ART. XXXIX.—*Petrology of the Hawaiian Islands; I. Kohala and Mauna Kea, Hawaii;* by HENRY S. WASHINGTON.

INTRODUCTION.

In this and succeeding papers there will be presented some studies of the lavas of the Hawaiian Islands, which studies are an outcome of the First Pan-Pacific Scientific Conference, held at Honolulu in 1920, and which are intended as a contribution to our too scanty knowledge of the petrology of the Pacific Ocean volcanoes.[1] The chief aim is to study the island group as a comagmatic district, a unit in the larger Intro-Pacific region, the petrology of which, it is believed, is probably represented fairly well by that of the Hawaiian Islands. Another aim is the examination of the petrological relations between the several islands and their volcanoes, as regards their relative ages and their positions in the group.

As these aims involve the general petrographical characterization of the Hawaiian lavas, petrographic descriptions and chemical analyses will be given chiefly of the common and most abundant types, so as not to emphasize unduly the rarer and more "interesting" rocks. The petrographic descriptions must necessarily be concise, with many details omitted, and they will be accompained by a large number of chemical analyses, most of which have been made by me for this study. The importance of a larger number of chemical analyses than exists at present to represent the rocks of the Hawaiian Islands will be apparent when it is recalled that, of the 43 analyses of Hawaiian lavas already published,[2] 29 are of the rocks of Hawaii (of which 22 are of Kilauea), 6 of Oahu, 4 each of Maui and Kauai, with none of Molokai, Lanai, or the smaller islands. A recent adjudication shows that, of the 43 analyses, only 19 may be considered as good or excellent, the others being fair or poor, or even bad.

[1] H. S. Washington, The Chemistry of the Pacific Volcanoes; the Limitations of our Knowledge. Spec. Pub. Bishop Museum, No. 7, 325-345, 1921.

[2] Cf. Whitman Cross, Lavas of Hawaii and their Relations, U. S. Geol. Survey, Prof. Paper 88, 1915. In this paper Dr. Cross gives a full bibliography of Hawaiian petrography up to 1915.

In all the new analyses published in the present series of papers, titanium, phosphorus, and manganese oxides have been determined, as the determination of these is an essential qualification for a good analysis. The other minor constituents, as zirconia, sulphur, chlorine, barium, and chromium, have been determined in only a few of the representative types. In this procedure I have followed a suggestion made some years ago,[3] namely, that the minor constituents need be determined in only some of the chief types, when a series of rocks is being studied. By this procedure a maximum number of analyses and thus a greater general knowledge of the main chemical features of the region are obtained, along with a sufficient idea of the occurrence of the very minor constituents.

Stress is laid on the chemical and mineral discrimination between the various types, especially those most often met with. Cross has already pointed out that, although most of the lavas are generally referred to as basaltic, yet there is, in fact, a very considerable diversity in composition, chemical and modal, and that many of the so-called "basalts" are really not such. Only incidental attention will be given to the structural features of the volcanoes, the characters of the lava flows, and other essentially volcanological matters. The aims and character of the papers are primarily petrological and, furthermore, my opportunities for field work were too limited for sufficiently extensive study.

Determinations have been made of the specific gravities of the specimens that have been analysed. Many of the determinations (of the compact rocks) were carried out with the hand specimen, weighing from 300 to 800 grams; some were made on fragments weighing from 10 to 30 grams; and some (especially of the vesicular rocks) were made on portions of from 3 to 6 grams of the powder used for analysis. The first two were made by the usual balance method, especial care being taken to expel inclosed or adherent air by exposure under water to low pressure, and subsequent soaking in water over night. The specific gravities of the powders were carried out with the pycnometer; these last determinations

[3] H. S. Washington, U. S. Geol. Survey, Prof. Paper 99, 17, 1917, Manual Chem. Anal. Ign. Rocks, 1919, 16.

are indicated by an asterisk (*). The data as to specific gravity, density, porosity, and other cognate subjects will be discussed in the final paper of the series.

The specimens on which these studies are based were, in part, collected by me on Oahu and Hawaii, the only islands which I visited, during and after the Pan-Pacific Conference of 1920. Very many more were placed at my disposal or were collected for me by various friends, to whom my warmest thanks are due. Through their generosity and friendly aid there has been available for this study the largest and most representative collection of rocks from all the Hawaiian Islands yet brought together.

Acknowledgments, by name, will be made in the appropriate places; but I would express my special gratitude to Dr. Sidney Powers, who has permitted me to study his very large collection of rocks from all the islands, made in 1915. I would also specially thank Prof. J. Allan Thomson, of New Zealand, for rocks from Maui and Hualalai; Dr. L. H. Daingerfield, of Honolulu, for rocks from Molokai, Maui, and Lanai; Prof. H. S. Palmer, of Honolulu, for rocks from Oahu; Dr. N. E. A. Hinds, of Harvard University, for rocks from Kauai; and Drs. Whitman Cross, R. A. Daly, and T. A. Jaggar for various specimens.

The map of Hawaii which accompanies this paper is based on the chart of Hawaii of the U. S. Coast and Geodetic Survey, No. 4115. The lavas of the various islands will be dealt with in separate installments, and the general discussions and conclusions will be reserved for the last paper of the series. The lavas of Hualalai, Mauna Loa, and Kilauea will be described in the next paper.

Before beginning the descriptions of the various rocks a few words must be said regarding some points of classification and nomenclature which have been adopted for the rocks of the Hawaiian Islands, especially the andesitic and basaltic lavas.

From the microscopical and chemical study of a very considerable number of specimens it appears that, with the exception of some comparatively few transitional rocks, the Hawaiian lavas may be referred to fairly well-marked and rather clearly distinguishable types, within which most of the specimens cluster quite closely. The distinctions between these types must be based chiefly on the microscopic and chemical characters, because the megascopic features fail very often among the lavas of the Islands to reveal their true characters. These are mostly well expressed in the norm and are also evident generally in the mode as seen in thin sections.

Iddings[4] has endeavored to harmonize the qualitative and the quantitative systems of classification in a way the general lines of which will be followed here. He bases the classification on the quantitative relations of the normative minerals present, which are generally indicated in the mode as seen in thin section. Quartz-bearing rocks do not occur on the Hawaiian Islands, so they may be disregarded here. The trachytic lavas are so rare and are so uniform on the Hawaiian Islands that they present no special difficulty, and the classification of the rocks which contain nephelite or melilite will be taken up when we discuss the rocks of Oahu and Kauai, where they occur.

For the present we shall consider only the "andesitic" and "basaltic" rocks, that is, lavas which are composed essentially of varying relative amounts of plagioclase (of varying composition) and pyroxene, with constant but small and negligible amounts of magnetite and apatite, and with or without olivine. Neither amphibole nor biotite are present in these lavas as found in the Hawaiian Islands. There is constantly present a very small amount of normative orthoclase, which is reckoned in with the albite molecule.

In consonance with the broad principles of the quantitative system, and following Iddings, the andesitic and basaltic lavas will be divided primarily into groups based on the relative amounts of the salic and the femic minerals shown in the norm, the salic minerals here being plagioclase, and the femic being pyroxene, in some cases also olivine, and small amounts of magnetite and apatite.

The first group, considered systematically, is that of lavas composed wholly or almost wholly of plagioclase, in which femic minerals are present in only negligible amounts, that is, less than 12.5 per cent. This group is not distinguished separately by Iddings, who combines it with the next one, (with dominant plagioclase) into

[4] Iddings, Igneous Rocks, 2, 21, 1913.

a group with preponderant plagioclase. There is no name yet given to this group as a whole, and I prefer not to coin one here. In the few examples of these extremely plagioclasic lavas found on the Hawaiian Islands, however, the feldspar is oligoclase, so I shall call these rocks *oligoclasite*. This follows the present generally accepted usage, but with a quantitative restriction to those rocks in which the amount of femic mineral is negligible. We meet with these lavas at Kohala, on Hawaii, and on Maui.

We have next the two chief groups: *andesite,* in which plagioclase dominates over femic minerals, that is, plagioclase constitutes from 87.5 to 62.5 per cent of the norm; and *basalt,* in which the amounts of plagioclase and femic minerals are about equal, that is, the percentage of feldspar lies between 62.5 and 37.5, and conversely with the femic minerals.

Iddings seems to make no provision for the broad group of basalt, as just defined, for he uses the term "basalt" to denote an olivine-bearing lava.[5] Here I differ with Iddings, in that I use the term basalt irrespective of whether olivine is present or not, as is also true of my use of the term andesite. The feldspar is generally labradorite, in which case the rock may be considered a basalt "proper," while other varieties would be oligoclase basalt and andesine basalt. This usage for basalt "proper," except for the recognition of the quantitative relations between the salic and femic minerals, conforms with that of Rosenbusch, Harker, Hatch, Daly, Holmes, and many others, who do not consider the presence of olivine as an essential character of a basalt. The usage of Iddings is that of Zirkel and the French petrographers, the last unfortunately bestowing the ambiguous name "labradorite" on olivine-free basalt.

Bowen and Andersen[6] have shown that clinoenstatite splits up into liquid and olivine at high temperatures, but that the olivine recombines with the free silica of the liquid at lower temperatures, clinoenstatite being reformed. This serves to explain such occurrences as that of olivine (fayalite) in highly silicic glassy rhyolite and pantellerite, and the concomitant presence of quartz and

[5] Iddings, Igneous Rocks, 2, 196, 1913.

