liminary commercial development and establishment on a firm business footing. The result of compulsory licensing would simply be the expansion of the large efficient units at the expense of the smaller ones.

If there is misuse of patents by industry to create unjustified monopolies or to extend them beyond the bounds which are prescribed by law or which are socially desirable, then there is adequate redress available in the various enactments bearing on restraint of trade, unfair competition, antitrust acts, etc. These can meet any legitimate need of the circumstance and have, of course, already been widely used for this purpose.

Finally, if industry and industrial research are to continue increasing in strength and productivity and thereby contribute to national welfare, they must have an atmosphere of assurance that they will be permitted to reap a fair reward for the results of their researches. In such an atmosphere of confidence the leaders of industrial research will feel that they stand on firm ground, from which unparalleled progress is inevitable.

Study of Experimentally Deformed Rocks[1]

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THE TIME HAS FINALLY COME when research no longer has to be restricted to purely military objectives. A particularly important subject for postwar geological research is the continuation of the study of experimental rock deformation that just got off to a good start when it was necessarily interrupted by wartime activities. At the request of the chairman of the Division of Geology and Geography of the National Research Council a Committee on Experimental Deformation of Rocks was organized in 1944 in connection with postwar planning in order to formulate a systematic program for the work, a sort of target at which to shoot in postwar research.

A special microscope technique, known as petrofabric analysis, which has been perfected during the last twenty years, has made it possible to visualize the way in which the more important rock-making minerals, in particular quartz, calcite, mica and feldspar, are arranged in rocks. This spatial visualization has proved that in practically all intensely folded and metamorphosed rock terranes some vectors in the rock constituents, either dimensional or crystallographic or both, are lined up in certain definite patterns of preferred orientation. That is to say, all the inequidimensional grains of calcite in a marble or of quartz in a quartzite may lie with their longer axes parallel. Or all of certain crystallographic directions such as the optic axis in quartz or calcite, or all of certain crystal planes such as the basal plane in mica, may be arranged in definite spatial patterns. The inference that this preferred orientation in rock constituents is induced by the type of movement followed by the constituents during rock deformation has opened up a new path of investigation of the mechanics of crustal movement.

But as long as the geologist cannot do as the metallographer does with his ductile metals, that is, deform rocks and determine how the position of rock constituents has been changed by the deforming movement, the kinematic interpretation of petrofabric diagrams must remain, like too many other geologic conclusions, a matter of more or less well-justified inference.

We know that these petrofabric diagrams differ in symmetry and in type, but what do these differences really show and how can we *prove* that they mean what we think they must mean? To establish a sound scientific basis for interpretation we must make the components of at least some rocks assume a definite spatial arrangement in response to some definite deforming force.

Strain to Rupture

Inasmuch as it is not an easy matter to produce a spatially continuous deformation in such ordinarily brittle material as rocks it is natural that the first experimental work on a known rock fabric was to strain the rock to rupture and to relate the ultimate strength to the fabric pattern. This was first done in 1929 by Drescher, who deformed a marble fabric that had been carefully studied in Innsbruck by Felkel, under the direction of Sander. The material chosen for the test was an Alpine calcite tectonite (marble) that showed no outward evidence of anisotropic structure. However, it was collected from what is known to be a zone of highly deformed rocks and it proved to have a marked preferred orientation. It was deformed in direct relation to the tectonic axes determined by the fabric pattern, which had been established by the work of Felkel. The marble was found

[1] Read before the Section of Tectonophysics, American Geophysical Union, Washington, June 1945.

to rupture most readily when the compressive force was applied parallel to the plane in which there is the strongest concentration of those crystallographic planes that have long been known to be glide planes in calcite. It also shows the greatest strength when the compressive force is applied normal to this plane.

Five years later Bell investigated a biotite granite in the same way and found that it ruptures most easily when the pressure is applied at an angle of 45° to the plane in which the majority of the biotite leaves are arranged. This fabric, like that of the marble, proved to have a marked girdle pattern, but unlike the marble it showed its maximum strength when the pressure is applied parallel to the axis of the girdle. The marble shows its intermediate strength when compressed in a direction parallel to the axis of the girdle. The difference in strength between the strongest and weakest directions in the fabric is about 38 per cent of the maximum strength in marble and about 15 per cent in the granite. Therefore an apparently disotropic marble has, in reality, a marked anisotropy, which has a definite influence on the crushing strength. Similarly, in a granite with a strong preferred orientation of biotite this fabric pattern predetermines a perceptible difference in strength in different directions.

Plastic Deformation

In these experiments there was no penetrative intragranular movement that would produce plastic deformation before rupture, so the movement merely broke the spatial continuity in the fabric without rearranging the crystalline grains. When the brilliant work of Griggs in the laboratory of Professor Bridgman at Harvard finally solved the problem of inducing a plastic deformation of marble cylinders that was perfectly homogeneous as far as could be told from the external shape, the time had come to study the internal fabric of these cylinders and to find out what really happens to the constituent calcite grains during the process of deformation.

