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CONTRIBUTIONS TO THE PETROLOGY OF HAWAIIAN BASALTS
1. THE PICRITE-BASALTS OF KILAUEA

I. D. MUIR and C. E. TILLEY

with chemical analyses by J. H. SCOON

ABSTRACT. This is the first of two contributions devoted to the petrology of Hawaiian basalts. In this part the petrography of some Kilauean tholeiitic picrite basalts and their metamorphic representatives is described. A discussion of the genetic features of the rocks based on new chemical data, particularly of the composition of pyroxene phases, is provided.

INTRODUCTION

Among the desiderata in discussions on Hawaiian basalt petrogenesis has been adequate knowledge of the quantitative chemical composition of the commoner mineral phases of the lava types of Hawaiian volcanic centers.

Numerous first class analyses of the rocks themselves are available but chemical data on the constituent minerals have been few[1]—two olivines from the 1789 and 1840 flows from the Kilauean center were analyzed by Aurousseau and Merwin (1928), an olivine from the 1852 flow of Mauna Loa was analyzed by Steiger (Cross, 1915), and an analysis of an augite from an augite picrite-basalt at Haleakala crater on East Maui has been reported by Washington and Merwin (1922).

This is the first of two papers intended to help in filling this gap by the provision of precise data, particularly on the pyroxene phases of the basalts, and thus further to aid in the elucidation of genetic problems of these lavas in their oceanic setting.

The rocks of Kilauea now under study are of ultrabasic composition and include the well known picrite-basalt flow of 1840 (at Nanawale Bay) which together with the basalt erupted during the same period at the upper vents near Kilauea, has provided evidence of gravitative differentiation (Macdonald, 1944a); an intrusive in the wall of Kilauea caldera (Daly, 1911), and three picrite basalts, two of which were ejected in the explosion of 1924 at Halemaumau including an assemblage which presents a study in thermal metamorphism (Macdonald, 1944b). Altogether with the two analyses provided in this account there are now available six analyses of these ultrabasic rocks from the Kilauean center.

Four of these are set out in table 1, nos. 1-4. Washington (1923) analysed a picrite basalt west of the Kamakaia Hills, S.W. of Kilauea, and

[1] More information is available on the minerals of basic and ultrabasic inclusions in Hawaiian basalts, for Ross and his colleagues (1954) have supplied for these assemblages at various Hawaiian centers, analyses, including spectrographic data, of olivines, pyroxenes and spinels. Other chemical data on some vein minerals from the basalts of Moiliili Quarry, Honolulu, are recorded by Dunham (1933).

Shepherd (1938) a block of baked picrite basalt ejected during the 1924 explosion at Halemaumau. Unfortunately there is no petrographic description available of this interesting rock.

TABLE 1

	1	2	3	4	5	6	Norm of 6		
SiO_2	46.59	47.00	47.33	47.25	50.60	43.90			
Al_2O_3	7.69	9.17	9.85	9.07	14.63	3.51			
Fe_2O_3	2.20	1.47	4.58	1.45	2.38	0.52		Or	0.56
FeO	10.46	10.47	7.28	10.41	10.15	10.67		Ab	2.10
MnO	0.18	0.17	0.17	0.13	0.12	0.14		An	8.06
MgO	21.79	20.25	19.11	19.96	6.38	33.54		Wo	9.51
CaO	7.41	7.73	8.04	7.88	9.56	6.20	Di	En	7.10
Na_2O	1.33	1.56	1.62	1.38	2.51	0.25		Fs	1.45
K_2O	0.28	0.30	0.28	0.35	0.54	0.16		En	6.00
H_2O+	0.37	0.07	0.03	0.04	0.13		Hy	Fs	1.32
H_2O-	0.04	nil	nil	0.08	—			Fo	49.49
TiO_2	1.83	1.90	1.75	1.61	2.29	0.93	Ol	Fa	11.52
P_2O_5	0.11	0.15	0.12	0.21	0.43			Il	1.82
Cr_2O_3	0.13	0.12	0.18	0.12	0.09	0.15		Mt	0.93
NiO	0.12	0.11		0.09	0.07 (SO_3)				99.86
	100.53	100.47	100.34	100.03	99.88	99.97			

1. "Porphyritic Gabbro", Uwekahuna 'laccolith', Kilauea (G. A. MacDonald 1949 (a) p. 73).
2. Picrite-basalt, ejected block 1924, Kilauea (Tilley 1950, p. 41).
3. Metamorphosed Picrite-basalt, ejected block 1924, Kilauea.
4. Picrite-basalt, flow of 1840, Nanawale Bay, Hawaii (G. A. MacDonald 1949 (b) p. 1572).
5. Basalt, lava of upper vents of 1840 eruption at Kilauea (G. A. MacDonald 1949 (b) p. 1572).
6. Composition of crystal extract (50%) from analysis 4 to produce analysis 5 = (removal of olivine 30.5%, clinopyroxene 12.7%, plagioclase 5.4% and ores 1.4%).