[6] Bowen and Andersen, this Journal, 37, 487, 1914; O. Andersen, ibid. 39, 407, 1915.

olivine in the "quartz basalts" of New Mexico and other localities, which were such an inexplicable puzzle to Iddings[7] and other petrographers many years ago.

The studies by Bowen and Andersen indicate that the presence of olivine in andesitic and basaltic rocks must very frequently be dependent on the rate of cooling and of solidification, and is therefore fortuitous. If the molten magma cools quickly and solidifies so as to preserve the high-temperature phases, olivine will be present in the rock, while the excess silica may not appear as quartz but would exist occult in the glassy groundmass. If, on the other hand, the cooling is slow enough to permit of the recombination of the olivine and silica, the rock will show no olivine, but rather augite, which is the modal representative of the laboratory clinoenstatite. We would have thus either an olivine-free or an olivine-bearing basalt according to the chance rate of cooling.[8] For this reason I consider that the presence or absence of olivine in the andesites and basalts is of importance subsidiary to the character of the feldspars. Unless the magma is so low in silica and so high in magnesia and ferrous oxide that considerable olivine appears in the norm, indicating the compulsory presence of olivine in the rock, the modal presence or absence of olivine is, to me, of scarcely more classificatory value than the presence or absence of glass; neither character is fundamental, but rather adventitious.

The two groups andesite and basalt will, therefore, be subdivided according to the predominant character of the normative feldspar, whether albite, oligoclase, andesine, labradorite, bytownite, or anorthite. Of these feldspars we need consider only oligoclase, andesine, and labradorite in the Hawaiian andesites and basalts.[9] We shall thus have: oligoclase andesite, andesine andesite, labradorite andesite; oligoclase basalt, andesine basalt, and labradorite basalt. The matter of these names will be discussed presently.

The presence of olivine is next taken into consideration. To indicate this the name "olivine" is prefixed to

[7] Iddings, this Journal, 36, 208, 1888; U. S. Geol. Survey, Bull. 66, 23, 1890.

[8] This phase of the subject is discussed very briefly by Bowen and Andersen in the paper cited above.

[9] Cross has made the same suggestion for the classification of the lavas of the Hawaiian Islands. (U. S. Geol. Survey, Prof. Paper 88, 46, 1915.)

the name of the distinguishing feldspar, the two being connected by a hyphen.[10] We would thus have: olivine-oligoclase andesite, olivine-andesine andesite, olivine-labradorite andesite, olivine-oligoclase basalt, olivine-andesine basalt, and olivine-labradorite basalt. If the term olivine does not appear in the name the implication is usually that the rock is olivine-free, unless the name be used in its broadest group sense, as should be inferable from the context.

There are two more groups of cognate lavas which should be recognized. In one the femic normative minerals (chiefly pyroxene or olivine, or both) dominate over plagioclase; that is, feldspar is present in subordinate amount, varying from 37.5 to 12.5 per cent of the rock. Iddings disregards this group which, furthermore, is not recognized separately as a group by any writer on petrography. I am loath to give a name to this group, in a paper which deals primarily with the rocks of a single district, but it will be found necessary to name one of its sub-divisions.

In the Hawaiian Islands there occur rather frequently lavas belonging to this group which contain abundant augite and olivine in about equal amount, the olivine being far more prominent in the form of large, abundant phenocrysts. Cross[11] calls these lavas "picritic basalt," while Holmes[12] gives the name "picrite-basalt" to similar lavas with abundant olivine phenocrysts and of analogous chemical composition. In this paper I shall use the name picrite-basalt for this type rather than Cross's name, because it states more clearly that the rock is intermediate between picrite and basalt, and is not primarily a basalt, in the sense used above.

Finally, the last group of this series needs a few words. This is that in which the femic minerals are extreme over the feldspars, that is, effusive lavas in which the amount of feldspar is negligible, less than 12.5 per cent. None of these occur on the Hawaiian Islands, so we need not concern ourselves with their nomenclature. The

[10] I adopt here the uniform scheme of the U. S. Geological Survey, "based on the single principle that like names are connected by a hyphen and unlike names are not." (G. McL. Wood, Suggestions to Authors, U. S. Geol. Survey, 1916, p. 14.)

[11] Cross, U. S. Geol. Survey, Prof. Paper 88, 39, 1915.

[12] A. Holmes, Q. J. G. S., 72, 244, 1917.

names augitite and olivinite suggest themselves as appropriate for two chief varieties, but these names have been already employed with other meanings.

For various members of the andesite and basalt group Iddings suggested two sets of names; the one compound and the other simple. Thus, he used oligoclase andesite or kohalaite, andesine andesite or andesite (proper), labradorite andesite or olivine-free basalt, olivine-oligoclase basalt or mugearite, olivine-andesine basalt or hawaiite, and so on. In the present series of papers the compound names will be used, but not the simple names. Thus we shall speak of oligoclase andesite not kohalaite, olivine-andesine basalt not hawaiite.

This decision to use compound names has been arrived at because I think, with Holmes,[13] Bowen,[14] and many others, that the number of rock names has become, and is increasingly becoming, so unwieldy as to be unmanageable, and so arbitrary and unsystematic as to be often absurd. The difficulty and complexity are especially great because a rock name which is derived, as most of them are, from a locality name can convey in itself no indication of the character of the rock.

This state of affairs is brought about largely through the readiness with which authors unnecessarily bestow new names on insignificant varieties of rocks. This results in a host of names, many of which are synonyms or near-synonyms and many of which are of only local significance. It is practically impossible to remember their meanings and, it may be added, it is not worth while remembering the meanings of most of them were it possible. Having myself yielded more than once to the temptation of this *cacoethes nominandi,* I know the fatal facility with which a new name slips from one's pen when one encounters a rock that is somewhat out of the ordinary, and especially when it differs notably from others of the series which is under study. It may happen, later on, that the baptizer himself wonders what may be the meaning of the name which he has thus carelessly thrust on the petrographic world, or indeed why it was ever given. One may thus appreciate the difficulties of another reader, who is not conversant with the

[13] A. Holmes, The Nomenclature of Petrography, 1920, 4.

[14] N. L. Bowen, Jour. Wash. Acad., 13, 3, 1923. The subject of rock names is discussed also by G. W. Tyrrell in Geol. Mag., 58, 495, 1921.

rocks of the region and to whom the name, in itself, conveys no idea of its meaning.

It seems better to revert to the simple method of employing certain fundamental rock names, such as granite, rhyolite, syenite, trachyte, diorite, andesite, gabbro, and basalt, which by long and general use and connotation imply the broadest and most fundamental characters of mode and texture, and which are to be modified by qualifiers to denote the more specific mineral or textural features or peculiarities. Such names as oligoclase andesite or olivine-andesine andesite are in accord with this principle, and they convey certain definite ideas of the chief characters of the rocks spoken of in a way that their equivalent simple names, kohalaite and hawaiite, can never do.

The total number of fundamental names would never be very large, probably not much over one hundred or so. One can find in Holmes' Nomenclature of Petrography about fifty such suitable fundamental names, the great majority of which are so well-known and which have, by long usage, such obvious connoted meanings, that they will serve as a basis for the nomenclature of all the ordinary and many of the rarer kinds of igneous rocks. Others would have to be invented or selected for certain of the modal and textural combinations (motexes) which are seldom met with or which are still unknown, so that the nomenclature would grow gradually by additions from time to time. But the number of these additional fundamental names would never be very large, and their meanings, being broad and simple, could be remembered with comparative ease.

In this series of papers there will be used the term *phyric* (with its corresponding prefix *phyro-*) instead of the usual term *porphyritic* to indicate a fabric composed of phenocrysts and groundmass, that is, the fabric of a porphyry. The term *aphyric* (with *aphyro-*) will be used instead of non-porphyritic, of a rock without phenocrysts.

The logical adjectival form of porphyry is porphyric, not the universally used porphyritic, which is derived ostensibly from the now obsolescent term porphyrite. The syllable *phyr* (best pronounced like *fear*) is accepted by all petrographers as implying a "porphyritic" fabric, and it is seen in many rock names, such as augitophyre, felsophyre, granophyre, leucitophyre, orthophyre,[15] and in the "orthophyric texture" of Rosenbusch. The term *aphyric* was suggested many years ago[16] to replace non-porphyritic, and its meaning is immediately obvious to all petrographers, although it has not come into general use.

Phyric and aphyric are two contrasted terms, which are much shorter than the corresponding porphyritic and non-porphyritic, enter more readily into compound words, are readily intelligible, and are fairly euphonious. All these terms are derived from the same Greek word (meaning purple), a word which has come only secondarily to have a textural significance.

Kohala.

