

## Composition and orientation of clinopyroxene lamellae in Bushveld-type orthopyroxene from the Greenhills ultramafic complex, Bluff Peninsula, Southland, New Zealand

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**SUMMARY.** Identification of clinopyroxene lamellae in Bushveld-type orthopyroxene from the Greenhills Ultramafic Complex has been made on the basis of partial analysis by electron microprobe as well as by unit cell determination by prolonged exposure to X-rays of single crystals of orthopyroxene. Lamellae averaging  $\text{Ca}_{42}\text{Mg}_{47}\text{Fe}_{11}$  in composition with an approximate unit cell  $a$  9.79,  $b$  8.90,  $c$  5.29 Å,  $\beta$  106° 14', occur in orthopyroxene  $\text{Ca}_2\text{Mg}_{67}\text{Fe}_{31}$  with unit cell  $a$  18.28,  $b$  8.85,  $c$  5.20 Å. The Greenhills lamellae are of orientation identical to those described by Hess (1960), which share  $c$  and  $b$  axes with host orthopyroxene.

ORTHOPIYROXENES containing lamellae parallel to {100} were designated Bushveld-type by Hess and Phillips (1940) in contrast to the Stillwater-type Fe-rich orthopyroxenes, which are inverted pigeonites containing lamellae of augite parallel to {001} of the original clinopyroxene. Poldervaart and Hess (1951) interpreted the Bushveld-type orthopyroxene as the result of primary crystallization of orthopyroxene and exsolution of clinopyroxene on slow cooling. According to Hess (1941) exsolution took place below the orthopyroxene-clinopyroxene inversion temperature.

Orthopyroxenes from the Greenhills Ultramafic Complex of southern New Zealand (Mossman, 1970) are of the Bushveld-type and are characterized by 2  $\mu\text{m}$  to 10  $\mu\text{m}$ -wide clinopyroxene lamellae. In sections cut parallel to {010} occasional thicker bleb-like lamellae extinguish at 40°  $\pm$  5° either side of [001] of the host crystal. The thinnest and most continuous lamellae extinguish at angles apparently as low as 30°  $\pm$  5° and show appreciably less birefringence; this suggests that they do not penetrate the full thickness of a thin section. Numerous optical studies of clinopyroxene lamellae and their orientation relative to host orthopyroxene are reported, but according to reviews by Henry (1942) and Deer, Howie, and Zussman (1963) the results are not concordant. The extinction angle of the Greenhills lamellae is comparable with the 39° to 43° extinction described by Hess (1960) but is much greater than the 8° extinction angle reported by Henry (1942, p. 184).

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Hess (1960, p. 29) is adamant that literature describing lamellae, striae, and twinning<sup>1</sup> in Bushveld-type orthopyroxene '... all refer to the same phenomenon with different interpretations of its nature'. Both Henry and Hess attempted to reconcile X-ray data with optical characteristics of the lamellar structure. From single crystal X-ray work Henry (1942, p. 188) showed that *a* and *c* axes of lamellae in orthopyroxene from several European localities are displaced relative to those of the main crystal '... in, or nearly in, the *a c* plane at angles up to about 10–15°'. Henry's observation that the lamellae and the host orthopyroxene showed equal birefringence led him to suggest that the lamellae are due to deformation, which occurred during crystallization. Hess agrees with Henry that X-ray oscillation photographs of orthopyroxene show multiple maxima resulting from disorientation of orthopyroxene through moderate angles. However, Hess concludes that this phenomenon is independent of the fine lamellae that are diagnostic of Bushveld-type orthopyroxenes. He showed, on optical grounds, that the lamellae are clinopyroxene apparently present in too small an amount to give X-ray reflections.

Various workers using the electron microprobe have recently confirmed instances where {100} lamellar structure in orthopyroxene is due to exsolved clinopyroxene. For example, Green (1963) identified diopside lamellae in orthopyroxene from the Tinaquillo alpine peridotite; Howie and Smith (1966) have described the difficulties of obtaining accurate analyses of plutonic orthopyroxenes because of the effects of clinopyroxene exsolution lamellae; Boyd and Brown (1967) studied the behaviour of the elements and exsolution and inversion relationships in pyroxenes.

Data on Greenhills orthopyroxene include semi-quantitative results on the composition of the orthopyroxene and its included lamellae and the results of an optical and single-crystal X-ray study. The work was undertaken to determine the chemical composition and unit cell parameters of the clinopyroxene lamellae and host orthopyroxene and to establish the precise orientation of the lamellae relative to the host.

