ART. XXX.—*Petrology of the Hawaiian Islands; III. Kilauea and General Petrology of Hawaii;* by HENRY S. WASHINGTON.

KILAUEA.

Kilauea lies on the southeast slope of Mauna Loa, the highest point of its rim, at Uwekahuna on the northwest, being 4,088 feet above sea level. Much has been written about the structural features and the activity of Kilauea,[1] but petrographic study has been confined very largely to the recent lavas.

Many superposed flows, mostly only a few feet thick, make up the walls of the great crater or "sink," and a noteworthy feature of these walls is the comparative rarity of ash beds between the flows.[2] The crater walls are also remarkable for the rarity of dikes. In the southwest part of the large crater is the active pit of Halemaumau, lavas from which overflow occasionally on to the floor of the main crater, while others break out from time to time elsewhere on its floor, thus gradually raising the level of this and filling up the crater.[3] On the outer slopes lava flows, ancient and modern, extend southward and westward, covering the eastern Kau District, the so-called Kau Desert, and flows also cover the Puna District to the east. Most of these flows originated in parasitic cones or in openings on the slopes. Of the recent flows those which will especially interest us are the flow of 1840, at Nanawale in east Puna, and that of 1920, which issued from the small cone of Mauna Iki, about 5 miles west of Halemaumau. A curving line of "pit craters" and small cinder cones extends eastward from the main crater to Kapoho on the southeast coast; the origin of these pits is still in dispute.[4]

The only recorded and last, great explosively paroxys-

[1] Descriptions of Kilauea will be found in the works cited under Mauna Loa, this Journal, 6, 109, 1923.

[2] S. Powers, Explosive ejectamenta of Kilauea; this Journal, 46, 227, 1916.

[3] Lava from Halemaumau overflowed the main crater at the southwest corner in March, 1921. See T. A. Jaggar, Bull. Hawaiian Volc. Observatory, 9, 46, 1921.

[4] I am informed by Dr. E. T. Allen that the crater pit of Makaopuhi, near the east end of this line, was in eruption and pouring out lava at the time of his visit in May, 1922.

mal eruption of Kilauea was that of 1789.[5] This covered with ashes a large area to the south in the Kau Desert, and to it are attributed the many large and small ejected blocks and some bombs which are found along the north and east rims and especially to the south and southwest of Halemaumau.

The eruption of 1789 seems to mark a change in some of the characters of the lavas, as has been observed at other volcanoes after a especially violent paroxysmal, or Plinian, eruption. At any rate this eruption may serve as a fixed time point and we may refer the lavas of Kilauea to two periods: the *ancient lavas* which antedate the eruption of 1789, and which include the flows of the crater walls, the ejected blocks, and the older flows of east Kau and of Puna; and the *recent lavas,* which include the flows of Halemaumau and of the crater floor, as well as the few of recent date on the outer slopes. The lavas of the two periods will be discussed separately, although the same or similar types recur in both.

The Ancient Lavas.

There are few good descriptions or analyses of the ancient lavas of Kilauea. Silvestri[6] describes a dozen specimens (with 12 poor analyses), which were collected by the astronomer Tacchini in 1883; the localities of these are not given, but they are presumably from the inner walls of the great crater. Some of Silvestri's specimens (his so-called "basaltoids") were not fresh, his descriptions are not very illuminating, and his analyses are so poor, especially as regards the iron oxides, that they are scarcely serviceable for modern use.

Silvestri calls several of these early lavas "basaltic hornblendophyres," and he bestows the name "kilaueite" on a certain type of basalt. His attribution of hornblende is tentative and there is little doubt that what he took for this amphibole was really a brownish augite, which is common in these lavas. Not a single crystal of hornblende has been seen by Cross or myself in any of the lavas of Hawaii. His "kilaueite" is merely a somewhat

[5] I accept this date on the authority of Brigham, rather than 1790, which is usually given.

[6] O. Silvestri, Boll. Com. Geol. Ital., 19, 168, 1888.

olivinic basalt with a dusty opaque groundmass that does not deserve a special name.

Dana[7] gives brief descriptions of specimens from the walls and from the ejected blocks, but without analyses. Daly[8] gives a detailed description of the picrite-basalt (his "olivine gabbro") from the Uwekahuna "laccolith," and describes a few ejected blocks, with an excellent analysis of the Uwekahuna rock; and Cross[9] devotes two or three paragraphs to a few blocks from the north rim, with a good analysis.

The ancient lavas of Kilauea may be placed under three types, judging from the descriptions of the authors just named and from study of my own specimens. These three types are: labradorite basalt (olivine-free), olivine basalt, and picrite-basalt. The first and third of these are well-defined, but the second is transitional and not very definite.

Labradorite basalt.—To this type belong most of the flows of the crater walls, about two thirds of Silvestri's specimens being referable here, as well as some of my specimens, with other flows observed by me in the walls but not collected. Most of the ejected blocks are also of this type, as are some of the old flows in eastern Kau and Puna, although these have been little collected or studied. A representative of them is found at an old quarry near the 30-mile post on the road from Hilo to Kilauea.

Rocks of this type are normally very light gray, generally compact or occasionally slightly vesicular (especially among the ejected blocks), but the vesicles are small and seldom rounded, usually very irregular and rather miaroles than true vesicles, as Daly points out. Into these cavities project, as noted by Dana, small tables of labradorite, small needles and prisms of brown or black augite, and hexagonal tables of hematite or ilmenite. A zeolite also occurs in the form of very small spherical groups; this is considered by Dana to be probably phacolite, but it needs further investigation. Small crystals of analcite also occur.

These lavas are typically phaneric and are apparently holocrystalline; the crystals of plagioclase are recogniz-

[7] E. S. Dana, this Journal, 37, 459, 1889.
[8] R. A. Daly, Jour. Geol., 19, 291, 303, 1911.
[9] W. Cross, U. S. Geol. Survey, Prof. Paper 88, 42, 1915.

able under the lens and even to the naked eye. There are no phenocrysts, except for some rare and small crystals of yellow olivine. Exceptions to the phaneric form are specimens from a dike 1.5 meters wide at the foot of the cliff just west of the faulted blocks below the Volcano House; this rock is gray and densely aphanitic. A 3-inch apophysis from this is black and very dense, and is shown by the microscope to be composed almost wholly of brown glass.

Some of the ejected blocks contain small (up to 1 cm.) inclusions of black glass, which were noted by Dana but seem not to have been found by Daly or by Cross. I did not observe them in any of the flows of the crater wall. In thin section this glass is dark brown and free from phenocrysts. Its refractive index varies somewhat, and for most of the glass was determined by Merwin as 1.56 and slightly higher up to a maximum of 1.575 for a small part. This refractive index is rather lower than those of the basalt glasses of Halemaumau (1911) and Mauna Iki (1920), which have almost the same chemical composition as the glass-free blocks. Tilley determined[10] the index of the Halemaumau glass as 1.605 and that of the glass of the Mauna Iki basalt as 1.603. This indicates that the glass inclusions have a chemical composition different from that of the inclosing basalt, and that the glass is probably higher in silica and more sodic. Lacroix[11] found similar patches and dikelets of brown glass in blocks of the leucite tephrite of the eruption of 1906 at Vesuvius. Analyses showed that this glass was much more salic and sodic than the tephrite. Two specimens had refractive indices of 1.525 and 1.534, while that of the tephrite glass of the Vesuvius lava of 1805 is 1.586 according to Tilley. Further study, both optical and chemical, of these glass inclusions at Kilauea will be made later.

