

ART. VII.—*Mineralogy. Augite of Haleakala, Maui, Hawaiian Islands*,¹ by HENRY S. WASHINGTON and H. E. MERWIN, Geophysical Laboratory, Carnegie Institution of Washington.

The Hawaiian lavas are, on the whole, of very simple mineral composition,² but we know little of the chemical characters of the minerals that compose them. Augite and olivine constitute almost the only mafic minerals; the orthorhombic pyroxenes, amphiboles, and micas being seldom present in the lavas. Of the olivines we have one analysis,³ that of one from a flow of Mauna Loa, Hawaii; and M. Aourousseau, of this Laboratory, is now studying others. But no analysis has been published of any augite from the islands, although this mineral is more constant and abundant in the lavas than is olivine, which frequently occurs as large phenocrysts and is therefore more prominent. Some knowledge of the general composition of the Hawaiian augite is consequently of considerable importance for the study of the petrology of the Hawaiian Islands, so it is a pleasure to have the opportunity to determine the optical and chemical data for a Hawaiian augite. The augite crystals described here were collected in September, 1920, by Dr. J. Allan Thomson, of Wellington, New Zealand, who very kindly placed them at our disposal for study, a courtesy for which we extend our hearty thanks.

The augite crystals were found "along the trail from the Rest House to Red Hill," a small parasitic cone at the southwest corner of the rim of the great crater of Haleakala, on the island of Maui. The crystals are unquestionably some of those that are mentioned by Cross⁴ and other writers as abundant in this locality, and are probably derived from a lava that is perhaps identical with one which is called picritic basalt by Cross, who gives an analysis by Steiger.

The crystals vary from about one half to one centimeter in length, are of a shining jet-black color, and of

¹ Received November, 1921.

² Cf. W. Cross, U. S. Geol. Survey, Prof. Paper 88, 1915.

³ Analysis by G. Steiger, in Daly, Jour. Geol., 19, 295, 1911.

⁴ W. Cross, U. S. Geol. Survey, Prof. Paper 88, p. 28, 1915.

the simple habit which is usually shown by such loose crystals of augite from basaltic rocks. The planes present are: $a(100)$, $b(010)$, $m(110)$, and $s(\bar{1}11)$. Some of the crystals are twinned on the front pinacoid (100). The crystals were measured goniometrically, but subsequent sectioning showed the presence of a surface film, about 0.05 mm. thick, having a much higher refractive index, stronger pleochroism, and other properties, indicating a higher ferric iron content than the rest of the crystal, so that the goniometric measurements cannot be of definite value, and they are therefore not given.

In thin section the color is a very pale gray, almost colorless, but with a faint tinge of green; the pleochroism is so slight as to be scarcely noticeable. Extinction angles were measured on two sections parallel to the side pinacoid (010), cut centrally through two crystals that were twinned on $a(100)$. The angle $\gamma \wedge c = 47^\circ\text{--}48^\circ$ for red ($630\ \mu\mu$), and 49° for blue ($480\ \mu\mu$). For the same wave lengths $2V_r$ measured $61^\circ\text{--}62^\circ$ and $2V_b = 58^\circ\text{--}60^\circ$. The birefringence $\gamma - \alpha$ on these sections was .024; $\beta - \alpha$ (calculated) is .006.

Measurements of refractive indices were made on a sample of the powder prepared for analysis. The lowest value found was 1.695, the highest was 1.727; β was 1.704–1.709. Thus, the following indices represent the material used for the chemical analysis; $\alpha = 1.700$, $\beta = 1.706$, $\gamma = 1.724$.

The density was kindly determined by Dr. L. H. Adams, using a pycnometer and thermostat, on the material used for the analysis. The value obtained was 3.358.

A chemical analysis was made of material carefully separated by heavy solutions and the electromagnet, that was practically free from the outer film and from glass and other inclusions. The powder was dried at 110° . The results are shown in the table of analyses, with analyses of other augites from basalts for comparison. The analysis does not differ materially from those of other augites from basaltic lavas, but the presence of about one-quarter of one per cent of chromic oxide is of interest. Steiger found 0.18 per cent of Cr_2O_3 in the olivine of Mauna Loa, and several analyses of various Hawaiian lavas show that this constituent is present in many of them in readily determinable amounts.

Analyses of augites from basalts.

