ART. XXXII.—*Augite from Stromboli*; by S. KOZU and
H. S. WASHINGTON.

INTRODUCTION.

The crystals of augite that are found loose in the ashes around the crater of Stromboli have been mentioned by several of the geologists who have visited and described the island. It would seem, however, that their optical and chemical characters have not been determined. At least no mention of them is made in the standard handbooks of Dana, Hintze, and Doelter, and we have been unable to find any mention of such data elsewhere in the literature. It was therefore thought that a somewhat detailed study of these crystals along these two lines would be of interest, especially in connection with a projected general study of the pyroxenes from Italian lavas. The optical study was undertaken by Kozu at Tohoku University, Sendai, Japan, and the chemical analyses were carried out by Washington at the Carnegie Geophysical Laboratory at Washington.

The crystals are found loosely scattered, and quite abundant, on and among the fine ashes that cover the slope encircling the active crater terrace.¹ Those examined by us were collected on August 12, 1914, during a visit to the island with Dr. A. L. Day. They came mostly from the ash ridge called Il Liscione, south of the crater terrace, and occur also near the gap between the Serra Vancori and the pile of ancient lava with a recently built hut, which is the head of the usual descent to San Vincenzo. This is called Porta delle Croci, probably, as Bergeat suggests, because of the abundance of the cruciform pyroxene twins. Similar crystals were also present in the masses of scoria and vesicular slag that were ejected by the explosions during our visits to the crater.

The crystals² are small, up to 12 or rarely 15 millimeters long, by about one third or one quarter of the length in thickness. In color they are black or brownish black. They show fairly sharp edges, but the faces are dull, though not pitted. Some of them have very slight

¹ For maps cf. H. S. Washington, *Bull. Geol. Soc. Am.*, 28, p. 249, 1917.

² Cf. A. Bergeat, *Die aeolischen Inseln*, *Abh. Bay. Ak. Wiss.*, 20, p. 46, 1899.

streaks of lava adherent to the surface, but we saw none of the olivine grains mentioned by Bergeat.

As noted by Bergeat, the forms are very simple. Only the planes $a(100)$, $b(010)$,³ $m(110)$, and $s(\bar{1}11)$ were observed. In habit they are elongated in the direction of the vertical axis and, with this modification, are represented by figs. 16, 17, 18 on page 354 of Dana's System. Twinning according to $a(100)$ is common, and inter-penetration cruciform twins, some of them complex and made up of several individuals, are frequent. These have been studied by H. L. Barvir,⁴ who recognizes five twinning laws besides that just mentioned. Though this was not studied by us, it would seem that some of the complex individuals are merely fortuitous intergrowths.

The regular cleavage is fairly perfect and the fracture is conchoidal, both giving bright surfaces. In thin splinters and cleavage flakes the color is a light olive-green. Pleochroism is scarcely discernible.

The specific gravity is 3.243 at 19°, as determined on selected fragments used for the analysis, with the pyknometer of Johnston and Adams,⁵ which is capable of very accurate results.

OPTICAL CHARACTERS.

The three principal refractive indices were determined with Klein's total-reflectometer. The mean values of the observed critical angles for sodium light are as follows:

$$\theta_a = 70^\circ 23.5' \quad \theta_\beta = 70^\circ 58.7' \quad \theta_\gamma = 73^\circ 3.9'$$

The images produced by total reflection were not distinct, owing to hour-glass and zonal structures. However, trials made at different parts of the crystal on different dates showed that the deviations of the indices, caused by the crystal structure mentioned above, fall within the limit of the fourth decimal place. Hence the following values, obtained by computation from the angles given, were taken as the means of the principal refractive indices of the mineral.

$$\begin{array}{l} a = 1.693 \quad \beta = 1.699 \quad \gamma = 1.719 \\ \gamma - a = 0.026 \quad \gamma - \beta = 0.020 \quad \beta - a = 0.006 \end{array}$$

³ This is usually very narrow.

⁴ Cf. abstract in *Zs. Kryst.*, 39, p. 398, 1904.

⁵ Johnston and Adams, *J. Am. Chem. Soc.* 34, p. 566, 1912.