The mode of all the specimens of this type is essentially the same, but there is some variation in the texture. Labradorite, in thin plates, and a slightly brownish augite, usually in anhedral grains, make up almost all of the rock, the two minerals being present in about equal amount. Small grains of magnetite, or occasionally very

[10] C. E. Tilley, Min. Mag., 19, 279, 1922.
[11] A. Lacroix, Nouv. Arch. Mus., 9, 38-46, 1907.

thin plates of ilmenite, are seen in some specimens, but these are absent in most of them and their place is taken by a small amount of interstitial dusty dark glass. Olivine is either absent or is present as very rare and small grains.

The texture is diabasic in most of the specimens especially those of the ejected blocks, the labradorite plates being rather large (up to 2 mm.) and with interstitial grains of augite. In others, as in the flow and dike in the crater wall (Nos. 1 and 2, Table I), the texture is typically basaltic, with some dusty glass base. The thin apophysis from the dike is composed almost entirely of a dark brown almost opaque glass, containing very few and small prisms of labradorite and one or two olivine grains, but with ghost-like small plates of feldspar dimly visible through the glass. The color of this glass resembles that of the small patches that are present in some of the ejected blocks. A typically gabbroic texture is also met with, as mentioned by Daly. The basalt of the quarry at the 30-mile post is extremely dense and fine-grained, composed mostly of very minute granules of brownish augite, with small, mostly forked, tables of labradorite, and some glass; it contains no olivine.

TABLE I.

	1	2	3	4	5
SiO_2	51.06	51.77	50.53	50.46	50.03
Al_2O_3	12.91	13.54	13.61	12.75	12.10
Fe_2O_3	1.33	0.75	1.69	0.82	2.10
FeO	9.63	9.63	9.30	10.68	9.97
MgO	8.09	7.33	7.01	9.68	9.57
CaO	11.03	10.57	10.75	10.43	10.58
Na_2O	1.92	2.18	2.16	2.42	2.01
K_2O	0.43	0.45	0.35	0.51	0.44
H_2O+	0.16	0.16	0.27	0.15	0.32
H_2O-	0.06	0.05	0.07	0.10	0.16
TiO_2	3.59	4.01	3.68	2.14	2.57
ZrO_2	none	n.d.	n.d.	n.d.	n.d.
P_2O_5	0.22	0.26	0.20	0.19	0.21
S	none	n.d.	n.d.	n.d.	n.d.
Cr_2O_3	none	n.d.	n.d.	n.d.	n.d.
MnO	0.16	0.15	0.13	0.18	0.16
BaO	none	n.d.	n.d.	n.d.	n.d.
	100.59	100.85	99.75	100.51	100.22
Sp. gr.	3.009	2.896	2.819	3.043	
at	24°	24°	24°	24°	

NORMS.

	1	2	3	4	5
Q	3.78	5.16	4.62	....	0.54
Or	2.78	2.78	2.22	2.78	2.78
Ab	16.24	18.34	18.34	20.44	16.77
An	25.02	25.85	26.13	22.52	22.80
Di	22.31	20.08	21.42	23.09	23.42
Hy	21.38	18.96	16.74	18.13	25.21
Ol	....	....	....	7.57	....
Mt.	1.86	1.16	2.55	1.16	3.02
Il	6.84	7.60	6.99	4.10	4.86
Ap	0.67	0.67	0.34	0.34	0.34

1. Labradorite basalt, III."5.4.4(5). Flow in crater wall, Kilauea, Washington analyst.
2. Labradorite basalt, III."5.4.4(5). Dike in crater wall, Killauea. Washington analyst.
3. Labradorite basalt, III."5.4.(4)5. Apophysis of dike, Kilauea. Washington analyst.
4. Olivine basalt, III.5.(3)4.(4)5. Ejected block, southwest of Halemaumau, Kilauea. Washington analyst.
5. Olivine basalt, III".5.4.4(5). Ejected block, near Uwekahuna, Kilauea, Steiger analyst. Cross, Prof. Paper **88**, 48, 1915.

The three analyses of lavas from the crater wall are much alike and call for little comment here. They all show notable amounts of normative quartz—another example of the fallacy of considering the presence of olivine in basalts as essential. The resemblance between the three is the more striking because of the different modes of occurrence of the three rocks. The intruded dike is of almost the same composition as the flow, although it is later, and the material which filled a crevice from the main dike is of essentially the same composition as it. Evidently the narrow apophysis represents the magma of the dike before it began to crystallize, and does not represent its groundmass. Close analogues of these analyses may be found among the analyses of the labradorite basalts of Kohala, Mauna Kea, and Mauna Loa.

Olivine basalt.—This type appears to be fairly common among the early lavas, about one-third of Silvestri's specimens from the crater walls falling here, and olivine basalt having been noted by Dana, Daly, Cross, and myself among the ejected blocks. Rocks of this type greatly resemble those of the preceding, and the former descriptions will, on the whole, apply to this. The essential difference is the presence of considerable, 10 to 20 per cent, of olivine, mostly as megaphenocrysts, but also as grains in the groundmass.

A variant of the microtexture was found in one specimen of the blocks from the southwest, that which was analysed. The mode is the same as in the others, though olivine occurs only in the groundmass, but the labradorite plates show a markedly regular arrangement, radiating from many centers, with the augite grains between the divergent plates. This radiate or stellate texture is mentioned by Cross[12] as that of a labradorite basalt of Kauai.

The chemical composition of this type is shown by two analyses given in Table I, one of a block from the southwest collected by me and the other (by Steiger) from the north rim near Uwekahuna collected by Cross. The two analyses resemble those of the preceding non-olivinic type, but differ in their slightly lower silica, alumina, and titanium, and higher magnesia. The norm of my specimen, No. 4, shows 7.47 per cent of olivine, whereas the rock contains about 12 per cent of this mineral. On the other hand, the closely similar analysis of Cross' specimen, No. 5, shows no normative olivine but a trace of quartz. The difference is brought about, as is evident on inspection of the analyses and calculation of the norms, by the slightly lower soda and higher ferric oxide of No. 5, which liberate just about enough silica to convert potential olivine into hypersthene.

Picrite-basalt.—Along with the two types just mentioned there are found among the ancient lavas some specimens that are very rich in olivine, so much so that they may justly be classed as picrite-basalt. These are apparently much less abundant than the others, two only of Silvestri's specimens falling here, one of Dana's, one or two of Daly's and several of mine. Dana's specimen of this type was a block from Waldron's Ledge, Daly's chief representative was from his so-called laccolith below Uwekahuna, and I found specimens at four prominent localities; an old flow west of Kamakaia in the Kau Desert (analysed), some of the flows in the northeast crater wall, the Uwekahuna "laccolith" and some of the ejected blocks in the plain southwest of Halemaumau.

[12] W. Cross, U. S. Geol. Survey, Prof. Paper 88, 13, 1915.

The type as represented by my specimens is characterized by an abundance of light, slightly greenish yellow olivine phenocrysts, in diameter up to 1 cm., abundantly scattered through fine-grained, rather light gray groundmass. The most coarsely textured of these is a specimen from Daly's Uwekahuna "laccolith." This rock becomes finer grained near the border, as stated by Daly,[13] whose detailed description of the main rock applies to specimens of this lava which were given me by Dr. T. A. Jaggar. The dark gray, slightly and finely "porous" rock contains dark olive-green olivine phenocrysts in such abundance that, at first glance, it appears to be rather coarsely and evenly granular. Under the microscope most of the olivine phenocrysts are seen to be highly automorphic; they range up to 4 mm. in length. There are no other phenocrysts. The texture of the groundmass varies from granular to diabasic, the groundmass being made up of tables of anorthite, about Ab_2An_3 (Daly), grains of brownish augite, with very little magnetite and ilmenite. No apatite is visible, and most of the specimens are holocrystalline. Daly gives the mode as:

Olivine	40.0
Augite	31.0
Labradorite	27.0
Ores	1.7
Apatite	0.3

An accident prevented my visiting this basalt at close quarters, but I am inclined to agree with Cross,[14] Powers,[15] and others, that this much-talked of mass is a lava flow that entered a pre-existent lava tunnel, and not a truly laccolithic intrusion, as is thought by Daly. J. D. Dana[16] mentions the possibility of lava flows entering "subterranean cavities" or lava tunnels.

