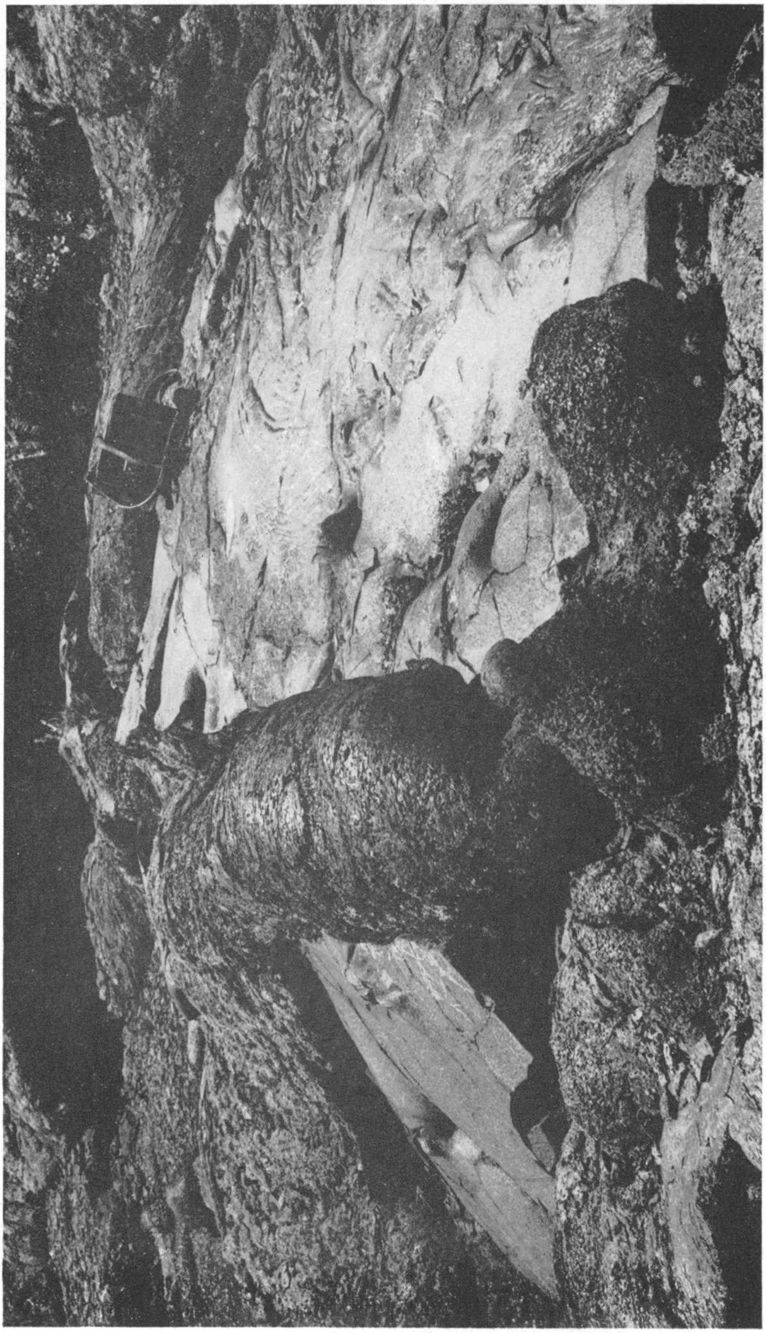

FIGURE 29.—Bulbous squeeze-up, on 1919 lava flow in Kilauea caldera. The squeeze-up is filamented pahoehoe which has come up through cracks in sharkskin pahoehoe. Photo by G. A. Macdonald.

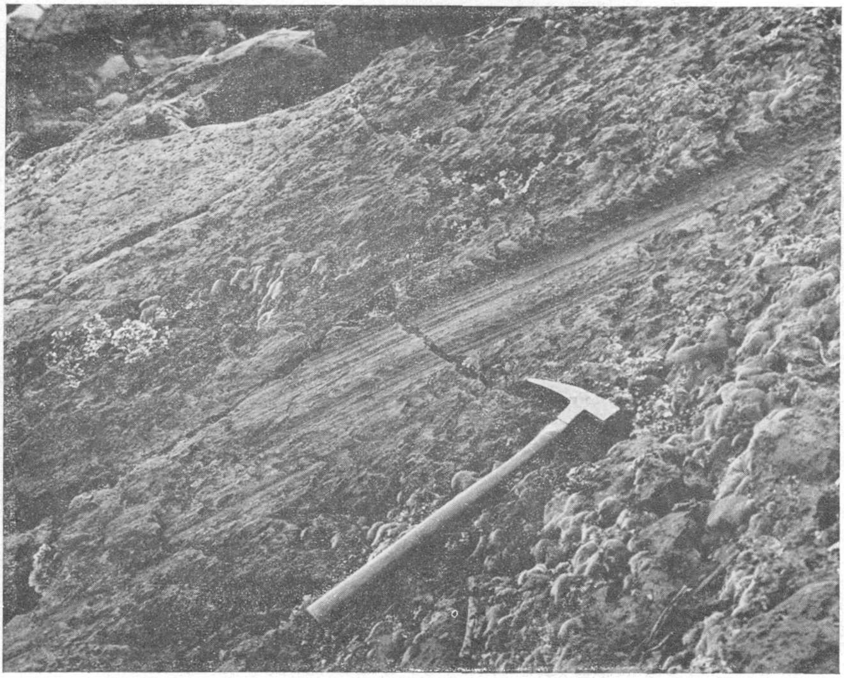

FIGURE 30.—Plastic striations in lava, southwest slope of Mauna Kea. Photo by C. K. Wentworth.

not loose at all, but are sprouts and crags connected with the continuous ledge beneath." The sprouts and loose clinker fragments are almost indescribably rough and jagged, cutting stout boots to ribbons within a few days. The clinker fragments range from a fraction of an inch to several feet in diameter, although most are less than 1 foot. The character of the flow surface and of the clinker fragments is best shown in photographs (figs. 31, 33).

The almost universally clinkery surface of aa flows gives rise to the misapprehension in the minds of many geologists, and even some volcanologists, that aa flows consist of loose clinker throughout. That impression is generally false (Macdonald, 1945c, p. 1179–1180). Certainly hundreds, and probably thousands of aa flows in the Hawaiian Islands have been examined in cross section by the writers, in cliffs and canyon walls, road cuts, well shafts, tunnels, and diamond-drill cores. Almost all have a central massive phase. Rarely, a flow may locally consist of clinker through its entire thickness, but all such flows that have been traced laterally in cliffs or canyon walls have passed into a massive central layer within a few feet. The margins of many recent aa flows appear to be solid banks of clinker, but digging into the bank 1 to 6 feet exposes the massive phase.

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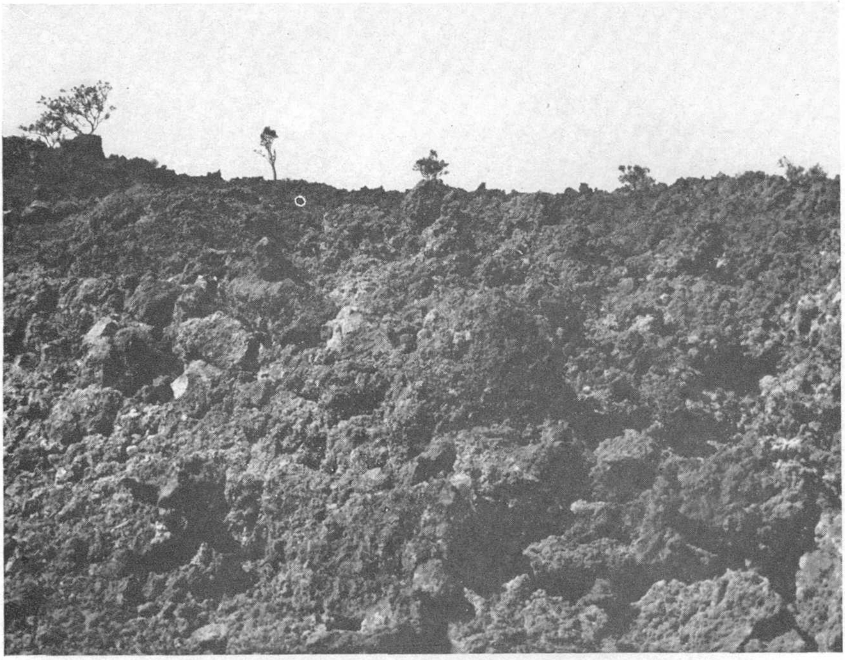

FIGURE 31.—Surface of aa flow, on trail from Kilauea to Puu Ulaula. Photo by C. K. Wentworth.

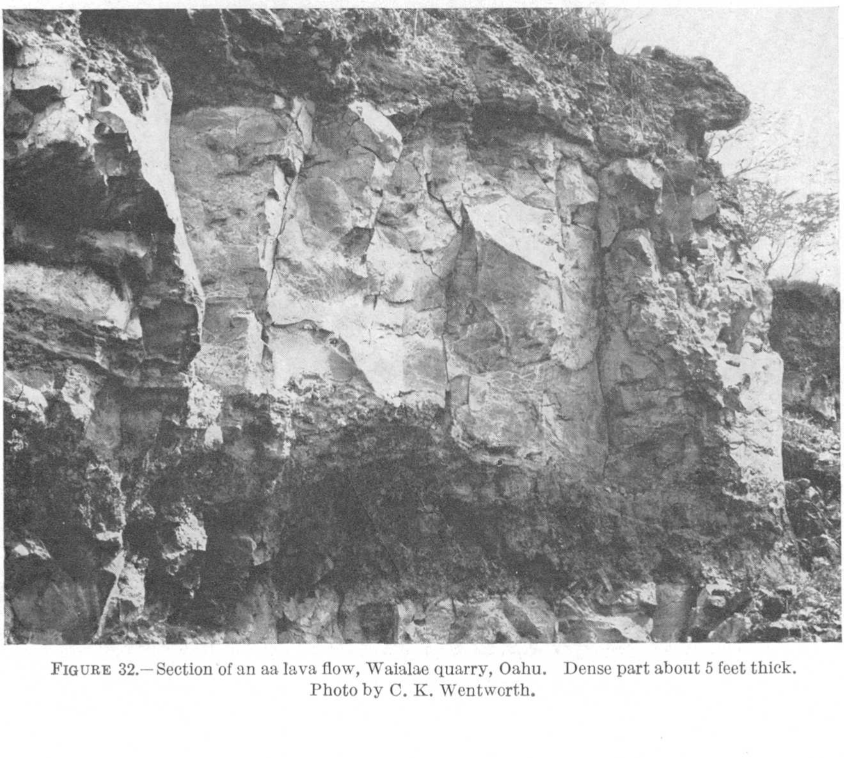

FIGURE 32.—Section of an aa lava flow, Waialae quarry, Oahu. Dense part about 5 feet thick. Photo by C. K. Wentworth.