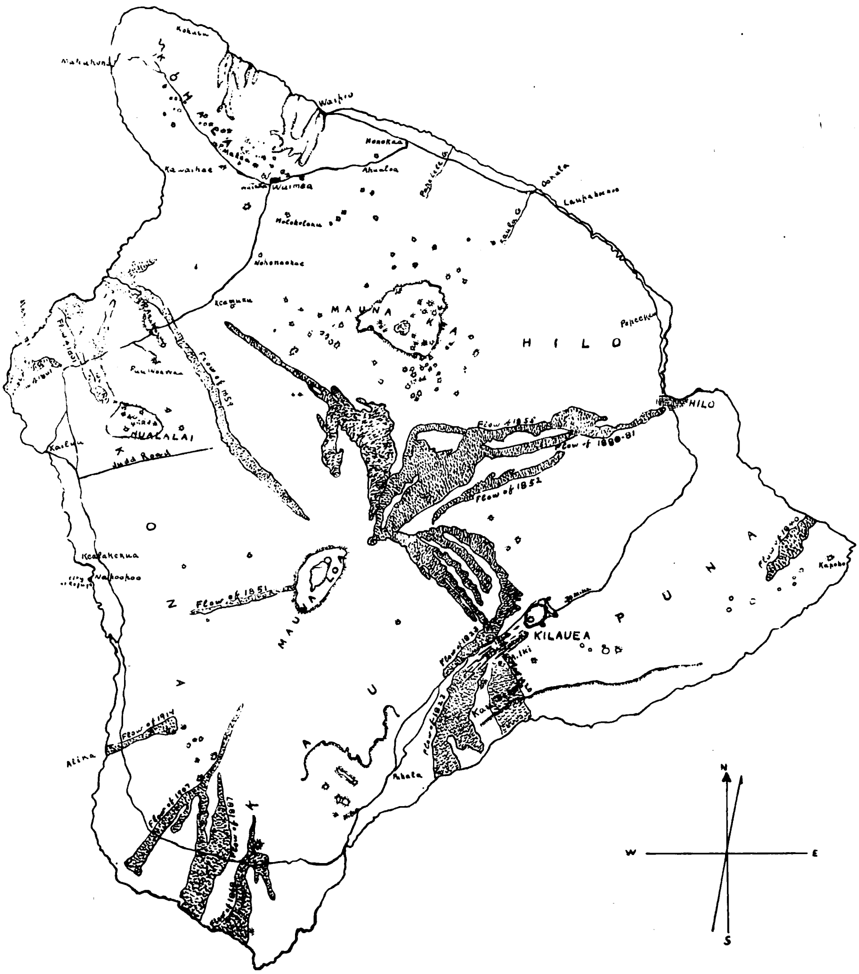
The Kohala Mountains, at the north end of Hawaii, are the remains of the oldest volcano on the island. Kohala (the Whale) has been neglected by most geological visitors to Hawaii, and no good description of it is to be found. Dutton, Dana, and Hitchcock give but scanty notice of it; Lyons seems, like Dutton, to have seen only the southern end; while Cross visited only the small port of Mahukona at the extreme northwest.[17] Sidney Powers visited and collected over the western slope and on the eastern as far north as the Waipio Valley, but he has published[18] only a paragraph on this volcano. My visit, which was made in company with Mr. W. O. Clark and Dr. J. Allan Thomson, in the course of a trip around the island, was confined to the stretch of the Waimea-Kohala road as far as Puu Makea.

The Kohala Mountains differ in form from the dome-shaped other volcanoes of Hawaii; they form a ridge, nearly twenty-five miles long, running northwest-southeast, and with a maximum elevation of 5,505 feet. The mass may be interpreted as the remnant of a huge cone, of which the former center of activity lay to the east, the vanished portions having dropped down along a fault line. It would thus be analogous to the Koolau and

[15] Chrysophyre was used by J. D. and E. S. Dana for the Hawaiian basalts with olivine phenocrysts. The term is worthy of resuscitation.
[16] Cross, Iddings, Pirsson, Washington; Quantitative Classification of Igneous Rocks, Chicago, 1903, p. 173.
[17] W. Cross, U. S. Geol. Survey, Prof. Paper 88, 13, 1915.
[18] S. Powers, this Journal, 50, 266, 1920.

Waianae Mountains on Oahu and the eastern volcano on Maui.[19]

The western side of the ridge is a gentle, uniform slope, covered by "basaltic" lava flows; while the eastern,



windward side is more broken and is deeply dissected by ravines among which the Waipio Valley is the largest and most striking. The crest of the ridge is accessible with difficulty, because of the abundant vegetation and

[19] Cf. W. Lindgren, U. S. Geol. Survey, Water Supply Paper 77, 13, 1903.

the presence of many bogs. A considerable number of small parasitic cones, composed of scoria with lava flows, occur below the western line of the crest, and farther down along the upper part of the west slope. These cones show a marked linear arrangement, and are apparently of quite recent origin, belonging to the last visible phase of volcanic activity. The eastern side of the ridge is devoid of such cones.

The specimens studied include those collected by me, those collected by Powers, and one by Cross. They represent very well the west slope and the west edge of the crest with some from the southern end, while the eastern slope and the interior are not represented.

Megascopically, most of the specimens may be referred to three quite distinct types: a light gray, aphyric and aphanitic lava, which is apparently highly feldspathic, and seems to be the most abundant kind of rock; a dense, black, aphyric and aphanitic "basalt," of the cones and other flows; and a phyric "basalt," with many feldspar phenocrysts in a dense, black groundmass. Study of the thin sections shows, however, that these color distinctions do not invariably correspond with the true character. Some of the black "basalts" are really very feldspathic oligoclase andesite, while some of the light gray rocks are really rather femic olivine basalt. We shall meet with similar discrepancies elsewhere among the islands.

Aphyric oligoclase andesite.—Rocks which belong to this type appear to be among the most abundant at Kohala. They were found by me at several places along the Waimea-Kohala road, as at Puu Makea and in Momoualoa Gulch, and a number of Powers' specimens also belong here. This is the kohalaite of Iddings.

The specimens of oligoclase andesite which I have examined are dense, very fine grained or aphanitic, but not glassy, and are mostly entirely free from phenocrysts, although a few of feldspar may be present. A platy structure is common, and more or less vesicular forms are found, but they seem to be rare. The color is generally light ash gray, as at Puu Makea, while in fewer specimens it is dark gray, as in the blocks of Momoualoa Gulch. In these last, however, only the interior of the blocks is dark; the outer portion is light gray, apparently due to incipient weathering, but this strengthens the impression of the generally andesitic character of the Kohala lavas.

In thin section this type shows a decidedly trachytic texture, in that the rock is composed very largely of very small tables or laths of oligoclase, with marked fluidal arrangement. Considerable augite is present, in very small anhedral grains; there are many small grains of magnetite, and a few minute prisms of apatite. An occasional small grain of olivine is seen in some of the sections, but this mineral is rare and its presence is certainly not characteristic of the type. There is, finally, a little interstitial colorless base, of low refractive index. Generally this is birefringent and is probably orthoclase, while elsewhere it is glass.

With this type may be mentioned a lava which has been very briefly described by Lyons,[20] who states that it "is the prevailing rock in the Kohala Mountain, at least in the Waimea neighborhood." Lyons says: "It is a bluish gray, compact, minutely crystalline lava, containing much feldspar and very little chrysolite." He does not seem to have studied it in thin section. Judging from its analysis by Lyons, and its close resemblance to an oligoclasite from Maui, this Waimea rock is to be considered as an oligoclasite. I could not identify this rock among my specimens or among those collected by Powers.

Chemical analyses (see Table I) were made of two specimens of the Kohala oligoclase andesite. One is from a massive flow at Puu Makea, at an elevation of about 3,600 feet, about 8 miles northwest of Waimea along the Waimea-Kohala road. The other (2) is from one of the many light gray blocks in the stream bed of Momoualoa Gulch, just above the bridge, about 4 miles from Waimea. These blocks probably come from the cone of Puu Kamoa, which is a short distance above. The Puu Makea lava is very light gray and slightly vesicular, while that from Momoualoa Gulch is very dark gray in the interior (from which the portion analysed was taken), but light gray near the surface. Both are very dense and aphyric.

The analysis by Lyons of the oligoclasite from "near Waimea" is also given as well as an analysis of an oligoclasite from Iao Canyon, Maui, which will be described in a subsequent paper.

[20] A. B. Lyons, this Journal, 2, 425, 1896.

TABLE I.

	1	2	3	4
SiO_2	52.27	51.99	58.06	59.74
Al_2O_3	17.05	16.30	18.21	18.86
Fe_2O_3	3.51	2.75	4.87	1.94
FeO	7.20	7.44	2.01	3.75
MgO	3.13	3.19	1.59	0.90
CaO	5.82	6.67	3.29	3.00
Na_2O	5.40	5.64	6.12	7.33
K_2O	2.22	2.13	2.75	2.89
H_2O+	0.44	0.29	....	0.12
H_2O-	0.08	0.07	....	0.26
TiO_2	2.13	3.02	1.88	1.02
ZrO_2	none	n.d.	n.d.	n.d.
P_2O_5	0.62	1.25	0.65	0.26
SO_3	0.13	n.d.	0.05	n.d.
Cl	trace	n.d.	n.d.	n.d.
MnO	0.16	0.11	0.36	0.13
BaO	0.05	n.d.	n.d.	n.d.
	100.21	100.85	99.99	100.20
Sp. gr.	2.736	2.756		2.680
at	22.0°	23.5°		23.5°

NORMS.

	1	2	4
Or	12.79	12.23	17.24
Ab	42.97	44.01	58.16
An	16.12	13.07	10.01
Ne	1.42	1.99	1.99
Di	7.61	9.58	2.57
Ol	8.08	6.23	3.50
Mt	5.10	3.94	2.78
Il	3.95	5.78	1.98
Ap	1.85	3.02	0.67

1. Aphyric oligoclase andesite, II.5.2(3).4. Elevation 3,600 feet, Puu Makea, Kohala. Washington analyst.
2. Aphyric oligoclase andesite, II.5.2.4 Elevation 2,900 feet. Puu Kamoa (?), Momoualoa Gulch, Kohala. Washington analyst.
3. Oligoclasite. "Near Waimea," Kohala. Lyons analyst. this Jour., **2**, 424, 1896. Includes: 0.05 S., 0.10 Cu.
4. Oligoclasite, I (II).5.2.4. Block in Iao Canyon, Maui. Washington analyst.

