Reports

Glide Mechanisms in Experimentally Deformed Minerals

Abstract. *A method for study of mechanisms of twin and translation gliding in minerals in rocks has been devised by which slip markings produced experimentally on polished surfaces are related to crystallographic planes by universal stage measurements of the crystal orientations. In specimens strained 5 to 10 percent at 5 to 7 kilobars confining pressure and 700° to 850°C, the glide plane and glide direction for slip and twinning have been determined in olivine, enstatite, kyanite, and diopside. Slip occurs in closest-packed directions, in which also lies the shortest Burgers vector of a unit edge dislocation in the slip plane.*

Progress in the study of plastic flow in rock-forming minerals has been retarded because, among other reasons, the techniques available to petrographers for determination of the glide mechanisms are inadequate for several important minerals. In recent years, glide mechanisms have been determined primarily from the rotations undergone by lamellar structures present in the crystals prior to deformation. For example, the *e*-twin lamellae of calcite rotate through the lattice during translation, gliding on *r* about an axis defined by the intersection *e* : *r* (*1*). However, when such lamellar structures are not present or are orientated unfavorably, this method is not feasible. Furthermore, the assumption implicit in the method, that the internal rotation is accomplished by slip on a single mechanism, may not be necessarily valid.

Metallurgists, being generally unable to use transmitted light methods, have evolved a technique which utilizes the linear markings, called slip lines, formed by the offset produced by glide on slip planes intersecting the polished surface of a deformed metal crystal. As the slip lines are parallel to the active slip plane, the crystallographic orientation of the plane may be determined by observations of slip lines on two faces of a single crystal of known orientation. Where slip lines occur on crystals of differing orientation on the polished surface of an aggregate, the slip plane, or planes, can be determined by finding the orientations of the slipped crystals from back-reflection Laue photographs.

Christie, Griggs, and Carter (*2*) have found that slip traces on single crystals of quartz are aligned with the basal plane, determined as the active slip plane by transmitted light techniques. It is important, however, to be able to observe slip in grains in polycrystalline aggregates and useful in that large single crystals of rock-forming silicates are not always readily available. The following method, which combines metallurgical and petrographic techniques, has been devised for the study of slip in crystals in experimentally deformed rocks.

Cores of rock 0.7 or 1 cm in diameter were prepared for deformation by fitting together two half-cylinders split along an axial median plane. The opposing plane faces were polished and then separated by a piece of 0.0025-cm platinum foil. After a few percent strain at high pressure and temperature the polished surfaces, showing slip markings or twinning, were photographed in incident light on a scale large enough to show details of the slip markings and grain boundaries (Fig. 1). The polished faces were then lightly ground to remove surface irregularities resulting from deformation, cemented to a slide glass with epoxy resin, and cut in thin-sections in the usual way.

The greatest advantage of this method lies in the ease with which the crystallographic orientations of the grains may be determined. By measuring the orientation of the optical indicatrix of a grain in thin section in polarized light on a universal stage, a procedure requiring only a few minutes, the orientation of the crystallographic axes of crystals of orthorhombic symmetry (parallel to the principal axes of the indicatrix) are determined uniquely. For crystals of higher or lower symmetry, crystallographic elements such as twin or exsolution lamellae or cleavages are usually present in thin section and serve, in addition to the indicatrix, to fix the orientation of most grains. The orientations of the crystal axes of each grain are plotted on a stereographic projection, and the azimuth of the slip lines taken from the photographs is plotted as a point on