Typically, the central massive part of the flow is both overlain and underlain by layers of clinker (fig. 32). As pointed out above, the upper surface layer of clinker is essentially continuous throughout the extent of the flow. It ranges in thickness from less than a foot to as much as 8 or 10 feet, being in some degree proportional to the total thickness of the flow. The lower clinker layer is commonly thinner and less continuous than the upper clinker layer. It may be absent over considerable areas. Locally, layers or irregular masses of clinker are found within the massive phase. In 11 carefully measured sections, from 150 to 400 feet thick, on the walls of South Halawa, Moanalua, and Waimalu valleys, on Oahu, the proportion of clinker to total aa ranges from 15 to 45 percent (fig. 3). In the shaft of the skimming well at Paauilo, on the northeastern slope of Mauna Kea on Hawaii, a section 267 feet thick consists entirely of aa. Twenty flow units from 4 to 28 feet thick are exposed, and in the individual flow units the proportion of clinker to the total thickness of the flow unit ranges from 17 to 66 percent, averaging 39 percent. Such measurements demonstrate that, far from composing the entire thickness of an aa flow, clinker generally comprises well under half of the thickness.

The central massive phase of an aa flow is generally not dense. In exceptionally thick flows, especially those which were ponded, the lower part may be quite dense with very few vesicles. However, the upper part of thick flows and all thinner flows are commonly mark-

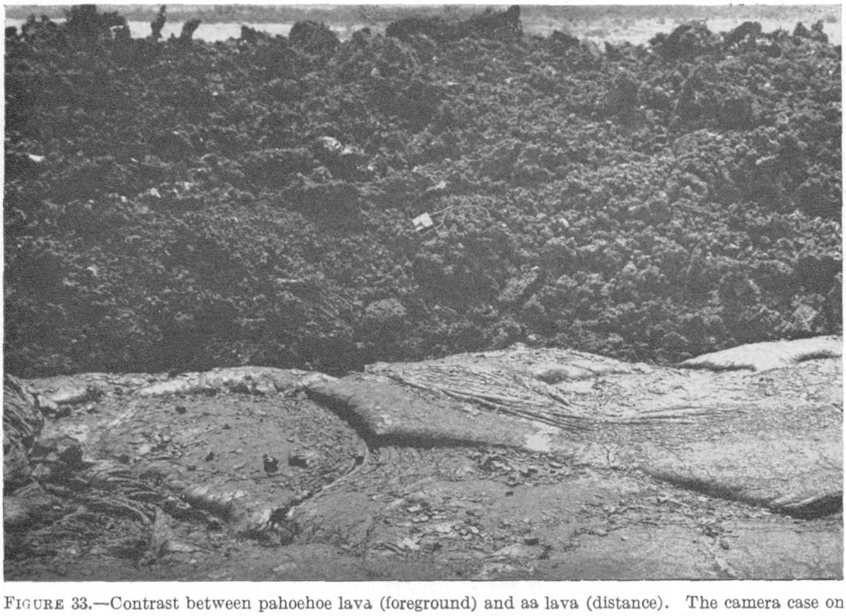

FIGURE 33.—Contrast between pahoehoe lava (foreground) and aa lava (distance). The camera case on the edge of the aa flow is 6 inches across. Photo by G. A. Macdonald.

edly vesicular. The massive phase of aa generally is less vesicular than pahoehoe, but there is so much variation in the vesicularity of both types that there are many exceptions to the rule. Vesicularity of aa may reach as much as 50 percent, but generally it is less than 30 percent. In contrast to the regularity of outline of pahoehoe vesicles, those of aa are typically irregular, and commonly much stretched in the direction of flowage. Their character is shown in figure 14.

An aa lava flow is fed by a main lava river that flows down the mountainside in an open channel. On either side of the main river, and particularly at the advancing toe of the flow, the pasty central layer of the flow pushes outward. Locally and for short distances, the movement may be quite rapid, but generally the most active front portion of the flow advances only a few tens or at most a very few hundreds of feet a day. There are many exceptions, but generally aa flows advance much less rapidly than pahoehoe flows.

The advance of the flow front generally occurs much as follows. The black clinkery front of the flow may appear temporarily as a steep, relatively immobile bank. Its liveness is shown only by moderate fume liberation, the typical "foundry" odor, the incessant grating and cracking of surficial rock resulting from cooling and slight shifting, an occasional boulder tumbling down the flow front, and especially at night by innumerable viciously red eyes glaring out through the clinker from the deeper parts of the flow. During such times, radiant heat often is so low that it is possible to walk directly up to the flow front. Gradually, however, the front steepens and bulges, sometimes imperceptibly but at other times quite noticeably. Eventually the bulging results in instability of the flow front, and a slab of black clinkery rock peels off the front, breaks up, and tumbles to the foot of the bank with a sound like the clinking of breaking crockery. The large block commonly is accompanied and followed by a slide of finer incandescent debris. Where the block separates from the flow front it reveals a glowing hot face of pasty lava in the interior of the flow. It is in this lava paste that the flow movement principally occurs, material in the pasty layer moving toward the front or sides of the flow beneath a relatively much less mobile surface layer of bristling clinker.

The top of the flow generally moves also, but less rapidly, dragged along by the flow of the pasty material beneath. The movement differs from that of pahoehoe principally in the degree of fluidity. On exposure of a large area of the glowing pasty flow interior to the air, radiant heat is suddenly greatly increased, making it decidedly uncomfortable to remain close to the flow margin. The exposed glowing paste is quickly chilled to a black clinkery flow front, which again remains relatively immobile until bulging makes it unstable.

The flow thus tends to advance over a layer of its own debris, formed by collapse of the repeatedly bulging front. The spasms of bulging may occur every few seconds or at intervals of several minutes, depending on the activity of the flow. In rapidly advancing flows it is essentially continuous. Occasionally, particularly in thin flows, the pasty flow layer may glide forward with little or no collapse of the front, chilling to form a spinose clinkery top, but developing no basal clinker layer.

AA CHANNELS

The lava river that feeds an aa flow moves down the mountainside in an open channel. Near the vent, in early stages of the eruption, the river may be as much as 50 feet wide, but in the late stages of the eruption it generally dwindles to 15 feet or even less. Commonly, on gentle gradients, the lava river may repeatedly divide and reunite, like a braided stream. The volume of lava fluctuates considerably, and the channel is at times full to overflowing, whereas at other times the surface of the stream is several feet below the banks. During times of overflow, blocky material and congealing lava along the banks build up walls, or natural levees, that may confine the stream several feet above the level of the surrounding land surface. As the level of liquid lava in the channel drops, spatter from the surface of the stream commonly forms a veneer on the walls, hung with lava stalactites. From the behavior of aa rivers, and the common discrepancies between the estimated depth of the freely flowing lava stream and the observed depth of the empty channel after cessation of the eruption, Jaggar (1919, p. 136) and Finch (1943a, p. 1–2) have concluded that the flowing aa river is actually dual in nature, consisting of an upper rapidly flowing portion and a lower, more viscous, slower-moving portion.

At the end of activity, the upper fluid portion of the lava river and part of the lower less fluid portion drain away, leaving an open channel, 10 to 50 feet wide and 2 to 15 feet deep. The channel is floored with typical spinose aa, part of which may, however, show festoons resembling in both general form and origin those typical of pahoehoe, but with the spinose granulated surface of aa.

SPINES

The surfaces of some aa flows, particularly the thick massive flows of andesite, exhibit monolithic crags and spines of solid lava rising above the general flow surface. These are similar in origin to the squeeze-ups of more fluid flows and to the spines which form in great number on the surface of many viscous domes (tholoids) (Williams, 1932, p. 51–146). They are protrusions of lava squeezed up in viscous condition from the underlying part of the flow, through openings in the solidified upper carapace. They have been found on a jagged aa flow on the floor of the Koolau Gap in the summit depression of Haleakala (East Maui) volcano, and on andesite flows on Mauna Kea. They range in height from 3 or 4 feet, commonly to 15 or 20 feet, and may rarely reach as much as 100 feet (Stearns and Macdonald 1942, p. 161). The monolithic core is generally surrounded by a talus bank of angular debris formed by crumbling of the outer part of the spine on cooling.

ACCRETIONARY LAVA BALLS

Accretionary lava balls are the balls found on the surfaces of many aa flows, formed by the rolling up of viscous lava around some fragment of solidified lava as a center, in much the same way as a snowball rolling down hill gains in diameter through the accretion of additional snow (Macdonald, 1943, p. 253–254). These balls have been called "bombes à roulement", but the name is inappropriate, as they are not at all like true volcanic bombs in origin. Jaggar (1926, p. 27, 45) has referred to them as concretionary balls. They range from approximate spheres to spheroids in which the long axis is nearly twice as long as the short axis. In diameter they range from about 3 inches to 15 feet (fig. 34). The core may be a fragment of clinker from the flow top, a massive block which caved off the bank of the channel, or even a fragment of older lava torn off the walls of the conduit by the rising magma (fig. 35). The surface of the ball may be quite smooth, but is more commonly very irregular.

A closely related form is the ball lava, or spheroidal lava, in the flow of 1823 along the Great Crack on the southwest rift zone of Kilauea volcano (Stone, 1926b, p. 434–440; Stearns, 1926, p. 336–351). The flow, where it is exposed in cross section in the walls of the fissure, contains great numbers of spheroidal lava balls, from 3 inches to 4 feet in diameter, in a matrix of vesicular pahoehoe. Each ball consists of a core made up of one or more angular fragments of lava, enclosed in a shell of the 1823 pahoehoe. The shells range in thickness from 1 inch to 8 or 10 inches. The core fragments may be chilled clots of 1823 lava, hurled into the air by fountaining along the fissure, to fall back into the liquid lava; or fragments of older lava picked up from the walls of the eruptive fissure. Both types became wrapped in a coating of viscous pahoehoe. Similar balls, in smaller number, have been observed in other flows. In origin they resemble the cored bombs (see p. 83).