The first two rocks are very much alike, although one is light and the other very dark gray. The rather high silica and alkalies, and the low magnesia and lime, show that they are andesite and not basalt. There is clearly not enough potash (and hence not enough orthoclase) present to justify the name trachyandesite which has been given to these rocks by some petrographers. The percentages of phosphoric oxide are high, and we shall see that this feature is usual in lavas from the other Hawaiian Islands. The figures of the two norms show that the normative feldspar is oligoclase, which harmonizes with the microscopic examination. The mode is highly normative, except for the very small amount of nephelite. The subrang in which they fall, II.5.2.4.,[21] is one in which many such rather sodic andesites fall.

The analysis by Lyons of the oligoclasite is unsatisfactory because the rock powder was ignited prior to being analysed; so that much of the ferrous oxide was oxidized to ferric. For this reason its norm is not given. It is, however, certainly much higher in silica and alkalies, and more salic, than the two preceding andesites, and it would be of interest to discover its locality. In chemical composition it greatly resembles a rock from Iao Canyon, Maui, collected by Dr. J. Allan Thomson (No. 4), which is composed almost entirely of oligoclase laths, with small grains of augite and magnetite. This is to be described in a later paper.

Aphyric olivine-oligoclase andesite.—The lavas of the cones which occur along the upper part of the western slope of Kohala, and flows from which cover it down to the sea, seem to be mostly of one type, and would be commonly called "basalt." These lavas are dark gray to black, with very few or generally with no phenocrysts, and are very dense and fine grained or aphanitic. Many of the flows are vesicular, and much scoria, ash, and some bombs occur at the cones. These lavas and their unconsolidated varieties must be regarded as the last visible products of the activity of the Kohala volcano. Some of the flows and other masses are so fresh as to indicate a very recent period of eruption.

[21] The symbols of the subrangs show so clearly the general chemical and normative characters of a rock that they may well be used instead of the subrang names which were proposed in the C. I. P. W. quantitative classification. Personally, I now think of and use the subrang symbols to the almost total exclusion of the subrang names.

In thin section these rocks show a well-marked flow texture, like that of most of the preceding type, and in great contrast to the texture of the phyric basalts next to be described. They are composed in great part of small tables or laths of oligoclase-andesine, with many small anhedral grains of olivine and magnetite, and fewer small augite grains, in a colorless glass base. There are some small apatite prisms, but the visible quantity of these is much less than the amounts of apatite (about 5 per cent) which the analyses indicate as being present. The specimens of this type which were specially studied by me came from the cones of Puu Kawaiwai (collected by me), Puu Lahikiola (collected by Powers), and some of the flows at Mahukona (Cross). The thick flows which form the torrent walls at the bridge over Waiaka Gulch are of this type. These and the Mahukona specimen are coarser grained and more doleritic than the others. The flows at Mahukona are not all of this type, as a specimen collected by Powers is a phyric basalt.

Analyses were made of three specimens, the results being shown in Table II, with one by Lyons of a "vesicular basalt" from an unnamed cinder cone.

TABLE II.

	1	2	3	4	5
SiO_2	47.39	45.33	49.09	47.33	49.24
Al_2O_3	16.46	16.52	15.15	17.96	15.84
Fe_2O_3	3.75	5.60	2.95	12.64	6.09
FeO	8.42	6.92	10.22	0.51	7.18
MgO	5.08	7.38	4.94	3.97	3.02
CaO	7.37	7.89	8.47	6.29	5.26
Na_2O	4.71	4.24	4.03	3.67	5.21
K_2O	1.65	1.49	1.31	1.10	2.10
H_2O+	0.28	0.28	0.17	....	1.61
$H_2O—$	0.09	0.05	0.07	....	1.08
TiO_2	2.83	2.45	2.66	4.84	1.84
ZrO_2	none	n.d.	n.d.	n.d.	n.d.
P_2O_5	2.22	2.32	0.80	1.05	1.47
SO_3	0.06	n.d.	n.d.	0.07	n.d.
Cr_2O_3	trace	n.d.	n.d.	n.d.	trace
MnO	0.09	0.10	0.09	0.64	0.29
BaO	0.04	n.d.	n.d.	n.d.	0.09
	100.44	100.57	99.95	100.29	100.53
Sp. gr.	2,795*		2,960*		2.79
at	22°		22°		

NORMS.

	1	2	3
Or	10.01	8.90	7.78
Ab	36.68	31.96	34.06
An	18.90	21.68	19.46
Ne	1.42	1.99	....
Di	3.16	2.22	14.22
Hy	....	....	0.81
Ol	13.70	15.35	12.41
Mt	5.34	8.12	4.18
Il	5.32	4.71	5.02
Ap	5.04	5.38	2.02

1. Olivine-oligoclase andesite, II.5.″3.″4. Elev. 3,200 feet. Puu Kawaiwai, Kohala. Washington analyst.
2. Olivine-oligoclase andesite, II(III).5.3.4. Elev. about 3,000 feet. Puu Lahikiola, Kohala. Washington analyst.
3. Olivine-oligoclase andesite, (II)III.5.3.4. Sea level. Mahukona, Kohala. Washington analyst.
4. "Vesicular basalt," Cinder cone, Kohala. Lyons analyst. This Journal, **2**, 424, 1896. Includes; 0.07 S, 0.15 Cu.
5. Mugearite, II. 5. 2″. 4. Druimna Criche, Skye, Scotland. Pollard analyst. Harker, Igneous Rocks of Skye, 263, 1904. Includes; 018F, 0.03 S, traces Ni, SrO.

The first three rocks are much alike chemically, the chief differences being in the silica and magnesia, with slight differences in the state of oxidation of the iron, although the total amounts of iron oxides are about the same in all. The amounts of alkalies, especially soda, are decidedly high for rocks which are so low in silica and which contain no modal nephelite. The percentages of magnesia and lime are also low, while titanium is rather high. One of the most striking features is the very large amount of phosphoric oxide present, especially in the lavas from the cones.[22] Lyons remarks on the high phosphorus content of the lavas of Hawaii and Oahu and of the soils derived from them. The large amount of normative olivine is the most prominent feature of the norms, which is in harmony with the mode as shown by the thin sections. Lyons' analysis suffers (like all

[22] P_2O_5 was determined in duplicate in Nos. 1 and 2. Schaller found 2.20 percent of P_2O_5 in the kauaiite (oligoclase gabbro) of Waimea Canyon, Kauai (Cross, op. cit., p. 15).

of his analyses) from having been made on previously ignited material, so that his Fe_2O_3 is too high and his FeO is correspondingly low. His rock was "red," and he found 3.08 H_2O+ and 2.38 H_2O- before ignition, so that his specimen was far from fresh. His MnO is almost certainly too high, as are probably his Al_2O_3 and TiO_2.

These rocks greatly resemble, both chemically and modally, the mugearite of Harker,[23] a name used by him for an olivine-oligoclase basalt or andesite, with trachytic microtexture. Harker's typical mugearite contains oligoclase rather than oligoclase-andesine, and somewhat more orthoclase than the Kohala rocks just described. But olivine is more abundant than augite in both the Kohala and the Skye lavas, and in both the texture is trachytic. The chemical similarity may be seen on comparison of Nos. 1 and 2 with No. 4 of Table II. As a minor feature, the very high phosphorus in the mugearite of Skye corresponds with that in the andesite of Kohala.

Feldspar phyric basalt.—In several of the gulches over which the Waimea-Kohala road passes are seen massive flows (Kawaihae and Momoualoa) or many blocks (Waiaka) of a phyric basalt, which seems to be a fairly common type at Kohala. Powers collected specimens of this type at Puu Hue, Mahukona, and other localities.

This type is a conspicuously phyric basalt, showing many well-shaped phenocrysts of plagioclase, up to about one centimeter long, in a densely aphanitic, dark gray to black groundmass. There are no phenocrysts of augite and only exceptionally a few of olivine.

In thin section the feldspar phenocrysts are seen to be unzoned, with the usual twinning lamellae, and of labradorite of about the composition Ab_1An_1. Most of them contain long, straight, slender inclusions of dusty glass, which are arranged regularly parallel to the vertical axis. In the Kawaihae Gulch[24] specimen are a few microphenocrysts of augite and olivine, which are not present in the others. The groundmass has a typically

[23] A. Harker, Tertiary Igneous Rocks of Skye. 1904, 257, 264.

[24] Dana (op. cit., p. 463) mentions a specimen of feldspar phyric basalt as coming from Kawaihae, on the coast, so that the flow from which I got my specimen probably extends to the sea.

basaltic texture, composed of small laths of andesine or andesine-labradorite, with many very small grains of slightly brownish augite and grains of magnetite. In some specimens there is little interstitial orthoclase, while in others there is interstitial glass.

Two of my specimens (both from flows in place) were analysed, with the result given in Nos. 1 and 2 of Table III, with them being given an analysis by Lyons of a "porphyritic lava from Kohala mountain."

TABLE III.

