ORTHOPYROXENES OF THE BUSHVELD TYPE*

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The orthopyroxenes of the Bushveld Complex, Transvaal; Stillwater Complex, Montana; Bay of Islands Complex, Newfoundland; Great Dyke of Southern Rhodesia; peridotites of Cuba and most of the other mafic plutonic bodies thus far examined by the writers, have a peculiar striated or laminated appearance in a thin section and exhibit certain abnormal extinction angles. Much confusion concerning these pyroxenes exists in the literature. Niggli, Johannsen, Scholtz, and Chudoba, for example, state that the optic plane is parallel to 100, whereas Larsen, Winchell, Dana, and others place the optic plane of orthopyroxenes parallel to 010.† The laminated appearance and small extinction angles have been considered to be the result of twinning on a very fine or submicroscopic scale; and the mineral, though outwardly appearing to be orthorhombic, is interpreted as monoclinic. Chudoba suggests that the lamination is due to polysynthetic twinning with translation parallel to 100 (1).

The purpose of this paper is to give an explanation for the lamination, anomalous extinction angles and optical orientation of the constituents, as well as to present data on the chemical composition and optical properties of a few typical examples of such pyroxenes. Certain conclusions are drawn as to the physical chemistry of their crystallization with respect to their mode of occurrence.

DISCUSSION OF OPTIC PROPERTIES

A careful examination of these orthopyroxenes in thin section definitely shows that the lamination is entirely due to the presence of very fine lamellae of another mineral. These lamellae form closely spaced thin sheets, about .002 mm. thick, parallel to the optic plane of the orthopyroxene. It is difficult to determine the orientation of the optic plane, and not surprising that there is disagreement as to whether it is parallel to 100 or 010. One must determine from a basal section whether the optic plane bisects the obtuse angle (92°) of the prismatic cleavages or the acute (88°).[1] In the former case the optic plane is parallel to 010, and

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* Contribution No. 1 of a series of papers under preparation by the writers dealing with the optical and chemical properties of rock-forming minerals. Index of refraction and optic angle curves for the orthopyroxenes will be dealt with in a later paper and therefore are not included here.

† See footnote at end of paper.

[1] In some cases where the pinacoidal partings are present, the obtuse angle between the apparent prismatic cleavages seems to be abnormally large, as though they were not true cleavages but sets of cracks diagonal to the two directions of parting.

in the latter to 100. The prismatic cleavages often appear slightly irregular in thin section, and the difference between 92° and 88° is not very great. Obviously the determination must be made on a section exactly perpendicular to the cleavages, or one rotated to that position on a universal stage. A number of such determinations made by the writers on a pyroxene from the Stillwater and Bay of Islands show the optic plane to be parallel to 010.

Nature of the Lamellae

The lamellae have approximately the same mean index as the orthopyroxene host (regardless of the proportion En:Fs in the host) since they are barely visible, if at all, in plane polarized light, and have somewhat higher birefringence. They have large extinction angles, so it
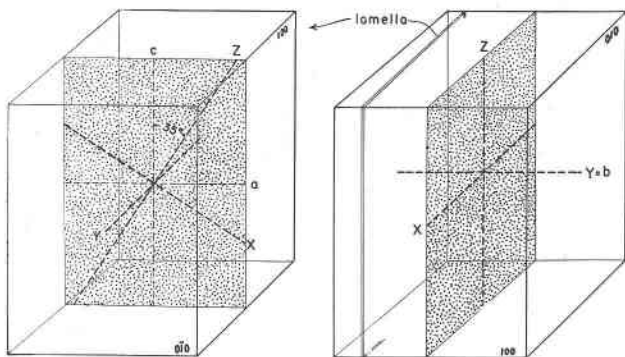

Fig. 1

appears that they are monoclinic pyroxenes, probably of the diopside-hedenbergite series with approximately the same Mg/Fe ratio as the host. The orientation of the lamellae is such that the "*a*" axis of the orthopyroxene coincides with the "*b*" axis of the clinopyroxene lamellae, and the optic plane of the clinopyroxene is parallel to 100 of the orthopyroxene, as shown in Fig. 1.