TABLE 2

Norms of Rocks of Table 1

	1	2	3	4	5
Qz					3.48
Or	1.67	1.67	1.67	2.22	2.78
Ab	11.53	13.10	13.62	11.53	20.96
An	13.90	17.24	18.90	17.51	27.24
Di	17.48	16.19	15.99	16.68	14.38
Hy	16.90	15.66	21.64	17.96	21.64
Ol	31.33	30.40	17.99	28.25	—
Il	3.50	3.65	3.34	3.04	4.41
Mt	3.47	2.27	6.96	2.31	3.48
Ap	0.34	0.34	0.34	0.34	1.01
Rest	0.41	0.07	0.03	0.12	0.29
	100.53	100.59	100.48	99.96	99.67

The position of these six analyses on a silica—magnesia variation diagram of Kilauean lavas is given in figure 1.

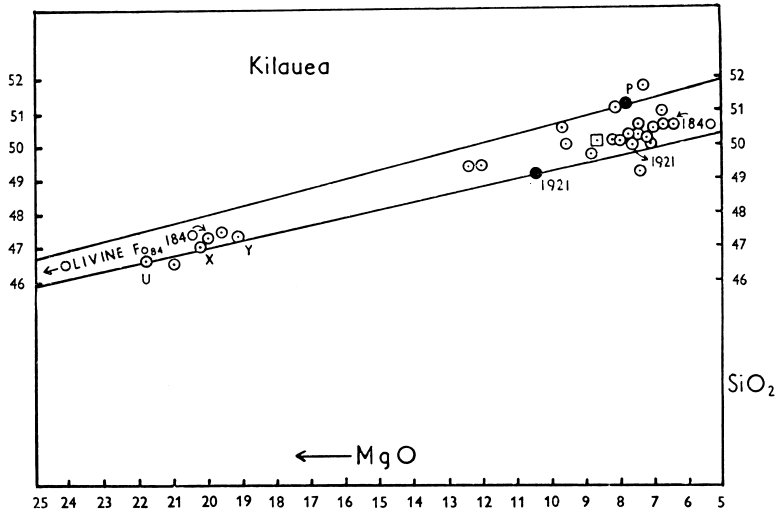


Fig. 1. Plot of variation of silica and magnesia in analyses of basaltic rocks of Kilauea. Control lines from olivine (Fo_{84}) through olivine basalt flow of 1921 (table 3, no. 1) and a prehistoric olivine basalt P (table 3, no. 2). The data for the picrite-basalts referred to in the text are indicated :-

U = Uwekahuna 'gabbro'; X and Y ejected blocks of picrite basalt (1924 explosion) (table 1, nos. 2 and 3); 1840 analysis of picrite-basalt of Nanawale Bay (table 1, no. 4) and corresponding basalt of upper vents (table 1, no. 5). A variant of the 1921 lava flow is shown in the figure by an open circle. Average composition of Kilauean historic magma (Powers, 1955, p. 85) shown by square around point.

On this have been placed olivine control lines from Fo_{84}(wt percent) through the composition points for the 1921 and prehistoric lava flows of Kilauea (table 3, nos. 1 and 2), a procedure which Powers (1955) has developed in his analysis of the nature of parental Kilauean magma.

Further reference to this diagram will be made in the sequel. We proceed to the new data now available on the rocks of table 1.

GABBRO MASS AT UWEKAHUNA BLUFF, KILAUEA CALDERA

This rock was originally described by Daly (1911, p. 291) who regarded it as a laccolithic intrusion. He noted it showed a distinctly chilled phase several decimetres thick, and Macdonald (1949a, p. 67) has supported this interpretation of it as an intrusive, recording also that a dike about two feet thick extends from it into the overlying lavas. The analysis given by Daly is by Steiger and is here reproduced (table 1, no. 1). Daly presented a mode as follows: olivine 40, augite 30, labradorite 27, iron ore and apatite 2 percent. The normative composition gives olivine 31.3 percent.

Pyroxene, however, is present both as augite and hypersthene, the latter hitherto not recognized in published accounts of the rock. Both these pyroxenes have been isolated from the rock and analysed (table 4, nos. 1a and 1b).

Both pyroxenes and olivine have a yellowish tint in thin section, the hypersthene feebly pleochroic with stronger absorption along α and β.

TABLE 3

	1	2		1	Norms 2
SiO_2	49.16	51.18	Qz	—	0.30
Al_2O_3	13.33	14.07	Or	2.78	2.22
Fe_2O_3	1.31	1.35	Ab	17.82	20.96
FeO	9.71	9.78	An	25.30	26.13
MnO	0.16	0.17	Di	22.93	22.04
MgO	10.41	7.78	Hy	15.35	22.44
CaO	10.93	10.83	Ol	9.14	—
Na_2O	2.15	2.39	Mt	2.09	1.86
K_2O	0.51	0.44	Il	4.41	3.95
H_2O+	0.04	0.10	Ap	0.34	0.34
H_2O-	0.05	0.01	Rest	0.09	0.16
TiO_2	2.29	2.10		100.25	100.40
P_2O_5	0.16	0.15			
Cr_2O_3	0.09	0.05			
	100.30	100.40			

1. Olivine Basalt, 1921 flow, South edge of Kilauea caldera.
2. Olivine Basalt, prehistoric flow, National Park Quarry on highway 0.75 mile NE of Volcano Observatory Kilauea (P(•) of figure 1).