Other specimens of the older picrite-basalt of Kilauea show much less crystalline groundmasses and these of varied kinds. A specimen of a flow about 12 feet thick in the northeast crater wall has a diabasic groundmass,

[13] Daly, R. A., Jour. Geol., 19, 291, 1911.
[14] W. Cross, op. cit., p. 43.
[15] S. Powers, Intrusive bodies at Kilauea, Zeits. Vulkan., 3, 28, 1916; Notes on Hawaiian Petrology, this Journal, 50, 277, 1920.
[16] J. D. Dana, Characteristics of Volcanoes, 240, 1890.

similar to but finer than that of the Uwekahuna rock, made up of rather thick tables of labradorite and many grains of brownish augite, without magnetite, but with considerable brownish glass. Another, from a quarry near the 19th mile post on the Hilo road, has a very fine-grained groundmass, made up of minute granules of almost colorless augite, very small and thin laths of labradorite, some grains of magnetite, and very little colorless interstitial glass. An old flow in the Kau Desert, west of Kamakaia (analysed), shows abundant thin but long tables of labradorite, which are mostly split or forked, with few augite grains, in an opaque black base, which higher powers show to be a densely dusty glass.

The chemical composition of the old picrite-basalt of Kilauea is shown by two analyses (Table II), one by Steiger of the Uwekahuna "gabbro" and the other by me of the old flow in the Kau Desert. The specimens from the crater wall and from the quarry on the Hilo road were not fresh enough to warrant analysis. With them is given Steiger's analysis of the Nanawale flow of 1840, which will be taken up later.

TABLE II.

	1	2	3
SiO_2	46.59	46.50	47.25
Al_2O_3	7.69	9.37	9.07
Fe_2O_3	2.20	2.47	1.45
FeO	10.46	10.79	10.41
MgO	21.79	21.00	19.96
CaO	7.41	6.25	7.88
Na_2O	1.33	1.52	1.38
K_2O	0.28	0.22	0.35
H_2O+	0.37	0.14	0.04
H_2O-	0.04	0.03	0.08
TiO_2	1.83	1.70	1.61
ZrO_2	none	n.d.	none
P_2O_5	0.11	0.10	0.21
SO_3	none	n.d.	n.d.
Cr_2O_3	0.13	n.d.	0.12
MnO	0.18	0.11	0.13
NiO	0.12	n.d.	0.09
BaO	none	n.d.	none
SrO	none	n.d.	none
	100.53	100.20	100.03
Sp. gr.	3.001	3.031	3.066*
at		24°	21°

NORMS.

	1	2	3
Or	1.67	1.12	2.22
Ab	11.00	13.10	11.53
An	14.46	18.07	17.51
Di	17.05	9.76	16.65
Hy	18.23	20.62	18.12
Ol	30.49	30.35	28.17
Mt	3.25	3.48	2.09
Il	3.50	3.19	3.04
Ap	0.34	0.34	0.34

1. Chrysophyric picrite-basalt, IV.1(2).3.1(2).2. Below Uwekahuna, Crater wall, Kilauea. Steiger analyst. Daly, Jour. Geol., **19**, 293, 1911.
2. Chrysophyric picrite-basalt, "IV.1(2).3.1(2).2. Old flow, west of Kamakaia, Kau Desert, Kilauea. Washington analyst.
3. Chrysophyric picrite-basalt, IV.1".3.1(2).2. Flow of 1840 Nanawale, Puna, Kilauea. Steiger analyst. Cross, U. S. Prof. Paper **88**, 44, 1915.

The two picrite-basalts are closely alike in chemical composition, and are also like other Hawaiian picrite-basalts, as that of Kaula Gulch, Mauna Kea. The presence of chromium and nickel in small but easily determinable amount, as shown by the analysis by Steiger, is noteworthy. On comparison of the norm of the Uwekahuna rock with its mode it will be seen that considerably more olivine is actually present in the rock than in the norm, another example of the general rule among Hawaiian lavas.

THE RECENT LAVAS.

The petrographic characters of the recent lavas of Kilauea have been described by several petrographers, especially Cohen,[17] Dana,[18] and Cross,[19] but attention has been most often directed to their textural features. Among these features of special interest are the varied glassy forms, for which Kilauea is famous, the lava stalactites and stalagmites, and the differences between the aa and pahoehoe lavas. In this paper we shall have little to do with the study of these textural phases of

[17] E. Cohen, Neues Jahrb. Min., 1880, 2, 23.
[18] E. S. Dana, this Journal, 37, 458, 1889.
[19] W. Cross, U. S. Geol. Survey, Prof. Paper 885, 40, 1915.

Kilauean lavas, except for a brief setting forth of some chemical differences between aa and pahoehoe.

The recent lavas of Kilauea appear to be referable to only two types: labradorite (or occasionally andesine-labradorite) basalt, and chrysophyric picrite-basalt. The intermediate type of olivine basalt, which occurs among the older lavas, seems to be either very rare or unrepresented among the recent lavas of Kilauea; at least, no specimen which can be definitely placed here has come under my observation. Picrite-basalt also appears to be very uncommon among the recent lavas of Kilauea, the only well-authenticated occurrence of it being the Nanawale flow of 1840, which is supposed to be of Kilauean origin.

Labradorite basalt (*crystalline facies*).—The more crystalline facies of the labradorite basalt, that is to say, the "stony" portion of the flows beneath the excessively rough and jagged surface of the aa blocks, and beneath the highly glassy outer crust of the pahoehoe show, in general, the characters which we have already noted in the labradorite basalt of Mauna Loa, and there seem to be no differences between recent lavas of different known dates. Megascopically, these forms are densely aphanitic, the aa is usually of lighter gray than the pahoehoe, which may be almost or quite black. The different characters of vesicularity which seem to be typical of each will be discussed later. These lavas are typically quite aphyric, although a few small grains of olivine may be present in some specimens. The presence of these, however, seems to be due to the Bowen-Andersen effect in almost all cases and they are therefore of negligible classificatory importance. The pahoehoe fracture surfaces very often give evidence of the glassy composition of the lava, while those of the aa type do not normally show this.

These labradorite basalts are composed essentially of labradorite, usually about Ab_1An_1, and a brownish augite, which together make up generally about 90 per cent of the rock. In the aa form tables of labradorite and some large augite grains form microphenocrysts, and there may be an occasional olivine, with a few grains of magnetite. The microgroundmass is very fine-grained and is composed of a confused mass of small granules of brownish augite and small labradorite tables, with little or no interstitial glass. The pahoehoe form is different. This shows many microphenocrystic tables of labradorite, which are usually somewhat forked, and very few augites, with no magnetite. The abundant base is a glass, so dusty with minute black particles as to appear opaque; or in some specimens it is a slightly dusty brownish glass.

Labradorite basalt (*glass facies*).—To this facies belong the numerous, well-known glassy forms of the recent Kilauean lavas, such as the crusts of the pahoehoe flows, the materials of the spatter cones, large blister-like bubbles, and the so-called "Pele's hair" and "Pele's tears." These forms have been studied in some detail by Cohen, Dana, and Krukenberg, and little need be said of their physical characters here as they have nothing to do with our main topic, the general petrology of the Hawaiian Island lavas.

In the more solid forms this basalt glass is jet black on a fresh surface, with a perfect conchoidal fracture. Pele's hair, however, in the mass is of a light brownish olive, about Ridgway's 19″k, but the color is somewhat variable. The walls of large blisters, drops from spatter cones, "Pele's tears," and other solid forms show few or no vesicles but the uppermost thin crust of fresh pahoehoe flows is highly spongy, although flattened down to the surface of the solid lava beneath, and it has a steely look that is very characteristic. This glass typically shows no megaphenocrysts.