JOINTS

Both pahoehoe flows and the massive part of aa flows are generally broken by joints into innumerable irregular blocks. Well-developed columnar jointing is rare in Hawaii, but has been observed at a few

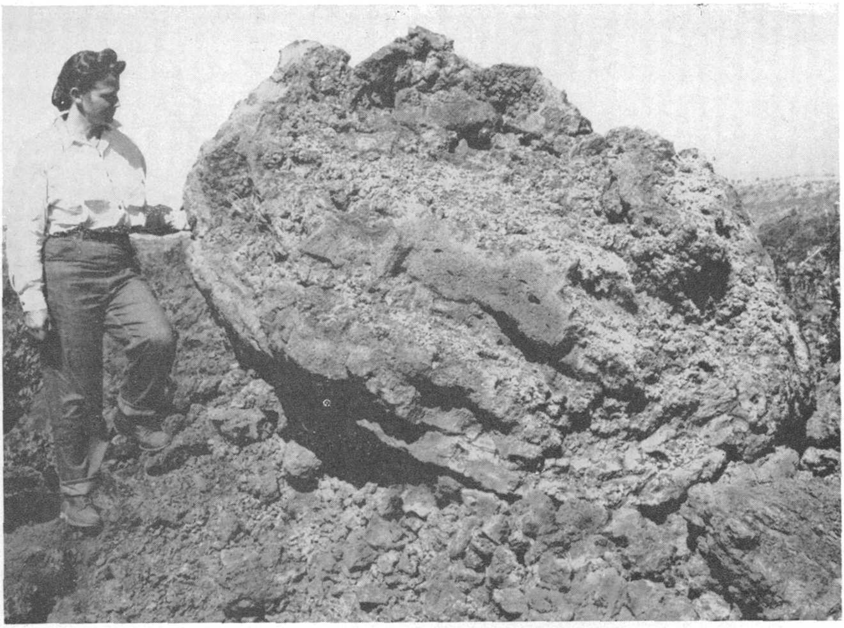

FIGURE 34.—Accretionary lava ball, shown in section, Keamoku lava flow from Mauna Loa, west of Kilauea caldera. Photo by G. A. Macdonald.

FIGURE 35.—Ball lava in the flow of 1823, exposed along the edge of the Great Crack on the southwest rift zone of Kilauea. Each ball contains a nucleus of older lava. Width of foreground about 10 feet. Photo by G. A. Macdonald.

localities, generally where the lava either certainly or possibly overflowed wet ground. The columns, where present, are approximately normal to the cooling surface.

More commonly the joint blocks are highly irregular. Two or more sets of nearly vertical joints are roughly at right angles to a set of nearly horizontal joints, the latter being approximately parallel to the surface of the lava flow. The joint blocks are irregularly cubical or polygonal, and less commonly platy. They range in size from 1 inch or 2 to several feet across. Jointing is generally much more prominent in dense lavas than in highly vesicular lavas.

Thick masses of the ultra basic rocks of the Honolulu volcanic series are commonly broken by cooling joints into great blocks, 10 or more feet across, with somewhat curved faces and roughly similar dimensions in all directions. The major faces of these blocks are often marked by a secondary system of cooling joints with a mesh of a few inches or a foot, indicating that they were still very hot when separation took place along the primary joint surfaces and provided a new focus of cooling (fig. 36).

FIGURE 36.—Secondary cooling joints on joint surfaces of large block of ultrabasic lava of the Nuuanu volcanics. Height about 5 feet. Photo by C. K. Wentworth.

ORIGIN OF AA AND PAHOEHOE

The reasons for the formation of aa and pahoehoe have been discussed at length in another paper (Macdonald, 1953). Only a brief summary of the conclusions is given here.

It is believed that the formation of aa instead of pahoehoe is the result of greater viscosity, resulting from greater loss of dissolved gases in the lava, and greater degree of crystallization. Both loss of gas and crystallization progress as the flow continues downslope, and consequently it is common to find pahoehoe in the portion of the flow near the vents changing into aa farther down the flow. Both loss of gas and crystallization are promoted by stirring, and consequently a flow is likely to change from pahoehoe to aa where it plunges over any steep escarpment. Violent fountaining at the vents also promotes the change of the lava into aa. On the other hand, if the lava erupts quietly, and flows quietly, crusting over and the formation of lava tubes may so retard the loss of gas that the lava remains pahoehoe to great distances from the vents. Loss of gas and crystallization eventually produce a degree of viscosity beyond which continued flowage results in breaking up of the upper portion of the flow into fragments. The spinose character of typical aa fragments results partly from pulling apart of still plastic surfaces, and partly from granularity caused by crystallization. The fragments continue to be modified in shape so long as the flow is moving by slight plastic deformation and by attrition against each other in the moving flow top.

PYROCLASTIC FORMATIONS

GENERAL DEFINITION

The term pyroclastic is an adjective applying to detrital material which has been projected into the air from a volcanic vent (Wentworth and Williams, 1932, p. 24–25). Among volcanic vents we would include rootless vents such as those induced where a lava flow reaches the sea or other body of water (see p. 26). On the other hand the scope of the term pyroclastic is not synonymous with fragmental because parts of aa flows are fragmental without being in any significant sense aerial. Adherence to the criterion of aerial projection is justified because the shapes and textures of fragments and their sorting and distribution are characteristically related to such projection, and are often diagnostic of distinctive volcanic episodes, or relationships.

We learn especially from Hawaiian observations that significant amounts of pyroclastic material are commonly produced in the course of volcanic action that is predominantly nonexplosive. True explosive activity occasionally takes place in Hawaii and in addition pyroclastic material is ejected from nearly all lava flow vents to form crescentic source cones, ramparts of spatter material, or widely disseminated Pele's hair and pumiceous cinders. The amount of material so expelled aerially, despite being a small fraction of the total output, may amount to a million cubic yards in the course of a day or two and be sufficient to produce distinctive topographic effects. Terms for the various types of pyroclastic ejecta will be defined under the suitable headings below.

SIZES AND FORMS OF PYROCLASTIC CONES

Conical pyroclastic accumulations found in Hawaii may be discriminated as tuff cones, cinder cones, and driblet cones. The tuff cones (tufa cones of Dana) occur notably on southeastern Oahu and are typified by Diamond Head at Honolulu (Wentworth, 1926). A few tuff cones occur elsewhere, such as Molokini near Maui and Lehua and Kaula near Kauai (Palmer, 1927, 1930, 1936), and all occur near the coast or offshore from the larger, basaltic islands. Cinder cones occur at all elevations and all distances from the sea and commonly mark rift zones or appear in groups near the summits of major shields such as Mauna Kea, and Hualalai, Kohala, or Haleakala volcanoes (Stearns and Macdonald, 1942, p. 20–23; Wentworth, 1938; Stearns and Macdonald, 1946, p. 162–164).

The tuff cones are the saucer type, the rim is the form of a wide circle, and the central depression often nearly as low as the surrounding country. The in-dipping beds and the out-dipping beds of all the higher rims approach an angle of repose of about 35°. The structure indicates clearly that the form has resulted from preponderant growth at a rather fixed radius by progressive mantle bedding. These tuff cones consist chiefly of palagonitized ash of grain size less than 1 millimeter and in many instances show maximum growth on the southwest side, leeward in respect to the prevalent trade winds. Occurrence of the tuff cones at or near the coast shows the agency of sea water in producing these phreatic explosions and in achieving the fineness of grain which in turn has promoted extensive alteration to palagonite. The same fineness of grain with violence of explosion has been responsible for the wideness of the circular rims and the marked effect of trade wind drift, especially in such cones as Koko Crater on Oahu. All these characteristics, plus the narrowness and symmetry of rims, give strong support to the doctrine of brevity of tuff cone eruptions first voiced by Sereno Bishop in 1901 (Wentworth, 1926, p. 48–54).

The cinder cones, on Mauna Kea, Haleakala volcano and elsewhere, are higher than the tuff cones in relation to the diameter of the rim, and the bottom of the central bowl is usually higher above the external base. It appears that cones of this type were produced by explosive action having less tendency to spread and thus producing a smaller rim circle. These cones show much less effect of trade wind drift, though such is not entirely lacking. This may be due to the coarseness of the material, probable lesser height of explosion, and also that many of these cones in the summit areas lie at altitudes where the trade wind is weak or infrequent. Tantalus cone on Oahu, unlike Diamond Head and others of the Honolulu ultrabasic series, consists of cinders and ball agglomerate and is a fairly typical cinder cone. This is due to the absence of phreatic explosion, probably because of its inland position. The cinder cones give the impression of having steeper slopes, perhaps as much owing to their more commonly reaching angles of repose as to slightly higher inherent angles of repose of the coarser materials. Finally it should be noted that at higher elevations, where chemical weathering is less active and where the loose, uncemented pyroclastic material is resistant to physical weathering, the summit cinder cones are so porous as to be very little subject to erosion. Aside from slight displacement of cinder slopes by glacial ice and slow creep due to snow and frost, producing types of rock stripes or polygonboden, the forms of these cones have suffered very little change.

Cinder-and-spatter cones associated with lava flows are common along the rift zones of Mauna Loa and some other shields. These cones consist of ill-sorted material ranging from cinders to bombs, and including spatter and driblet material reconstructed while still hot and plastic. Because of the eccentricities of eruption at a given vent and because of the cementing of larger masses of driblet, neither the expulsion nor the accumulation of the ejecta tends in these cones to such symmetry as is shown in true cinder or tuff cones. The cinder-and-spatter cones are commonly breached on the downslope side and show other irregularities. Because of the cementing of part of the material, the walls may not collapse but may preserve the configuration of the upper part of the vent (Wentworth, 1938, p. 25–28).

Cones of cinder and ash formed along the coast by contact of lava flows with the sea are common along the coast of southern Hawaii (Wentworth, 1938, p. 102–104). With few exceptions, such littoral cones are now partly cut away by the sea, so that only part of the form can be seen. They appear to be piles of steeply dipping beds of ash or cinders, and may not have been built symmetrically around a fixed vent. Commonly a heap of cinder accumulated on each side of the principal lava stream where it entered the sea, resulting in twin cones.