Both are of similar grain size (1 mm) and their optical properties are set out below:-

Augite: α 1.684, β 1.689, γ 1.712. $2V_\gamma$ 52° - 50°.
Hypersthene: α 1.685, β 1.692, γ 1.696. $2V_\alpha$ 65°.

TABLE 4

Compositions of Pyroxenes of Rocks of Table 1

	1(a)	1(b)	4(a)	4(b)	Formula on basis of 6 oxygens	1(a)	1(b)	4(a)	4(b)
SiO_2	51.62	52.87	51.72	52.39	Si	1.894	1.907	1.890	1.924
Al_2O_3	3.14	2.14	3.82	4.00	Al	.106	.091	.110	.076
TiO_2	0.72	1.12	0.92	1.43	Al	.026	—	.052	.096
Cr_2O_3	0.49	0.11	0.52	0.54	Ti	.019	.031	.024	.040
Fe_2O_3	1.25	1.10	0.90	1.55	Cr	.013	.004	.013	.013
FeO	5.63	12.59	5.77	8.59	Fe‴	.035	.031	.026	.040
MnO	0.14	0.26	0.14	0.21	Fe″	.164	.379	.175	.262
MgO	17.42	26.70	16.80	15.25	Mn	.004	.006	.004	.007
CaO	19.45	2.72	19.13	15.17	Mg	.960	1.448	.921	.840
Na_2O	0.32	0.16	0.45	0.70	Ca	.763	.104	.750	.597
K_2O	0.01	0.04	0.05	0.21	Na	.022	.009	.030	.049
H_2O+	n.d.	n.d.	n.d.	n.d.	K	—	—	—	.009
H_2O-	n.d.	0.03	nil	nil	z	2.000	1.998	2.000	2.000
	100.19	99.84	100.22	100.04	x + y	2.006	2.012	1.995	1.953
					Ca	39.5	5.3	40.0	34.2
					Mg	49.8	73.4	49.0	48.0
					Fe	10.7	21.3	11.0	17.8

1 (a) and 1(b), clinopyroxene and hypersthene of "Porphyritic gabbro" (table 1, no. 1)
4 (a) and 4(b), clinopyroxenes-phenocryst (4(a)) and groundmass (4(b)) of picrite-basalt, flow of 1840 (table 1, no. 4).

The olivines are in larger grains and may reach 3 mms. in diameter. They show β1.673, $2V_\gamma$ 86°-90° corresponding to Fa_{11} (mol percent). The zoned plagioclase has a composition range An_{64}-An_{58}. There is a little brownish glass interstitially and cristobalite in small amount is also recorded.

The rock powder treated on a steam bath with 1:9 HCl left a residue of 37 percent indicating the high modal content of olivine in the sample studied (pl. I, fig. 2).

PICRITE-BASALT, 1840 FLOW, PUNA, NANAWALE BAY

This rock has been described at length by Cross (1915, p. 43) and subsequently by Macdonald (1944a, p. 177).

The rock was analyzed by Steiger (Cross, 1915, p. 44) while Aurousseau and Merwin (1928, p. 560) have analyzed its phenocryst olivine (Fa_{12} mol percent).

A specimen made available to us by Dr. Macdonald has been used for the isolation of the phenocryst and groundmass pyroxenes. The analytical data for these two minerals are set down in table 4, columns 4a and 4b; the analysis of the rock itself in table 1, No. 4.

The optical properties of the olivine and clinopyroxenes are as follows:

Olivine: β 1.687 (Fa_{17}); $2V_\alpha$ 88° (Fa_{17}); Xray (Fa_{16})

Clinopyroxene α 1.686, β 1.692, γ 1.713, $2V_\gamma$ 56°-52° (phenocrysts)

Clinopyroxene α 1.688 (min.) to γ 1.717 (max.) $2V_\gamma$ 46°-32° (groundmass)

Microphenocrysts of plagioclase have the composition An_{60} while the groundmass plagioclase is zoned to An_{52}.

The rock powder treated on the steam bath with 1:9 HCl gave a residue of 44 percent.

A photomicrograph of this rock is presented in plate I, figure 1.

PICRITE BASALTS AS EJECTED BLOCKS FROM THE 1924 EXPLOSION AT HALEMAUMAU, KILAUEA

Macdonald (1944b, 1949a) has described the characters of blocks of basalt thrown out by the phreatic explosion of 1924. Attention is here directed to two such blocks of picrite-basalt composition. Both have been analyzed.

