

OPTICAL PROPERTIES AND CHEMICAL COMPOSITION OF MAGNESIAN ORTHOPYROXENES*

H. H. HESS AND A. H. PHILLIPS, *Princeton University,*
Princeton, New Jersey.

PREFACE

There is urgent need for more accurate chemical and optical data on common rock-forming minerals. Mineralogists have naturally been more interested in seeking and describing the rare, remarkable and beautiful among minerals, and have thus neglected somewhat the everyday minerals with which the petrologist is concerned. A comprehensive investigation to collect such data was begun by the writers in 1934. The present paper is the second article to be published as a result of this plan and a number of others were under way at the time of Professor Phillips' death.¹ These will be completed and published from time to time in the future. In order to call attention to the continuity of the series they will be designated as the "Princeton Investigations of Rock-forming Minerals."

ACKNOWLEDGMENTS

The writers are much indebted to Dr. W. F. Foshag of the U. S. National Museum for permitting us to use his new analysis of the enstatite from the Shallowater meteorite, and for giving us some of the powder from which the analysis was made. Material from the Espedalen enstatite was very kindly given us by Dr. H. E. Merwin of the Carnegie Geophysical Laboratory. Professor B. V. Lombard of the University of Pretoria sent us a piece of the Jagdlust bronzitite, an analysis of which appears in Dr. A. L. Hall's memoir on the Bushveld Complex, and we are also much indebted to Professor Lombard for a new bronzitite analysis and a sample of the rock to accompany it. We wish to thank Dr. E. P. Henderson of the U. S. National Museum for a small amount of the original material of the following previously analyzed pyroxene specimens: Webster bronzite; Johnstown meteorite hypersthene; Nain Labrador hypersthene.

CRYSTALLOGRAPHIC ORIENTATION OF ORTHOPYROXENE

In the previous paper by the writers the crystallographic orientation of orthopyroxene as given by Dana and followed by other American texts, was used. This orientation follows the general rule used for ortho-

* Contribution No. 2. Princeton Investigations of Rock-forming Minerals.

¹ Hess, H. H., and Phillips, A. H., Orthopyroxenes of the Bushveld Type: *Am. Mineral.*, **23**, 450-456 (1938).

rhombic crystals, that the b -axis be intermediate in length between a and c . This orientation makes the angle $110 \wedge \bar{1}\bar{1}0$ equal to approximately 88° and the angle $110 \wedge \bar{1}10$ approximately 92° .^{*} In the clinopyroxenes where the orientation is fixed by their symmetry the angle $110 \wedge \bar{1}\bar{1}0$ is near 92° . It seems, therefore, that it would be much more satisfactory to orient the orthopyroxenes so that they would correspond to the clinopyroxenes, as done in most European texts. This is particularly necessary where intergrowths of the two types of pyroxenes are being considered. The revised orientation considerably simplifies and clarifies the relations. It is, therefore, recommended by the writers that the European orientation be generally adopted in the future, making b the shortest axis and the angle $110 \wedge \bar{1}\bar{1}0$ 92° . With this orientation the optic plane becomes parallel to 100 and the diopsidic lamellae in the orthopyroxenes also lie parallel to this plane. In these respects our previous paper should be revised.

SCOPE OF THIS PAPER

Though data has been collected for the whole range of compositions exhibited by orthopyroxenes only the magnesian end of the series is fully considered at this time. The range from $En_{100}Of_0$ to $En_{70}-Of_{30}$ ² is described.³ Though much data, including a number of new analyses of the more iron-rich orthopyroxenes, are at hand, a number of puzzling relationships have turned up which necessitate further study. Inasmuch as the range En_{100} to En_{70} contains most of the orthopyroxenes commonly found in rocks it was thought advisable to publish this material immediately and hold the remainder until more information could be obtained.

Among the uncertainties encountered in the more iron-rich portion of the series are the following: new optical data and chemical analyses of Bushveld and Stillwater orthopyroxenes, more iron rich than En_{71} , indicating either a discontinuity at about that composition or a marked bend in both the optic angle and index of refraction curves. These orthopyroxenes also have the peculiarity of having two sets of diopsidic lamellae, instead of merely one set, as found between En_{100} and En_{71} in that variety which exhibits the lamellae. One of these sets is the same as that in the magnesian end of the series (parallel to 100), and the other is at a high angle to it, apparently near 112 . Still more iron-rich orthopyroxenes from the Adirondacks, near En_{20} in composition, show only one set, the one parallel to 100.

Certain other orthopyroxenes described in the literature suggest no

^{*} Angle between the poles of these faces.

² Of-orthoferrosilite, see Henry, N. F. M.: *Mineral. Mag.*, **24**, 221-226 (1936).

³ For those analyses quoted from the literature the optical properties in every case were determined or redetermined by the writers on material from the original samples.

bend or break in the curves at En_{71} so that perhaps there may be two types of iron-rich hypersthene, one identical in structure with those described in this paper and another different in structure. The analyses now available show no marked chemical differences between the two types.

