X-ray study of deformation lamellae in olivines of ultramafic rocks

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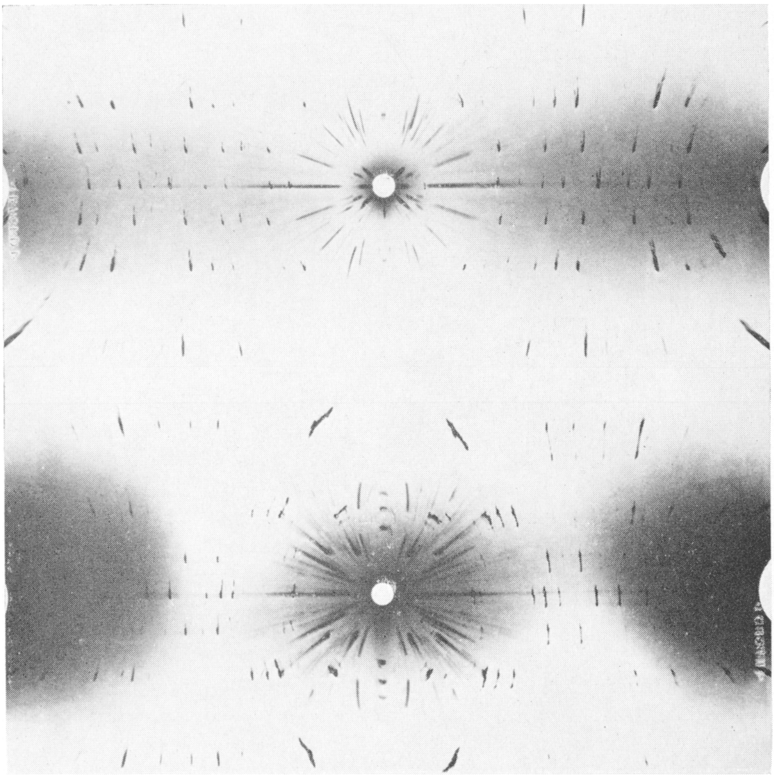
Summary. Olivine crystals showing {100} deformation lamellae between crossed polars show spots streaked out transversely to $00l$ layer lines in X-ray oscillation photographs. Compositional inhomogeneity is ruled out by optics and electron microprobe analysis. Structurally controlled gliding on {100} (plane of greatest atom density) in the direction [001] (close-packing direction) is deduced on analogy with deformed metals. Mechanism of lamella formation is discussed in terms of superincumbent load; but it is concluded that pressures due to crystal growth are mainly responsible.

UNDULOSE extinction and deformation lamellae (sometimes called translation lamellae) in olivines from ultramafic rocks and nodules have been described by numerous authors including the well-known studies by Turner (1942) and Chudoba and Frechen (1950). More recently Raleigh (1965) and Riecker and Rooney (1966) have studied the glide systems in experimentally deformed olivines. Although these authors have studied the deformed olivines by various optical methods, olivines have not yet been the subject of single crystal X-ray examination, as far as the present writer is aware. Optical methods indicate that the lamellae in naturally deformed olivines are generally parallel to {100}, and that the difference in orientation between different parts of a crystal (measured by difference in extinction position), is usually less than 10° (Turner, 1942).

For the present work X-ray oscillation photographs were taken with c as the oscillation axis and with a and b parallel to the X-ray beam at the centre of a 15° oscillation range. Three crystals were studied, all of which were single crystals carefully freed from all adhering material. Two of the crystals showed a number of lamellae (5 to 8), with slightly differing extinction positions. The third crystal contained only two bands, and was rather small. X-ray photographs of one of the larger crystals are shown in fig. 1. The two larger crystals gave identical results; the crystal with only two deformation bands differed slightly and will be discussed later.

The main points to note in the photographs are the streaking out of individual spots in the [001] direction, and the splitting of some spots into two streaks, only one of which lies on a curve of constant θ. The



a

b

FIG. 1. *a*. Single crystal oscillation photograph of olivine with eight deformation bands. Oscillation axis *c*; beam parallel to *a* at centre of 15° oscillation range. Note the streaking and splitting of spots. *b*. Single crystal oscillation photograph of olivine with eight deformation bands. Oscillation axis *c*; beam parallel to *b* at centre of 15° oscillation range. Note streaking, but little splitting of spots.

range of orientation of the deformation bands in the three crystals examined (determined from the length of the asterism streaks) is 7 to 8°. In a perfect crystal the reflecting planes should produce sharp spots, and streaking out of spots might be caused by inhomogeneity of the crystal (due to adhering particles or compositional variations), or to variation in lattice orientation within the crystals. As there is no optical or microanalytical indication of inhomogeneity in composition, lattice misorientation is possible. The splitting of the streaks, noted particularly in fig. 1*a*, could also be due to compositional zoning. To exclude this possibility, Dr. J. V. P. Long of Cambridge made a series of electron-microprobe analyses at 10μ intervals across several olivine grains. Uncorrected counts for Fe, averaged from 39 analyses, varied by no more than 27 cps in 2200 cps (1·2 %) between centres and margins. This variation in counts could represent at the most a difference of 0·10 % in the Fe content of the olivines, taking the average Fe content obtained by chemical analysis (Challis, 1965) as 6·5 %. The very small differences could hardly account for the observed streaking of the spots.