ASH BEDS

The most extensive pyroclastic formation in Hawaii is the Pahala ash which shows several different phases, with maximum thicknesses of more than 50 feet reaching 10 feet over at least two or three hundred square miles. Except for the red tuff lenses of the Koolau volcanic series on Oahu, this is the chief ash formation not closely continuous with known ash or cinder cones. The bedded deposits of tuff comprising the Pahala ash and Ninole volcanic series have been described elsewhere (Stearns and Clark, 1930, p. 61–68; Wentworth, 1938, p. 37–86; Stearns and Macdonald, 1946, p. 71–76). The distribution and form of such deposits is a product of their mantle bedding from the air and there is an important contrast between such distribution and that of lava flows that must move downslope continuously from the source. Tuff formations may result from single eruptions, or they may in some places be accumulated from many eruptions whose products elsewhere may be interbedded throughout a great aggregate thickness of lava flows. In the wetter sections of the island of Hawaii, the Pahala ash is banded and includes many thin layers of recognizable tuff interbedded with equally thin layers of soil which because of their similar wide extent can hardly be other than weathered ash or tuff (Wentworth, 1938, p. 55–56).

Many if not all the lava-flow formations of Hawaii locally have thin lenses of ash or tuff produced by subordinate explosive phases of some eruptions. Those in the Koolau volcanic series of eastern Oahu range up to several feet thick and may extend laterally for one or two thousand feet. They contain some accidental detritus but consist mostly of primary, palagonitized, fine-grained glass fragments. Such lenses are much more abundant in some areas than others. Relatively small masses of coarser and more steeply bedded agglomerate are found in some of the lava formations, on Oahu particularly in the Waianae volcanic series (Stearns and Vaksvik, 1935, p. 79–86).

Coarse "black sand" or volcanic-cinder beds extend over several square miles in the Honolulu area lying east of Punchbowl. The deposits were derived from the Tantalus and Sugar Loaf eruptions and the mantle bedding reaches a thickness more than 10 feet on parts of the low ground due south of Punchbowl and more than 2 miles to leeward of the vents. Other smaller black sand formations are found elsewhere.

STRUCTURE AND TEXTURE OF MATERIALS

DYNAMICS OF DISTRIBUTION

In respect to the origin of their size, composition, and their stratification, pyroclastic materials are sedimentary rocks. Their distributions in given thicknesses and sizes are primarily fixed by a very definite, if not easily definable, event or a series of events. In any single explosion, the fall and dispersal of the fragments of various sizes through quiet or drifting air gives rise to a symmetrical and somewhat systematic pile of material. The sizes of particles influence both the height of trajectory and the rates and paths of fall through the air.

If the slope on which the ash has fallen is steep, fragments may roll, giving rise to change in shape of particle, to growth by accretion, and to sorting of particles by size. Secondary transportation by water or wind is not considered here, but gravity effects on a slope built to the angle of repose must be considered as a necessary part of the original pyroclastic event. No more than these brief suggestions can be offered.

MANTLE BEDDING

Because of distribution from the air with little or no influence by topography, the initial deposition of pyroclastic particles on a land or under-water surface produces a continuous mantle. According to the form of explosion, deposition at one point or in one zone may be maximum, but the amount does not change abruptly, the maximum position being like the mode of a frequency-distribution graph. Away from the mode the thickness and the coarseness of particles in a given layer may change slowly with distance, but there is a continuity and sequence of layers in the section that is only equalled in marine deposits (fig. 37).

On a nearly level surface, the continued accumulation of ash or cinders may build the maximum pile or rim so that the slopes reach the angle of rest for the material. Such a condition may be produced also on original steep slopes or at the edge of a cliff. Because of differences in rate of accumulation, or irregularities in the surface on

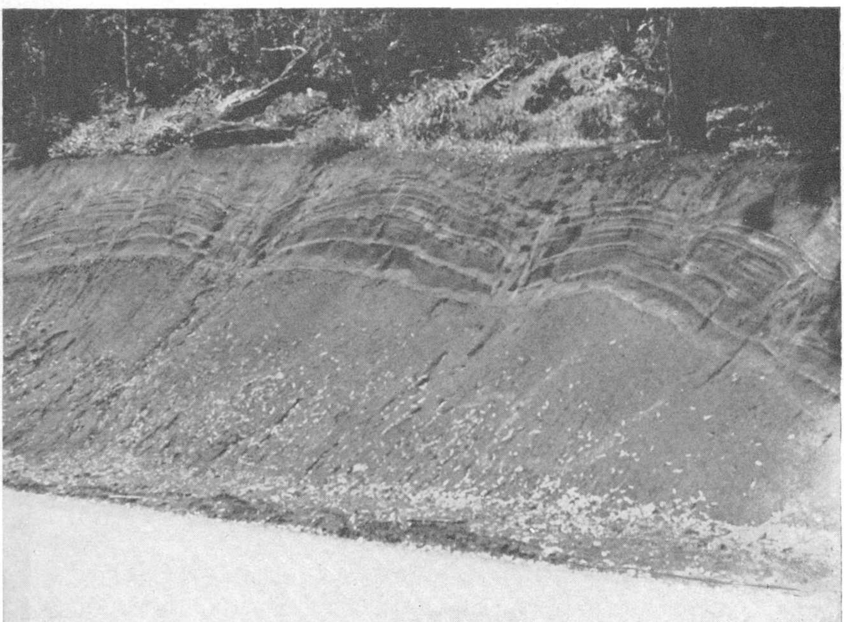

FIGURE 37.—Mantle bedding in volcanic cinders, Tantalus Road, Oahu. Photo by C. K. Wentworth.

which pyroclastics are deposited, monoclines, synclines, or anticlines may be formed that are occasionally misinterpreted as due to deformation. Rapidly accumulated pyroclastics may suffer contemporaneous slumping and form small normal faults or other distortions. Channels may be promptly eroded during rain showers that often accompany such eruptions. Thus, during continuous deposition small unconformities may be produced which, though valid, are of very limited significance, both in time and space.

Compared with most sediments, successive layers in pyroclastics are commonly less sharply set off from those adjacent because of the overlapping of each sort of material by those coming before and after. Thus from phase to phase there is a gradual transition in both coarseness, shape, and composition that produces a distinct lamination but often does not form clearly marked strata. In tuffs, the laminations are often accentuated by alteration or deposition of cementing materials deposited in layers of favorable texture or permeability.

ANGLES OF REPOSE

Subaerial angles of repose of beds in tuff cones most commonly range up to about 31°, depending on shapes and sizes of fragments, moisture content, and other factors. The angle of repose in cinders

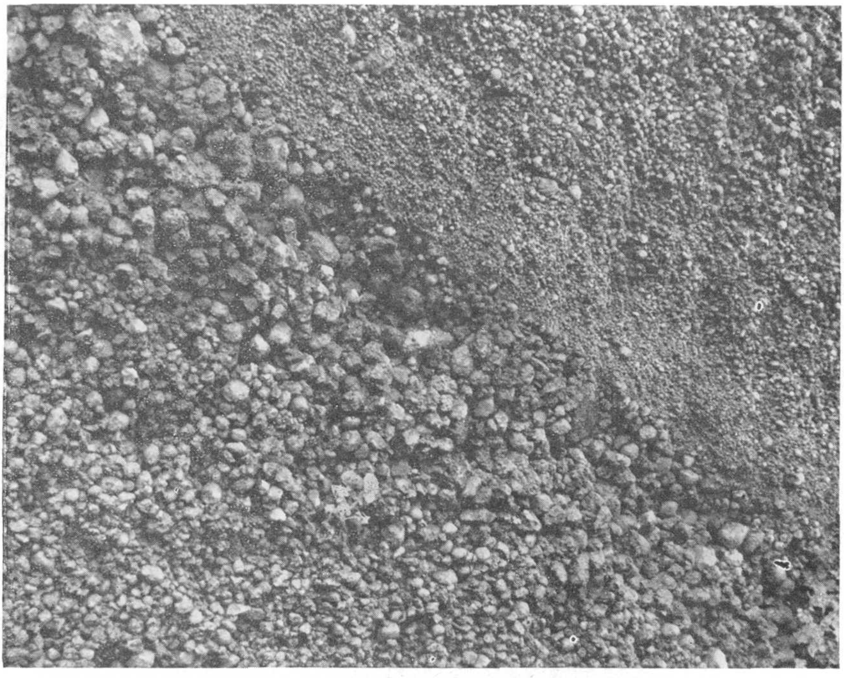

FIGURE 38.—Section of black cinders showing "reversed coarseness," Tantalus, Oahu. These lapilli range from about 2 to 16 millimeters. Photo by C. K. Wentworth.

reaches 33° or 34° maximum. True angles of repose due to gravity commonly grade smoothly into lower angles of slope determined by effects of moisture, frost, wind, and plant growth. In some cinder beds at the angle of repose the fragments are finer at the base and grade upward to coarser material at the top, giving way again to the finer material of the base of another such layer (fig. 38). This is the reverse of what might result from winnowing of heterogeneous products of a single explosion. It is possible that the mechanics of explosion produces more finely comminuted fragments at the beginning of a spasm than toward the end. It has also been suggested that this effect may be due to progressive accumulation by rolling and sliding, on the premise that coarse material will roll on finer, but not the reverse.

TYPES OF MATERIAL AND FRAGMENTS

DRIBLET

Driblet is a term applied to fragments larger than lapilli and showing forms assumed while plastic at the time of detachment from the magma or when landing after flight (Wentworth and Williams, 1932, p. 46). The term spatter is essentially synonymous (Stearns and Macdonald, 1946, p. 17). Deposits are not uncommon in which the components lie pancaked, sagging over one another while still showing their discrete character. A considerable part of the Mauumae cone inland from Kaimuki, Oahu, consists of driblet beds, as shown both in outcrops and also in the tunnel recently driven through its flank. The component cakes range in size from 2 to 10 inches across and are molded over one another to form a complexly interlocked although still quite porous mass (fig. 10). The individual masses are somewhat vesicular but may be fairly dense between the vesicles.

Occasionally small masses of flow lava are interbedded with the detrital material of such accumulations, often at steep angles, and these may be derived from overflow, or may be built from recombined driblet that is still liquid. Driblet is capable of building up to very steep slopes, vertical or slightly overhanging in places, and small driblet cones or hornitos may be formed around a persistent vent. These are commonly well bonded through being kept near melting temperature and the surfaces of the vent tubes are often strikingly glazed by remelting.

