Petrography of the Island of Hawaii

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By GORDON A. MACDONALD

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A study of representative samples of rock types from every volcano on Hawaii by thin sections, mineral grains, and hand specimens.

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CONTENTS

ILLUSTRATIONS

PETROGRAPHY OF THE ISLAND OF HAWAII

By Gordon A. Macdonald

ABSTRACT

The lavas of Mauna Loa and Kilauea Volcanoes consist predominantly of olivine basalt, with smaller proportions of basalt and picrite-basalt. Andesites are unknown. Hypersthene-bearing lavas are moderately abundant on Mauna Loa but rare on Kilauea. The lavas of Mauna Loa show considerably greater variation than those of Kilauea.

Hualalai Volcano is built largely of olivine basalt, with associated smaller amounts of basalt, of rocks transitional between olivine basalt and picrite-basalt, and of rare andesite. The lava flow of 1801 is olivine basalt. Xenoliths of gabbro, dunite, and augite peridotite are present in the lavas. Soda trachyte forms a cinder cone and thick flow on the north flank of the mountain. Only the earliest stages of magmatic differentiation are indicated, thus strengthening the conclusion reached at other Hawaiian volcanoes that appreciable differentiation commences near the end of the caldera-filling stage.

The lavas of Mauna Kea Volcano are divided into the older Hamakua volcanic series and the younger Laupahoehoe volcanic series. The Hamakua volcanic series consists of two members. The lavas of the lower member are very largely olivine basalt, with less numerous flows of basalt, and primitive picrite-basalt containing abundant phenocrysts of olivine. The lavas of the upper member include olivine basalt, basalt, andesine andesite, and augite-rich picrite-basalt. The Laupahoehoe volcanic series is preponderantly andesine andesite, with a smaller proportion of olivine basalt. Coarse-grained inclusions and ejecta comprise gabbro, dunite, and augite peridotite.

The lavas of Kohala Volcano are divided into the earlier or Pololu volcanic series and the later or Hawi volcanic series. The Pololu lavas are largely olivine basalt, and to a minor extent basalt and picrite-basalt. The Hawi lavas are predominantly oligoclase andesite, with less abundant trachyte. Coarse-grained inclusions of gabbro, dunite, and augite-hypersthene peridotite are present.

Differentiation was largely or entirely by crystal settling. The parent magma was olivine basalt. Sinking of intratelluric olivine crystals during early magmatic phases produced olivine-rich picrite-basalt and a reciprocal phase of basalt poor in olivine. Later, the removal of crystals of calcic plagioclase, hypersthene, and augite yielded rest-magmas equivalent to andesine andesite, oligoclase andesite, and trachyte.

INTRODUCTION

The study of the petrography of the island of Hawaii, the results of which are described in this paper, is a part of the general investigation of the geology and ground-water resources of the island by the United States Geological Survey in cooperation with the Territory of Hawaii. Most of the rock specimens from Mauna Loa, Kilauea, and Mauna Kea, and part of those from Kohala, were collected by the writer during areal surveys of those parts of the island in 1941, 1942, and 1943. Most of the specimens from Hualalai and the western slope of Mauna Loa, and about half of those from Kohala, were collected by H. T. Stearns in 1940 and 1943. One specimen from Kohala was collected by W. O. Clark. Several thin sections of pyroclastic rocks were loaned by C. K. Wentworth.

The investigation has involved the study of about 400 thin sections. In addition, many specimens have been studied by means of mineral grains immersed in oils of known refractive index, and many others have been studied with a hand-lens. An effort has been made to obtain representative samples of every rock type, and from all parts of each volcano. The latter objective was not entirely fulfilled on Hualalai and Kohala, but the entire surface area of the other volcanoes is fairly well represented in the collections.

The composition of the feldspar has been determined in some rocks by extinction-angle methods but in most rocks by immersion of fragments of the rock in oils of known refractive index. Optic-axial angles have been estimated from the appearance of optic-axis or acute-bisectrix interference figures.

The writer wishes to thank C. S. Ross and H. T. Stearns of the United States Geological Survey, who have read and criticized the manuscript of this paper.

PREVIOUS INVESTIGATIONS

Mauna Loa.—Several previous investigators have examined and described specimens of lavas of Mauna Loa from scattered localities, but none of the collections were sufficiently large or from localities widely enough dispersed to represent adequately the petrography of the entire volcano.

The earliest microscopic investigations of the lavas of Mauna Loa were those of Cohen (1880), who studied several specimens collected by Hillebrand. However, many of the rocks were largely glassy, and Cohen's descriptions were for the most part generalized. He reports olivine-rich basalt from the Mokuaweoweo caldera and basaltic pumice from the eruption of 1868.

Dana (1889) studied a large suite of specimens collected by E. P. Baker, many of which came from

Mokuaweoweo. Probably all of them were of the late lavas of Mauna Loa, termed in the present paper the Kau volcanic series. Dana distinguished three general types of lavas: (1) "Clinkstonelike basalt," fine grained and mostly dense, characterized by the paucity or absence of olivine; (2) lavas with minute crystals of labradorite and pyroxene projecting into the vesicles, characterized by grains of olivine scattered throughout the mass; and (3) lavas containing very abundant olivine, comprising nearly 50 percent of some specimens termed by him chrysolitic basalt.

Daly described the lava of 1852, which he termed an "ultrafemic olivine basalt," and published analyses by Steiger of the lava and its olivine phenocrysts. He also briefly mentioned the lavas of 1881, 1855, and 1859 (Daly, 1911, pp. 294–297, 303). Cross (1915, pp. 38–39) reviewed previous work and briefly described a lava midway between Kilauea caldera and Punaluu, which he believed to be the lava of 1823 from Kilauea but which was probably the late-prehistoric Keamoku flow (Kau volcanic series) from Mauna Loa. He stated that all the historic lavas apparently were normal olivine basalts. Rocks from Mokuaweoweo, which Dana had called basalts, he classified as andesitic, apparently because of the absence of olivine.

Cross later examined several specimens collected in the Kau District by Noble and Clark. His descriptions, as contained in Noble's unpublished report to the United States Geological Survey, were briefly reviewed by Washington (1923b, pp. 120–121), and fuller descriptions were published by Stearns and Clark (1930, pp. 159–162). These specimens were the first of the older lavas collected with a knowledge of their stratigraphic relationships. Four of them were analyzed chemically by R. K. Bailey, of the Geological Survey. The analyses were published, and the rocks were redescribed by Washington, who also contributed chemical analyses and petrographic descriptions of six other lavas of Mauna Loa (Stearns and Clark, 1930, pp. 112–125). Two analyses of lavas of Mauna Loa by J. J. Fahey were published by H. A. Powers (1931, p. 2) but the rocks were not described.

From a study of the specimens collected by Noble and Clark on the south flank of Mauna Loa, Cross concluded that the oldest or pre-Pahala lavas (now called the Ninole volcanic series) are mainly olivine-poor basalts, the Pahala basalts (now called the Kahuku volcanic series) are for the most part moderately poor to moderately rich in olivine, and the post-Pahala lavas (now called the Kau volcanic series) are mainly olivine-rich basalts (Washington, 1923b, pp. 120–121). This concept of a general increase in olivine content from the oldest to the youngest lavas was accepted by Washington (1923b, p. 125) and by Stearns and Clark (1930, pp. 158–162), the latter, however, stating emphatically that all the lava types could be found in each of the three main stratigraphic groups. As a result of the redetermination of the stratigraphic position of the most salic rock collected by Noble, the widest range in composition is found in the late lavas, whereas Noble had believed it to occur in the earliest group (Stearns and Clark, 1930, p. 161). This change results in making the picture much more conformable to the general sequence of differentiation found in other Hawaiian volcanoes.

Kilauea.—The lavas of Kilauea have been studied more thoroughly than those of Mauna Loa. Petrographic descriptions of Kilauean lavas have been published by a whole series of investigators (Krukenberg, 1877; Cohen, 1880; Silvestri, 1888; Dana, 1889, pp. 441–467; Daly, 1911, pp. 291–294, 303–304; Cross, 1915, pp. 39–44; Washington, 1923c, pp. 338–353; and Stone, 1926, pp. 12–22, 27–35), but previous studies have been confined largely to the immediate vicinity of Kilauea caldera and comparatively little has been known of the innumerable flows that cover the outer slopes of the mountain. The present studies of Kilauean lavas have therefore been particularly concerned with the lavas erupted along the rift zones, especially in the region of Puna.

Hualalai.—Cohen (1880, pp. 49, 51) described several rocks from Hualalai Volcano, among which were olivine basalts and rocks transitional between basalts and andesites. Both Dutton (1884, p. 174) and Daly (1911, p. 304) referred to the rocks of Hualalai in a general fashion as olivine basalts, but neither described any individual specimens. Daly recorded the occurrence of gabbro among the ejected blocks near the summit. Cross (1904) was the first to recognize the existence of trachyte at Puu Waawaa and Puu Anahulu. Analyses of the trachyte were made by Hillebrand. Cross (1915, pp. 34–36) made collections along the trail from Huehue ranch to the summit and along the highway, and briefly described basaltic lavas, inclusions of dunite, augite peridotite, and gabbro, and an ejected block of basaltic porphyry containing hornblende and biotite. Washington (1923b, pp. 100–109) described and analyzed several specimens collected along the highway and along the summit trail, including olivine basalts, gabbro, and basalts which appear from his descriptions and analyses to be olivine-poor or olivine-free. He gives a new analysis of the trachyte at Puu Anahulu. The physical features of the lavas and ash on the west slope of Hualalai were briefly described by Powers (Powers, Ripperton, and Goto, 1932, pp. 6–10).

Mauna Kea.—Surprisingly little has previously been published regarding the petrography of Mauna Kea, although several petrographers have described a few scattered specimens. Cohen (1880, pp. 46–55) examined specimens collected by Hillebrand and recognized two of the main types of lavas of Mauna Kea—

basalts and pyroxene andesites—as well as transitional varieties. A suite of specimens collected by Preston was briefly described by Merrill (1893) and was re-examined by Cross (1915, pp. 36–37), who concluded that they were all olivine basalts. Most of them were partly glassy, however, and were not satisfactory for microscopic determination. Daly collected and described two samples of lava from the south slope and summit of Mauna Kea, one of which he termed andesitic basalt and the other trachydolerite. The rocks were analyzed in the United States Geological Survey laboratory by Steiger (Daly, 1911, pp. 297–300). Both are classed in the present paper as andesites. Daly (1911, pp. 301–303) also described nodules of ultrabasic rock from the summit area. Brief statements as to the nature of the rocks of Mauna Kea, based on megascopic examinations, were made by Goodrich (1833), Dutton (1884, pp. 160–164), and Hitchcock (1911, p. 52). An olivine (dunite?) nodule was reported by Powers (1920, p. 276) from lavas of Mauna Kea at Kapulena.

A suite of specimens was collected by Washington (1923a, pp. 487–502) along the highway that circles Mauna Kea, and both chemical analyses and microscopic descriptions of them were published. They form the most useful previous source of information regarding the rocks of Mauna Kea. Insofar as possible, the rocks analyzed by Washington have been recollected and restudied in connection with the present report.

Wentworth's report (1938) on his investigation of the ash deposits of the island of Hawaii contains many descriptions, both megascopic and microscopic, of the tuffs and cinder cones of Mauna Kea and chemical analyses of several samples of palagonitized ash.

Kohala.—Cohen (1880, pp. 46–49, 51–52) examined several rocks from Kohala Volcano, which he classified into two groups, basalts rich in olivine and rocks transitional to augite andesite. As pointed out by Cross (1915, p. 33), however, his argument that the scarcity of augite in relation to feldspar shows the relationship of the latter group to augite andesite is not very convincing without the support of other substantiating data. Dutton (1884, p. 171) also noted the resemblance of many lavas of Kohala to augite andesite and remarked that the rocks appeared less ferruginous and more feldspathic than those of Mauna Kea and Mauna Loa. Olivine was stated to be generally less abundant than in the typical basalts of the other volcanoes.

Lyons (1896, pp. 424–426) published chemical analyses of three lavas of Kohala, one of them a basalt with feldspar phenocrysts, another a basaltic fragment from a cinder cone, and the third apparently an oligoclase andesite. Cross (1915, pp. 33–34) collected and described a single specimen of andesite from Mahukona, on the western coast of Kohala. Several specimens, including the one collected by Cross, were described and analyzed by Washington (1923a, pp. 474–487), who clearly recognized the existence of two great groups of lavas—basalts and oligoclase andesites—at Kohala Volcano.

PRINCIPAL ROCK TYPES

The principal rock types of the Hawaiian volcanoes are so much alike on the several mountains that a single description of the general features of each type will suffice. Minor features and variations characteristic of the lavas of individual volcanoes will be pointed out in the discussion of each volcano.

The Hawaiian lavas are very largely crystallized, except for thin chilled selvages and pyroclastic ejecta. They are, therefore, more amenable to microscopic study and classification without the use of chemical analyses than are the lavas of many other volcanic districts, in which the proportion of glass is commonly large.

The average composition of the modal feldspar has been used as the determining factor in naming the rocks, those containing labradorite or bytownite being termed basalt, and those containing andesine or oligoclase being termed andesite. Lavas containing less than 35 percent feldspar are termed picrite-basalt. Washington (1923a, pp. 469–470) has objected to the use of modal olivine in classifying the lavas, on the grounds that the olivine content is frequently greater than that justified by the norm, owing to the early crystallization of olivine in excess of its stoichiometric proportions. This excess undoubtedly occurs, but the classification of the lavas entirely on the basis of chemical composition is impractical because of the relatively few lavas that have been analyzed. The percentage of olivine has therefore been used in classification, lavas containing more than 5 percent olivine (and more than 35 percent feldspar) being termed olivine basalt, and lavas containing less than 5 percent olivine being termed basalt.

Two types of picrite-basalt are recognized. In one the mafic phenocrysts are entirely or almost entirely olivine. This type, because of its close association with the undifferentiated, primitive olivine basalts, is called primitive picrite-basalt. The other type contains abundant phenocrysts of augite in addition to numerous olivine phenocrysts, and is called the augite-rich type of picrite-basalt. The two types are intergradational, although transitional examples are rare.

Andesites in which the dominant feldspar is andesine are termed andesine andesite, and those in which it is oligoclase are termed oligoclase andesite. Rocks in which the dominant feldspar is alkalic are classified as trachyte.

The general characteristics of each of the principal rock types are shown in the table on page 55.

BASALTIC ROCKS

It is immediately obvious from an inspection of the table that the differences between the basalts, olivine basalts, and picrite-basalts result largely from variations in type and abundance of phenocrysts. Considered alone, the groundmass in all three is nearly identical in both texture and composition, although in the basalts groundmass olivine is less abundant than in most of the olivine basalts and picrite-basalts, and may be entirely absent.

The olivine phenocrysts of the basaltic rocks all have an optic axial angle close to 90°, and $\beta=1.681-1.684$. These properties indicate a fayalite content of about 15 percent. Analyses of olivine phenocrysts from the 1840 lava of Kilauea and the 1852 lava of Mauna Loa indicate fayalite contents of 15.4 and 15.9 percent, respectively. (See tables, pp. 61 and 66.) In some flows the olivine phenocrysts are highly tabular parallel to the side pinacoid, but in most they are thick and stubby. In most rocks the olivine phenocrysts are partly rounded and embayed by resorption, often with liberation of finely granular iron ore. In many they are altered around the edges to iddingsite. Quite commonly the iddingsite is enclosed in a thin shell of fresh olivine deposited contemporaneously with the olivine of the groundmass, demonstrating the magmatic origin of the iddingsite.

The plagioclase phenocrysts exhibit normal zoning and less commonly oscillatory zoning. Most of them show a continuous progression from a calcic core to a rim having the composition of the groundmass plagioclase. Some, however, show a partly resorbed calcic core passing without gradation into a thin rim of more sodic plagioclase. The groundmass feldspar is labradorite and rarely shows much zonal variation in composition.

Some rocks contain a small amount of interstitial andesine or oligoclase. Commonly, this interstitial plagioclase shows a small positive optic angle and is believed to be potassic (Macdonald, 1942b).

All the phenocrysts of monoclinic pyroxene are augite, with an optic-axial angle of 55° to 60°, $\beta=1.702-1.709$, and moderate inclined dispersion. Some show hourglass zoning. In some rocks, particularly in the augite-rich picrite-basalts, they are partly resorbed. The augite phenocrysts are commonly enclosed in a thin shell of pigeonitic augite or pigeonite (Macdonald, 1944b). In many rocks the pyroxene of the groundmass occurs in such small grains that its character cannot be determined with certainty, but in many others the grains are large enough to yield usable interference figures, under conoscopic illumination. In all these rocks the groundmass pyroxene is pigeonitic, with optic-axial angles ranging from 0° to 50°, thus including both true pigeonite and pigeonitic augite. Microphenocrysts of pigeonitic augite occur in some rocks but are related to the groundmass rather than to the intratelluric phenocrysts.

Small phenocrysts of hypersthene occur in some of the lavas of Mauna Loa and very rarely in those of Kilauea. They have indices of refraction $\beta=1.690$ to 1.696, corresponding to 80 to 76 percent of enstatite. In most rocks the hypersthene forms microphenocrysts, generally rounded by resorption, and enclosed in thin rims of pigeonitic pyroxene. More rarely it forms irregular poikilitic grains, which enclose many smaller grains of feldspar.

The opaque minerals include both magnetite and ilmenite, generally in about equal abundance. Apatite is present in small amounts in many rocks, generally as minute acicular crystals enclosed in the last-crystallized feldspar.

ANDESITES

Probably the most characteristic macroscopic feature of the andesites is the existence of moderately to well-developed platy joints parallel to the flow planes, the surfaces of which show a distinct sheen owing to the parallel orientation of innumerable minute tabular feldspar grains. Most of the andesites are porphyritic, but nonporphyritic rocks are common.

Feldspar phenocrysts are generally less than 5 millimeters long but rarely reach lengths of as much as 2 centimeters. They are typically shorter and more blocky in habit than those of the basaltic lavas. Olivine phenocrysts are less common than those of feldspar. Augite phenocrysts are very rare.

In all but one rock specimen in which its nature could be determined the pyroxene of the groundmass is pigeonite or pigeonitic augite. Both ilmenite and magnetite are present, but magnetite is distinctly the more abundant. In the oligoclase andesites the groundmass olivine has a (−) $2V$ of about 75°, corresponding to a fayalite content of about 50 percent, comparable to that in the olivines of similar rocks on West Maui (Macdonald, 1942a, pp. 313–314).

Biotite is a common minor groundmass constituent of the andesites and is found also in a few basalts. It is strongly pleochroic, from deep reddish brown to pale yellow, with $2V=0°-10°$, and strong dispersion, $r<v$. In some rocks it occurs as small anhedral grains between the other constituents, but more commonly it forms euhedral plates projecting into vesicles. It is of late orthomagmatic or pneumatolytic origin.

Hornblende has not been found in the andesine andesites but occurs in a few oligoclase andesites. In some it is in the groundmass and is either brown or green in color. In others there occur rare phenocrysts of basaltic hornblende, partly or even largely resorbed, with the liberation of finely granular iron ore.

Many of the oligoclase andesites and trachytes and a very few of the andesine andesites contain a peculiar mineral, apparently an amphibole, which has also been

MAUNA LOA FROM THE SOUTHEAST, SHOWING MOKUAWEOWEO CALDERA AND THE ROW OF PIT CRATERS ALONG THE UPPER PART OF THE SOUTHWEST RIFT ZONE.

Note the broad gentle slopes of the shield of Mauna Loa, built of thin, highly fluid lava flows of the Kau volcanic series. The slope of Mauna Kea is visible in the right background. Photo by 18th Air Base Photo Laboratory, Wheeler Field, T. H.

Principal rock types of the Island of Hawaii

Rock name	Texture		Composition	
	Megascopic texture	Groundmass texture	Phenocrysts	Groundmass
Olivine basalt.	Porphyritic, less commonly nonporphyritic.	Generally intergranular or intersertal. Thin chilled crusts and glassy pyroclastic ejecta are hyalopilitic or hyaloophitic. Average grain size, 0.02 to 0.2 mm.; most commonly about 0.07 mm.	Olivine, 0–20 percent, 1–8 mm. long. Plagioclase, 0–25 percent, rarely more; 1–10 mm. long, rarely as much as 25 mm., zoned from Ab_{20}–Ab_{50}. Augite, 0–15 percent, 1–10 mm. long.	Plagioclase (Ab_{35}–Ab_{50}), 25–45 percent; a little interstitial andesine; monoclinic pyroxene, 25–45 percent; olivine, 1–15 percent; iron ore, both magnetite and ilmenite, 7–15 percent; apatite recognizable in a few specimens; some contain glass.
Basalt.	Porphyritic, less commonly nonporphyritic.		Olivine, 0–3 percent, 1–4 mm. long. Plagioclase, 0–20 percent, 1–5 mm. long, zoned from Ab_{20}–Ab_{50}. Augite, 0–3 percent, 1–5 mm. long.	Plagioclase (Ab_{35}–Ab_{50}), 30–50 percent; a little interstitial andesine; monoclinic pyroxene, 30–50 percent; olivine, 0–3 percent; iron ore, both magnetite and ilmenite, 7–15 percent; rare rutile; apatite recognizable in a few specimens; some contain glass.
Hypersthene-bearing basalt.	Porphyritic, rarely nonporphyritic.		Olivine, 0–10 percent, 1–8 mm. long. Plagioclase, 0–20 percent, 1–5 mm. long, zoned from Ab_{25}–Ab_{45}. Augite, rare. Hypersthene, 1–5 percent, rarely more; 0.4–1.5 mm. long.	Plagioclase (Ab_{35}–Ab_{50}), 27–45 percent; a little interstitial andesine; monoclinic pyroxene, 30–48 percent; olivine, 0–7 percent; iron ore, both magnetite and ilmenite, 8–15 percent; apatite recognizable in some specimens; some contain glass.
Primitive picrite-basalt.	Porphyritic.		Olivine, 20–50 percent, 1–10 mm. long. Plagioclase, 0–5 percent, 1–5 mm. long, zoned from Ab_{20}–Ab_{45}. Augite, 0–5 percent, 1–10 mm. long.	Plagioclase (Ab_{30}–Ab_{45}), 20–30 percent; monoclinic pyroxene, 20–35 percent; olivine, 1–5 percent; iron ore, both magnetite and ilmenite, 5–15 percent; rare rutile; some specimens contain glass.
Augite-rich picrite-basalt.	Porphyritic.		Olivine, 15–25 percent, 5–10 mm. long. Plagioclase, 0–7 percent, 1–5 mm. long, zoned from Ab_{20}–Ab_{45}. Augite, 10–30 percent, 6–10 mm. long.	Plagioclase (Ab_{35}–Ab_{45}), 20–30 percent; monoclinic pyroxene, 20–35 percent; olivine, 1–5 percent; iron ore, both magnetite and ilmenite, 5–10 percent; some specimens contain glass.
Andesine andesite.	Porphyritic or nonporphyritic.		Olivine, rare, 0–5 percent, 1–4 mm. long. Plagioclase, 0–15 percent; 1–5 mm. long, rarely up to 20 mm., zoned from Ab_{20}–Ab_{70}. Augite, rare, 0–1 percent, 1–2 mm. long.	Plagioclase (Ab_{50}–Ab_{70}), 40–55 percent; monoclinic pyroxene, 20–40 percent; olivine, 1–10 percent; iron ore, magnetite commonly predominant over ilmenite, 10–20 percent; biotite, 0–3 percent; apatite recognizable in many specimens; a riebeckitelike amphibole, rare; some specimens contain glass.
Oligoclase andesite.	Porphyritic or nonporphyritic.	Trachytic. The trachyte pumice of Puu Waawaa is largely glass, but glass is not abundant elsewhere. Average grain size is commonly about 0.04 mm.	Olivine, rare, 0–1 percent, 1–7 mm. long. Plagioclase, 0–5 percent, 1–8 mm. long, zoned from Ab_{45}–Ab_{80}. Riebeckitelike amphibole, 0–1 percent, less than 1 mm. long. Basaltic hornblende, rare.	Plagioclase (Ab_{70}–Ab_{85}), 50–60 percent; monoclinic pyroxene, 15–30 percent; olivine, 1–8 percent; iron ore, mostly magnetite but some ilmenite, 10–25 percent; biotite, 0–2 percent; riebeckitelike amphibole, 0–1 percent; apatite, about 1 percent; hornblende, rare, 0–1 percent; some specimens contain glass.
Trachyte.	Porphyritic or nonporphyritic.		Olivine, 0–1 percent, rarely more; as much as 1 mm. long. Plagioclase, 0–10 percent, 1–4 mm. long, zoned from Ab_{70}–Ab_{95}. Hornblende, 0–1 percent, 1–2 mm. long, both brown and green. Riebeckitelike amphibole, 0–1 percent, less than 1 mm. long. Biotite, rare.	Plagioclase (Ab_{90}–Ab_{95}), 65–85 percent; monoclinic pyroxene, 5–25 percent; olivine, 0–5 percent; iron ore, largely or entirely magnetite, 5–15 percent; apatite, about 1 percent; biotite, 0–2 percent; green hornblende, 0–1 percent; some specimens contain glass.

recognized in the rocks of West Maui Volcano (Macdonald, 1942a, p. 322). It is distinctly pleochroic, with X=grayish brown or bluish gray and Z=pale yellowish brown, absorption $X>Y>Z$, nearly parallel extinction, negative elongation, moderate refringence, $+2V$ large (probably about 75°), and very low birefringence. It most closely resembles riebeckite. It commonly forms small microphenocrysts, many of which are partly resorbed. Rarely it occurs in the groundmass.

Apatite occurs as minute acicular grains enclosed in the feldspar of many rocks, and in a few of the oligoclase andesites it forms grains as much as 0.5 millimeter long and 0.1 millimeter thick.

The andesine andesites show all gradations into the basalts. In fact, most of the andesine andesites have a distinctly basaltic aspect, both in habit and in the abundance of mafic minerals. The oligoclase andesites appear to grade into the trachytes, although actual gradational examples are rare.

TRACHYTES

Most of the trachytes contain phenocrysts of plagioclase, and some contain also a few small phenocrysts of olivine. Hornblende, biotite, and the riebeckitelike mineral also occur sparingly as phenocrysts and are commonly partly resorbed with liberation of finely granular iron ore. The groundmass pyroxene is diopside in some specimens and aegirine-augite in others. Rarely the two occur together. A mineral in the trachyte of Puu Anahulu, Hualalai, may be acmite.

MAUNA LOA

GENERAL GEOLOGY

Mauna Loa is a broad shield volcano (pl. 11) more than 50 miles in north-south dimension from the Humuula Saddle to Ka Lae Point, and more than 60 miles in east-west dimension from the Kona coast to Leleiwi Point southeast of Hilo Bay. These diameters are determined by the arbitrary datum of sea level, and the true diameters at the ocean floor are much greater. Mauna Loa rises 13,680 feet above sea level and about 30,000 feet above the surrounding ocean floor. On the northeast and northwest, respectively, Mauna Loa overlaps the volcanoes Mauna Kea and Hualalai. On its southeast flank is located the much smaller volcano Kilauea, the low dome of which forms a scarcely perceptible bulge on the slope of the greater volcano. Allowing for interfingering of its lavas with those of the adjoining volcanoes, Mauna Loa probably covers an area of about 5,000 square miles and has a volume of the order of 10,000 cubic miles above the −15,000-foot contour level. Its enormous volume is especially impressive when it is compared to that of 80 cubic miles contained in Mount Shasta, Calif., which is probably the largest volcanic cone of the Cascade Range (Williams, 1934, p. 228).

