Lamellar structure in orthopyroxenes.

(With Plate IV.)

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THE fine lamellar structure (pl. IV, fig. 1 *a* and *b*) which is described here is very common in the orthopyroxenes of plutonic and regionally metamorphosed rocks. This structure can be seen under crossed nicols in sections inclined at a high angle to the optic axial plane (100), except on those sections which make a low angle with (001). When the main part of the crystal is in extinction, the fine lamellae stand out because their extinction position is different from that of the main crystal. Although this structure is common, it is not described in any of the widely used text-books, but several descriptions and references to it have been published in recent years. The purpose of this paper is to draw attention to the nature of this lamellar structure.

Previous References.

In several text-books rather vague remarks are made about secondary lamellar twinning due to deformation. These remarks refer to the work of Bücking (1883) and Mügge (1898) and they have been repeated on numerous occasions with neither drawing nor fuller description. Bücking described lamellar twinning on a flat dome face (104)[1] in a bronzite from Ultenthal which he said showed characteristics of glide-twinning. Mügge discusses the bending of the (100) cleavage about the *b*-axis which he ascribes to translation on the (100) plane along the *c*-axis, and he suggests that the lamellar twinning of Bücking is due to the same cause. The structures described by Bücking and Mügge are found also in monoclinic pyroxenes and are clearly different from the fine lamellar structure with no bending which we are discussing here. In the text-book of Rosenbusch-Wülfing (1927) mention is made of a structure, described as lamellar intergrowth, according to a definite law, of monoclinic and orthorhombic pyroxenes. This microperthitic structure is common in

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[1] The orientation $a > b$ is used throughout this paper.

pyroxenes of some plutonic rocks, but is quite different from the structure under discussion here.

In describing an intergrowth of clino- and orthopyroxenes Wager and Deer (1939) say that 'It does not resemble the fine-scale structure, parallel to the optic plane which has frequently been observed but not yet explained'. Chudoba (1932) mentions in his text-book the occasional occurrence of a polysynthetic twin structure which may be partly due to translation on (100). As he does not say anything about bending, he may be referring to the fine-scale lamellar structure.

In recent years several specific occurrences of this structure have been described and different explanations offered. Wagner (1924, p. 41) in describing a bronzite from the Bushveld complex says: 'The bronzite often exhibits fine polysynthetic twinning parallel to the plane (100). The twin lamellae, which are very thin, have an extinction $c : Z$ of about 9°. The twin[n]ed portions are sometimes irregularly distributed through the untwinned, and a core of twinned bronzite was found in one instance to be surrounded by an irregular shell showing no trace of twinning. The prevalence of this twinning, which is exhibited by the bronzite of the bronzitites and allied rocks throughout the Bushveld complex, appears to support Zambonini's view that all enstatite (or bronzite) is clino-enstatite in which the twinning is sub-microscopic.'

Phemister (1928) describes with a photomicrograph the same lamellar structure in orthopyroxene in the Cobalt diabase. The lamellae occur sometimes in patches, the junction-plane is the optic axial plane, the interference-figure is of an acute bisectrix due to the main orientation of the more numerous lamellae, while the difference in extinction position between the two groups of lamellae is 15°. The explanation offered is that the obliquely extinguishing lamellae are of a highly magnesian monoclinic pyroxene which has its optic axial plane perpendicular to that of the hypersthene and so low a birefringence that it does not affect the interference-figure given by the hypersthene.

In describing an iron-rich hypersthene from a eulysite, Sundius (1932) remarks on the lamellar structure which appears only in sections perpendicular to the optic axial plane and within the acute optic axial angle. As the junction-plane of the lamellae is (100) he says the structure cannot be due to twinning, and he ascribes it to intergrowth of the orthorhombic mineral with a monoclinic lime-bearing pyroxene, showing oblique extinctions of 4–12°, but these lamellae form only 5 % of the whole mineral.

Guimarães (1930), in describing quartz-gabbros from north Brazil, gives photographs of lamellar hypersthenes which appear to be similar to those studied in this paper. The structure is explained as being due to intercalations of magnesian diopside.

