

PETROLOGY OF THE HAWAIIAN ISLANDS: V. THE  
LEEWARD ISLANDS.

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INTRODUCTION.

In previous papers<sup>1</sup> there have been published petrographical descriptions and chemical analyses of the lavas of the Island of Hawaii, the first installments of a series descriptive of the lavas of the Hawaiian Islands, which, it is hoped, will eventually cover the whole group. Analyses have been, and are being, made of the lavas of the other islands, and the results of their study will appear from time to time. For information as to the classification of the andesitic and basaltic rocks that has been used in this paper, and for the use of certain petrographic terms, the reader is referred to pages 468-474 of the first paper.

The Leeward Hawaiian Islands<sup>2</sup> include about thirteen islets and shoals that extend for over one thousand miles northwest of Kauai, the most westerly of the main, large islands of the Hawaiian group. The eight or nine most westerly of these are small, and mostly uninhabited, islets and atolls, with shoals and reefs, while the four most easterly are higher. Counting from the west, these are: Gardner (170 feet high), La Pérouse Rock (120 feet) in French Frigates Shoal, Necker (260 feet), and Nihoa (895 feet). With these is included, for the purposes of this paper, the island of Niihau, near Kauai.

These small islands have been seldom visited or described by geologists, so that little is known in detail of their petrography. Möhle<sup>3</sup> studied a few specimens from Necker and Laysan, and Sidney Powers<sup>4</sup> has published brief notes on the lavas of Necker, Nihoa, and Niihau, which he visited in 1915. Neither of these authors communicates any chemical analysis. Prof. H. S. Palmer, under the auspices of the Bishop Museum

<sup>1</sup> Washington, this Journal, 5, 465, 1923; 6, 100, 1923; 6, 338, 1923; 6, 409, 1923. These will be referred to in the present paper as Petrol. Hawaii, I, II, III, and IV.

<sup>2</sup> Hitchcock, Hawaii and its volcanoes (2d ed.), Honolulu, 1911, p. 4; Bryan, Natural History of Hawaii, Honolulu, 1915, p. 93. See also Wetmore, Nat. Geog. Mag., 48, 77 (July), 1925 (chiefly ornithological).

<sup>3</sup> Möhle, Neu. Jahrb. Beil. Band 15, 90-93, 1902. Cf. W. Cross, U. S. Geol. Surv., Prof. Paper 88, 9, 1915.

<sup>4</sup> S. Powers, this Journal, 50, 257, 1920.

of Honolulu, visited the Leeward Islands in 1923, and it is expected that his report will appear in the near future.

We have studied specimens from Niihau and Nihoa, collected by Powers, and from Nihoa, Necker, La Pérouse, and Gardner, collected by Palmer. To their generosity we are much indebted and to them we would extend our thanks. Our thanks are also due to Mr. A. F. Judd and Dr. S. C. Ball, of the Bishop Museum, for permission to study and describe the rocks collected by Palmer.

#### NIIHAU ISLAND.

Niihau Island, which lies 17 miles west of Kauai, "is in line with the islands \* \* \* \* forming the leeward chain" (Bryan), and may be connected with them tectonically,<sup>5</sup> although it is mentioned usually in connection with Kauai, of which Dana<sup>6</sup> regards it as the remnant of a second volcanic cone.

Niihau<sup>7</sup> is about 28 kilometers long, from southwest to northeast, and 13 kilometers across at its widest part, having an area of about 252 square kilometers. Near the center of the eastern side is an elevated area, called Kaeo, the western remnant of the original cone; this is about 423 meters high and is precipitous on the sea face toward Kauai. Surrounding this, on the north, west, and southwest, is a low plain, of coralline origin, partly covered by basaltic flows, and with small parasitic cones and pit-craters here and there. "Kawaihoa Crater and the (adjacent) islands Lehua and Kaula are composed of tuff of unknown composition."

The lavas of Niihau are basaltic, most of them labradorite basalt with very notable amounts of olivine. A few are andesine basalt, with comparatively small amounts of olivine, and one specimen is of a limburgitic basalt. In these respects the Niihau lavas much resemble those of the neighboring island of Kauai,<sup>8</sup> although at Niihau nephelite-melilite basalt and oligoclase gabbro, which occur on Kauai, are not represented among the specimens studied by us. Hinds<sup>8a</sup> has recently

<sup>5</sup> Powers (Bull. Geol. Soc. America, 28, 501-514, 1917) does not discuss this point.

<sup>6</sup> Dana, J. D., Characteristics of Volcanoes, p. 312, New York, 1890.

<sup>7</sup> Hitchcock, op. cit., p. 10; Bryan, op. cit., p. 101; Powers, this Journal, 50, 257, 1920 (map).

<sup>8</sup> Möhle, Neu. Jahrb. Beil. Band 15, 90, 1902; Cross, U. S. Geol. Surv. Prof. Paper 88, 9, 1915; Powers, this Journal, 50, 259, 1920.

<sup>8a</sup> Hinds, Jour. Geol., 33, 534, 1925.

described a nephelite-melilite basalt collected by him on Niihau.

*Andesine basalt.* This basalt is represented by specimens from the Keanahui Valley, in the center of the Kao cone remnant. A specimen from "north of Kawaewae cone," near the southern end of the coralline platform, appears also to belong here.

This lava is dense and dark gray, with very few and small phenocrysts of augite, and fewer of olivine, in a dense aphanitic groundmass. The micro-texture is doleritic, the rock being made up of thin tables of andesine (about  $Ab_1An_1$ ), some large rounded grains of olivine, with brownish borders, many small grains of colorless augite, but no magnetite. There is much dusty, dark brown glass.