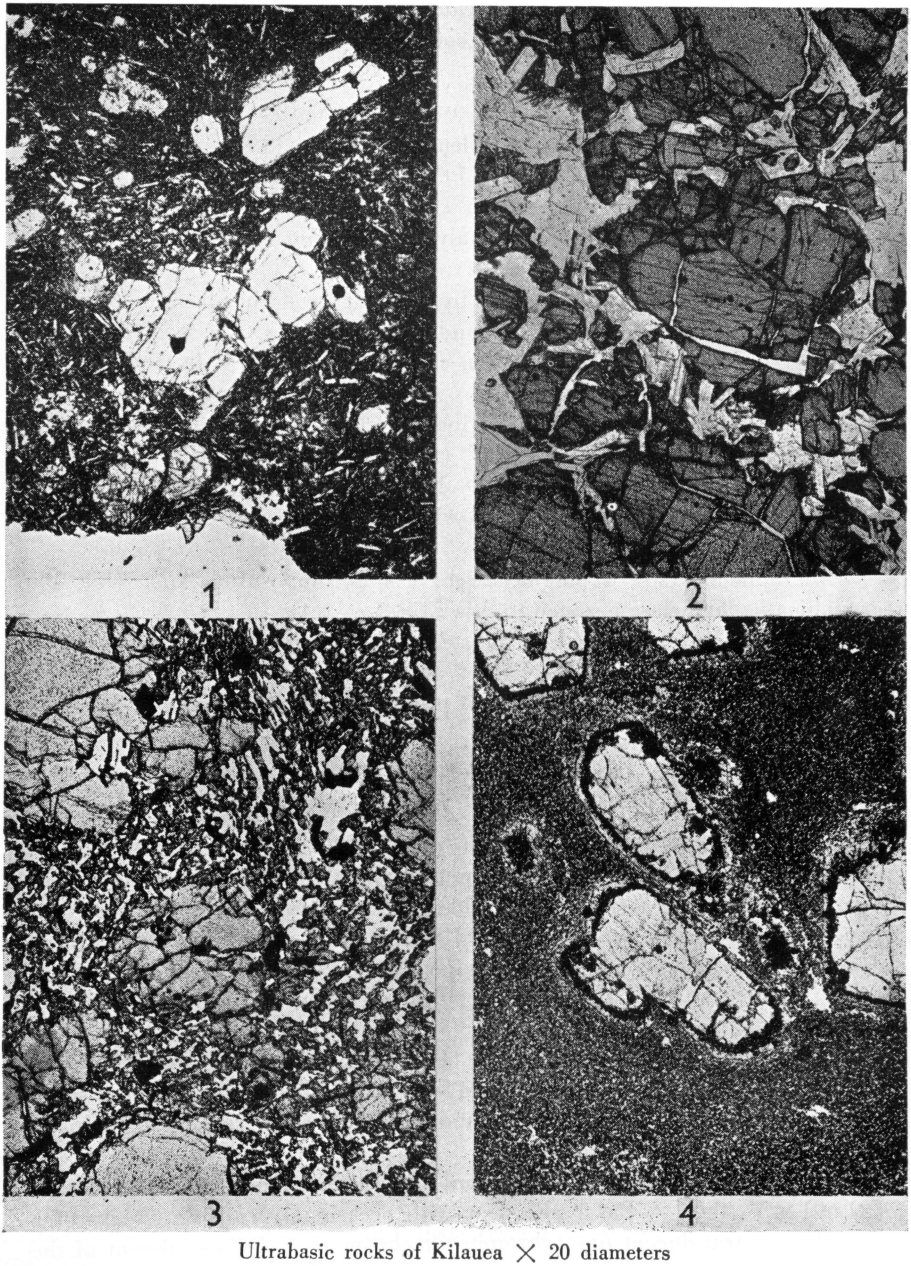
The first of these (analysis 2, table 1) corresponds to the description of hand specimens given by Macdonald (1944b, p. 323)—pale yellowish green of dense aspect and with numerous olivine phenocrysts, green-brown in color, with a brilliant lustre, almost submetallic and iridescent on the conchoidal fractures.

The second example (analysis 3, table 1) corresponds to the description by Macdonald of another variety (1944b, p. 324). The olivine in hand specimens is black and the color of the groundmass, dark gray—usually fine grained but showing coarser grained patches.

In the first type (X) as seen in thin section the olivine phenocrysts (β1.691, $2V_\alpha$ 89° = Fa_{19}) are clear with occasional dendritic streaks of a platy brown translucent ore (chromite or chrome spinel) reminiscent of the

translucent dendrites seen in the olivines of the Rum allivalites. The plates are oriented in the plane (100).

PLATE I



Ultrabasic rocks of Kilauea × 20 diameters

The groundmass is built of plagioclase augite and hypersthene (both yellowish to yellow green in section) and platy ilmenite. The texture in places shows a crude radial arrangement of the felspar laths (pl. I, fig. 3).