Bowen and Schairer (1935) also mention lamellar structure which they noticed in the South African bronzite used for inversion experiments, and they state that 'These minerals usually show a rather obscure lamellar twinning with extinctions up to about 9° against the composition plane'. They point out that this is quite different from the twinning of the true clinopyroxenes and also that this 'twinning' does not appear to be on the flat dome (104).

Scholtz (1937) studied the lamellar structure in orthopyroxene from hyperites and picrites and he gives a photomicrograph of the structure. He states that the lamellation, which is not related to the composition of the mineral, is developed parallel to (100), the lamellae having the α direction in common while the β and γ directions of different sets are inclined to each other usually at angles of 5–11°. Sections in the zone [100] sometimes show irregular patches which extinguish uniformly along with one set of lamellae. Scholtz suggests the existence of some twinned relationship, although he admits that the evidence is by no means conclusive, and he refers to the hypothesis that orthopyroxene may be composed of sub-microscopically twinned monoclinic individuals. Another description of this structure from the Bushveld complex is given by Nel (1941), who mentions that the striations sometimes pinch out before they reach the borders of the crystals and that there may be patches of crystal free from striations.

Hess and Phillips (1938) state that the lamination is entirely due to the presence of very fine lamellae of another mineral, which form thin sheets, 0·002 mm. thick, parallel to the optic axial plane and which have approximately the same mean refractive index as the host crystal, regardless of the composition. The lamellae have large extinction-angles, so it appears that they are monoclinic, probably of the diopside-hedenbergite series, with approximately the same Mg/Fe ratio as the host, and their optic axial plane is at right angles to that of the orthorhombic host crystal. These diopsidic lamellae formed as a result of exsolution on cooling from an orthopyroxene and supply the 2 % of CaO which is present in many analyses of enstatites and hypersthenes. Rapid cooling prevents the exsolution in the orthopyroxenes of volcanic rocks.

The lamellar structure has been seen in sections of the Manegaon meteorite. In a recent description of the Chicora meteorite, Preston, Henderson, and Randolph (1941) refer to the occurrence of fine lamellar twinning in a few grains of hypersthene, and this may be the same structure.

In considering the literature it is sometimes difficult to decide whether the reference is to the same structure. The lamellar structure described here is quite different from the glide-twinning on a dome face and from the deformation shown by the bending of the (100) cleavage, both of which are mentioned in German text-books. It is also different from the common lamellar intergrowths of ortho- and clinopyroxenes described by several authors, because in these the two sets of lamellae have different birefringences. If we consider the cases where the authors appear to be dealing with the same structure as that under consideration, the explanations offered fall into two groups.

1. Polysynthetic twinning.
2. Intergrowths of the orthopyroxene with a clinopyroxene of the nature of a clinoenstatite or a magnesian diopside. The optic axial plane of the clinopyroxene is (010) and that of the orthopyroxene is (100). The contact plane of the lamellae is (100) and for sections which show the intergrowth, the birefringences of the two minerals are very similar.

Hess and Phillips suggest that, on slow cooling, exsolution of diopsidic lamellae occurs, owing to the existence of about 2 % of CaO in most orthopyroxenes. Although orthopyroxenes of lavas have similar amounts of CaO they do not show lamellae, and the non-occurrence of the intergrowth is ascribed to rapid cooling. Hess and Phillips go on to suggest that the amount of the intergrowth is dependent on the amount of CaO present. The only definite statement about the presence or absence of this lamellar structure in an orthopyroxene of low CaO content is that of Tilley (1936) who describes the iron-rich hypersthene from the eulysite of Loch Duich, Scotland, as having this structure well developed, although it has only 0·83 % CaO. Foshag (1940) says that in the enstatite (0·32 % CaO) of the Shallowater meteorite, 'undulatory and other extinction anomalies are common, including a hackly pattern suggestive of twinning'. This may refer to the lamellar structure. In view of the scantiness of the data, the suggestion of Hess and Phillips that lime-poor orthopyroxenes can in many cases be recognized by the fewness of their lamellae appears to be unsupported. It seems that orthopyroxenes of any composition can have atoms of (Mg,Fe) replaced by atoms of Ca, to the amount corresponding to 2 or 3 % CaO, without destroying the symmetry of the crystal. Reference to CaO or diopsidic molecules being soluble in crystals of orthopyroxene does not help in the understanding of problems of this kind.