The analysis of this specimen (No. 1, Table I) is almost that of the average basalt of Daly,<sup>9</sup> but with slightly less  $Al_2O_3$  and alkalis, and slightly more MgO and  $TiO_2$ . The amount of modal olivine is much more than that shown in the norm, a feature that is usually met with in the lavas of the Hawaiian Islands, of Etna, and elsewhere.

*Olivine-labradorite basalt.* Most of the lavas of Niihau appear to be of this variety. We have studied especially specimens from Robinson's house, Kalaalau Valley, at the southern edge of the old cone; and from the small cones of Puuwai and Nonopapa, on the coralline platform.

These basalts, megascopically, are dark gray, almost black, fine-grained but not aphanitic, and generally aphyric, some showing a few phenocrysts of yellow olivine. The microtexture is typically doleritic, with many thin tables of labradorite (about  $Ab_1An_2$ ), intersertal grains of colorless augite, and rather large, rounded grains of olivine, which are perfectly fresh in almost all the specimens. Magnetite is generally absent, but a few grains are present in the specimen from Kalaalau Valley. These lavas are holocrystalline.

Three analyses of these olivine basalts are given in Table I (Nos. 2, 3, 4). These closely resemble each other in their  $SiO_2$  content, in the high ratio of FeO to  $Fe_2O_3$ , the high MgO and CaO, low alkalis, moderate  $TiO_2$ , and low  $P_2O_5$ . The amount of normative olivine is about 20 per cent, which appears to be about that seen in thin section.

*Limburgitic basalt.* An unusual type of basaltic lava is a specimen from a flow at Nonopapa Landing, at the south-

<sup>9</sup> Daly, *Igneous Rocks and their Origin*, 27, 1914.

west corner of the island. This may be a flow from the nearby Nonopapa Cone, but we have no information as to this. The lava is slightly brownish black, densely aphanitic, and wholly without phenocrysts. The microtexture is peculiar. Numerous very small (0.02-0.05 mm. long) and thin laths of plagioclase, about  $Ab_1An_2$ , are scattered through a very deep brown, almost opaque base, which consists, as seen under high powers, of dark brown mottled glass. There is not a single grain of either augite, olivine, or magnetite.

The analysis (No. 5, Table I) shows very low  $SiO_2$ , and high  $MgO$  and  $CaO$ , with not much  $Na_2O$ . In the norm is a notable amount of nephelite, so much that nephelite would have been present, along with much augite and olivine, were the rock holocrystalline. It is somewhat difficult to decide on a name for this lava. On the whole, however, it may be called limburgitic basalt, in spite of the presence of feldspar and the total absence of augite and olivine. This is justified as its analysis greatly resembles analyses of several limburgites, found in III.6.4.4 and in III.6.3.4, and because of the large quantity of highly sodic glass. In this connection it is interesting to note that Powers<sup>9a</sup> says that the presence of lavas containing nephelite "is suspected on or near Niihau," and that limburgite occurs on the neighboring large island of Kauai.

TABLE I. Lavas of Niihau Island.

	1	2	3	4	5
$SiO_2$ .....	49.73	46.44	46.86	46.36	43.46
$Al_2O_3$ .....	14.56	16.21	14.78	14.77	15.34
$Fe_2O_3$ .....	3.60	1.98	1.78	2.13	1.46
$FeO$ .....	8.55	7.85	9.85	8.82	8.17
$MgO$ .....	6.89	9.45	9.93	12.42	12.60
$CaO$ .....	9.66	11.21	10.98	10.84	11.39
$Na_2O$ .....	2.25	2.52	2.88	2.16	2.61
$K_2O$ .....	0.62	0.48	0.40	0.53	0.69
$H_2O+$ .....	1.24	0.54	0.13	0.57	0.59
$H_2O-$ .....	0.71	0.10	0.16	0.12	0.47
$TiO_2$ .....	2.21	2.11	1.67	1.31	2.21
$ZrO_2$ .....	n.d.	none	n.d.	n.d.	n.d.
$P_2O_5$ .....	0.22	0.21	0.20	0.19	0.48
S .....	n.d.	0.11	n.d.	n.d.	n.d.
$Cr_2O_3$ .....	n.d.	0.07	n.d.	n.d.	n.d.
$MnO$ .....	0.11	0.21	0.15	0.14	0.16
$BaO$ .....	n.d.	none	n.d.	n.d.	n.d.
	100.35	99.49	99.77	100.36	99.63

<sup>9a</sup> Powers, this Journal, 50, 272, 1920.

## NORMS.

	1	2	3	4	5
Or .....	3.34	2.78	2.22	2.34	3.89
Ab .....	27.77	20.96	19.39	14.15	5.76
An .....	23.35	31.69	26.13	28.91	28.08
Ne .....	....	....	2.84	2.27	8.80
Di .....	18.24	17.67	22.34	19.43	22.92
Hy .....	14.22	....	....	....	....
Ol .....	2.36	17.93	20.38	24.63	22.23
Mt .....	5.34	2.78	2.55	3.02	2.09
Il .....	4.28	3.95	3.19	2.43	4.26
Ap .....	0.67	0.67	0.34	0.34	1.01

1. Andesine basalt, III.5.3<sup>5</sup>. Keanahui Valley, Kaeo Cone. Keyes analyst.
2. Olivine-labradorite basalt, III.5.4.(4)5. Kalaalau Valley, Kaeo Cone. Keyes analyst.
3. Olivine-labradorite basalt, III.5.(3)4.5. Puuwai Cone. Keyes analyst.
4. Olivine-labradorite basalt, III.5.4.4-5. Nonopapa Cone. Washington analyst.
5. Limburgitic basalt, III.6."4.4. Nonopapa Landing. Keyes analyst.