Effect of Lamellae on Optical Properties

A large proportion of sections of random orientation will have a banded appearance under crossed nicols, and adjacent bands will extinguish in different positions making angles which will commonly lie between 0° and 15° from the trace of the cleavages. If an attempt is made to locate the principal optical directions on two such adjacent bands by standard universal stage methods, one would find that two, or perhaps all three, of these directions would fall on the stereographic

projection at slightly different points. From such observations one might logically conclude that we were dealing with a polysynthetically twinned pyroxene of monoclinic rather than orthorhombic crystal structure. Scholtz (2) shows such a projection. Actually one would be observing a composite effect produced by the lamellae and orthopyroxene when viewed from a position where the lamellae are dipping at low to moderate angles to the plane of the section. In such sections a definite outcrop of the lamellae is not seen.
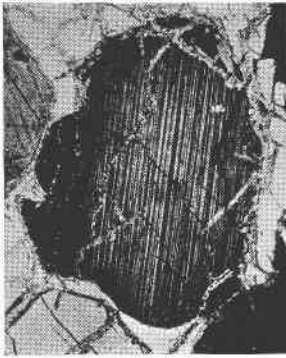

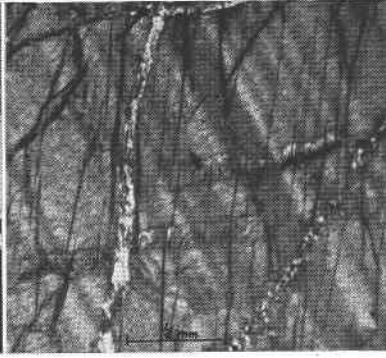FIG. 2   FIG. 3

FIG. 2. Section parallel to 100 under crossed nicols. Fine lamellae of clinopyroxene visible at extinction position of orthopyroxene, Note that lamellae die out near borders of crystal. Photograph exaggerates thickness of lamellae somewhat. (×25)

FIG. 3. Section inclined to all three axes. The lamellae of clinopyroxene here are dipping at a low angle to section giving the appearance of twinning lamellae. (×78)

The extinction angles of this orthopyroxene may thus be explained by the composite effect mentioned above, and by the normal extinctions which may be observed in any orthorhombic crystal with prismatic cleavage in sections equivalent in position to a pyramid. It should be noted that if the cleavage is more than 30° from the normal to the section, its trace will not be visible in the section lying flat on the microscope stage.

TABLE 1. SUMMARY OF OPTICAL OBSERVATIONS ON ORTHOPYROXENE AND LAMELLAE

1. *Section exactly parallel to 001*
    a. Extinction directions bisect angles between prismatic cleavages.
    b. Parting parallel to 100 and 010, common.
    c. Lamellae cannot be seen.
    d. Interference figure: bisectrix perpendicular to section, 2V very large.
    e. Z perpendicular, X direction bisects obtuse cleavage angle and Y bisects acute cleavage angle. (X=a, Y=b, Z=c, optic plane 010.)

2. *Section inclined a few degrees to 001 toward 100*
   a. Straight, fine lamellae appear parallel to X.
3. *Section parallel to 100* (Fig. 2)
   a. Extinction is parallel to cleavage.
   b. At the extinction position bright lamellae are seen parallel to cleavage appearing as sharp, fine, straight lines. (This proves the lamellae are parallel to 010.)
   c. The lamellae themselves extinguish at about 40° either side of the c axis of the orthopyroxene.
   d. The lamellae are brighter (i.e., have higher birefringence) and sharper in this section than in any other section.
   e. Interference figure of orthopyroxene: bisectrix perpendicular to section, 2V very large. Figure slightly affected by the lamellae when optic plane of orthopyroxene is in N–S or E–W position. Otherwise it is normal.
4. *Section parallel to 010*
   a. No lamellae visible.
   b. Highest birefringence for orthopyroxene (1st order yellow).
   c. Extinction parallel to c.
5. *Section displaced from 010 toward 110* (Fig. 3)
   a. Effect of lamellae becomes visible as broad indistinct darker and lighter bands parallel to cleavage. Bands show small extinction angles to cleavage ($\pm 5°$). Acutal outcrop of lamellae not discernible. (Such sections could easily be mistaken for polysynthetically twinned pyroxene.)
6. *Section displaced from 010 toward pyramid*
   a. Same as 5, but bands are inclined to cleavage.