X-Ray Study.

Several specimens from different localities were used. After examination on the universal stage, suitable sections were cut out and studied by means of X-rays, the optical information being used in the preliminary setting. The oscillation photographs taken about the *b*-axis are quite normal, although in two cases a slight elongation of the spots can be seen. In the photographs taken about the *c*-axis, however, (fig. 2*a* and *b*) there are additional spots forming a complete oscillation photograph of a similar crystal with its *c*-axis inclined at about 7° to that of the main crystal in the (010) plane. The spots of this tilted oscillation photograph match those on the layer-lines of the main photo-

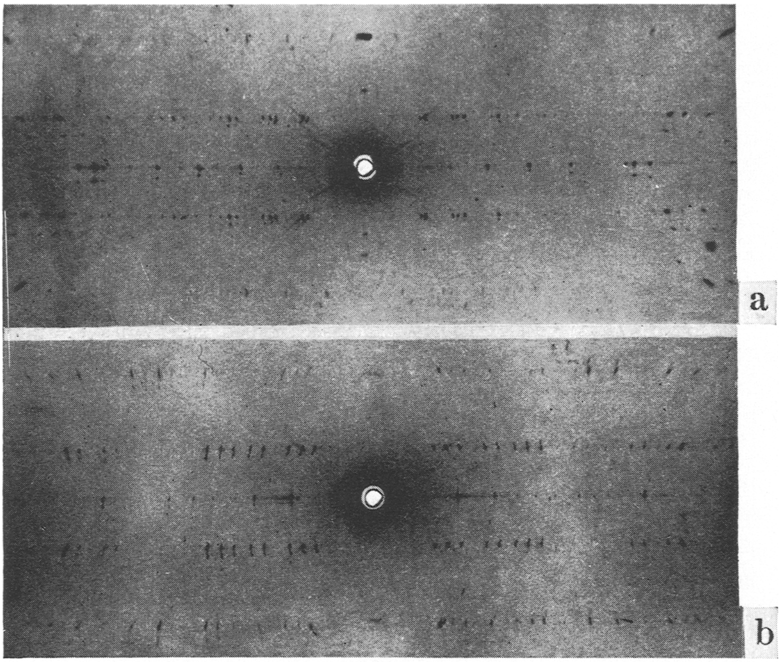

FIG. 2.

FIG. 2. X-ray photographs of orthopyroxenes with lamellar structure. Co-$K\alpha$ radiation; cylindrical camera of radius 3 cm. Approx. $\frac{3}{5}$ original size.

(*a*) Hypersthene from norite: Baste, Harz. Oscillation-axis *c*; oscillation-angle $7\frac{1}{2}°$ on either side of *a*-axis.

(*b*) Hypersthene from quartz-biotite-norite: Glen Buchat, Aberdeenshire. Oscillation-axis *c*; oscillation-angle $7\frac{1}{2}°$ on either side of *b*-axis.

graph and are connected to them by Debye-Scherrer curves on which are superposed, in some cases, the spots from other preferred orientations. These photographs show that most of the subsidiary lamellae, which produce the tilted oscillation photographs, are inclined to one side of the main crystal and that one or two orientations are strongly preferred. But the elongation visible in the strong spots shows that a small proportion of the material is inclined on both sides of the main crystal at angles up to about 15° from it. From this evidence it is clear that:

(*a*) The lamellae are orthopyroxenes of the same composition as the main crystal.

(*b*) The lamellae are inclined to the main crystal in the (010) plane of the latter. (In some cases a slight inclination of the *b*-axes of the two sets of lamellae can be detected, so that the displacement is not always strictly in the (010) plane.)

(*c*) The structure is not a regular twin structure because there is a range of orientations.

Optical Study.