NIHOA ISLAND.<sup>10</sup>

Nihoa Island<sup>11</sup> is about 200 kilometers northwest of Niihau. Its length, from east to west, is about 1.6 kilometers, and its greatest width is about 600 meters. It attains its greatest height, 895 feet (293 meters), at Miller Peak, at the northwest corner, and Tanager Peak, at the northeast corner, is 852 feet (279 meters) high. According to Hitchcock: "Nihoa is the small remaining portion of an extremely eroded and deeply submerged volcanic dome homologous with the larger islands. \* \* \* \* \* It seems to be a pair of clinkery pinnacles out of the inner core of a once mighty dome." "Perhaps 40 or 50" basaltic dikes cut the island "from end to end and from summit to base."

We have studied 13 specimens collected by Palmer and others from the Powers collection. They are all basaltic and are referred to the following varieties: andesine basalt, labradorite basalt, olivine basalt, and picrite-basalt. The specimens that were analysed come from the central, saddle-like part of the island.

*Andesine basalt.* The typical specimens of andesine basalt are medium gray, densely aphanitic, and entirely free from phenocrysts (aphyric). Vesicular forms are not represented. Thin sections show that the rock has a sub-trachytic texture and that it is composed in large part of very small and slender

<sup>10</sup> Also called Bird Island.

<sup>11</sup> Hitchcock, op. cit., p. 9; Bryan, op. cit., p. 98.

laths of much twinned feldspar, of about the composition  $Ab_3An_2$ . Interstitial between these, and in almost equal amount, are small, equant, anhedral grains of slightly brownish augite, with very rare and small grains of olivine. Some small grains of magnetite are present, and there is a little interstitial glass base. Megascopically and microscopically these lavas much resemble the aphyric andesine basalt of Mauna Kea and Hualalai on Hawaii, some of which they also closely resemble chemically.<sup>12</sup>

The chemical composition is shown by the analysis (No. 1, Table II) of a specimen from a dike, two feet wide, at the head of Camp Cove, on the south side of the island. It is very much like those of some of the andesine basalts of Hawaii mentioned above. The rather high  $TiO_2$  is one of the characteristics of these rocks. The presence of a little quartz in the norm (excess  $SiO_2$ ), although the rock contains some olivine, is also frequent in the lavas of Hawaii and, as was stated in previous papers, is ascribed, for the most part, to the so-called Bowen-Andersen effect,<sup>13</sup> although some, at least, of this apparent excess of silica is due to assumptions made in calculating the norm, more especially in assigning FeO to form magnetite and ilmenite, some of which ferrous molecules must modally enter pyroxene and thus be combined with silica.

*Labradorite basalt.* Rocks of this type are dark gray, but lighter than the preceding. They are not wholly aphanitic, as very minute crystals of feldspar and augite are visible, scattered through the dense rough groundmass. The specimen analysed shows numerous, small, miarolitic cavities, in which are small plates of feldspar and still smaller ones of tridymite, as was kindly determined by Dr. Bowen.

In thin section the texture is seen to be typically basaltic. There are many thick tables of highly twinned labradorite, of the average composition  $Ab_1An_1$ , with rather more abundant, interstitial, grains of pale brownish augite, some small anhedral olivines with narrow yellow borders, and few small grains of magnetite. There is a little dusty, light brownish glass base.

An analysis (No. 2, Table II) was made of a specimen from a flow near the center of the island, 200 feet above sea level. This greatly resembles that of the andesine basalt, the

<sup>12</sup> Washington, Petrol. Hawaii, I, 492 and II, 112.

<sup>13</sup> See Washington, Petrol. Hawaii, I, 469.

chief differences being the slightly lower  $\text{SiO}_2$  and  $\text{Na}_2\text{O}$ , and the higher  $\text{Al}_2\text{O}_3$  of No. 2. The rock resembles modally and chemically some aphyric basalts from Waiaka Gulch, Kohala, on Hawaii; Nuuanu Pali, on Oahu; and from Lanai Island.<sup>14</sup>

*Feldspar-phyric basalt.* This type of lava is rather light gray, and the specimen analysed is slightly vesicular, with the irregular, aa form of vesicle. In the densely aphanitic groundmass are many small laths, up to 2-3 mm. long, of dull white feldspar and fewer small, granular phenocrysts of dull brownish olivine.

In thin section the groundmass shows a doleritic texture, and is seen to be composed almost entirely of laths of labradorite and interstitial grains of brownish augite. A few small magnetite grains and some glass base are present, but there is no olivine in the groundmass. The evidently somewhat kaolinized feldspar phenocrysts have mostly fallen out in making the section, but the remaining fragments indicate a labradorite, slightly more anorthitic than the laths of the groundmass. The rather numerous, euhedral olivine phenocrysts are largely altered to a serpentinous substance. A few small phenocrysts of fresh, colorless augite are seen here and there.

An analysis was made of the least altered specimen, from a flow in the western part of the island, 350 feet above sea level, the results of which are shown in No. 3 of Table II. The composition is distinctly more femic than that of the two preceding rocks, and the higher  $\text{Fe}_2\text{O}_3$ : FeO ratio and the considerable amount of water are in accord with the slightly altered condition of the rock. Here also we meet with a slight excess of normative silica, in spite of the presence of modal olivine.