The optical properties of the two pyroxenes are:

Hypersthene: $2V_\alpha$ 63°; β 1.694, γ 1.699 (Fs_{27})

Augite: $2V_\gamma$ 45½°; α 1.690, β 1.695, γ 1.718 ($Ca_{38}Mg_{41}Fe_{21}$)

A colorless glass (n = 1.502) is sparingly developed, wedged between the feldspar laths (composition An_{52-42}, average An_{46}).

The second picrite-basalt (Y) is a thoroughly metamorphosed rock with a hornfelsic texture in the groundmass as described and figured by Macdonald (1944b, fig. 1a).

This texture merges into one similar to that met with in the first example, and this is associated with still coarser textured patches.

The constituents of this variable textured groundmass are augite, hypersthene—both notably colored in thin section, yellow to greenish yellow—plagioclase (An_{62}) together with brown translucent laths of a mineral identified as pseudobrookite. Some tridymite plates appear among the felspar laths of the coarse textured patches.

The olivine phenocrysts (β1.693, $2V_\alpha$ 88½°, Fa_{20}) unlike those of picrite-basalt X are in process of dissolution with separation of magnetite (strongly magnetic, cell size 8.40 Å) on their peripheries. This release of iron oxide is in part accompanied by the formation of hypersthene which appears as a wreath around the olivines as well as intergrown with the magnetite. The same process has been at work at scattered centres in the interior of the olivines. The olivines are otherwise clouded with opaque clots of magnetite strung together in curved lines.

The smaller olivine phenocrysts may be completely replaced by magnetite and granular hypersthene. These features are revealed in the photomicrograph of plate I, figure 4, which presents a clear picture of the hornfelsic groudmass of this picrite-basalt. The optical data of the two pyroxenes in their varying environment are indicated below.

Fig. 1. Picrite-basalt, 1840 flow of Nanawale Bay, E. of Kilauea. Phenocrysts of olivine and clinopyroxene (lower edge) in a fine grained base of plagioclase, clinopyroxene and iron ores. The phenocryst and groundmass pyroxenes have been analyzed (table 4, nos. 4(a) and 4(b)).

Fig. 2. Gabbro of Uwekahuna Bluff, Kilauea caldera wall. Large olivines, clinopyroxene, hypersthene and plagioclase. The pyroxenes have been analyzed. (table 4, nos. 1(a) and 1 (b)).

Fig. 3. Picrite-basalt ejected block from the 1924 explosion of Halemaumau. Phenocryst olivine in a groundmass of hypersthene, clinopyroxene, plagioclase and iron ore. The rude radiate arrangement of the plagioclase laths is visible. Rock analyzed (table 1, no. 2).

Fig. 4. Metamorphosed picrite-basalt, ejected block from the 1924 explosion of Halemaumau. Phenocryst olivine in a dense hornfelsic aggregate of hypersthene, augite, plagioclase and laths of pseudobrookite. The larger olivines mantled by magnetite and surrounded by a sheath of new hypersthene. Smaller grains of olivine are almost completely replaced by an aggregate of magnetite and hypersthene. Rock analyzed (table 1, no. 3).

Coarse textured patches.

hypersthene: $2V_\alpha$ 68°, (Fs_{27})

augite: $2V_\gamma$ 51°, α 1.692, β 1.698, γ 1.720, ($Ca_{40}Mg_{37}Fe_{23}$)

Hornfelsic textured patches

hypersthene: $2V_\alpha$ 71°, (Fs_{24})

augite: $2V_\gamma$ 52°, α 1.691, β 1.695 γ 1.718, ($Ca_{39}Mg_{40}Fe_{21}$)

Coronas around olivine

hypersthene: $2V_\alpha$ 76°, (Fs_{21}); in coarse patches near olivine $2V_\alpha$ 71°, (Fs_{24}); α 1.684, β 1.690, γ 1.695.

Enclosures in olivine

hypersthene: $2V_\alpha$ 78°, α 1.678, β 1.683, γ 1.688 (Fs_{19})

The rock powder treated on the steam bath with 1:9 HCl gave a residue of 63.3 percent.

TABLE 5

	Olivine	Hypersthene	Clinopyroxene
Picrite-basalt (CD) 1840 flow	Fa_{17}	—	‡$Wo_{40.0}$ $En_{49.0}$ $Fs_{11.0}$ ‡$Wo_{31.2}$ $En_{48.0}$ $Fs_{17.8}$
Picritic basalt (W) (pre-1924 explosion)	Fa_{14} ↓ $Fa_{16(rims)}$	—	Wo_{37} En_{47} Fs_{16} ↓ Wo_{29} En_{47} Fs_{24} Wo_{15} En_{53} Fs_{32}
"Olivine gabbro Porphyry (AB)	Fa_{11}	‡$Wo_{5.3}$ $En_{73.4}$ $Fs_{21.3}$	‡$Wo_{39.5}$ $En_{49.8}$ $Fs_{10.7}$
Picrite-basalt (X) 1924 explosion	Fa_{19}	Fs_{27}	Wo_{38} En_{41} Fs_{21}
Picrite-basalt (Y) 1924 explosion.	Fa_{20}	Fs_{27} (coarse patches) Fs_{24} (hornfelsic patches) Fs_{21} (olivine coronas) Fs_{19} (olivine enclosures)	Wo_{40} En_{37} Fs_{23} (coarse patches) Wo_{39} En_{40} Fs_{21} (hornfelsic patches) — —

‡ data from chemical analysis

PICRITIC BASALT (W), PRE-1924 EXPLOSION KILAUEA

An olivine-rich basalt with a distinctive igneous texture and mineralogy found as a bomb at Kilauea remains to be noted.