The rocks of Mauna Loa have been divided, from oldest to youngest, into the Ninole volcanic series, the Kahuku volcanic series, the Pahala ash, and the Kau volcanic series (Stearns and Macdonald, 1946, pp. 63–81). The Ninole volcanic series was formerly termed the Ninole basalt (Stearns and Clark, 1930, p. 61). The Kahuku volcanic series represents the Mauna Loa portion of the rocks formerly termed the Pahala basalt (Stearns and Clark, 1930, p. 65) and the Kau volcanic series the Mauna Loa portion of the rocks formerly termed the Kamehame basalt (Stearns and Clark, 1930, p. 69). The name Pahala ash is here restricted to the thick ash deposits, which overlie the Kahuku volcanic series on Mauna Loa and correlative rocks on other volcanos and which were formerly designated as the upper member of the Pahala basalt (Stearns and Clark, 1930, p. 66).

The oldest rocks on Mauna Loa are found only in a small area in the Kau District, on the southeast side of the ridge built along the southwest rift zone. These rocks, the Ninole volcanic series, are regarded as probably of Tertiary age. The land mass formed by the Ninole lavas underwent extensive erosion, with the formation of large amphitheater-headed valleys more than 2,000 feet deep, resulting in a profound unconformity between the Ninole and later lavas. First Noble, and later Stearns, recognized the fact that the dips of the Ninole lavas projected from a point situated not at the present center of activity of Mauna Loa, under Mokuaweoweo, but at an altitude of about 10,000 feet on the southwest rift. This, together with the period of profound erosion following Ninole time, was taken as evidence that the Ninole lavas formed part of an ancient volcano situated southwest of the present Mauna Loa and now nearly buried by lavas of Mauna Loa. Such a conclusion, however, does not necessarily follow. Dips of the recent lavas of Mauna Loa for the most part do not project to the summit area, as they would in a volcano of approximately conical form, but instead project toward points on the rift zones from which they originated. Adjacent late lava flows have directions of dip similar to those in the Ninole lavas, which may well have originated along the rift zone of a volcano occupying the position of the present Mauna Loa. Nor does the period of erosion following Ninole time indicate that the Ninole Volcano was other than an early phase of Mauna Loa. Erosional periods at least equally great are known to have occurred during the history of East Maui Volcano (Stearns and Macdonald, 1942, pp. 53, 58).

The post-Ninole period of erosion was terminated by the eruption of a series of lavas and intercalated ash beds, known as the Kahuku volcanic series. In part of the Kau District these lava and ash beds lie unconformably on the Ninole volcanic series, but elsewhere their base is not exposed. Overlying the Kahuku volcanic series is the Pahala ash. The Kahuku lavas and Pahala ash have been recognized as kipukas projecting through the later lavas from the southwest rift zone around the southeastern and eastern slopes of the volcano nearly to its junction with Mauna Kea and up to an altitude of nearly 5,000 feet (pl. 12). Above that altitude and on the western and northern slopes of the mountain they appear to be buried by later lavas everywhere except possibly in the cliff at the north edge of Kealakekua Bay.

The post-Kahuku lavas of Mauna Loa and their associated pyroclastic materials have been named the Kau volcanic series. They overlie the Kahuku lavas essentially conformably, in most places being separated from them only by the thick bed of Pahala ash. In places where the ash is absent or where the thick bed is replaced by several thin beds with intercalated lavas, it is impossible to be certain of the contact between the two series. Along the Kahuku-Kaoiki fault system, on the south and southeast slopes of Mauna Loa, they are locally unconformable, the fault scarps that truncate Kahuku lavas being veneered with Kau lavas. The eruption of the Kau lavas has continued uninterrupted to the present time.

Mauna Loa has been active approximately 6.3 percent of historic time. Eruptions have occurred on an average of every 3.6 years (Macdonald, 1943, pp. 241–242). In a general way, eruptions in the summit caldera have alternated with eruptions from the rift zones lower on the flanks of the mountain. However, probably without exception, every flank eruption has commenced with activity in or near the summit caldera, so that activity in the summit area has been approximately twice as frequent as flank activity. Nevertheless, flank eruptions generally discharge much larger volumes of lava than summit eruptions. The outstanding feature of the latter is the ebullition of enormous quantities of gas. By far the greater number of flank eruptions in Kau time have been in the zone above 5,000 feet altitude. The lower part of the east rift zone, below 6,500 feet, has been completely inactive since Pahala time, and the only historic flow on the southwest rift of which the principal vents were situated below 5,000 feet is that of 1868. The area of mountain flank to be covered by lava increases as the square of the distance from the summit. This, together with the concentration of activity in the upper zone, has resulted in a cap of Kau lavas that is thick in the center and thin and discontinuous around the edges. The Kau lavas are more than 600 feet thick in the walls of Mokuaweoweo caldera but do not exceed a few tens of feet in thickness along the lower eastern and southeastern slopes.

LAVAS OF THE NINOLE VOLCANIC SERIES

The lavas of the Ninole volcanic series include olivine basalt, basalt, picrite-basalt, and hypersthene-bearing basalt. The proportions of the various rock types, among specimens chosen at random, are indicated in the table on page 57. The great predominance of olivine basalt in the series is evident. The Ninole lavas include both aa and pahoehoe types. They are typically light or medium gray in color and moderately to highly vesicular. Olivine phenocrysts are generally sparse and small, feldspar phenocrysts are rare, and augite phenocrysts have not been found.

No hypersthene has been found by the writer in Ninole lavas, but it was reported by Cross (1915, p. 160) and Washington (1923b, p. 123) in a basalt exposed at Clover Hill, 0.9 mile northwest of Naalehu.

Chemical analyses of an olivine basalt and a hypersthene-bearing basalt of the Ninole volcanic series are given in columns 1 and 2 of the table on page 63.

Approximate percentages of principal rock types in the groups of lavas of Mauna Loa and Kilauea

Volcano	Geologic formation		Olivine basalt	Basalt	Primitive picrite-basalt	Hypersthene-bearing basalt
Kilauea.	Puna volcanic series.	Historic	80	13	7	2
		Prehistoric	71	22	5	2
	Hilina volcanic series		67	30	3	0
Mauna Loa.	Kau volcanic series.	Historic	16	26	11	47
		Prehistoric	43	26	21	10
	Kahuku volcanic series		42	28	20	10
	Ninole volcanic series		62	15	15	8

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LAVAS OF THE KAHUKU VOLCANIC SERIES

The lavas of the Kahuku volcanic series are dominantly olivine basalt but include also basalt, picrite-basalt of the primitive type, and hypersthene-bearing basalt. A basalt in which the norm indicated andesitic tendencies was described by Washington (1923b, p. 124) and stated to be of Pahala [Kahuku] age but has since been shown to be of Kau age (Stearns and Clark, 1930, p. 161). It has been suggested that the Kahuku lavas are on the average a little more mafic than the Ninole lavas (Stearns and Clark, 1930, p. 160), but that is not borne out by the present investigation. The percentage of picrite-basalt is a little greater in the Kahuku than in the Ninole lavas, but the increase in percentage of basalt as compared to olivine basalt is greater yet. The real difference between the two series probably arises from the existence of lower temperatures in the magma chamber during eruption of the Kahuku lavas, resulting in the more general formation of intratelluric phenocrysts and settling of these to produce more abundant magma of differentiated types.

Olivine phenocrysts are common in the Kahuku lavas but are generally small. Most specimens contain feldspar phenocrysts, but augite phenocrysts have not been found.

A hypersthene basalt that forms a massive flow near the top of Kahuku Pali, 5 miles north of Kalae Point, is so unusual that it merits individual description. In a hand specimen it is a medium gray sparingly vesicular pahoehoe containing many phenocrysts of olivine up to 2 millimeters across. The olivine phenocrysts are slightly rounded and embayed by resorption but are not altered to iddingsite. Many are surrounded by thin jackets of hypersthene. Other grains of hypersthene are scattered throughout the groundmass and are commonly poikilitic, with inclusions of all the other groundmass minerals. A few small acicular crystals of deep reddish-brown basaltic hornblende also are present and are strongly resorbed and heavily charged with exsolved iron ore. The approximate mineral composition of the rock is:

	Percent
Olivine (phenocrysts)	10
Hypersthene	20
Basaltic hornblende	1
Monoclinic pyroxene	25
Medium labradorite	38
Iron ore (both magnetite and ilmenite)	5
Glass	1

This is the only lava found on the island of Hawaii in which hypersthene comprises more than 2 percent and the only basaltic rock found to contain hornblende.

A fairly common feature in the Kahuku lavas, as well as in those of the other groups, is a thin layer of glass surrounding the vesicles. This is well shown in an olivine basalt at a depth of 73 to 81 feet in the shaft of the Olaa well. Each vesicle is surrounded by a shell about 0.1 millimeter thick, which is much richer in glass than is the rest of the rock, the glass being rendered black and opaque by abundant finely granular iron ore. The glassy shell apparently results from local chilling caused by expansion of the gas bubble that formed the vesicle.

PAHALA ASH ON MAUNA LOA AND KILAUEA

In many places the Pahala ash is sufficiently consolidated to be termed tuff. Separation of the ash and tuff phases is, however, not practical, either in mapping or in discussion. The Pahala ash has been described in detail at many localities by Wentworth (1938, pp. 41–56, 137–141), and its characteristics will be only briefly summarized here. Many specimens of Pahala ash have been examined by immersion methods, and Wentworth has kindly loaned the writer several thin sections.

The ash ranges in color from predominantly light buff or tan in dry areas to reddish brown in areas of high rainfall. Gray colors are less common but are not rare. In most places the ash consists largely of sandy to silty material, through which are scattered lapilli up to 1 or 2 centimeters in diameter. In places the lapilli are scattered sporadically through the ash, but more generally they are concentrated in certain bands, giving rise to crude bedding. Lapilli beds are especially prominent at Hilina Pali, on the south slope of Kilauea. More or less well developed finer lamination is present in some localities and is caused by minor differences in texture of successive layers of the fine material. The lapilli are generally pumiceous and closely resemble the basaltic pumice produced by lava fountains during eruptions of Mauna Loa and Kilauea.

The Pahala ash is typically composed of pale brown to brownish-green pumiceous glass fragments. Many shards show the characteristic outlines resulting from the shattering of highly vesicular glass. Some glass fragments are rendered black and opaque by abundant finely disseminated iron ore. Rarely the lapilli are partly or even entirely crystalline. Olivine and plagioclase phenocrysts occur embedded in the glass or scattered through the ash. The glass is invariably partly altered, generally to yellowish-brown or orange palagonite. The palagonite is partly massive and isotropic and partly in minute doubly refracting fibers. The refractive index of the palagonite was found to range in different specimens from 1.537 to 1.547. Alteration to palagonite appears to start at the edges of the grains and to proceed inward. In general the glass, which is black and opaque owing to abundant finely granular iron ore that has separated from solution, appears to be less readily altered than the clear glass, in which the ore has remained in solution. Many specimens in which the original glassy material has been completely altered to palagonite still show the outlines of pumice lapilli.

Wherever possible, the composition of the plagioclase grains in the lapilli or scattered through the ash was determined in immersion media. In every specimen they were labradorite or sodic bytownite, corresponding to the plagioclase in the associated basaltic lavas. The refractive index of the fresh glass fragments is close to 1.60, which corresponds to basaltic glass (George, 1924). There can be little doubt that the composition of this portion of the ash was originally basaltic, but fresh glass fragments have been found only close to Kilauea, and so this conclusion cannot be extended to the ash as a whole. The regular decrease in thickness away from Mauna Kea shows that much of the ash was derived from that source. The late cones of Mauna Kea, which produced much of the ash, are partly basaltic but very largely andesitic. Most of the Pahala ash on Mauna Kea and the east slope of Mauna Loa probably was originally mafic andesite in composition.

The following table shows two analyses of Pahala palagonitic ash, quoted from Wentworth, compared with the average of 13 basalts of Mauna Loa. Sample 1 consisted of as nearly pure a separation of palagonite as it was possible to attain. Columns 3 and 4 of the table show the analyses of the same two samples of palagonite tuff recalculated to 100 percent on a water-free basis for easier direct comparison with the basalt analysis.

Composition of Pahala palagonitic ash

	1	2	3	4	5
SiO_2	45. 34	46. 03	54. 28	52. 74	50. 08
Al_2O_3	12. 56	13. 38	15. 04	15. 31	11. 06
Fe_2O_3	12. 20	9. 28	14. 61	10. 63	2. 83
FeO	1. 14	4. 22	1. 36	4. 84	8. 99
MgO	2. 72	3. 45	3. 26	3. 95	10. 62
CaO	2. 10	5. 67	2. 51	6. 50	9. 73
Na_2O	2. 44	1. 04	2. 92	1. 19	2. 13
K_2O	1. 27	. 38	1. 52	. 44	. 42
H_2O+	9. 20	6. 62			. 46
H_2O-	7. 02	6. 05			. 19
TiO_2	3. 54	2. 93	4. 22	3. 36	3. 18
P_2O_5	. 12	. 58	. 14	. 65	. 26
MnO	. 12	. 34	. 14	. 39	. 10
	99. 77	99. 97	100. 00	100. 00	100. 05

1. Palagonite from Pahala ash at coast 0.5 mile east of Kalae Lighthouse. Analyst, J. G. Fairchild. (Wentworth, 1938, p. 128.)
2. Pahala ash, at 600 feet altitude in face of Puu Kapukapu, 0.5 mile east of summit. Analyst, Charles Milton. (Wentworth, 1938, p. 128.)
3. Sample 1, recalculated to 100 percent on water-free basis.
4. Sample 2, recalculated to 100 percent on water-free basis.
5. Average of 13 analyses of basalts of Mauna Loa.

As pointed out by Peacock (1926, pp. 67–74) and by Wentworth (1938, p. 131), the changes involved in palagonitization are principally hydration, nearly complete oxidation of the iron, and partial loss of lime and magnesia. Silica is removed to a lesser extent in some palagonites. Alumina, titania, and iron oxide undergo relative concentration by the removal of other materials. The alkalies in some specimens are leached out but in others are slightly concentrated, probably by adsorption.

Wentworth (1938, p. 132) is of the opinion that the palagonitization is probably a hydrothermal process taking place chiefly at the time of eruption of the ash. However, examination of many recent deposits of vitric ash of Mauna Loa and Kilauea, similar to those from which the Pahala ash appears to have been derived, has revealed no traces of palagonitization. The writer considers it more probable that the palagonitization of the Pahala ash was a process of ordinary weathering. However, it is not intended to extend this conclusion to the palagonite tuff cones such as those on the island of Oahu, which were erupted through the ocean or through water-saturated sediments. The ash of such cones probably contains on deposition a large amount of hot salt water, and alteration of the glass probably proceeds very rapidly.

KAU VOLCANIC SERIES

LAVAS OF PREHISTORIC AGE

The lavas of prehistoric age of the Kau volcanic series are more widely exposed at the surface than any of the other groups of lavas of Mauna Loa. Like the earlier lavas, they are predominantly olivine basalt, but basalt and picrite-basalt are more abundant than in either of the earlier groups. (See table, p. 61.) Hypersthene-bearing rocks are present in about the same proportion as among the earlier lavas. Basalts with distinct andesitic tendencies make their first appearance but are still rare. True andesites are unknown.

Both aa and pahoehoe types are present. Many flows are pahoehoe near the vent and change to aa farther down the slope, so that in general the abundance of aa increases seaward. Some flows, however, such as the one of 1881 which entered the outskirts of Hilo, remain pahoehoe to their very ends, and conversely a few flows appear to issue from the vent as aa. Many of the pahoehoe flows on the upper flanks of Mauna Loa are exceedingly frothy and may show the effects of extreme vesiculation in a layer of pumice, a quarter of an inch to 2 inches thick, on the surface of the flows. The formation of these pumiceous flow tops was first recorded by Green (1887, pp. 281–282). The pumice is of the variety that has essentially equidimensional cells, termed "thread-lace scoria" by Dana (1888, pp. 223–226) and "reticulite" by Wentworth and Williams (1932, p. 41). The pumiceous flow tops are the result of vesiculation of the flows themselves and are not the result of accumulation of pyroclastic pumice on the flows. The earliest lavas of an eruption commonly exhibit the pumiceous top, whereas the later lavas of the same eruption, having a smaller gas content, are lacking in pumice.

The following stratigraphic section, measured in the west wall of Mokuaweoweo caldera 0.65 mile northeast of benchmark 13,680 feet, is typical of the Kau volcanic series. A section with a thickness of 600 feet is exposed 0.6 mile farther southeast but is inaccessible for study

Section of Kau volcanic series in west wall of Mokuaweoweo caldera

	Feet
Top of cliff	
Basalt aa, with about 1 percent olivine phenocrysts and 2 percent feldspar phenocrysts reaching 2 mm. in length	5
Olivine basalt pahoehoe, with about 5 percent olivine phenocrysts as much as 2 mm. long and 2 percent feldspar phenocrysts as much as 1 mm. long	8
Basalt pahoehoe, with about 1 percent each of olivine and feldspar phenocrysts as much as 1 mm. long	10
Basalt pahoehoe, with about 2 percent each of olivine and feldspar phenocrysts as much as 1.5 mm. long	5
Do	4
Olivine basalt pahoehoe, with about 10 percent olivine phenocrysts as much as 3 mm. long	4
Olivine basalt pahoehoe, with about 8 percent olivine phenocrysts as much as 2 mm. long. Composed of several thin flow units averaging about 8 in. thick	8
Olivine basalt pahoehoe, with about 7 percent olivine phenocrysts as much as 2 mm. long	5
Do	3
Olivine basalt pahoehoe, with about 4 percent olivine phenocrysts	4
Olivine basalt pahoehoe, with about 7 percent olivine phenocrysts	3
Basalt pahoehoe, with about 2 percent olivine phenocrysts as much as 1.5 mm. long	3
Olivine basalt pahoehoe, with about 5 percent olivine phenocrysts as much as 3 mm. long	4
Basalt pahoehoe, with about 2 percent olivine phenocrysts as much as 2 mm. long	2
Do	1
Do	11
Break in section; continued 300 feet to the southwest.	
Basalt pahoehoe, with about 2 percent olivine phenocrysts as much as 2 mm. long	9
Olivine basalt pahoehoe, with about 7 percent olivine phenocrysts as much as 2 mm. long. Composed of several thin flow units averaging about 6 in. thick	3
Olivine basalt pahoehoe, with about 7 percent olivine phenocrysts and a few feldspar phenocrysts as much as 2 mm. long	4
Like that above; some of the olivine phenocrysts very tabular	2
Do	5
Olivine basalt pahoehoe; olivine phenocrysts as much as 1.5 mm. long	5
Basalt pahoehoe, containing about 1 percent each of olivine and feldspar phenocrysts as much as 1 mm. long. The rock is moderately dense and banded, with some very dense bands	19
Basalt pahoehoe, nonporphyritic	14
Basalt pahoehoe, with about 3 percent each of olivine and feldspar phenocrysts as much as 2 mm. long	4
Do	8
Olivine basalt pahoehoe, like that below, but composed of many thin flow units averaging about 5 in. thick. The content of olivine phenocrysts ranges from 4 to 10 percent	34
Olivine basalt pahoehoe, with about 10 percent olivine phenocrysts as much as 3 mm. long	10
Olivine basalt pahoehoe, containing about 5 percent each of olivine and feldspar phenocrysts as much as 2 mm. long. Consists of many thin lenticular flow units averaging about 3 in. thick	2
Olivine basalt pahoehoe, containing about 20 percent olivine phenocrysts as much as 5 mm. long	15
Olivine basalt pahoehoe, containing about 20 percent olivine phenocrysts as much as 6 mm. long and many feldspar phenocrysts as much as 1.5 mm. long	7
Picrite-basalt pahoehoe, with about 30 percent olivine phenocrysts as much as 8 mm. long and many feldspar phenocrysts as much as 1.5 mm. long	4
Do	5
Olivine basalt pahoehoe, with about 15 percent olivine phenocrysts as much as 7 mm. long	8
Picrite-basalt pahoehoe, containing about 25 percent olivine phenocrysts as much as 8 mm. long. The lower part is very dense	20
Picrite-basalt pahoehoe, with about 30 percent olivine phenocrysts as much as 1 cm. long	10
Olivine basalt pahoehoe, composed of thin flow units averaging about 8 in. thick. Olivine phenocrysts as much as 4 mm. long range in abundance from about 10 to 15 percent	12
Like that above, with about 8 percent olivine phenocrysts as much as 3 mm. long and less abundant feldspar phenocrysts as much as 1.5 mm. long	5
Basalt pahoehoe, nonporphyritic	5
Basalt pahoehoe, containing about 2 percent olivine phenocrysts as much as 1.5 mm. long. Consists of many thin flow units averaging about 6 in. thick	12
Pod-shaped basalt porphyry intrusive body, fed by a dike and showing slightly discordant relations to the enclosing beds. (See p. 62)	26
Olivine basalt pahoehoe, with about 4 percent olivine phenocrysts as much as 2 mm. long largely altered to iddingsite	4
Olivine basalt pahoehoe, with about 15 percent olivine phenocrysts as much as 3 mm. long. The groundmass is reddish brown in color	8
Olivine basalt pahoehoe, with about 5 percent olivine phenocrysts as much as 2 mm. long	3
Basalt pahoehoe, with about 2 percent olivine phenocrysts as much as 1.5 mm. long	5
Basalt pahoehoe, essentially nonporphyritic but with rare olivine phenocrysts as much as 1 mm. long. Consists of many thin flow units averaging about 2 in. thick. Cut by a dike of olivine basalt 1 ft. thick, containing about 5 percent olivine phenocrysts as much as 2 mm. long	10
Olivine basalt pahoehoe, containing about 7 percent olivine phenocrysts as much as 3 mm. long. The size and abundance of the phenocrysts decrease slight upward	12
Basalt pahoehoe, nonporphyritic	5
Olivine basalt pahoehoe, with about 15 percent olivine phenocrysts as much as 4 mm. long and a few feldspar phenocrysts as much as 1 mm. long. Cut by a dike of olivine basalt 9 in. thick, containing about 5 percent olivine phenocrysts as much as 2 mm. long	6
Picrite-basalt pahoehoe, with about 35 percent olivine phenocrysts as much as 1 cm. long. Composed of thin flow units averaging about 6 in. thick	4
Picrite-basalt, like that above, but consisting of a single massive bed. The vesicles contain small botryoidal growths of calcite. Base hidden by the 1942 lava	7
Slump scarp of 1942 lava; black glassy crustal phase of basalt pahoehoe	18
Total thickness of section	410

owing to the extreme steepness of the cliff. The rock types range from nonporphyritic basalt containing little olivine to picrite-basalt containing abundant olivine phenocrysts. The relative abundance of flows poor in olivine phenocrysts increases toward the top of the section. The rocks were mostly named from hand-lens examination only.

Olivine phenocrysts are present in most of the Kau lavas. They are commonly partly resorbed and rarely show narrow reaction rims of finely granular monoclinic pyroxene. Plagioclase phenocrysts are widespread although not nearly so abundant as those of olivine. Augite phenocrysts occur in both the olivine basalts and the picrite-basalts but are rare. In the earlier groups of lavas no basalts are known that are entirely free of olivine, but several such rocks have been found among the Kau lavas.

Basalts exposed along the highway north of Kealakekua, in Kona, contain minute brown acicular crystals with high birefringence, straight extinction, and no distinct pleochroism, which are probably rutile. The same mineral was noted in a picrite-basalt at the top of the sea cliff 0.4 mile north of Napoopoo (pl. 12). A bright-yellow prismatic mineral resembling rutile was observed by Cross (Stearns and Clark, 1930, p. 162) in a specimen of basalt collected 1.5 miles northeast of Hilea, in the Kau District.

Small amounts of hypersthene are present in many of the Kau lavas. Hypersthene is known from the lavas of several other Hawaiian volcanoes (Macdonald, 1942a, p. 317), but only in the lavas of the Koolau volcano, on Oahu (Wentworth and Winchell, 1947, p. 66), is it as common as in the Kau lavas.

Although some of the basalts, both with and without olivine, show an approach to the andesites in the composition of their feldspars, the writer has found no true andesite among the lavas of Mauna Loa. Washington (1923b, pp. 114–116) described a specimen said to come from the lava flow beneath the City of Refuge at Honaunau, Kona, which he classified as an "oligoclase basalt" but which would be classed by the writer as an andesite. However, specimens collected by the writer from the pahoehoe flow on which the City of Refuge is built, do not correspond in composition to that described by Washington. They are an olivine basalt in which the feldspar is intermediate labradorite (β= 1.563), with a few scattered anhedral grains of andesine. Because of the possibility that Washington's specimen was wrongly located, it appears best to omit the analysis in a consideration of lavas of Mauna Loa.

The Keamoku flow from Mauna Loa, which reaches the highway 2 miles west of Kilauea caldera, is probably the lava described as the 1823 flow of Kilauea by Cross (1915, p. 39) and Washington (1923b, p. 112). It was classified by Washington as "andesine-basalt," but as in the other rocks so classified by him the index of refraction of the feldspar, determined by immersion methods, shows it to be labradorite. The rock is a hypersthene-bearing basalt.

LAVAS OF HISTORIC AGE

The lavas of Mauna Loa that have been erupted during historic times include representatives of all the major rock types among the earlier lavas, but basalts and hypersthene-bearing lavas are much more prominent than among the earlier groups. In the following table are listed all the historic eruptions of Mauna Loa of which the lava can now be identified, together with the type of rock constituting each flow, the rift zone on which the eruption took place, and the approximate altitude of the principal vent. Most of the eruptions in the summit caldera have necessarily been omitted, because their lavas have been buried by those of later eruptions and are no longer available for study, but all the historic flank eruptions are represented.

Types of lava produced by historic eruptions of Mauna Loa

Date	Location	Approximate altitude of principal vent (feet above sea level)	Type of rock
1750?	North flank [1]	7, 800	Hypersthene-bearing basalt.
1832?	Southwest rift?	8, 200?	Do.
1843	North flank	7, 900	Do.
1851	Summit	13, 300	Basalt.
1852	Northeast rift	8, 400	Picrite-basalt.
1855	do	10, 500	Olivine basalt.
1859	North flank	9, 200	Basalt.
1868	Southwest rift	3, 300	Picrite-basalt.
1880–81	Northeast rift	10, 400	Hypersthene-bearing basalt.
1887	Southwest rift	5, 700	Do.
1899	Northeast rift	10, 700	Do.
1907	Southwest rift	6, 200	Do.
1916	do	7, 400	Do.
1919	do	7, 700	Olivine basalt.
1926	do	7, 600	Do.
1933	Summit	13, 000	Basalt.
1935	Northeast rift	12, 100	Do.
1940	Summit	13, 000	Hypersthene-bearing olivine basalt.
1942	Northeast rift	9, 200	Basalt.

[1] Keamoku flow, on north flank of Mauna Loa.

Four of these lavas, those of the eruptions of 1859, 1880–81, 1887, and 1919, were stated by Washington (1923b, p. 112) to contain modal andesine. Examination of crushed samples of these rocks in oils of known refractive index, has however, revealed no andesine. In each, the feldspar is labradorite. The normative feldspar is in some rocks andesine and in others labradorite (see p. 63), but in all it is close to the andesine-labradorite line. In each, except the lava of 1881, the modal plagioclase was distinctly more calcic than that of the norm. The same is true of the picrite-basalt of the 1868 flow. Likewise, in all analyzed historic lavas except that of 1852, modal olivine was found to be considerably more abundant than that of the norm, probably because of the so-called Bowen-Anderson effect, which has been discussed in relation to Hawaiian lavas by Washington (1923a, pp. 469–470).