In grains or in thin section this basalt glass is normally of a light yellowish brown color, about of Ridgway's "honey yellow," No. 19″, and it shows generally no streaks or evidences of flow. It is an almost pure glass, but practically all the specimens of all the various forms contain a few small microphenocrysts. Most of these are very thin long tables of twinned labradorite, and small, sharp, very well-formed crystals of olivine are also present. These show almost invariably embayments due to corrosion, which is evidence that the olivines were formed at a high temperature, by the Bowen-Andersen effect, but that they began to be reabsorbed as the temperature fell; the reabsorption being stopped by the solidification of the lava on exposure to the air. No phenocrysts of either augite or magnetite were seen in any of my specimens of this glass. The refractive index of this glass was determined by Tilley on two specimens that were sent him by me.[20] The refractive index of the lava of 1911, dipped from the crater of Halemaumau by Perret and Shepherd, was 1.605, and that of the purely glassy part of a large blister on the 1920 flow at Mauna Iki was 1.603. Merwin found the mean value 1.605 for Pele's hair collected in 1920 about two and one-half miles southwest of Halemaumau (where it was unacted on by the acid vapors), the specimen having been sent me by Dr. Jaggar. The refraction was slightly variable, and the fibres showed a very thin surface film of decidedly lower refractive index, which may be attributed to surface alteration, possibly by the fumes in the crater. In some of the specimens of glass there is evidence of partial or incipient devitrification, in the appearance of small, irregularly rounded spherulites of very dark brown, not very transparent glass, which does not seem to be dusty, the color being apparently due to pigmentation. These spherulites are formed around the phenocrysts, chiefly those of feldspar. In a cross-section of a large blister from the 1920 Mauna Iki flow, the walls of which are about one centimeter thick, and with a "shark-skin" outer surface, the outer half is of solid black glass, clear and yellow-brown in thin section; the inner half is megascopically dull dark iron-gray, and in this section is seen to be composed entirely of dark brown, nearly opaque spherulitic glass. The junction is slightly irregular but quite sharp. There are some microphenocrysts of both olivine and labradorite in both layers of glass.

Chemical composition.—About nine recent lavas of Kilauea have been analysed by Silvestri, Cohen, and Phillips, the results being given by Cross in his table of analyses; but all of these are either of such early date, so incomplete, or otherwise so unsatisfactory that they are not cited here. Ferguson[21] has made two very complete analyses of recent lavas of Halemaumau, and these are given in Table III, with three made by me of more recent lavas.

[20] C. E. Tilley, Min. Mag., 19, 279, 1922. The index, 1.605, was also found by Merwin for the lava glass of 1911; see Day and Shepherd, Bull. Geol. Soc. Am., 24, 586, 1914.

[21] A. L. Day, and E. S. Shepherd, Bull. Geol. Soc. Am., 24, 586, 1913. Ferguson, J. B., this Journal, 37, 400, 1914.

TABLE III.

	1	2	3	4	5
SiO_2	50.07	49.74	50.32	50.63	49.21
Al_2O_3	13.32	12.36	12.83	13.08	12.93
Fe_2O_3	1.92	1.64	1.74	1.09	1.76
FeO	9.28	10.08	9.93	10.10	9.28
MgO	8.01	8.83	7.39	7.44	7.42
CaO	10.64	10.88	11.06	11.38	11.27
Na_2O	2.16	2.45	2.38	2.36	2.64
K_2O	0.45	0.55	0.41	0.47	0.59
H_2O+	0.49	0.17	0.33	0.15	0.74
H_2O-	0.22	0.05	0.05	0.08	0.08
TiO_2	2.70	2.49	3.10	3.33	2.75
ZrO_2	none	trace	n.d.	n.d.	n.d.
P_2O_5	0.26	0.41	0.30	0.33	1.21
Cl	0.08	0.10	0.04	n.d.	n.d.
S	0.11	0.04	n.d.	n.d.	n.d.
Cr_2O_3	0.05	0.04	n.d.	n.d.	n.d.
V_2O_3	none	0.02	n.d.	n.d.	n.d.
MnO	0.16	0.14	0.10	0.12	0.08
NiO	0.04	0.05	n.d.	n.d.	n.d.
BaO	none	trace	n.d.	n.d.	n.d.
SrO	trace	0.07	n.d.	n.d.	n.d.
MoO_3	trace	0.01	n.d.	n.d.	n.d.
	99.97	100.08	99.98	100.56	99.96
Sp. gr.		2.851	2.956*	2.859*	2.850*
at			24°	24°	28°

NORMS.

	1	2	3	4	5
Q	2.16	....	2.04	4.80	0.18
Or	2.78	3.34	2.22	2.78	3.34
Ab	18.34	20.96	20.44	21.13	22.53
An	25.30	30.85	23.07	23.63	21.68
Di	20.83	24.78	24.23	25.69	21.70
Hy	21.06	17.00	18.43	12.67	29.26
Ol	....	4.67	....	....	....
Mt.	2.78	2.32	2.55	1.62	2.55
Il	5.17	4.71	5.93	6.38	5.17
Ap	0.67	1.01	0.67	0.67	0.67

1. Labradorite basalt (pahoehoe), III.5.4.(4)5. Lava of 1894 (?), Floor of crater, Kilauea. Ferguson analyst. Day and Shepherd, Bull. Geol. Soc. Am., **24**, 586, 1913.

2. Labradorite basalt, III.5.3(4).4. Dipped from crater, 1911, Halemaumau, Kilauea. Ferguson analyst. Day and Shepherd, op. cit. 586. Sp. gr. by Tilley, op. cit., p. 279.
3. Labradorite basalt (aa), III.5."4.(4)5. Flow of 1920, Mauna Iki, Kilauea. Washington analyst.
4. Labradorite basalt (pahoehoe), III.(4)5."4.(4)5. Flow of 1920, Mauna Iki, Kilauea. Washington analyst.
5. Labradorite basalt (Pele's hair), III.5.3(4).(4)5. Collected 1920, 2½ miles S.W. of Halemaumau, Kilauea. Washington analyst.

The five analyses are all much alike, the only difference of note being the higher magnesia and lower lime in Ferguson's analyses as compared with mine. Both of us, however, used the same methods and precipitated the calcium oxalate twice, so that the difference may be ascribed to a slight change in the composition of the magma rather than to differences in analytical procedure. As between the aa and the pahoehoe of 1920 the iron of the former seems to have undergone a slight oxidation, but the difference is very small. This matter will be discussed presently. The small amounts of chromium, nickel, and molybdenum found by Ferguson are of interest; heretofore molybdenum has been found only in the more siliceous rocks.[22] The reactions that Ferguson obtained for this element, which I saw, were marked and decisive. Ferguson looked for it in a number of other rocks, mostly sodic, but without success. The presence of both chlorine and sulphur in these lavas is of interest, inasmuch as chlorine (hydrogen chloride), sulphur vapor, and sulphur dioxide have been found in the gases of Kilauea and Mauna Loa, chlorine being present in the smaller amount.[23]

These recent lavas of Kilauea resemble in chemical composition the older labradorite basalt described above, although the composition of the specimens that Ferguson analysed is transitional to the olivine basalt type.

Picrite-basalt.—The only known occurrence of this type among the recent lavas of Kilauea is the so-called Nanawale flow of 1840, in Puna, east of the main crater.

[22] W. F. Hillebrand, this Journal, 6, 216, 1898. J. B. Ferguson, ibid., 37, 399, 1914.