AGGLOMERATE

The term agglomerate has been applied in Hawaii to poorly sorted and somewhat indurated pyroclastic material coarser than the palagonitic tuff. In the Honolulu volcanic series of Oahu, the chief agglomerate is that near the Sugar Loaf and Tantalus vents. Some of this material contains cored bombs (Brady and Webb, 1939) several inches in diameter, probably formed by growth within the vent.

CINDERS

This term is applied to glassy, vesicular ejecta coarser than sand sizes and ranging up to an inch or more in diameter. Such material is light in weight and the particles show glazed, pulled, or freshly broken surfaces that are often iridescent when fresh. Some cinders are extremely light, ranging to reticulite (see below) but the more common texture is pumiceous, with irregular, complete vesicles. More rarely the lapilli may be dense glass having but few vesicles. The cinder formations in place are commonly very porous. Some representative porosities are given below.

Specific gravity and porosity of cinders from island of Hawaii

Specimen no.	Specific gravity			Porosity			Description
	Gross	Of lapilli	Of powder	Gross (percent)	Aggregate (percent)	Of lapilli (percent)	
544a	0.287	0.467	2.562	89	39	82	Pumiceous cinders erupted from Halemaumau, July 1929.
626	.548	1.00	2.58	79	45	61	Cinder beds, near Kalapana, island of Hawaii.
623	1.29	2.07	2.99	57	38	31	Ash, from cone near Kalapana, island of Hawaii.
744	.306	.919	2.435	87.5	67	63	Basaltic cinders, Puu Waawaa, island of Hawaii.
813	1.533		2.84	46			Black ash sand, Punaluu, island of Hawaii.

Specific gravity and porosity of black ash from island of Oahu

Specimen no.	Specific gravity		Porosity (total percent)
	Gross	Of grains	
Diamond Head:			
50	1.30	2.44	0.470
85	1.08	2.37	.544
161	1.08	2.57	.581
Punchbowl: 515 B	.99	2.39	.586
	1.00	2.40	.585
	1.00	2.47	.597
Tantalus: 535	.82	2.25	.637
Round Top: 559	.83	2 41	.655
Average	1.02	2.41	.577

The cinders of the 1929 eruption of Kilauea volcano (544a) thrown and wafted from the 1,000-foot pit of Halemaumau, were very light, probably because of selective winnowing. The units are rounded, mostly 4 to 12 millimeters in diameter, with a glassy, dark-brown, iridescent skin. The cinders of Tantalus, Oahu, are closer to the dense, vitreous end of the series. Many particles are broken sections of pulled masses. From most descriptions it appears that some very light pumiceous cinders and reticulite are generally produced at the sources of lava flows (Stearns and Clark, 1930, p. 112–113). On the contrary, the lapilli of littoral cones are usually a more dense glass with a few larger vesicles; because the lava of such flows has lost much of its magmatic gas, the explosions are due to external action of steam (Macdonald, 1949a, p. 72).

No sharp line can be drawn between volcanic cinders and volcanic sand, though intermediate material is more likely to be designated cinders if the grains are vesicular and attenuate, and sand if they are equidimensional and dense. The Tantalus-Sugar Loaf pyroclastics consist mainly of material coarse enough not to have been conspicuously palagonitized, but they include both sand and cinders. Material that is mostly ½ to 4 millimeters in diameter and fairly dense is commonly called "black sand"; parts that are coarser and more vesicular are called cinders. If still coarser, usually partly lithic, and not vesicular, the aggregate is more commonly called agglomerate. In practical excavation and construction usage in Hawaii, volcanic detritus coarser than black sand has often been called "gravel".

VOLCANIC ASH (BLACK ASH, BLACK SAND)

Despite the objection that is sometimes voiced in regard to the term "ash", no better one has been proposed. In a descriptive sense there is also much justification for the occasional use of terms sand, dust, and grit, in reference to particular pyroclastic beds. Juvenile pyroclastic detritus of grain sizes from 4 millimeters down to dust occurs in several different units of the Honolulu volcanic series in southeastern Oahu, and as parts of cinder cones, and littoral cone formations on Hawaii and other islands of the group. Accumulations consisting chiefly or wholly of sand or dust grains derived by explosion from earlier rocks, and hence accessory, are shown in some variety in the area surrounding the Kilauea vent, and to a limited extent elsewhere.

Occasional layers of juvenile black ash may be found in some of the cones formed chiefly of palagonitic tuff, though such nonpalagonitized layers more commonly consist of cinders. They apparently result from some condition of lesser moisture or heat that did not favor the alteration to palagonite. In such places, most of the black ash is slightly coarser or more uniform in grain than other formations that were altered to palagonite on the grain surfaces. The two best examples of black ash on Oahu are the Diamond Head ash of the Black Point area and the black ash of the Punchbowl area which is a fine-

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grained phase of the Tantalus-Sugar Loaf basalt. The characteristics of the Diamond Head ash have been set forth by various observers and were analysed in detail in substantiating the origin of this formation by explosion of magmatic material, rather than by marine abrasion of volcanic rocks as had been suggested (Hitchcock, 1909, p. 35–36; Wentworth, 1926, p. 99–100, 1937, p. 91–103; Stearns and Vaksvik, 1935, p. 138, 142).

Such juvenile ash consists chiefly of more or less vesicular glass with many of the grains showing pulled, twisted, or droplet forms and including crystals of olivine, magnetite, and occasional other minerals both within the glass and free. Nearly everywhere such ash beds are marked by layers and joint or plant-stem fillings of calcium carbonate. Such calcification may be aided by leaching from accidental calcareous grains or fragments deposited at the time of the explosion and derived from underlying reef limestone. However, it is also common where no such source of calcium carbonate is evident, and it is logically presumed to have been provided through weathering of the ash itself.

Where the ash beds or similar cinder beds are thick and even only slightly cemented or interlocked, they often stand in vertical exposures and in such places extraordinarily deep and narrow rill clefts may be cut, even to vertical depths of 50 or more feet with a width at the top less than 2 feet. These are especially characteristic of the saddle areas on the uphill sides of small ash and cinder cones on the flanks of Mauna Kea, and in the head of Pauoa Valley, Honolulu.

Among the conspicuous black sand deposits of littoral origin are those near the east cape of Hawaii, and at Kalapana and Punaluu on the southern coast of Hawaii, where they give rise to well-known black sand beaches. The vitric grains of these littoral cones are fairly dense glass and become abraded black beach sand grains, contrasting strikingly with the gray tone of the equally abraded but larger lithic pebbles of basalt associated with them. Puu Hou (New Hill), a littoral cone formed where the Kahuku lava flow reached the coast of Hawaii west of South Point in 1868, carries in its Hawaiian name the equivalent of the similar, well-known Monte Nuovo near Naples.

Some pyroclastic beds in the Kilauea caldera area are composed of wholly essential material, such as the reticulite beds, or the mantles of pumiceous lapilli like that thrown out in 1929. The material of others is totally accessory, gray or lavender dust, or multicolored grit and lapilli, such as the deposits of 1790 and those of earlier explosions (Powers, 1948). Various intermediate sorts occur, especially olive-green sandy layers (Wentworth, 1938, Spec. 552a, p. 150).

TUFF

The principal application of the term tuff in Hawaii is to the brown, tan, or mottled and lavender tuffs of the southeast Oahu variety that are generally palagonitized, although to a limited extent the term may be required in Hawaii for certain indurated beds of cinders or other pyroclastics that are not palagonitic. These rocks were called tufa by Dana, and considered by him as having been deposited as a mud (Dana, 1890, p. 292). More extensive study fails to reveal structures in the rock indicating movement as a mud, so all recent workers have recognized the aerial placement of the material as discrete grains, even though moisture and heat probably aided the alteration to palagonite.

The palagonite tuff is a compact rock of chalklike texture and variable grain size. Fragments of basalt, essential or accessory, are commonly found in it, but the bulk of the rock consists of dust or coarser grains, or aggregates of grains, of basaltic glass, of which the outer portion has been altered to palagonite. Extremely little, if any, fresh glass is exposed in the fracture surface of the tuff. In thin section, the interiors of nearly all grains and a large fraction of the whole appear as clear, fresh glass with only narrow rims of palagonite.

The tuff breaks into irregular blocks of various sizes with little tendency to form slabs parallel to the lamination. The tuffs of Hawaii generally show more variation from bed to bed, are more subject to natural separation into small blocks, and do not show the massive, nearly unbedded appearance characteristic of occurrences of palagonite tuff in some other parts of the world, such as Iwo Jima.

The dominant structure of palagonite tuff of Hawaii is mantle bedding, identical with that shown in the black cinders and black ash. Some calcareous cementation and joint filling, including some well-banded travertine zones, is general, but the induration of the mass is principally achieved by the formation of the palagonite (fig. 39). Occasional beds have the firmness of a medium brick but most are more friable than brick and do not permit dressing of well-shaped hand specimens. Hawaii tuff is generally not now used in construction of any sort.

Owing to the wide range of grade sizes, the interlocking of the shards and irregular pellets of glass, and the formation of palagonite, the tuff is a comparatively impervious rock. In the Honolulu artesian area the tuff is part of the cap rock and is never an aquifer. In the Pahala region of Hawaii, tuff beds intercalated with lava flows serve as water perching layers (Meinzer, 1930), and successful water tunnels have been driven on their upper surfaces. Beds of red tuff in the Koolau volcanic series of the Honolulu area perch water in the same way, but in areas too small to attract exploitation.

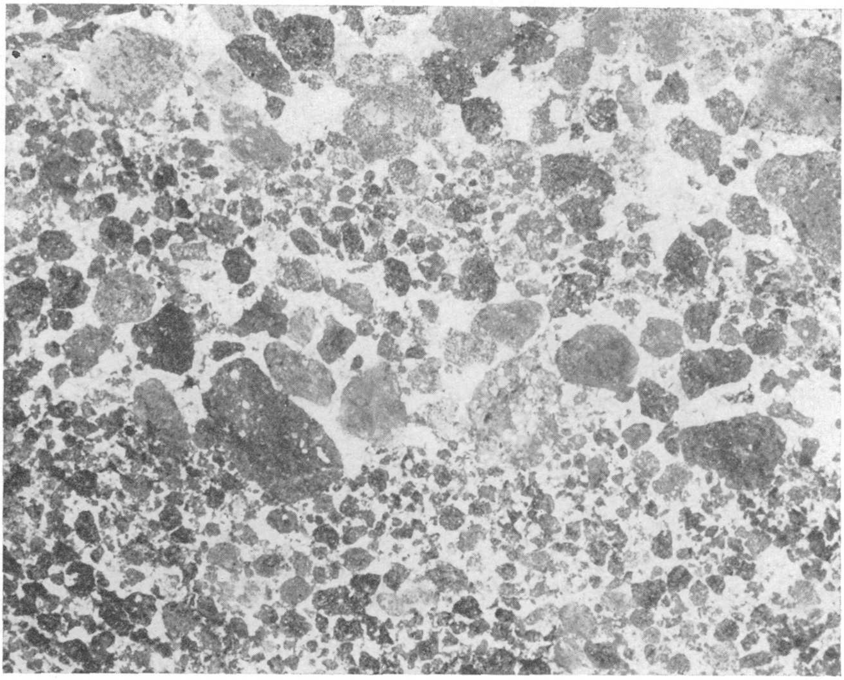

FIGURE 39.—Megascopic texture of palagonite tuff, Salt Lake Crater, Oahu (×2). Photo by C. K. Wentworth.