Lavas of very similar textural character, with many feldspar phenocrysts, occur at Kohala, Mauna Kea, and Hualalai, on Hawaii.<sup>15</sup> These are much alike chemically, but differ from the Nihoa rock in containing more  $\text{Al}_2\text{O}_3$  and CaO, and less MgO; although they are, in other respects, very like the lava of Nihoa.

*Picrite-basalt.* This, the most femic type, is represented by two or three specimens, with others that are intermediate between it and the preceding rocks. The specimen from Nihoa described by Powers<sup>16</sup> is, almost unquestionably, of this variety. The type is highly phyric. Many clear, glassy,

<sup>14</sup> Washington, *Petrol. Hawaii*, I, 485, 487.

<sup>15</sup> Washington, *Petrol. Hawaii*, I, 482, 496; II, 103.

<sup>16</sup> Powers, this *Journal*, 50, 257, 1920.

yellow olivine phenocrysts, up to about one-half centimeter long, lie in a densely aphanitic, rather dark gray groundmass. The specimen that was analysed is very fresh and contains some aa vesicles.

The microscope shows that the abundant groundmass is very fine grained, composed mostly of very small granules of colorless augite, with very small laths of feldspar, which ranges from  $Ab_1An_1$  to  $Ab_3An_2$ . There are also small grains and thin tables of "ore," the former being presumably of magnetite and the latter of ilmenite. It is noteworthy that these tables of ilmenite occur, in the lavas of the Leeward Islands, almost only in the picrite-basalts, where they are fairly constant, and that these rocks are generally rather higher in  $TiO_2$  than the average. The groundmass contains no olivine grains and apparently no glass. The phenocrysts are all of olivine, which forms large, very well-formed crystals, clear and colorless, without inclusions but with a thin yellow border. They show little evidence of corrosion.

The results of the analysis of the freshest specimen (from a flow) are shown in No. 4 of Table II, which differs from all the preceding in its somewhat lower  $SiO_2$  and  $CaO$ , and its much lower  $Al_2O_3$  and higher  $MgO$ ; the percentages of the other constituents not differing much from those in the other rocks. The large amounts of pyroxene and olivine in the norm are its most notable feature; these cause the classificatory position of the rock to fall in dofemane, as is true of the various picrite-basalts of Mauna Kea, Mauna Loa, and Kilauea, on Hawaii,<sup>17</sup> which the picrite-basalt of Nihoa much resembles, texturally, modally, and chemically. The modally similar picrite-basalt of Haleakala, on Maui,<sup>18</sup> is higher in  $CaO$  and lower in  $MgO$ . The Nihoa picrite-basalt also resembles a picrite basalt from near Lihue, on Kauai, (collected by Powers); although in this rock the very abundant olivine is mostly microphenocrystic. An analysis of this picrite-basalt (hitherto unpublished) is given in No. 5 of Table II. The rock, briefly described by Powers,<sup>19</sup> carries many dunitic xenoliths. Somewhat similar "olivine basalts" from Olokele Canyon on Kauai have been described by Cross,<sup>20</sup> but their analyses show somewhat less  $MgO$  than does the Nihoa rock.

<sup>17</sup> Washington, *Petrol. Hawaii*, I, 501; II, 117; and III, 344, 352.

<sup>18</sup> Cross, U. S. Geol. Survey, Prof. Paper 88, 29, 1915.

<sup>19</sup> Powers, this Journal, 50, 275, 1920.

<sup>20</sup> Cross, U. S. Geol. Survey, Prof. Paper 88, 10, 1915.

TABLE II. Lavas of Nihoa Island.

	I	2	3	4	5
SiO <sub>2</sub> .....	51.28	50.02	47.34	45.94	40.56
Al <sub>2</sub> O <sub>3</sub> .....	13.03	15.92	13.85	10.28	8.81
Fe <sub>2</sub> O <sub>3</sub> .....	2.72	2.21	5.38	3.78	5.98
FeO .....	9.11	8.57	6.43	9.17	8.23
MgO .....	6.57	7.34	10.35	17.47	16.33
CaO .....	9.85	9.46	8.65	7.37	11.77
Na <sub>2</sub> O .....	3.09	2.17	2.40	1.92	3.13
K <sub>2</sub> O .....	0.51	0.43	0.10	0.61	1.19
H <sub>2</sub> O+ .....	0.58	1.09	1.79	0.74	0.27
H <sub>2</sub> O- .....	0.23	0.16	0.49	0.34	0.06
TiO <sub>2</sub> .....	3.10	2.34	3.23	2.55	2.73
P <sub>2</sub> O <sub>5</sub> .....	0.14	0.16	0.33	0.25	0.82
MnO .....	0.12	0.15	0.13	0.15	0.15
	100.33	100.02	100.47	100.57	100.03

## NORMS.

	I	2	3	4	5
Q .....	2.52	2.94	1.92	....	....
Or .....	2.78	2.78	0.56	3.34	....
Ab .....	26.20	18.34	20.44	16.24	....
An .....	20.02	22.25	26.41	17.79	6.39
Lc .....	....	....	....	....	5.67
Ne .....	....	....	....	....	14.20
Di .....	23.21	11.50	11.55	14.11	36.83
Hy .....	14.64	23.12	22.75	20.74	....
Ol .....	....	....	....	18.50	20.74
Mt .....	3.04	3.25	7.89	5.57	8.82
Il .....	5.93	4.41	6.08	5.32	5.17
Ap .....	0.34	0.34	0.67	0.67	2.02

1. Andesine basalt, III.5.3.5. Dike. Keyes analyst.
2. Labradorite basalt, "III.5.4.(4)5. Flow. Keyes analyst.
3. Feldsparphyric basalt, III.5.4.5. Flow. Keyes analyst.
4. Picrite-basalt (III)IV."2.2".1(2).2. Flow. Keyes analyst.
5. Picrite-basalt, IV.2.2(3).2.2. Lihue, Kauai Island. Washington analyst.