[23] E. S. Shepherd, Bull. Hawaiian Volc. Observ., 7, 94, 1919; 8, 66, 1920; 9, 83, 1921.

The lower part of this flow is aa. The explosion caused by the lava entering the sea formed two hills of volcanic sand on the shore; this sand consists partly of grains of yellow olivine which has been analysed by Aurousseau.[24] Cross's[25] description of this lava applies to my specimens.

The rock is highly phyric with abundant bright yellow phenocrysts of olivine, up to 1 centimeter in diameter, in a dark gray, densely aphanitic groundmass. There are no other phenocrysts. The abundant and irregular vesicles contain no minerals. Microscopically the groundmass is very fine-grained, composed of very small grains of colorless augite, small and thin tables of rather calcic labradorite in less amount, and some grains of magnetite. There is very little glass or dusty black interstitial matter, and the rock is almost holocrystalline. Steiger's analysis of this basalt is given in Table II, where the close chemical resemblance between this recent lava and the earlier picrite-basalts of Kilauea will be noted.

To sum up the chief petrological characters of Kilauea; the older lavas belong to three types, olivine-free labradorite basalt, intermediate olivine basalt, and highly olivinic picrite-basalt, the abundance of which is about in this order. The recent lavas appear to be more uniform, the greater number being of labradorite basalt, with few of picrite-basalt, and the intermediate olivine basalt being apparently unrepresented or at least comparatively very rare. The lavas before the eruption of 1789 show considerable variety, as in silica from 51.77 to 46.50 per cent., but those since then are more uniform, the silica percentage varying from 50.63 to 47.25.

The General Petrology of Hawaii.

Relative ages of the volcanoes.—There is some uncertainty regarding the exact order of succession of the five main centers of eruption on Hawaii. All authorities are agreed that Kohala is the oldest volcano, this opinion being based on the ridge-like form of the mountain (which may be explained as due to eruption from a fissure or, as I think more probable, as the remains of a huge

[24] Aurousseau and Merwin, this Journal, 6, 1923.
[25] W. Cross, U. S. Geol. Survey Prof. Paper 88, 43, 1915.

crater); the profound erosion that it has undergone; the lack of fresh ejectamenta and the generally worn condition of the comparatively few parasitic cinder cones; and the superposition of the flows from Mauna Kea over the Kohala lavas. A connection between Haleakala (on Maui) and Kohala is suggested by Powers.[26]

There is general concordance of opinion that Mauna Kea and Hualalai are next in age to Kohala, and it appears to be generally believed that Mauna Kea is older than Hualalai.[27] This is indicated by the greater size of Mauna Kea and by the occurrence of modern eruptions at Hualalai but none at Kea.

Mauna Loa and Kilauea are unquestionably the latest volcanoes on Hawaii and are the only two in activity at present. There is, however, some doubt as to which is the older and what are their relations. As far back as the Wilkes expedition in 1840 J. D. Dana[28] noted that the volcanoes of the Hawaiian Islands were situated along two slightly curving parallel lines, with a northwest-southeast trend. On the eastern (Kea) line are Kohala and Mauna Kea and on the western (Loa) line are Hualalai and Mauna Loa. At this time, and for many years after, Dana thought that Kilauea was connected with Mauna Loa as a subsidiary vent situated on a radial fissure. E. S. Dana's study of the lavas of the two volcanoes, which showed a great similarity between them, lent support to this hypothesis. Later, however, Dana abandoned this belief and concluded that Mauna Loa and Kilauea are independent, this view being based chiefly on the apparent independence in the activity of the two centers and on the position of the Kilauea crater on the eastern Kohala-Kea line. This last view had previously been held by Brigham, Dutton, Green, and others,[29] and is now generally accepted. Daly[30] holds a slightly different view; that Kilauea is independent of Mauna Loa, and is fed from a laccolith that is "an off-

[26] S. Powers, Notes on Hawaiian petrology, this Journal, 50, 266, 1920.

[27] J. D. Dana, Characteristics of Volcanoes, 259, 1890; T. A. Jaggar, The Cross of Hawaii, separate from the 1912 Annual of the Honolulu Chamber of Commerce.

[28] J. D. Dana, Characteristics of Volcanoes, 260, 1890.

[29] G. Mercalli, I Vulcani Attivi della Terra, 334, Milan, 1907.

[30] R. A. Daly, The nature of volcanic action, Proc. Am. Acad. Arts and Sci., 47, 112, 1911.

shoot of the main Pacific fissure which located the Hawaiian archipelago.'' Dr. Jaggar, who, as Director of the Hawaiian Volcano Observatory for many years, has had especially excellent opportunity to study the two volcanoes, believes that Kilauea is older than Mauna Loa and that there is connection between the two, shown by alternation of their eruptive periods rather than by their synchronism.[31] He says that there ''is little doubt that the Mauna Loa and Kilauea columns are connected and that the connection is that of correlated gas vents and not that of hydrostatic siphon tubes.'' He regards ''Kilauea as a decadent volcano of older origin, acting as a gas pressure-gauge adjacent to and partially buried by the young and vigorous Mauna Loa.'' Dr. Noble, in his report on the older lavas of Mauna Loa, states his belief that the pre-Pahala lavas underlie Kilauea and Puna, and that possibly the flows in the crater walls of Kilauea are pre-Pahala. It would appear, on this interpretation, that the pre-Pahala flows are common to both Mauna Loa and to Kilauea.

For present purposes I accept Jaggar's view and assume that the order of beginning of activity of the Hawaii volcanoes was: Kohala (followed by a probably long interval of repose), Mauna Kea, Hualalai, Kilauea, and Mauna Loa. The question of the independence of or connection between Mauna Loa and Kilauea will be discussed in connection with the averages.

General Petrographic Characters.—The lavas of Hawaii are petrographically very simple and on the whole very uniform and the minerals that compose them are few. By far the greater part of the igneous mass is of andesite and basalt, which together make up at least 75 per cent of the lavas. These comprise oligoclase andesite, andesine andesite, oligoclase basalt, andesine basalt, and labradorite basalt. These are mostly without olivine or with only the small amount of olivine that has been produced by the Bowen-Andersen effect and that has remained unabsorbed. Olivine-free labradorite basalt is the most abundant type, followed in abundance by andesine basalt and this by oligoclase andesite. There is a comparatively small amount of olivine-labradorite basalt and less

[31] T. A. Jaggar, this Journal, 40, 639, 1915 and 43, 288, 1917.

olivine-oligoclase andesite, which contain from 10 to 20 per cent of olivine, and picrite-basalt (with about 50 per cent of olivine) occurs in probably somewhat less quantity. Trachyte is known to occur at but two localities, although much more of this rock may be buried under later flows, and at Kohala there is a little·oligoclasite. No quartz-bearing, nephelite-bearing, nor melilite-bearing rocks are known to occur on Hawaii.

Plagioclase feldspar, which is mostly labradorite with less andesine and still less oligoclase, is the most abundant mineral, although there is almost as much augite. This pyroxene seems to be of fairly uniform composition and is dominantly diopsidic (magnesic) rather than hedenbergitic to judge from an analysis of an augite from Haleakala[32] and from the norms of the analyses of the Hawaiian lavas; the ratio of magnesia to ferrous oxide varying from 2 : 1 to 5 : 1. The pyroxene carries little or none of the acmite molecule, and acmite itself is found only in the rare trachyte. Olivine is subordinate to augite in quantity, although small amounts of it occur in many basalts and it is very prominent in a few of the flows, such as those of picrite-basalt. The olivine also is highly magnesic, to judge from the composition of that of the 1852 Mauna Loa flow[33] and from two analyses by Aurosseau of olivines from the ejected blocks and from the Nanawale (1840) flow of Kilauea.[34] A little orthoclase appears as residual base in some of the lavas but is present in appreciable quantity only in the trachyte, where it is highly sodic. Orthorhombic pyroxene, hypersthene, is very rare, occurring only in the pre-Pahala lavas and some of the recent Mauna Loa flows, such as that of 1880-81. These contain an excess of silica, shown by the presence of quartz in the norm, and this distribution is in accord with the fairly well-known tendency of the orthorhombic pyroxenes to occur in the more silicic rather than in the less silicic effusive rocks. As has been said, none of the lavas of Hawaii contain nephelite, leucite, or melilite, and also hornblende and biotite are lacking. Neither quartz, tridymite, nor cristobalite was seen by either Cross or myself in any of

[32] Washington and Merwin, this Journal, 3, 117, 1922.
[33] R. A. Daly, Jour. Geol., 19, 295, 1911. Analysis by Steiger.
[34] Aurousseau and Merwin, this Journal, 6, 1923.

our specimens of the lavas of Hawaii, although some of them show a decided excess of silica in the norm.