It is hoped that these problems will be cleared up during the coming year and the results published.

CHEMICAL ANALYSES

Larsen⁴ has recently discussed the accuracy of chemical analyses of silicates. There has been a general tendency among petrologists to fail to evaluate the degree of error in such analyses. In the present case the materials analyzed are rather simple and do not involve such complicating elements as F and B, so that chemical analysis should be relatively easy. There seems to be a tendency however, for CaO to be low in the analyses, presumably some of the CaO goes into the magnesia precipitate, unless special precautions are taken. It seems likely that the gamma index of orthopyroxenes can be determined with such precision that it gives a more accurate figure for the MgO/FeO ratio in orthopyroxenes than does a first-class chemical analysis. The scattering of the points on either side of the gamma index curve is probably largely the result of slight errors in the chemical analyses, and to a lesser extent it is due to errors in the optical work or the effects of minor constituents.

It is very difficult to obtain a perfect separation of a rock-mineral from the other constituents of the rock. On the specimens prepared in this laboratory the chief method of removing impurities was by repeated separations in a Franz isodynamic magnetic separator. Hand picking and heavy liquid separations were used as well in some cases. If only a small percentage of impurities are present in the sample analyzed, and *their amount and composition* known with a fair degree of accuracy, no great disadvantage is encountered as the analysis may be recalculated minus these constituents. In this case, however, there will be some uncertainty concerning minor constituents present in the bulk analysis in very small amounts.

The three analyses given in Table 1 below are considered thoroughly reliable in every respect. They have been made by experienced analysts of well-known reputation. The materials analyzed have been examined by the authors. They are practically free of all impurities.

These three analyses are about evenly spaced along the range of compositions investigated. They have been used as key specimens for the determination of the gamma index curve and have been given more

⁴ Larsen, Esper S., *Am. Jour. Sci.*, **35**, 94-103 (1938).

weight in determining the position of the curve than the other analyses. No doubt some of the remaining nine analyses given in Table 2 are of equal quality. In others the amount and nature of the impurities is not known with sufficient accuracy and slight errors in analysis are suspected. Nevertheless all of the analyses may be considered reasonably reliable and of high quality as mineral analyses go. Data are given in the notes on each analysis concerning the impurities present, their amount and the accuracy with which this is known, and remarks are made regarding any known or suspected deficiencies of the analyses themselves.

In several cases a slight alteration of the orthopyroxene to a colorless or pale green amphibole has been noted. Fortunately this alteration does not change the bulk composition very much and may, as a rule, be neglected. The MgO:FeO:CaO ratios do not seem to be appreciably disturbed, though there may be a slight reduction in the amount of SiO₂ present and an increase in H₂O. Inasmuch as the curves are based on the MgO:FeO ratio they are not affected.

In a general way, but with no great regularity, TiO₂ and MnO increase with increase in FeO. CaO increases with increase in FeO from enstatite to En₅₀, or thereabouts, and then probably decreases again (Fig. 4).^a Al₂O₃ shows a tendency to increase with increase in FeO from enstatite to En₅₀Of₅₀, but varies rather irregularly. Fe₂O₃ is very low in pure enstatites but shows no marked variation through the range of hypersthènes to orthoferrosilite.

TABLE 1

	1	2	11
SiO ₂	59.92	57.28	51.81
Al ₂ O ₃	.00	0.90	2.16
Fe ₂ O ₃	.00	0.42	4.52
FeO	0.38	6.43	13.96
MgO	39.51	34.94	24.57
CaO	0.32	0.13	1.95
Na ₂ O	.00	0.22	0.39
K ₂ O	—	0.01	0.03
H ₂ O+	—	0.13	0.19
H ₂ O—	—	—	—
TiO ₂	—	0.05	0.76
P ₂ O ₅	—	—	—
Cr ₂ O ₃	—	—	—
MnO	—	tr	0.16
	100.13	100.51	100.50

^a Excluding those orthopyroxenes which occur in rocks deficient in CaO, and some that have crystallized at lower temperatures than normal.

$\frac{\text{En}}{\text{En}+\text{Fs}} \times 100$	99.5	90.8	76.0
$\frac{\text{Di}}{\text{Di}+\text{Hy}} \times 100$	1.1	0.4	8.3
γ	1.6592	1.6750	1.6967
β	1.6525	—	—
α	1.6508	—	—
$\gamma - \alpha$.0084	—	—
2V	54 $\frac{1}{2}$ °	—	(79 $\frac{3}{8}$ °)
Optic Sign	+	+	—
Lamellae	—	—	+
SiO ₂	59.84	56.98	51.55
Al ₂ O ₃	.00	0.90	2.15
Fe ₂ O ₃	.00	0.42	4.50
FeO	0.38	6.40	13.89
MgO	39.46	34.76	24.45
CaO	0.32	0.13	1.94
Na ₂ O	.00	0.22	0.39
K ₂ O	—	0.01	0.03
H ₂ O	—	0.13	0.19
TiO ₂	—	0.05	0.75
P ₂ O ₅	—	—	—
Cr ₂ O ₃	—	—	—
MnO	—	tr	0.16
	100.00	100.00	100.00

1. Enstatite, Shallowater meteorite. Analyst W. F. Foshag. No impurities.

2. Enstatite, Espedalen Norway. Analyst Washington. No impurities. (Optic angle could not be determined because material was ground to a fine powder and grains were too small to measure on the universal stage. Index determination with a high power objective presented no difficulty). Reference: Washington & Merwin, *Am. Mineral.*, **8**, 63-64 (1923).

