OFFICE OF NAVAL RESEARCH
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# Preferred Orientation of Calcite and Dolomite in Experimentally Deformed Marbles

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## FINAL REPORT

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## Nature of Project

Prior to initiation of this project in January 1952, a pure calcite marble from Yule Creek, Colorado, had been plastically deformed under high confining pressures by D. Griggs and co-workers, Institute of Geophysics, University of California, Los Angeles. Cylinders (1" x 1/2") of three different orientations, cut from the same block of marble, were employed. The experiments were carried out at 20°C. and 150°C. under a confining pressure of 10,000 atmospheres. Results of these experiments and of studies by F. J. Turner and co-workers on the effect of deformation upon preferred orientation of calcite grains in the marble were published in 1951 (Griggs, Turner _et_ _al_., 1951, Parts I-IV).

Project NR 081 134 concerns further investigation of changes in preferred orientation of calcite and of dolomite plastically deformed at higher temperatures. Again the material was supplied by Griggs, with whom I have been in close collaboration throughout the research. The material investigated falls into four categories:

1. Yule marlbe deformed at 300°C. and 400°C., 5,000 atmospheres, alternately dry and in presence of water.

2. Naturally deformed, i.e., metamorphic, marbles.

3. Dolomite rock from Dover Plains, New York, deformed at 380°C. and 4,000 atmospheres, dry.

4. Single crystals of pure calcite, of twelve different orientations, deformed at 20°C., 10,000 atmospheres; 20°C., 5,000 atmospheres; 150°C., 5,000 atmospheres; 300°C., 5,000 atmospheres; and 400°C., 3,000 atmospheres.

The results of our investigations are summarized below. The summary is brief since all results have already been published or are now in the press.

## Yule Marble

Results of petrographic work on Yule marble deformed at 300°C. appear in Part V of the series of papers by Griggs and myself. (Griggs, Turner, *et al.*, Part V, 1953). Under the microscope the deformed rock resembles naturally deformed marble much more closely than does material deformed at lower temperatures. Clouding and marginal distortion of grains is less pronounced. There is some evidence to suggest that grain boundaries merge to give continuous *s*-surfaces of slip inclined at about 30° to the axis of extension or 60° to the axis of compression.

Where grains are oriented favorably for $\{01\bar{1}2\}$ twinning they become nearly or completely twinned on the favorably oriented plane. Grains of other orientations apparently deform by some other means. In them sharp $\{01\bar{1}2\}$ lamellae of linear thickness, not optically recognizable as twin lamellae, develop profusely on planes of low resolved shear stress. These lamellae cannot be glide lamellae belonging to the glide system that was effective in deforming the grains in question.

In compression experiments *c* axes of the calcite grains become oriented subparallel to the axis of applied stress. In extension experiments the *c* axes concentrate in a girdle normal to the extension axis. The newly developed preferred orientation pattern tends to conform to the symmetry of the stress system.

The various types of visible lamellae that develop in calcite grains during deformation at 20° to 300°C. were investigated in detail (Borg and Turner, Part VI). They include:

1. Twin lamellae, $\{01\bar{1}2\}$ developed parallel to planes of high resolved shear stress for the well-known twin-gliding system. In this the glide direction is normal to the edge $\{01\bar{1}2\} : \{0001\}$, and the sense

of shear is such as to displace upper layers of the lattice upward towards the c axis.

2. "Nontwinned" $\{01\bar{1}2\}$ lamellae of linear thickness, parallel to planes of low resolved shear stress (sense of shear, unfavorable for twinning).

3. Dark $\{10\bar{1}1\}$ partings and faint $\{10\bar{1}1\}$ cleavage cracks.

4. Thin $\{02\bar{2}1\}$ lamellae in grains oriented unfavorably for twinning on $\{01\bar{1}2\}$. They are either normal to the axis of extension or parallel to planes of high resolved shear stress. They are found mainly in material deformed at 20°C.

5. Rough partings, $\{10\bar{1}0\}$, parallel to planes of high resolved shear stress.

6. Anomalous lamellae of three types not conforming to simple planes of the lattice. These are interpreted as pre-existing $\{01\bar{1}2\}$ lamellae that have been rotated bodily through the crystal as the latter is progressively deformed by gliding on another set of slip planes:

a. $L_1$ are lamellae intersecting $(01\bar{1}2)$ at 5°-12°, and so cutting the c axis at 69°-76° instead of at 64°.

b. $L_2$ lamellae, occurring in grains strongly twinned on $(01\bar{1}2)$. They are cozonal with $(01\bar{1}2)$ and $(\bar{1}012)$, and are inclined to the former at 50°-65°, and to the latter at 5°-20°.

c. $L_3$ lamellae, occurring in grains that are completely twinned on $(01\bar{1}2)$. They coincide with $\{11\bar{2}0\}$ of the twinned lattice. Lamellae $L_2$ and $L_3$ are shown to be $(\bar{1}012)$ lamellae that have rotated through the grain, still maintaining their identity, as the grain has deformed by twin gliding on $(01\bar{1}2)$. Lamellae $L_1$ occur in non-twinned grains and must have been rotated by some other glide mechanism.

## Naturally Deformed Marbles

Dynamic interpretation of $\{01\bar{1}2\}$ lamellae observed in natural specimens of metamorphically deformed marble is the topic of three published papers (McIntyre and Turner, 1953; Turner, 1953a; Turner 1953b). Some general conclusions, based on comparison with experimentally deformed material, are as follows:

1. Where marbles consist of lensoid grains lacking obvious twin lamellae, but with plentiful non-twinned lamellae, measure and plot the best-developed set of lamellae in each grain. If these show a strong preferred orientation they may indicate compression at right angles to their mean trend. Such lamellae probably developed late in metamorphism.