*Chemical composition.* Samples of orthopyroxene referred to in this paper are from the noritic marginal gabbro that forms the border of the Greenhills Ultramafic Complex. Coexisting with orthopyroxene  $\text{Ca}_2\text{Mg}_{67}\text{Fe}_{31}$ , in a typical specimen<sup>2</sup> (O.U. 25828) are sodic anorthite  $\text{An}_{90}$  ( $\beta$  1.579 ± 0.002), olivine  $\text{Fo}_{74\pm 1}$  (X-ray), and clinopyroxene  $\text{Ca}_{48}\text{Mg}_{46}\text{Fe}_{11}$  (chemical analysis). Colorimetric techniques were employed in the analysis of the clinopyroxene except for determination of Ca and Mg by atomic absorption and alkalis by flame photometry. Partial electron-microprobe analyses of orthopyroxene and lamellae in O.U. 25828 and O.U. 25809 were carried out by Dr. G. A. Challis at the New Zealand Geological Survey, Wellington. According to Dr. Challis (pers. comm.) absolute amounts particularly in the case of Mg may be one per cent low; analysis of the lamellae is subject to error in so far as about

<sup>1</sup> Twinning on (100) in the orthorhombic system is prohibited. Thus the *b*-axis, which is of two-fold symmetry, cannot function as twin axis. As Phillips (1963, p. 165) has pointed out '... no new orientation is produced by rotation through 180° about such an axis'. Notwithstanding this condition a number of modern texts on mineralogy describe twinning of orthopyroxene as simple and lamellar on (100).

<sup>2</sup> O.U. numbers refer to specimens housed in the Department of Geology, University of Otago.

20  $\mu\text{m}$  is generally considered the minimum size for avoidance of matrix effects. Silica in the electron microprobe analyses has been calculated by difference. Ionic structures of the pyroxenes were computed using a Fortran IV program developed by Dr. E. Essene (Australian National University) and Dr. P. B. Read and written by

TABLE I. Analytical data on pyroxenes from the Greenhills marginal gabbro

	A	B	C	C <sub>1</sub>	D
SiO <sub>2</sub>	49.75	55.4	54.4	53.2	55.8
TiO <sub>2</sub>	0.37	n.d.	n.d.	n.d.	n.d.
Al <sub>2</sub> O <sub>3</sub>	3.04	1.8	2.0	2.9	2.3
Fe <sub>2</sub> O <sub>3</sub>	2.67	n.d.	n.d.	n.d.	n.d.
FeO	5.02	18.8*	18.6*	8.7*	19.1*
MnO	0.22	n.d.	n.d.	n.d.	n.d.
MgO	16.78	23.0	24.0	18.0	21.8
CaO	21.75	1.0	1.2	17.2	1.0
Na <sub>2</sub> O	0.31	n.d.	n.d.	n.d.	n.d.
K <sub>2</sub> O	0.00	n.d.	n.d.	n.d.	n.d.
P <sub>2</sub> O <sub>5</sub>	0.29	n.d.	n.d.	n.d.	n.d.
Total	100.20	100.0	100.0	100.0	100.0
Ca	42.74	2.10	2.44	35.08	2.16
Mg	45.87	67.12	67.99	51.07	65.59
Fe	11.39	30.78	29.56	13.85	32.24
<i>Number of ions on the basis of 6 oxygens</i>					
Si	1.848	2.014	1.979	1.946	2.207
Al <sup>iv</sup>	0.133	0.0	0.021	0.054	0.0
Al <sup>vi</sup>	0.0	0.077	0.065	0.071	0.098
Ti	0.010	0.0	0.0	0.0	0.0
Fe <sup>3+</sup>	0.075	n.d.	n.d.	n.d.	n.d.
Fe <sup>2+</sup>	0.156	0.572	0.566	0.266	0.580
Mn	0.007	0.0	0.0	0.0	0.0
Mg	0.930	1.246	1.301	0.981	1.180
Ca	0.866	0.039	0.047	0.674	0.039
Na	0.022	0.0	0.0	0.0	0.0
K	0.0	0.0	0.0	0.0	0.0
Z	1.98	2.01	2.00	2.00	2.03
WXY	2.07	1.93	1.98	1.99	1.90

\* Total iron as FeO.

A, Clinopyroxene O.U. 25828; not corrected for 1 % uraltization. Anal. D. Mossman.

B, C, C<sub>1</sub>, D. Partial electron-probe analyses by G. A. Challis, silica by difference: B, Orthopyroxene O.U. 25828; C, Orthopyroxene O.U. 25809; C<sub>1</sub>, Clinopyroxene lamellae, O.U. 25809; D, Orthopyroxene O.U. 25828.

the latter. Chemical data on the pyroxenes are given in table I. According to the terminology of Poldervaart and Hess (1951) all of the clinopyroxenes classify as augites.