	1	2	3	4
SiO ₂	47.70	47.06	50.09	50.94
Al ₂ O ₃	6.82	7.77	3.71	3.37
Fe ₂ O ₃	3.36	1.30	1.47	2.05
FeO	4.43	8.15	4.96	7.41
MgO	13.34	13.52	14.01	14.59
CaO	21.35	19.33	22.48	20.34
Na ₂ O	0.65	0.33	0.73	0.61
K ₂ O	0.03	0.11	0.01	0.18
H ₂ O+	0.15	0.20	0.22	0.08
TiO ₂	1.89	1.82	2.11	0.96
Cr ₂ O ₃	0.23	trace	n. d.	n. d.
MnO	0.16	0.20	0.21	0.10
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	100.11	99.85	100.00	100.71
Density	3.358		3.366	3.236

1. Augite, near Red Hill, Haleakala, Maui, Hawaiian Islands, Washington analyst.
2. Augite, near Grant's, Mount Taylor Region, New Mexico, Chatard analyst. J. S. Diller, U. S. Geol. Survey, Bull. 591, p. 149, 1915.
3. Augite, Monti Rossi, Eruption of 1669, Etna, Sicily, Washington analyst. Washington and Merwin, this Journal, 1, 29, 1921. Corrected for 4 per cent of magnetite.
4. Augite, Il Liscione, Stromboli. Washington analyst, Kozu and Washington, this Journal, 45, 467, 1918. Contains 0.08 SrO.

When we attempt the interpretation of the analysis in terms of mineral molecules we are confronted with the question of the disposition of the sesquioxides, that is, the alumina and ferric oxide above the amounts needed to form aemite or possibly jadeite molecules. This is the crux in the interpretation of all aluminous augites, and it is usually met, it is scarcely necessary to say, by the assumption of the existence of the so-called Tschermak molecule (Mg, Fe)O.(Al, Fe)₂O₃.SiO₂. This is not the place for a proper discussion of this vexed matter, which must be postponed to a later occasion when the general subject of the composition of the pyroxenes is taken up. It may, however, be said here that our studies so far have led us to disbelief in the existence of the Tschermak molecule, a conclusion in which we are at one with Boeke⁵ and Zambonini.⁶ We cannot, however, agree with Boeke's conclusion that "the aluminous monoclinic augite is

⁵ H. E. Boeke, Zs. Kryst., 53, 445, 1914.

⁶ F. Zambonini, Atti Acc. Sci. Napoli, 16, No. 2, p. 9, 1914.

essentially a mix-crystal of the components SiO_2 , CaO , $(\text{Mg}, \text{Fe})\text{O}$, and $(\text{Al}, \text{Fe})_2\text{O}_3$ '' whose saturation boundaries are defined according to his tetrahedral projection. According to this view the aluminous augites would differ from the other pyroxenes in the lack of stoichiometric relations or the presence of definite molecules, and would be regarded as indefinite mixtures. Zambonini assumes the presence in the aluminous augites of three general molecules, diopside-hedenbergite (with their components), aemite-jadeite, and spinel. While we agree with him that the augites are best regarded as made up for the most part or almost wholly of the first two mineral molecule groups, yet there are serious difficulties in the way of assuming the presence of a spinel molecule to account for the presence of the sesquioxides. The most important of these, and the only one to be mentioned here, is that combination of the basic RO needed for the spinel would subtract just that amount from the bases needed to satisfy the silica in order to conform to the metasilicate ratio and would leave unsatisfied the equivalent amount of silica. This is especially true of the best analyses of the augites,⁷ and would seem to be an insuperable objection to Zambonini's view of the composition of the aluminous augites.

For various reasons, which it is not necessary to discuss fully here, we assume that, in general, the alumina and ferric oxide (above that needed for aemite-jadeite molecules) are present as such in solid solution with diopside-hedenbergite (with or without clinoenstatite) and aemite-jadeite. As was pointed out many years ago by Piccini,⁸ the Tschermak molecule is equivalent to one of $(\text{Mg}, \text{Fe})\text{O} \cdot \text{SiO}_2$ plus one of alumina or ferric oxide, that is, $\text{RSiO}_3 + \text{R}_2\text{O}_3$. It should furthermore be noted that the assumption of the Tschermak molecule binds an amount of $(\text{Mg}, \text{Fe})\text{O}$, equal to that of the $(\text{Al}, \text{Fe})_2\text{O}_3$, which would otherwise enter into the diopside molecule; this tends to the formation of molecules of wollastonite,

⁷ It may be pointed out that a very considerable number of the analyses of augite used by Boeke (and also by Zambonini), are of very poor quality, either because of incompleteness (as regards titanium and soda especially), or because of inaccuracy in the execution (such as Doelter's analyses of Cape Verde augites). A much more critical and exacting selection of analyses is necessary for study of the problem.