11. Hypersthene, Nain, Labrador. Analyst Washington, No impurities. Optic angle abnormal. Reference: same as preceding analysis.

TABLE 2

	3	4	5	6	7	8	9	10	12
SiO ₂	53.61	55.76	55.60	55.40	54.68	53.60	53.65	52.16	53.20
Al ₂ O ₃	1.67	1.66	2.96	1.60	1.80	3.51	1.03	3.91	2.24
Fe ₂ O ₃	1.48	1.34	1.19	.00	0.50	0.79	1.59	—	0.83
FeO	6.70	7.17	6.97	9.35	9.19	11.38	13.82	13.39	15.15
MgO	33.15	32.42	29.45	32.45	30.19	25.34	27.69	27.60	24.58
CaO	2.32	0.74	2.37	0.45	2.22	4.19	1.06	1.97	2.61
Na ₂ O	0.04	0.03	0.69	tr	0.04	0.25	0.03	—	0.06
K ₂ O	0.06	0.04	0.21	tr	0.03	0.03	0.00	—	0.01
H ₂ O+	0.54	0.43	0.26	0.00	0.46	0.27	0.51	—	0.48
H ₂ O-	0.08	0.08	0.02	0.15	0.05	0.04	0.01	—	0.10
TiO ₂	0.09	tr	—	0.10	0.11	0.29	0.18	—	0.26
P ₂ O ₅	tr	0.10	0.02	0.20	0.02	—	—	—	tr
Cr ₂ O ₃	0.38	0.33	0.62	0.65	0.47	—	0.30	0.69	0.10
MnO	0.16	0.21	0.20	0.15	0.21	0.19	—	0.56	0.32
	100.28	100.31	100.56	100.60*	99.97	99.88	99.87	100.28	99.94
$\frac{100 \text{ En}}{\text{En}+\text{Fs}}$	89.7	88.7	88.4	86.3	85.6	79.4	78.6	76.9	74.5
$\frac{100 \text{ Di}}{\text{Di}+\text{Hy}}$	8.5	2.8	7.6	5.6	8.4	8.7	4.2	7.8	10.6
γ	1.6770	1.6790	1.6798	1.6816	1.6826	1.6920	1.6930	1.6959	1.6985
β	—	1.6733	—	—	—	—	—	1.6921	—
α	—	1.6679	—	—	—	—	—	1.6837	—
$\gamma-\alpha$	—	0.0111	—	—	—	—	—	0.0122	—
2V	87 $\frac{1}{4}$ °	89 $\frac{1}{2}$ °	88 $\frac{1}{4}$ °	86°	83 $\frac{1}{2}$ °	73 $\frac{1}{4}$ °	70 $\frac{1}{2}$ °	69 $\frac{1}{4}$ °	65 $\frac{3}{4}$ °
Optic Sign	+	—	—	—	—	—	—	—	—
Lamellae	+	weak	+	+	+	+	+	—	+
SiO ₂	53.46	55.58	55.38	54.49	54.70	53.66	53.72	52.01	53.23
Al ₂ O ₃	0.67	1.65	1.70	1.57	1.80	2.15	1.03	3.90	2.24
Fe ₂ O ₃	1.48	1.34	1.24	.00	0.50	0.85	1.59	—	0.83
FeO	6.68	7.15	7.27	9.20	9.19	12.34	13.84	13.35	15.16
MgO	33.05	32.32	30.69	31.92	30.20	27.47	27.73	27.52	24.60
CaO	2.31	0.74	1.85	1.48	2.22	2.19	1.06	1.97	2.61
Na ₂ O	0.04	0.03	0.48	tr	0.04	0.07	0.03	—	0.06
K ₂ O	0.06	0.04	0.22	tr	0.03	0.03	0.00	—	0.01
H ₂ O	0.54	0.51	0.29	0.15	0.51	0.34	0.52	—	0.58
TiO ₂	0.08	tr	—	0.10	0.11	0.12	0.18	—	0.26
P ₂ O ₅	tr	0.10	0.02	0.20	0.02	0.02	—	—	tr
Cr ₂ O ₃	0.38	0.33	0.65	0.64	0.47	0.53	0.30	0.69	0.10
MnO	0.16	0.21	0.21	0.15	0.21	0.23	—	0.56	0.32
	100.00	100.00	100.00	100.00*	100.00	100.00	100.00	100.00	100.00

* NiO 0.10.

3. Enstatite MVL3a, Stillwater Complex, Montana. Analyst Phillips. From chromite horizon at Mountain View lake. Large, poikilitic crystals including olivine and chromite. Impurity, a little chromite.