INCLUSIONS IN LAVAS

Dunite and gabbro inclusions have long been known to exist in the lavas of other Hawaiian volcanoes but do not appear to have been recorded previously from Mauna Loa. Small angular dunite inclusions, averaging about 1 centimeter across, are present in a lava transitional to picrite-basalt, which is exposed along the highway 2.68 miles north of Kealakekua. They are composed entirely of olivine, except for scattered grains of an opaque ore mineral, probably magnetite.

A few gabbro inclusions occur in an olivine basalt at the coast 0.6 mile north of Kuamoo Point. They are angular, ranging up to 5 centimeters in length, and have an average grain size of about 1 millimeter. The rock is a troctolite, composed of anhedral grains of intermediate labradorite (75 percent), olivine (15 percent), and iron ore (10 percent). No pyroxene could be found. The olivine grains are slightly altered to iddingsite. An olivine basalt exposed along the highway 2.1 miles southeast of the south boundary of the Kona District contains small angular inclusions of gabbro composed of labradorite, augite, olivine, and iron ore. The gabbro has an open miarolytic structure similar to certain gabbros from West Maui Volcano (Macdonald, 1942a, pp. 328–330). Similar gabbro xenoliths are present in cores from depths of 56 to 100 feet in a test boring 0.9 mile west of Kurtistown, on the east flank of Mauna Loa.

INTRUSIVE ROCKS

Several dikes are exposed in the walls of Mokuaweoweo caldera and in the adjacent pit craters, South Pit and Lua Poholo. Some of these can be seen to feed pod-shaped intrusive bodies (pl. 14, *A*) which are essentially parallel to the bedding but locally cut across it. One of these intrusive bodies, in the west wall of the caldera 0.65 mile northeast of benchmark 13,680 feet, shows the effects of gravitative crystal differentiation. The upper chilled phase contains about 7 percent olivine phenocrysts. Below this is a nonporphyritic zone about 10 feet thick in which the rock is medium gray and vesicular. The vesicles are of the type resembling miarolytes in granitoid rocks, irregular in outline, with many small inward-projecting crystals of feldspar and pyroxene. Below the nonporphyritic zone is a zone of porphyritic rock containing an average of about 12 percent olivine phenocrysts, some of them up to 8 millimeters long. In other respects the rock resembles that of the nonporphyritic zone.

EJECTED BLOCKS NEAR MOKUAWEOWEO

Angular blocks of rock ejected by explosions are scattered about the rim of Mokuaweoweo. They include all the rock types described in the stratigraphic section of the caldera wall (p. 60). Especially prominent is a light-gray dense variety, essentially nonporphyritic but with a few small phenocrysts of olivine. Many of these exhibit small miarolytelike vesicles lined with projecting feldspar crystals. The blocks attain maximum dimensions of about 3 feet on the east rim of the caldera and 5 feet on the west rim. Lithic ash is prominent in the vicinity of Pendulum Peak, on the east rim, averaging about 4 inches thick. Individual fragments range in size from dust to blocks 2 feet across. No magmatic ejecta have been found associated with the blocks, and none of the blocks show bread-crust cracking or other evidence of reheating. Therefore the explosions almost certainly were phreatic.

The distribution of the ejected blocks is not uniform. On both east and west rims they are confined to the central sectors and are absent near the rift zones, where they have been buried by later lavas. The variation in abundance of the blocks on different adjacent lava flows indicates a succession of explosive periods rather than a single big explosion. The time of most of the explosions is believed to have been at least several hundred years ago, because many of the lava flows that are later than the blocks appear quite old. At Pendulum Peak the blocks were already present in 1841, and some of them were used in construction of the walls of the camp built there by Lieutenant Wilkes during that year. It has been suggested by Jaggar (1934, p. 6) that some of the blocks were ejected during the summit eruption of 1877, at which time there was an unusually high fume column towering 16,000 feet above the mountain-top. If so, however, the new blocks must have been confined to sectors of the rims where older blocks had escaped inundation by lava flows, for in many places lavas certainly much older than 1877 are entirely devoid of ejected blocks.

CHEMICAL ANALYSES

The accompanying table contains all the modern chemical analyses of rocks of Mauna Loa that appear reliable. Analyses of several other lavas of Mauna Loa and Kilauea were published by McGeorge (1917, p. 4), but the specimens are poorly located and the analyses appear probably to be too high in alumina. They have therefore been omitted.

The chemical analyses of Mauna Loa will be discussed in connection with those of Kilauea (p. 72).

SURFICIAL ASH DEPOSITS AT THE SOUTH EDGE OF KILAUEA CALDERA.

Well-bedded prehistoric vitric tuffs are overlain unconformably by tuff-breccia of the explosions of 1790.

A. A SMALL LENTICULAR SILL, 26 FEET THICK, AND ITS DIKE FEEDER, CUTTING LAVAS OF THE KAU VOLCANIC SERIES IN THE WEST WALL OF MOKUAWEOWEO CALDERA.

B. CROSS SECTION OF A THICK AA FLOW OF ANDESITE BELONGING TO THE LAUPAHOEHOE VOLCANIC SERIES EXPOSED IN A QUARRY NEAR PAAUILO ON THE NORTHEASTERN SLOPE OF MAUNA KEA.

The dense central portion is overlain by a thick upper clinker phase and underlain by a thinner lower clinker phase. The base of the lower clinker phase rests on a thin bed of tuffaceous soil just below the hammer handle.

Chemical analyses and norms of lavas of Mauna Loa

Analyses

	Ninole lavas		Kau volcanic series												
			Lavas of prehistoric age				Lavas of historic age								Olivine
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	48.60	49.24	45.97	49.24	50.41	52.14	48.57	49.27	51.55	51.82	51.90	52.28	52.30	52.65	40.42
Al_2O_3	10.75	12.72	5.98	13.51	12.37	13.60	10.51	9.38	13.59	13.66	11.69	10.83	11.84	12.12	.32
Fe_2O_3	3.92	4.27	5.86	3.86	1.94	2.31	2.19	1.28	2.33	1.50	2.24	1.90	2.06	2.19	.15
FeO	9.38	8.44	7.39	8.88	9.56	8.80	9.45	10.31	9.04	9.68	8.84	9.30	9.03	8.87	11.44
MgO	9.80	7.10	23.55	5.90	7.68	7.26	17.53	17.74	8.02	7.24	7.37	7.69	7.15	7.43	47.08
CaO	10.38	9.74	6.47	10.44	12.56	10.14	8.06	7.46	10.31	10.09	9.87	10.03	10.60	10.12	.23
Na_2O	2.54	1.87	1.50	2.40	1.68	2.02	1.59	1.80	2.43	2.30	2.07	2.29	2.47	2.25	------
K_2O	.34	.28	.42	.46	.40	.48	.34	.42	.27	.30	.41	.51	.49	.35	------
H_2O+	.22	1.57	.64	.70	.22	.16	.37	.12	.07	.11	.31	.15	.15	.24	------
H_2O-	.06	1.15	.04	.47	None	.06	.10	.06	.02	.01	.04	.08	.03	.07	------
TiO_2	3.37	3.40	1.75	3.70	2.26	2.20	1.48	2.58	1.98	2.07	4.89	4.43	3.98	3.52	.08
P_2O_5	.18	.08	.21	.17	.57	.29	.19	.26	.24	.39	.28	.32	.28	.25	------
MnO	.05	.10	.11	.12	.06	.07	.16	.09	.12	.13	.11	.12	.10	.11	.10
CO_2	None	None	None	None	------	------	None	------	------	------	------	------	------	------	------
Cr_2O_3	------	------	------	------	.05	.02	.10	------	.08	.04	------	------	------	------	.18
NiO	------	------	------	------	.004	.005	.08	------	------	------	------	------	------	------	.34
	99.59	99.96	99.89	99.85	99.76	99.55	100.72	100.77	100.05	99.37	100.02	99.93	100.48	100.17	100.34

Norms

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Quartz	------	8.28	------	5.10	4.08	6.90	------	------	2.82	4.68	9.96	7.74	6.42	7.98	------
Orthoclase	2.22	1.67	2.78	2.78	2.22	2.78	2.22	2.22	1.67	1.67	2.22	2.78	2.78	2.22	------
Albite	21.48	15.72	12.58	21.68	14.15	16.77	13.62	15.20	20.44	19.39	17.82	19.39	20.96	18.86	------
Anorthite	16.96	25.58	8.34	24.46	25.30	26.69	20.29	16.40	25.30	26.13	18.63	17.79	19.74	21.96	0.97
Nepheline	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------
Diopside	27.15	17.57	17.25	20.67	27.17	17.62	15.14	14.89	20.30	17.28	22.95	24.16	24.91	21.10	------
Hypersthene	18.35	15.20	19.62	12.19	18.10	20.22	22.88	27.67	21.72	22.97	14.00	15.75	14.19	17.24	------
Olivine	1.25	------	26.34	------	------	------	20.35	16.74	------	------	------	------	------	------	[a] 98.43
Magnetite	5.57	6.26	8.58	5.57	2.78	3.25	3.25	1.86	3.25	2.09	3.25	2.78	3.02	3.25	.23
Ilmenite	6.38	6.54	3.34	6.99	4.41	4.26	2.89	4.86	3.80	3.95	9.27	8.36	7.60	6.69	.15
Apatite	.34	.34	.67	.67	1.34	.67	.34	.67	.34	1.01	.67	.67	.67	.67	------

[a] The normative olivine contains forsterite 82.29 percent, fayalite 15.94 percent, tephroite 0.20 percent; chromite 0.22 percent and NiO 0.34 percent are also present in the norm.

1. Olivine basalt, Kaumaikeohu Spring, Kau District. Analyst, R. K. Bailey. (Washington 1923b, p. 122.)
2. Hypersthene-bearing basalt, Clover Hill, 0.9 mile northwest of Naalehu, Kau District. Analyst, R. K. Bailey. (Washington, 1923b, p. 122.)
3. Picrite-basalt, Makanao Valley, 1.5 miles northwest of Hilea, Kau District. Analyst, R. K. Bailey. (Washington, 1923b, p. 122.)
4. Basalt, 0.7 mile north of Naalehu, Kau District. Analyst, R. K. Bailey. (Washington, 1923b, p. 122.)
5. Olivine basalt, on volcano highway at southern boundary of Waiakea Forest Reserve, 1.65 miles northwest of the mill at Olaa. Analyst, J. J. Fahey. (Powers, 1931, p. 2.)
6. Olivine basalt, reservoir No. 1, Piihonua, near Hilo. Analyst, J. J. Fahey. (Powers, 1931, p. 2.)
7. Picrite-basalt, lava flow of 1852. Analyst, G. Steiger (Daly, 1911, p. 296). Norm from Washington (1923b, p. 116).
8. Picrite-basalt, lava flow of 1868. Analyst, H. S. Washington (1923b, p. 115).
9. Basalt, lava flow of 1926, at 1,400 feet altitude near highway. Collector, T. A. Jaggar. Analyst, E. S. Shepherd (1938, p. 336).
10. Basalt, lava flow of 1926, pumiceous phase near summit. Collector, T. A. Jaggar. Analyst, E. S. Shepherd (1938, p. 335). Total includes S=0.02, and BaO=trace.
11. Hypersthene-bearing basalt, lava flow of 1887. Analyst, H. S. Washington (1923b, p. 113).
12. Basalt, lava flow of 1859. Analyst, H. S. Washington (1923b, p. 113).
13. Olivine basalt, lava flow of 1919. Analyst, H. S. Washington (1923b, p. 113).
14. Hypersthene-bearing basalt, lava flow of 1881, near Hilo. Analyst, H. S. Washington (1923b, p. 113).
15. Olivine phenocryst from 1852 lava. Analyst, G. Steiger. (Daly, 1911, p. 295.)

KILAUEA

GENERAL GEOLOGY

Kilauea is a basaltic shield volcano situated on the southeast flank of Mauna Loa, probably at the intersection of gravity faults in the flank of Mauna Loa with the more easterly of the two fundamental zones of fissuring that gave rise to the Hawaiian volcanoes (Stearns and Clark, 1930, p. 103). The shield is elongated in a nearly east-west direction, owing to building along the two major rift zones.

Along the south coast of Kilauea fault scarps expose lavas and intercalated ash beds overlain by a thick layer of yellow ash. The thick upper ash bed is believed to be correlative in time with the Pahala ash on Mauna Loa (Stearns and Clark, 1930, pp. 65–68). The lavas underlying the ash formerly were grouped with the Kahuku lavas on Mauna Loa as the Pahala basalt. However, projection of the dips of the Kahuku lavas beneath Kilauea shows that at the fault cliffs along the southern shore the Kahuku lavas, if present, lie well below sea level. The lavas underlying the Pahala ash in the fault cliffs, as much as 1,400 feet above sea level, are therefore believed to have been erupted by Kilauea Volcano and have been renamed the Hilina volcanic series (Stearns and Macdonald, 1946, p. 102).

Overlying the Pahala ash in the southern fault cliffs and covering most of the surface of the Kilauean shield is a series of lava flows with minor amounts of intercalated ash, named the Puna volcanic series (Stearns and Macdonald, 1946, p. 103). Some of the Puna lavas probably were erupted at or near the apex of the volcano before the formation of the summit caldera, but most of them were poured out along the rift zones on the flanks of the volcano. The eruption of the Puna volcanic series, like the Kau volcanic series on Mauna Loa, has continued without interruption to the present time.

The thickness of the cap of Puna lavas exceeds 400 feet in the walls of Kilauea caldera but decreases to only a few tens of feet at the fault cliffs along the southern coast. Its thickness along the rift zones is entirely unknown. Lavas of the Puna and Kau volcanic series undoubtedly are interfingered along the contact between Kilauea and Mauna Loa.

HILINA VOLCANIC SERIES

Among the rocks of the Hilina volcanic series olivine basalts are approximately twice as abundant as basalts (table, p. 57). Primitive picrite-basalt is very rare. However, exposures are limited to small windows in the fault cliffs along the south coast of Kilauea and may not be fairly representative of the series as a whole.

The olivine basalts are entirely normal. Olivine phenocrysts range in length up to about 2 millimeters and in abundance up to about 10 percent. In some specimens they are highly tabular parallel to 010, in the habit described by Dana (1889, pp. 446–447). Some skeleton crystals, containing cores of groundmass material, were observed. Feldspar phenocrysts are rare, and pyroxene phenocrysts have not been found. The basalts differ from the olivine basalts only in their smaller proportions of olivine. None have been found in which olivine is entirely absent.

PUNA VOLCANIC SERIES

LAVAS OF PREHISTORIC AGE

The lavas of the Puna volcanic series include olivine basalts, basalts, and primitive picrite-basalts. Hypersthene has been found in only two specimens. These are from a prehistoric aa flow half a mile east of Pahoa, and lava of the 1840 eruption west of Kane Nui o Hamo. In the latter it is very rare.

The following stratigraphic section at Uwekahuna Bluff, on the west wall of Kilauea caldera, is typical of the prehistoric lavas of the Puna volcanic series. It will be seen that the flows are all basaltic and nearly all pahoehoe. Not all of the flows have been studied under the microscope, and it is therefore uncertain how many of the nonporphyritic lavas or those containing only a few olivine phenocrysts are olivine basalts and how many are basalts poor in olivine. Of five such rocks studied in thin section, two are basalts containing less than 2 percent olivine, and the other three are olivine basalts containing 7 or 8 percent olivine. These samples were selected at random, and it is probable that the proportions are about the same among the other nonporphyritic and poorly porphyritic flows. If so, the relative abundance of types exposed at Uwekahuna Bluff is, approximately: Olivine basalt, 70 percent; picrite-basalt, 5 percent; basalt, 25 percent. The proportions are nearly the same as those determined for the prehistoric lavas on the lower flanks of the volcano. The abundance of basalt is about the same as in the prehistoric lavas of the Kau volcanic series on Mauna Loa, but olivine basalt is relatively more abundant, and picrite-basalt and hypersthene-bearing basalt are less abundant. (See table, p. 57.)

These results do not agree with those of Washington (1923c, p. 353) and Stone (1926, p. 14), both of whom state that basalt is the most abundant type in the walls of Kilauea caldera. The difference of opinion may be partly due to the fact that basalt is more abundant in the lower and more accessible parts of the walls than it is higher up. Moreover, Washington's classification of the few rocks he studied was based largely on norms calculated from the chemical analyses, whereas the writer's classification is based on modal composition, as only a few chemical analyses are available. The large proportion of pyroxene listed by Stone as occurring in these rocks suggests that some of the groundmass olivine may have been misidentified as pyroxene. It appears, however, that the olivine basalts of Kilauea contain fewer and smaller olivine phenocrysts than the primitive lavas of most of the other Hawaiian volcanoes.

Stratigraphic section of prehistoric lavas of Puna volcanic series at Uwekahuna Bluff, Kilauea caldera

	Feet
Tuff-breccia, largely lithic, containing a few blocks as much as 3 ft. across; probably largely the result of the 1790 eruption. Locally, small pockets of pumice overlie the tuff-breccia. (Top of fault block 42 ft. below Uwekahuna triangulation station.)	3
Pumice and vitric ash	1
Olivine basalt pahoehoe, with moderately abundant olivine phenocrysts as much as 2 mm. long	12
Do	14
Pahoehoe, with a few olivine and feldspar phenocrysts as much as 1.5 mm. long	12
Olivine basalt pahoehoe, with moderately abundant olivine phenocrysts as much as 1.5 mm. long. Composed of several lenticular flow units from 8 in. to 2 ft. thick	12
Pahoehoe, with a few olivine phenocrysts as much as 1 mm. long	35
Pahoehoe, with rare olivine phenocrysts as much as 1.5 mm. long. Consists of thin flow units averaging about 10 in. thick	9
Pahoehoe, with scattered olivine phenocrysts as much as 1.5 mm. long	20
Pahoehoe, essentially nonporphyritic but with rare olivine phenocrysts less than 1 mm. long	5
Pahoehoe, with scattered olivine phenocrysts less than 1 mm. long	4
Olivine basalt pahoehoe, with moderately abundant olivine phenocrysts as much as 1.5 mm. long	16
Do	6
Pahoehoe, nonporphyritic	23
Olivine basalt pahoehoe, with moderately abundant olivine phenocrysts as much as 1.5 mm. long	16
Pahoehoe, with rare olivine phenocrysts as much as 1 mm. long	10
Pahoehoe, essentially nonporphyritic but with rare olivine phenocrysts less than 1 mm. long. Ropy tachylite top. Composed of several thin lenticular flow units 1 to 3 ft. thick	9
Olivine basalt pahoehoe, with abundant olivine phenocrysts less than 1 mm. long	10
Pahoehoe, nonporphyritic	12
Olivine basalt pahoehoe, with olivine phenocrysts as much as 6 mm. long forming about 15 percent of the rock. The lower 4 ft. is massive and dense, but the upper part is moderately to highly vesicular and formed of many thin flow units averaging about 5 in. thick	13

Stratigraphic section of prehistoric lavas of Puna volcanic series at Uwekahuna Bluff, Kilauea caldera—Continued

	Feet
Olivine basalt, transitional to picrite-basalt. Consists of many thin layers of frothy pahoehoe, averaging about 2.5 in. thick, but probably all parts of one flow. Olivine phenocrysts as much as 5 mm. long form 20 to 30 percent of the rock	19
Olivine basalt pahoehoe. Olivine phenocrysts as much as 6 mm. long form about 20 percent of the rock	4
Olivine basalt pahoehoe. Olivine phenocrysts as much as 4 mm. long form 15 to 20 percent of the rock	8
Olivine basalt, transitional to picrite-basalt. Olivine phenocrysts as much as 6 mm. long form about 25 percent of the rock. The upper 5 ft. consists of many thin flow units averaging about 4 in. thick	17
Olivine basalt pahoehoe, with olivine phenocrysts as much as 2 mm. long forming about 5 percent of the rock	7
Pahoehoe, essentially nonporphyritic but with rare olivine phenocrysts as much as 0.5 mm. long	11
Olivine basalt pahoehoe. Olivine phenocrysts as much as 2.5 mm. long form about 10 percent of the rock	1
Olivine basalt pahoehoe, with about 15 percent olivine phenocrysts as much as 6 mm. long	8
Olivine basalt pahoehoe. Olivine phenocrysts as much as 2.5 mm. long form about 15 percent of the rock near the base but decrease upward in both size and abundance, forming only about 7 percent near the top	16
Picrite-basalt pahoehoe, with about 35 percent olivine phenocrysts as much as 3 mm. long	4
Like that above. May be another member of the same flow	9
Uwekahuna ash (Puna volcanic series) (see p. 67). Overlaps underlying lavas	7
Unconformity.	
Aa, with clinkery top. Contains scattered olivine phenocrysts as much as 1 mm. long	5
Do	6
Pahoehoe, with a few olivine phenocrysts less than 1 mm. long. Consists of several thin flow units	6
Pahoehoe, with scattered olivine phenocrysts as much as 1.5 mm. long	14
Pahoehoe, with scattered olivine phenocrysts as much as 1.5 mm. long; top poorly exposed	19
Pahoehoe, with scattered olivine phenocrysts as much as 1.5 mm. long; reddened top	13
Pahoehoe, nonporphyritic, the vesicles lined with minute plates of feldspar	8
Not exposed; probably clinkery top of underlying aa flow	5
Olivine basalt, nonporphyritic, with the irregular vesicle shapes of aa. Many crystals of feldspar project into the vesicles. The rock is very massive. Although no olivine phenocrysts are present, the miscroscope reveals about 7 percent of olivine	17
Total thickness of section	446

Most of the Puna lavas contain phenocrysts of olivine, but in the predominant olivine basalts they are generally a little smaller and a little less abundant than in the Kau volcanic series. Plagioclase phenocrysts show a more striking contrast, being on the average decidedly less abundant and smaller than in the Kau lavas. No phenocrysts of augite have been found.

A little interstitial glass is present in many specimens. In most of them it forms less than 10 percent of the rock, and only rarely does it exceed 20 percent except in the ejecta of cinder and spatter cones or the thin tachylite crust that forms on the surface of some pahoehoe flows. It may constitute 90 percent or more of the tachylite crust. The glass of the tachylite has a refractive index of 1.603 to 1.609. The refractive index decreases with the percentage of glass in the rock, however, and where glass comprises less than 4 or 5 percent the refractive index is less than 1.54. Highly glassy rocks contain many fine examples of crystallites and skeleton crystals. These have been carefully described by earlier workers (Krukenberg, 1877; Cohen, 1880, pp. 28–32; Dana, 1889, pp. 450–452; Stone, 1926, p. 15) and have not been restudied.

A fairly common structure in both the olivine basalts and the basalts consists in a network of crystals with open spaces between them, as though the remaining fluid had drained away. The structure resembles, but is somewhat less well developed than that found by Fuller (1931, p. 116) in lavas of Washington and Oregon, for which he proposed the name diktytaxitic. Another common structure is one resembling miarolytic structure in plutonic rocks, in which well-formed tabular or acicular crystals of feldspar, prisms of monoclinic pyroxene, and plates of ilmenite project into small irregular vesicles (Daly, 1911, p. 303).

EJECTED BLOCKS FROM HALEMAUMAU

Blocks torn from the walls of the conduit and hurled out by the rare explosions at Halemaumau are of special interest because they are the only source of information as to the types of rocks buried beneath the surface lavas of Kilauea caldera. Blocks thrown out by the phreatic explosions of 1924 have been described by Stone (1926, pp. 18–21), and others ejected during earlier explosions, probably largely those of 1790, have been described by Dana (1889, p. 460), Daly (1911, pp. 303–304), Cross (1915, p. 42), and Washington (1923c, pp. 340–344).

The blocks of the earlier explosions include olivine basalt, basalt, primitive picrite-basalt, diabase, and gabbro. Peculiar patches of black glass were observed in some of the basaltic blocks by Dana and Washington, and similar ones have been observed by the writer in the blocks of the 1924 eruption. They have recently been studied by Chapman (1947). One of the basalts described by Cross contains phenocrysts of augite, which are very rare among Kilauean lavas. The gabbro, as described by Daly (1911, pp. 303–304), is an olivine-free variety, hypidiomorphic granular in texture with grains ranging from 1 to 5 millimeters in length, composed of labradorite, augite, abundant iron ore that is probably ilmenite, and very abundant needles of apatite.

The blocks ejected in 1924 include all the types described from the blocks of the earlier explosions. Olivine basalt appears to predominate, but basalt is abundant. Probably the commonest variety is an olivine basalt containing abundant phenocrysts of olivine up to about 4 millimeters long in a light-gray lithoidal groundmass. Many of the vesicles are lined with projecting crystals of feldspar and monoclinic pyroxene. The groundmass is intergranular, composed largely of labradorite and monoclinic pyroxene with less abundant olivine and iron ore. It exhibits crude radial arrangements of the feldspar laths. This structure was noted by Stone. It has been found by the writer in some of the blocks of basalt and was observed by Washington in blocks from the 1790 explosion. It also occurs in the olivine basalt of the 1840 eruption exposed along the trail 0.7 mile southwest of Napau Crater and in an olivine basalt of Mauna Loa, which crops out along the highway 2.68 miles north of Kealakekua.

A block of basalt contains pegmatitoid veinlets, consisting of euhedral tabular crystals of sodic labradorite ($\beta=1.559$), acicular crystals of pigeonite, and plates of ilmenite, up to 1 millimeter in length, projecting into open cracks averaging about 2 millimeters wide. Many of the vesicles are lined with similar material. Such crystal-lined vesicles are common in the ejected blocks both of the 1924 and of earlier explosions. Besides the feldspar, pyroxene, and iron ore crystals that project into them, many contain small round white grains of cristobalite (Stone, 1926, p. 20).

In the blocks which contain patches of black glass, Chapman (1947) has recognized three stages of congelation. Slow cooling at depth resulted in the formation of microphenocrysts of olivine and augite. Intrusion of the magma as a sill resulted in more rapid cooling and precipitation of crystals of labradorite and augite. This crystallization was interrupted, however, by the explosions which hurled fragments of the sill into the air and chilled the residual liquid to glass.

Reddened blocks of picrite-basalt contain partly resorbed olivine phenocrysts in which the resorption appears to have been accompanied by deposition throughout the crystal of minute granules of iron ore, scattered at random throughout the crystals, or arranged in curving and branching lines. The olivine has a $2V$ close to 90°, a value characteristic of the olivines in other Kilauean lavas, indicating that the deposition of iron ore was probably not accompanied by any notable change in composition of the olivine. Similar olivine phenocrysts containing abundant finely granular iron ore dispersed throughout the crystal are found in a picrite-basalt of Mauna Kea, exposed in the north wall of Kaawalii Gulch, and in an olivine basalt from Umiahu Cone on Hualalai. They have been described from basalts near Auckland, New Zealand (Bartrum, 1942).

Several blocks of gabbro ejected during the explosions of 1924 have been studied by the writer. All but one contain olivine. One block of gabbro porphyry very rich in olivine contains a few flakes of biotite. Another block of porphyritic olivine gabbro contains about 1 percent of hypersthene, in part mantling olivine phenocrysts. The monoclinic pyroxene of the gabbros is augite. In some blocks the magnetite is arranged in long trains of octahedral grains, in the manner observed by Stone (1926, p. 15) in some lavas.

The most noteworthy type among the ejected blocks is a rather light greenish-gray dense picrite-basalt containing abundant phenocrysts of olivine in a microcrystalline groundmass. The latter lacks typical igneous texture but shows instead a mosaic texture identical with that found in contact-metamorphic hornfels. The groundmass pyroxene is a mixture of augite and hypersthene, which are believed to have resulted from the unmixing, under prolonged high temperature, of original pigeonite (Macdonald, 1944d).