⁸ A. Piccini, *Trans. Acad. Lincei*, (3), 4, 224, 1880. Cf. Zambonini, *op. cit.*, p. 10.

a mineral which must be regarded as but doubtfully pyroxenic, and which does not appear in the recasting of the best analyses of the non-aluminous pyroxenes.

The molecular composition of the Haleakala augite, on the basis assumed by us, and with titanium dioxide reckoned with silica, is as follows:

CaMgSi ₂ O ₆	69.12
CaFeSi ₂ O ₆	15.13
NaFeSi ₂ O ₆	5.08
MgSiO ₃	1.90
FeSiO ₃	0.40
(Al, Fe) ₂ O ₃	8.65
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	100.28

The SiO₂ + TiO₂ demanded by the bases on this interpretation is (molecularly) 0.828 or 49.68 per cent (reckoned as silica), while there was actually found 0.819 or 47.70 SiO₂ + 1.89 TiO₂, that is 49.59 per cent, a fairly satisfactory agreement. The augite is thus essentially a hedenbergite-diopside, with small amounts of acmite, clinoenstatite, and alumina in solid solution.

It may be instructive to give the molecular composition as calculated on the basis of Zambonini's assumption, that the Al₂O₃ is present as a spinel (RO.R₂O₃) in solid solution. The composition on this basis is as follows:

CaMgSi ₂ O ₆	58.97
CaFeSi ₂ O ₆	12.65
NaFeSi ₂ O ₆	5.08
CaSiO ₃	6.61
(Mg, Fe)O.(Al, Fe) ₂ O ₃	12.23
SiO ₂ (excess)	4.20

This interpretation is clearly not as satisfactory as the preceding one, chiefly because of the presence of excess silica, and partly because of the presence of the doubtfully pyroxenic wollastonite molecule instead of the purely pyroxenic clinoenstatite molecule. The presence of both of these somewhat exotic molecules is directly brought about by the assumption of a spinel molecule rather than free alumina and ferric oxide in solid solution.

In calculating the mode from the norm in rock classification, it has been found to be very convenient to calculate the norms of the mafic minerals present in the rock (augite, hornblende, or biotite), the process being the

same as that for the calculation of the norm of a rock, and to use the standard mineral molecules thus obtained for making the necessary readjustments.⁹ The recalculation of norm into mode, or mode into norm, is thus much simpler than if the ratios of the various constituents of the mineral are used, as was advocated in the original publication of the quantitative classification.¹⁰ The norm of the Haleakala augite is given here, as it will be of use in calculating the modes of many Hawaiian, and probably other, lavas.

Norm of Haleakala Augite.

Anorthite	15.57
Nephelite	3.12
Diopside	70.68
Olivine	2.23
Magnetite	4.87
Ilmenite	3.65
Chromite	0.37

Attention may be called to the presence of the outer film of more highly ferric material, which was noted on a previous page. This points to a state of more highly oxidizing conditions in the magma during the last stages of crystal growth. Possibly a similar relation might be detected in other zonally built augite phenocrysts by observation of the differences in extinction angle between the border and the interior, if a definite relation between the extinction angle and the ferric oxide content could be established. The case of our augite seems to be analogous with that of the aegirite-aegirite group, in which it has been often noted that mixed crystals of aegirite and aegirite generally show a border of aegirite with an interior of aegirite. This is readily observable because of the very pale yellow color of aegirite and the bright green, pleochroic color of aegirite. This subject of the higher state of oxidation of the iron in the outer parts of pyroxene crystals suggests some interesting lines of thought, but discussion of them must await another occasion.

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⁹ Cf. H. S. Washington, *The Roman Comagmatic Region*, Carnegie Publication No. 57, p. 134, 1906.

¹⁰ Cross, Iddings, Pirsson, and Washington, *A Quantitative Classification of Igneous Rocks*. Chicago, 1903, p. 211.