TABLE 2. CHEMICAL COMPOSITION

	I	II	III	IIIa	IIIb	IV
SiO_2	53.61	54.68	53.60	—	53.75	54.63
Al_2O_3	1.67	1.80	3.51	—	3.66	2.39
Fe_2O_3	1.48	0.50	0.79	—	0.83	1.71
FeO	6.70	9.19	11.38	—	11.91	7.07
MgO	33.15	30.19	25.34	—	26.55	30.30
CaO	2.32	2.22	(4.19)	2.19	2.19	2.20
Na_2O	0.04	0.04	0.25	—	0.26	0.45
K_2O	0.06	0.03	0.03	—	0.03	0.11
H_2O+	0.54	0.46	0.27	—	0.28	0.52
H_2O-	0.08	0.05	0.04	—	0.04	—
TiO_2	0.09	0.11	0.29	—	0.30	0.36
P_2O_5	tr.	0.02	—	—	—	0.12
Cr_2O_3	0.38	0.47	—	—	—	—
MnO	0.16	0.21	0.19	—	.20	0.14
	100.28	99.97	99.88		100.00	100.00

I. Bronzite, chromite horizon, Mountain View Lake, Stillwater Igneous Complex, Montana. Collected by E. Sampson. Field No. M.V.L. 3a. Impurities, a little chromite. Analyst, A. H. Phillips.

II. Bronzitite, near chromite horizon at Dunham's house, Boulder Valley. Collected by J. W. Peoples. Impurities, a little chromite. Field No. 465-E-3h. Reference J. W. Peoples, Ph.D. thesis, Princeton University. Analyst, T. Kameda.

III. Bronzite from norite, higher in complex than I, near top of Banded Zone, East Boulder Plateau. Collected by Hess. Impurity, small individual crystals of diopsidic monoclinic pyroxene. Field No. EB 32A. Analyst, A. H. Phillips.

IIIa. Determination of CaO of specimen II from small sample from which an impurity, diopsidic pyroxene, was carefully removed.

IIIb. Recalculated minus the diopside.

IV. Average bronzitite from Daly.

The following features may be noted in the analyses:

1. They contain rather uniformly about $2\frac{1}{4}$ per cent of CaO, which is equivalent to a little less than 9 per cent of the diopsidic molecule.

2. Calculation of the "norms" of these analyses shows a considerable SiO_2 deficiency, equivalent to about 10 per cent of the orthosilicate molecule. No explanation of this is apparent. Deficiency in silica is a common attribute of orthopyroxenes; see Fenner, p. 376 (3).

3. The presence of a considerable amount of Al_2O_3 and a smaller amount of Fe_2O_3, which are not present in ideal orthopyroxenes, may be noted as well as a little Na_2O and K_2O.

4. The Cr_2O_3 in I and II is present as an impurity, in the form of minute chromite grains. No chromite was associated with III.

5. TiO_2 increases with the increase in FeO, but is always small.

Only feature number 1 has a direct bearing on the problem at hand. The uniform occurrence of approximately 9 per cent of the diopsidic molecule in the orthopyroxenes can logically be referred to the fine lamellae of clinopyroxene noted in the optical examination. These lamellae, it was estimated in the optical analysis, make up about 10 per cent of the total pyroxene by volume.

Since these orthopyroxenes are Mg-Fe pyroxenes with a relatively small amount of Ca, some clue as to their origin may be obtained from Bowen's and Schairer's work on the system FeO-MgO-SiO_2 (4). Their Fig. 8 is particularly instructive. Considering that portion of the diagram where the MgO:FeO ratios are similar to those present in the ortho-pyroxenes under discussion, it is found that in this region a clinopyroxene crystallizes at a temperature slightly above 1500°, which in turn inverts to an orthopyroxene in the neighborhood of 1130°C. In view of these facts, two possible explanations of the development of the laminated orthopyroxenes can be suggested: (1) That a clinopyroxene of the pigeon-ite type crystallized first, which on slow cooling inverted to orthopy-roxene with the segregation of diopsidic lamellae; and (2) that crystal-lization took place originally below the inversion temperature, so that an orthopyroxene separated which was capable of holding in solution

diopsidic pyroxene to the extent of 9 per cent, but on further cooling, exsolution of this calcic pyroxene took place to form the clinopyroxene lamellae. Of the two possibilities, the writers favor the second, inasmuch as a clinopyroxene of diopsidic nature is found also in separate individual crystals in the rocks containing the orthopyroxene. It seems unlikely that two similar clinopyroxenes would separate simultaneously from a magma under conditions of equilibrium resulting from slow cooling and crystallization.