## NECKER ISLAND.

Necker Island,<sup>21</sup> about 250 miles northwest of Kauai, is slightly over 1 kilometer long and about 160 meters across at its widest part. It is about 100 meters high. Three specimens of its lavas have been briefly described by Möhle,<sup>22</sup> while Powers<sup>23</sup> still more briefly describes one specimen. One of Möhle's specimens, which "represents most of the flows," is a plagioclase basalt, with scarcely any olivine. His other two specimens (from dikes) are evidently of picrite-basalt, of

<sup>21</sup> Hitchcock, op. cit., p. 9, Bryan, op. cit., p. 97.

<sup>22</sup> Möhle, Neu. Jahrb. Beil. Band 15, 90, 1902.

<sup>23</sup> Powers, this Journal, 50, 257, 1920.

doleritic texture, with abundant large olivine phenocrysts, purplish augite in the groundmass and, as phenocrysts, laths of plagioclase, and many rods and plates of highly titaniferous "ore" (ilmenite?). The specimen examined by Powers is apparently an olivine-labradorite basalt.

The twelve specimens studied by us (collected by Palmer), are referable to 4 types: andesine basalt, olivine-labradorite basalt, picrite-basalt, and nephelitic basalt.

*Andesine basalt.* This medium gray rock is very fine-grained and aphanitic, without vesicles, and with no phenocrysts. The thin section shows a somewhat doleritic, fine-grained texture. The abundant feldspar laths have about the composition  $Ab_3An_2$ . Between them are many grains of light gray augite, some small grains of magnetite and short rods of ilmenite, and very few small grains of fresh olivine. There is considerable dusty, dark brownish glass base.

The analysis (No. 1, Table III) is that of an andesine-labradorite basalt dike, and closely resembles that of the andesine basalt of Nihoa (No. 1, Table II), except that  $Al_2O_3$  and  $Na_2O$  are somewhat lower. The norm of the Necker basalt also shows much more excess silica, part of which is probably present in the glass. This basalt much resembles, chemically and otherwise, the recent flows of Mauna Loa and a basalt from Waipio Pali, on Hawaii.<sup>24</sup> Möhle's "plagioclase basalt" probably belongs to this type.

*Olivine basalt.* The single specimen that belongs here is almost black, very fine grained but not quite aphanitic, as the glisten of minute feldspars is visible on fracture surfaces. There are no megascopic phenocrysts. In thin section it is almost identical with the preceding type, except that there are many small subhedral microphenocrysts of olivine, which are fresh and without yellow borders. Some very small grains of olivine also appear in the groundmass.

The chemical composition of a sill is shown in No. 2, Table III. It calls for no remark, except that the amount of modal olivine is higher than that in the norm. This readjustment of silica would change some or all of the normative nephelite to albite and would correspondingly diminish the amount of the hypersthene molecule in the pyroxene. The relations of this olivinic to the olivine-free basalt of Necker seem to be analogous to those of the corresponding types at Mauna Loa and Kilauea. The specimen described by Powers probably

<sup>24</sup> Washington, Petrol. Hawaii, II, 112; I, 494

belongs here, although that showed some feldspar and olivine phenocrysts.

*Picrite-basalt.* Two closely similar specimens represent this type. They show many clear, glassy, yellow phenocrysts of olivine, up to 5 mm. across, with a few of black augite. The groundmass is dark gray and densely aphanitic.

Microscopically the groundmass is seen to be very fine-grained, composed mostly of small granules of colorless augite, with few very small and indefinite laths of feldspar, that appears to be labradorite. There are many grains of magnetite and plates of ilmenite, and a little glass may be present. The abundant, large, euhedral phenocrysts of olivine are clear, with very few inclusions of magnetite, and with very narrow yellow borders, the edges of some being slightly corroded. The few subhedral or anhedral phenocrysts of augite are colorless, perfectly fresh, and without inclusions.

The two analyses of flows of this type (Nos. 3 and 4, Table III) closely resemble each other. In contrast with those of the preceding rocks, their lower  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  and much higher  $\text{MgO}$  will be noted. They are very like the analysis of the picrite-basalt of Nihoa, and, indeed, the rocks of this type from both islands are almost identical in all respects. The analogies of the Nihoa rocks to the picrite-basalts of Hawaii apply equally to those of Necker. The specimens of olivine basalt from Necker, described by Möhle clearly belong to this type, although he speaks of the augite as violet-brown. To this type also obviously belong the specimens of olivine basalt from Laysan Island, described by Möhle.<sup>25</sup> It would appear that the blocks and pebbles of Laysan formed part of the island itself and that they were not brought there from elsewhere.

*Nephelitic basalt.* This type, represented by one or two specimens, is somewhat indefinite, chiefly because of the fineness of grain. The rock is rather dark gray, of dull luster, very dense and aphanitic, and wholly aphyric. The specimen analysed has no vesicles, shows sub-conchoidal fracture, with a tendency to platy parting. It comes from the dense margin of a dike. The other specimen, which probably belongs here, shows aa vesiculation and possibly comes from a flow.