The optic axial angle computed from these indices is $2V = 57^\circ 58.7'$.

If we compare these refractive indices with those⁶ of the augite crystals from the Auvergne and Renfrew, determined by Michel-Lévy⁷ and Lacroix⁸ respectively, it will be seen that the values for the Stromboli augite are much lower than these. It will also be seen that the birefringences ($\gamma - a$) and ($\gamma - \beta$) of the Stromboli augite are higher than those of the others, while the value of ($\beta - a$) is practically equal to them. Hence the optic axial angle of the Stromboli augite must be smaller than those of the others.

In order to prove this, the measurement of the angle was made by the more direct method, using Wülfing's axial angle apparatus.⁹ The mineral section was cut nearly perpendicular to the acute bisectrix and was immersed in a liquid whose refractive index for sodium light was 1.6220. The result obtained is $2H = 61^\circ 24.5'$ for sodium light. $2V$ computed from H , β , and the refractive index of the liquid is $2V = 58^\circ 20.5'$. Comparing this value with that obtained by computation from the refractive indices, the difference between them is $21.8'$, which is so small as to be negligible in this case.¹⁰

	a	β	γ	$\gamma - a$	
Auvergne	1.706	1.712	1.728	0.022	Michel-Lévy
Auvergne	1.712	1.717	1.733	0.021	and Lacroix
Renfrew	1.6975	1.7039	1.7227	0.0252	Wülfing

⁷ Michel-Lévy and Lacroix, *Les Minéraux des Roches*, 1888, p. 265.

⁸ E. A. Wülfing, *Min. petr. Mitt.*, 15, p. 45, 1896.

⁹ Thanks are offered to Prof. B. Koto for his kind permission to make use of the instrument in his laboratory at the Geological Institute, Science College, Tokyo, Imperial University.

¹⁰ The effect on the calculated optic axial angle of errors in the refractive indices is given by

$$dV = \frac{\partial V}{\partial a} da + \frac{\partial V}{\partial \beta} d\beta + \frac{\partial V}{\partial \gamma} d\gamma.$$

Assuming that the refractive indices are each affected by 0.001, we have

$$\frac{\partial V}{\partial a} da = -2^\circ 2' 5'', \quad \frac{\partial V}{\partial \beta} d\beta = +2^\circ 57' 58'', \quad \frac{\partial V}{\partial \gamma} d\gamma = -0^\circ 35' 48''$$

Hence we see that any one of the three values given above is greater than the difference ($21.8'$) between the optic axial angles obtained by the different methods. Supposing that $d\gamma = 0.003$ and $da = -0.001$ when $d\beta$ is the only one which is zero, then $dV = 14.7'$, which is less than the difference above. In such a case, however, the birefringence ($\gamma - a$) must differ to a great extent from that obtained by the total reflectometer. To test this, the compensation method was used as described below and it was proved that the value of ($\gamma - a$) must not differ much from 0.027.

From the close agreement of the results obtained by the two different methods, it follows that the relative values of the three principal refractive indices may be accepted as almost correct, so far as these methods are concerned.

The birefringence ($\gamma - \alpha$) was tested by another method, using Babinet's compensator. In order to eliminate the difficulty of determining accurately the thickness of the mineral plate, a crystal of the Stromboli augite and one of a diopside whose indices¹¹ were carefully determined by the writer (Kozu), were affixed to a glass plate with the side pinacoids (010) parallel to it, and both crystals ground down to equal thickness and with their ground faces in the same plane.

The section thus made was used for the determination of the retardation of light passing through the crystal plates between crossed nicols. The divisions read by the compensator were 1250 ± 10 for the Stromboli augite and 1256 ± 10 for the Sano diopside. Hence, the retardations produced by the two mineral plates are

$$\begin{aligned} 1250 \times \kappa &= 1273.8 \text{ for Stromboli augite,} \\ 1256 \times \kappa &= 1279.9 \text{ for Sano diopside,} \end{aligned}$$

where κ is the constant of the compensator, 1.0190 for the wave length 589 $\mu\mu$. If we take the value of $(\gamma - \alpha) = 0.0274$ for the diopside as the standard, the corresponding value for the augite is approximately 0.027. Though the result obtained by this method is not accurate enough for the discussion of the birefringence in detail, it is sufficiently so to show that the value of $(\gamma - \alpha)$ of the Stromboli augite is higher than those of augites which have been examined by many mineralogists.