In texture the lavas of Hawaii tend to be fine-grained and aphyric. There are a few rather coarse ophitic forms, such as the basalts of Waipio Gulch and above Laupahoehoe on Mauna Kea, blocks on the summit of Hualalai, and some of the early blocks of Kilauea. Phenocrysts are almost only of two minerals, of labradorite in the feldspar phyric basalts, as at Kohala, Mauna Kea, and Hualalai, and of olivine, which forms very prominent phenocrysts in the olivine basalts and picrite-basalts of all the volcanoes of the island. Indeed, olivine phenocrysts are so abundant in some of the picrite-basalts that the rock looks, at first glance, like an olivine gabbro, as at the Uwekahuna mass. It is characteristic of the lavas of Hawaii that augite rarely forms phenocrysts and then generally small, inconspicuous and sparse ones. In the Hawaiian lavas augite (and magnetite) appear to belong generally to the later or last phases of crystallization, in contra-distinction to the feldspars and olivine. Cross[35] has already pointed out that there is generally more modal than normative olivine or, as he puts it, "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." This characteristic of the Hawaiian lavas is due to, and is a striking example of, the so-called Bowen-Andersen effect which has been so often mentioned in preceding pages.

We have little information, detailed or general, as to the succession of the lavas at the various centers; my observations were too limited to permit me to state anything very definite except as to what are the most recent outflows. At Mauna Loa we have the observations of Clark and Noble on the succession of the older lavas but, apart from this, little attention has been paid to the older lavas and their succession at any of the volcanoes. This is an aspect of Hawaiian petrology that should well repay study in the field. Nor have we very definite knowledge of the relative abundance of the various kinds of lava at the several volcanoes. So far as my observations and

[35] W. Cross, U. S. Geol. Survey, Prof. Paper 88, 12, 53, 55, 1915.

those of others permit me to judge, the chief petrographic characters of the different volcanoes on Hawaii are as follows.

At Kohala we knew only the flows that appear at the surface, especially on the west slope; the earlier flows that may be exposed in the steep walls of the deep erosion ravines of the northeast side, as in the upper parts of the Polulu, Honokane, Waimanu, and Waipio Valleys, have not yet been studied. The true relations of the trachyte flows of Puu Waawaa and Puu Anahulu to Kohala are also unknown, although it appears to be probable that the latter, at least, are connected with Kohala rather than with Hualalai. If this be true trachytic lavas are probably among the earliest in the upper accessible part of this volcano. Disregarding these, aphyric labradorite basalt, such as that at Waiaka Gulch and Kaala, is probably one of the earliest lavas, with some feldspar phyric forms as later flows of the same magma. Oligoclase andesite and olivine-oligoclase andesite form most of the later known flows and the latter especially composes some, at least, of the small parasitic cones, such as Puu Kawaiwai and Puu Lahikiola, which are almost certainly among the most recent outbursts. In relative amount these oligoclase andesites seem to be much more abundant than basaltic lavas, a feature of this volcano which has been mentioned by most observers from Dutton onward. There is no picrite-basalt and little olivine-labradorite basalt at Kohala.

Of Mauna Kea not much can be said, as the lavas of this immense volcano are very little known and I had no opportunity to study the succession of the flows in the gulches along the eastern slope. It would appear that labradorite basalt and some andesine basalt, with and without olivine, form the most abundant and the earliest lavas and with these are associated comparatively few flows of picrite-basalt, although the relations between them are unknown. Andesine andesite, mostly without or with little olivine, appears to be the latest lava to be extruded, if we may judge from the occurrence of rather fresh flows of this at sea level at Laupahoehoe and on the summit. Oligoclase andesite is not known from Mauna Kea.

Of the relations at Hualalai we are still more ignorant.

The Puu Waawaa trachyte obsidian cone is earlier than some of the Hualalai flows but its connection with Hualalai is not established. The lavas that are known to form Hualalai are decidedly uniform, more so than at any other volcano on Hawaii, and they are mostly olivine-labradorite basalt. The texture of some of the early flows, now hidden from view, is gabbroic and others are phyric with feldspar phenocrysts, as is indicated by ejected blocks at the summit. The latest flows, as that of 1801, are much richer in olivine than the earlier ones. The 1801 lava carries many xenoliths of dunite, lherzolite, etc., which are also found in the olivine-labradorite basalt at Mauna Kea.

At Mauna Loa we have some definite information regarding the earliest flows, thanks to the labors of Clark and Noble. The earliest known, the pre-Pahala series, are mostly of labradorite basalt wanting or poor in olivine and with an excess of normative silica. These were followed by the much less abundant andesine basalts of the Pahala series which contain some olivine and these by the dominantly picrite-basalt flows of the post-Pahala, in which olivine makes up about one-half of the rock. These merge into the Mokuaweoweo crater-wall flows which appear to be composed of the same or similar types, but as to whose succession we know nothing. Little is known of the recent historic flows but two of the types of the earlier lavas occur among them, olivine-free andesine basalt, with normative excess silica, being the most abundant, picrite-basalt being less so, and the intermediate type of olivine-basalt being apparently rare.

The earlier flows at Kilauea deserve much more study than they have received, but they seem to be mostly of labradorite basalt, the greater part without and some with olivine, and a few flows of picrite-basalt also belong to this period. The recent flows are very preponderantly of labradorite basalt, usually without essential olivine, and there is very little picrite-basalt, as in the Nanawale (1840) flow. The present-day lavas of Halemaumau and parasitic side-cones as Mauna Iki are very uniform in composition.

The differentiation on the Island of Hawaii has been very moderate and simple and it has yielded few extreme or aberrant types, such as the two occurrences of trachyte

The order of succession is not the same at the various volcanoes but, leaving this time-element aside, the various differentiated rock types form a strictly serial progression, from the highly salic and domalkalic oligoclasite of Kohala, through lavas with increasingly more calcic plagioclase and increase in the amount of augite to labradorite basalt, and with the appearance of essential olivine through increasingly olivinic basalts to picrite-basalt and the lherzolite and dunite of the xenoliths of Mauna Kea and Hualalai. Apart from the trachyte, whose relations to the other lavas we do not know, there has been no splitting off of alkalic sub-magmas with nephelite or acmite and, on the other hand, there has been no such increase in silicity sufficient to produce quartz-bearing rocks, although some of the lavas show an excess of silica, the potential quartz in these being occult. It is also worthy of note that the only purely or almost purely feldspathic lavas are toward the alkalic end of the series, shown in the oligoclasite and trachyte, but that there is no purely feldspathic lava composed of labradorite or even of andesine.

Cross[36] has already called attention to the general simplicity of the differentiation on Hawaii and, indeed, on all the Hawaiian Islands, but a fuller treatment of this aspect of the petrology of the islands must await a later paper of the series.