Thin sections show that the rock is composed chiefly of small, irregular grains of augite, fewer, not very well defined laths of andesine or oligoclase-andesine, many thin plates of

<sup>25</sup> Möhle, Neu. Jahrb. Beil. Band, 15, 91, 1902.

ilmeneite, and fewer grains of magnetite. The few microphenocrysts of olivine are entirely altered to a yellow-brown substance. Interstitial between the augite grains and the feldspar laths is a considerable amount of colorless base, which is in part isotropic and in part feebly doubly refracting and with low index of refraction. This is to be referred to nephe-

TABLE III. Lavas of Necker Island.

	1	2	3	4	5
SiO <sub>2</sub> .....	50.95	46.87	45.20	44.86	47.89
Al <sub>2</sub> O <sub>3</sub> .....	11.45	13.27	6.60	10.48	16.21
Fe <sub>2</sub> O <sub>3</sub> .....	2.96	3.48	5.36	3.36	5.39
FeO .....	8.52	8.09	8.01	9.79	4.99
MgO .....	6.35	7.61	18.14	17.25	3.19
CaO .....	10.16	12.04	8.02	8.34	7.79
Na <sub>2</sub> O .....	2.41	2.83	1.29	1.54	7.73
K <sub>2</sub> O .....	0.43	1.00	1.71	0.60	1.38
H <sub>2</sub> O+ .....	1.21	1.31	0.65	0.46	0.62
H <sub>2</sub> O- .....	0.81	0.10	0.56	0.12	0.10
CO <sub>2</sub> .....	p.n.d.	none	none	none	none
TiO <sub>2</sub> .....	3.73	3.37	4.50	3.12	4.81
ZrO <sub>2</sub> .....	none	n.d.	n.d.	n.d.	n.d.
P <sub>2</sub> O <sub>5</sub> .....	0.06	0.31	0.34	0.41	0.19
S .....	0.06	n.d.	n.d.	n.d.	n.d.
Cr <sub>2</sub> O <sub>3</sub> .....	none	n.d.	n.d.	n.d.	n.d.
MnO .....	0.20	0.13	0.19	0.27	0.06
BaO .....	none	n.d.	n.d.	n.d.	n.d.
	99.30*	100.41	100.57	100.60	100.35

\* Low sum due to non-determination of CO<sub>2</sub>.

NORMS.

	1	2	3	4	5
Q .....	7.20	....	....	....	....
Or .....	2.78	6.12	10.01	3.34	8.34
Ab .....	20.44	16.24	11.00	13.10	29.34
An .....	19.18	20.57	7.23	20.02	5.56
Ne .....	....	3.98	....	....	19.31
Di .....	25.12	29.84	23.98	14.79	17.68
Hy .....	11.16	....	7.56	13.01	....
Wo .....	....	....	....	....	4.18
Ol .....	....	8.12	21.92	24.03	....
Mt .....	4.41	5.10	7.89	4.87	2.09
Il .....	6.99	6.54	7.30	5.93	9.12
Hm .....	....	....	....	....	4.00
Ap .....	....	0.67	0.67	1.01	0.34

1. Andesine basalt, III.4(5).3.(4).(4)5. Dike, Southwest Cape. Keyes analyst.
2. Olivine basalt, III.5".3.4. Sill, Northwest Cape. Keyes analyst.
3. Picrite-basalt, IV.2.3."2.2. Flow. Washington analyst.
4. Picrite-basalt, (III)IV.2.3.1(2).2. Flow. Keyes analyst.
5. Nephelitic basalt, II(III).6.(1)2.(4)5. Margin of dike. Keyes analyst.

lite, but its amount is apparently rather less than that of the normative nephelite.

The chemical analysis (No. 5, Table III) shows remarkable features in its very high  $\text{Na}_2\text{O}$  and low  $\text{MgO}$ , in which respects it resembles the olivine-oligoclase andesites of Kohala and andesine andesites of Mauna Kea.<sup>26</sup> These also show considerable nephelite in the norm, although there is little if any of this mineral detectable in the thin section. For this reason, and because of the difference in texture, the rock is called nephelitic basalt, rather than nephelite tephrite.

According to Powers:<sup>27</sup> "Rocks containing nephelite, usually as a very subordinate constituent, have been identified on only four islands of the group, Kauai, Oahu, Molokai, and Maui, but their presence is suspected on or near Niihau." Powers gives a list of these occurrences of nephelite basalt and nephelite basanite, some of which contain melilite, as have been observed by him, by Cross, and by Möhle. The occurrence of this nephelite lava on Necker, which adds another locality to the list, is, thus, by no means exceptional.

#### LA PÉROUSE ROCK.

About 100 miles west of Necker Island is French Frigates<sup>28</sup> Shoal, with an area of about 30 square miles. In the middle of this rises a small mass of volcanic rock, about 120 feet high, called La Pérouse Rock, after the discoverer of the shoal in 1786. Two specimens of the lavas, collected by Palmer, were studied. The two are almost identical and are both olivine basalt.

*Olivine basalt.* These lavas are dark gray, almost black, showing some small phenocrysts of fresh yellow olivine in a dense, aphanitic groundmass. That represented by analysis No. 1, Table IV is vesicular, with the pahoehoe form of vesicle, while the other appears to be aa. In thin section the two differ chiefly in size of grain. The former shows many olivine phenocrysts, which are somewhat corroded, but fresh and without yellow borders. There are no feldspar or augite phenocrysts. The groundmass greatly resembles the limburgitic basalt from Nonopapa Landing, on Niihau (p. 338).