4. Enstatite, Webster, North Carolina. Analyst Phillips. Separated from diopside in Websterite. No impurities.

5. Bronzite 91, Bushveld Complex. Rock analysis. Analyst C. F. v. d. Walt. Impurities 4.4 per cent plagioclase of approximately An_{56} composition and $\frac{1}{2}$ per cent diopside. Recalculated analysis corrected for these. CaO redetermined by Ellestad on orthopyroxene, free of impurities equals 1.85%. Reference, L. G. Boardman, not published.

6. Bronzite, Jagdlust, Bushveld Complex. Rock analysis. Analyst H. G. Weall. Impurities 0.20 per cent diopside. CaO redetermined by Ellestad equals 1.48 per cent. Original analysis deficient in this respect. Recalculation somewhat uncertain. Reference: A. L. Hall. The Bushveld Igneous Complex: *Geol. Surv. Union S. Af.*, mem. **28**, 315 (1932).

7. Bronzite 465E3h, Stillwater Complex. Analyst T. Kameda. Rock analysis. Impurities a little chromite and two per cent of olivine approximately Fo_{86} . Corrections for impurities made in recalculated analysis. Some alteration to colorless amphibole. Reference: J. W. Peoples. The Stillwater igneous complex. Ph.D. thesis. Princeton University (1932).

8. Hypersthene EB32a, Stillwater Complex. East Boulder Plateau. Analyst Phillips. Impurities rather high,⁵ 5 per cent plagioclase An_{80} and 4 per cent diopsidic pyroxene. CaO redetermined by Phillips on pure material, equals 2.19 per cent. Analysis recalculated minus above impurities.

9. Hypersthene 374, Bay of Islands Complex, Newfoundland. Rock analysis. Analyst A. Willman. Impurities: some alteration to colorless amphibole (8%), which probably does not alter chemical composition appreciably, and a little chromite and iron sulfide present (2%). Reference: J. R. Cooper: *Newfoundland Dept. Nat. Res. Geol. Sect., Bull.* **4**, (1936).

10. Hypersthene, Johnstown meteorite, Colorado. Analyst E. V. Shannon. No impurities. Reference: E. O. Hovey, *Am. Mus. Novitat.*, **203** (1925).

12. Hypersthene, EB43, Stillwater Complex. Analyst R. B. Ellestad. Impurities, less than $\frac{1}{2}$ % diopside and labradorite, no correction made in recalculation.

Note: Analyses 7, 9 and 12 made at Rock Analysis Laboratory, University of Minnesota. Analysis 5 published by permission of the Director of the Geological Survey of the Union of South Africa.

OPTICAL PROPERTIES

1. Determinative methods

(a) Index of refraction determinations.

As Walls⁶ points out the gamma index of orthopyroxenes can be determined with the greatest ease and accuracy, because practically all of the fragments in crushed grains lie on a 110 cleavage face. These are parallel to the *c*-axis and therefore parallel to the direction of the gamma index. The determinations of gamma were made on a temperature-control stage. Curves were made for change in index with temperature for the several immersion liquids used in these determinations. The grains were then mounted on the temperature-control cell and the temperature

⁵ This was the first specimen separated for analysis. Some plagioclase dust remained in the final separate. The sample should have been washed to remove dust as was done in all other cases. An estimate was made of the amount of dust but it could not be very accurate.

⁶ Walls, R., *Mineral. Mag.*, **24**, 165-172 (1935).

noted at which the index of the liquid and gamma of the pyroxene were equal. (The liquids were so chosen that little variation from room temperature was necessary.) This can easily be done with an accuracy of $\frac{1}{2}^{\circ}$ to $\frac{1}{4}^{\circ}$ C. in temperature, or .00025 to .0001 in index. A sodium vapor lamp was used as a source of light for all determinations. The accuracy for the gamma index determinations is certainly better than $\pm .0005$. In any rock, even with complete lack of zoning in the pyroxene, there is a slight variation in composition of various crystals. Determinations must be made on from 6 to 25 grains so that the average will correspond to the analysis. The number of determinations necessary is dependent on the degree of variability of the crystals in a given specimen. A difference in index between two grains, of as little as .0002, can easily be noted in these determinations.

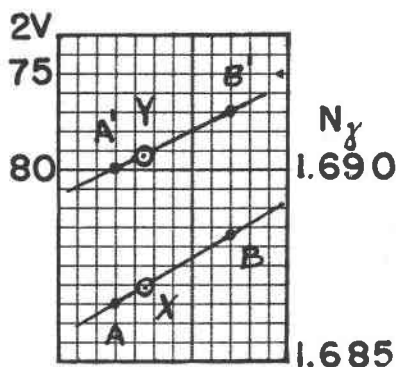


FIG. 1. The lower curve represents the values for the gamma index of refraction with change in composition. Point X represents the average value of gamma for a given specimen. Points A and B indicate the gamma index of two grains from the specimen. Points A' and B' represent the optic angle of the same two grains. Point Y then represents the value for 2V equivalent to point X on the gamma index curve, or the average value of 2V for the specimen under consideration.