It is noted that the splitting of streaks is more obvious in the photograph where the beam is parallel to *a*, and a possible explanation could be a small component of movement on a second glide-plane.

It was suggested to the writer (Dr. P. Gay, *pers. comm.*) that the streaking out of the spots for olivines was similar in appearance to the asterism shown on X-ray photographs of deformed metals (Gay and Honeycombe, 1951, pp. 844–845). In view of the suggestion (Griggs *et al.*, 1960, pp. 22–25) that deformation of calcite might be analogous to that of metals, and their observation of asterism in X-ray powder photographs of deformed calcite, it is interesting to compare the deformation of olivines with the behaviour of metals under plastic deformation.

Barrett (1943, p. 288) states: Plastic flow in crystals occurs by two fundamental mechanisms: slip and twinning. Turner (1942, p. 281) concludes that the {100} lamellae are not possible twins in olivine.

Considering the alternative of plastic flow by slip, it should be noted that there are at least three ways in which lattice reorientation can occur: by a uniform rotation of crystals in an aggregate; by bending of the lattice between glide planes; and by formation of deformation bands in single crystals in which the lattice rotates in different directions. In the last method, slip occurs as a movement of one part of the crystal over another, and movement is concentrated in a series of planes. The crystallographic plane along which this movement takes place is then defined as the glide plane, and the direction in which the movement occurs is the glide direction.

In metals, the most common glide plane is the plane of greatest atomic density and the glide direction is the direction of closest packing. Examining the olivine structure it is seen that {100} is the plane of greatest atomic density, and the close-packed direction is [001].

Therefore, as far as the glide plane is concerned, the behaviour of olivine would be similar to that of metals, if the {100} lamellae are the result of similar deformation processes.

Experimental deformation of olivines at pressures of 5 to 7 kilobars and 700 to 850° C (Raleigh, 1965) produced deformation lamellae parallel to {110} and in these experimentally deformed olivines the glide system seems to have {110} as the glide plane, *T*, and [001] as glide direction, *t*. Raleigh does point out that glide mechanisms in olivines (and other silicates) are probably controlled by structure, and that on structural considerations [001] is the most likely glide direction in olivines. However, {100} is, structurally, the most likely glide plane and deformation lamellae in naturally deformed olivines are parallel to {100} or occasionally to {010}, but have not been observed parallel to {110}. Riecker and Rooney (1966) studying experimentally deformed olivine from dunites of the Webster–Addie Complex, found that the slip system was $T = \{100\}$ $t = [001]$, the same as that found in naturally deformed olivines. The discrepancy observed between the experimentally deformed olivines may be explained by differences in the material used in the experiments. Raleigh used a peridotite nodule containing equidimensional undeformed olivine, enstatite, diopside, and chromite. The starting material in the experiments of Riecker and Rooney was dunite from the large Webster–Addie complex; some of the olivine in this material already possessed weak deformation lamellae parallel to {100}. In large ultramafic intrusions such as Red Hill in New Zealand (Challis, 1965) many of the olivines are dimensionally oriented and are flattened on the (010) face. The dimensionally oriented olivines commonly show a much greater development of deformation lamellae than the granular equidimensional grains.

The following mechanism would be consistent with the features shown on the single crystal X-ray films and with the observations on thin sections:

The olivines in large ultramafic intrusions, such as Red Hill and Dun Mountain (Challis, 1965), tend to adopt a preferred orientation, lying on the broad (010) face in the plane of a visible compositional layering. In this orientation, the planes of greatest atomic density would be parallel to the direction of compressive stress induced by a load of overlying crystals. (The idea of overlying load is introduced for the sake of argument only: see later regarding the efficiency of load.)

Simple sideways shear would be prevented by the surrounding crystals, which provide a lateral restraint, and the conditions here are similar to the conditions of experimental deformation of metals under constraint (Barrett, 1943, p. 303).

If the compressive stress is not strictly parallel to the {100} planes, either because the olivine crystal is not lying flat, or because a lateral stress is introduced (perhaps due to slumping of the crystal cumulate, or because adjoining crystals impinge on one another), slip may be initiated on the {100} planes.