LAVAS OF HISTORIC AGE

The types of lava erupted during all the historic eruptions of Kilauea Volcano, the products of which can now be definitely recognized, are shown in the following table, together with their location and the approximate altitude of the principal vent. Most of the historic lavas erupted in the caldera have been buried by later flows and are no longer accessible for sampling. Eruptions since 1924 have been confined to the bottom of Halemaumau pit and are likewise inaccessible.

Types of lavas produced by historic eruptions of Kilauea

Date	Location	Approximate altitude of principal vent (feet above sea level)	Type of rock
1750?	East rift	1, 500?	Olivine basalt.
1790?	Caldera	3, 500?	Do.
1790?	East rift	1, 050	Olivine basalt (with a few pyroxene phenocrysts).
1823	Southwest rift	1, 500–400	Basalt.
1832	East rim of caldera	3, 675	Do.
1840	Near Alae Crater	2, 700	Olivine basalt.
1840	East rift, in East Puna.	800	Picrite-basalt.
1868	Kilauea Iki and southwest rift.	3,400 and 2, 550	Olivine basalt.
1877	Keanakakoi Crater	3, 450	Basalt.
1894	Caldera	3, 650	Do.
1918	do	3, 650	Olivine basalt.
1919	do	3, 650	Do.
1920	Southwest rift	2, 950	Do.
1921	Caldera	3, 650	Do.
1922	Makaopuhi and Napau Craters.	2,850 and 2, 650	Basalt.
1923	Southwest flank of Kane Nui o Hamo.	3, 000	Olivine basalt.

The table indicates that the most abundant type among the historic lavas of Kilauea is olivine basalt. (See also table, p. 57.) Basalt and picrite-basalt also are represented but in much less abundance. In composition and texture the historic lavas closely resemble the prehistoric lavas.

The Kilauean lava of 1868 may be briefly mentioned in relation to the nearly simultaneous lava flow erupted on the southwest rift of Mauna Loa. That from Kilauea is an olivine basalt containing phenocrysts of olivine (10 percent) and calcic labradorite (5 percent) in a hyaloophitic groundmass containing about 2 percent olivine. In contrast, the lava of Mauna Loa is a picrite-basalt containing about 25 percent of olivine phenocrysts and a few microphenocrysts of sodic bytownite.

During the eruption of 1840, lava broke out on May 30th in Alae Crater and on May 31st both northeast and northwest of Makaopuhi Crater. All these flows were small. On June 1st the principal lava extrusion began on the east rift zone in eastern Puna, 15 miles farther east. The lavas erupted in the two regions are not alike. That in eastern Puna is a picrite-basalt containing about 30 percent of olivine phenocrysts, whereas that erupted near Makaopuhi Crater is a nonporphyritic olivine basalt. The difference lies in the abundance of olivine phenocrysts and is believed to have resulted from gravitative crystal differentiation in the Kilauean conduit (Macdonald, 1944c).

INTRUSIVE ROCKS

The intrusive bodies exposed at the surface in Kilauea Volcano are of two classes: Dikes, and lenticular bodies roughly parallel to the bedding. Some dikes are visible in the walls of Halemaumau pit, and others cut the lavas in the north wall of the caldera. Several dikes exposed in the southwest wall of the western pit of Makaopuhi Crater strike N. 50° E., parallel to the east rift zone of Kilauea. A few dikes with similar strike cut the lavas of the Hilina volcanic series in Hilina Pali.

The lenticular intrusives are essentially concordant, but are partly discordant with the bedding of the lavas. In places they deform the overlying beds in the manner of laccoliths. Several lenticular intrusives can be seen in the walls of Halemaumau, but the best known of them, first described by Daly (1911, pp. 291–294), is exposed in the west wall of the caldera north of the fault blocks at Uwekahuna.

The intrusive bodies in the walls of Halemaumau are not accessible to study, but fragments of some of them are undoubtedly represented among the blocks ejected from Halemaumau by explosions, described above.

One of the dikes in the north wall of the caldera has been briefly described by Washington (1923c, pp. 341–343), who made chemical analyses both of the dike and of a 3-inch apophysis from it. It is apparently a basalt. The apophysis is composed largely of dark-brown almost opaque glass. Another of the dikes is of olivine basalt.

The olivine gabbro porphyry of the intrusive body in the cliffs at Uwekahuna has been described in detail by Daly, and the rock has been analyzed chemically by Steiger. The analysis is quoted in column 2 of the table on page 73. The rock contains phenocrysts of olivine, up to 7 millimeters across, in a hypidiomorphic granular, locally diabasic, groundmass with an average grain size of approximately 0.4 millimeters. The olivine phenocrysts have a $2V$ close to 90°. In places they are slightly altered along fractures and around the edges to iddingsite. The groundmass consists of olivine, augite, plagioclase, and ore. The plagioclase is zoned from sodic bytownite in the center to labradorite-andesine on the outside. Small acicular crystals of apatite enclosed in the feldspar are abundant. A few small interstitial patches of glass are present and are clouded with iron-ore dust.

The gabbro mass at Uwekahuna Bluff was originally described by Daly as a laccolith, but doubt was cast on its intrusive origin by Powers (1916b, p. 28) and Washington (1923c, p. 345), who regarded it as probably a massive filling of a lava tube. There can be little doubt, however, of its intrusive character (Stone, 1926, pp. 17–18). A dike about 2 feet thick extends from it into the overlying lavas. The west edge of the body appears to cut sharply across the bedding, but at the north edge the enclosing lavas arch over it. The body appears, as stated by Daly, to be essentially laccolithic.

UWEKAHUNA ASH

A bed of ash is exposed for more than 4,000 feet in the lower part of the west wall of Kilauea caldera northeast of the fault blocks at Uwekahuna Bluff. Particularly at its north end the ash exposure is very irregular in thickness, ranging from a thin film to 4 feet. It apparently accumulated in hollows on an irregular lava surface. The average thickness of the ash increases southward, reaching a maximum of 7 feet just north of the northernmost fault block at Uwekahuna. (See stratigraphic section, p. 67.) A bed of ash more than 17 feet thick, which was formerly exposed at the foot of the southernmost Uwekahuna fault block (Powers, 1916a, p. 230), may be a continuation of the Uwekahuna ash. Just north of the Uwekahuna fault blocks the ash mantles an ancient northeastward-facing cliff in the older lavas and is progressively overlapped by younger lavas. Farther north the ash is overlain by as much as 10 feet of exceedingly thin-bedded pahoehoe, which must have been erupted in a very fluid condition, for the individual beds average only about 3 inches in thickness. A measured section follows on page 68.

Both the lower and the upper layer of essential ash thin northward, the lower one disappearing about 1,000 feet northeast of the Uwekahuna fault blocks. In places the coarse ash-breccia of the second layer fills

Section 50 feet north of Uwekahuna fault blocks

	Feet
Essential vitric ash, consisting largely of the debris of lava fountains, with the granularity of silt, sand, and fine gravel. Contains, especially near the base, some small accessory lithic fragments. Grades into the underlying beds	1
Coarse ash-breccia, containing angular accessory blocks of lithic material as much as 1 foot long, intermixed with finer essential ejecta. The lithic blocks include several different varieties of basalt. A few cored magmatic bombs are present. The texture becomes finer, and the amount of essential debris increases upward	2
Moderately well bedded buff to yellow ash, consisting largely of vitric essential ejecta of fine gravel, sand, and silt grades but containing some accessory lithic ejecta as much as 2 inches long. Some beds are pisolitic. A few inches of dark-brown pumiceous cinders are locally present at the base	4

small gullies in the lower layer. The ash-breccia everywhere contains much essential magmatic debris in the form of bombs and glassy lava fountain ejecta.

Most of the bombs contain cores of older rock, but a few of them are composed entirely of new magmatic material.

H. A. Powers (1948, p. 283) has described evidence of five magmatic explosions in the Uwekahuna ash, excluding the coarse lithic breccia layer. The latter he regards as probably talus and outwash accumulated near the base of a buried crater wall, although admitting that further work might demonstrate its explosive origin. A lens of what appears to be true talus, 35 feet long and as much as 3 feet thick, is exposed in the northwestern part of the caldera wall above the Uwekahuna tuff and separated from it by 5 feet of thin-bedded pahoehoe. However, two lines of evidence appear to indicate that the breccia in the Uwekahuna ash is actually of explosive origin and not a talus deposit. In the first place, it would be an amazing coincidence if the fault scarp of the present caldera wall should cut a talus accumulated at the foot of an older caldera wall in such a way as to produce an exposure of the continuity and uniformity of thickness exhibited by the breccia in the Uwekahuna ash. In the second place, two different classes of fragments in the breccia strongly suggest an explosive origin. At several places there were found in the breccia fragments of fine-grained gabbro, such as occurs at Kilauea only in small intrusive bodies. With the exception of the Uwekahuna laccolith, which is later than the Uwekahuna ash, the only bodies with this granularity known to exist are those exposed in the walls of Halemaumau pit. Fragments of these gabbroid intrusive bodies were thrown out of Halemaumau by the phreatic explosions of 1924, and it appears probable that the similar fragments in the breccia in the Uwekahuna ash were similarly ejected by earlier explosions. Furthermore, the magmatic ejecta in the breccia, and especially the bombs, appear to demonstrate its explosive origin. Such material would not be expected to be at all common in a talus deposit. Magmatic bombs are very rare at Kilauea, having been found almost exclusively in the Uwekahuna breccia and in the breccias of phreatic origin in the Keanakakoi formation (p. 69). It is very unlikely that they would be available for inclusion in a talus. Some, or even all, of the fine vitric debris in the breccia may have sifted or been washed down from the overlying bed into the interstices between the lithic blocks; but the magmatic bombs must have been deposited contemporaneously with the other coarse debris, and almost certainly as the result of contemporaneous explosions. It appears to the writer that at least a part, and perhaps all, of the Uwekahuna breccia must be the product of phreatic explosions.

A recent study by Powers (1948, pp. 278–292) has shown that the deposits are the result of some 20 separate explosive eruptions, extending over a period of perhaps 1,500 years ending with the explosions of 1924. The accompanying table indicates the general nature of each of the explosions and the maximum thickness attained by its deposits. The maximum thickness of all the individual deposits is not attained at any one locality, hence the total thickness of the deposits is much less than the sum of the maximum thicknesses of the individual deposits.

A sample of the bed of vitric ash, which was collected about 150 feet north of the Uwekahuna fault blocks and which was examined under the microscope, consisted of Pele's tears, fragments of ribbon bombs, and pieces of pumice in a matrix of vitric sand. The glass of the matrix is pale greenish brown and has a refractive index of 1.587. The larger fragments are pumiceous. The smaller fragments show the angular and arcuate outlines of typical shards. A few crystals of olivine are enclosed in the glass. This ash is a typical product of lava fountain activity.

The Uwekahuna ash thus records an opening episode of deposition of vitric ash, uninterrupted by the extrusion of lava flows, possibly because the area of accumulation was protected from inundation by cliffs such as the one now mantled by the ash at its south end. Admixed with the vitric ash were a few lithic fragments representing older rock material, torn from the conduit walls or more probably picked up from talus material that had slumped from the edge of a pit crater, such as the present Halemaumau, in which the lava fountains were playing. Following this came a period of more violent explosions, which hurled out much old lithic material, forming a coarse ash-breccia. The explosions were still magmatic in origin, however, for the ash-breccia contains abundant essential debris. The violence of the explosions gradually decreased, and less accessory lithic material was ejected until finally the deposits consisted almost entirely of the glassy pumiceous material produced by lava fountains.

SURFICIAL PYROCLASTIC DEPOSITS SURROUNDING KILAUEA CALDERA

The surface of the lavas surrounding Kilauea caldera is in most places buried by a blanket of ash and breccia (pl. 13), which attains a maximum thickness of about 35 feet (Stearns and Macdonald, 1946, fig. 26). The deposits have been described by several writers (Powers, 1916a, pp. 231–240; Stone, 1926, pp. 28–35; Stearns and Clark, 1930, pp. 149–152; Wentworth, 1938, pp. 92–102, 148–151; Finch, 1942, pp. 1–3; Stearns and Macdonald, 1946, pp. 106–110), but sufficient attention has not previously been paid to the nature of their component fragments, whether essential or accessory. All the surficial pyroclastics, including the deposits produced by the explosions of 1790 and 1924, have been grouped together by Wentworth (1938, p. 93) as the Keanakakoi formation.

Generalized section of surficial pyroclastic deposits in and adjacent to Kilauea caldera

[Modified after H. A. Powers, 1948]

Date of eruption	Dominant type of ejecta	Type of eruption	Maximum thickness (inches)	Location of maximum thickness
1924–1934	Essential	Magmatic	2	SW. floor of caldera.
1924	Accessory	Phreatic	18	Do.
About 1815	Essential	Magmatic	48	SW. rim of caldera.
About 1790	Accessory	Phreatic	45	W. rim of caldera.
	do	do	20	SW. rim of caldera.
	do	do	40	Do.
	Essential	Magmatic	21	SE. rim of caldera.
	Accessory	Phreatic	36	SW. rim of caldera.
	do	do	24	Do.
	Essential	Magmatic	80	SE. rim of caldera.
Pre-historic	Accessory	Phreatic	10	N. rim of caldera.
	do	do	7	NW. rim of caldera.
	do	do	12	SW. rim of caldera.
	Essential	Magmatic [1]	375±	SE. rim of caldera.
	Accessory	Phreatic	11	NE. rim of caldera.
	Essential	Magmatic	12	Do.

[1] Apparently represents 7 separate eruptive periods, the ash layers of which are separated by eroded and weathered surfaces, and the second and third layers by an old soil surface.

The ash is of two general types, essential or vitric, and accessory or lithic. The essential ash was produced by magmatic explosions and represents the congealed and quickly quenched spray of lava fountains. It is thus not the result of explosive eruption in the ordinary sense. It consists very largely of basaltic glass, pale green to brown under the microscope, but buff to yellow in the outcrop. None of the ash shows any definite evidence of palagonitization. Considering the high rainfall in part of the area, this lack of alteration supports Powers' contention of its recency of origin. The glass shards in the ash are obviously fragments of pumice, and show partly arcuate outlines resulting from the breaking across of vesicles. They grade into fragments of typical basaltic pumice of the sort called thread-lace scoria by Dana (1890, p. 163) and reticulite by Wentworth and Williams (1932, p. 47–50). The glassy ash contains in places crystals of olivine, and less commonly of plagioclase (bytownite to laboradorite), in part imbedded in the glass and in part free. Some beds of essential tuff are pisolitic.

At the very base of the surficial ash deposits is a remarkably persistent layer of pumice fragments, ranging from less than an inch to a foot in thickness. Individual fragments of pumice in this bed are as much as 1.5 inches in diameter. Above this pumice layer the essential ash is for the most part sandy in texture, although occasional lenses and thin beds of pumice fragments up to an inch or a little more in diameter are found. The eruptions since 1924 have been confined to the depths of the inner pit (Halemaumau), and only small amounts of pumice and ash have been blown out onto the caldera floor to the southwest of the pit, where it is found in isolated pockets.

Stratigraphic section of surficial pyroclastic deposits of Kilauea west of Keanakakoi Crater

	Inches
1790 breccia: Angular to subrounded accessory blocks as much as 3 ft. in diameter, but mostly less than 10 in., grading down to a matrix of smaller accessory fragments, sand, and dust. Contains a few cored bombs scattered from top to bottom of the deposit. Poorly bedded and sorted and very little cemented. Undoubtedly contains a little gravel and sand of the 1924 explosion in its upper part	20
Prehistoric tuffs:	
Poorly bedded lapilli-ash, consisting largely of accessory material. Most fragments less than half an inch but a few as much as 2 in. across	18
Local unconformity, with minor gullying.	
Moderately well bedded buff ash, some beds pisolitic, consisting largely of essential vitric material, including many pumice lapilli as much as half an inch across; some beds contain fragments of accessory lithic material as much as a quarter of an inch across but mostly less than a quarter of an inch, in a matrix of sand and silt. A few lithic blocks as much as 1 ft. across are scattered throughout the deposit	20–30
Moderately well bedded buff ash, containing abundant accessory lithic fragments as much as 3 in. across, but mostly less than 1 in., in a matrix of vitric sand and silt	8
Pisolitic ash containing many small chips of accessory lithic material as much as a quarter of an inch across in a matrix of vitric sand and silt	10
Dark-brown vitric lapilli-ash, composed of pumiceous lava-fountain debris as much as 1 in. across	15
Fine-grained, thinly laminated buff to greenish-brown vitric ash, largely of sand and silt grades but containing many lumps of pumice as much as a quarter of an inch across	60

Stratigraphic section of surficial pyroclastic deposits of Kilauea west of Keanakakoi Crater—Continued

	Inches
Prehistoric tuffs—Continued	
Dark-brown vitric lapilli-ash, well bedded, containing pumiceous lava-fountain debris as much as a quarter of an inch across	20
Fine-grained, thinly laminated buff to greenish-brown vitric ash, largely of sand and silt grades, but containing many lumps of pumice as much as a quarter of an inch across	58
Yellowish-brown pumice lapilli as much as 1 inch across	4
Pahoehoe basalt.	

Stratigraphic section of surficial pyroclastic deposits in wall of rift crack 100 feet south of highway southwest of Halemaumau

	Inches
1924 breccia: Accessory lithic silt, sand, and gravel; fragments as much as 2 in. across. No magmatic material. Unconsolidated	0–2
Ash deposits formed between 1790 and 1924: Vitric greenish-brown lava-fountain debris, largely pumice, fragments as much as 1½ in. across	12
1790 explosion deposits:	
Lapilli-ash moderately well bedded, consisting of accessory lithic fragments as much as 1 in. across but mostly less than half an inch, in a matrix of comminuted rock of sand to dust grades. Locally pisolitic. No essential ejecta could be found in this layer	8
Grayish-brown pisolitic ash of silt and dust grades	1
Lithic lapilli-ash, like upper layer	4
Prehistoric tuffs:	
Lapilli-ash, composed largely of accessory fragments as much as 1½ in. across but containing rare essential ejecta. Increases in coarseness upward	6
Gray ash of fine to coarse sand grades, consisting largely of accessory lithic debris	2
Ash-breccia, with lithic accessory fragments as much as 5 in. across in a matrix of rock dust. Contains a few magmatic lapilli	8
Ash-breccia, with fragments as much as 6 in. across but mostly less than 1½ in. Accessory fragments predominate, but essential magmatic ejecta, including cored lapilli and irregular lava shreds, are abundant. (Throughout the thickness of the 1790 tuff are scattered angular accessory blocks as much as 1½ ft. across not referable to any definite layer.)	14
Moderately well bedded and thinly laminated greenish-brown vitric ash of sand and silt grades. Entirely essential ejecta	50
Massive brown silty vitric ash, pisolitic	8
Well-bedded glassy ash, consisting of alternate beds, an eighth of an inch to an inch thick, of sand ash and fine-gravel ash, the latter composed of pumice fragments, Pele's tears, and other lava-fountain debris	12
Moderately well bedded and thinly laminated greenish-brown vitric ash of sand and silt grades	37
Brownish-gray lapilli-ash, containing fragments of pumice as much as three-quarters of an inch across but mostly less than a quarter of an inch, in a matrix of vitric sand and silt. Bedding poorer than in overlying beds	46
Moderately well bedded greenish-brown vitric sandy ash	6
Pahoehoe basalt.	

A specimen of the basal sandy ash collected by Wentworth 0.75 mile southwest of Keanakakoi Crater has been studied in thin section by the writer. It is typical of most of the prehistoric essential ash. It consists of fragments of pale greenish-brown glass showing typical shard structure. The larger fragments are pumiceous. Olivine phenocrysts are abundant in the glass, and scattered plagioclase phenocrysts also are present. The rock resembles the sample of Uwekahuna ash described above and, like it, is a product of lava-fountain activity.

In some places, the prehistoric essential ash contains lithic accessory fragments, such as are not ordinarily ejected by the lava-fountain type of explosion. They may represent fragments of talus that fell into the pit in which the fountaining was occurring, or they may be pieces torn from the walls of the conduit. The former appears the more probable.

The accessory ash consists very largely of rock material which was already solidified and largely crystallized at the time it was disrupted by explosions. Most of it contains little or no magmatic debris, and consequently it is interpreted as having been formed by explosions which were non-magmatic in nature. Such explosions were observed (Jaggar and Finch, 1924, pp. 353–374; Stearns, 1925, pp. 193–208) in 1924 and interpreted as phreatic, caused by the entrance of ground water into the hot volcanic conduit following the recession of the magma level to great depths. The debris of some of the earlier explosions closely resembles that of the explosions of 1924, and consequently these earlier explosions are believed to have been phreatic also. They are so listed in the accompanying table. To some extent the material making up the deposits was fragmented by the explosions, but much of it represents talus formed by caving in of the oversteepened vent walls, partly fractured and pulverized by the fall, and thrown out by succeeding explosions.

The accessory ash is lithic, in contrast to the vitric essential ash. It consists very largely of fragments of basalt having the same textures and compositions found in the lava flows. Some of the fragments are partly glassy, but only in the same degree commonly found in flows. Some phenocrysts of olivine and plagioclase are present, partly enclosed in the fragments of basalt, and partly free of them. The lithic ash is more commonly pisolitic than the vitric ash. The pisolites appear to be of two varieties, formed respectively by gathering together of dust particles around raindrops in the air, and by accretion around raindrops rolling on the surface of soft ash on the ground. Some of the former variety are distinctly flattened on the under side by impact. The pisolites formed on the ground tend to be less regular in shape than those formed in the air, and a few of them are distinctly roller-shaped.

Magmatic bombs were first recognized and described from the deposits of 1790 by Perret (1913, pp. 612–614).

Most of the bombs are of the cored variety (Brady and Webb, 1943), consisting of fragments of older lava coated with new lava. Less abundant are bombs consisting entirely of new lava, chilled on the outside and with vesicular centers. Similar bombs and lapilli are present in some of the prehistoric deposits. Some of the beds of accessory ash contain a few essential ejecta. This magmatic material forms such a small proportion of the whole (generally less than one percent) that it appears obvious that the presence of magmatic material is purely coincidental. The explosions must have been largely or wholly phreatic. Possibly at the time the magma level was lowered, permitting ground water to enter the conduit, some liquid magma still remained in the lake basin and in pockets in the semisolid epimagma (Jaggar, 1920, pp. 163–164) to be hurled out as magmatic ejecta during the phreatic explosions. Along the southwest margin of the caldera these deposits contain a large proportion of fine-grained material, but along the east edge the deposits consist of a coarse poorly sorted breccia with very little fine-grained material. It is probable that the usual northeast trade winds blew most of the fine material to the southwest, and only the fragments too heavy to be drifted by the wind fell toward the east. Along the east edge of the caldera the deposits contain blocks of several different types of rocks, reaching a maximum of 3 feet in diameter. (See p. 72.) Many of the blocks of dense lava show bread-crusted surfaces. Also, many of the blocks between 2 and 4 inches in diameter are quite well rounded (Powers, 1916a, p. 235), as though they had been milled by repeated tossing in the vent. Magmatic bombs occur throughout the deposit. At Uwekahuna Bluff the ash-breccia of 1790 is 3 to 4 feet thick and is composed largely of lithic material, some of the blocks reaching 6 inches across. Magmatic lapilli are present but are rather rare.

The size distribution of the magmatic ejecta in the deposits of 1790 suggests that the vent from which they issued was closer to Keanakakoi Crater than it was to Uwekahuna or the south rim of the caldera.

The skin of a cored bomb collected on the horst that projects into Kilauea caldera west of Keanakakoi Crater was examined under the microscope to determine the nature of the magma erupted in 1790. The rock is an olivine basalt, essentially nonporphyritic; but containing rare phenocrysts of olivine up to 1.5 millimeters long. The olivine crystals are partly rounded and embayed by resorption. Small inclusions of various types of older basalt have been much rounded by remelting. There is no evidence of reaction between the magma and the inclusions, but that would hardly be expected as the differences in composition are only slight.

It has been suggested by Finch (1942, p. 2) that unconformities within the material on the south rim of the caldera commonly considered as the ejecta of 1790 may indicate that the lower part of the material was ejected at an earlier date. However, these unconformities are of very limited extent, and although they are locally distinct, a few feet away deposition frequently appears to have been continuous. Moreover, if they represented any appreciable time interval during which normal activity proceeded in the caldera they would probably be marked by beds of vitric lava-fountain debris, like that intervening between the deposits of 1790 and 1924. It seems more likely that they represent merely local wind erosion and gullying by heavy rains which probably accompanied the explosions.

Southwestward from the caldera the material ejected in 1790 gradually becomes finer until it is almost entirely composed of thinly laminated silty ash, many of the beds being pisolitic. A sample was collected west of Mauna Iki, 6.5 miles southwest of the rim of Kilauea caldera, from a bed in which were found footprints believed to have been made by members of Keoua's army (Jaggar, 1921), some of whom were killed by the eruption of 1790. It is a medium-gray silty ash containing many pisolites up to 1.5 millimeters in diameter. Under the microscope the rock is a crystal-vitric ash (Williams, 1927) composed largely of pale brownish-green glass with a refractive index of 1.595. Fragments of olivine and feldspar crystals are also found, but no pumice is present. The glass ranges in structure from dense to moderately vesicular but lacks the high degree of inflation characteristic of the lava-fountain deposits and more nearly resembles the fragmental glass in the littoral cones (p. 72). The glass appears to have been pulverized rather than being a frozen liquid spray. The liquid was torn apart by gas explosion, but the gas was probably of extraneous origin; the magma was not itself actively expanding, as it is in the lava fountains.

In the deposits of 1790 on the southwest edge of the caldera the proportion of magmatic material decreases upward until in the topmost bed none could be found. The magmatic explosions appear to have gradually given way to phreatic explosions, possibly as the magma level lowered in the conduit. Possibly the entire explosive episode was occasioned by the lowering of the magma level, permitting ground water to enter the conduit, as in 1924 (Stearns, 1925; Finch, 1943), except that in 1790 some magma remained in the lake basin and in pockets in the porous semisolid epimagma (Jaggar, 1920, pp. 163–164), to be hurled out as magmatic ejecta during the earlier explosions but becoming largely exhausted before the final explosions. If this deduction is correct, the explosions of 1790, although involving some magmatic material, were essentially phreatic in origin, and the same may be true of the various prehistoric explosions in which abundant accessory material was ejected. Such an explanation appears more probable, both theoretically and empirically, than that the accessory material was ejected during the course of purely magmatic lava-fountain activity, for lava fountains have never been observed to eject any appreciable proportion of older accessory rock fragments.

Much of the surface around the south end of the caldera is covered with a layer of basaltic pumice, which locally attains a maximum thickness of about 3 feet (Jaggar, 1925). It rests on the breccia of the 1790 explosions and is overlain by a thin layer of lithic debris from the explosions of 1924. Many large blocks belonging to the upper part of the breccia of 1790 project through the pumice, and over considerable areas that breccia is exposed directly at the surface, the pumice layer never having been deposited there or having been later removed by wind erosion. As pointed out by Jaggar (1925, p. 3), the lava fountains that produced this pumice must have been large, resembling those typical of the eruptions of Mauna Loa, rather than the diminutive fountains which characterized Kilauea throughout the period of dominant lava-lake activity during the latter part of the 19th century. R. H. Finch has suggested that these large fountains accompanied the resumption of activity following the period of repose, which was presumably initiated by the explosions of 1790. Such a period of quiet would be conducive to the accumulation of volatile matter in the upper part of the magma column, and the rapid release of this matter upon the breaking of the overlying seal might reasonably be expected to produce large fountains of frothy lava. Similar large fountains, resembling those of Mauna Loa, played briefly in the pit of Halemaumau during the eruption of 1934 (Jaggar, 1936).