The alpha and beta indices were not determined directly, since it was found to be far more accurate to determine the index of the direction perpendicular to gamma on the 110 cleavages and calculate the other two principal indices after 2V was determined. The figures for birefringence were also taken from this determination. It is not necessary to make more than two or three determinations of the index perpendicular to gamma, if gamma was determined on the same grains. In this case the gamma found on the grains can be compared to the average value for gamma, and the values alpha and beta adjusted slightly to the value for average gamma along already determined curves, as shown in Fig. 1.

A similar procedure was used in determining the average optic angle to eliminate the necessity of measuring this angle on as many as 25 grains in extreme cases.

(b) Optic angle determinations.

Optic angle determinations were made on a universal stage in sodium light. A grain was rotated until the prism cleavage was north-south. If diopside exsolution lamellae are present it is merely necessary to rotate on the north-south axis until the lamellae are perpendicular, bringing the optic plane perpendicular and Bx_a practically vertical (in the case of enstatite Bx_0). If no lamellae are present the usual universal stage method of grain orientation is employed. After rotating the stage to the 45° position the angle between the optic axis emergence positions (extinction positions) was measured directly. The accuracy of this observation is probably better than $\pm 1^\circ$ for orthopyroxenes.

In the case of enstatite (the Shallowater meteorite specimen) the optic angle had to be determined in thin section, since the angle was small and could not be reached from the prism zone. The determination was not very accurate for two reasons: (1) the birefringence was low so that the extinction position representing the emergence of an optic axis was not very definite. (2) The rate of change of this angle with slight change in composition ($\frac{1}{2}\%$) was so rapid that it was difficult to get a satisfactory average value.

2. *Optical properties and chemical composition*

A number of trial curves were drawn to test the effects of different chemical constituents on the optical properties of the orthopyroxene series. It was found that the variation of properties was controlled almost entirely by the $MgO \cdot SiO_2 / Fe(Mn)O \cdot SiO_2$ ratio, and the final curves are based entirely on it.⁷ Determination of the gamma index of refraction is the easiest and most accurate method of finding the En:Of ratio of an orthopyroxene. The gamma index value seems to be practically independent of the Al_2O_3 , Fe_2O_3 , Cr_2O_3 , TiO_2 and alkalis contained in the mineral in small but variable amounts. Where lamellae of diopside pyroxene are present the CaO is probably contained almost exclusively in the lamellae, so it can have no effect on the optical properties of the orthopyroxene host. Where the lamellae are absent and one to three per cent of CaO is contained in the orthopyroxene, it still does not seem to make an appreciable change in the optical properties, and so may be neglected. With reasonable care the En:Of ratio of an orthopyroxene

⁷ This is in accord with the conclusion reached by Henry for the more iron-rich orthopyroxenes: Henry, N. F. M., *Op. Cit.*

2 P

may be determined from the gamma index with an accuracy of $\pm \frac{1}{2}$ per cent provided a sufficient number of grains are examined to insure that the determination represents a true average for the specimen. Washington and Merwin⁸ state that Al_2O_3 and Fe_2O_3 should be considered as present in solid solution in the orthopyroxene and are not present in a separate molecule, such as the Tschermak molecule. The lack of effect of these trivalent oxides, as well as the other oxides mentioned above, with the possible exception of CaO , on the optical properties of orthopyroxenes, suggests that these oxides present in small amounts may merely be included in holes in the crystal lattice and do not themselves form part of the lattice. It is interesting to note that Cr_2O_3 is present in all specimens on which analysis for that oxide was performed, though the amount is small, probably less than one half per cent in all cases except where actual minute inclusions of chromite can be observed. Nickel was determined for only one specimen. Only one tenth of a per cent was found.

A rapid determination of the En:Of ratio can be made on thin sections without resorting to the slower immersion methods. This can be done by measuring the optic angle, $2V$, on a universal stage. The accuracy of this method is about \pm one per cent. In certain cases it is unreliable. In the deformed *but not recrystallized* hypersthene-bearing anorthosites and gabbros of the Adirondacks and Labrador many of the orthopyroxenes have abnormally large optic angles, departing by as much as 15° from the curves given in this paper. This appears to be the result of strain in the orthopyroxene. Where the rocks are not deformed or deformed to a greater extent and recrystallized, the optic angles are normal. Many optic angle determinations reported in the literature are high compared to the curve here presented. Though further investigation seems necessary to account definitely for these, all specimens exhibiting an anomalous $2V$, which have been examined by the writers, are in such deformed rocks as described above.

A rough test of the accuracy of the optical property determinations and of the inference that the En:Of ratio controls the properties may be made by plotting a curve with $2V$ in one direction and N_γ in the other (Fig. 3). If it be assumed that the points which are not on the curve are displaced from it because of errors in optical determinations, an error of $\pm .0005$ in gamma and 1° in optic angle would be sufficient to account for those points which are farthest displaced from the curve. The curve itself was drawn by reading values from the N_γ curve and $2V$ curve in Fig. 2 (this procedure tends to iron out errors of individual determinations and gives a smooth curve) and then plotting the values for individ-

⁸ Washington & Merwin: *Am. Jour. Sci.*, 3, 119 (1922).