<sup>26</sup> Washington, *Petrol. Hawaii*, I, 480 and 490.

<sup>27</sup> Powers, *this Journal*, 50, 272, 1920.

<sup>28</sup> Brigham, W. T., *Index to the Islands of the Pacific Ocean*, Honolulu, 67, 1915; Bryan, W. A., *Natural History of Hawaii*, Honolulu, 97, 1915. The spelling "Frigates," rather than "Frigate," appears to be the more correct.

It is composed of a multitude of similarly very small tables of labradorite, about  $Ab_1An_2$ , in a dark, opaque, brownish base, which high powers show to be for the most part a dark brown glass. The second specimen is more crystalline, shows also many olivine phenocrysts, with a narrow alteration border, and the groundmass is made up of small feldspar tables, with augite and some magnetite granules, and some colorless glass.

Analyses were made of the two specimens of the lavas of La Pérouse (Nos. 1 and 2, Table IV). The two are almost identical and are noteworthy chiefly for the low  $SiO_2$  and the high  $MgO$ . They are closely like the analyses of the olivine basalts of Nihoa and Necker Islands, and like some of those of Hawaii.

#### GARDNER ISLAND.

About 100 miles northwest of La Pérouse "is a cone-shaped rock 170 feet high by 600 or more feet in diameter." This is Gardner Island or Gardner Pinnacle, and is the westernmost of the Hawaiian Leeward Islands on which volcanic rocks are exposed,<sup>29</sup> according to Hitchcock and Bryan, although Möhle<sup>30</sup> describes some specimens of lava that are said to have been collected at Laysan Island, a low coral atoll, some 200 miles west-northwest of Gardner. I am informed by Dr. A. Wetmore, who spent three weeks on Laysan in 1923, that no volcanic rocks occur on the island.

*Labradorite basalt.* The specimen studied by us, received from Prof. Palmer, was collected by Dr. Ball of the Bishop Museum, who says that it is part of the "predominating mass." The rock is dark gray, very dense, aphanitic and aphyric, with some very small vesicles filled with calcite. The thin section shows that the rock is much decomposed. It is very fine-grained, containing many small granules of augite with smaller ones of magnetite, which lie in a colorless base, of rather high refractive index, that Dr. Bowen thinks is probably prehnite. No unaltered feldspar, or at least very little, is present, and no olivine is visible. Rounded vesicles contain calcite, which is present also here and there. Because of the altered condition of the rock the analysis (No. 3, Table IV) is of interest chiefly as showing that the unaltered rock was probably a labradorite basalt, with little or no olivine.

<sup>29</sup> Hitchcock, *Hawaii and its Volcanoes*, p. 9, Honolulu, 1911; Bryan, *Natural History of Hawaii*, p. 97, Honolulu, 1915.

<sup>30</sup> Möhle, *Neu. Jahrb. Beil. Band* 15, 91, 1902. Cf. Hitchcock, *op. cit.*, p. 6, and Bryan, *op. cit.*, p. 95.

TABLE IV. Lavas of La Pérouse and Gardner Rocks.

	I			2			3			NORMS.		
									I	2	3	
SiO <sub>2</sub> .....	44.58	45.67	46.78									
Al <sub>2</sub> O <sub>3</sub> .....	11.38	11.30	13.42	Or .....	2.22	2.78					16.68	
Fe <sub>2</sub> O <sub>3</sub> .....	3.08	1.77	5.30	Ab .....	18.34	16.77					17.82	
FeO .....	6.12	7.99	6.79	An .....	20.29	20.57					13.34	
MgO .....	17.30	15.95	5.58	Ne .....	.....	.....					5.40	
CaO .....	9.39	9.34	9.25	Di .....	17.90	18.28					25.91	
Na <sub>2</sub> O .....	2.21	1.98	3.26	Hy .....	1.53	7.52					.....	
K <sub>2</sub> O .....	0.41	0.52	2.82	Ol .....	26.56	22.73					4.03	
H <sub>2</sub> O+ .....	0.49	0.76	3.02	Mt .....	4.41	2.52					7.66	
H <sub>2</sub> O- .....	1.52	0.56	0.18	Il .....	5.47	6.08					4.86	
CO <sub>2</sub> .....	none	none	p.n.d.	Ap .....	1.34	1.01					.....	
TiO <sub>2</sub> .....	2.90	3.15	2.55									
P <sub>2</sub> O <sub>5</sub> .....	0.53	0.41	0.05									
Cl .....	0.05	0.09	n.d.									
MnO .....	0.14	0.13	0.10									
	100.10	99.62	99.10*									

1. Olivine basalt, III.5.(3)4.5. La Pérouse Rock. Keyes analyst.
2. Olivine basalt, III.5."4.(4)5. La Pérouse Rock. Keyes analyst.
3. Labradorite basalt (altered), III.5(6).2(3).(3)4. Gardner Rock. Keyes analyst.

\* Low sum due to non-determination of CO<sub>2</sub>.

#### CONCLUSIONS.

The lavas of the volcanic Leeward Hawaiian Islands, including Niihau,<sup>31</sup> Nihoa, Necker, La Pérouse, and Gardner, are predominantly, if not entirely, basaltic. Assuming that the specimens studied by us are representative, andesine basalt is comparatively rare, olivine-free labradorite basalt is more abundant, olivine-labradorite basalt is most common, and picrite basalt is somewhat less so. One specimen of nephelitic basalt and one of limburgitic basalt were found. There seem to be no andesites and no trachytic rocks or oligoclase. The general facies is one of decidedly femic rocks, low in silica and alkalies, with high lime and very high magnesia and iron oxides. Titanium is high, but phosphorus is low. There appears to be an increase westward in olivine, as well as in magnesia and titanium, with a concomitant decrease in silica.