The debris of the explosions of 1924 is entirely lithic and accessory. The types of rocks among the ejected blocks have already been described. Blocks weighing up to 14 tons were left in the vicinity of Halemaumau, but around the east and south edges of the caldera the debris consists of sand and gravel, the largest fragments seldom exceeding 2 inches in diameter and the bed ranging in thickness from a thin film to 2 inches. In the same area the debris of the 1790 explosions averages about a foot in thickness and includes a few blocks more than 2 feet in diameter. Thus the amount of material ejected and the violence of the explosions were considerably greater in 1790 than in 1924.

LITTORAL CONE DEPOSITS

The cones formed where lava flows enter the sea are composed largely of vitric ash of sand and silt grades, in which are enclosed irregular shreds of lava from less than an inch to a foot or two in diameter, many of them showing drawn-out ribbon forms indicating that they were thrown into the air in a liquid condition. The glass of the littoral ash is pale greenish brown to black under the microscope, with an index of refraction ranging from 1.595 to 1.601. In the ash of Sand Hill, where the lava flow of 1840 entered the sea, olivine crystals are abundant, partly free and partly enclosed in the glass. A few of the small glass grains show droplet form, but most are angular and owe their shapes to shattering. The ash exposed along the shore at MacKenzie Park, 0.5 mile northeast of Kaakepa Cone in eastern Puna, contains many fragments that are much drawn out, some of them approaching true Pele's hair. Many of the latter have bulbous swellings at the ends or along the length of the filament.

The grains of vitric ash in the littoral cones differ from the vitric ash produced by lava fountains at the sources of flows in being much less vesicular. In contrast to the pumiceous fragments derived from lava fountains, the glassy fragments of the littoral cones are dense to only moderately vesicular. This difference results from the fact that the gases accompanying lava fountains are of internal origin, the lava undergoing active inflation during the explosion; whereas the steam that atomizes the liquid lava in the littoral explosions is of external origin, having been derived from the vaporization of the sea water.

CHEMICAL ANALYSES

In the accompanying tables are shown all the modern chemical analyses of rocks of Kilauea that appear reliable. Several older analyses have been omitted, because in one respect or another they are not comparable with the more recent analyses (Dana, 1879, p. 134; Cohen, 1880, p. 41; Silvestri, 1888; Phillips, 1894, p. 473; Lyons, 1896, p. 424; McGeorge, 1917, p. 4). Most of the older analyses have been quoted by Cross (1915, pp. 47–48). Analyses by Mau (Payne and Mau, 1946) have been omitted because the silica percentages appear to be too high.

For the most part, the lavas of Kilauea are closely similar in composition to those of Mauna Loa. However, some of the analyzed rocks of Mauna Loa are richer in silica than any known from Kilauea. The lavas of Mauna Loa show a greater degree of variation than do those of Kilauea, but no analyzed specimen from either volcano is sufficiently silicic to be classed as an andesite.

The average composition of the lavas of Mauna Loa and Kilauea is quite close to the averages of basalt from the Deccan Plateau in India and the Columbia Plateau in Oregon, but it is distinctly less rich in alkalies, particularly in potash. (See table, p. 74.) It is more silicic than the average of basalts from the North Atlantic region. Alumina and ferric iron are lower than in the basalts of the other regions, and magnesia is distinctly higher. The average of the lavas of Mauna Loa and Kilauea approaches quite closely to the average basalts of the world, as calculated by Daly, but in general with the same chemical differences as noted for the other groups of basalts. The lavas of Mauna Loa and Kilauea are thus somewhat more magnesian and less alkalic than the plateau basalts or the average basalts of the world (which includes many basalts erupted on the continental platforms), possibly owing to their derivation from a deeper part of a general basaltic substratum.

Calculation of the norms shows the average of the Kilauean lavas to be almost exactly saturated with respect to silica, whereas the average of the lavas of Mauna Loa shows a slight excess of silica, expressed as normative quartz. Both contain a little normative orthoclase. The average normative plagioclase of the lavas of Mauna Loa is sodic labradorite, whereas that of the Kilauean lavas is intermediate labradorite. None of the averages of the various groups of basalts (table, p. 74) departs greatly from normative saturation in silica, although all but the average of world basalts show a small degree of oversaturation.

The analyses of the lavas of Mauna Loa are largely from the outermost shell of the mountain, representing principally the latest lavas erupted from that vent. If more of the earlier lavas were represented the average for Mauna Loa might not depart so much from that for Kilauea.

Chemical analyses and norms of lavas of prehistoric age of Kilauea

Analyses

	1	2	3	4	5	6	7	8	9	10
SiO_2	46.50	46.59	47.45	50.03	50.46	50.50	50.53	51.06	51.35	51.77
Al_2O_3	9.37	7.69	8.83	12.10	12.75	13.31	13.61	12.91	13.36	13.54
Fe_2O_3	2.47	2.20	1.07	2.10	.82	1.21	1.69	1.33	1.32	.75
FeO	10.79	10.46	10.57	9.97	10.68	10.03	9.30	9.63	9.85	9.63
MgO	21.00	21.79	19.66	9.57	9.68	6.73	7.01	8.09	7.62	7.33
CaO	6.25	7.41	7.93	10.58	10.43	11.30	10.75	11.03	10.74	10.57
Na_2O	1.52	1.33	1.72	2.01	2.42	2.20	2.16	1.92	1.93	2.18
K_2O	.22	.28	.13	.44	.51	.53	.35	.43	.50	.45
H_2O+	.14	.37	.07	.32	.15	.26	.27	.16	.29	.16
H_2O-	.03	.04	.01	.16	.10	None	.07	.06	None	.05
TiO_2	1.70	1.83	1.77	2.57	2.14	3.63	3.68	3.59	2.50	4.01
P_2O_5	.10	.11	.37	.21	.19	.47	.20	.22	.28	.26
MnO	.11	.18	[a].15	.16	.18	.15	.13	.16	.07	.15
Cr_2O_3		.13	.15					None	.03	
S		None	.02			.08		None		
NiO		.12							.025	
BaO		None	.01					None		
SrO		None								
ZrO_2		None						None		
Cl			.03			.02				
	100.20	100.53	99.94	100.22	100.51	100.42	99.75	100.59	99.86	100.85

Norms

	1	2	3	4	5	6	7	8	9	10
Quartz				0.54		4.02	4.62	3.78	4.26	5.16
Orthoclase	1.12	1.67	.56	2.78	2.78	2.78	2.22	2.78	2.78	2.78
Albite	13.10	11.00	14.15	16.77	20.44	18.34	18.34	16.24	16.24	18.34
Anorthite	18.07	14.46	16.12	22.80	22.52	25.02	26.13	25.02	26.41	25.85
Diopside	9.76	17.05	16.46	23.42	23.09	22.47	21.42	22.31	20.65	20.08
Hypersthene	20.62	18.23	19.15	25.21	18.13	17.43	16.74	21.38	21.84	18.96
Olivine	30.35	30.49	27.44		7.57					
Magnetite	3.48	3.25	1.62	3.02	1.16	1.86	2.55	1.86	1.86	1.16
Ilmenite	3.19	3.50	3.34	4.86	4.10	6.84	6.99	6.84	4.71	7.60
Apatite	.34	.34	1.01	.34	.34	1.34	.34	.67	.67	.67

[a] Stated in original analysis as MnO_2=0.17.

1. Picrite-basalt, west of Kamakaia Hills, Kau Desert. Analyst, H. S. Washington (1923c, pp. 346–347).
2. Olivine gabbro porphyry, Uwekahuna laccolith, Kilauea caldera. Analyst, G. Steiger. (Daly, 1911, p. 293.)
3. Olivine basalt, transitional to picrite-basalt, fragment from wall of conduit ejected during explosions of 1924. Analyst, E. S. Shepherd. (Piggott, 1931, p. 2.)
4. Olivine basalt, fragment from wall of conduit ejected during explosions of 1790, collected near Uwekahuna. Analyst, G. Steiger. (Cross, 1915, p. 48.) Norm from Washington, H. S. (1923c, p. 343).
5. Olivine basalt, fragment from wall of conduit ejected during explosions of 1790, collected southwest of Halemaumau. Analyst, H. S. Washington (1923c, pp. 342–343).
6. Basalt (?), a flow of unknown date in Kilauea caldera. Analyst, E. S. Shepherd (1938, p. 335).
7. Basalt, 3-inch apophysis of dike in north wall of Kilauea caldera (analysis of the dike itself in column 10). Analyst, H. S. Washington (1923c, pp. 342–343).
8. Basalt, flow in caldera wall. Analyst, H. S. Washington (1923c, pp. 342–343).
9. Olivine basalt, National Park quarry on highway 0.75 mile northeast of Volcano Observatory. Analyst, J. J. Fahey. (Powers, 1931, p. 2.)
10. Basalt, dike 5 feet thick, in wall of Kilauea caldera just west of the fault blocks below Volcano House. Analyst, H. S. Washington (1923c, pp. 342–343).

Chemical analyses and norms of lavas of historic age of Kilauea

Analyses

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	47.25	39.54	49.21	49.33	49.42	49.74	50.07	50.14	50.19	50.32	50.37	50.52	50.63	50.85	51.00
Al_2O_3	9.07	.66	12.93	11.57	11.83	12.36	13.32	13.93	13.34	12.83	14.20	13.85	13.08	15.30	13.03
Fe_2O_3	1.45	1.03	1.76	2.31	3.83	1.64	1.92	.57	1.23	1.74	1.28	.98	1.09	.28	1.83
FeO	10.41	10.87	9.28	9.48	8.08	10.08	9.28	10.07	9.85	9.93	10.10	9.77	10.10	10.42	10.02
MgO	19.96	46.57	7.42	12.41	12.04	8.83	8.01	8.25	7.96	7.39	7.75	7.07	7.44	7.80	6.76
CaO	7.88	Tr.	11.27	9.14	9.28	10.88	10.64	11.17	11.65	11.06	11.24	11.33	11.38	11.45	12.40
Na_2O	1.38	.46	2.64	2.20	2.35	2.45	2.16	1.29	2.09	2.38	2.20	1.51	2.36	.70	2.02
K_2O	.35	.15	.59	.44	.59	.55	.45	.41	.54	.41	.56	.47	.47	.58	.73
H_2O+	.08	.18	.74	.11	.16	.17	.49	.03	.09	.33	.06	.04	.15	.18	.35
H_2O-	.04	.04	.08	.01	.02	.05	.22	None	None	.05	None	None	.08	Tr.	None
TiO_2	1.61	.09	2.75	2.85	2.42	2.49	2.70	3.20	2.60	3.10	2.33	3.63	3.33	1.55	2.33
P_2O_5	.21	-------	1.21	.37	.39	.41	.26	.23	.41	.30	.02	.22	.33	.22	.14
MnO	.13	.13	.08	.14	.14	.14	.16	.06	.15	.10	.14	.14	.12	.10	.18
Cr_2O_3	.12	.13	-------	.08	.13	.04	.05	.07	-------	-------	.05	.06	-------	.05	[a] .008
S	-------	-------	-------	.03	.01	.04	.11	-------	.07	-------	-------	-------	-------	-------	-------
NiO	.09	[b] .38	-------	-------	-------	.05	.04	.002	-------	-------	.008	Tr.	-------	.002	Tr.
BaO	None	-------	-------	.02	.04	Tr.	None	-------	-------	-------	-------	-------	-------	-------	-------
SrO	None	-------	-------	-------	-------	.07	Tr.	-------	-------	-------	-------	-------	-------	-------	-------
ZrO_2	None	-------	-------	-------	-------	Tr.	None	-------	-------	-------	-------	-------	-------	-------	-------
Cl	-------	-------	-------	.03	.02	.10	.08	-------	.02	.04	-------	-------	-------	-------	-------
V_2O_3	-------	-------	-------	-------	-------	.02	None	-------	-------	-------	-------	-------	-------	-------	-------
MoO_3	-------	-------	-------	-------	-------	.01	Tr.	-------	-------	-------	-------	-------	-------	-------	-------
	100.03	100.23	99.96	100.52	100.75	100.12	99.96	99.42	100.19	99.98	100.31	99.59	100.56	99.48	100.80

Norms

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Quartz	-------	-------	0.18	-------	-------	-------	2.16	4.62	0.96	2.04	-------	5.88	4.80	5.40	2.70
Orthoclase	2.22	-------	3.34	2.22	3.34	3.34	2.78	2.22	2.78	2.22	3.34	2.78	2.78	3.34	4.45
Albite	11.53	-------	22.53	18.34	19.91	20.96	18.34	11.00	17.82	20.44	18.34	12.58	21.13	5.76	16.77
Anorthite	17.51	-------	21.68	20.85	20.02	30.85	25.30	30.86	25.30	23.07	27.24	29.47	23.63	36.97	24.19
Diopside	16.65	-------	21.70	17.39	18.38	24.78	20.83	19.22	24.23	24.23	23.40	21.29	25.69	15.98	29.87
Hypersthene	18.12	-------	29.26	26.43	23.42	17.00	21.06	23.91	21.02	18.43	20.61	18.79	12.67	28.00	15.56
Olivine	28.17	[c] 96.40	-------	5.35	4.18	4.67	-------	-------	-------	-------	.97	-------	-------	-------	-------
Magnetite	2.09	-------	2.55	3.25	5.57	2.32	2.78	.93	1.86	2.55	1.86	1.39	1.62	.46	2.55
Ilmenite	3.04	-------	5.17	5.32	4.56	4.71	5.17	6.08	5.02	5.93	4.41	6.84	6.38	2.89	4.41
Apatite	.34	-------	.67	1.01	1.01	1.01	.67	.34	1.01	.67	-------	.34	.67	.34	.34

[a] Quantity of sample insufficient.
[b] Includes CoO.
[c] Includes forsterite 81.0 percent, fayalite 15.4 percent.

1. Picrite-basalt, lava flow of 1840, Nanawale Bay. Analyst, G. Steiger. (Cross, 1915, p. 44.) Norm from Washington (1923c, p. 347).
2. Olivine from 1840 lava at Nanawale Bay. Analyst, M. Aurousseau. (Aurousseau and Merwin, 1928, p. 560.)
3. Pele's hair collected in 1920, 2.5 miles southwest of Halemaumau. Analyst, H. S. Washington (1923c, p. 351).
4. Olivine basalt, lava of 1923, pahoehoe phase, near Makaopuhi Crater. Analyst, E. S. Shepherd (1938, p. 335).
5. Olivine basalt, lava of 1923, aa phase, near Makaopuhi Crater. Analyst, E. S. Shepherd (1938, p. 335).
6. Olivine basalt, dipped from Old Faithful lava fountain in Halemaumau by Perret and Shepherd in 1911. Analyst, J. B. Ferguson. (Day and Shepherd, 1913, p. 586.) Norm from Washington (1923c, p. 351).
7. Olivine basalt, lava of 1894(?), floor of caldera. Analyst, J. B. Ferguson. (Day and Shepherd, 1913, p. 586.) Norm from Washington (1923c, p. 351).
8. Splash from Halemaumau lava lake, 1917. Analyst, J. J. Fahey. (Powers, 1931, p. 2.)
9. Olivine basalt, liquid lava collected by T. A. Jaggar in 1919. Analyst, E. S. Shepherd (1938, p. 335).
10. Olivine basalt, lava flow of 1920, aa phase, Maunaiki. Analyst, H. S. Washington (1923c, p. 351).
11. Olivine basalt, splash from lava lake in Halemaumau during eruption of 1919 lava flow from Mauna Loa. Analyst, J. J. Fahey. (Powers, 1931, p. 2.)
12. Olivine basalt, 1919 lava flow at northeast edge of caldera floor. Analyst, J. J. Fahey. (Powers, 1931, p. 2.)
13. Olivine basalt, lava flow of 1920, pahoehoe phase, Maunaiki. Analyst, H. S. Washington (1923c, p. 351).
14. Olivine basalt, lava flow of 1921, south edge of Kilauea caldera. Analyst, L. T. Richardson. (Powers, 1931, p. 2.)
15. Basalt, scoria from lava fountain in Halemaumau during eruption of July 1929. Analyst, R. E. Stevens. (Powers, 1931, p. 2.)

Average composition of lavas of Kilauea and Mauna Loa compared with those of other regions

Analyses

	1	2	3	4	5	6
SiO_2	49.80	50.42	50.61	49.98	47.46	49.06
Al_2O_3	12.42	11.62	13.58	13.74	13.89	15.70
Fe_2O_3	1.53	2.71	3.19	2.37	3.58	5.38
FeO	9.91	9.07	9.92	11.60	9.38	6.37
MgO	10.31	10.11	5.46	4.73	6.79	6.17
CaO	10.32	9.74	9.45	8.21	9.83	8.95
Na_2O	1.96	2.09	2.60	2.92	2.90	3.11
K_2O	.45	.39	.72	1.29	1.01	1.52
TiO_2	2.68	2.97	1.91	2.87	2.71	1.36
P_2O_5	.29	.27	.39	.78	.43	.45
MnO	.13	.10	.16	.24	.22	.31

1. Average of 24 analyses of rocks of Kilauea.
2. Average of 14 analyses of rocks of Mauna Loa.
3. Average of 11 analyses of lavas from the Deccan region, India (Washington, 1922, pp. 774–775).

Norms

	1	2	3	4	5	6
Quartz	------	2.58	4.14	2.16	0.84	------
Orthoclase	2.22	2.22	4.45	7.78	5.5[illegible]	8.90
Albite	16.24	17.29	22.01	24.63	23.0[illegible]	26.20
Anorthite	24.19	20.57	23.07	20.57	23.91	24.46
Diopside	20.21	20.18	17.41	12.03	18.1[illegible]	13.81
Hypersthene	28.70	25.60	17.78	20.72	12.8[illegible]	13.03
Olivine	.34	------	------	------	------	.97
Magnetite	2.09	4.18	4.64	3.48	5.5[illegible]	7.89
Ilmenite	5.02	5.93	3.65	5.47	7.4[illegible]	2.58
Apatite	.67	.67	1.01	2.02	1.01	1.01

4. Average of 6 analyses of lavas of the Columbia Plateau and Snake River region, Oregon and Idaho (Washington, 1922, p. 779).
5. Average of 33 analyses of lavas from the North Atlantic (Thulean) region, includ ing Iceland, Greenland, and the British Isles (Washington, 1922, pp. 789–790).
6. Average composition of world basalts (Daly, 1933, p. 17).

HUALALAI

GENERAL GEOLOGY

Hualalai Volcano is a basaltic shield that rises to a summit altitude of 8,251 feet. On the south, east, and northeast its base has been overlapped by lavas of Mauna Loa. At depth the flows of Hualalai must interfinger with those of Mauna Loa and probably also with those of Mauna Kea. Most of the eruptive vents lie along three rift zones, the two most prominent of which trend N. 60° W. and S. 10° E. from a point about 3 miles east-southeast of the summit of the mountain. The third rift zone is less well defined. It trends a little west of north and appears probably to be a prolongation of the southeast rift zone. The rifts are marked at the surface by many cinder and spatter cones. The cones are in general larger than those of Mauna Loa but smaller and with a larger proportion of spatter than those of Mauna Kea. The lavas and pyroclastic rocks forming the major cone of Hualalai have been named the Hualalai volcanic series.

Puu Waawaa is a large cone of trachyte pumice on the north slope of the volcano. A thick flow of trachyte from this cone trends northwestward, underlying the small hill Puu Anahulu. The trachyte was both preceded and followed by basaltic flows from Hualalai and is partly buried by flows from Mauna Loa.

Most of the lavas along the lower western slopes of Hualalai are covered with a blanket of yellow to buff palagonitized ash. The thickness is greatest in kipukas that have not been covered by lava flows for long periods. The ash was originally vitric, composed of the drifted debris of lava fountains (Powers, Ripperton, and Goto, 1932, pp. 6–10). In general the thickness increases upslope, indicating that most of the ash probably came from eruptions on Hualalai. A large area near the top of Hualalai is covered with fresh drifted ash and basaltic pumice.

The only historic activity of Hualalai Volcano occurred at the beginning of the 18th century, probably during the years 1800 and 1801. Several flows were extruded at that time. One, the Kaupulehu flow, originated at a vent between 5,500 and 6,000 feet above sea level on the northwest flank. Another, the Huehue flow, originated at a row of cones at 1,500 feet altitude, probably shortly after the Kaupulehu flow. A little above the vent of the Kaupulehu flow Stearns has found three small flows, which from their freshness are believed to have been erupted about the same time as the Kaupulehu flow. Still another fresh-appearing flow lies just inland from the highway near the Huehue Ranch (Stearns and Macdonald, 1946, pp. 147–148).

HUALALAI VOLCANIC SERIES

LAVAS

The lavas of the Hualalai volcanic series include olivine basalt, basalt, olivine basalt transitional to picrite-basalt, and andesine andesite. Olivine basalt is greatly predominant, and andesite is rare. The proportions are roughly olivine basalt two-thirds; basalt and olivine basalt transitional to picrite-basalt, in about equal amounts, one-third. The rocks resemble those of the Kau volcanic series, on Mauna Loa, except that augite phenocrysts are more common. No true picrite-basalts have been found. Most of the rocks transitional to picrite-basalt contain phenocrysts of augite, but in few are they more than one-third as abundant as the olivine phenocrysts. They thus resemble the primitive picrite-basalts more nearly than the augite-rich picrite-basalts.

Olivine basalt from Umiahu Cone, at the top of Hualalai, contains scattered olivine phenocrysts up to 2 millimeters long which are crowded with iron-ore inclusions, constituting about half the bulk of the crystals. These iron-ore inclusions, probably liberated from the olivine by exsolution, are irregular, sometimes vermiform, and are arranged principally along prismatic cleavages but to a lesser degree along irregular fractures. An olivine basalt from the top of Puu Iki, 5 miles N. 12° E. of the top of Hualalai, shows distinct enlargement of the olivine phenocrysts. The latter, which were partly rounded by magmatic resorption before or during extrusion, show an outer zone about 0.02 millimeter thick, optically continuous with the core, which was apparently deposited contemporaneously with the crystallization of the groundmass. The contact of the outer zone with the core is marked by a row of inclusions of groundmass material.

Only one flow of andesite has been found on Hualalai. It crops out near the gate of the Territorial Forest Service cabin at Puu Laalaau, a little more than a mile southwest of the top of the mountain. The rock is a medium- to light-gray moderately vesicular pahoehoe containing a few phenocrysts of augite and sodic labradorite. The groundmass feldspar is calcic andesine. A specimen of another flow, collected 1.4 miles S. 19° E. of Puu Anahulu, is transitional in composition between basalt and andesite. The dominant feldspar is labradorite-andesine.

The various flows erupted in 1801 are closely similar petrographically, although the Kaupulehu flow is largely aa and the Huehue flow is largely pahoehoe. At the highway, the Kaupulehu flow is a typical olivine basalt with scattered phenocrysts of olivine up to 6 millimeters long but mostly less than 1.5 millimeters and a few augite phenocrysts up to 1 centimeter or more in length. A little potash-andesine is present in the groundmass.

GABBROIC AND ULTRABASIC XENOLITHS

Xenoliths of hypabyssal or plutonic igneous rock are abundant in the lavas of Hualalai. They are found in the lava of 1801, in several older flows along the highway, and among the ejected blocks at the summit of the mountain. An olivine gabbro, resembling the rock of the intrusive at Uwekahuna Bluff on Kilauea, was recorded by Daly (1911, p. 304) from the explosion debris near the summit, and in the lavas along the highway east of Huehue ranch Cross (1915, pp. 34–35) found xenoliths of dunite, augite peridotite (wehrlite), and olivine gabbro. Augite gabbro without olivine was identified by Washington (1923b, p. 104) among blocks collected in the summit area by Clark and Thomson. The analysis of the latter rock, by Washington, is quoted on page 78.

Four xenoliths, all of them from the Kaupulehu flow of the eruption of 1801, have been studied by the writer. Two of them are olivine gabbro. One is a light gray, slightly pinkish angular fragment of dense granitoid rock about 7 centimeters across. The texture is granitoid, with an average grain size of about 1.5 millimeters. The rock consists of olivine (15 percent), pyroxene (27 percent), plagioclase (55 percent), and iron ore (3 percent). The olivine has an optic-axial angle close to 90°. The plagioclase is intermediate labradorite, with $\beta=1.561$. The pyroxene is augite, with $+2V=60°$, and $\beta=1.702$. Many of the pyroxene grains have a pronounced schiller structure, owing to minute reddish-brown plates, probably of hematite, arranged along the cleavages. The other gabbro xenolith is unusually rich in feldspar, consisting of plagioclase (79 percent), monoclinic pyroxene (6 percent), olivine (14 percent), and iron ore (1 percent). The plagioclase is intermediate bytownite ($\beta=1.571$).

A subangular inclusion of pale-green dunite, 8 centimeters across, is allotriomorphic granular in texture, with an average grain size of about 0.8 millimeter. It is composed of olivine (94 percent), augite (1 percent), iron ore (2 percent), and yellow glass (3 percent). The glass occupies angular interstices and has an index of refraction close to 1.54. The ore mineral is probably magnetite but may be chromite. The margin of the dunite against the enclosing lava shows no evidence of chemical reaction between the two, but the dunite was obviously disintegrating mechanically. The margin is irregular, controlled by the edges of olivine grains, and narrow tongues of lava extend along fractures into the dunite.

An angular inclusion of augite peridotite, 5 centimeters across, is crudely banded, layers of almost pure olivine alternating with thinner layers rich in pyroxene. The banding resembles that observed in many norites and peridotites. The texture is allotriomorphic granular, and the average grain size is about 1.5 millimeters. Many plates of augite are poikilitic, containing smaller grains of olivine. The rock consists of olivine (80 percent), augite (16 percent), and iron ore (4 percent). Like the dunite, the augite peridotite shows no evidence of chemical reaction with the enclosing lava but was undergoing mechanical disintegration when the lava congealed. This xenolith differs from the one described by Cross in that feldspar is lacking and augite is much less abundant. Other specimens show all gradations between augite peridotite and dunite.

The cone at the head of the Kaupulehu flow contains innumerable small cored bombs and lapilli, consisting of a fragment of dunite enclosed in a thin skin of black glassy lava.

PHREATIC EXPLOSION DEBRIS

Numerous angular blocks scattered over the surface near the summit of Hualalai appear to have been ejected by phreatic explosions. A wide variety of rock types is represented, including olivine basalt, basalt, olivine gabbro, and augite gabbro. Blocks of olivine basalt from the south rim of the large crater at the summit contain a few small grains of biotite. The rock is probably the one described by Cross (1915, p. 35) and analyzed by Washington (1923c, p. 102). The analysis is quoted in column 3 of the table on page 78. Hornblende was reported in this rock by Cross but has not been found by the writer.

TRACHYTE OF PUU WAAWAA

The trachyte of Puu Waawaa and Puu Anahulu is petrographically much more closely allied to the late oligoclase andesites of Kohala Volcano than to the lavas of Hualalai Volcano, but its situation on the slope of Hualalai, far off the projection of the Kohala rift zone, indicates that it is probably genetically related to Hualalai. Puu Waawaa is a trachyte pumice cone containing fragments of obsidian and the cliff extending from Puu Huluhulu to Puu Anahulu is the edge of a thick flow of viscous trachyte, which probably issued at the northeast edge of the cone (Stearns and Macdonald, 1946, pp. 143–145). Both cone and flow are partly buried by late lavas from Hualalai and Mauna Loa.