RETICULITE

Dana (1890, p. 163–166) described this remarkable material as "thread-lace scoria." The name reticulite was proposed by Wentworth and Williams (1932) to avoid certain objections to the use of the word scoria in Dana's term. Well-developed reticulite is found chiefly in the vicinity of Kilauea caldera, although small amounts of open-textured pumice may be found in certain lava-fountain deposits elsewhere in Hawaii. The true reticulite is remarkable in that practically all the walls between the cells have burst and essentially no closed space exists in the thread network. Pumice, on the other hand, typically consists of closed gas-formed cells. Pumice commonly floats, but reticulite, while weighing very much less than pumice, is open to nearly complete penetration by water and does not float for long. In a genetic series reticulite lies between pumice and ash.

The notable occurrence of reticulite at Kilauea caldera is a stratum 10 to 16 inches thick over 2 or 3 square miles north and east of the caldera. This layer, which thins rapidly away from the caldera, forms the basal member of a series of pyroclastic beds antedating the ash of 1790. Reticulite also is found in lesser amounts in other parts of the Kilauea pyroclastics, both older and younger. The reticulite beds consist of masses of typical glass network partly enclosed in a thin, brown or iridescent membrane. The masses are commonly 1 inch in diameter and occasionally reach 3 inches. Much of the accumulation consists of broken material, probably crushed in place.

The structure of reticulite has been thoroughly described by Dana and others. It is important, however, to emphasize the completeness with which the walls of vesicles have been resorbed into the threads which join the solid angles and the failure of those threads to assume a round cross section. They retain the cross section of a triangle with recurved sides and extremely sharp edges, indicating prompt cooling after the walls of vesicles had burst. Probably the rapid expansion of gas and the change in mechanical conditions induced this nearly instantaneous freezing.

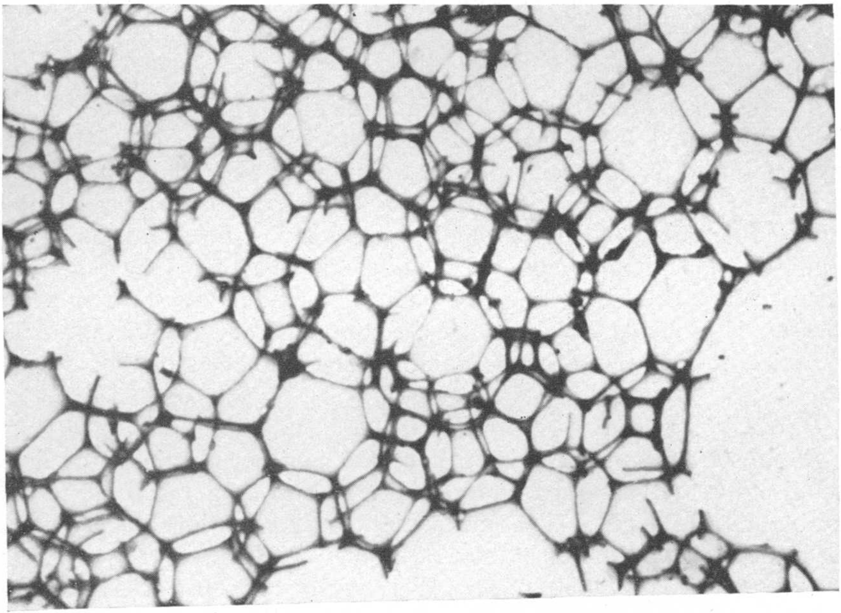

FIGURE 40.—Detail of texture of reticulite, photomicrograph of immersed section. The larger rings have a diameter of about one-fourth millimeter. Photo by C. K. Wentworth.

It is apparent that such a change must have taken place at some stage in the explosive rise of expanding foam. The general network is made up of polygonal rings ¼ to 2 millimeters in diameter and the threads are about 1/20 millimeter across the whole triangular section (fig. 40) (Wentworth, 1938, p. 149). The porosity of reticulite specimens has been determined at 98.3 percent by Dana and 98 percent by Wentworth. The amount of water required to account for the expansion of the reticulite has been calculated to be about 1.1 percent by weight (Dana, 1890, p. 67).

PELE'S HAIR

The threads of rock glass drawn out by flying clots of molten lava during bubbling or fountaining stages of volcanic activity have long been called Pele's hair (Dana, 1890, p. 160), and have been described by various observers (Brigham, 1887, p. 22; Krukenberg, 1877). These threads commonly have nearly uniform cross section for several inches and may occasionally reach a yard in length. The diameter mostly ranges from 0.01 to 0.10 millimeter but may be greater. The smaller threads are clear, light-green glass; larger threads carry crystallites and bubbles, the latter sometimes expanded to form glass bulbs one-half millimeter in diameter. Some of the threads show a pulled, minutely striated structure and configuration and show slight anisotropism between crossed nicols, owing to strain in the glass.

Pele's hair is often carried high into the air during strong fountaining and wafted for several miles by the wind. Probably the hot updraft of active fountains permits spinning of such glass during the period of several seconds corresponding to the trajectory of the higher fountains, and the branching and complex forms are probably due to collision and adherence while still plastic. Given certain temperatures and velocities of pulling, the diameter of the spun threads is probably a measure of the contemporary viscosity, but no practical formulation of these conditions has yet been offered.

BOMBS

Bombs are fragments of lava that were liquid or plastic at the time of ejection and assumed characteristic forms as a result of forces acting during flight. The mechanics causing various forms have been discussed in detail by several students (Reck, 1915, p. 39–61; Stearns and Clark, 1930, p. 115; Wentworth, 1938, p. 111–115; Macdonald, 1949a, p. 81–82). There is much variety in the forms and commonly those of a given locality are of one kind only, leading to misapplication of names or misinterpretation of mode of origin.

Bombs of the Hawaiian volcanoes may be classified according to their shape, which in turn appears largely to depend on the viscosity of the lava. The very fluid ejecta of Mauna Loa and Kilauea volcanoes commonly flatten out on striking the ground to produce the so-called "Hawaiian type" (cow dung or pancake) bombs. Blobs ejected during the 1790 and late prehistoric explosive eruptions of Kilauea were sufficiently fluid to draw into spherical shapes during flight, but solid enough to retain their shape on striking the ground (Macdonald, 1949a, p. 82). Less fluidity in the ejected blobs apparently results in the fusiform (almond-shaped or spindle-shaped) bombs. The solidified and broken up strings of magma ejected with the fusiform bombs, and to some extent drawn out from them, constitute the ribbon bombs.

In Hawaii bombs are found most abundantly on many of the cinder cones of Mauna Kea, Kohala, Hualalai, and Haleakala volcanoes, and of a few other localities. These are chiefly of the fusiform and ribbon types, and range from less than 1 inch to 6 feet long, some of them weighing more than a ton (fig. 41). It is noteworthy that bombs appear to be much more abundant in the surficial layers of some cones than in the interior of the cones. The formation of bombs apparently is favored by increasing viscosity and waning violence of explosion toward the end of an eruption. The shapes and structure of the Mauna Kea bombs have been described elsewhere (Wentworth, 1938, p. 111–115).

It appears that the fusiform bombs are typically due to modification, during flight, of a blob of lava detached from other lava at both ends. The chief factors involved in shaping the bomb are the surface tension, which tends to produce the globose form, and the fluid drag of surrounding air that tends to cause skin flowage and develop a contrast between the forward and following sides. No basis is seen for accepting the view that the shapes, particularly the end projections, are due to rotation during flight (Stearns and Clark, 1930, p. 115).

The concept that the "ears" or ends are due to centrifugal force is unsound in a dynamic sense, there being no dynamic reason for genesis of two protuberances. Stearns states that "the spiral motion causes the bomb to develop earlike projections on the ends of its axis of rotation." The dominant elements of shape are the continuity of comparable cross section from end to end caused by pulling, the thickening of the middle brought about by surface tension while aloft, and the surface drag and contrast between stoss and lee sides caused by air resistance and drag while holding a nearly steady orientation during the flight. These elements do not indicate or require spinning and the latter denies it. Breadcrust bombs, that is, bombs showing shrinkage cracks in the skin, are found sparingly on Mauna Kea and elsewhere. Ribbon bombs are filaments of lava without medial swellings. This type commonly shows continuity of ribbing from one end to the other, and passes uninterruptedly into fusiform bombs. Juvenile lava fragments are found in the tuff craters of southeast Oahu but distinctive shapes that would be called bombs are rare.

FIGURE 41.—Pile of almond-shaped bombs gathered within a 100-foot radius at the cone Kalepeamoa, on the south slope of Mauna Kea, to illustrate relative abundance and similarity of form through a large size range. Photo by C. K. Wentworth.

BLOCKS

Accessory or accidental blocks are found in the tuff cones of the Honolulu volcanic series of southeast Oahu, and accessory blocks are common in the several formations that surround Kilauea caldera. Both lava blocks and blocks of reef limestone are found in the tuffs of the Honolulu volcanic series. The limestone fragments range upward from single small shells to reef blocks of several hundred pounds weight. They occur throughout the tuff section, in some layers more markedly than in others, and up to the tops of cones 1,000 feet or more above sea level. From the occurrence of these marine forms, some observers have wrongly deduced emergence of the land without recognizing the process of emplacement by explosive eruption and opening of vents through the lava and reef formations.