General Chemical Characters.—The general chemical characters of the lavas may be studied from the averages of the analyses of the lavas at the various volcanoes, which are given in Table IV, the averages being based on only the superior and most recent analyses given in the preceding tables. The averages for Mauna Kea, Hualalai, Mauna Loa, and Kilauea are those of all of the analyses of their rocks that have been made by Steiger, Hillebrand, Ferguson, Bailey, and myself. The older analyses are disregarded. For Kohala I have used my analyses and the three by Lyons, except that his figures for the iron oxides are omitted. As there is uncertainty regarding the relations of the trachytic rocks of Puu Waawaa and Puu Anahulu, that is, whether they belong to Kohala or to Hualalai, I have calculated two averages

[36] W. Cross, op. cit., 91-93.

for each of these two volcanoes; in one of these the two complete analyses of the trachytes are reckoned in and in the other they are omitted.

TABLE IV.—Hawaiian Averages.

	1	2	3	4	5	6	7	8
SiO_2	51.52	49.50	48.69	51.05	47.21	49.58	50.20	49.73
Al_2O_3 ...	16.25	15.87	14.90	15.53	14.66	11.97	10.78	13.71
Fe_2O_3 ...	3.33	3.39	3.79	3.13	3.17	1.63	2.97	2.92
FeO	7.07	8.31	8.14	7.11	9.00	9.96	9.02	8.64
MgO ...	4.34	4.99	7.19	6.27	8.19	11.04	11.27	8.27
CaO	7.11	8.13	9.34	8.15	10.55	10.09	9.48	9.10
Na_2O ...	4.68	4.17	3.47	4.19	3.04	2.15	2.18	3.16
K_2O	1.92	1.40	1.29	1.84	0.80	0.42	0.41	1.02
TiO_2	2.81	3.20	2.55	2.18	2.79	2.73	3.35	2.84
P_2O_5	0.83	0.92	0.48	0.42	0.49	0.31	0.23	0.48
MnO	0.14	0.12	0.16	0.13	0.10	0.12	0.11	0.13
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Sp. Gr. ..	2.843	2.854	2.969	2.978	3.021	2.932	2.953	2.940

NORMS.

	1	2	3	4	5	6	7	8
Q	....	....	....	....	....	....	1.50	....
Or	11.12	8.34	7.98	11.12	5.00	2.22	2.22	6.12
Ab	39.82	35.63	29.34	33.01	24.89	18.34	18.34	26.72
An	17.51	20.29	21.13	17.79	23.91	21.96	18.63	20.02
Ne	....	....	....	1.42	0.43	....	....	....
Di	9.92	11.74	18.17	16.13	20.18	21.07	21.67	17.43
Hy	3.06	0.56	....	....	....	23.06	26.38	12.53
Ol	6.51	9.90	12.28	10.88	14.56	5.34	....	6.44
Mt	4.87	4.87	5.57	4.41	4.64	2.32	4.41	4.18
Il	5.32	6.08	4.86	4.26	5.32	5.17	6.38	5.32
Ap	2.02	2.02	1.01	1.01	1.34	0.67	0.67	1.34

1. Kohala, with trachyte, II″.5.(2)3.4. 14 analyses.
2. Kohala, without trachyte, II(III).5.3.4. 12 analyses.
3. Mauna Kea, ″III.5.3.4. 12 analyses.
4. Hualalai, with trachyte, II(III).5.3″.4. 8 analyses.
5. Hualalai, without trachyte, III.5.3(4).4(5). 6 analyses.
6. Kilauea, III″.5.″4.(4)5. 13 analyses.
7. Mauna Loa, III″.5.(3)4.(4)5. 11 analyses.
8. Hawaii, III.5.3.4″. 56 analyses.

These averages present a remarkably regular serial progression, which corresponds with the assumed order of eruptive activity. This is also brought out very clearly in the norms and symbols.

Cross has already pointed out the uncertain relations of the trachytes of Puu Waawaa and the Puu Anahulu scarp,[37] and he suggests that the Anahulu flows are possibly connected with Kohala, the cone of Puu Waawaa, more probably with Hualalai. That the lavas of Kohala have marked alkalic affinities is shown by the abundance of oligoclase andesite and the occurrence of oligoclasite (described by Lyons) and, indeed by their average composition and symbol, shown in No. 2 above. If we assume that these trachytes belong to the Kohala center the average No. 1 heads the list and differs strikingly from the others in its higher silica, much higher alkalies and lower magnesia; oddly enough, if the decidedly alkalic character of the average is considered, it is abnormally high in phosphoric oxide. It is also the highest in alumina and the lowest in lime and total iron oxides (except No. 4). Average No. 2 (without the trachytes) shows all these features but not quite so well. On the whole, I believe that the Anahulu trachyte (less probably that of Puu Waawaa) belongs to the Kohala mass and that No. 1 represents its average better than does No. 2. Search for other occurrences of trachytic lavas on the broad Waimea Plateau and near the west foot of the Kohala ridge (as suggested by Cross) would be a promising bit of work for some geologist. The lavas of Kohala present the widest range in composition of all the volcanoes of Hawaii, especially if trachytic rocks occur there. It is noteworthy that highly olivinic lavas, such as the picrite-basalts of Kea, Loa, Hualalai, and Kilauea, are not present at Kohala.

The Mauna Kea lavas are decidedly more uniform than those of Kohala; silica reaches about 52 per cent in only one rock, and the great majority have silica between about 50 and 46.5 per cent, and high soda (that is, above 4 per cent) is rare. The main characters are well shown in the average and espcially in the tendency of the class to be dosalic as seen in the symbol.

The Hualalai average with trachyte (No. 4) resembles closely that of Kohala without trachyte (No. 2), but that of Hualalai without trachyte (No. 5) closely resembles that of Mauna Kea. Both of their norms show especially a very marked increase in olivine over the Kohala aver-

[37] W. Cross, An occurrence of trachyte on the island of Hawaii, Jour. Geol., 12, 516, 1904; Lavas of Hawaii and their relations, U. S. Geol. Survey, Prof. Paper 88, 35, 92, 1915.

age. Olivine rocks are common at Kea and Hualalai, and it will be recalled that both belong to the second, post-Kohala period of volcanicity. It is chiefly these considerations that lead me to doubt the genetic connection of the trachytes with Hualalai.

With the averages for Kilauea and Mauna Loa we meet with a third type of average. In these two, although the silica remains at about 50 per cent, as in the Kea and Hualalai averages, there is a very notable drop in alumina, soda, and potash, and an equally well-marked rise in magnesia. There seems to be a slight rise in iron oxides and in lime, but these are not very decisive, and phosphoric oxide has greatly decreased, especially as compared with the Kohala average. Indeed, the averages for Kilauea and Mauna Loa resemble each other so closely and differ so markedly from the other averages that a connection between the two volcanoes and a community of origin for their lavas is clearly indicated.

The average for the whole Island of Hawaii most resembles that for Mauna Kea, and nearly as well that for Hualalai without trachyte. The general course of differentiation at Hawaii would thus appear to have been somewhat as follows.

It is possible that the earliest eruptions at the top of this already very high submarine cone formed an island of highly alkalic, trachytic lavas, a suggestion already made by Cross. This would be quite analogous to the rather large Sardinian volcanoes of Monte Ferru and Monte Arci, which began with very alkalic lavas (rhyolite, trachyte, and phonolite), followed by andesitic rocks, and closed with vast floods of basalt. The objection raised by Cross that no inclusions of trachyte are found in the lavas of the island is of little weight in view of the absence of such inclusions (according to my observations) in the basalts of the Sardinian volcanoes, at which erosion has so clearly exposed the structure of the volcano that there can be no doubt as to the course of the general succession of the lava types.