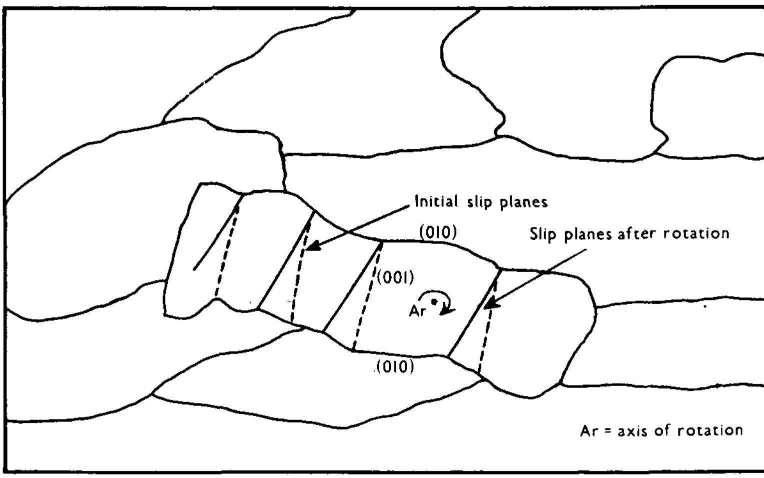


FIG. 2. Diagrammatic representation of suggested mechanism of olivine deformation in a crystal cumulate. The olivine is lying on the flattened (010) face and [001] is normal to the page.

When the potential glide planes in the olivines depart from a position parallel to the main compressive stress, the planes would tend to rotate towards a position normal to the stress direction (fig. 2). Beyond a certain degree of rotation, the shear stress on this set of planes diminishes, whereas other planes may be subjected to increasing stress and a second glide plane may start to operate. This might account for the second set of bands parallel to {010} that have been observed by Dr. E. D. Jackson (*pers. comm.*). It should be noted that {010} is, structurally, a likely glide plane.

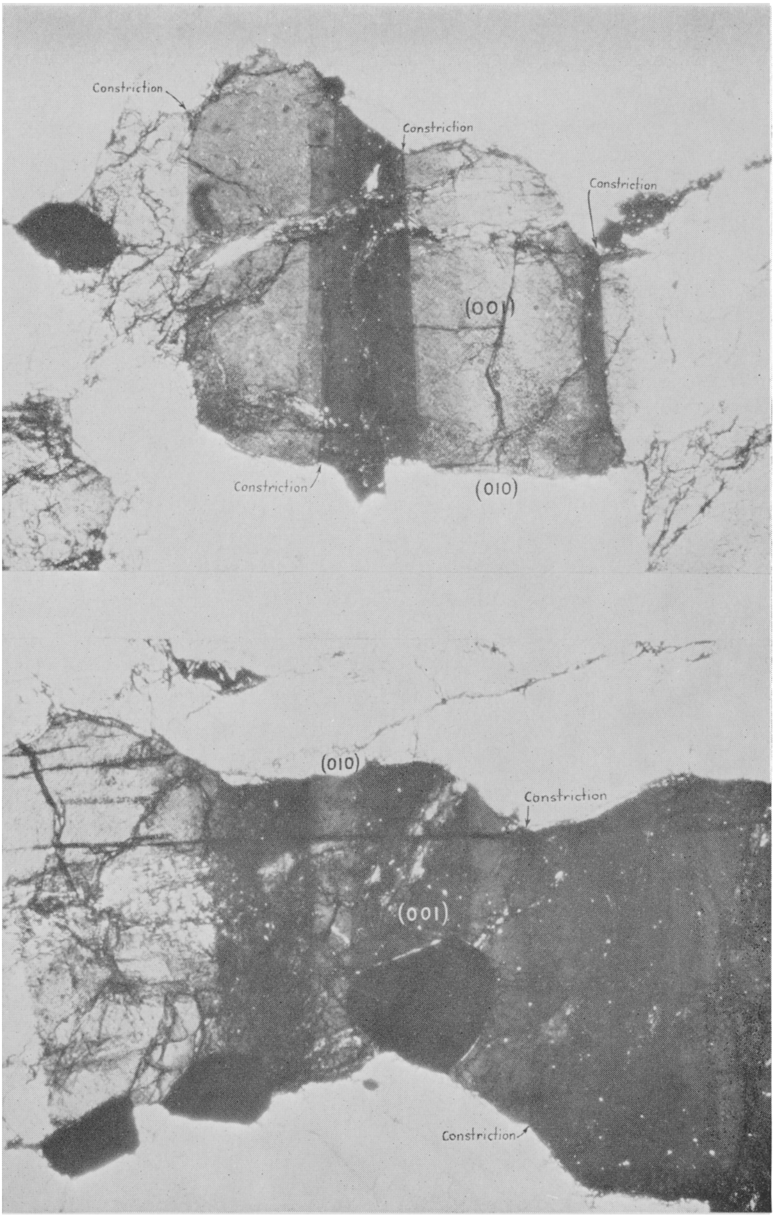
In addition to the above mechanism for production of deformation lamellae, there is the possibility of lattice bending within individual deformation lamellae, or within a single crystal. This type of deformation could account for the undulose extinction observed in many olivines, even where actual deformation lamellae are absent.