At Kilauea the caldera floor immediately surrounding the pit of Halemaumau is strewn with blocks of various types of basalt thrown out during the explosive eruption of 1924. Approximately 60 million cubic feet of material was thrown out over the surrounding country (Finch, R. H., in Jaggar, 1924, p. 117), and the blocks, all sizes and ranging up to several tons weight, represent only a very small part of the total. They came from the walls of Halemaumau, which was collapsing by progressive engulfment, and were thrown out by spasmodic steam explosions. A block estimated at 8 tons was thrown 3,500 feet from the center of Halemaumau, and a still larger block was thrown out onto the edge but fell back into the pit with a wall avalanche 6 years afterward. All these are angular blocks of wall rock and show no signs of fusion, though some were incandescent when ejected.

CORED BOMBS

Bombs containing xenolithic nuclei have been termed "cored bombs" by Brady and Webb (1943). Bombs of this type are fairly common in cinder cones on Kilauea and Mauna Kea volcanoes, and in the deposits of the 1790 and late prehistoric explosive eruptions in and near Kilauea caldera, and are occasionally found at other localities in Hawaii. The nucleus may be either an accessory fragment picked up from the walls of the conduit, or an essential fragment of clinker, produced during the same eruption as the bomb. The rock fragment, or piece of clinker which fell back into the vent, becomes coated with liquid magma and is ejected as a bomb. Most of the cored bombs are nearly spherical, but some are distinctly fusiform. In size they range from about 1 foot in diameter to lapilli about half an inch in diameter. The vent of the 1801 lava flow of Hualalai volcano threw out many lapilli and small bombs that consist of cores of bright-green dunite surrounded by a shell of black glassy lava.

ACCRETIONARY LAPILLI

Volcanic pisolites from Kilauea vent, with diameters of 3 to 10 millimeters, were described by Perret (1913). Because the etymology of the word "pisolite" has nothing to do with the volcanic variety and because the usage is not very firmly established, the term *accretionary lapilli* has been suggested (Wentworth and Williams, 1932, p. 37), and is used here.

Accretionary lapilli are formed by rain drops, which fall through ash-laden air, and also by rolling of wet nuclei on a surface covered with fresh ash (Macdonald, 1949a, p. 70). The occurrence of some in steeply dipping strata suggests the latter genesis. Accretionary lapilli 5 to 20 millimeters in diameter have been found in steeply dipping layers in the Koko Crater region and elsewhere on Oahu, and these are thought to result from accretion while rolling down the slopes of the cones. Other larger lapilli found near Sugar Loaf vent in the Honolulu area are probably formed by accretion and milling during repeated tossing within a volcanic vent.

MINOR STRUCTURES IN PYROCLASTIC FORMATIONS

BOMB SAGS

These structures are displayed chiefly in the fine-grained palagonite tuff of various cones where a bomb or block has landed on ash already fallen and is presently buried in the later ash. In section, the laminae below are slightly depressed or deranged and the laminae above are mantle bedded over the bomb in the form of a shallow dome (fig. 42). The effect is confined to two or three diameters of the bomb laterally and even a shorter distance below and above. Where the bomb lies exposed on an eroded bedding surface, the bomb sag appears as a sort of nested structure of layers dipping under the bomb from all sides.

TREE AND OTHER MOLDS

External molds of tree trunks or of other parts of plants are found in tuff formations or in cinder or black sand beds. In the latter case the form is often preserved through filling and cementation by calcium carbonate. Though this may occur in the tuff the more usual condition is a simple opening. A number of such openings, both vertical and prostrate, some branched, are especially well preserved in the upper tuff of the road cut a few yards toward Red Hill saddle from the South Halawa bridge, on Oahu. Leaf molds have been found in tuff in the Kalae area, Hawaii, and probably elsewhere, but none but modern plant forms are known to have been identified.

JOINTING

Several kinds of jointing are seen in the pyroclastic rocks, especially the palagonitic tuffs. The major joints are commonly vertical and

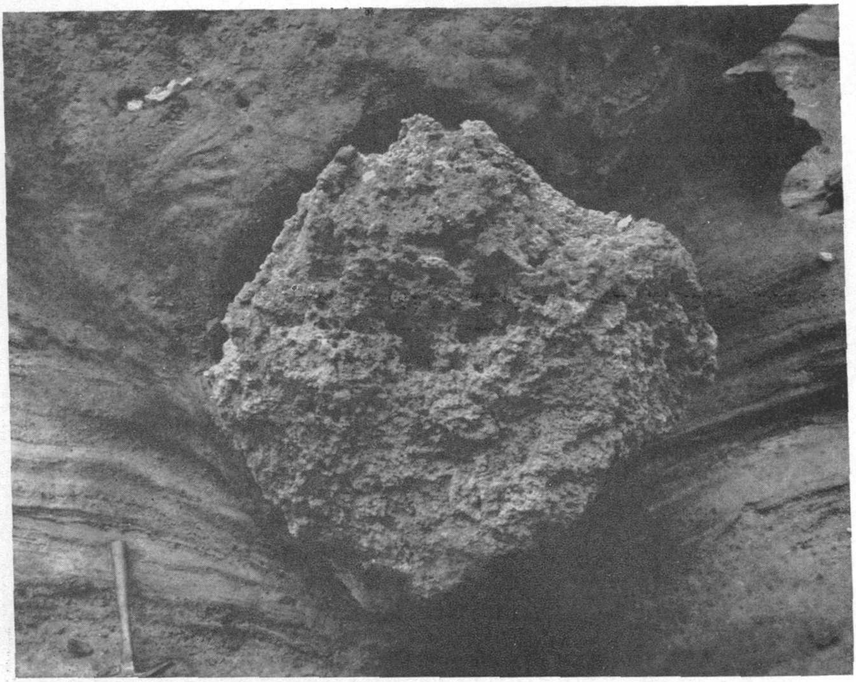

FIGURE 42.—Outcrop of tuff showing bomb sag, where a block or bomb depresses the underlying strata and causes a domed structure in the mantling beds above. *Photo by C. K. Wentworth.*

transverse to the greatest dimension of the mass. In a crater rim they are radial to the vent and cut across the circular rim. Spacing in some parts of the Diamond Head tuff cone is not more than 3 or 4 feet; wider spacing is found in some other masses. Commonly these joints are filled by calcium carbonate.

In some places where lava flows have cooled immediately over tuff beds, the upper few inches of the tuff beds have a columnar structure with joints spaced only 2 or 3 inches apart. A third type of jointing is displayed in many places where the palagonite tuff crumbles on dry, bare rock surfaces. To a slight extent the tuff splits along bedding surfaces but more commonly it crumbles to small, rudely cuboidal or compact polyhedral masses, generally from a fraction of 1 to 2 or 3 inches in diameter, from which corners tend to spall off rather neatly. This crumbling is probably induced by the volume expansion associated with wetting followed by drying. It has some features in common with the spheroidal weathering that takes place in deeply weathered basalt, but forms are less pronounced.

CEMENTATION

Most of the pyroclastic accumulations are only weakly cemented but there is a considerable range in this respect. Occasionally black sand or cinder beds are without any bonding and slump down to an angle of rest as freely as dry dune sand. More commonly such beds are lightly and almost imperceptibly cemented by calcium carbonate, or in the coarser sizes so interlocked by irregular shape that the mass will stand in a vertical cut 10 or 20 feet high. Only rarely and locally are black sand or cinders sufficiently cemented to require a hammer for collecting any particular bed, although a few beds come out in slabs that can be prepared for very careful handling as hand specimens.

Masses of driblet often are rather tightly interlocked and in hornitos may become fully welded. Some bombs are so plastic when they hit the ground that fragments of rock or other bombs may be inbedded in them.

Palagonitic tuff commonly carries an appreciable amount of cementing calcium carbonate, but even without this it would be moderately well cemented by the palagonite shells. This rock commonly has about the strength of chalk.

Beds of the finer grained accessory volcanic dust from such eruptions as 1790 and 1924 at Kilauea caldera often are slightly indurated. This induration is probably due to bonding that takes place in the drying of many fine-grained materials.

INTRUSIVE FORMATIONS

DIKES

No large intrusive masses are exposed in Hawaii; erosion has reached only two or three thousand feet downward into any of the lava shields and there is no positive knowledge that large intrusive masses exist at any depth.

Dikes locally follow the jointing at a few degrees off vertical but in the over-all course tend to offset to approximate a vertical attitude. They are found sparingly in most of the lava formations of Hawaii; the concentration over much of the area is of the order of one dike per thousand transverse feet or fewer. The most detailed and systematic mapping has been done in the Honolulu area, where dikes are found to increase in abundance from the periphery of the shield toward the rift axis along which the Koolau dike complex is developed (Wentworth and Jones, 1940). Subordinate dike swarms are found in this area and there are some variations in the decrease of frequency of dikes away from the rift zone. Because of the greater numbers, the character of the dikes has mostly been observed in the area of dike complexes. Columnar jointing is general but the polygonal sections of the columns are often quite irregular (fig. 43). Many of the larger dikes show three phases of jointing. They are shown in the central part where the finely crystalline texture is most fully developed, on the two sides where the rock is less perfectly crystalline and where

FIGURE 43.—Dike in channel of Wailupe Stream, Oahu, showing principal columnar jointing. Near the end of each column is splinter jointing that marks the dike margin. Photo by C. K. Wentworth.

incipient splintering invades from the sides, and finally, in the fine-meshed checking of the glassy selvage, often with a spacing of not over ¼ to ½ inch. These patterns are related to thickness and tensile properties of the respective masses; dikes several feet thick have columns a foot across in the central phase (fig. 44).

In the Honolulu area the prevailing thickness of dikes is 2 to 3 feet, with very few dikes more than 6 feet thick. In parts of the dike complex, a few thicker dikes are found, but commonly these are compound. Studies of the Koolau mass indicate that most of the dikes have resulted from the passive rise of lava toward the surface and that commonly no more pressure was required than the hydrostatic pressure needed to reach the surface. In a close pattern of dikes and sills, pressure of intrusion may have somewhat exceeded load pressure. It was concluded that the thickness of dikes was the amount of shrinkage of the lava flows represented in the rather moderate distance along which horizontal displacement could take place (Wentworth and Jones, 1940, p. 985).