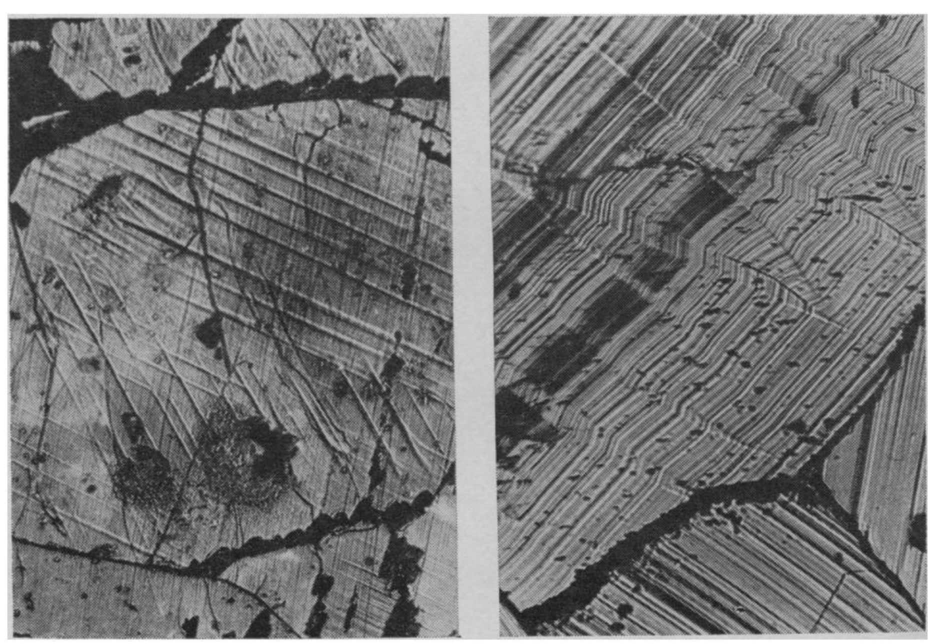

Fig. 1. (Left) Two sets of {110} slip lines (trending NW in photograph) on surface of experimentally deformed olivine viewed in incident light (~ × 150). (Right) Traces of (100) slip planes in kyanite. Kink bands with external rotation about [010] trend nearly normal to the slip lines. (~ × 120).

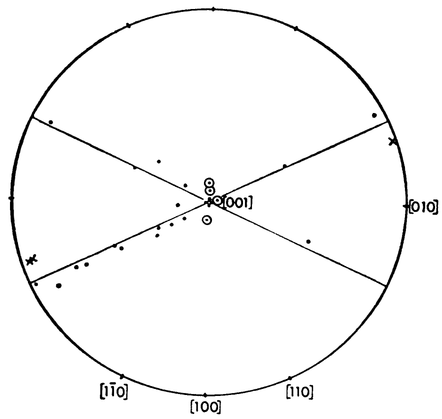

Fig. 2. Equal-area projection showing relation of slip lines (dots) to olivine crystallographic axes. The planes containing the slip lines are {110}. Normals to kink-band boundaries (⊙) lie near [001] and axes of external rotation (+) approximately normal to [001] in {110}.

the primitive (outer) circle of the projection, parallel to the plane of the thin section and the original polished surface. Next, the crystal axes of each grain are rotated on the projection to a standard orientation (Fig. 2). The slip lines will also be rotated by an equivalent amount to a point somewhere on the great circle defining the crystallographic orientation of the slip plane. The example (Fig. 2) shows the orientations of the slip lines from several olivine grains aligned along great

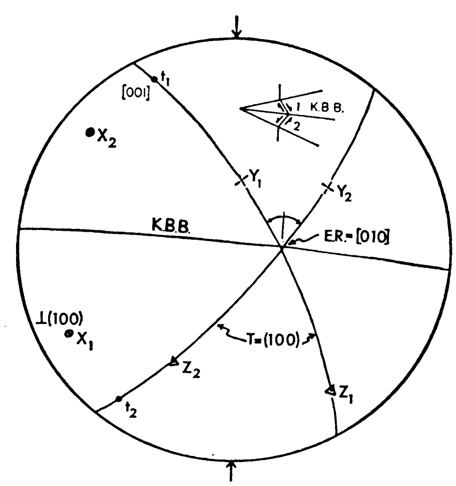

Fig. 3. Equal-area projection showing geometry of kinking in kyanite. The axis of external rotation, *E.R.*, lies in the kink-band boundary, *K.B.B.*, parallel to its intersection with the slip plane, $T = (100)$. The slip direction, $t = [001]$, is normal to the axis of external rotation in the slip plane. The sketch at top shows the orientations of the slip traces in incident light and the sense of shear on either side of the kink-band boundary.

circles which define the slip planes as {110}.