	1	2	3	4
SiO_2	47.98	49.14	49.01	49.62
Al_2O_3	15.32	14.64	16.29	16.00
Fe_2O_3	2.49	4.49	7.61	2.81
FeO	8.86	7.17	4.89	7.61
MgO	6.16	3.94	3.62	5.20
CaO	10.28	9.67	9.79	10.25
Na_2O	3.56	4.45	3.82	4.12
K_2O	1.08	1.00	0.80	1.46
H_2O+	0.62	0.65	....	0.22
H_2O-	0.25	0.14	....	0.07
TiO_2	3.53	4.21	3.93	1.64
ZrO_2	none	n.d.	n.d.	none
P_2O_5	0.22	0.43	0.49	0.62
SO_3	0.02	n.d.	0.20	0.05
Cr_2O_3	none	n.d.	n.d.	none
MnO	0.12	0.10	0.27	0.13
BaO	0.06	n.d.	n.d.	0.09
	100.55	100.03	100.84	99.92
Sp. gr.	2.989	2.847		
at	22°	22°		

NORMS.

	1	2
Or	6.67	6.12
Ab	26.20	36.15
An	22.52	16.96
Ne	1.99	0.85
Di	21.64	22.57
Ol	9.79	1.18
Mt	3.71	6.50
Il	6.69	8.06
Ap	0.67	1.01

1. Feldspar phyric basalt, III.5.3.4″. 3,400 feet. Kawaihae Gulch, Kohala. Washington analyst.
2. Feldspar phyric basalt, (II)III.5.3.4.(5). 2,900 feet. Momoualoa Gulch, Kohala. Washington analyst.
3. "Porphyritic basalt." Kohala. Lyons analyst. Op. cit., p. 424. Includes; 0.02 S, 0.10 Cu. Ignited before analysis.
4. Aphyric basalt, (II)III.5″.3.5. Lava of 1669, Catania, Etna. Includes; 0.03 Sr. Washington analyst. Manual Chem. Anal. Rocks, 3rd. ed., 242, 1919.

The close chemical resemblance between the first two analyses indicates the chemical definiteness of the type, which is seen also in the modal and textural features. Lavas of similar mode and texture (motex), and very similar in chemical composition, occur at Mauna Kea and Hualalai. The first two analyses are those of a basalt, except that the alkalies are rather high, which leads to the presence of andesine rather than labradorite in the groundmass, while the norm shows that the average feldspar is andesine. Titanium dioxide is high, but the phosphoric oxide is but little above the average.

The analysis by Lyons differs from my No. 2 notably only in the alumina and in the iron oxides, his higher ferric and lower ferrous oxide being brought about by ignition of the rock powder before analysis; the total amount of iron oxides, however, is almost the same as mine. The close correspondence otherwise between the two analyses makes it almost certain that Lyons analysed a specimen from the same flow at the bridge over Momoualoa Gulch as that from which my specimen was taken. This is the more probable, as this is the first place along the Waimea-Kohala road where this basalt porphyry is seen in place, as a flow and not as blocks.

This type of rock belongs to the olivine-free basalts, as olivine is present in only very subordinate amount and is absent from some specimens. The figures shown by the norm, which place it in the salfemane class, with about equal amounts of salic and femic components, also justify the name basalt. Although the phenocrysts are of labradorite, yet the average feldspar is andesine, so the type should be called strictly an andesine basalt. The qualifying terms "feldspar phyric" denote the texture and the kind of phenocrysts.

It may be worth noting here, as bearing on the relations of these and other Hawaiian basalts to the more alkalic lavas, (a matter which will be discussed later), that basalts of very similar modal and chemical composition occur on the islands of Pantelleria[25] and Linosa,[26] at Monte Ferru, Sardinia,[27] and at Etna.[28] The rocks of the first three localities belong to an obviously sodic cogmagmatic region, while at Etna we find lavas corresponding to the oligoclase andesite of Kohala, as is evident from the descriptions and the analyses given by von Waltershausen.[29] At these Italian localities these basalts are generally aphyric, as in the Etna basalt the analysis of which is given in Table III, but the type with many feldspar phenocrysts occurs at Monte Ferru, Linosa, and Etna.

Aphyric basalt.—Under this name are described a few specimens of basaltic lavas, which seem to be of less frequent occurrence at Kohala than the types described above, although very similar lavas are met with elsewhere on Hawaii and on the other islands.

This basalt is represented by blocks which occur abundantly in the stream bed of Waiaka Gulch, the first stream beyond Waimea on the Waimea-Kohala road. It is represented also by a specimen collected by Powers "south of Kaala," about 3 miles east of Waimea. The type is a light gray, almost aphanitic lava, except that some rare, very small feldspar phenocrysts may be present, and a few phenocrysts of olivine are seen in most of the specimens. Indeed, the presence of these olivine phenocrysts may serve as a diagnostic character to distinguish this type from oligoclase andesite. The texture is rough and trachytic, so that the rock would probably be considered an andesite or trachyte in the field. Most specimens are dense and very fine grained or aphanitic, but vesicular forms may occur.

The thin section of the Waiaka rock shows a rather peculiar texture and mode. There are some small thin

[25] H. S. Washington, Jour. Geol., 22, 711, 1914.
[26] H. S. Washington, Jour. Geol., 16, 17, 1908.
[27] H. S. Washington, this Journal, 39, 522, 1915.
[28] H. S. Washington, (lava of 1910), U. S. Geol. Survey Prof. Paper 99, 619, 1917; (lava of 1669), Manual Chem. Anal. Ign. Rocks, 3d ed., 242, 1919. The lavas of Etna are to be described by M. Aurousseau and myself in a forthcoming paper.
[29] S. von Waltershausen, Der Etna, 2, 432-441, 1880.

laths of labradorite, a few grains of olivine and many prominent subhedral grains of magnetite, which range in diameter from 0.03 to 0.10 mm., magnetite occurring also as small dendritic clusters of granules. These microphenocrysts lie in a groundmass made up in large part of grains of slightly brownish augite, with some thin and ill-defined laths of andesine or andesine-labradorite, and considerable glass in the small interstices. High powers are needed for study of the sections, and even they do not yield very satisfactory results. The microtexture is not typically basaltic, because of the abundance and predominance of the augite grains, but is characteristic of many of the Hawaiian basalts.

The thin section of the rock from near Kaala shows a somewhat different texture, which is more characteristically basaltic. There are many laths of labradoite and a considerable number of subhedral olivine phenocrysts, in a groundmass of labradorite laths and many augite and magnetite grains, with a little dusty glass. It may be of interest to mention that an analysis of this specimen was begun, before the thin section was made, because its very light color gave rise to the hope that this was Lyons' lava with about 58 per cent of silica. This is mentioned as illustrating the frequently deceptive character of these lavas, if one judges of their chemical and mineral characters from the color alone.

The chemical composition of these basalts is shown by two analyses given in Table IV, along with two analyses of similar basalts from Oahu and Lanai Islands, the last collected by Dr. Daingerfield. The analysis of the Waiaka basalt is considered the more representative of the Kohala basalts, as that from Kaala is not very fresh, and contains an abnormal amount of titanium. The absence of olivine and the presence of a little excess silica in the norm of No. 1, and the very small amount of olivine in that of No. 2, in spite of the modal presence of considerable olivine, may be taken as an indication that these lavas cooled so quickly that the olivine remained un-reabsorbed, as has been suggested by Bowen[30] in the case of other olivine-bearing rocks.

[30] N. L. Bowen, Jour. Wash. Acad., 13, 2, 1923.

TABLE IV.

	1	2	3	4
SiO_2	49.70	45.79	50.80	51.35
Al_2O_3	14.65	11.67	14.42	15.60
Fe_2O_3	1.88	2.99	2.83	1.34
FeO	8.03	10.32	8.53	8.50
MgO	7.80	8.90	6.88	6.70
CaO	12.10	9.60	10.58	10.40
Na_2O	2.09	2.20	2.70	2.43
K_2O	0.52	0.66	0.30	0.64
H_2O+	0.22	1.85	0.31	0.44
H_2O-	0.09	0.82	0.06	0.09
TiO_2	1.92	5.00	2.55	1.89
P_2O_5	0.56	0.40	0.32	0.28
MnO	0.15	n.d.	0.09	n.d.
	99.71	100.20	100.37	99.66
Sp. gr.	2.895		2.834	2.878
at	21°		21°	21°

NORMS.

	1	2	3	4
Q	0.72	....	2.82	2.04
Or	2.78	3.89	1.67	3.89
Ab	17.82	18.34	23.06	20.96
An	28.91	20.29	26.13	29.47
Di	22.24	19.62	19.81	16.57
Hy	19.23	19.28	16.84	20.18
Ol	....	1.39	....	....
Mt	2.78	4.41	4.18	1.86
Il	3.65	9.58	4.86	3.65
Ap	1.34	1.01	0.67	0.67

1. Aphyric basalt, III.5.4.4(5). Waiaka Gulch, near Waimea, Kohala. Washington analyst.
2. Aphyric basalt, III″.5.(3)4.4″. South of Kaala, near Waimea, Kohala. Washington analyst.
3. Aphyric basalt, III.5.4″.5. Nuuanu Pali, Oahu Island. Washington analyst.
4. Aphyric basalt, ″III.5.4.4(5). Elevation 1,360 feet, Lanai Island. Washington analyst.

MAUNA KEA.

Mauna Kea, the "White Mountain," the highest volcano of the Hawaiian Islands, reaching an altitude of

13,825 feet, lies immediately south of Kohala.[31] The volcano has the form of a low dome, without a central crater or caldera; the triangular summit is dotted with many small cinder cones, while many others are scattered over the slopes of the volcano. To the north and northwest the mountain descends gently to the broad Waimea plateau, about 2,700 feet above sea level, while on the west its lavas mingle with those of Hualalai. The point of separation between the Hualalai and the Kea lavas, along the Kona-Waimea road, seems to be indicated by the abrupt change to red soil near the Keamuku sheep station, although flows from Mauna Loa have passed between Mauna Kea and Hualalai. On the northeast and east sides, from Waipio Bay to Hilo, the sea has cut deeply into the lower mountain slopes, forming almost vertical cliffs some hundreds of feet high, and deeply furrowed by many narrow ravines. Many of these show very well the structure of the mass, or at least of its upper portion, made up of numerous superposed lava flows, where the almost complete absence of dikes and of ash and scoria beds is very noticeable. To the south the Kea lavas are buried beneath the later flows of Mauna Loa.