Lattice bending, without actual slip on a system of glide planes, could also account for the asterism seen in the X-ray photographs. However, Barrett (1943, p. 360) states that: It is the rule, rather than the exception, for different portions of the crystal to rotate in different directions forming deformation bands of differing orientation. . . . They produce asterism much like that attributed to local distortion.

In support of the fact that the asterism is the result of slip on a number of glide planes is the difference observed between X-ray photographs of the larger crystals with 5 to 8 lamellae, and a small crystal with only two lamellae. The photograph of the small crystal showed two sharp spots, connected by a faint streak, lying on a curve of constant θ. The length of the streak was less than half that of the longest one observed in the larger crystals, but was otherwise identical in position and appearance. The two spots are apparently the result of the slightly differing orientation of the two deformation bands, and presumably in the larger crystal the eight deformation bands with their differing orientations has produced a streak rather than individual spots. These results indicate that the deformation bands are at least one cause of asterism. Whether they are the only cause could be proved by applying a microbeam technique to individual deformation bands and to single olivine crystals, showing undulose extinction, but no actual lamellae. It is hoped to carry out this work as the equipment becomes available.

Lauder (1965) in a detailed petrological study of the Dun Mountain ultramafic rocks, has drawn attention to the frequency with which deformation lamellae occur at points of constriction in the olivine crystals (fig. 3). Proof that the deformation lamellae were produced after most of the rock had crystallized is provided by the fact that deformation bands extend right to the edges of crystals, even in cases where secondary growth continued after crystal settling. However, deformation bands do not appear to be produced by cataclasis of the solid dunite, as smaller interstitial olivines in undeformed dunites show deformation lamellae, and they are absent in recrystallized olivines in cataclastic, partially mylonitized dunites from Red Hill and Dun Mountain, and in the tectonically deformed olivine norites and peridotites of the Longwood Range. Quite severe tectonic deformation of the basic and ultramafic rocks of the Bluff-Longwoods complex in New Zealand, which has ruptured and bent grains of feldspar and orthopyroxene, has failed to produce any deformation lamellae in the olivines.

Brothers (1960) makes an interesting observation on olivine nodules



a

b

FIG. 3. *a*, *b*. Photomicrographs of olivine crystals in dunite from Dun Mountain, New Zealand. The olivine crystals are platey and deformation lamellae are particularly developed at points where the crystal is constricted by growth of adjacent olivines. The opaque grains are chromite. Crossed polars. Photomicrographs: S. N. Beatus.

in which he finds that deformation lamellae are rare in specimens where olivine forms only 34 % of the rock, but are abundant in dunites or harzburgites with a high olivine content and a small amount of inter-precipitate minerals. Similarly, deformation lamellae are not seen in the olivines of the Cyprus glassy ultramafic lava (Gass, 1958), where olivine forms about 57 % of the rock and a glassy ground-mass is present. If the deformation lamellae had been produced by simple load of overlying crystals as suggested by Brothers (1960) for the peridotite nodules, and all the nodules were the result of crystal accumulation either in the mantle or in a magma chamber, then the olivines should show deformation lamellae independent of the amount of other phases present. It appears that neither simple load of overlying crystals nor tectonic deformation of the solid rock could satisfactorily explain the production of deformation lamellae in olivines. It is suggested that the lamellae are produced mainly in the last stages of crystallization in a largely monomineralic rock where rapidly growing olivine crystals are competing for space and are impinging on each other. The weight of the overlying crystals perhaps favours the development of lamellae in suitably oriented crystals, but the predominant factor is that of crystallization pressure.

Conclusions. Single crystal X-ray oscillation photographs of olivines showing deformation lamellae show certain similarities to those of experimentally deformed metals. From a consideration of the olivine structure, examination of the X-ray photographs, and analogy with deformation of metals, the probable glide plane in naturally deformed olivines is {100} and the most likely glide direction is [001]. A second glide plane may be initiated if rotation exceeds a critical value. The most likely second plane, on theoretical considerations, is the plane of second greatest atomic density, {010}. Undulose extinction may be an expression of bending of the lattice rather than actual slip.

It is concluded that stresses imposed by growth of overlying and surrounding crystals in a largely monomineralic rock could produce the deformation during the later stages of crystallization in suitably oriented olivine crystals.

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