The trachyte was first recognized and fully described by Cross (1904), and analyses of the rock were made for him by Hillebrand. The trachyte was briefly mentioned by Powers (1916a, p. 269) and was again carefully described and analyzed by Washington (1923b, pp. 105–109).

The trachyte obsidian from Puu Waawaa is typically dark gray to black, resembling pitchstone in slight waxiness of luster, and is crudely banded with alternate thin streaks and irregular lenses of black glass and dark-gray partly crystalline material. Splinters of the glass are transparent and nearly clear on thin edges. The refractive index is 1.512. Under the microscope the more crystalline parts of the rock are seen to consist of a matrix of colorless glass, containing irregular anhedral grains of untwinned alkalic feldspar up to 0.2 millimeter long, and slender colorless microlites of some ferromagnesian mineral with straight extinction, negative elongation, and moderately high relief. Many of the microlites show feathery terminations.

Trachyte pumice from Puu Waawaa is similar in composition to the obsidian. It is light gray to buff and much inflated, the vesicles ranging from a fraction of a millimeter to nearly a centimeter across. The vesicles are more stretched than in the typical basaltic pumice of Hawaii but less so than in pumice from many continental localities as, for example, the Cascade Range of Oregon between Crater Lake and the city of Bend (Williams, 1942, pp. 68–79).

A specimen of lapilli tuff from Puu Waawaa is light gray and crudely bedded, consisting of angular to subangular fragments of dense trachyte with less abundant fragments of buff pumice. The texture ranges from that of coarse sand to that of medium gravel, with a few fragments as much as 1.5 centimeters in diameter. The dense trachyte fragments are largely crystalline, consisting principally of alkalic feldspar.

A specimen of trachyte from the thick flow exposed in a highway cut 2.95 miles N. 10° W. of the top of Puu Waawaa is medium gray and dense, with crudely defined flow structure and poorly developed platy jointing parallel to the flow structure. Surfaces of the platy joint blocks show a micaceous-appearing sheen owing to the parallel arrangement of innumerable tabular feldspar crystals. The rock consists largely of anhedral grains of alkalic feldspar, which have the optical properties of albite ($+2V$ large, $\beta=1.533$) but which, as pointed out by Washington (1923b, p. 107), must contain a considerable proportion of potash feldspar. Scattered through the matrix of feldspar are many subhedral to anhedral grains of magnetite (7 percent), pale-green subhedral grains of aegirine-augite (5 percent), subhedral colorless grains of monoclinic pyroxene, probably diopside (4 percent), a few subhedral prismatic grains of a riebeckitelike mineral (1 percent), and rare small reddish-brown flakes of biotite. The riebeckite-like mineral is less strongly colored than typical riebeckite, and the mineral in the trachyte of Puu Anahulu is even paler than that in the lavas of the Kohala and West Maui Volcanoes. The bleaching appears to accompany a partial break-down of the mineral, with liberation of abundant fine dust of iron ore and some unidentified transparent mineral with moderately high refractive index, possibly a pyroxene. Decomposition is often intense, and in many places a shadow of this fine dust is all that is left of a former grain of the riebeckitelike mineral.

Trachyte from the top of Puu Anahulu closely resembles that just described, except that it contains scattered flakes of hematite and a few minute grains of a pale-yellow mineral with high birefringence—probably the mineral thought to be acmite by Washington and Merwin (1922, p. 107). The biotite flakes in this rock are pleochroic from pale yellowish brown to deep reddish brown.

Chemical analyses of the trachyte from Puu Anahulu and the obsidian from Puu Waawaa are quoted in the table on page 78.

CHEMICAL ANALYSES

The accompanying table lists all the reasonably complete analyses of rocks from Hualalai Volcano known to the writer. All but one are by H. S. Washington. The first three analyses are of the predominant olivine basalts; the fourth analysis is of a basalt poor in olivine, showing a trend in composition toward the andesites; and the fifth is of a still more andesitic rock, in which the normative feldspar is andesine. There is a wide gap between the composition of these basaltic rocks and that of the highly feldspathic and sodic trachyte.

In chemical composition the trachyte closely resembles that of Launiupoko Hill and other vents on West Maui (Cross, 1915, p. 27; Macdonald, 1942a, p. 334), and some of the trachytes of American Samoa (Daly, 1924, pp. 105–110; Macdonald, 1944a, pp. 1344–1347). It is less silicic than that of Mauna Kuwale, in the Waianae Range of Oahu (Macdonald, 1940b, pp. 81–84).

The average composition of the analyzed lavas of Hualalai, omitting the trachytes, is shown in column 7 of the table. As compared with the average composition of the analyzed lavas of Mauna Loa and Kilauea (p. 74), that of the lavas of Hualalai is distinctly higher in alkalies—and consequently in normative orthoclase and albite—is higher in alumina, and is a little lower in silica and magnesia. Surprisingly enough, the normative plagioclase falls within the range of andesine, probably because the lavas chosen for analysis were of the less common types.

Chemical analyses and norms of rocks from Hualalai

Analyses

	1	2	3	4	5	6	7	8	9
SiO_2	46.01	46.43	46.76	47.69	48.04	48.17	47.18	62.02	62.19
Al_2O_3	15.40	10.91	13.78	16.92	15.35	15.45	14.64	18.71	17.43
Fe_2O_3	1.22	3.15	1.26	3.69	5.72	3.98	3.17	4.30	1.65
FeO	8.15	10.26	10.43	8.83	7.67	8.67	9.00	.10	2.64
MgO	13.25	11.08	11.07	4.02	5.77	3.97	8.19	.40	.40
CaO	10.74	10.09	10.54	10.73	10.13	11.00	10.70	.86	.86
Na_2O	2.30	3.16	3.59	2.89	3.26	3.04	3.04	6.90	8.28
K_2O	.67	.54	.64	1.17	.79	.98	.80	4.93	5.03
TiO_2	1.80	2.59	2.12	2.79	3.13	4.32	2.79	.31	.37
H_2O+	.19	.66	.10	.57	.27	.25	.34	.80	.39
H_2O-	.07	.15	.10	.09	.04	.06	.08	.31	.14
ZrO_2		None						.06	.04
P_2O_5	.62	.67	.32	.67	.33	.35	.49	.24	.14
SO_3		.07						.02	None
Cr_2O_3		None						None	Tr.
MnO	.08	.09	.08	.13	.10		.09	.15	.32
BaO		None						.02	.03
CO_2								None	.02
Cl								None	
	100.50	99.85	100.79	100.29	100.60	100.24		100.13	99.93

Norms

	1	2	3	4	5	6	7	8	9
Quartz						2.58		1.80	
Orthoclase	3.89	3.34	3.89	6.67	4.45	5.56	5.00	28.91	29.47
Albite	15.72	23.84	15.72	24.63	27.77	25.68	25.68	58.16	51.87
Anorthite	29.75	13.90	19.46	29.75	24.74	25.58	23.63	2.22	
Nepheline	1.99	1.56	7.95				.85		5.40
Corundum								1.22	
Acmite									4.62
Noselite									.73
Diopside	16.03	25.31	25.00	15.33	18.65	21.00	20.86		2.88
Hypersthene				9.69	8.91	3.62		1.00	
Olivine	26.22	19.97	22.02	1.14	.76		14.42		3.35
Magnetite	1.86	4.64	1.86	5.34	8.35	5.80	4.64		
Ilmenite	3.50	4.86	3.95	5.32	5.93	8.21	5.32	.15	.76
Hematite								4.30	
Apatite	1.34	1.68	.67	1.68	.67	1.01	1.34	.67	.34
Rutile								.24	

1. Olivine basalt, "average lava" from an altitude of 7,400 feet on the north slope of Hualalai. Collector, R. A. Daly. Analyst, H. S. Washington (1923b, p. 102).
2. Olivine basalt, lava of 1801, Hualalai. Analyst, H. S. Washington (1923b, p. 102).
3. Olivine basalt, block from pit crater near summit of Hualalai. Collector, R. A. Daly. Analyst, H. S. Washington (1923b, p. 102).
4. Basalt, block from near summit of Hualalai. Analyst, H. S. Washington (1923b, pp. 104–105).
5. Basalt, with tendency toward andesite, flow near summit of Hualalai. Analyst, H. S. Washington (1923b, pp. 104–105).
6. Gabbro, block from near summit of Hualalai. Analyst, H. S. Washington (1923b, pp. 104–105).
7. Average of analyses 1 to 6. The norm is calculated from the average chemical composition and not by averaging the norms of the previous analyses.
8. Trachyte, Puu Anahulu. Analyst, H. S. Washington (1923b, p. 108).
9. Trachyte obsidian, Puu Waawaa. Analyst, W. F. Hillebrand. (Cross, 1904, p. 514.) Norms from Washington (1923b, p. 108).

MAUNA KEA

GENERAL GEOLOGY

The rocks of Mauna Kea have been divided into the Hamakua and Laupahoehoe volcanic series (Macdonald, 1945, pp. 210–217; Stearns and Macdonald, 1946, pp. 152–165). The Hamakua volcanic series is exposed on the lower slopes of the mountain, in kipukas that have remained uncovered by later flows. For the most part the Hamakua lavas were erupted in a highly fluid condition, forming thin flows that spread out far from their vents, and built a broad shield volcano like nearby Mauna Loa and Kilauea. Unlike most Hawaiian lava shields, however, the slopes of the Hamakua volcanic edifice steepened greatly in its upper part, the average inclination changing from 5° to 16°. The steepening appears to be partly the result of interbedded pyroclastic material in the upper part of the cone but may also be caused in part by a tendency toward restriction of eruptions to the apical part of the mountain.

The passage from the Hamakua to the Laupahoehoe volcanic series is gradational. Locally they are separated by erosional unconformities, but there is no general widespread unconformity between them.

On the north the late lavas of the Hamakua volcanic series are banked against and interbedded with the late lavas of the older and smaller Kohala Volcano. On the south the lavas of the Laupahoehoe volcanic series are overlapped by late flows from Mauna Loa, but deflection of late flows from Mauna Kea eastward and westward along the depression between the two mountains indicates that the north slope of Mauna Loa must already have been built nearly to its present position at the time the late Laupahoehoe lavas were erupted. Mauna Kea and Mauna Loa must have grown to a large extent simultaneously, and their lavas must interfinger at depth. A similar relation probably exists between Mauna Kea and Hualalai.

During the Pleistocene epoch the upper part of Mauna Kea was covered by a small glacier (Gregory and Wentworth, 1937, pp. 1730–1742; Wentworth and Powers, 1941, pp. 1203–1206). Volcanism continued during the period of glaciation, and a few eruptions have taken place in postglacial time.

HAMAKUA VOLCANIC SERIES

LAVAS

The lower part of the Hamakua volcanic series is composed of an assemblage of rocks closely similar to that of Mauna Loa and Kilauea. Olivine basalt is greatly predominant, but associated with it are lesser amounts of basalt and primitive picrite-basalt. Olivine phenocrysts are present in nearly all the flows. Augite and plagioclase phenocrysts are comparatively rare, although a few of augite occur in nearly all the picrite-basalts. Basalts are somewhat less abundant than on Mauna Loa and Kilauea, and basalts entirely free of olivine have not been found.

In the upper part of the Hamakua volcanic series there occur, interbedded with the primitive types of lavas, more strongly differentiated types, including augite-rich picrite-basalt and andesine andesite. The transition from the lower to the upper member is gradual. Although primitive picrite-basalt has not been found in the upper member, basalt and olivine basalt recur throughout the section, basalt being a little more abundant than in the lower member. Phenocrysts of augite and feldspar are common in the lavas of the upper member, although types with phenocrysts of olivine alone still persist. Some of the rocks with feldspar phenocrysts contain no other phenocrysts, but most contain phenocrysts of olivine and augite. Some flows contain phenocrysts of olivine and augite but none of feldspar. Flows containing phenocrysts of olivine and feldspar but none of augite are unknown. The andesites and augite-rich picrite-basalts are closely similar to those of the upper (Kula and Hana) volcanics on Haleakala Volcano (Macdonald, 1942a, pp. 285–302).

The following geologic section is typical of the rock assemblage of the Hamakua volcanic series. It clearly shows the great preponderance of olivine basalts in the lower part of the Hamakua volcanic series and the relative abundance of other rock types in the upper part.

Stratigraphic section of Hamakua volcanic series along road up south wall of Laupahoehoe Gulch

	Feet
Hamakua volcanic series:	
Upper member:	
Olivine basalt pahoehoe, thin-bedded, moderately to highly vesicular, with moderately abundant phenocrysts of olivine as much as 3 mm. long	10
Red tuffaceous soil	0.1–0.5
Local unconformity.	
Andesite aa, containing a few olivine phenocrysts as much as 4 mm. long, and many plagioclase phenocrysts as much as 2 cm. long	35
Local unconformity.	
Andesite aa, with scattered olivine phenocrysts as much as 3 mm. long	10
Red fine-grained ash	0–0.1
Andesite aa, with rare olivine phenocrysts as much as 2 mm. long	8
Red fine-grained ash	0.1–0.4
Olivine basalt aa, with scattered olivine phenocrysts as much as 6 mm. long	10
Local erosional unconformity.	
Picrite-basalt aa, with abundant phenocrysts of olivine and augite, some as much as 1 cm. long	15
Poorly sorted boulder conglomerate	4
Buff fine-grained ash	0–0.7
Picrite-basalt aa, with abundant phenocrysts of olivine and augite as much as 7 mm. long	8
Lower member:	
Reddish to grayish-brown tuffaceous silty soil	0.3–1.3
Olivine basalt pahoehoe, consisting of many thin flow units 0.6 to 8 ft. thick, mostly between 1 and 2 feet. Olivine phenocrysts as much as 3 mm. long are moderately abundant in some units, but rare in others	65
Olivine basalt aa, with moderately abundant olivine phenocrysts as much as 2 mm. long	6
Olivine basalt aa, with a few olivine phenocrysts as much as 5 mm. long	9
Olivine basalt aa, with moderately abundant olivine phenocrysts as much as 3 mm. long	5
Olivine basalt aa, locally grading into pahoehoe, with moderately abundant olivine phenocrysts as much as 4 mm. long	6
Olivine basalt pahoehoe, locally grading into aa, with a few olivine phenocrysts as much as 1.5 mm. long	5
Olivine basalt pahoehoe, like that above	6
Olivine basalt aa, with a few olivine phenocrysts as much as 1.5 mm. long	4
Olivine basalt pahoehoe, with scattered olivine phenocrysts as much as 5 mm. long, some of them very tabular. Composed of flow units 0.6 to 2 ft. thick	8
Olivine basalt aa, with a few olivine phenocrysts as much as 1.5 mm. long	3
Olivine basalt aa, like that above	6
Red fine-grained ash	0.1–0.3
Olivine basalt pahoehoe, with moderately abundant olivine phenocrysts as much as 7 mm. long. Composed of flow units 0.5 to 2 ft. thick	7
Olivine basalt aa, with moderately abundant olivine phenocrysts as much as 5 mm. long	9
Picrite-basalt pahoehoe, of primitive type, with abundant olivine phenocrysts as much as 8 mm. long, but only rare augite phenocrysts. Base hidden by talus	7+

All the analyses of lavas of the Hamakua volcanic series in the table on page 83 represent rocks of the upper member, except that of the primitive picrite-basalt (column 2). The picrite-basalt was stated by Washington (1923a, p. 501) to come from Kaula Gulch, above Ookala. The writer has, however, been unable to identify this rock at that locality. Picrite-basalt exposed along Kaula Gulch near the highway above Ookala is of the augite-rich type, whereas that described by Washington is lacking in augite phenocrysts. The locality description would place the rock in the upper member of the Hamakua volcanic series. However, no other primitive picrite-basalt has been found in the upper member, and it more probably belongs in the lower member.

INCLUSIONS IN LAVAS

Inclusions of coarse-grained rocks are much less abundant in the lavas of the Hamakua than in the Laupahoehoe volcanic series, but small inclusions of dunite and gabbro are found in a few flows. One of them is an olivine basalt exposed in an old quarry in Kaula Gulch just above the highway.

An olivine basalt flow 71 feet above the base of the section up the south wall of Laupahoehoe Gulch contains many subrounded patches of basalt with an intersertal texture and an average grain size of about 0.08 millimeter. The boundaries of these patches are marked by rims of small magnetite granules. The enclosing lava is intergranular, with a distinctly smaller average grain size (0.02 millimeter). The coarser patches appear to be inclusions of another lava partly absorbed by the enclosing flow.

LAVAS OF THE LAUPAHOEHOE VOLCANIC SERIES

The lavas of the Laupahoehoe volcanic series are preponderantly andesine andesites, although olivine basalts also are present in small volume. Neither basalt nor picrite-basalt has been found among the Laupahoehoe lavas.

Many of the andesite flows are very massive, and some single flows reach thicknesses of more than 100 feet, contrasting strikingly with the characteristically thin flows of the Hamakua volcanic series. At some places the viscous andesite lava piled up around the vents to build small domes. The greater viscosity of the andesites, coupled probably with a greater concentration of gas in the upper part of the conduit, resulted in more explosive eruptions than those characteristic of the earlier series and consequently in larger cinder cones. Some of the andesite flows are pahoehoe, but most of them are aa. A cross section of a typical aa flow is shown in plate 14, *B*.

Olivine basalts probably occur scattered throughout the Laupahoehoe volcanic series. Erosional dissection has been slight, however, and in most places only the uppermost part of the series is accessible for study. The olivine basalts of the Laupahoehoe volcanic series differ from those typical of the Hamakua volcanic series in that olivine phenocrysts are generally absent, or where present are few and small. Augite phenocrysts have not been found. Some of the rocks have many small irregular open pores and approach a diktytaxitic structure, resulting from the draining away of the interstitial fluid at an advanced stage of crystallization.

The andesites of the Laupahoehoe volcanic series closely resemble those of Haleakala Volcano on East Maui (Macdonald, 1942a, pp. 285–302). Most of them are characterized by rather well developed platy jointing parallel to the flow planes, and in most places approximately parallel to the top and bottom of the flow. Porphyritic and nonporphyritic types are about equally abundant. In the porphyritic rocks the phenocrysts are generally feldspar. Olivine phenocrysts, with or without accompanying feldspar phenocrysts, are rare and small. Microphenocrysts of magnetite are present in a few flows.

All the postglacial flows, shown on plate 12, are andesine andesite. In the flow from Puu Kole, which crosses the road north of Puu Oo ranch, biotite is unusually abundant. It forms about 2 percent of the rock and occurs as small anhedral interstitial grains and flakes projecting into vesicles.

Angular to subangular inclusions of dunite and gabbro are fairly common in the andesites. Similar fragments among the ejecta of the cinder cones are described in the next section.

PYROCLASTIC ROCKS

ASH BEDS

Thin layers of ash, from less than an inch to a few inches thick, are intercalated with the lavas of the Hamakua volcanic series (see pp. 79–80) and are even more numerous in the Laupahoehoe volcanic series. The Pahala ash, which overlies the Hamakua lavas, is the result of accumulation throughout the period of eruption of the Laupahoehoe lavas, and its maximum thickness in any area is found only where its deposition has not been interrupted by lava flows. Most of the Laupahoehoe lavas are covered with a varying thickness of Pahala ash. Near Hilo the Pahala ash is in places 15 feet thick, but it decreases in thickness northwestward until between Ookala and Kukaiau it has a maximum thickness of only 5 to 6 feet, and near Waimea a maximum thickness of only 4 to 5 feet. Where its accumulation has not been interrupted by intervening lava flows, its thickness increases up the mountain. Thus, along the road from Kukaiau to Umikoa the thickness increases more or less regularly from 4 feet at 1,000 feet altitude to 13 feet at 3,500 feet altitude (Wentworth, 1938, pp. 78–80).

Both the layers of ash in the Hamakua volcanic series and the Pahala ash on the lower slopes of Mauna Kea were originally largely vitric, with scattered crystals of plagioclase, olivine, and augite. However, much of the glassy portion has been altered to palagonite. The ash is generally buff or reddish brown in the wet areas on the northeastern slopes, but on the dry western slopes it is yellow. Gray beds are much less common. Granularity appears to have been originally fine in most places, coarsening toward the vents. In places lapilli of pumice can still be recognized, although they are largely altered to palagonite.

Several specimens have been examined in thin section and in oil immersion. Others have been described by Wentworth (1938, pp. 144–145). Typically, the ash consists of small shards, many of them showing the characteristic arcuate outlines resulting from the disruption of highly vesicular lava froth. Some contain microlites of plagioclase and less commonly of pyroxene. Some are clouded by finely granular iron ore. All are partly altered to palagonite, and the alteration appears to proceed more readily in the wholly vitreous fragments than in those containing abundant microlites. Secondary calcite is present in some specimens. Alteration is much less complete in the dry areas than in areas where the ash is almost continuously saturated with water, and on the western slopes some specimens contain a large proportion of little-altered glass. The feldspar microlites in these unaltered fragments appear to be andesine, and the erupted lava was probably of andesitic composition, similar to the great bulk of the Laupahoehoe volcanic series.

On the upper slopes of Mauna Kea, below the late glacial moraines, there are large areas of dark-gray to black sandy ash, which have been derived from the late eruptions. The ash is largely glassy lava-fountain debris, with scattered phenocrysts of plagioclase and olivine. Many of the fragments are drop-shaped, but most are broken angular shards. In two specimens examined by immersion in refractive index liquids, the plagioclase is sodic labradorite ($\beta=1.560$), like many of the small phenocrysts in the andesitic lavas, and the glass has $n=1.566$. The latter corresponds to a silica content of about 52 percent (George, 1924), which is a little higher than the percentages of silica determined by chemical analysis in the andesites of Mauna Kea (p. 83).

The following table gives chemical analyses of three samples of Pahala ash on Mauna Kea; also the same analyses recalculated on a water-free basis. All are quoted from Wentworth (1938, p. 128). For comparison, there is also given the average of five chemical analyses of andesites of Mauna Kea. Specimen 2 is obviously the least altered. Specimens 1 and 2 are from the dry side of the mountain, and alteration has consisted largely of palagonitization, which in specimen 2 is probably not complete. Specimen 3 is from the wet side of the island, and has undergone extensive leaching under the same warm subtropical conditions that lead to the production of laterite. The alteration has involved the removal of part of all the constituents except iron oxide, phosphorous oxide, and possibly alumina (Wentworth, 1938, p. 129).

Chemical analyses of Pahala ash on Mauna Kea

	1	2	3	4	5	6	7
SiO_2	37. 16	50. 73	3. 39	42. 77	57. 90	4. 98	49. 97
TiO_2	3. 51	1. 79	5. 01	4. 03	2. 05	7. 36	2. 79
Al_2O_3	18. 94	19. 06	31. 72	21. 75	21. 79	46. 64	16. 77
Fe_2O_3	7. 37	7. 48	24. 90	8. 46	8. 54	36. 60	4. 41
FeO	5. 93	1. 03	. 84	6. 81	1. 18	1. 23	6. 99
MnO	. 12	. 11	. 13	. 14	. 13	. 19	. 19
MgO	3. 72	1. 55	. 12	4. 27	1. 76	. 18	4. 23
CaO	5. 58	1. 92	. 03	6. 38	2. 19	. 04	7. 28
Na_2O	2. 67	1. 79	. 44	3. 07	2. 05	. 65	4. 24
K_2O	1. 00	1. 98	. 30	1. 15	2. 26	. 44	1. 83
H_2O+	6. 33	6. 60	24. 27	------	------	------	. 54
H_2O-	6. 51	5. 14	8. 22	------	------	------	. 37
P_2O_5	1. 02	. 13	1. 15	1. 17	. 15	1. 69	. 62
	99. 86	99. 31	100. 52	100. 00	100. 00	100. 00	------

1. Yellowish-brown ash, from an altitude of 5,175 feet in Auwaiakeakua Gulch, southeast of Waikii. Analyst, J. G. Fairchild. All analyses of ash quoted from Wentworth (1938, p. 128).
2. Red ash, from an altitude of 3,500 feet in Kemole Gulch. Analyst, J. J. Fahey.
3. Red ash, 5 feet below top of road cut, 0.25 mile south of Pepeekeo. Analyst, Charles Milton.
4. Same as 1, recalculated on water-free basis.
5. Same as 2, recalculated on water-free basis.
6. Same as 3, recalculated on water-free basis.
7. Average of 5 analyses of andesites of Mauna Kea.

Thick deposits of coarse tuff-breccia are exposed in the large gulches on the south flank of Mauna Kea at altitudes of 9,000 to 10,000 feet. They are intercalated in lava flows and cinder referred to the Hamakua volcanic series. The deposits were formerly considered to be glacial moraine (Wentworth and Powers, 1941, pp. 1207–1210), but are believed by Stearns (1945, p. 273) to be pyroclastic. Locally they are as much as 90 feet thick, but they decrease in thickness rapidly both upslope and downslope. They are moderately well bedded and show a fair degree of sorting. Cobbles and boulders up to 2 feet in diameter are abundant in some beds but absent in others. Beds of lapilli also are present. In Waikahalulu Gulch the deposits consist of blocks of olivine basalt in a matrix of vitric-crystal ash. The blocks are fresh, but their surfaces show evidence of attrition by collision during flight. Part of the fine matrix was undoubtedly derived by pulverisation of the surfaces of the blocks. In Pohakuloa Gulch and a small gulch 0.25 mile farther east the deposits are similar but contain in addition to the olivine basalt many blocks of augite-rich picrite-basalt.

CINDER CONES

Numerous cinder cones, many of them of large size, were built at the sources of the late lava flows of the Hamakua and Laupahoehoe volcanic series. They include all the rock types of those ages, but the cones of andesite and picrite-basalt are especially prominent. The latter are restricted to the areas of Hamakua lavas on the lower slopes of the volcano, whereas the cones on the upper slopes are predominantly andesitic.

The ejecta composing the cones range from fine ash to bombs several feet in length. Most of the bombs are of Strombolian type, ejected in a fluid condition and sufficiently solidified during flight to retain their shapes on striking the ground, but at some cones there are Hawaiian bombs, which fell in a still fluid condition. Nearly spherical bombs characterize the picrite-basalt cones, whereas the bombs of the andesitic and basaltic cones are typically spindle-shaped. The spherical bombs resemble those ejected at Kilauea in 1790. (See p. 70–71.) They appear to indicate a low viscosity of the lava, permitting surface tension to draw the ejected drop or filament into a nearly spherical shape before it is frozen to immobility. The spindle bombs were too viscous to be drawn into spherical shape. Both the spherical and the spindle bombs typically show small projections at the poles, and represent local thickening of lava ribbons. As pointed out by Reck (1915, pp. 39–61) and Wentworth (1938, pp. 111–115), rotation during flight was of little or no importance in shaping the spindle bombs. A few of the spindle bombs on the andesitic cones show poorly developed bread-crust cracking. Many of the cones contain a few bombs with cores of lava, either essential or accidental, or of accessory plutonic rock fragments. The latter include both gabbro and ultrabasic types and will be described in the next section.

Many well-formed loose crystals of augite and olivine occur in the picrite-basalt cinder cones. At Puu Pa, southwest of Waimea, the augite crystals reach a length of 2 centimeters. They are prismatic parallel to the *c* axis, most of them being rather stubby but some moderately elongated. The common crystal forms are 100, 010, 110, and 11Ī.[1] Many arrowhead twins, resulting from twinning on 100, are present. The augite has $+2V=60°$, very weak dispersion, and $\beta=1.706$. The other optical properties as determined by Winchell (1940) are: $Z \wedge c=37°$, and $\gamma-\alpha=0.030$. The olivine crystals reach a length of 8 millimeters and show the following forms: 010, 110, 120, and 021. A few are notably elongated parallel to the *c* axis, but most are stubby. They have a $-2V$ close to 90°, and $\beta=1.699$.