The petrology of the Mauna Kea lavas is known little better than that of those of Kohala. According to Cross only Cohen, Merrill, and Daly have given any petrographic descriptions of the rocks, Daly[32] communicating also two excellent analyses made by Steiger, the only ones made so far of the lavas of Mauna Kea. The specimens studied by me were collected, during the trip with Messrs. Clark and Thomson, along the Kona-Waimea and Waimea-Honokaa roads, north of the volcano, and from Honokaa by the coast road to Hilo, on the northeast and east lowest slopes, where specimens were collected in the ravines crossed by the road. A special trip was made also to Laupahoehoe.[33] Some specimens collected by Powers along the coast road were also

[31] Descriptions of Mauna Kea are given by: W. T. Brigham, Mem. Boston Soc. Nat. Hist., 1, 384, 1866; C. E. Dutton, U. S. Geol. Survey, 4th Ann. Report, 161, 1884; C. H. Hitchcock, Hawaii and its Volcanoes, 2nd ed., 1911, p. 50; W. A. Bryan, Natural History of Hawaii, 1915, p. 149. Daly (Jour. Geol. 19, 289, 1911) gives a few details.

[32] R. A. Daly, Jour. Geol., 19, 298, 301, 1911.

[33] This Laupahoehoe must not be confused with the Hamakua Laupahoehoe, north of Waipio.

studied, but his collections at Mauna Kea seem to be few.

In their general features many of the Mauna Kea lavas much resemble those of Kohala, and we find some of the same types at both volcanoes. But there occur at Kea some lavas containing much olivine, which are lacking at Kohala, and the very feldspathic and distinctly sodic oligoclase andesite seems to be unrepresented among the Kea lavas. In general, the Mauna Kea lavas are rather more femic than those of Kohala.

Andesine andesite.—This type is of frequent occurrence at Mauna Kea but is probably not the most abundant. I collected specimens from flows in some of the gullies crossed by the Kona-Waimea road, along the lower edge of the northwest slope, as near Nohonaohae and Holoholoku cones. It forms a massive flow at Kaaihue, about 9 miles east of Waimea; and is met with in some of the ravines along the Honokaa-Hilo road, on the northeast and east slope, as at Papalele Gulch, about 3 miles east of Honokaa. It also forms a recent lava flow at Laupahoehoe, which issued from the base of the wave-cut cliff, and formed a low flat peninsula of aa lava projecting about one-half of a mile into the sea. As noted by Powers,[34] "this is the most recent flow near the base of the mountain." The "andesitic basalt" and "trachydolerite" which are described by Daly[35] as occurring near and at the summit of the volcano must also be referred to this type. The occurrence of what is essentially the same lava, modally and chemically, at sea level, at 2,700 feet on the north slope, and at the summit, is worthy of attention as bearing on Daly's hypothesis of magmatic differentiation at Mauna Kea.

The Kea andesite, in general, is dark to rather light gray, very dense and fine grained, and either entirely aphyric or with very few and small phenocrysts of feldspar or (in Daly's rocks) olivine, the last being absent from my specimens. Some of the specimens are vesicular, but this appears to be unusual. Some of the specimens show signs of flow in a slightly platy appearance. The Laupahoehoe rock differs from the others in its much darker gray color; beneath the rough aa surface

[34] S. Powers, this Journal, 50, 266, 1920.

[35] R. A. Daly, Jour. Geol., 19, 297-300, 1911; Proc. Am. Acad., 47, 104, 1911.

the lava is dense, aphanitic, and wholly without phenocrysts.

In thin section this type closely resembles the olivine-oligoclase andesite of Kohala described above. The texture, however, although tending toward trachytic, is less so than at Kohala and is rather more basaltic. This is most marked in the Laupahoehoe lava. In general, microphenocrysts are few and small, mostly of andesine-labradorite, which are quite abundant in a specimen from near Holoholoku. Microphenocrysts of augite and of olivine are very few, as was noted by Daly. The rock is made up very largely of small laths of andesine, with many small prismoids and grains of a brown augite, grains of magnetite and few of olivine, and some prisms of apatite. In most there is a residual base of orthoclase or oligoclase, in small amount as a rule. Most of the specimens are holocrystalline.

Four analyses of this type of andesine andesite are given in Table V; two of them were made by Steiger for Daly, and two of them are of my specimens.

TABLE V.

	1	2	3	4
SiO_2	50.68	50.09	49.73	50.92
Al_2O_3	16.42	19.49	16.39	17.59
Fe_2O_3	5.79	0.73	7.58	3.80
FeO	6.22*	8.47	3.98	6.69
MgO	4.25	4.33	4.06	3.90
CaO	6.47	6.92	7.17	6.97
Na_2O	4.70	4.82	4.12	4.28
K_2O	2.16	1.93	1.93	1.86
H_2O+	0.23	0.32	0.54	0.79
H_2O-	0.19	0.08	0.81	0.35
TiO_2	2.64	2.47	3.05	2.55
ZrO_2	n.d.	n.d.	0.03	n.d.
P_2O_5	0.17	0.78	0.84	0.40
MnO	0.22	0.15	0.23	0.20
BaO	n.d.	n.d.	0.03	n.d.
	100.14	100.58	100.53	100.30
Sp. gr.	2.709		2.911	2.761
at	21°			

NORMS.

	1	2	3	4
Q	....	....	1.68	....
Or	12.79	11.12	11.12	11.12
Ab	38.77	33.01	34.58	36.15
An	17.24	25.85	20.85	23.07
Ne	0.57	3.98	....	....
Di	11.28	2.29	7.13	6.99
Hy	....	....	6.90	7.31
Ol	5.43	15.30	....	3.18
Mt	8.35	1.16	4.64	5.57
Il	5.02	4.71	5.78	4.86
Hm	....	....	4.48	....
Ap	0.34	2.02	2.02	1.01

1. Andesine andesite, II.5.(2)3.4. Sea level. Laupahoehoe, Mauna Kea. Washington analyst.
2. Andesine andesite, II.5.3.4. Elevation 2,700 feet. Near Nohonaohae, northwest flank, Mauna Kea. Washington analyst.
3. Andesine andesite, (''andesitic basalt''), II.5.3.4. Elevation 11,000 feet. Southeast slope, Mauna Kea. Steiger analyst. Daly, Jour. Geol., **19**, 296, 1911. Includes, 0.00 S, 0.00 Sr.
4. Andesine andesite (''Trachydolerite''), II.5.3.4. Elevation ca. 13,000 feet, Poliahu Cone, Summit of Mauna Kea. Steiger analyst. Daly, op. cit., 301.

*A duplicate determination gave 6.25 FeO.

The four analyses resemble each other closely, although there are a few minor differences in the alumina, the iron oxides, and the phosphorus. The high ferric oxide relative to ferrous in the Laupahoehoe flow is in marked contrast with the high ferrous and low ferric oxides in the lava of Nohonaohae. Inasmuch as the former contains considerable glass, while the latter is holocrystalline, the relation of the iron oxides is an exception to the general rule that ferrous oxide is higher relative to ferric oxide in rocks which contain glass than in those which are holocrystalline.[36] The two lavas of Daly show rather high ferric oxide and they were ejected from near the summit of the volcano. The Laupahoehoe lava flowed into the sea, and this would suggest the pos-

[36] H. S. Washington, this Journal, 50, 458, 1920. Cf. C. E. Tilley, Min. Mag., 19, 288, 1922.

sibility that the heated water partially oxidized the ferrous oxide, were it not for the consideration that basalts of submarine eruptions show very high ferrous oxide relative to ferric.[37] Ferguson[38] has shown, also, that basaltic lavas in powder are only slightly oxidizable by steam at high temperatures. The Laupahoehoe basalt must be considered as an exception to a rather general law.

The norms of these lavas which have been analysed show that they are all dosalic and, therefore, andesite, while they are alkalicalcic and the feldspar is, therefore, an andesine on the average. Comparison with the analyses and the norms of the texturally and modally similar oligoclase andesite of Kohala will be instructive and will serve to exemplify the principles on which the classification of the andesitic rocks adopted here are based.

Aphyric andesine basalt.—Lavas which belong to this type do not seem to be as abundant at Mauna Kea as those of the preceding type. The only localities where I collected specimens of this type are: a flow exposed in a shallow stream bed west of Holoholoku, on the northwest flank; and in Papalele Gulch and in Haakoa Gulch, near Papaaloa, at which last place the rock occurs as rounded inclusions in a dark gray aphyric basalt of the succeeding type.

This basalt is notable for its very dark gray, or rather black, color, and its very fine, dense, and aphanitic texture. The type is wholly free from phenocrysts and no vesicular forms were seen. In thin section it usually presents a sub-trachytic texture; composed of predominant small laths of andesine, with numerous small anhedral grains of a brownish augite, and some magnetite grains and apatite prisms. Olivine is typically absent, although a few small grains are present in a Holoholoku specimen. A little glass is present in the finest grained specimens.

