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°).† In the former case the optic plane is parallel to 010, and

* 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.
† 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 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

![Fig. 1](image-url)
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](image1)
![Fig. 3](image2)

**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. (X25)

**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. (X78)

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.)
ORTHOPYROXENES OF THE BUSHVELD TYPE

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 (±5°).
      Actual 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

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<th>I</th>
<th>II</th>
<th>III</th>
<th>IIIa</th>
<th>IIIb</th>
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<td>—</td>
<td>.20</td>
<td>0.14</td>
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</table>

|     | 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


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\(\frac{1}{2}\) 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\(_2\)O\(_3\) and a smaller amount of Fe\(_2\)O\(_3\), which are not present in ideal orthopyroxenes, may be noted as well as a little Na\(_2\)O and K\(_2\)O.

4. The Cr\(_2\)O\(_3\) 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 orthopyroxenes 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 pigeonite type crystallized first, which on slow cooling inverted to orthopyroxene with the segregation of diopsidic lamellae; and (2) that crystallization took place originally below the inversion temperature, so that an orthopyroxene separated which was capable of holding in solution
diopсидичный пироксен до степени 9 пер с., но на дальнейшем охлаждении, ксенолиты этого кальциевого пироксена, чтобы сформировать клинопироксен. Из двух возможностей, авторы предпочитают вторую, поскольку клинопироксен диопсидичной природы также найден в отдельных кристаллах в породах, содержащих ортopyрексен. Столь маловероятно, что два клинопироксена сходной природы отделяются одновременно из магмы при условии равновесия, возникающем из медленного охлаждения и кристаллизации.

Сведения из литературы и работы микроскопических препаратов в Принстонском университете указывают, что ортopyрексены с восклицательными отложениями, сходные с теми, как описаны здесь, характерны для глубоких, медленно охлаждающихся интрузивов, но не встречаются в лавах или близповерхностных диэках и силях. Ортopyрексены группы второго типа всегда однородны и не имеют восклицательных отложений, хотя они могут показывать относительно крупные срастания с клинопироксеном или иметь другие особенности, такие как наклонное уничтожение, как описано Верхоозеном (5), пояснения которых не входят в рамки настоящей статьи. Отсутствие этих восклицательных ортopyрексенов в вулканических и близповерхностных горных породах может быть связано с относительно быстрым охлаждением этих пород, которое не позволяет ксенолитам диопсидичных восклицательных отложений. Было бы интересно определить, особенно содержание CaO в ортopyрексене, чтобы определить, если это предположение верно.

Для проверки этого гипотезы, авторы собрали из литературы несколько анализов, которые они считали надежными. Результат показал, что тринадцать ортopyрексенов из магматических пород среднего состава давали 2.15% CaO, в то время как одиннадцать из вулканических давали 2.28% CaO. Это ясно говорит о том, что ортopyрексены, независимо от того, показывают ли они восклицательные отложения или нет, все же содержали бы сходное количество диопсидичной молекулы. Однако, никакой особой значимости, однако, нельзя приписать абсолютным значениям средних в отдельных анализах, которые могут варьироваться на ±1/2% от среднего. Для более точных определений содержания CaO этих пироксенов необходимо использовать материал, свободный от загрязнений клинопироксенов, которые обычно присутствуют в исходной породе. Была некоторая тенденция к небольшому увеличению содержания CaO с увеличением FeO, в отношении магм, из которых они кристаллизуются. Ортopyрексены в диоритах тяготеют к иметь больше CaO, чем в габбро, норитах, и т.д. Ортopyрексены из пород, которые авторы считают, что они выплавлены из ультрабазитового магма, показывают в некоторых случаях нормальный 2.4% CaO, в то время как в других случаях содержание ниже. Следовательно, что CaO является растворимым в пироксенах до степени 2.4% CaO, но что в большинстве случаев исходная мagma не имела этого количества 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 24 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 “c” 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.

**References**