The extinction angle ($c \wedge c$) on (010) for sodium light is

¹¹ The refractive indices of two crystals of this diopside, from Sano, Province Kai, Japan, were determined. They are

α	β	γ	$\gamma - \alpha$	2V (obs)	Ext. angle ($c \wedge c$) on (010)
1.6732	1.6795	1.7006	0.0274		
1.6729	1.6793	1.7005	0.0276	58° 32.5'	39°

These crystals commonly occur as large, untwinned phenocrysts, reaching 3 cm. in length, in a dike rock. The mineral is quite fresh, the fractured surface showing a dark green color, and a thin section being almost colorless. In some crystals the marginal part is brown and the center green. The determinations were made on the green crystals. The mineral has been considered to be common augite by Prof. K. Jimbo and others, but without giving any optical data. In its lower refractive indices, higher birefringences, and smaller angles of the optic axes and of the extinction, it resembles much more the diopside from Ala and other localities.

43° 20' with the edge (010) $\wedge$ (100) in the acute angle made by (100) and ($\bar{1}$ 01).

From this description it will be seen that the Stromboli augite is somewhat different from common augite, in the lower refractive indices, in the higher birefringences ($\gamma-a$) and ($\beta-a$), and in the smaller angles of the optic axes and of the extinction. These characters seem to suggest that the Stromboli augite contains somewhat larger quantities of the diopside molecule than common augite.

CHEMICAL CHARACTERS.

The material used for chemical analysis was very carefully selected. A lot of good-sized crystals was coarsely crushed and fragments from the interior, not contaminated by adherent scoria, were picked out by hand under a lens. These were almost quite free from inclusions, very few and small grains of magnetite being seen in some of them. The amount of these was not sufficient to affect the study of the chemical composition. The specific gravity of the selected fragments was 3.243 at 19°. The analysis was carried out by the usual methods. Three precipitations with ammonia were made, to ensure a complete separation of MgO from Al₂O₃. TiO₂ and MnO were determined colorimetrically. The alkalis were determined by the Lawrence Smith method. The results are shown in Column A of Table 1.

TABLE I. ANALYSES OF AUGITES.

	A	B	C	D	E	Aa
SiO ₂	50.94	50.13	50.88	51.27	49.42	.849
TiO ₂	0.96	1.91	1.02	0.70	0.55	.012
Al ₂ O ₃	3.37	7.08	5.36	3.05	4.28	.033
Fe ₂ O ₃	2.05	1.10	1.21	3.08	2.86	.013
FeO	7.41	4.41	4.67	4.34	5.56	.103
MnO	0.10	0.05	trace	0.28	0.10	.001
NiO	n. d.	0.02	n. d.	0.03	n. d.	
MgO	14.59	13.73	13.78	14.21	13.58	.365
CaO	20.34	20.06	22.96	22.58	22.35	.363
SrO	0.08	n. d.	n. d.	none	n. d.	.001
Na ₂ O	0.61	1.88	0.50	0.67	1.04	.010
K ₂ O	0.18	0.25	...	0.06	0.38	.002
H ₂ O+	0.08	0.11	0.34	n. d.	n. d.	
H ₂ O—	...	...	...	none	0.09	
	100.71	100.73	100.72	100.27	100.21	

- A. Augite in basalt; Il Liscione, Stromboli (Aug. 12, 1914), H. S. Washington analyst.
 B. Augite in analcite basalt; Scano, Monte Ferru, Sardinia, H. S. Washington analyst, *Jour. Geol.*, 22, p. 747, 1914.
 C. Augite in andesitic tuff; Monterano, near Bracciano, Italy, F. Zambonini analyst, *Zs. Kryst.*, 40, p. 57, 1890.
 D. Augite in syenitic lamprophyre; Two Buttes, Colorado, W. F. Hillebrand analyst. W. Cross, *Jour. Geol.*, 14, p. 168, 1906.
 E. Augite in shonkinite; Square Butte, Montana, L. V. Pirsson analyst. Weed and Pirsson, *Bull. Geol. Soc. Am.*, 6, p. 410, 1895.
 Aa. Molecular numbers of A.