The hand specimen shows conspicuous olivine as green phenocrysts in a grey groundmass.

These olivines are colorless in thin section ($2V_\alpha$ 88°, β1.681, Fa_{14}) and range in size from four millimetres to less than one millimetre. They are frequently sharply zoned by a narrow rim, light yellow in color ranging in composition to Fa_{27} ($2V_\alpha$ 82°) indicating regrowth during the later stages of crystallization.

Octahedra of chromespinel occur as enclosures.

There are a few scattered microphenocrysts of augite ($2V_\gamma$ 49°-38° average 44°, β 1.691 corresponding to $Ca_{37}Mg_{47}Fe_{16}$). The groundmass is fine grained built of two clinopyroxenes, augite and pigeonite, less than 1/10 mm. in length, plagioclase (An_{60}) and ilmenite. Cristobalite of late development is present in interstitial patches.

The augite of the groundmass has a composition of $Ca_{29}Mg_{47}Fe_{24}$ with a limiting 2V of 30°, range 38°-30°, while the pigeonite, the dominant groundmass pyroxene in subidiomorphic stumpy prisms has the properties $2V_\gamma$ 0°-15°, optic plane (010), β 1.693 with a mean composition $Ca_{15}Mg_{53}Fe_{32}$. The compositions of the phenocryst and groundmass augite and pigeonite (W^1, W^{11} and W^{111}) are plotted in figure 3.

TABLE 6

Comparison of Iron Enrichment in Associated Olivines and Pyroxenes (atom percent)

	Picrite-basalt 1840 flow	Olivine gabbro Porphyry	Olivine Basalt 1921 flow	Picritic basalt pre-1924 (W)	Picrite-basalt (X)	Picrite-basalt (Y)
Olivine	17	11	18	14-16	19	20
Hypersthene	—	22.3*	—	—	27	27 (coarse patches) 24 (horn-felsic areas)
Clinopyroxenes	18.2 ↓ 26.9	17.4	17.5 ↓ 28.6 ↓ 30.9	25 ↓ 34 38	34	38 (coarse patches) 34 (horn-felsic areas)

* In the case of the hypersthene ($Fs_{22.3}$) from the olivine gabbro porphyry, the agreement between the chemical composition and the optical properties is not very close, for the refractive indices correspond with Fs_{26} and the optical axial angle (mean value 65°, limits 67°-63°) corresponds with Fs_{28} using Hess's chart. (AM. JOUR. SCI., 1952, Bowen volume p. 180). The discrepancies can probably be attributed to the notably high ferric iron and titanium content of this pyroxene which would certainly influence its refractive indices. Dr. P. Gay kindly determined the parameters of this hypersthene using a Geiger counter spectrometer. The dimensions a = 18.31 Å ± .03, b = 8.867 Å ± .014, c = 5.201 Å ± .001 agree fairly well with Hess and Kuno's curves (Hess, 1952) for volcanic pyroxenes of this composition high in alumina.

The hypersthene from picrite-basalt X is similar in colour to that from the olivine gabbro porphyry; its refractive indices and optic axial angle indicate Fs_{27} and Fs_{30}, very iron-rich compositions for Hawaiian orthopyroxenes.

It is probable that this hypersthene is closely similar to that discussed above, and is more magnesian than the composition indicated in the table from its optical properties. The orthopyroxenes of the picrite-basalt Y appear to be completely normal.

DISCUSSION

The chemical composition and optical data on the olivines and pyroxenes of the five rocks just described are set down together in table 5, and a comparison of the relative iron enrichment of these associated mineral phases summarized in table 6.

The composition of the chemically analysed pyroxenes is graphically depicted in figure 2, which also includes the three fractions of the clinopyroxene (E, F, G) analyzed from the 1921 lava of Kilauea (table 3, no. 1).