Examination on the universal stage shows that:

(*a*) The lamellae form very thin irregular sheets, 0·001–0·002 mm. thick, parallel to (100), which have a bent, pinched-out appearance (see fig. 1 *b*, pl. IV).[1]

(*b*) The refractive indices and the birefringences of the sets of lamellae are equal.

(*c*) The lamellae of the subsidiary orientations can be distinguished from those of the main crystal only under crossed nicols by their different extinction positions.

When the pole of the section is (010) the lamellae are very thin and the boundary lines are sharp: but as the pole is inclined away from the *cb* plane, the lamellae become thicker and eventually become invisible when the pole makes an angle of more than about 30° with the *cb* plane. When the pole is inclined in the *cb* plane the lamellae retain their sharpness until the pole approaches (001), when they disappear. On (010) the extinction-angle of the fine lamellae varies up to about 8°, but thicker patches remain in extinction over a large angle. In the 45° position all trace of the structure has vanished and the birefringence colour is quite uniform. The thicker patches which appear to give

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[1] This appearance is seen, also, in fine lamellar structures of different kinds in other minerals.

higher extinction-angles are composed of several lamellae which the eye cannot separate, and their optical behaviour is due to the superposition of several crystals. When the pole of the section is inclined to (010), the extinction-angle varies up to 90° (slow vibration-direction to trace of junction-plane).

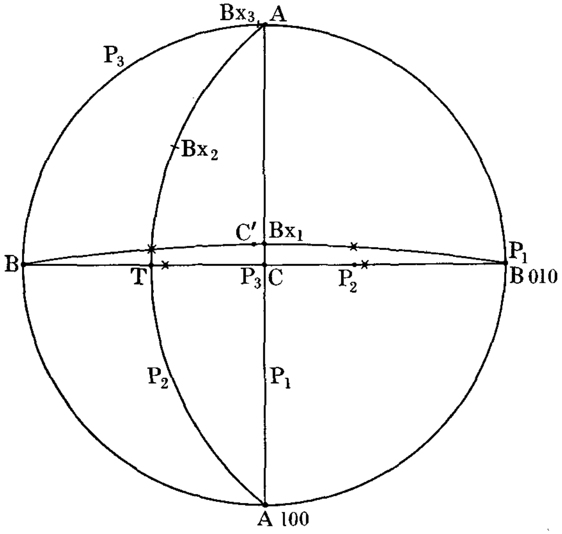

FIG. 3.

FIG. 3. Stereogram showing extinction-angles in an inclined lamella of an orthorhombic pyroxene with 2V 90°.

C and C' are the poles of the c-axes of the main crystal and an inclined lamella respectively, while × marks the poles of their optic axes. P_1, P_2, P_3 are the poles of sections and the corresponding great circles. Extinction-angles are measured from the slow vibration-direction to the trace of the (100) plane of the main crystal.

For P_1 the extinction-angle is C : $\text{Bx}_1 = 10°$,
„ P_2 „ „ T : $\text{Bx}_2 = 45°$,
„ P_3 „ „ B : $\text{Bx}_3 = 89°$.

The extinction of the main crystal is straight in each of these cases.

In fig. 3 the optic orientation of an orthopyroxene with 2V 90° is represented on a stereogram, along with that of a similar crystal displaced relative to the first nearly in the *ca* plane. If we consider the pole P_1 of a section which coincides with (010) of the main crystal, we see that the extinction-angle of the second crystal is equal to the displacement of the *c*-axes projected on to the *ca* plane (all extinction-angles are measured from the slow vibration-direction to the trace of the junction-plane, i.e. approximately the *cb* plane of the main crystal).

But if we take the pole P_2 the extinction-angle is 45°. It is well known that sections nearly perpendicular to an optic axis of a biaxial crystal can show all variations of extinction-angle. On (001) the extinction would, of course, be straight if the displacement were in the *ca* plane, but even if it is 5° off this, as in the diagram, the extinction is too small to be noticeable (see fig. 3). In this discussion we have assumed that the pole of the main crystal moved in the *cb* plane so that its extinction would always be straight, although it changes from 0° to 90° at the optic axis. But if the section were tilted out of this plane, the main crystal can show any extinction-angle. We considered it in the first way because the important thing is the difference between the extinction positions of the two crystals in any given orientation, as it is that which makes the lamellae visible.