References in the literature and examinations of slides at Princeton University indicate that laminated orthopyroxenes similar to those here described are characteristic of large deep-seated, slowly cooled intrusives, whereas they do not occur in lavas or near-surface dikes and sills. The orthopyroxenes of the latter group are always uniform and not laminated, although they may show relatively coarse intergrowths with clinopyroxene or possess other peculiarities, such as inclined extinction described by Verhoogen (5), the explanations of which are beyond the scope of this paper. The absence of these laminated orthopyroxenes in volcanic and near-surface igneous rocks may be ascribed to the relatively rapid cooling of these rocks which does not permit the exsolution of the diopsidic lamellae. It would be interesting to determine especially the CaO content of a number of orthopyroxenes of such rocks to determine if this postulate is correct.

In order to test this hypothesis, the writers collected from the literature a number of analyses which they considered reasonably reliable. The result showed that thirteen orthopyroxenes from plutonic igneous rocks average 2.15 per cent CaO; while eleven from volcanics gave 2.28 per cent CaO. This clearly suggests that orthopyroxenes, whether they show the lamellae or not, nevertheless contained originally about the same amount of the diopsidic molecule. No very great validity, however, can be attached to the absolute values of the averages inasmuch as individual analyses vary by as much as $1\frac{1}{2}$ per cent either side of the mean. A number of very accurate determinations of the CaO content of these pyroxenes are needed on material free from contamination of the monoclinic pyroxene which is nearly always present in the original rock. There is some indication of a slight increase in the CaO content with increase in FeO, or in respect to the magmas from which they crystallize, orthopyroxenes in diorites tend to have more CaO than those in gabbros, norites, etc. Orthopyroxenes from rocks which the writers consider to be derived from an ultramafic magma, show in some cases the normal $2\frac{1}{4}$ per cent CaO, and in others much lower values. It is suggested that CaO is soluble in those pyroxenes to the extent of $2\frac{1}{4}$ per cent, but that in many cases the original magma did not have this amount of CaO.

In many cases, orthopyroxenes low in CaO, have conspicuously few lamellae, so that they can be recognized in thin section without the necessity of an analysis.

SUMMARY

Orthopyroxenes of the Bushveld type are not polysynthetically twinned monoclinic pyroxenes, but are truly orthorhombic, at least so far as their optical properties are concerned. The laminated appearance, apparently twinning, is actually the result of the presence of thin lamellae of a clinopyroxene oriented parallel to the optic plane of the orthopyroxene. The optic plane is parallel to 010. The small anomalous extinction angles are a result of the composite effect of lamellae and host where the lamellae are inclined at low to moderate angles to the plane of the section. Pyroxenes of this type occur in slowly cooled plutonic igneous rocks, whereas orthopyroxenes of volcanics do not have such lamellae. Chemical analyses of orthopyroxenes from both sources show approximately $2\frac{1}{4}$ per cent of CaO, or a little less than 9 per cent of the diopsidic molecule. It is suggested that this represents the solubility of the diopsidic molecule in Mg-rich orthopyroxenes at high temperatures. With slow cooling this diopsidic material is exsolves and forms the lamellae.

NOTE: Since the completion of the manuscript it has been noted that, following Goldschmidt, German texts orient orthopyroxenes so that "a" axis is longer than "b" axis, whereas Dana and most English language texts make "a" the shorter axis. This accounts for the fact that some authors considered the optic plane to be parallel to 100, and others, parallel to 010. It depended upon which orientation they had adopted and not on any differences in observation. The present authors have used Dana's orientation in this paper, though it is now apparent that the other orientation would be advisable considering the relationship between the lamellae and orthopyroxene host.

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