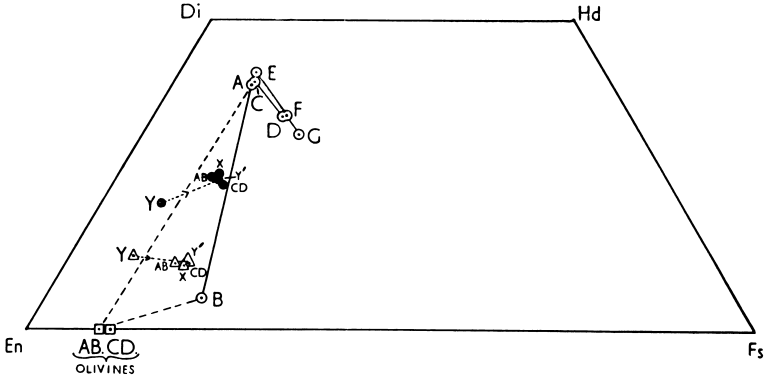


Fig. 2. Plot of compositions of analysed pyroxenes from picrite basalts and a related ultrabasic rock from Kilauea:

A-B from the 'porphyritic gabbro' (AB) of Uwekahuna (table 1, no. 1);

C-D from the picrite-basalt (CD) 1840 flow at Nanawale Bay (table 1, no. 4);

Also plotted are the three fractions (E-F-G) of pyroxenes isolated from the 1921 olivine basalt flow of Kilauea. (table 3, no. 1). The solid circles and open triangles give the compositions respectively of mol normative pyroxenes and mol normative pyroxenes + olivines of the rocks AB, CD and two ejected blocks of picrite-basalt (1924 explosion) from Kilauea—X and Y (table 1, nos. 2 and 3);

Y′ the corresponding compositions for rock Y in which the Fe_2O_3 content has been adjusted (table 7, no. 2).

The compositions of the olivines of rocks AB and CD are projected on to the plane of the diagram.

In this diagram the compositions of normative pyroxenes, normative pyroxenes + olivines, mol percent, are also indicated, together with other data noted in the legend of this figure.

In the artificial system MgO—FeO—SiO_2, olivine in equilibrium with a magnesia-iron pyroxene is less magnesian than that pyroxene (Bowen and Schairer, 1935) and this relationship has been confirmed by Ramberg and De Vore (1951) in their study of natural olivine-orthopyroxene pairs, though they note that in highly magnesian parageneses the natural olivine may in some cases be richer in magnesium than the coexisting hypersthene. In the present assemblages however, olivine is uniformly more magnesian than the associated hypersthene, or the bulk composition of the associated clinopyroxenes—a relation corresponding to non-equilibrium conditions associated with the early separation of olivine in these assemblages (fig. 2). This statement applies not only to the rocks with a straight igneous crystallization but also to

the metamorphic representatives where olivine is in effect a residual of igneous crystallization.

The relations of the ortho- and clino-pyroxenes are not so uniform. In the 'olivine gabbro porphyry' the greater relative enrichment in iron of the hypersthene is in accord with the findings of Hess (1941) for the two pyroxenes of some mafic intrusions.

The enrichment of iron in the later fractions of a series of clinopyroxenes is also well shown in the data for the phenocryst and groundmass clinopyroxenes of the 1840 picrite-basalt flow and the 1921 Kilauean lava (table 6).

In the picrite basalt Y the metamorphic texture indicates the simultaneous crystallization of hypersthene and augite in the hornfelsic groundmass and this would apply to the coarser textured patches, where it may be suspected recrystallization took place in the presence of interstitial liquid. We may interpret the textures seen in picrite-basalt X which has also been reheated as indicating recrystallization in the presence of some liquid to give the rude radiate arrangement of the felspar laths seen in plate I, figure 3.

Optical data on the associated groundmass pyroxenes of both these rocks reveal now that the clinopyroxene is the one relatively enriched in iron (table 6).

In picrite basalt Y however. we have a second hypersthene which has been produced partly at the expense of olivine seen in the magnetite-hypersthene coronas which surround this phenocryst mineral.

As seen from the table these hypersthenes are somewhat more magnesian than those associated with the main groundmass.

The strong development of magnetite associated with the olivine is a result of oxidation processes probably in the presence of water vapor and as

TABLE 7

	1	2		Norms 1	Norms 2
SiO_2	47.33	47.33	Or	1.67	1.67
Al_2O_3	9.85	9.85	Ab	13.62	13.62
Fe_2O_3	4.58	1.50	An	18.90	18.90
FeO	7.28	10.05	Di	15.99	16.22
MnO	0.17	0.17	Hy	21.64	15.90
MgO	19.11	19.11	Ol	17.99	27.83
CaO	8.04	8.04	Il	3.34	3.34
Na_2O	1.62	1.62	Mt	6.96	2.32
K_2O	0.28	0.28	Ap	0.34	0.34
H_2O+	0.03	0.03	Rest	0.03	0.03
H_2O-	nil	nil			
TiO_2	1.75	1.75		100.48	100.17
			normative	pyroxene	(atom %)
P_2O_5	0.12	0.12	Ca	20.5	24.5
Cr_2O_3	0.18	0.18	Mg	71.6	61.6
	100.34	100.03	Fe	7.9	13.9

1. Metamorphosed Picrite-basalt, ejected block 1924, Kilauea.
2. The same rock with Fe_2O_3 adjusted to 1.50, FeO 10.05 (total iron as in 1).

we have noted smaller olivines may be completely replaced by magnetite-hypersthene aggregates.