*Orientation of the lamellae.* X-ray work was carried out on a 57.3 mm diameter Weissenberg camera. Orthopyroxene grains suitable for single crystal study were selected

from uncovered thin sections of O.U. 25828. Portions of optically homogeneous crystals showing a maximum number of lamellae were removed and cleaned of balsam in acetone prior to X-ray work. Stereographic projection of optical data recorded on these crystals is given in fig. 1. Due to the thinness of the lamellae unequivocal determinations of their optic angle could not be made.

In a Weissenberg normal beam 48-hour exposure rotated about the *b*-axis only orthopyroxene reflections could be detected. A moderate-intensity reflection that can be indexed as 070 in the orthopyroxene unit cell is present but prohibited in both orthopyroxene *Pbca* and clinopyroxene *C2/c* space groups (Henry and Lonsdale, 1952; Clark *et al.*, 1969). This suggests that there are more than one space group for orthopyroxene. The 070 reflection was accepted by a modified Fortran IV program for least-squares refinement of unit-cell dimensions (Cox and Steward, 1967). Single crystal photographs gave: *a* 18.28, *b* 8.85, *c* 5.20 Å, all ±0.01 Å, *V* 841.94 ± 0.5 Å<sup>3</sup>. Approximate composition En<sub>77</sub>Fs<sub>23</sub> (Kuno, 1954).

An 84-hour Weissenberg exposure of the same grain oscillated 15° either side of *a*\* showed a number of very weak reflections some of which lay along the *a*\* direction of the orthopyroxene; these could not be explained by the orthopyroxene lattice but were compatible with the *a*\* dimension of clinopyroxene. Coincidence of *a*\* clinopyroxene with *a*\* (= *a*) orthopyroxene is expected according to Hess (1960, p. 30) who states that 'The exsolution takes place in such a way that the lamellae and host have their *b* and *c* axes, 100 plane, in common. This is the only plane on which the clinopyroxene and orthopyroxene have the same structure, and it is the plane which might be expected to give the lowest energy interface between the two structures'.

To confirm that the several weak reflections belonged to clinopyroxene in the orientation described by Hess (1960) a clinopyroxene grain was chosen as a standard from the same rock (O.U. 25828) for a comparative *b*-axis oscillation, a technique of identification advocated by Bown and Gay (1959). Superposition of the resulting photograph of the clinopyroxene lattice on the photograph of orthopyroxene for the same setting showed that the following weak reflections in the latter are coincident with strong reflections of clinopyroxene: 40 $\bar{2}$ , 402, 600, 60 $\bar{2}$ , 800, 802. Since *oko* reflections of clinopyroxene could not be distinguished on X-ray oscillation photographs of orthopyroxene an estimation of the *b* dimension of the lamellae was made by calculating *2θ* for 010, 020, 030, and 040 from a *b*-axis oscillation photograph of

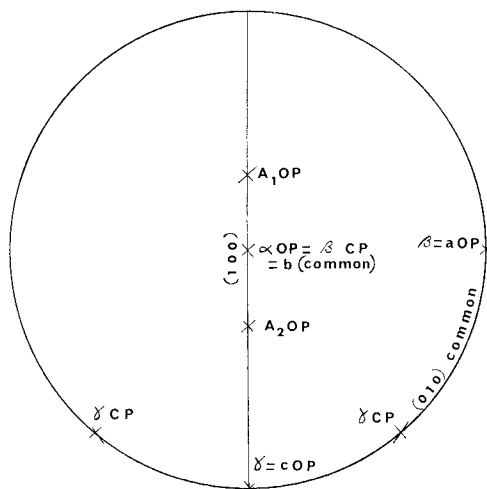


FIG. 1. Stereographic projection on (010) of optical relations of Greenhills orthopyroxene (OP) and clinopyroxene (CP).

the clinopyroxene standard. An approximation of the unit cell of the lamellae was made with the aid of a Fortran IV program (modified from Cox and Steward, 1967):  $a$  9.79,  $b$  8.90,  $c$  5.29 Å, all  $\pm 0.04$  Å,  $\beta$   $106^\circ 14' \pm 1'$ ,  $V$   $442.62 \pm 0.5$  Å<sup>3</sup>.

*Conclusion.* The X-ray study shows that the  $c$  and  $b$  axes of orthopyroxene host and clinopyroxene lamellae are coincident in the Greenhills example, in agreement with the results of Hess (1960) on Bushveld-type lamellae.

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