The general course of the succession on the Island of Hawaii as a whole is well shown by the averages given in Table IV and especially by their norms, from which last both the general chemical and the mineral characters may be learned. We may here omit consideration of the averages and norms Nos. 2 and 4, namely those of Kohala without trachyte and of Hualalai with trachyte. There is a strictly serial progression from Kohala to Mauna Loa which corresponds well with the general succession of these volcanoes in time and also with their division into three groups; Kohala, Mauna Kea and Hualalai, and Kilauea and Mauna Loa. The ratio of salic to femic normative minerals drops quite regularly and still more regular is the progressive change in the average feldspar, whether orthoclase be reckoned in with albite or not. The average feldspar at Kohala is oligoclase, about Ab_3An_1, at Mauna Kea it is andesine (Ab_3An_2), and at Hualalai a more calcic andesine (Ab_5An_4); at Kilauea and Mauna Loa andesine-labradorite (about Ab_1An_1). Similarly the amount of diopside (which includes both magnesium diopside and hedenbergite) increases quite regularly from Kohala to Mauna Loa, some normative hypersthene accompanying it, in small amount at Kohala and in large amounts at Kilauea and Mauna Loa. The quantity of normative olivine increases regularly from Kohala, through Mauna Kea, to a maximum at Hualalai, then drops to a low figure at Kilauea, and is not present in the Mauna Loa average, being replaced by normative quartz in this. Magnetite and ilmenite show little variation, but apatite falls from a maximum at Kohala, in the rocks of which the amount of P_2O_5 is about three times that in the average rock of the earth, to a minimum at Kilauea and Mauna Loa.

The chemical succession at the different volcanoes is indicated by that of the rock types already described. At Kohala, if we disregard the trachyte of Puu Anahulu, there has been a progressive increase in silica, alumina, and the alkalies, that is in the salic constituents, and decrease in lime, magnesia, and iron oxides. Phosphoric oxide, however, is much higher in the latest lavas at Kohala than in the earlier ones.

After a probably rather long period of quiescence, although the small parasitic cones at Kohala seem to have been active into quite recent time, there began the Kea-Hualalai period, Kea almost certainly preceding Hualalai. At Mauna Kea the lavas are somewhat less diverse chemically than at Kohala, but there seems to have been here also a progressive increase in salic constituents, especially soda, and decrease in line, magnesia, and iron oxides. At Hualalai, on the other hand, although its lavas are very uniform and their average is like that of Mauna Kea, the chemical progression is the reverse, as the older flows (shown by elected blocks) are higher in silica, and alumina, and much lower in magnesia than the later flows, there being little difference in the relative amounts of the alkalies, lime, and iron oxides. The only known modern flow is especially low in alumina and high in magnesia which corresponds to its high modal content in olivine. At Kilauea there is little evidence of progressive change in chemical composition. Both the early and the recent labradorite basalts are quite uniform, although the earlier ones have somewhat higher silica and hence more normative quartz than the later ones, but both series show intercalated flows of picrite-basalt low in silica and lime and very high in magnesia. At Mauna Loa there is a definite known change in composition shown by the earliest flows from labradorite basalts of fairly average composition to the picrite-basalts with their low silica, alumina, and lime and very high magnesia. Among the more recent lavas there seems to have been little regular change, although too little is known of these lavas to enable us to speak with assurance. The modern lavas, however, are much higher in silica than the corresponding basalts of the Pahala period, in this respect the change being the reverse of that seen at Kilauea. With these highly quaric lavas also occur some that are picrite and with the concomitant chemical features.

It may not be out of place here to discuss very briefly some suggestions that have been made by Daly regarding the origin of the trachytes and the picrite-basalts of Hawaii, although fuller treatment must be reserved until the lavas of all the islands have been studied and described.

In accordance with his well-known hypothesis of the derivation of alkalic rocks from basaltic magmas by desilication brought about by the absorption of limestone, Daly[38] suggests that the trachytes of Hawaii are produced by the "solution of coral or foraminiferal limestones such as are known to be interbedded with the older lavas of the archipelago." Although I agree with Daly

[38] R. A. Daly, Magmatic differentiation in Hawaii, Jour. Geol., 19, 309, 1911.

in the view that these alkalic lavas as well as the oligoclasite of Kohala, are connected genetically with the basaltic rocks of the Hawaiian volcanoes, I am quite at one with Cross[39] in seeing no grounds for his main hypothesis in the geology or petrology of Hawaii. Leaving out of consideration here the chemical and physico-chemical aspects of the problem, Cross has pointed out the inadequacy in amount of coral reefs on the islands and the difficulty of conceiving how such thin and superficial calcareous deposits as may have existed could bring about such profound changes in these large masses of magma. I may add that if the magma had passed through such masses of coral rock as would have been necessary to trachytize the basalt, some remnants of them surely would have been left unabsorbed or undissolved. But not a fragment, so far as I know, of limestone or coralline inclusions has ever been found in Hawaiian lavas, even by Clark and Noble in the earliest lavas of Mauna Loa about the Pahala region. Whereas at the Italian volcanoes, Vesuvius, Bracciano, and Monte Vico and the Monti Cimini, limestone inclusions, derived from the subjacent limestone platform and often much metamorphosed, are very common. Furthermore, the table of the averages of the Hawaiian volcanoes shows that the average amount of lime remains fairly constant, varying in the averages only from 7.11 to 10.55 and remaining much within these limits in the great majority of the lavas of all the volcanoes. Indeed lime is one of the least variable constituents of all these Hawaiian lavas—a feature which would not be expected were the absorption of limestone one of the most important causes of differentiation. The course of differentiation, as we have seen, seems to be best marked by changes in the amounts of magnesia and alkalies. The evidence of the lavas of Hawaii would, then, appear to be adverse to Daly's hypothesis.

Daly[40] also suggests the hypothesis that the origin of the highly olivinic picrite-basalts is to be found in a "mixture of a large amount of the ferromagnesian and cafemic (calcium-iron-magnesium) constituents of the basalt with the average basalt," and he refers the place of origin of the olivine crystals (if I understand him

[39] W. Cross, U. S. Geol. Survey, Prof. Paper 88, 90, 1915.
[40] R. A. Daly, Jour. Geol., 19, 305, 314, 1911.

aright) and the ultrabasic xenoliths to great depths in the volcanoes, only to reach the surface through low lateral extrusions of lava.

Two points would seem to have been ignored by Daly in this suggestion of a very deep-seated origin for the ultrabasic lavas and xenoliths. One is that the Hawaiian volcanoes as we see them are but the upper parts of gigantic cones, some 25,000 to 30,000 feet high in all, so that the differences in level between the points of extrusion of the picrite-basalt and the summits are almost negligible and certainly insignificant if compared with the total heights of the volcanoes. Furhermore, I doubt that any such differences in height of extrusion point for the picritic basalts and the ordinary basalts and salic andesite can be established. We find such flows alternating with each other at several of the volcanoes, as at Mauna Kea, Mauna Loa, and Kilauea. Picrite-basalt in abundance was poured out at the summit of Mauna Loa, as well as lower down, and the same highly femic type of lava occurs at Kilauea 10,000 feet below the summit of Mauna Loa. Also at Kohala the only lavas that are specially rich in olivine are those of the most recent parasiic cones, and many of these lavas issued from points well up the mountain slope. Again, at Mauna Kea the same type of lava has poured out in the last stages of this volcano's activity from a point at the sea level (Laupahoehoe) and from the summit 13,000 feet above.

The very femic xenoliths appear to be present only in lavas that are very femic and rich in olivine, so far as can be judged at present from my studies and from the observations of others, whereas on Daly's hypothesis of their origin and their connection with alkalic rocks one would expect to find them present in the trachytes or the oligoclase andesites, or that the eruption of the lavas that carry them would be uniformly preceded (or followed) by extrusions of such more alkalic lavas, neither of which conditions is found to exist.

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