The various lavas of the Leeward Islands closely resemble, modally and chemically, the corresponding rocks of the larger, easterly islands of the group, but those of the Leeward Islands appear to be much more uniform than at any one of the larger islands. This may be, and probably is, because at the Leeward Islands the rocks from only the tips of the submerged volcanoes are available for study. In any case, the generally

<sup>31</sup> Niihau may be connected tectonically with Kauai, rather than with the Leeward Islands.

femic, and hence decidedly heavy, character of the Leeward lavas is adverse to the idea of gravitative adjustment at volcanoes, such as has been suggested for Mauna Kea and others.

A comparison of the average composition of the Leeward Island lavas with that of those of the island of Hawaii,<sup>32</sup> the only one of the group of the lavas of which there are sufficient analyses to furnish a fairly satisfactory average, is of interest. With them may be compared the average of the Deccan traps,<sup>33</sup> representing the plateau basalts, and Daly's average basalt.<sup>34</sup> These are given in Table V. They are all calculated on a water-free basis, and the analysis of the Gardner rock was not used because of its altered condition.

TABLE V. Averages of analyses.

	1	2	3	4
SiO <sub>2</sub> .....	47.64	49.73	51.68	49.65
Al <sub>2</sub> O <sub>3</sub> .....	13.24	13.71	13.83	16.13
Fe <sub>2</sub> O <sub>3</sub> .....	3.19	2.92	3.25	5.47
FeO .....	8.22	8.64	10.13	6.45
MgO .....	11.28	8.27	5.57	6.14
CaO .....	9.77	9.10	9.65	9.07
Na <sub>2</sub> O .....	2.64	3.16	2.65	3.24
K <sub>2</sub> O .....	0.66	1.02	0.73	1.66
TiO <sub>2</sub> .....	2.92	2.84	1.95	1.41
P <sub>2</sub> O <sub>5</sub> .....	0.28	0.48	0.40	0.48
MnO .....	0.16	0.13	0.16	0.30
	100.00	100.00	100.00	100.00

1. Average of lavas of the Leeward Islands: 16 analyses.
2. Average of the lavas of Hawaii Island: 56 analyses.
3. Average of the Deccan traps: 11 analyses.
4. Average of "basalt" (Daly): 161 analyses.

Objections have been and will be raised against such averages, on the score that they take no account of the relative volume or mass of the different kinds of rock and that the data are insufficient for safe generalization. The force of these objections, up to a certain point, may be admitted, but still such averages, if based on fairly adequate data, are capable of furnishing some trustworthy information, even though it be admittedly imperfect, tentative, and subject to future revision. In any case, they are the only data as yet available and the indications afforded by them are of interest, provided that their tentative character be kept in mind.<sup>35</sup>

<sup>32</sup> Washington, this Journal, 6, 361, 1923.

<sup>33</sup> Washington, Bull. Geol. Soc. Amer., 33, 797, 1922.

<sup>34</sup> Daly, Igneous Rocks (No. 54), 27, 1914.

<sup>35</sup> Cf. Clarke and Washington, U. S. Geol. Survey Prof. Paper 127, 7, 1924.

The lavas of the Leeward Islands and of Hawaii much resemble each other in their main features, but the more femic character of the former is clearly evident, shown especially by the lower silica, alumina, and alkalies, and higher magnesia and lime, of the former, there being little difference in the figures for the iron oxides and the minor constituents. It is clear that they all belong to the same general magma. There are greater differences between them and the Deccan traps or plateau basalts, shown chiefly in the higher silica and iron oxides and lower magnesia of the latter, the amounts of the other constituents being almost identical. The bearing of these relations on certain geophysical problems, especially the derivation of the plateau basalts from the supposed basaltic substratum of the earth's crust, need not be discussed here. As compared with Daly's "average basalt" the chief differences are seen in the much higher alumina and somewhat higher silica and alkalies of the "average basalt," and its lower magnesia, the differences between the amounts of the other constituents being insignificant. As to Daly's average, it might be said that the amount of ferric oxide relative to ferrous is probably too high, due to the inclusion in the data for the average of analyses of altered basalts, which is also indicated by the high percentage of H<sub>2</sub>O (1.76). One has also, inevitably, the suspicion that the figure for alumina is too high and that for magnesia is too low, because of the imperfections of many of the analyses in this regard. Manganese oxide is also unquestionably too high, because of another common analytical error; but this is a matter of small moment.

On the whole, taking all the facts (and suppositions) into consideration, we believe that the average composition of the lavas of the Leeward Hawaiian Islands represents the composition of the average basalt (III.5.3.4) better than does that of Daly. The relation of the average Leeward and of the average Hawaiian lavas to that of the Pacific lavas<sup>36</sup> must be postponed until further data as to the lavas of the whole Hawaiian group are available. It is the opinion of those who have devoted most study to the tectonics and volcanism of the Hawaiian Islands (Brigham, Dana, Hitchcock, Bryan, etc.) that the Leeward Islands are older than those of the south-eastern end, and it is possible that the greater femicity of the small, northwesterly islands is connected with this.

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<sup>36</sup> Clarke and Washington, U. S. Geol. Survey Prof. Paper 127, 67, 1924; Washington, Bull. Geol. Soc. Amer., 33, 388, 1922.