The direction of slip in the plane may be determined in one of three ways.

1) Even at small strains some grains will kink or bend owing to inhomogeneous slip along the glide plane. The axis of external rotation of the bent lattice lies in the slip plane normal to the slip direction if single slip has operated. The orientation of the axis of external rotation may be determined on the stereographic projection by finding the line about which the indicatrix may be rotated from its orientation on one side of a kink-band boundary to the orientation measured from the other side. However, because it is often difficult to locate this axis accurately, especially where the amount of rotation is small, the following methods may be used in preference.

2) The geometry of external rotations across kink-band boundaries requires that, for single slip, the slip direction must lie at right angles to the intersection of the slip plane and the kink-band boundary (*2*). Otherwise, the crystal must part at the boundary. Thus the slip direction, *t*, is a line in the great circle on the projection (Fig. 3) defining the slip plane, *T*, 90° from the line of intersection of the slip plane with the kink-band boundary. The intersection is parallel to the axis of external rotation (Fig. 3).

3) Grains for which the shear stress on the slip plane is high may show no slip markings; for such cases it may be assumed either that, statistically, there is low or no resolved shear stress in the slip direction, or that the slip direction is parallel to the polished surface so that no steps in the surface would be observed. Measurements on several such grains should resolve the ambiguity and therefore serve to determine the direction of slip.

Several silicate minerals have been examined with the foregoing technique after deformation at confining pressures of 5 or 7 kb at 750° to 850°C in M. S. Paterson's deformation apparatus. The strain rates for all experiments were approximately 2×10^{-4} sec^{-1}.

Olivine. Cores of a peridotite nodule from a basalt dike in the Snowy Mountains tunnel, New South Wales, contain undeformed forsterite ($2V_z = 88°$) with enstatite, diopside, and chromite in a granular aggregate. The cores were shortened 5 percent at 5 kb, 800°C. One or two sets of slip lines lying in {110} planes (Fig. 2) were observed

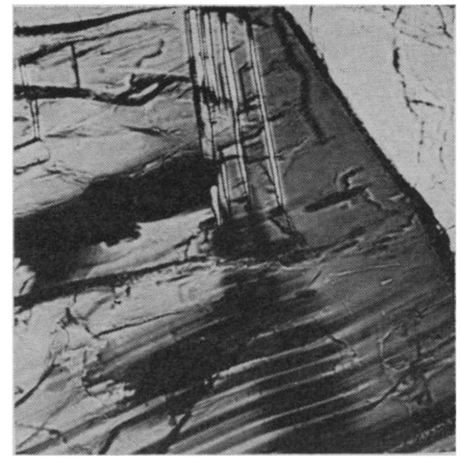

Fig. 4. Mechanical twins on (001) (NNW in photo) and (100) (ENE in photo) in diopside viewed in transmitted light between crossed polarizers. The slight flexure in the (100) twin lamellae is an adjustment to the strain produced by the (001) twins and is accomplished by an increase in the number of (100) lamellae in the bent region. ($\sim \times 300$).

in most grains and kink bands were observed in a few grains lying nearly normal to a single set of slip lines. Where both sets are present the traces commonly become wavy. The slip direction, defined as the line in {110} normal to the intersection of {110} and the kink-band boundaries and by the normal to E.R., the axis of external rotation in {110}, is [001]. The slip system is $T = \{110\}$, $t = [001]$. Deformation lamellae observed in transmitted light are parallel to {110} and are nearly identical in appearance (*3*) to those in experimentally deformed quartz (*4*). The optical effects observed around the lamellae are considered by Christie *et al.* (*2*) to be produced by a planar array of locked-in slip dislocations having like sign.