Calculated in terms of the generally accepted pyroxenic molecules, the Stromboli augite has the following composition:

$\text{Ca(Mg,Fe)Si}_2\text{O}_6$	80.12
$(\text{Mg,Fe})\text{SiO}_3$	7.48
$(\text{Mg,Fe})\text{Al}_2\text{SiO}_6$	7.03
$\text{NaFeSi}_2\text{O}_6$	5.46
	<hr/>
	100.00

That is, it consists very largely of the diopside molecule (with $\text{MgO} : \text{FeO} = 3.5:1$), accompanied by small amounts of the acmite, hypersthene, and Tschermak's aluminous molecules. This composition is in accordance with the conclusions drawn from the optical data above. Whether, with this composition and with its optical characters, it should be called diopside, augitic diopside, or augite, need not be discussed here. For the present the last name has been used, as it is in accordance with Dana's System. The other pyroxenes, of very similar composition, whose analyses are given in the table, are all called augite by their describers. The name diopside may well be reserved for one of the end-members, and augite for intermediate mixtures. It is hoped to take up this question later in conjunction with Dr. H. E. Merwin.

The analyses of the other pyroxenes given, which are considered to be reliable, much resemble in their general features that of the Stromboli mineral. The only notable differences are the somewhat higher values above the others of Al_2O_3 in B, FeO in A, and Na_2O in B. As a matter of interesting comparison, though the subject cannot be discussed here, the analyses of the rocks in which they occur are given in Table II.¹² The differ-

¹² The Monterano augite (C) occurs in an andesitic tuff, of which no analysis is given.

ences in composition, as shown by their analyses and as expressed by the names applied to them, containing much the same augites, is rather striking.

TABLE II. ANALYSES OF THE ROCKS CONTAINING THE AUGITES OF TABLE I.

SiO ₂	50.83	51.05	44.85	50.41	46.73
Al ₂ O ₃	16.66	15.09	12.55	12.27	10.05
Fe ₂ O ₃	1.52	2.07	3.33	5.71	3.53
FeO	6.64	6.88	5.30	3.06	8.20
MgO	6.08	6.52	10.27	8.69	9.68
CaO	10.99	11.34	8.32	7.08	13.22
Na ₂ O	2.66	2.53	4.77	0.97	1.81
K ₂ O	2.05	2.02	0.72	7.53	3.76
H ₂ O +	0.36	0.15	2.01	1.80	1.24
H ₂ O —	...	...	0.95	0.46	...
TiO ₂	0.81	0.83	5.07	1.47	0.78
P ₂ O ₅	1.61	1.44	1.17	0.46	1.52
MnO	0.12	0.13	0.07	0.15	0.28
NiO	n. d.	n. d.	0.23	0.04	n. d.
	100.33	*100.12	99.60	†100.42	‡100.97

* Includes ZrO₂ = none, SO₃ = 0.06, Cr₂O₃ = 0.05.

† Includes V₂O₅ = 0.03, BaO = 0.23, SrO = 0.06. ‡ Includes Cl = 0.18.

A. Basalt scoria; August, 1914, Stromboli, H. S. Washington analyst.
F. A. Perret, this Journal, 42, p. 451, 1916.

B. Basalt scoria; November, 1915, Stromboli, H. S. Washington analyst.
F. A. Perret, *ibid.*

C. Analcite basalt; Scano, Monte Ferru, Sardinia, H. S. Washington analyst, Jour. Geol., 22, p. 748, 1914.

D. Syenitic lamprophyre: Two Buttes, Colorado, W. F. Hillebrand analyst. W. Cross, Jour. Geol., 14, p. 163, 1906.

E. Shonkinite; Square Butte, Montana, L. V. Pirsson analyst. Weed and Pirsson, Bull. Geol. Soc. Am., 6, p. 414, 1895.

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