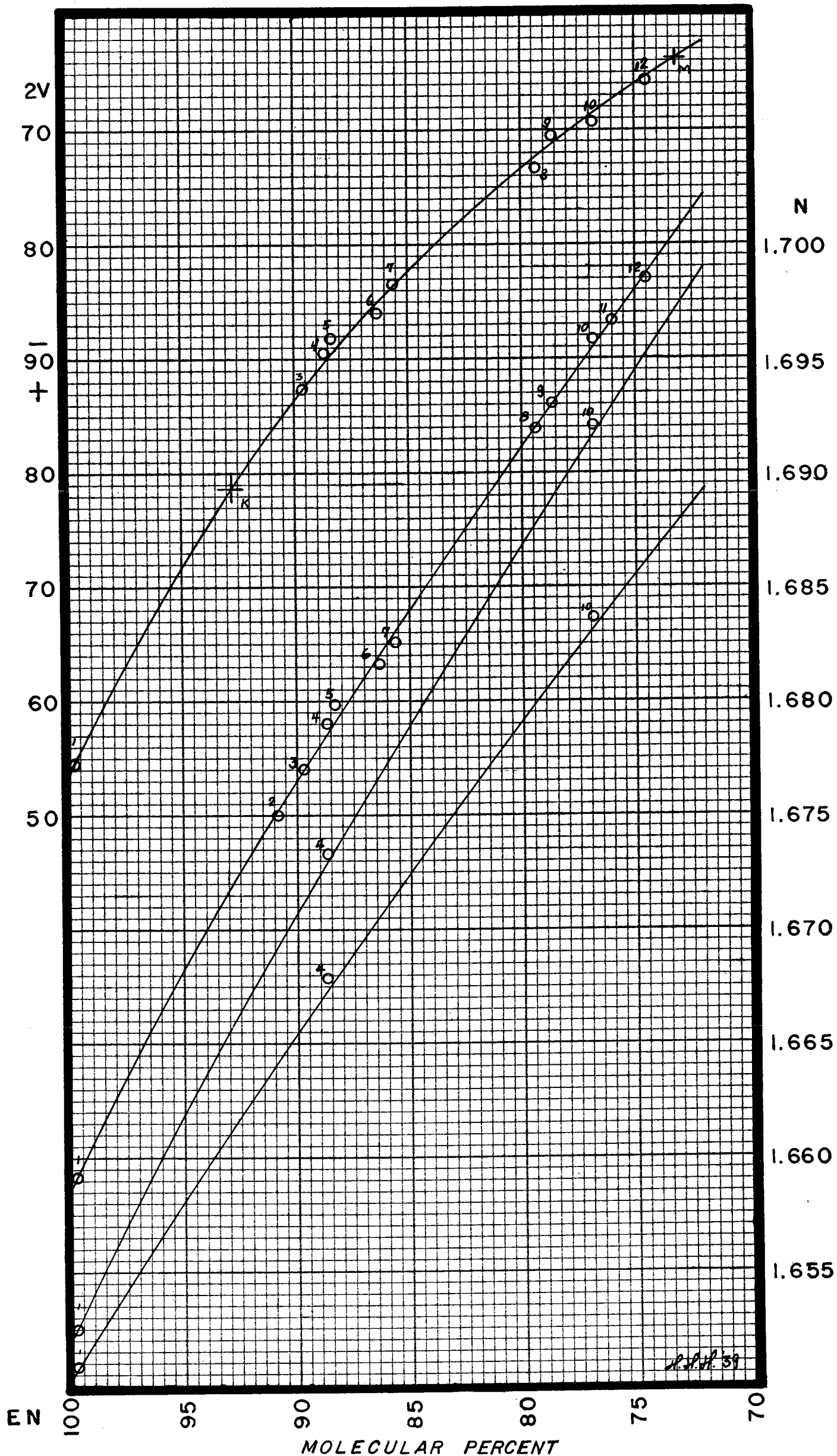


PLATE I

ual grains on the graph. The points plotted include not only the analyzed specimens but a number of other orthopyroxene specimens, on which 2V and gamma were determined as listed in Table 3. If part of the scattering of points on either side of the curve is due to the effects of minor constituents this effect must be exceedingly small.⁹