Most kink bands in olivine deformed in nature are approximately parallel to (100), and only a few are approximately parallel to (001) as in these experiments. It is likely, that slip on another plane or planes, probably in the [100] direction, is responsible (*4a*).

Enstatite. Enstatite ($2V_z = 83°$) present in the Snowy Mountains peridotite nodules shows a single set of slip lines lying in the (100) plane. Axes of external rotation are parallel to [010], that is, normal to [001] in the slip plane. The slip system is $T = (100)$, $t = [001]$. This is the mechanism proposed by Turner, Heard, and Griggs (*5*), which is based on the observations that (i) exsolution lamellae parallel to (100) maintained rational orientation across kink-band boundaries and that (ii) [010] was the axis of external rotation in the kink-band boundaries. Inversion to clinoenstatite in highly deformed parts of the enstatite grains was observed by Turner *et al.* (*5*). Inversion to clinoenstatite in kink bands and also in lamellae parallel to (100) was produced in the present experiments.

Diopside. Diopside in a eucrite gabbro and bright green diopside in the peridotite nodule deformed at 700°C to 850°C, when viewed in incident light, showed broad discontinuous twins parallel to (001) and narrow slip (or twin) traces parallel to (100). In thin section, lamellar twinning on (100) is seen to occur on a fine scale. In the undeformed diopside of the peridotite, exsolution lamellae or twins parallel to (100) are rare, and therefore the lamellar twinning observed must have been produced experimentally. Twinning elements determined by universal stage measurements in both polished and thin sections are $K_1 = (100)$, the composition plane; $\eta_1 = [001]$, the twin axis; $K_2 = (001)$; and $\eta_2 = [100]$. It is not possible to determine whether slip on (100), as invoked by Griggs *et al.* (*6*) to account for large external rotations, and the absence of internal rotation of (100) exsolution lamellae in kinked diopside may have occurred in addition to twinning on (100) in my experiments. However, such rotation of the untwinned lattice as I have observed, although in accord with inhomogeneous slip on the system $T = (100)$, $t = [001]$, may be accounted for entirely by variation in the density or spacing of the (100) twin lamellae within the crystal (Fig. 4).

Basal twins (Fig. 4) have been produced experimentally in diopside by other workers (*6*), and the twinning elements deduced are in agreement with those determined in the present work. The composition plane is (001), the twin axis $=$ [100], and (100) twin lamellae remain parallel to (100) in the twinned lattice after rotation by the basal twin gliding. The twinning elements are, therefore, $K_1 = (001)$, $\eta_1 = [100]$, $K_2 = (100)$, and $\eta_2 = [001]$.

Kyanite. Slip traces are parallel to (100), and well-developed kink bands (Fig. 1, right) in which external rotation takes place about [010] serve to define the slip direction as [001] (Fig. 3). The slip system so determined confirms the early observations of Mügge (*7*). No mechanical twins were produced experimentally. However, the kink bands which also occur in naturally deformed kyanite superficially resemble twins and may be mistaken for them, as Mügge (*7*) pointed out.

Although it is premature to draw any broad conclusions about the relation between glide mechanisms and crystal structure of the silicates in general, some structural control of the glide elements in the crystals studied is apparent. (i) For the three minerals—olivine, enstatite, and kyanite—for which translation gliding could be demonstrated, the choice of glide plane is such that the strong silicon-oxygen bonds remain unbroken. In olivine and kyanite more than one such plane exists (*8*) but in the enstatite structure, (100), the slip plane is the only planar surface which satisfies this criterion. (ii) Within the glide plane, for each mineral, the glide direction is that direction for which the Burgers vector for a unit edge dislocation in the plane is least, thereby minimizing the length of a unit translation during slip. In olivine and kyanite the slip directions, [001], are also parallel to close-packed rows of oxygen atoms; in enstatite, one-third of the oxygens in the slip plane are close-packed in the slip direction.