PLUTONIC EJECTA

Coarsely crystalline plutonic ejecta are found in many of the late cinder cones on the upper slopes of Mauna Kea. They are of two general types, gabbro and ultrabasic rocks. Both types range in shape from angular to subangular and rarely are subrounded. They occur as the cores of bombs and also as independent blocks. Many of the latter, however, may once have had a coating of lava that was cracked off when the bomb struck the ground. Ejecta of both gabbro and ultrabasic rocks are exceedingly abundant in the small cinder cone that lies just west of Hale Pohaku, 0.7 mile north of Puu Kalepeamoa, on the south flank of Mauna Kea (pl. 12), and are abundant also in Puu Kalepeamoa and Puu Haiwahine, which lies just west of Kalepeamoa.

[1] Pabst, Adolf, Personal communication, October 9, 1943.

Most of the gabbro ejecta are of ordinary olivine gabbro, consisting of plagioclase, augite, olivine, and iron ore. Typical of them is a block from the northeast side of a cone 0.6 mile east of the cone with a summit altitude of 10,226 feet, on the west flank of Mauna Kea. The texture is granitoid, and the average grain size is about 1.5 millimeters. Calcic labradorite constitutes about 55 percent of the rock, augite 26 percent, olivine 18 percent, and iron ore 1 percent. The iron ore is largely or entirely magnetite. The olivine has a $-2V$ close to 90°. The augite has $+2V=60°$, and $r>v$ moderate. In a similar block from the same locality the plagioclase is intermediate labradorite, and the augite has $\beta=1.702$, and $+2V=60°$. A gabbro fragment forming the core of a bomb on Kalepeamoa Cone contains an angular inclusion of dunite 2 centimeters across.

A block of olivine gabbro collected on the cone with a summit altitude of 10,427 feet, on the west flank of the mountain, is nearly devoid of pyroxene. It is composed of intermediate labradorite, which forms about 60 percent of the rock, olivine 33 percent, iron ore 5 percent, and augite 2 percent. The rock may be classed as a troctolite.

The gabbros grade into the ultrabasic rocks by a decrease in feldspar. In the cone west of Hale Pohaku every gradation can be found from olivine gabbro, through picrite, to augite peridotite (wehrlite). The dunites are less obviously connected by transitions with the gabbros. A few of the augite peridotites are cut by thin dikelets, up to a few millimeters thick, of fine-grained feldspathic gabbro. Typical of the augite peridotite inclusions is a block from the south side of the summit cone. It is an equigranular rock with an average grain size of about 1.5 millimeters, composed of about 75 percent olivine and 25 percent augite. The augite is concentrated in narrow bands, which are made up of approximately equal amounts of augite and olivine. The augite has $+2V=60°$, $\beta=1.704$, and weak dispersion. The olivine has a $2V$ close to 90°, and $\beta=1.699$. These rocks were termed lherzolite by Daly (1911, pp. 301–302), but he recorded no orthorhombic pyroxene, and none has been found by the writer.

The dunites are dense sugar-granular rocks, oil green or brownish green on fresh surfaces. They are aggregates of anhedral olivine grains, with a few subhedral grains (2 or 3 percent) of an opaque spinel, probably magnetite. A few small anhedral grains of augite are present in some specimens. In a block from the summit cone the olivine has a $2V$ close to 90°, and $\beta=1.699$.

CHEMICAL ANALYSES

The accompanying table shows the existing chemical analyses of lavas of Mauna Kea. All the general types occurring in the upper member of the Hamakua volcanic series are represented except augite-rich picrite-basalt. Among the lavas of the Laupahoehoe volcanic series only andesite is represented.

Figure 1 is a variation diagram for the principal oxides in the lavas of Mauna Kea plotted against percentage of silica. The trend lines are rather uncertain, however, owing to the small number of analyses and to the frequently wide variation in percentage of most of the oxides in adjacent analyses. Most of the curves are very similar to those for the lavas of Haleakala Volcano (Macdonald and Powers, 1946, p. 122), but the curve for soda rises less rapidly because of the smaller percentage of that oxide in the andesites of Mauna Kea.

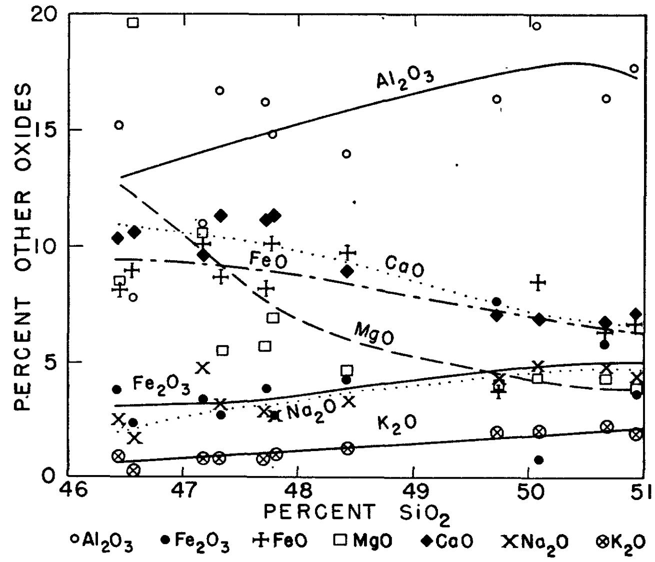

FIGURE 1.—Variation diagram of lavas of Mauna Kea.

Like the andesites of Haleakala, those of Mauna Kea are chemically most closely related to trachydolerite and to the rocks termed mugearite by British petrographers (Rosenbusch, 1923, p. 460). They are lower in silica, and a little lower in alumina, than typical andesites, but in abundance and relative proportions of alkalies and lime they more closely resemble typical andesites than they do typical basalts.

The alkali-lime index of the lavas of Mauna Kea is 50.8, placing them in the alkalic group near the boundary of the alkali-calcic group (Peacock, 1931).

Chemical analyses and norms of lavas of Mauna Kea

Analyses

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	46.43	46.57	47.19	47.32	47.72	47.79	48.42	49.73	50.09	50.68	50.92
Al_2O_3	15.22	7.81	10.95	16.68	16.19	14.80	13.97	16.39	19.49	16.42	17.59
Fe_2O_3	3.79	2.40	3.31	2.63	3.82	2.63	4.17	7.58	.73	5.79	3.80
FeO	8.19	8.91	10.21	8.67	8.25	10.04	9.57	3.98	8.47	6.22	6.69
MgO	8.40	19.74	10.52	5.43	5.68	6.89	4.61	4.06	4.33	4.25	3.90
CaO	10.37	10.65	9.73	11.27	11.20	11.31	8.86	7.17	6.92	6.47	6.97
Na_2O	2.55	1.70	4.69	3.08	2.80	2.56	3.30	4.12	4.82	4.70	4.28
K_2O	.99	.33	.93	.79	.84	.94	1.29	1.93	1.93	2.16	1.86
H_2O+	.82	.11	.17	.23	.51	.54	.84	.54	.32	.23	.79
H_2O-	.38	.09	.07	.17	.25	.09	.42	.81	.08	.19	.35
TiO_2	3.03	1.67	2.27	3.09	2.48	1.90	3.25	3.05	2.47	2.64	2.55
ZrO_2								.03			
P_2O_5	.33	.34	.55	.53	.43	.26	.91	.84	.78	.17	.40
MnO	.10	.13	.16	.16	.08	.14	.17	.23	.15	.22	.20
BaO								.03			
Cr_2O_3		.23						None			None
	100.60	100.68	100.75	100.05	100.25	99.89	99.78	100.53	100.58	100.14	100.30

Norms

	1	2	3	4	5	6	7	8	9	10	11
Quartz							0.84	1.68			
Orthoclase	6.12	1.67	5.56	5.00	5.00	5.56	7.78	11.12	11.12	12.79	11.12
Albite	19.39	14.15	19.91	25.68	23.58	22.80	27.77	34.58	33.01	38.77	36.15
Anorthite	26.97	12.79	6.12	29.19	29.19	26.13	19.46	20.85	25.85	17.24	23.07
Nepheline	1.14		10.79	.28					3.98	.57	
Diopside	17.79	30.26	30.96	19.04	19.16	23.04	15.49	7.13	2.29	11.28	6.99
Hypersthene		.40			7.01	3.25	12.88	6.90			7.31
Olivine	14.10	34.14	17.29	9.68	3.78	11.77			15.30	5.43	3.18
Magnetite	5.57	3.48	4.87	3.71	5.57	3.71	6.03	4.64	1.16	8.35	5.57
Ilmenite	5.78	3.19	4.26	5.93	4.71	3.65	6.23	5.78	4.71	5.02	4.86
Hematite								4.48			
Apatite	.67	.67	1.34	1.34	1.01	.67	2.02	2.02	2.02	.34	1.01

1. Nonporphyritic olivine basalt, Hamakua volcanic series; quarry above Laupahoehoe, at 200 feet altitude. (The locality could not be located by the writer.) Analyst, H. S. Washington (1923a, p. 497).
2. Picrite-basalt, primitive type, Hamakua volcanic series; Kaula Gulch, "above Ookala." (No rock corresponding to the description given could be found by the writer at that locality.) Analyst, H. S. Washington (1923a, p. 500).
3. Andesite (?), Hamakua volcanic series; Kaula Gulch, "above Ookala." (No rock the mode of which appears to fit the above analysis has been found at this locality by the writer.) Analyst, H. S. Washington (1923a, p. 500).
4. Olivine basalt, with feldspar phenocrysts, Hamakua volcanic series; 900 feet altitude in Papalele Gulch. Analyst, H. S. Washington (1923a, p. 497).
5. Basalt, Hamakua volcanic series; at road north of Nohonaohae Cone. Analyst, H. S. Washington (1923a, p. 497).
6. Olivine basalt, nonporphyritic, Hamakua volcanic series; 1,910 feet altitude on highway at Ahualoa, near Honokaa. Analyst, H. S. Washington (1923a, p. 497).
7. Andesite, Hamakua volcanic series; 900 feet altitude in Papalele Gulch. Analyst, H. S. Washington (1923a, p. 493). Includes Cl-0.00.
8. Andesite, Laupahoehoe volcanic series; 11,000 feet altitude on the southeast slope of Mauna Kea. Analyst, G. Steiger (Daly, 1911, p. 298). Includes S-0.00, SrO-0.00. Norm, H. S. Washington (1923a, p. 491).
9. Andesite, Hamakua volcanic series; 2,700 feet altitude, near Nohonaohae Cone. Analyst, H. S. Washington (1923a, p. 490).
10. Andesite, Laupahoehoe volcanic series; Laupahoehoe peninsula, at sea level. Analyst, H. S. Washington (1923a, p. 490). A duplicate determination gave 6.25 percent FeO.
11. Andesite, Laupahoehoe volcanic series; Poliahu Cone, at 13,000 feet altitude near summit of Mauna Kea. Analyst, G. Steiger (Daly, 1911, p. 301).

KOHALA

GENERAL GEOLOGY

Kohala is an elongate shield volcano built by innumerable eruptions from a northwestward-trending rift zone. It rises to a summit altitude of 5,505 feet. Many cinder cones, some of them several hundred feet high, mark the position of the rift zone.

The rocks of Kohala are divided into the Pololu volcanic series and the Hawi volcanic series (Stearns and Macdonald, 1946, pp. 170–180). The Pololu lavas constitute the great bulk of the Kohala shield, the Hawi lavas forming only a thin veneer over part of the surface.

Along the crest of the mountain a series of late faults lie approximately parallel to the rift zone. Most of the faults lie northeast of the rift zone, with downthrow to the southwest, and produced escarpments that faced the rift zone and to a large extent shielded the central northeast slopes from lava flows of the Hawi volcanic series. During that interval, four huge erosional valleys were carved into the northeast side of the mountain. Finally, a few flows escaped northeastward and entered the big valleys, lying with profound erosional unconformity on the old basalts. On the western, southern, and northern slopes, which were less shielded from lava flows, no widespread erosional unconformity exists between the Pololu and Hawi volcanic series. Local unconformities are present at many localities, however, and the lavas of the two series are generally separated by a bed of red ash.

Kohala Volcano appears to have become extinct about the end of the period of eruption of the Hamakua lavas on Mauna Kea. In the sea-cliff near Kukuihaele, oligoclase andesites of the Hawi volcanic series of Kohala are interbedded with lavas of the upper member of the Hamakua volcanic series of Mauna Kea.

POLOLU VOLCANIC SERIES

The Pololu volcanic series is exposed in the walls of the large valleys on the northeast side of Kohala Mountain, and in kipukas on the northern, western, and southern slopes. Nearly all the lavas are olivine basalt. Only a small portion is basalt, and no rocks entirely free of olivine have been found. A few flows of primitive picrite-basalt occur throughout the section, and at the very top picrite-basalts of the augite-rich type are prominent. The olivine basalts of the Pololu volcanic series differ slightly from those among the early lavas of the other volcanoes on the island of Hawaii in containing more abundant phenocrysts of feldspar. In that respect they resemble the basalts of the Honomanu volcanic series on East Maui (Macdonald, 1942a, p. 279). Only one andesite has been found among the Pololu lavas. The general characteristics of the Pololu volcanic series are well exemplified in the accompanying stratigraphic section.

The lavas of the Pololu volcanic series are typically thin bedded, with flow units averaging only 4 or 5 feet thick. Pahoehoe is the more abundant, but aa is present also. The commonest rock type is a fine-grained medium-gray basalt containing a few scattered phenocrysts of olivine up to 1 millimeter or a little more in length. Less abundant are lavas containing more numerous olivine phenocrysts up to several millimeters long. The type containing abundant large phenocrysts of feldspar is especially prominent in the middle and upper parts of the exposed section. The phenocrysts typically are tabular and from 1 to 2.5 centimeters long. In a few flows they show a roughly stellate arrangement, but generally they show no regular arrangement or are crudely alined by flowage. Augite phenocrysts are very rare throughout most of the section but are common in the latest lavas.

Stratigraphic section of Pololu volcanic series along trail up southeast wall of Waipio Valley

	Feet
Hawi volcanic series:	
Red ash	2
Oligoclase andesite aa	33
Pololu volcanic series:	
Olivine basalt pahoehoe, thin-bedded, much weathered, reddish-brown and soft, many joint surfaces coated with a purplish black submetallic substance, probably manganese oxide. Many vesicles partly filled with calcite and probably zeolites	89
Olivine basalt pahoehoe, with scattered phenocrysts of feldspar as much as 3 mm. long	4
Basalt pahoehoe, nonporphyritic	9
Olivine basalt pahoehoe, very rich in feldspar phenocrysts as much as 1 cm. long, in thin flow units averaging 3 to 4 ft. thick. Upper 6 in. reddened	20
Olivine basalt pahoehoe containing as much as 50 percent of feldspar phenocrysts as much as 2.5 cm. long	67
Olivine basalt pahoehoe, with a few feldspar phenocrysts as much as 7 mm. long	6
Olivine basalt pahoehoe, thin-bedded, with abundant feldspar phenocrysts as much as 2.5 cm. long, forming 10 to 25 percent of the rock	7
Olivine basalt pahoehoe, thin-bedded, with a few feldspar phenocrysts as much as 7 mm. long	10
Olivine basalt pahoehoe, with feldspar phenocrysts as much as 2 cm. long forming 60 percent of the rock	2
Olivine basalt pahoehoe, nonporphyritic, thin, bedded	12
Olivine basalt pahoehoe, with scattered feldspar phenocrysts as much as 1 cm. long	9
Olivine basalt aa, with feldspar phenocrysts as much as 2 cm. long forming about 20 percent of the rock	17
Olivine basalt pahoehoe, with scattered olivine phenocrysts as much as 1 mm. long, thin-bedded	6
Red ash	0–0. 2
Olivine basalt pahoehoe, thin-bedded with scattered olivine phenocrysts as much as 1 mm. long	50
Olivine basalt aa, with rare phenocrysts of olivine and feldspar as much as 1 mm. long	6
Red ash	0. 1–0. 2

Stratigraphic section of Pololu volcanic series along trail up southeast wall of Waipio Valley—Continued

	Feet
Pololu volcanic series—Continued	
Olivine basalt pahoehoe, with scattered olivine phenocrysts as much as 1 mm. long, thin-bedded	83
Olivine basalt, nonporphyritic, thin-bedded, largely aa but with a few layers of pahoehoe. Beds average 2 to 3 ft. thick	50
Olivine basalt aa, with rare olivine pheonocrysts as much as 1.5 mm. long	15
Olivine basalt pahoehoe, nonporphyritic	12
Olivine basalt aa, nonporphyritic	9
Olivine basalt pahoehoe, thin-bedded, nonporphyritic	13
Olivine basalt aa, nonporphyritic, alternate massive and clinkery beds averaging about 2 ft. thick	15
Olivine basalt pahoehoe, nonporphyritic	5
Olivine basalt aa, with rare olivine phenocrysts as much as 1 mm. long	8
Olivine basalt pahoehoe, with scattered olivine phenocrysts as much as 1 mm. long, thin-bedded	53
Olivine basalt aa, with rare olivine phenocrysts as much as 1 mm. across	7
Olivine basalt aa like that above, upper 8 ft. clinker	15
Olivine basalt pahoehoe, with scattered olivine phenocrysts as much as 1 mm. long	10
Olivine basalt aa, nonporphyritic, upper 7 ft. clinker	18
Olivine basalt, with scattered olivine phenocrysts as much as 1 mm. long, thin-bedded	78
Olivine basalt aa, nonporphyritic, close to pahoehoe in structure	10
Olivine basalt pahoehoe, with scattered olivine phenocrysts as much as 1 mm. long	4
Olivine basalt aa, with moderately abundant olivine phenocrysts as much as 6 mm. long. Trace of red ash at top	4
Olivine basalt aa, like that above	6
Olivine basalt aa, nonporphyritic, upper 3 ft. clinker	10
Olivine basalt aa, nonporphyritic	6
Olivine basalt aa, nonporphyritic, upper 4 ft. clinker	17
Olivine basalt pahoehoe, with scattered olivine phenocrysts as much as 1 mm. long, thin-bedded	22
Olivine basalt pahoehoe, massive, with a few olivine phenocrysts as much as 3 mm. long	12
Olivine basalt pahoehoe, thin-bedded, with scattered olivine phenocrysts as much as 1 mm. long, and in some flow units apparently absent; base not exposed	+60
Total	+891

Along the upper part of the trail down the southeast wall of Waipio Valley, thin flow units of feldspar-rich olivine basalt pahoehoe show definite evidence of the sinking of plagioclase crystals. The individual flow units average 3 to 4 feet thick, each flow top being marked by a thin, glassy crust. The upper 2 to 8 inches of each flow is nearly devoid of phenocrysts but grades downward through a very thin zone into rock that is rich in phenocrysts of plagioclase (Ab_{20}–Ab_{45}), up to 1 centimeter long. In the lower two-thirds of each flow unit plagioclase phenocrysts constitute 30 to 50 percent of the rock. Several such flow units occur one above another and aggregate 20 feet in thickness. They are underlain by a massive bed 67 feet thick in which plagioclase phenocrysts comprise about half the rock and reach lengths of 2.5 centimeters. Some crystals appear to have settled in this bed also, but the evidence is much less definite.

In the sea cliff just west of the mouth of Waimanu Valley a pahoehoe flow is exposed in which olivine phenocrysts are small and sparse in the outer part but larger and more numerous toward the centers of the feeding tubes, where they reach 5 millimeters in length and constitute about 30 percent of the rock (Stearns and Macdonald, 1946, p. 171). A similar relationship was found by Stearns in a flow on Ofu Island, Samoa (Macdonald, 1944a, p. 1349), where olivine basalt grades inward into augite-rich picrite-basalt. It appears probably to result from gravitative differentiation in the volcanic conduit. Phenocrysts forming in the conduit magma sank and enriched the lower portions with crystals of olivine. During eruption, the first lava extruded contained only a few small phenocrysts; but later, as extrusion drained the magma column to lower levels, magma progressively richer in olivine phenocrysts made its appearance, following the phenocryst-poor magma through the same tubes.

A lava collected by Cross (1915, p. 33) in a railroad cut just north of Mahukona was analyzed by Washington (1923b, pp. 480–481). The analysis is given in column 7 of the table on page 87. The rock obviously is more silicic than a typical basalt and was correctly classed by Washington as an oligoclase andesite. Reexamination of the locality has shown what appears to be the flow sampled by Cross exposed in cuts from 0.1 to 0.4 mile north of Mahukona. It is underlain and overlain by a red ashy soil that ranges in thickness from a thin film to 12 inches, and because of the ash capping it has been mapped with the Pololu lavas (Macdonald, 1946, p. 196). It is the only andesite in the Pololu volcanic series.

HAWI VOLCANIC SERIES

LAVAS

The lavas of the Hawi volcanic series are widespread on the northern, western, and southern slopes of Kohala Mountain, but on the northeast side they are confined to the few flows that cascaded into the heads of the big valleys. The flows are much thicker and more massive and produce a more rugged topography than those of the Pololu volcanic series. The greater viscosity of the lavas, probably together with a greater content of volatiles, caused explosive eruptions, which built big cinder cones resembling the andesitic cones of Mauna Kea. In a few places the viscous lavas piled up at the vents to form domes.

The Hawi volcanic series is composed very largely of oligoclase andesite. Trachyte is present, but it forms only a small proportion. The only andesine andesite found among the Hawi lavas is that from

Puu Kawaiwai, 9 miles west-northwest of Waimea. Although it is situated on the flank of Kohala Volcano, the Puu Kawaiwai vent may belong to the approximately contemporaneous late lavas of the Hamakua volcanic series of Mauna Kea, among which andesine andesites are abundant.

The oligoclase andesites consist largely of plagioclase, monoclinic pyroxene, olivine, and iron ore, with small amounts of other minerals, and in some a little interstitial glass. The dominant feldspar is generally calcic oligoclase, but in some rocks it is intermediate oligoclase. In many rocks some of the oligoclase grains show a small positive optic angle and are probably potassic. Most flows are nonporphyritic, but many contain phenocrysts of feldspar. Phenocrysts of olivine occur in only a few flows, but groundmass olivine is present in every rock examined.

Many of the oligoclase andesites contain small irregular grains of brown biotite and a few prismatic crystals of riebeckitelike amphibole. Hornblende is present in only a few rocks. In rocks exposed near the old mill site at Niulii, and in Waiaka Gulch at the highway, common brown hornblende occurs in the groundmass. Phenocrysts of basaltic hornblende occur in rocks collected 0.6 mile N. 20° W. of Hokuula Cone, and at Puu Makea. In the latter rocks the phenocrysts are partly resorbed, with the liberation of rims of finely granular iron ore.

The trachytes differ from the oligoclase andesites in the more sodic nature of the prevalent feldspar, which is albite, and rarely in the presence of small amounts of sodic ferromagnesian minerals.

A specimen of a trachyte dike near the head of Waima Valley, the southernmost tributary of Waipio Valley, was collected by W. O. Clark. The rock is medium gray and dense, with abundant phenocrysts of feldspar up to 4 millimeters long, but mostly less than 2 millimeters, and with scattered partly resorbed phenocrysts of hornblende and biotite. The feldspar phenocrysts are intermediate oligoclase. The hornblende is a brown variety, with $-2V=75°$, strong dispersion with $r<v$, and weak pleochroism. The groundmass is trachytic and very fine-grained. It is composed largely of untwinned subhedral to anhedral grains of calcic albite, with less abundant subhedral prismatic grains of monoclinic pyroxene, magnetite, small highly acicular grains of apatite enclosed in the feldspar, and irregular patches of finely fibrous brownish-green chloritic material. The pyroxene is pale green, with $+2V=60°\pm$, and $Z\wedge c$ about 70°. It is probably aegirine-augite. Other dikes of trachyte are found in the other branches of Waipio Valley and in Honokane and Pololu Valleys. A dike 20 feet thick in the head of Pololu Valley contains partly resorbed oligoclase phenocrysts and microphenocrysts of olivine partly altered to iddingsite. The groundmass consists of subhedral grains of colorless monoclinic pyroxene, magnetite, and a little pale-green hornblende and brown biotite in a matrix of anhedral calcic albite.

Several cinder cones, domes, and thick massive flows of trachyte are known. The rocks closely resemble the dike rocks already described. Some contain partly resorbed phenocrysts of brown hornblende and biotite, and in others the former presence of an acicular mafic mineral, probably hornblende, is attested by resorption shadows of finely granular iron ore. Prismatic grains of apatite, as much as 0.5 millimeter long, are found in some specimens. Partly resorbed phenocrysts of calcic to intermediate oligoclase occur in all the trachytes studied. In one, a flow from a dome 3.4 miles N. 5° E. of Puu Kawaiwai, which crops out along the highway 3.3 miles northwest of Puu Kawaiwai, the phenocrysts of calcic oligoclase are much rounded and embayed by resorption and enclosed in a rim of calcic albite. In some of the phenocrysts the core of oligoclase has been partly replaced by albite, the two feldspars forming a very irregular vermiform intergrowth. In most specimens of trachyte the grains of pyroxene in the groundmass are too small to yield optical interference figures, but in the rock last described they are colorless diopside, with $+2V=60°$ and no detectable dispersion. In none of the trachytes except the dike in Waipio Valley, described above, do the groundmass pyroxenes appear to be sodic. There appears to be a complete gradation in composition of the groundmass feldspar from the trachytes to the oligoclase andesites.

As compared with the trachytes of West Maui Volcano (Macdonald, 1942 a, pp. 323–325) and with the trachyte of Puu Anahulu on the flank of Hualalai (p. 78), the trachytes of Kohala are typically less sodic, both in the composition of the dominant feldspar and in the general absence of sodic pyroxenes in the groundmass.

INCLUSIONS IN LAVAS

Coarse-grained inclusions are not abundant in the lavas of Kohala Volcano but have been observed at a few localities. They are especially numerous in a bed of oligoclase andesite exposed in the sea cliff a quarter of a mile west of the sugar-loading station at Kukuihaele Landing. Angular xenoliths up to 3 inches long include dunite, olivine gabbro, augite-hypersthene peridotite (lherzolite), and transitional varieties. The gabbro has an average grain size of about 1 millimeter and consists of about 50 percent calcic labradorite, the rest being largely olivine and pyroxene in approximately equal proportions. Only a little iron ore is present. The pyroxene includes both augite and hypersthene. The augite has $+2V=60°$, weak dispersion, and $\beta=1.701$. The hypersthene has $\beta=1.698$ and is pleochroic from pale pink to pale green. The olivine has a $2V$ close to 90°, and $\beta=1.703$. Through a decrease in the percentage of feldspar the gabbro grades into picrite, and the picrite into augite-hypersthene peridotite.

Through a decrease in the amount of pyroxene the peridotite grades into dunite.

Gabbro included in basalt near the ditch crossing in the west branch of Honokane Nui Valley (the first large valley southeast of Pololu Valley) contains an angular xenolith of dunite.

INTRUSIVE ROCKS

Numerous dikes are exposed in the upper parts of the big valleys cut into the northeast slope of Kohala Volcano. Many of them are the congealed feeders of lava flows. They show the same variations in composition as do the flows.