Observations in the Honolulu area show a systematic, if somewhat irregular, relationship between the texture of dikes and the depth below the surface at which they were probably intruded. At depths 300 feet or more below the surface of the volcanic mass, the dikes are commonly dense rock with few vesicles and conspicuous columnar jointing, as if formed under pressure and with an orderly history of cooling in relation to the surrounding rock. On the other hand,

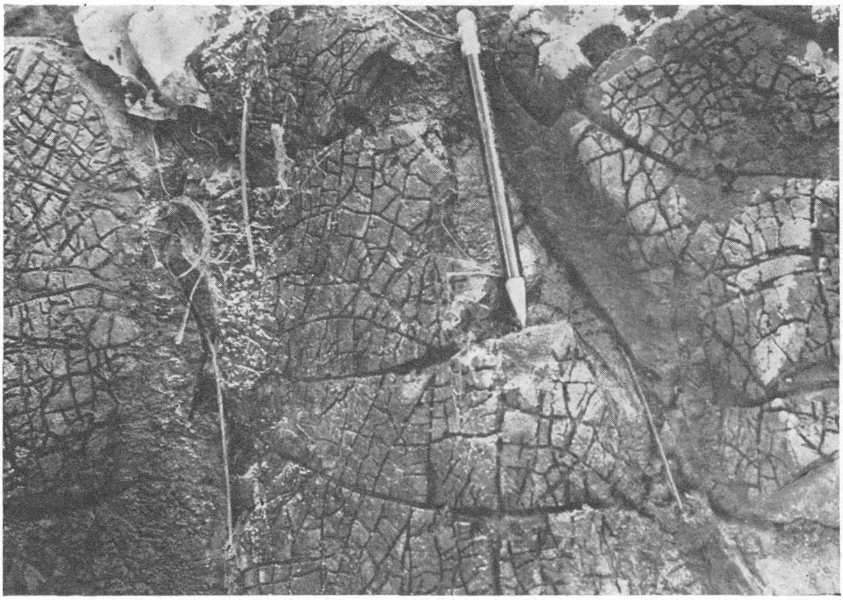

FIGURE 44.—Detail of checking in the glass selvage layer of a dike. The pattern of the larger columns, as well as the intermediate splintering of these units, is shown. Photo by C. K. Wentworth.

dikes intruded at depths of 200 feet or less show imperfect columnar jointing and commonly show bands of vesicles parallel to the contact with the country rock. There are many differences in individual dikes, due to thermal and other differences in the adjacent rock, and these figures give an approximate view of the prevailing condition inferred from data collected mainly by A. E. Jones (Wentworth and Jones, 1940, p. 990–993).

SILLS

Most sills in Hawaii are inclined less than 15° to the horizontal, conformable to the lava-flow bedding. Commonly they follow one bedding plane for a few tens of feet, then break across the bedding to a new horizon and resume their sill character. Sills are commonly offset or bifurcated as seen in section and are commonly associated with irregular dikes. They are less abundant than dikes and probably represent a more aggressive intrusive action. A few large sills have been traced with only a few breaks for 1,000 feet or more but probably most extend for much shorter distances. The jointing and the selvages of sills are similar to those of dikes. Sills are sufficiently impermeable to play a part in the perching of ground water. Small springs or seeps commonly emerge from above the outcrops of sills. However, we know of no instance in Hawaii where substantial amounts of water are perched by a sill without a preponderant confining of ground water in the same area by associated dikes.

NECKS, PLUGS, AND BUDS

Fillings of tubular conduits are not abundant in exposed sections in Hawaii. A few are found on the island of Maui in the Kula volcanic series (Stearns and Macdonald, 1942, p. 83–84, 164). The Palolo quarry mass of the Koolau Range on Oahu is an expanded complex dike, which shows in various parts columnar joints, platy joints, and irregular polyhedral masses according to local placement and cooling history. It is not evident that this mass at depth has any form other than that of a thick dike.

In several localities in the southeastern Koolau Range of Oahu masses of intrusive rock have an oval ground plan with the long axis in many instances coinciding with a known dike. These masses occur at or very near the elevation of the original surface of the shield and are believed to be thickened parts of the dikes that have taken a somewhat bulbous form near the point of pressure relief at the surface. They have been called buds and show centripetal jointing and concentric selvage and texture zones comparable to those of dikes (Wentworth and Jones, 1940, p. 988–990).

The rounded domes (tholoids) of trachyte and related rocks that occur on West Maui are considered to be partly intrusive. They range from 100 to 600 feet high and 1,000 to 3,000 feet in diameter and are believed to have been squeezed from a small central opening when in a viscous condition (Stearns and Macdonald, 1942, p. 21–23).

DIKE COMPLEXES

The term dike complex was first applied by Stearns in his description of the rift zone formation of the Koolau Range (Stearns and Vaksvik, 1935, p. 77, 95). As a general term it is quite satisfactory but with increasing knowledge of the occurrence of such formations further attention to definition may be required. A dike complex is characterized by a notable concentration of dikes. In some instances they make up almost the whole mass with only small amounts of normal lava flows between them (fig. 45). Stearns and Vaksvik refer to the impracticability of mapping the individual dikes, and comment on the rapidity with which the frequency of dikes falls off outside the limits of the dike complex proper.

The most extensively exposed dike complexes are those of the Koolau Range and Waianae Mountains on Oahu and that of East Molokai. Others are mostly less deeply eroded.

The essential characteristic of the dike complexes of Hawaii is that they represent recurrent intrusion in parallel or subparallel pattern along the line of a source rift zone. The concentration of dikes necessary to justify the use of the term dike complex must vary somewhat with the nature of the normal surrounding lava-flow

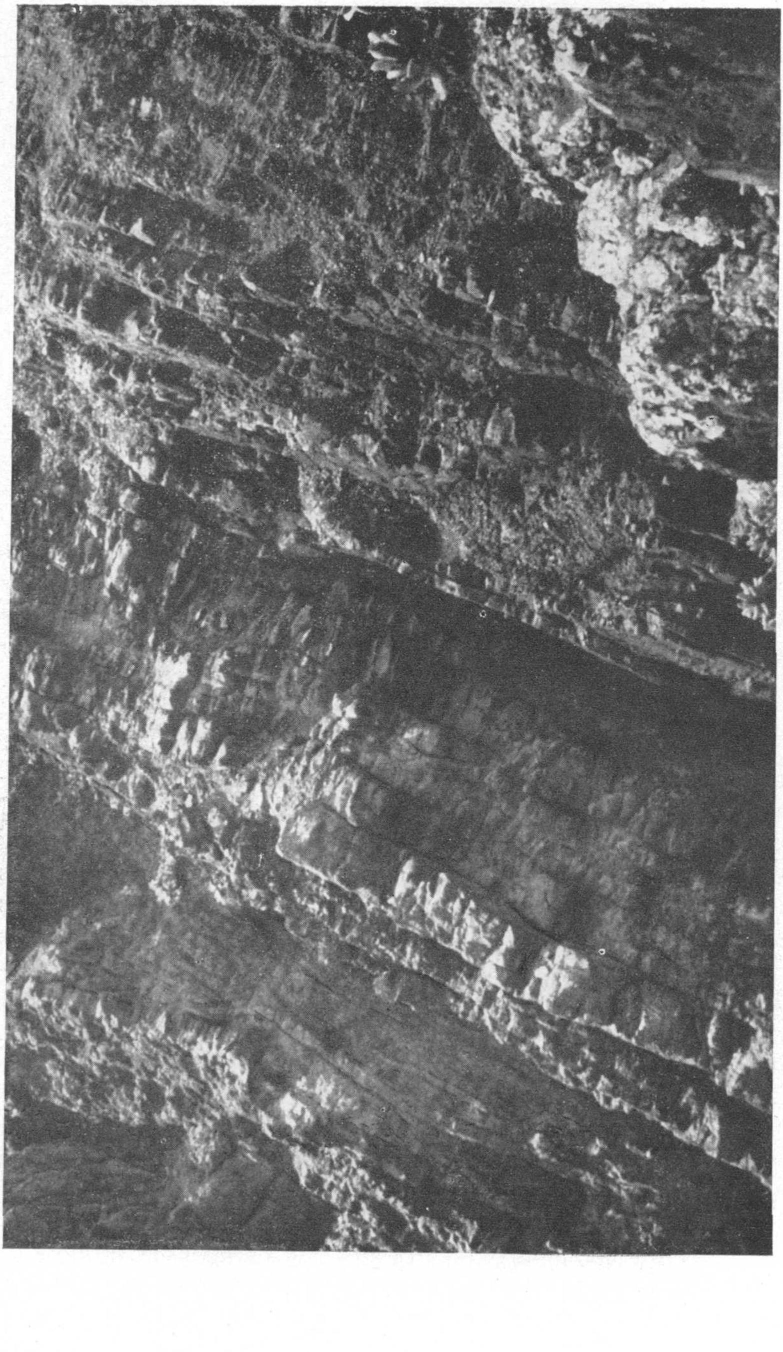

FIGURE 45.—Dike complex, Mokulua Island, off Lanikai, Oahu. Here dikes are so numerous as to make up the entire structure; the original lava flows are not visible at this point. View looking east. Center height is about 50 feet. Photo by C. K. Wentworth.

formation and in practice will be difficult to define precisely. Parts of the well-exposed dike complexes of the Mokulua Islands off Oahu, of the Kolekole Pass area, and of the Waikane–Waiahole area show dikes in excess of 100 to the mile, measured transversely, and locally approaching 1,000 to the mile.

It may be profitable to consider what number of dikes might be required to build the upper part of such a shield as the Koolau mass. Assume that in any given section transverse to the rift zone each lava flow reaches from its vent to the coast or beyond and averages 10 feet of increased height to the range on one side. Assume another flow to be required for the same gain on the other side and that each has come from a separate dike. Assume the lengths of dikes to be comparable to the widths of the resulting flows. This would mean two dikes for each 10 feet or 200 for each 1,000 feet of rise. If the dike complex is 2 miles wide and the horizontal section be considered at 1,000 feet below the attained crest, the dikes would on these assumptions average 100 to the mile. This is consistent with the earlier suggestion that concentration of 100 to the mile is common in the recognized dike complexes. Apparently a limit between 10 and 100 dikes to the mile as a threshold for dike complexes is consistent with the depth of dissection and other conditions found in much of Hawaii.

Where the lava flows are comparatively permeable and where the dikes do not constitute more than a minor part of the whole mass, perhaps nearer the lower limit mentioned above, the dike complex may under suitable rainfall conditions serve an important function in confining high-level water bodies and it is in such areas that are somewhat dissected that tunneling for water has yielded the most direct and quantitative information of the attitudes and distribution of dikes. On the other hand, definitely effective water development has not been carried out in sections showing a concentration more than 100 to the mile.

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