The lamellae become invisible in two ways as we have seen: first, when the section makes too low an angle with the plane of junction so that the structure is only seen on sections which are nearly perpendicular to the *cb* plane: secondly, when the difference in extinction-angle becomes very small, as happens when the pole of the section approaches (001). The undulose extinction which is always present indicates intermediate positions of displaced crystals, but the amount of material in these positions is smaller than that in definite positions. Most of the lamellae, also, extinguish to one side of the extinction position of the main crystal. Both these observations are supported by examination of the X-ray photograph in fig. 2, which shows Debye-Scherrer lines connecting the spots from the main and from the subsidiary lamellae, while a little elongation occurs on the other side of the main spots.

The optical behaviour of this structure has been interpreted by most authors as produced by intercalated lamellae of clinopyroxene in the same structural orientation as the orthopyroxene host (i.e. $c \parallel c$ and $b \parallel b$). But in that case the extinction-angle on a (010) section should equal the $c : \gamma$ angle of the clinopyroxene, which must be at least 22° if the crystal is clinoenstatite or magnesian diopside. Mention is made of fairly high extinction-angles of lamellae by some authors, but where it is stated that care was taken to make the observations on sections orientated parallel to (010), no angle higher than 10° is reported. Apart from a few stray lamellae and the anomalously extinguishing patches mentioned previously, no higher angle has been observed on clearly defined lamellae during the observations recorded in this paper.

A lamellar structure due to deformation has been observed in halite and sylvine in which the doubly-refracting lamellae produced by stretching have been studied optically. The process whereby bending of parts of the crystal takes place on gliding is called 'Biegegleitung', a term which was first used by Mügge. It seems reasonable to ascribe the structure under discussion to such a process of translation on (100) in the direction [001], accompanied by bending about [010]. It would be expected that the bending might not always be strictly about [010], but the evidence shows that the divergence from this direction is never considerable.

Geological Occurrence.

Orthopyroxenes occur in basic and ultrabasic plutonic and volcanic rocks of normal type; in the rocks of the charnockite series and in those of the eclogite type; in contaminated norites; in high-grade thermally metamorphosed rocks of both igneous and sedimentary origin; in high-grade regionally metamorphosed rocks of both igneous and sedimentary origin; and in stony meteorites. Owing, however, to the scarcity of precise observations, only general and tentative conclusions can at present be reached about the geological occurrence of the lamellar structure. It does occur in many basic and ultrabasic plutonic masses, but is not seen in volcanic rocks. It is rather poorly developed in the noritic members of the charnockite series, but does not seem to be present in the more acid ones. It occurs in hypersthene-eclogites. In the contaminated cordierite-norites of Aberdeenshire the structure is found, but it dies out as the amount of magmatic material decreases and the rock becomes more like a hornfels. No orthopyroxene from a thermally altered rock has yet been seen to show this structure. It does, however, occur in katazone rocks such as eulysites and pyroxene-granulites. It is seen, also, in some meteorites. As a generalization of these observations we can say that the conditions of crystallization in an ordinary plutonic basic magma allow the best development of the lamellar structure. Conditions in the katazone, whether of intrusion or of metamorphism, also produce the structure, as do the conditions of formation of some meteorites. In the case of volcanic rocks and of thermal metamorphism the conditions are not favourable for the development of the structure. The process of cataclastic deformation, also, does not allow the structure to develop, although the 'Knickung' of Mügge and Bücking is produced in such conditions. In some cases the fine lamellae of the structure are seen to be bent by subsequent shearing.

Summary.

Previous statements about the common lamellar structure in orthopyroxenes are reviewed. New X-ray evidence is produced along with the results of optical examination of specimens from several localities. It is shown that the lamellae are composed of the same orthorhombic material as the main crystal and that the visibility of the structure is due to differences in extinction position between the sets of lamellae. These sets of lamellae have their *a*- and *c*-axes displaced relative to those of the main crystal in, or nearly in, the *ca* plane at angles up to about 10–15°. This structure appears to be due to deformation and is evidently formed during crystallization.