TABLE 3

	N gamma	2V	Sign	Occur- rence
13. Kupferberger enstatite	1.6719	78.5°	-	P
14. Bonin Islands bronzite	1.6805	87.5	+	V
15. Stillwater St-1 bronzite	1.6821	86	+	P
16. Webster N.C. 2 bronzite	1.6823	85.5	+	P
17. Bushveld 7704 bronzite	1.6820	84.5	+	P
18. Stillwater EB42 hypersthene	1.7010	73.5	+	P
19. Bushveld Pyramids norite 7493 hypersthene	1.7110	53	+	P
20. Stillwater, hornfels? EB89 hypersthene	1.7160	48	+	M
21. ¹ Dominica I. andesite ferrohypersthene	1.7210	45.2	+	V
22. ¹ Dominica I. andesite ferrohypersthene	1.7214	45.6	+	V
23. ¹ Dominica I. andesite ferrohypersthene	1.7221	47.2	+	V
24. ¹ Dominica I. andesite ferrohypersthene	1.7240	48	+	V
25. ² Glen Buchat, contaminated norite, ferrohypersthene	1.731	51	+	P,M
26. ² Loch Duich ferrohypersthene	1.755	68	+	M
27. ² Vittinki, eulysite, ferrohypersthene	1.757	70	+	M
28. ² Tunaberg, eulysite, ferrohypersthene	1.768	81	+	M
29. ² Mansjö Mt., eulysite, ferrohypersthene	1.769	83	+	M

P = Plutonic igneous rock. M = metamorphic work. V = volcanic igneous rock.

¹ Determinations somewhat less accurate on account of zoning.

² Quoted from Henry, *op. cit.*

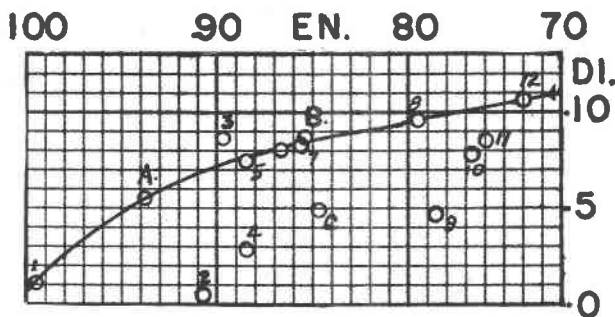


FIG. 2

⁹ Inasmuch as this curve is independent of the composition of the orthopyroxene (no analyses are needed to construct it) it is drawn for the whole known range of these pyroxenes and not limited to the magnesian end of the series.

OCCURRENCES OF ORTHOPYROXENES WITH AND WITHOUT LAMELLAE

Orthopyroxenes of plutonic igneous rocks normally show well developed diopsidic lamellae. In volcanic rocks the lamellae are absent though rare exceptions have been found where they are present to a limited extent. Kuno,¹⁰ for example, has described a phenocryst in a lava from Japan which shows lamellae at its core, the outer portions being free of lamellae. Evidently rapid cooling prevents exsolution of the diopsidic

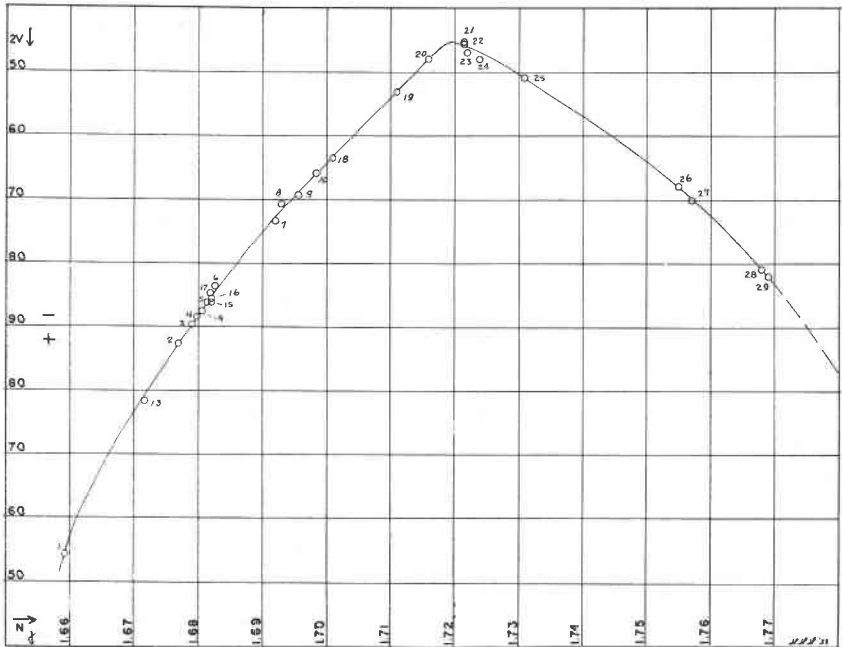


FIG. 3

material to form the lamellae. The absence of lamellae is not due to any difference in composition between orthopyroxenes of plutonics and effusives. The lamellae are also present in certain very high temperature hornfelses (perhaps 1000°C.) such as those found along the floors of the Stillwater Complex and the Duluth gabbro. In other metamorphics, as for example the recrystallized hypersthene-bearing rocks of the Adirondacks, no lamellae are found. In this case the absence of lamellae cannot be due to rapid cooling. It seems more likely that the metamorphic recrystallization, during which the hypersthene was formed, took place at a temperature below the level at which diopside is appreciably soluble in

¹⁰ Kuno, H., *Proc. Imp. Acad. Tokyo*, **14**, 218 (1938).

hypersthene. If this is true the hypersthene should have little or no CaO. No chemical analyses are available at present to check this conclusion. There is, however, a considerable body of indirect evidence to support the hypothesis.