Besides the dikes, there are also present small bodies of olivine gabbro. Typically, the gabbro is a fine grained granitoid rock of medium to dark gray color. A few miarolytic cavities are present in most specimens, but none have the extremely porous structure encountered in similar gabbros at West Maui Volcano (Macdonald, 1942a, pp. 323–330, pl. 43c). All the gabbros of Kohala Volcano are similar in mineral composition. A specimen from the western branch of Waipio Valley, at 1,350 feet altitude, is typical. It consists of plagioclase and augite, with smaller amounts of olivine, iron ore, interstitial glass, and a little alkalic feldspar. Small needles of apatite are enclosed in the feldspar. The augite has $+2V=60°\pm$ and weak dispersion. Some of the olivine is partly altered to serpentine. The plagioclase is zoned from labradorite-bytownite in the core to calcic andesine on the outside. The texture is granitoid and locally diabasic. The average grain size is about 1 millimeter.

CHEMICAL ANALYSES

The existing chemical analyses of lavas of Kohala Volcano are shown in the accompanying table. Ten of them are by H. S. Washington and the other three by A. B. Lyons. Those by Lyons were ignited prior to analysis and consequently are anhydrous and with very high ferric and low ferrous iron.

Chemical analyses and norms of lavas of Kohala Volcano

Analyses

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	45.33	45.79	47.33	47.39	47.98	49.01	49.09	49.14	49.70	51.97	51.99	52.27	58.06
Al_2O_3	16.52	11.67	17.96	16.46	15.32	16.29	15.15	14.64	14.65	12.65	16.30	17.05	18.21
Fe_2O_3	5.60	2.99	12.64	3.75	2.49	7.61	2.95	4.49	1.88	4.60	2.75	3.51	4.87
FeO	6.92	10.32	.51	8.42	8.86	4.89	10.22	7.17	8.03	7.05	7.44	7.20	2.01
MgO	7.38	8.90	3.97	5.08	6.16	3.62	4.94	3.94	7.80	7.98	3.19	3.13	1.59
CaO	7.89	9.60	6.29	7.37	10.28	9.79	8.47	9.67	12.10	10.59	6.67	5.82	3.29
Na_2O	4.24	2.20	3.67	4.71	3.56	3.82	4.03	4.45	2.09	2.77	5.64	5.40	6.12
K_2O	1.49	.66	1.10	1.65	1.08	.80	1.31	1.00	.52	.34	2.13	2.22	2.75
H_2O+	.28	1.85	------	.28	.62	------	.17	.65	.22	.26	.29	.44	------
H_2O-	.05	.82	------	.09	.25	------	.07	.14	.09	.11	.07	.08	------
TiO_2	2.45	5.00	4.84	2.83	3.53	3.93	2.66	4.21	1.92	2.11	3.02	2.13	1.88
P_2O_5	2.32	.40	1.05	2.22	.22	.49	.80	.43	.56	.25	1.25	.62	.65
MnO	.10	------	.64	.09	.12	.27	.09	.10	.15	.16	.11	.16	.36
BaO	------	------	------	.04	.06	------	------	------	------	------	------	.05	------
Cl	------	------	------	------	------	------	------	------	------	------	------	Tr.	------
SO_3	------	------	.07	.06	.02	.20	------	------	------	------	------	.13	.05
ZrO_2	------	------	------	None	None	------	------	------	------	------	------	None	------
Cr_2O_3	------	------	------	Tr.	None	------	------	------	------	------	------	------	------
	100.57	100.20	100.29	100.44	100.55	100.84	99.95	100.03	99.71	100.84	100.85	100.21	99.99

Norms

	1	2	3	4	5	6	7	8	9	10	11	12	13
Quartz	------	------	------	------	------	------	------	------	0.72	4.26	------	------	------
Orthoclase	8.90	3.89	------	10.01	6.67	------	7.78	6.12	2.78	2.22	12.23	12.79	------
Albite	31.96	18.34	------	36.68	26.20	------	34.06	36.15	17.82	23.58	44.01	42.97	------
Anorthite	21.68	20.29	------	18.90	22.52	------	19.46	16.96	28.91	20.85	13.07	16.12	------
Nepheline	1.99	------	------	1.42	1.99	------	------	.85	------	------	1.99	1.42	------
Diopside	2.22	19.62	------	3.16	21.64	------	14.22	22.57	22.24	23.72	9.58	7.61	------
Hypersthene	------	19.28	------	------	------	------	.81	------	19.23	14.50	------	------	------
Olivine	15.35	1.39	------	13.70	9.79	------	12.41	1.18	------	------	6.23	8.08	------
Magnetite	8.12	4.41	------	5.34	3.71	------	4.18	6.50	2.78	6.73	3.94	5.10	------
Ilmenite	4.71	9.58	------	5.32	6.69	------	5.02	8.06	3.65	3.95	5.78	3.95	------
Apatite	5.38	1.01	------	5.04	.67	------	2.02	1.01	1.34	.67	3.02	1.85	------

1. Oligoclase andesite, Hawi volcanic series; Puu Lahikiola, about 3,000 feet altitude. Analyst, H. S. Washington (1923a, pp. 480–481).
2. Olivine basalt, Pololu volcanic series; south of Kaala Cone. Analyst, H. S. Washington (1923a, p. 487).
3. Oligoclase andesite, Hawi volcanic series; cinder cone on Kohala. Analyst, A. B. Lyons (1896, pp. 422–424). Includes S=0.07, CuO=.15.
4. Andesine andesite, Hawi volcanic series; Puu Kawaiwai, at 3,200 feet altitude. Analyst, H. S. Washington (1923a, pp. 480–481).
5. Olivine basalt, Pololu volcanic series; 3,400 feet altitude in Kawaihae Gulch. Analyst, H. S. Washington (1923a, p. 483).
6. Olivine(?) basalt, Pololu volcanic series; no locality given. Analyst, A. B. Lyons (1896, pp. 422–424). Includes S=0.02, CuO=0.10.
7. Oligoclase andesite, Pololu volcanic series; sea level at Mahukona. Analyst, H. S. Washington (1923a, pp. 480–481).
8. Olivine basalt, Pololu volcanic series; 2,900 feet altitude in Momoualoa Gulch. Analyst, H. S. Washington (1923a, p. 483).
9. Olivine(?) basalt, Pololu volcanic series; first stream west of Waimea on the Waimea-Kohala road (wrongly called Waiaka Stream by Washington). Analyst, H. S. Washington (1923a, pp. 485–487).
10. Basalt, Pololu volcanic series; east wall of Waipio Valley. Analyst, H. S. Washington (1923a, pp. 493–494).
11. Oligoclase andesite, Hawi volcanic series; 2,900 feet altitude at Momoualoa Gulch. Analyst, H. S. Washington (1923a, p. 478).
12. Oligoclase andesite, Hawi volcanic series; 3,600 feet altitude at Puu Makea. Analyst, H. S. Washington (1923a, p. 478).
13. Oligoclase andesite, Hawi volcanic series; near Waimea. Analyst, A. B. Lyons (1896, pp. 424–425). Includes S=0.05, CuO=0.10.

The olivine basalts are similar in composition to those of other Hawaiian volcanoes. All but one of the oligoclase andesites are much lower in silica, alumina, and alkalies and are higher in lime, magnesia, and iron than is the only existing analysis of an oligoclase andesite from West Maui Volcano (Macdonald, 1942a, p. 334). In both chemical and mineral composition the oligoclase andesites are closely related to the rocks termed "mugearite" by British petrographers. No analysis of trachyte from Kohala exists.

The norms nearly all indicate the presence of a considerable amount of orthoclase. This has not been recognized as an independent mineral but appears to be incorporated in the plagioclase.

MAGMATIC DIFFERENTIATION

The lavas of Kilauea and Mauna Loa are largely normal olivine basalts. This type predominates among the early lavas of all the Hawaiian volcanoes (Macdonald, 1940a, p. 171; 1940b, p. 90; 1942a, pp. 280–285, 314–320), and undoubtedly represents the parent magma of the Hawaiian petrographic province. Interbedded with them are less abundant lavas of other types differing only slightly from the primitive lavas. The primitive type of picrite-basalt differs from the olivine basalts only in the greater abundance of olivine phenocrysts, and the basalts differ from the olivine basalts principally in their smaller proportion of olivine and a slightly higher degree of saturation in silica. The increase in saturation in silica is reciprocal to the decrease in the undersaturated olivine molecule. Inasmuch as olivine phenocrysts are known to form early in the course of crystallization, and in amounts which frequently exceed the stoichiometric proportion of the olivine molecule in the magma, it is a reasonable assumption that the small amount of differentiation shown by the lavas of Mauna Loa and Kilauea is largely the result of settling of early formed crystals of olivine, impoverishing the upper part of the magma body in olivine to form basalts and enriching lower portions in olivine to form picrite-basalts. The assumption is strengthened by the demonstrated existence of the process in the Kilauean magma column (Macdonald, 1944c).

The olivine-free and olivine-poor basalts correspond in every respect to the "tholeiitic" basalt as described by Kennedy (1933), who regards it as one of two primary basalt magmas. The tholeiitic basalts, according to Kennedy, give rise by differentiation to andesites and rhyolites, whereas the other primary magma, olivine basalt, differentiates to trachyandesites, trachytes, and phonolites. Kennedy states that tholeiitic basalts are absent from the oceanic volcanoes, but it has been shown above that they are present in considerable abundance at Kilauea and Mauna Loa. Moreover, it is clear that they must have been derived from the parent magma of the Hawaiian province, olivine basalt. If the tholeiitic basalts can originate by differentiation of olivine basalt, there appears to be no necessity for Kennedy's assumption of the existence of a second primary basalt magma of tholeiitic composition.

At Mauna Loa and Kilauea augite phenocrysts are rare and probably had little effect on the differentiation. However, at the other volcanoes, which are farther advanced in their life history, lowering temperatures of the magmatic hearths has resulted in the precipitation of abundant intratelluric augite phenocrysts, the settling of which has probably had considerable effect on the differentiation.

In discussing the trend of pyroxene crystallization in basalts, Barth (1931) states that the sequence is from augites rich in diopside to pigeonites. Kennedy (1933, p. 252), however, contradicts this, and states that in olivine basalts the trend is from "basaltic augite" to diopside and eventually to aegirine-augite. Examination by the writer of several hundred thin sections of Hawaiian lavas confirms the statement by Barth. Wherever a definite change in composition of the crystallizing pyroxene can be detected, the trend is from diopsidic augite to enstatite-augite (pigeonite). In most of the rocks in which they occur, the pyroxene phenocrysts are augite rich in the diopside molecule, and the groundmass pyroxene is pigeonitic augite and pigeonite. Wherever zoning can be detected in the pyroxenes, the outer layers show a progressive decrease in extinction angle and optic axial angle, indicating a decrease in lime content.

This does not in any way detract from the efficacy of the process suggested by Kennedy (1933, p. 253) whereby the crystallization of lime-rich augites in olivine basalts would impoverish the residual liquid in lime, thus decreasing the amount of alumina used up in the formation of anorthite and forcing the remaining alumina into combination with alkalies to form alkalic feldspar or feldspathoids. The pyroxene which would be effective in this process is that which crystallizes early, as phenocrysts, and as already pointed out, when pyroxene phenocrysts are present in Hawaiian lavas they are almost always lime-rich augite. Porphyritic rocks were ruled out of consideration by Kennedy on the ground that they may not represent actual melts. However, if differentiation be partly or entirely by crystal settling, the phenocrysts of porphyritic rocks should be considered, as it is the removal of the phenocrysts that brings about the differentiation.

The rocks of Kilauea show less variation in chemical composition than those of any of the other volcanoes on the island of Hawaii, and no systematic trend in change of composition can be recognized with certainty. Cross (1915, pp. 60–61) pointed out the slightly greater abundance of normative quartz in the historic, as compared with the prehistoric, lavas, but additional analyses by Washington, made since the publication of Cross' paper, make the contrast much less striking.

The slightly greater variation in composition among the lavas of Mauna Loa as compared with those of Kilauea probably indicates that Mauna Loa has reached a slightly more advanced stage in the magmatic history. The same conclusion is indicated by the more common occurrence of augite phenocrysts in the lavas of Mauna Loa. This strongly suggests, although it does not conclusively prove, the slightly greater age of the Mauna Loa vent.

Hualalai Volcano has reached a stage of differentiation a little more advanced than that of Mauna Loa. The lavas are predominantly olivine basalts, with less abundant basalts, andesites, and rocks transitional to picrite-basalts. Picrite-basalts are fairly abundant among the lavas of Mauna Loa, whereas true picrite-basalts have not been found on Hualalai. However, the picrite-basalts of Mauna Loa are primitive in type, containing phenocrysts of olivine alone. In contrast, the lavas of Hualalai approaching picrite-basalt in composition contain many augite phenocrysts and are thus representative of a more advanced stage of intratelluric crystallization. No andesites have been found on Mauna Loa or Kilauea, but one flow of andesite has been found on Hualalai.

The stage of differentiation exhibited by Hualalai fits in well with the generalized magmatic history of Hawaiian volcanoes adduced in earlier papers (Macdonald, 1940a, pp. 171–172; 1940b, p. 90). Throughout the early stages of frequent voluminous eruptions differentiation produces little effect beyond the accumulation of sunken olivine crystals to form the primitive type of picrite-basalt. A broad shield of olivine basalts is built, and at the apex of the shield a caldera generally develops. Gradually the frequency of eruption diminishes, and the vent remains closed and the magma chamber undisturbed by eruption for longer periods, permitting differentiation to produce rock types more and more markedly different from the early olivine basalts. The beginnings of notable digression from the olivine basalts are found toward the end of the period of filling of the caldera.

The trachyte of Puu Waawaa and Puu Anahulu probably is best regarded as the result of differentiation in a small partly or entirely isolated adventive magma chamber, which was undisturbed by magmatic movements in the main chamber and conduit.

At Mauna Kea the primitive olivine basalts continued to be the dominant type of lava throughout the time of extrusion of the Hamakua volcanic series, building a huge shield volcano.

The earliest exposed basalts of the Hamakua volcanic series contain abundant phenocrysts of olivine, showing that by the time the volcano had built above present sea level, cooling in the magma chamber had progressed sufficiently to bring about the extensive intratelluric crystallization of olivine. Augite phenocrysts are rare, but a few are found in some flows, which indicates that augite also had started to crystallize, although much less abundantly than olivine. Feldspar phenocrysts have not been found in the early Hamakua lavas, which indicates that the magma had not yet reached saturation in that component. The abundant olivine and sparse augite phenocrysts were heavier than the enclosing magma and tended to settle in it, producing local masses of picrite-basalt magma very rich in phenocrysts of olivine.

In the late lavas of the Hamakua volcanic series phenocrysts of both feldspar and augite are abundant, and olivine phenocrysts continue to be prominent, showing that the magma body feeding the volcano had then cooled sufficiently to become saturated in all three of the principal mineral constituents. It is noteworthy that hypersthene phenocrysts, which are fairly common in the lavas of Mauna Loa, have not been found in the lavas of Mauna Kea. Accumulation of settling phenocrysts of olivine and augite, with or without feldspar phenocrysts, brought about the formation of picrite-basalts of the augite-rich type. At the same time, the removal of the constituents of the settling phenocrysts from the upper part of the magma body produced residual magmas of andesitic composition. Both complementary types were erupted, along with olivine basalts that showed no effects of differentiation. No order of eruption has been recognized, and the types of lava appear to be interbedded indiscriminately. Probably the eruption of different types can be largely attributed to conduit fissures tapping different levels in the magma reservoir (Macdonald, 1942a, pp. 310–311, fig. 45).

The Laupahoehoe volcanic series consists preponderantly of andesites, although olivine basalts also are still present. Picrite-basalts are absent, however, and the only representatives of the mafic pole of differentiation are the small inclusions and ejecta of dunite and augite peridotite. The latter are generally angular and appear to have been derived from essentially solid bodies of rock. No magmas more mafic than olivine basalt were erupted. Their absence, and the comparative fewness of olivine basalts, appear to indicate that conduit fissures no longer tapped deep levels in the magma reservoir. There is a strong suggestion in the distribution of vents that toward the end of the volcanic history of Mauna Kea activity became more and more centralized toward the eruptive axis of the mountain. This may account, wholly or in part, for the feeding fissures tapping only the upper part of the magma reservoir. On the other hand, the lack of ultrabasic types among the late lavas may be entirely the result of the gradual deepening of the zone of felsic differentiate to a point where feeding fissures did not extend below it.

The oligoclase andesites of Kohala, and the soda trachytes of Kohala and Puu Waawaa, represent the most salic of the differentiation products of the volcanoes of Hawaii. There can be no doubt that, like the intermediate types, they were derived from the olivine basalts. Likewise, there can be no doubt that crystal differentiation was of great importance in their production. To what extent other processes may have entered is, however, debatable.

Assuming the lavas of Kilauea, because they show the least variation, to represent most closely the parent magma of the Hawaiian province, there has been calculated the composition of the least possible amount of material, which, subtracted from the average Kilauean lava, would yield the andesine andesites, oligoclase andesites, and trachytes. The volatile fraction of the magma must, of course, be ignored in this connection. The smallest possible amount of material which subtracted from the Kilauean average would yield the oligoclase andesites was found to contain 0.9 percent normative quartz. The unlikelihood of the early separation of quartz or polysilicates is obvious, and therefore a sufficiently greater percentage of crystallization of the parent magma (which is under-saturated in respect to silica) was assumed to make the removal of quartz unnecessary, and the composition of the subtracted material was recalculated. The amounts of the principal oxides subtracted from the average Kilauean lava to yield the other lava types are shown in the table on page 92. The oxide that shows the greatest proportional change is potash, and for the purpose of the calculation it has been assumed that all the potash remained in the residual liquid. Actually, some of the potash would separate in the early formed minerals, particularly the feldspars, and the total amount of material involved in yielding the various salic end-magmas would therefore be a little greater than shown, and the proportion of silica removed would be a little greater. If all the potash remained in the rest-magma, the proportions of material subtracted from the average Kilauean lava (the degree of crystallization of the parent magma) to yield the andesites would be approximately 75 percent and to yield the trachyte of Puu Waawaa approximately 90 percent.

The norms in the table indicate the theoretical composition of the subtracted material. It consists largely of calcic plagioclase, diopside, and hypersthene. The feldspar—sodic bytownite to calcic labradorite—corresponds reasonably well in composition with the intratelluric phenocrysts found in the olivine basalts. The more sodic nature of the plagioclase separated during the much greater degree of crystallization of the parent magma in the formation of the trachyte is to be expected. The theoretical diopside contains approximately 51 percent $CaSiO_3$, 30 percent $MgSiO_3$, and 18 percent $FeSiO_3$. In comparison with this, the modal augite which separates from Hawaiian lavas as intratelluric phenocrysts contains about the same proportion of lime, but it is richer in magnesia and poorer in iron, and is aluminous (Washington and Merwin, 1922). The iron has all been treated as FeO. If some of the iron was in the ferric state and separated as magnetite, the resulting rest-magma would be slightly richer in silica than is shown in the table. (See p. 92.) Any normative quartz that might result in the rest-magma from such crystallization of magnetite is, however, easily eliminated by the assumption of a slightly greater degree of crystallization of the parent magma.

The greatest discrepancy between the theoretical minerals indicated by the norms in the table (p. 92) and the minerals found as intratelluric phenocrysts in Hawaiian lavas is the large proportion of hypersthene and very little olivine in the norms, whereas modally olivine is the most abundant intratelluric phenocryst and hypersthene is comparatively rare in the lavas that have been poured out on the surface. The normative hypersthene contains 63 to 66 percent enstatite, whereas the relatively few hypersthene phenocrysts in the lavas of Mauna Loa are richer in magnesia, containing approximately 75 to 80 percent enstatite. The hypersthene rarely encountered in the coarse-grained ultrabasic inclusions is of similar composition. The crystallization of some iron as magnetite would reduce the proportion of iron in the pyroxenes to a value corresponding more nearly to that actually found. No plutonic pigeonite, equivalent to hypersthene (Edwards, 1942, pp. 597–602) has been found.

The occurrence of theoretical hypersthene instead of the olivine observed in the erupted rocks is explained by Larsen, in discussing the origin of the magmas of the Central Montana Province, as the result of high pressure during crystallization. The high pressure is believed to favor the formation of hypersthene at depth instead of the olivine observed in lavas that were formed in the upper part of the magma chamber and erupted at the surface (Larsen, 1940, pp. 925–926). This appears probable, as the density of hypersthene is considerably greater than the average density of an equivalent mixture of olivine and amorphous silica.

If the differentiation had been by the settling of olivine instead of hypersthene, there should have resulted a marked enrichment of the rest-magmas in silica. That is not true. The andesine andesites and trachytes are slightly undersaturated with respect to silica, and the oligoclase andesites are still more undersaturated. Therefore, if any noteworthy proportion of the differentiation was by the sinking of olivine crystals, there must have been operative some other factor to counteract the passive concentration of silica in the rest-magma. That factor might be the sinking of larger amounts of some mineral containing a greater proportion of silica than those in the norms of the table. However, the only minerals the settling of which would remove a greater relative proportion of silica from the rest-magma are a more sodic plagioclase, potash feldspar, or quartz. There is no evidence that any of them formed, and theoretically it is very unlikely that any would form during early stages of crystallization.

The possibility of modification of the magma by the assimilation of limestone, suggested by Daly to have been an important factor in the origin of the trachyte (1910; 1911, pp. 306–316), should not be ignored. Limestone is almost certainly not present in more than negligible amounts within the structure of the Hawaiian volcanoes. During the period of growth of the basaltic shield volcanoes, inundation of the surface by lava flows was too frequent to permit the formation of reefs, even after the volcanic pile had built into water shallow enough for the growth of reef-forming organisms. Moreover, any small reefs that did develop would be on or within the outermost carapace of the volcano where the limestone would not be subject to assimilation. Daly's more recent suggestion (1944), that the entire ocean floor is covered with a thick layer of limestone, some of which has been assimilated, is less readily disproven. However, the assimilation of limestone does not appear to be a necessary factor in deriving the andesites and trachytes from olivine basalt.

Another possibility is the transfer of certain elements upward within the magma reservoir by rising volatiles. If such transfer occurred, the principal oxides most abundantly transported would probably be iron and the alkalies. There is certainly no evidence of enrichment in iron of the rest-magmas of the Hawaiian volcanic centers. If any enrichment in alkalies occurred it was probably small, as the crystal differentiation necessary to account for the changes in the bases such as magnesia and lime is quite sufficient to account also for the observed enrichment in alkalies. If the plagioclase which crystallized out was more sodic than that indicated in the table, there may have been an impoverishment of the rest-magma in soda, compensated by the addition of soda from depth through volatile transfer. That appears unlikely, however, both on theoretical grounds and empirically, for the compositions of feldspar indicated in the table correspond reasonably well with those of phenocrysts in the extruded lavas.

Still another possibility is that the excess silica accumulated in the upper part of the magma by the settling of olivine crystals may have been removed by escaping gases. In the dissected caldera areas of the East Molokai Volcano and the Koolau Volcano on Oahu much quartz and chalcedony was deposited in the rocks by rising volatiles. The total amount of this silica is, however, very small in comparison with the amount that presumably would have to be removed to compensate for the silica enrichment in the magma. It appears unlikely that this process has been of much importance in modifying the composition of the magma.

Although the possibility of some volatile transfer cannot be definitely eliminated, the evidence appears to indicate that the differentiation was largely or wholly by crystallization. The slight differentiation shown by the early basalts was probably the result of sinking of olivine phenocrysts in the upper part of the magma body. The more extreme differentiation of the later phases probably occurred deeper in the magma chamber, where high pressure caused the separation of hypersthene instead of olivine, which formed in the shallower parts of the hearth. The composition of the end-magma appears to depend on the composition of the separated plagioclase, which in turn is determined partly by the cooling history. Where the temperature remained within the crystallization range of rather calcic feldspar, so that the total separated feldspar averaged calcic or intermediate bytownite for a long enough period to permit the crystallization of approximately 80 percent of the parent magma, there resulted an end-magma corresponding in composition to oligoclase andesite. Where the temperature fell more rapidly, at about the same degree of crystallization the total separated feldspar averaged sodic bytownite, and there resulted an end-magma corresponding in composition to andesine andesite. The latter appears to be the more general condition at Hawaiian volcanoes. Where crystallization proceeded 90 percent or more toward completion, passing into the field of crystallization of more and more sodic feldspar, the total separated feldspar averaging calcic or intermediate labradorite, there resulted an end-magma which crystallized to form trachyte.

If the differentiation that produced the andesites and trachytes has been by the settling of crystals of plagioclase, augite, and hypersthene, with only a minor amount of olivine, obviously the augite-rich picrite-basalts cannot represent the mafic pole of the same differentiating system, for olivine phenocrysts are abundant and hypersthene is very rare in them. The same holds true for the coarse-grained inclusions of dunite and other ultrabasic rocks. If the premise be accepted that the major differentiation which produced the andesites and trachytes involved the crystallization of large amounts of hypersthene under high pressure at considerable depth in the magma chamber, then it must be concluded that the augite-rich picrite-basalts, like the primitive picrite-basalts, are the result of local accumulation at shallower depths of crystals of olivine and augite formed in the upper part of the magma. However, even under this assumption there appears to remain considerable theoretical objection to considering the augite-rich picrite-basalts as the result of simple addition of sunken crystals of olivine and augite to olivine basalt magma. The subject is receiving further study. Presumably, olivine phenocrysts sinking beyond a certain depth would become unstable and react with the magma to form hypersthene, so that the net result would be the same as though hypersthene had formed originally. The major part of the mafic differentiate, with its large proportion of hypersthene, must accumulate at depths so great that it is never brought to the surface.

Composition of material subtracted from average Kilauean lava to yield andesine andesite, oligoclase andesite, and trachyte

Analyses

	1	2	3	4	5	6	7
SiO_2	49.80	49.97	49.21	62.10	49.9	50.2	48.6
Al_2O_3	12.42	16.77	16.30	18.07	11.1	11.7	11.9
FeO [a]	11.28	10.90	11.36	4.04	11.5	11.3	12.0
MgO	10.31	4.23	4.74	.40	12.4	11.6	11.4
CaO	10.32	7.28	7.24	.86	11.3	11.0	11.2
Na_2O	1.96	4.24	4.80	7.59	1.2	1.3	1.4
K_2O	.45	1.83	1.76	4.98		.2	
TiO_2	2.68	2.79	2.62	.34	2.6	2.7	2.9
Degree of crystallization [b]					77	83	89

Norms

	1	2	3	4	5	6	7
Orthoclase	2.22	10.56	10.56	29.47		1.1	
Albite	16.24	35.63	37.73	58.16	10.0	11.0	12.0
Anorthite	24.19	21.68	17.79	1.11	25.0	25.6	26.1
Nepheline			1.42	3.12			
Diopside	20.21	8.74	7.26	1.73	25.2	23.4	22.4
Hypersthene	28.70	5.42			33.2	33.4	28.1
Olivine	.34	4.23	11.55	.14	1.6		5.0
Magnetite	2.09	6.50	5.34	3.48			
Ilmenite	5.02	5.32	5.02	.61	5.0	5.2	5.5
Molecular ratio, MgO/FeO, in silicates					2.5	2.3	2.2
Composition of plagioclase					An 71	An 70	An 68

[a] Total iron as FeO.
[b] Percentage of material subtracted from the average Kilauean lava to yield the other rock types.

1. Average of 24 analyses of Kilauean lavas.
2. Average of 5 andesine andesites of Mauna Kea.
3. Average of 5 oligoclase andesites of Kohala.
4. Average of 2 analyses of trachyte of Puu Waawaa and Puu Anahulu.
5. Composition of least possible amount of material which, subtracted from the average Kilauean lava, yields the andesine andesites.
6. Composition of the least possible amount of material which, subtracted from the average Kilauean lava, yields the oligoclase andesites, without subtracting normative quartz.
7. Composition of the least possible amount of material which, subtracted from the average Kilauean lava, yields the trachyte.

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INDEX

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