The similarity between the structural arrangement of enstatite and diopside on the (100) face makes it probable that $T = (100)$, $t = [001]$ would be the easy glide system in diopside also. Twin gliding on (100) in the direction [001] has been demonstrated here, and the likelihood of translation glide on the same system, as suggested by Griggs *et al.* (*6*), is supported by these structural considerations.

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References and Notes

1. F. J. Turner, D. T. Griggs, H. C. Heard, *Bull. Geol. Soc. Amer.* **65**, 893 (1954).
2. J. M. Christie, D. T. Griggs, N. L. Carter, *J. Geol.* **72**, 734 (1964).
3. The lamellae in the experimentally deformed olivine were only faintly visible in standard thin sections because of being obscured by the high relief of the ground surface of the olivine against a mounting medium of considerably different refractive index. To combat this effect both surfaces of the specimen were smoothed with 600-grit carborundum and finished with polishing on diamond paste down to a grit size of 3 μ.
4. N. L. Carter, J. M. Christie, D. T. Griggs, *J. Geol.* **72**, 687 (1964).

4a. Slip lines lying in the plane (010) in combination with kink bands parallel to (100) produced in experiments at 1000°C and 5 kb indicate slip on the system $T = (010)$, $t = [100]$.

5. F. J. Turner, H. C. Heard, D. T. Griggs, *Int. Geol. Congr. 21st Session, Copenhagen, Norden*, part 18, 399 (1960).
6. D. T. Griggs, F. J. Turner, H. C. Heard, *Geol. Soc. Amer. Mem.* **79** (1960), p. 39.
7. H. Mügge, *Neues. Jahr. 6 Geol. Palentol. Abhandl.* **1**, 71 (1883).
8. The crystal structures were examined in scale models constructed by Crystal Structures Ltd., with the exception of kyanite, whose structure is referred to by St. Náray-Szábo, W. H. Taylor, W. W. Jackson, *Z. Krist.* **71**, 117 (1929).
9. The peridotite was supplied by D. Moye of the Snowy Mountains Authority, Australia. Diopside occurred in a eucrite gabbro kindly loaned by the Department of Geology, Australian National University. The manuscript was read critically by Dr. M. S. Paterson and Professor F. J. Turner. Professor Turner confirmed some of the optical measurements on clinoenstatite and diopside twinning. Techniques for polishing of the minerals were developed by G. Milburn.

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Potassium-Argon Age from a Granite at Mount Wilbur, Queen Maud Range, Antarctica

Abstract. *The basement complex of the Robert Scott Glacier area, Queen Maud Range, Antarctica, consists of a complex suite of metasedimentary and metavolcanic rocks intruded by light gray biotite granite. Brown biotite from a granite at Mount Wilbur was dated by the potassium-argon method at 470 ± 14 million years; this age coincides closely with many other ages from granitic rocks in the Transantarctic Mountains.*

Intrusive igneous rocks, mostly light gray biotite granite, are exposed extensively in the Robert Scott Glacier area, Queen Maud Range, Antarctica (Fig. 1). They make up the entire basement in the southern part of the area, while in the north they intrude thick sequences of metasedimentary rocks. The general geology of this area has been described (*1*).

Some of the oldest rocks exposed in the area are metagraywackes with a thickness estimated to exceed 3000 m; the beds dip vertically and strike parallel with the mountain front. The metagraywackes have been metamorphosed to the greenschist facies and are restricted to the LaGorce Mountains where they are intruded by the typical gray granite of this area.

North of the Watson Escarpment in the area of the Leverett Glacier the gray granite intrudes thick, more gently dipping, slightly metamorphosed carbonates, sandstones, and rhyolites. These beds of the Leverett group contain thin beds of carbonate rich in trilobite fragments that appear to be of Cambrian age. The carbonate beds are more than