The chemical composition is represented by one analysis, No. 1 of Table VI. This brings out, as does its norm, the intermediate character of this type between the preceding andesine andesite and the succeeding lab-

[37] W. S. Washington, this Journal, 7, 148, 1909.
[38] J. B. Ferguson, Jour. Wash. Acad., 9, 539, 1919.

radorite basalt. The differences are seen especially in the figures for alumina, magnesia, lime, and the alkalies.

TABLE VI.

	1	2	3
SiO_2	48.42	51.97	51.12
Al_2O_3	13.97	12.65	12.91
Fe_2O_3	4.17	4.60	1.75
FeO	9.57	7.05	9.71
MgO	4.61	7.98	7.88
CaO	8.86	10.59	10.56
Na_2O	3.30	2.77	3.94
K_2O	1.29	0.34	0.21
H_2O+	0.84	0.26	0.19
H_2O-	0.42	0.11	0.12
TiO_2	3.25	2.11	1.91
P_2O_5	0.91	0.25	0.27
Cl	none	n.d.	n.d.
MnO	0.17	0.16	0.09
	99.78	100.84	100.66
Sp. gr.	2.982	3.040*	3.039*
at	22.3°	22°	22°

NORMS.

	1	2	3
Q	0.84	4.26	....
Or	7.78	2.22	1.11
Ab	27.77	23.58	33.64
An	19.46	20.85	16.68
Di	15.49	23.72	27.69
Hy	12.88	14.50	0.90
Ol	....	....	13.55
Mt	6.03	6.73	2.55
Il	6.23	3.95	3.65
Ap	2.02	0.67	0.67

1. Aphyric andesine basalt, III.5.3.4. Elevation 900 feet. Papalele Gulch, Mauna Kea. Washington analyst.
2. Ophitic andesine basalt, III."5.3(4)."5. Waipio Pali, Mauna Kea. Washington analyst.
3. Ophitic andesine basalt, III.5.3.5. Lowest flow, near house, Kahoolawe Island. Washington analyst.

Ophitic andesine basalt.—There occurs sparingly at Mauna Kea a type of basalt which is rather coarse grained but aphyric, and which might be called a diabase. I prefer, however, to speak of it as an ophitic basalt, which serves to give an idea of its texture. Only two specimens were found. One of these was collected by Powers on the east pali (cliff) of Waipio Valley; the other by me from one of the massive flows in the upper part of the cliff along the road from the railroad station down to Laupahoehoe. It is somewhat uncertain whether the former belongs to the Mauna Kea volcano or to that of Kohala. It is considered as belonging to Mauna Kea from the indications of the topographic map,[39] as well as from the occurrence of the almost identical lava above Laupahoehoe.

These rocks are slightly brownish gray, medium grained, phaneric with doleritic texture, and show crystals of plagioclase and augite. They are quite aphyric. The thin section shows them to be quite typically ophitic in texture. Plates of well-twinned andesine, diversely arranged, are abundant; included in rather large grains of a slightly brownish augite. There are some rather large anhedra of magnetite, but olivine is absent. The Waipio rock is holocrystalline.

A lava with almost identical megascopic and microscopic characters was collected by Powers on the small island of Kahoolawe. This is somewhat finer grained, but the thin section shows the same ophitic texture, and almost the same mode, the rock consisting of tabular andesine and granular augite. There is, however, no magnetite, and a few grains of olivine are present, as well as some interstitial, very dusty glass.

An analysis of the Waipio dolerite, with one of that of Kahoolawe, are given in Table VI. The analysis of the Waipio rock shows some rather interesting features. With the exception of silica and alumina, the figures for the chemical constituents are about the same as in the aphyric and phyric andesine basalts. Silica, however, is considerably higher, indeed the highest of any of the Mauna Kea lavas as yet studied, and is about the same as that of most of the oligoclase andesite of Kohala (see Table I). This brings about the presence

[39] Waipio Quadrangle, Hawaii (1 : 62,500), U. S. Geol. Survey, 1916.

of about 4 per cent of quartz in the norm. The alumina, on the other hand, is low; lower than in any other of the Kea rocks, except the highly olivine-rich lavas next to be described.

The remarkably close chemical correspondence between the Waipio and the Kahoolawe lavas is obvious at a glance. The only notable divergence is that in the latter the ferrous oxide is much higher relatively to ferrous than in the Waipio rock, although the total amounts are about the same. As the former lava contains glass while the latter is holocrystalline, this furnishes another illustration of the general law that ferrous oxide increases relatively to ferric with the presence of, or increase in, the glass content.

Aphyric labradorite basalt.—This type appears to be one of the most abundant at Mauna Kea, and is represented by specimens from various parts of the volcano. Among them are: the small cone of Kuainihu, on the west; a flow near Holoholoku on the northwest; a massive flow at Ahualoa, southwest of Honokaa and on the north slope; at a large quarry in the Kaula Stream, above Ookala; and flows just below the Laupahoehoe railroad station and at the main quarry above Laupahoehoe.

This type is very uniform in megascopic appearance. The color is a medium gray, the rock is dense and very fine-grained, and vesicular forms are rare. Typically this rock is aphyric, but some specimens show very few and small phenocrysts of feldspar, and here and there a very small olivine is visible. In thin section the texture is much like the preceding, although it is more basaltic and less trachytic. Much of the rock is composed of small laths of labradorite, with a few microphenocrysts of this or andesine-labradorite. Augite, either colorless or but slightly brownish, is abundant in small anhedra. There is constantly a little olivine, usually in small anhedra, but in some specimens (as that from Ahualoa) in well-shaped microphenocrysts. Small grains of magnetite are abundant, and most of the specimens show some colorless glass.

I have made two analyses of these lavas, one from Ahualoa, and the other from the quarry above Laupahoehoe, which seem to be representative. They are given in Table VII, Nos. 1 and 2. The composition is seen to be typically basaltic and calls for no special comment. The silica is slightly lower than in the preceding types, as is alumina; while the iron oxides, magnesia, and lime have increased very considerably, and the alkalies are lower. The two specimens analysed resemble each other closely in chemical composition and this resemblance, as in other cases, indicates some degree of definiteness for the type. It will be noted that the norms of both specimens show a notable amount of olivine, which is greater than, but still in conformity with, the presence of this mineral in the rocks. It would appear that these rocks form an example of the application of Bowen and Andersen's laboratory studies mentioned above.

Feldspar phyric basalt.—The phyric type of basalt, with numerous phenocrysts of plagioclase, occurs at Mauna Kea, but it is represented by only a few specimens collected by me. It occurs as a flow crossed by the road north of Nohonaohae Cone, on the northwest slope, and is found also in Papalele Gulch. The type is well characterized, but it tends to grade into the preceding aphyric basalt, as is shown by a few specimens, from the Post Office above Laupahoehoe and at Papalele Gulch, which contain few but rather conspicuous phenocrysts.

The general description of this type as found at Kohala will apply to the specimens from Mauna Kea. Well-shaped phenocrysts of labradorite, up to about one centimeter long, are abundantly scattered through a dense, aphanitic, almost black groundmass. One or two specimens show a slight vesicularity of the aa type, as described by Daly.[40]

The microscopic appearance is much like that of the aphyric type, except for the presence of the large phenocrysts. These are of labradorite, are automorphic, and show the usual multiple twinning lamellae. Some well-shaped microphenocrysts of olivine are also present. The abundant feldspar laths of the groundmass are of andesine-labradorite and they show a rather more trachytic fabric than in the aphyric type. The small grains of augite and magnetite are much more abundant than in the aphyric basalt, and there are usually some small grains of olivine. There is a little interstitial glass.

[40] R. A. Daly, Proc. Am. Acad., 47, 107, 1911; Igneous Rocks, 1914, 290.

The chemical composition of this type of basalt scarcely differs from that of the aphyric type, as is seen from Nos. 3 and 4 of Table VII. The only difference of note is the slightly higher alumina and lower magnesia in the phyric basalt. These features are expressed in the norm by the higher anorthite and lower olivine.

TABLE VII.

	1	2	3	4
SiO_2	47.79	46.43	47.72	47.32
Al_2O_3	14.80	15.22	16.19	16.68
Fe_2O_3	2.63	3.79	3.82	2.63
FeO	10.04	8.19	8.25	8.67
MgO	6.89	8.40	5.68	5.43
CaO	11.31	10.37	11.20	11.27
Na_2O	2.56	2.55	2.80	3.08
K_2O	0.94	0.99	0.84	0.79
H_2O+	0.54	0.82	0.51	0.23
H_2O-	0.09	0.38	0.25	0.17
TiO_2	1.90	3.03	2.48	3.09
P_2O_5	0.26	0.33	0.43	0.53
MnO	0.14	0.10	0.08	0.16
	99.89	100.60	100.25	100.05
Sp. gr.	3.018	2.994	2.972	2.978
at	22.3°	22.3°	17°	22.3°

NORMS.

	1	2	3	4
Or	5.56	6.12	5.00	5.00
Ab	22.80	19.39	23.58	25.68
An	26.13	26.97	29.19	29.19
Ne	....	1.14	....	0.28
Di	23.04	17.79	19.16	19.04
Hy	3.25	....	7.01	....
Ol	11.77	14.10	3.78	9.68
Mt	3.71	5.57	5.57	3.71
Il	3.65	5.78	4.71	5.93
Ap	0.67	0.67	1.01	1.34

1. Aphyric basalt, III.5.3(4).4 Elevation 1,910 feet. Ahualoa, near Honokaa, Mauna Kea. Washington analyst.
2. Aphyric basalt, III.5.(3)4.4. Elevation 200 feet. Quarry above Laupahoehoe, Mauna Kea. Washington analyst.