The enstatites and bronzites of many ultramafic igneous rocks of the type which Hess has suggested are derived from an ultramafic magma have lamellae. In many (but not all) cases these orthopyroxenes have conspicuously fewer lamellae than normal and some of the chemical analyses (numbers 4 and 9) show a deficiency of CaO as compared with the orthopyroxenes of other plutonics (Fig. 2). This may result from the fact that the magma has very little CaO. In those cases where little orthopyroxene is present there may be enough CaO to permit the usual amount of CaO to go into the pyroxene, but where a greater amount of orthopyroxene is present there may be a deficiency in CaO so orthopyroxenes with few lamellae may result.¹¹

In orthopyroxene-bearing rocks intruded at shallow to moderate depths, lamellae may or may not be present. As a rule a poor development of lamellae has been noted. These lamellae are less regularly distributed through the crystal and tend to be more irregular in form than in the plutonics. In the plutonics they resemble fine, straight, ruled lines when the 010 face of a crystal is examined under crossed nicols. In the hypabyssal rocks some "lines" which are less regular and some oriented globs or quadrilateral areas of diopsidic pyroxene may be seen, and all these are mainly confined to the cores of the crystals.

The writers have noted orthopyroxenes with well-developed lamellae in rocks of the following localities: Stillwater Complex, Montana; Bushveld Complex, South Africa; Bay of Islands Complex, Newfoundland; Baltimore gabbro, Maryland; high temperature hornfels along the floors of the Stillwater Complex and Duluth gabbro; pegmatite, Roseland, Virginia; anorthosites and gabbros, Labrador; peridotites of Cuba and the Appalachians; and the anorthosites and gabbros of the Adirondacks (not recrystallized) and norites of the Harz Mountains.

Orthopyroxenes without lamellae were noted in the following localities: Lesser Antilles volcanics; Bonin Islands volcanics; trachytes, Hungary; porphyries, Harz Mountains; recrystallized rocks of the Adirondacks and pyroxene granulites of Saxony. Poorly developed lamellae are present in the Palisades diabase orthopyroxene. (This sill was intruded into Triassic sediments in Triassic time. Its depth could not have been more than two or three miles from the surface at a maximum.)

¹¹ Crystallization of the magma at a low temperature would also account for the lack of CaO in the orthopyroxene since less diopsidic material would be soluble in the orthopyroxene.

The hypersthene andesites of Tokaj, Hungary, show an incipient development of lamellae.

PETROLOGIC APPLICATIONS

Orthopyroxenes without lamellae are present in volcanic igneous rocks and in certain metamorphic rocks recrystallized at high temperatures (probably in the neighborhood of 600°C.). In the first case the lamellae are absent because rapid cooling has prevented exsolution of the diopsidic material contained in them. A large number of chemical analyses available in the literature show that the diopsidic content of these orthopyroxenes is the same as those which do have lamellae. In the second case mentioned above, certain high temperature metamorphic rocks, the absence of lamellae is presumably the result of recrystallization of orthopyroxene at a temperature below which diopside is soluble in hypersthene. These should contain little or no diopsidic material.

The presence of hypersthene without lamellae in the heavy mineral concentrates of sediments, particularly if the grains show traces of original crystal outlines, is almost certain proof of a source of the sediments from an area at least partly covered by volcanics. The metamorphic hypersthene without lamellae are relatively rare and seldom show crystal outlines. They are generally irregular anhedral grains. A test for CaO might distinguish between the two varieties, but as a rule geologic relations in the possible source areas will rule out one type or the other so that there is little chance for confusion. This criterion for distinguishing a volcanic source is important because none of the other minerals common in sedimentary heavy mineral suites is diagnostic of volcanics. In present day sediments hypersthene makes up roughly half of the heavy mineral suite of beach sands of the Lesser Antilles volcanic islands. It has been used successfully to indicate a partly volcanic source in various Tertiary sediments in the Caribbean region by one of the present authors.

The fact that stony meteorites contain orthopyroxenes without lamellae and that analyses of them prove that dissolved diopside is present (7.8 per cent in the Johnstown meteorite, analysis above) indicates rapid cooling of meteorites analogous to that of volcanics.

ORTHOPYROXENE NOMENCLATURE

In view of the more precise optical data now available a revised nomenclature for members of the enstatite-orthoferrosillite series is suggested on the opposite page.

Optically positive	$En_{100} - En_{88\frac{1}{2}}$	Enstatite
Optically negative	$En_{88\frac{1}{2}} - En_{80}$	Bronzite
	$En_{80} - En_{60}$	Hypersthene
	$En_{60} - En_{12\pm}$	Ferrohypersthene
Optically positive	$En_{12\pm} - En_0$	Orthoferrosilite