We are justified in recalculating the analysis of this picrite basalt by reducing its high Fe_2O_3 content to one comparable with that of picrite basalt X. When this is done (table 7, no. 2) the normative olivine rises from 18 to 27.8 percent, a figure comparable with that for olivine of rocks of table 1 nos. 1, 2, 4).

In the production of orthopyroxene and magnetite from olivine by an oxidation reaction, for every mol of fayalite converted to magnetite sufficient silica is released to convert one mol of forsterite to enstatite thus:

$$3\ Fe_2SiO_4 + 3\ Mg_2\ SiO_4 + O_2 \rightarrow 2\ Fe_3O_4 + 6\ MgSiO_3$$

This reaction however does not suffice to explain the replacement of an olivine Fa_{20} by the visible aggregates of magnetite and hypersthene ($Fs_{18\text{-}24}$) and it is clear that the mechanism involves introduction of iron from the environment of the phenocryst olivine, magnesia moving out, and silica likewise if the content of magnetite in the aggregate is high.

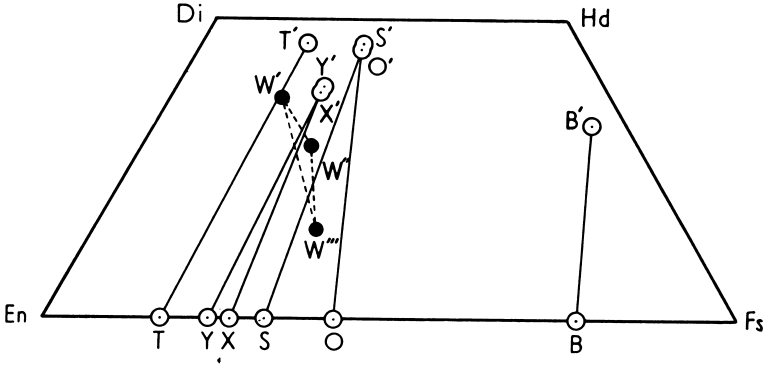


Fig. 3. Plot of compositions (optically determined) of pyroxenes of the picritic basalt W (W^1, W^{11}, W^{111}) and the two metamorphosed picrite-basalts X (X X^1) and Y (YY^1). In addition the tie lines of coexisting orthorhombic and monoclinic pyroxenes from four metamorphic assemblages have also been plotted in the figure—0-0^1 from a hypersthene diopside plagioclase hornfels (Class VI), Aarvold, Norway; S-S^1 from a hypersthene augite plagioclase gneiss from the Lewisian of Scourie, Sutherland; T-T^1 from an olivine hypersthene pyroxenite from the same rock group at Scourie.

B-B^1 gives the tie line for coexisting pyroxenes in an almanditic ultramafic pyroxenite gneiss from the Adirondacks (Buddington, 1952, p. 54).

The compositions of the pyroxenes of the picritic basalt and the metamorphosed picrite-basalts X and Y are plotted in figure 3. The metamorphic assemblages show a tie line trend which is in contrast to that revealed in many mafic intrusive bodies; the same feature is brought out by the tie line trend of the two pyroxenes of some other metamorphic assemblages which have been examined, and indicated in figure 3. The significance attached to this contrasting trend will be better appreciated when more examples of metamorphic assemblages, hitherto little studied, have been closely investigated.

PICRITE-BASALTS AS GRAVITATIVE DIFFERENTIATES

Powers (1955) in his analysis of the composition of Kilauean lavas concludes that movement of olivine phenocrysts from a silica saturated magma suffices to explain the main chemical variation of the suite of lavas emanating

from this center. This conception is illustrated in the diagram of figure 1 already referred to which is based on diagrams due to Powers. The same conclusion had already been reached for a specific pair of lavas by Macdonald (1944a, 1949b) in his investigation of the 1840 picrite basalt of Nanawale Bay and the 1840 basalt of the upper vents at Kilauea.

He attempted to show that subtraction of 29 percent of olivine of the appropriate composition from the picrite-basalt of 1840 gives a figure of composition of the residue comparable with the lava of the upper vents (columns 1, 2 and 3 of table 6, Macdonald. 1949b. p. 1572).

The match however is not very close as the product contains more lime and magnesia than the upper vent lava. It is unlikely that olivine is the only mineral to be extracted, for the picrite-basalt also contains phenocrysts of pyroxene and plagioclase.

A preferable solution is the extraction of olivine in bulk together with subordinate pyroxene and plagioclase, and the result shown in table 1 is on a basis of extraction of 50 percent of material of the composition shown in column 6.

Extraction of zero soda falls at a silica percentage of 43.1 (extract 45 percent) and the preferred solution extracts a small content of soda.

As we know crystallization of olivine from Kilauean basaltic liquid is followed closely in time by that of pyroxene and plagioclase. Choice must here be made between extracting too large an amount of crystallate and the limit presented by the relative soda contents of the two lavas.

CAMBRIDGE, ENGLAND

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