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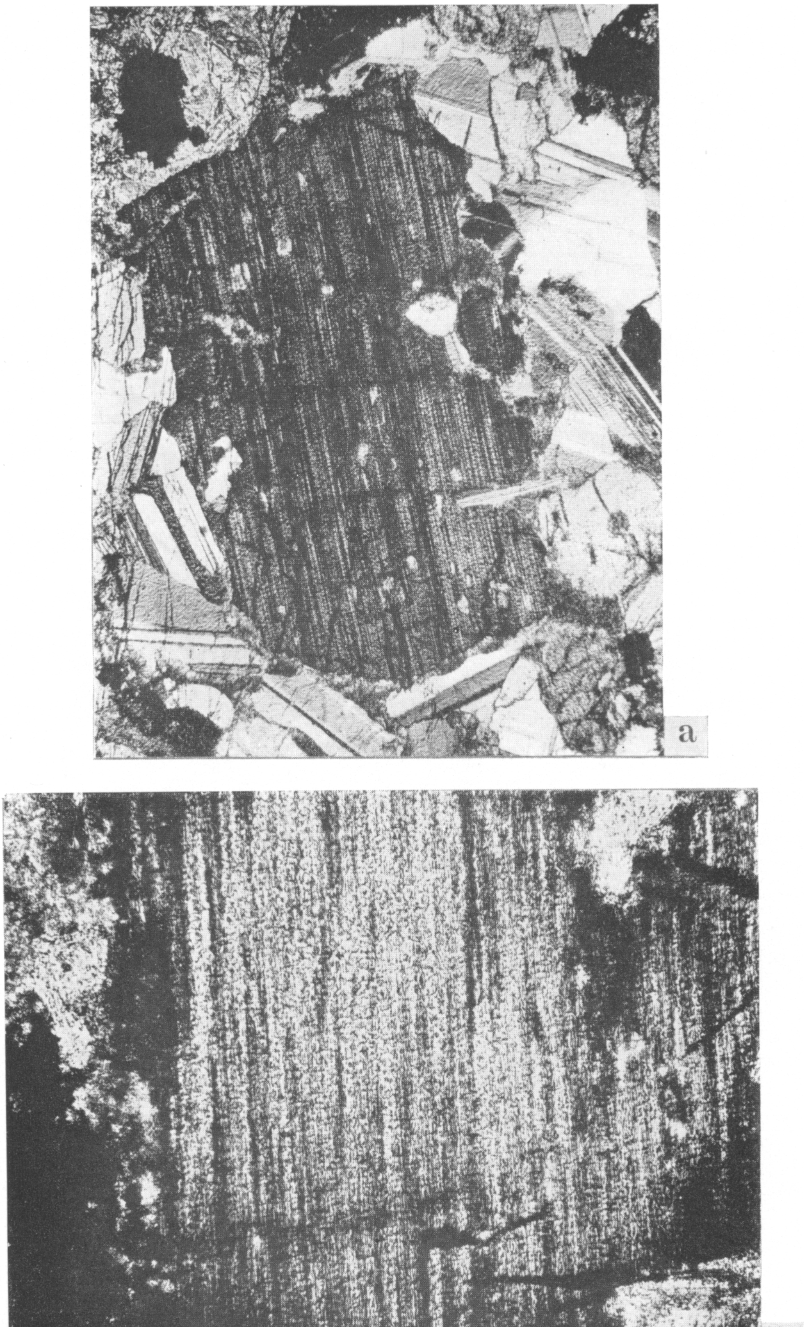
EXPLANATION OF PLATE IV.

Fine lamellar structure in orthopyroxenes. Crossed nicols with the main crystal in extinction position.

FIG. 1 *a*. Hypersthene from olivine-diallage-norite: Whitecairns, Belhelvie, Aberdeenshire. The small light patches are orientated inclusions of clinopyroxene. × 32.

FIG. 1 *b*. Hypersthene from norite: Baste, Harz. The fine lamellae are bent and pinched out. × 140.



N. F. M. HENRY: LAMELLAR STRUCTURE IN ORTHOPYROXENES