2. Where obvious twinning is confined to a small percentage of grains, twinning is attributable to late stresses operating after the main metamorphism. It is possible to reconstruct the compressive force most favorable to twinning on each set of observed twin lamellae (on a projection this compression is represented by a point 71° distant from <u>c</u> and 45° from the pole of the twin lamellae, on the same great circle). Such "compression points" determined individually for a number of grains, are closely grouped on the projection. They indicate the general direction of compression responsible for twinning.

3. In marbles where twinning is strongly developed, presence of apparent $\{11\bar{2}0\}$ lamellae--actually $L_3$ lamellae--shows that the grain concerned is completely twinned.

## Calcite Crystals

A lengthy report (100 pages and many illustrations) has been submitted for publication in the <u>Bulletin of the Geological Society of America</u>, (Turner, Griggs, and Heard, 1954b). It deals with experimental plastic deformation of cylinders cut from single crystals of clear calcite.

A wide range of crystallographic orientation in relation to compression or extension of cylinders is involved. Most experiments were conducted at 20°C. and 10,000 atmospheres confining pressure, or at 300°C. and 5,000 atmospheres. Temperatures of 150°C. and 400°C. were employed in a few additional cases. Shortening or extension of the whole cylinder ranges from 2% to 20%; but in some extension experiments necking of the cylinder has locally increased the strain by a factor of 3 or 4. Stress-strain curves for typical experiments are given. Where the orientation permits, the preferred mechanism of deformation at all temperatures is twin gliding on $\{01\bar{1}2\}$ . Cylinders so oriented that twin gliding cannot occur deform plastically by some alternative mechanism. At 20°C. calcite is many times stronger when oriented unfavorably for $\{01\bar{1}2\}$ twin gliding than when favorably oriented; but with rising temperature this difference rapidly diminishes. Analysis of stress-strain data for variously oriented crystals at 300°C. points to translation gliding on $\{10\bar{1}1\}$ as the alternative mechanism to twin gliding on $\{01\bar{1}2\}$ . However no satisfacotry correlation of stress-strain data for 20°C. could be established on the basis of this or any other simple glide system.

An independent approach to the problem is based on analysis of rotational effects observed microscopically in thin sections of the deformed material. Deformed sectors (e.g., kink bands) in the cylinder are found to be externally rotated about an axis which is parallel to the glide plane and normal to the glide line of the active system. At the same time, early-formed lamellae (such as $\{01\bar{1}2\}$ twin lamellae) become internally rotated within the deformed crystal, the axis of rotation being the intersection of the glide plane and the rotated lamella. The senses of internal and external rotation in a given sector of the crystal are mutually opposed, and for a given glide plane each can be deduced for a given stress system. Analysis of directions and amounts of internal and external rotation in many instances leads to unique identification of the active glide system. The glide systems so identified include: (1) twin gliding on $\{01\bar{1}2\}$, parallel to the edge $(01\bar{1}2):(10\bar{1}1)$; (2) translation gliding on $\{10\bar{1}1\}$ parallel to the edge $(10\bar{1}1):(02\bar{2}1)$, effective at all temperatures; (3) translation gliding on $\{02\bar{2}1\}$, parallel to the edge $(10\bar{1}1):(02\bar{2}1)$, effective at low temperatures. Translation gliding on $\{01\bar{1}2\}$ in the sense opposite to that of twin gliding has been invoked frequently during the past 50 years as a mechanism of plastic deformation in calcite. We have now shown that such a mechanism does not operate. Nor is there evidence for gliding on $\{0001\}$.

Lamellae $L_1$, previously recognized in deformed Yule marble, are shown to be early-formed $(\bar{1}012)$ lamellae, internally rotated to the $L_1$ orientation by translation gliding on $(10\bar{1}1)$.

## Dolomite Rock

Dolomite rock was deformed at 380°C. and a confining pressure of 4,000 atmospheres. The cylinder was shortened 9.4%. Deformation was plastic, but dolomite was found to be much less ductile than, and about three times as strong as Yule marble deformed under similar conditions.

Fabric analysis shows a rather weak pattern of preferred orientation of *c* axes and of *a* axes prior to deformation. This is but slightly modified by compression. Two mechanisms of deformation have been demonstrated:

1. Twin gliding on $\{02\bar{2}1\}$, the sense of shear being such as to displace upper layers of the lattice downward from the *c* axis.

2. Translation gliding on $\{0001\}$ with an *a* axis as glide direction. This seems to be the more effective mechanism. It causes internal rotation of pre-existing $(02\bar{2}1)$ lamellae through 5°-9°, about the zone axis of $(0001)$ and $(02\bar{2}1)$.

The above results are contained in a paper submitted to the American Journal of Science (Turner, Griggs and Heard, 1954a).

## Future Work

Transparent materials such as calcite, dolomite and most rock-forming minerals, are particularly susceptible to microscopic examination as compared with metals. With a universal stage it is possible to measure the orientation of optical directions and of visible crystallographic planes (twin lamellae, cleavages, etc.) in each individual grain of a rock section. From such measurements, plotted on a projection, the data of external and internal rotation due to deformation, can be reconstructed. And from these the effective glide systems can be deduced. Measurement of internal rotation in particular provides a powerful new tool for investigating glide systems.

We plan to continue work on marble at higher temperatures (400°-600°C). Indeed some work on 400° material has already been started under the present project. We hope also to work on olivine, dunite, quartz, granite, and other rocks and minerals, if these prove (as we expect) amenable to plastic deformation in new apparatus now being tested by Griggs.

An important result of the project is that we have now trained in Berkeley a number of petrographers who are now investigating natural marble fabrics in various parts of the world. So we are sure that reliable data will continue to be accumulated from widely distributed natural sources, for comparison with our own observations on experimentally deformed material.

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