3. Feldspar phyric basalt, "IIII.5."4.4". Elevation 2,700 feet. Near Nohonaohae Cone, Mauna Kea. Washington analyst.
4. Feldspar phyric basalt, (II)III.5."4.4(5). Elevation 900 feet. Papalele Gulch, Mauna Kea. Washington analyst.

Chrysophyric basalt.—It will have been noted throughout the preceding descriptions of the rocks of both Kohala and Mauna Kea that olivine is a very frequent constituent. It is usually present in small and accessory amounts, especially in rocks the norms of which do not show olivine. Indeed, as Cross has pointed out,[41] and as is substantiated by my own observations, the amount of olivine in the mode, present in the rock, is invariably more than that shown by the norm. As Cross puts it: "It appears to be a notable feature of the Hawaiian lavas that olivine occurs in greater abundance than it would if the available silica of the magma had been utilized to produce compounds of the highest possible silicity." We see clearly in this feature of the rocks the effect of the splitting up of the enstatite (metasilicate pyroxene) molecule as studied by Bowen and Andersen, and the general occurrence of such adventitious olivine constitutes a strong argument against the presence of olivine being considered as of first importance in the classification of effusive rocks.

There are, however, some lavas at Mauna Kea, as well as elsewhere on Hawaii and on the other islands, in which the amount of olivine, both modal and normative, is so large that it must be considered as an essential mineral, one that is necessarily present in the holocrystalline rock, and consequently of classificatory importance. The olivine in these rocks generally, so far as my observations go, occurs as megophenocrysts, at least in very great part, so that these lavas are olivine porphyries.

These lavas, which I shall call chrysophyric for convenience (using Dana's old name), belong, at Mauna Kea, to two groups, olivine basalts, with about equal amounts of feldspar and femic minerals, and picrite basalt, in which the femic minerals dominate over the salic. It happens, as we shall see, that the two are usually distinguishable readily from each other in the hand specimen.

[41] Cross, U. S. Geol. Survey, Prof. Paper 88, 53, 55, 1915.

We shall take up first the *chrysophyric basalt.* At Mauna Kea I collected this type of lava at only two localities; in Kaula Gulch, above Ookala; and at the small cone of Kaaihue, about 9 miles east of Waimea, near which occurs a massive flow of andesine andesite described above. It is probable, however, that the type is more abundant than my collections indicate.

The rocks are dense and compact, showing many greenish yellow olivine phenocrysts in a dark gray, wholly aphanitic groundmass. No other phenocrysts are visible, except an occasional small one of augite in some specimens. The thin section of the Kaula rock shows many well-formed olivine phenocrysts, which are perfectly fresh and free from inclusions, and very few phenocrysts of a colorless augite. The groundmass is of basaltic texture, made up of very abundant, small anhedral grains of brownish augite and fewer of magnetite, with many thin laths of twinned feldspar, which, in the Kaula Gulch specimen, is oligoclase-andesine. Between these is a colorless substance, usually with weak double refraction and low refractive index, which is probably nephelite. The amount of this is, however, much less than the amount of nephelite shown by the norm. The Kaaihue groundmass is similar but much finer grained, so fine-grained indeed that it is impossible to determine with certainty whether nephelite is present or not.

An analysis was made of the olivine basalt of Kaula Gulch, the results of which are given in No. 1 of Table VIII. This is characterized, as compared with all the analyses given in the preceding pages, by the low alumina and the high magnesia, the soda being also very high for a rock with so much magnesia. No analysis that is very similar to this is to be found among those already published and given by Cross in his table of analyses of Hawaiian rocks. The nearest approach to it is the analysis of an olivine basalt from Hualalai (No. 2), which will be described in the next paper of this series.

The most interesting feature of the norm is that the large amount of soda determines the presence of a notable amount of nephelite. The amount of normative nephelite is greater than that which is actually present in the mode; which is undoubtedly to be ascribed to the formation (through the Bowen-Andersen effect) of some extra modal olivine, which makes silica available to convert nephelite into albite, as has been pointed out by Cross in his monograph referred to above.

Inasmuch as the normative feldspar is oligoclase, modally oligoclase-andesine (through the effect of the formation of the extra olivine) this type may best be called specifically chrysophyric oligoclase basalt. In the highly sodic character of its average feldspar, together with large amounts of olivine, this type (as represented by the Kaula specimen) is almost unique among Hawaiian lavas.

This Kaula olivine basalt carries xenoliths of dunite, lherzolite, etc., as do the olivine basalts of Hualalai and other olivine basalts of others of the Hawaiian Islands.

TABLE VIII.

	1	2	3	4
SiO_2	47.19	46.76	46.57	47.25
Al_2O_3	10.95	13.78	7.81	9.07
Fe_2O_3	3.31	1.26	2.40	1.45
FeO	10.21	10.43	8.91	10.41
MgO	10.52	11.07	19.74	19.96
CaO	9.73	10.54	10.65	7.88
Na_2O	4.69	3.59	1.70	1.38
K_2O+	0.93	0.64	0.33	0.35
H_2O+	0.17	0.10	0.11	0.04
H_2O-	0.07	0.10	0.09	0.08
TiO_2	2.27	2.12	1.67	1.61
P_2O_5	0.55	0.32	0.34	0.21
Cr_2O_3	n.d.	n.d.	0.23	0.12
MnO	0.16	0.08	0.13	0.13
	100.75	100.79	100.68	100.63
Sp. gr.			3.164	
at			21°	

NORMS.

	1	2	3	4
Or	5.56	3.89	1.67	2.22
Ab	19.91	15.72	14.15	11.53
An	6.12	19.46	12.79	17.51
Ne	10.79	7.95	....	....
Di	30.96	25.00	30.26	16.65
Hy	....	....	0.40	18.12
Ol	17.29	22.02	34.14	28.17
Mt	4.87	1.86	3.48	2.09
Il	4.26	3.95	3.19	3.04
Ap	1.34	0.67	0.67	0.34

1. Chrysophyric oligoclase basalt, III.6.2.″5. Kaula Gulch, above Ookala, Mauna Kea. Washington, analyst.
2. Chrysophyric andesine basalt, III.″6.3.(4)5. Summit of Hualalai, Hawaii. Washington, analyst.
3. Picrite-basalt, IV.1″.3.2.2. Kaula Gulch, above Ookala, Mauna Kea. Washington, analyst.
4. Picrite-basalt, IV.1(2).3.1(2).2. Flow of 1840, Nanawale, Kilauea. Steiger, analyst. Cross, op cit., p. 44. Includes, 0.09 NiO, 0.00 CO_2, ZrO_2, SrO.

Picrite-basalt.—In the Kaula Gulch, above Ookala, there were seen blocks of a lava which showed very abundant and prominent phenocrysts of olivine. Their origin was not ascertained, but it is probable that they are derived from one of the numerous and varied lava flows which form the walls of the canyon above the quarry where we collected our specimens.

This picrite basalt is very highly phyric; light yellow, very fresh and glassy phenocrysts of olivine, up to nearly one centimeter long, form about one-fifth to one-fourth of the rock, as seen megascopically. There are no phenocrysts of either augite or feldspar. The groundmass is light gray and very fine-grained, almost aphanitic except that the glisten of a small feldspar table is seen here and there. The rock is dense and compact, except for very few small spherical vesicles.

In thin section the large, colorless, much-cracked olivine phenocrysts are prominent, but present no features of special interest. They grade in size down to small microphenocrysts. Augite microphenocrysts are very rare. The groundmass is somewhat peculiar. It is made up in great part of very small anhedral grains of a colorless diopsidic augite, with many somewhat larger magnetite grains and subhedral small olivines, and with rather less abundant small slender laths of labradorite. There seems to be no glass, but the groundmass is so confused that it is difficult to decide definitely as to this. It is interesting to observe that a specimen of medium gray, aphyric and aphanitic basalt from the sharp turn in the road at the head of the deep gulch above Laupahoehoe shows a mode and microtexture which is almost identical with those of the groundmass of the Kaula picrite-basalt, and that the basalt of Waiaka Gulch at Kohala also very much resembles it.

An analysis was made of the Kaula picrite-basalt, a large piece being sampled because of the abundant olivine phenocrysts. The results are given in No. 3 of Table VIII. In this we find slightly lower silica than in the usual Hawaiian basalt, about the same amounts of iron oxides (ferrous oxide being greatly dominant over ferric), lime, and alkalies. Titanium and phosphorus are not high. The type is most clearly characterized by the low alumina and the very high magnesia. The close resemblance to the similar but vesicular picrite-basalt of the flow of 1840, at Nanawale, Puna, which presumably came from Kilauea, an analysis of which is given in No. 4, is striking. We shall meet with similar rocks at Mauna Loa and among the older flows of Kilauea. The considerable amount of chromic oxide in both rocks is noteworthy.

It would appear that the norm expresses the mode with fair accuracy, although there is probably more modal than normative olivine. In comparing the norms of the Kaula and the Nanawale picrite-basalts it will be seen that the pyroxene of the former is purely diopside, whereas the pyroxene of the Nanawale basalt is made up of diopside and hypersthene in about equal amounts. This difference is probably connected with the differences in the characters of the groundmass grains of "augite" in the two rocks; those of the Kaula lava are colorless, while those of the Nanawale flow are brownish.

Geophysical Laboratory,
Carnegie Institution of Washington,
February, 1923.