The most desirable test material for such an investigation would undoubtedly be a statistically isotropic polycrystalline monomineral aggregate. The Yule marble, quarried by the Vermont Marble Company in Gunnison County, Colorado, is a polycrystalline aggregate and monomineral, being made up of calcite grains alone. It was therefore used for the work. It does not, however, fulfill the other desideratum of a statistically isotropic fabric, in other words a fabric made up of grains in random orientation. Such an arrangement is desirable because in a fabric of random orientation the influence of the deforming movement is free to rearrange the grains in strict conformity to the stress plan, uninfluenced by a pre-existent pattern. That a pre-existent pattern does exert an influence was proved by using the rather simple fabric of the Yule marble. Although this marble appears equigranular on casual inspection it has in reality a distinct planar structure produced by the parallel arrangement of discoid calcite grains. This dimensional preferred orientation proved to be accompanied by a marked crystallographic preferred orientation, in which the optic axes of the calcite crystals lie almost perpendicular to the planar structure determined by the dimensional orientation.

This planar structure was completely transposed by the deforming movement from a vertical position in the test cylinder to an approximately horizontal position in the shortened cylinder. The grains were found to be again discoid and again concentrated in one plane, but the orientation of the plane had changed entirely in response to the deforming movement. Microscopic analysis of the fabric also showed that this horizontal plane of flattening is really a compromise between two planes determined by the crystal lattice structure of the calcite. That is to say, the maximum concentration of the glide lamellae of the calcite is in two planes, intersecting at a low angle and bisected by the flattening plane. That the original fabric had controlled the course of the movement in deformation was proved by the very interesting fact that the cylinders, after shortening, had lost their original circular cross-section and had become elliptical. Now if the test cylinder had been cut from a statistically isotropic substance in which all potential directions of movement were the same, the movement would have been free to proceed through the fabric with equal ease in all directions normal to the direction of compression. As the confining pressure was equal on all sides, a differential force in the direction of the cylinder axis should have given rise to an outward movement of material that would be equal on all sides and thus maintain the circular cross-section of the cylinder. Such a movement would have an axial symmetry. The fact that the movement, instead of following such a "cone of shear," followed two "intersecting planes of shear" shows that the movement was actually orthorhombic in its symmetry plan. This orthorhombic symmetry proves that the original anisotropic structure, instead of being wiped out by the deformation, predetermined the axis of intersection of the operative slip planes that caused the deformation. Moreover, fabric analysis showed that the direction of the major axis of the ellipse coincides with the direction determined by the glide line relation between the lamellae and the axis maxima of the deformed calcite fabric. Thus the change in external shape was directly determined by the grain gliding.

Single Crystal Deformation

This anisotropy of the fabric, which has such a marked influence upon the progress of deformation, depends upon the field that is being considered. A polycrystalline calcite fabric of random orientation would be isotropic because the grains are not lined up in a preferred orientation. But if we examine farther into the field of the space lattice of the individual calcite crystal, the field is no longer isotropic, because the movement is no longer free to proceed with equal ease in all directions but is restricted to certain prescribed crystal glide planes in certain prescribed crystal directions.

Therefore, in formulating a program for systematic research on the mechanism of rock deformation the fundamental start should really be to determine the course of the deforming movement in the space lattice of the ionic crystals that make up the rock-making minerals. Much has been found out in recent years about the course of deformation in the space lattices of the easily deformed metal crystals. It remains, however, to the credit of the science of geology that twinning and translation, which are the processes of plastic deformation in metals, were first discovered and carefully studied by mineralogists, in ionic crystals. In later years it has been proved both by metallographers and by mineralogists that the course of deformation follows certain laws, predetermined by the anisotropy of the space lattice. The metallographer has the advantage over the geologist that he can deform his crystals more readily, but he has to contend with the handicap that he can only study the internal rearrangement of opaque crystals by X-ray analysis, whereas modern optical petrofabric analysis of transparent minerals gives an easy preliminary insight into the response of the crystal lattice to deforming movement, and certain ambiguities that may be inherent in the optical method can be solved later by X-ray analysis.

One of the first problems that cries for attention in single crystal research is: What is the relative function of twinning and translation in plastic slip? The metallographer has answered this for metal crystals by the statement that the slip is accomplished both by translation-gliding and by twin-gliding along prescribed crystal planes and in a prescribed crystal direction. The essential differences between these two types of deformation are threefold: (1) The movement in translation can proceed in both senses of the prescribed direction; in twin-gliding it is restricted to one direction sense. (2) In translation the movement can continue uninterrupted until strain hardening brings the plastic deformation to an end. In twin-gliding the movement is homogeneous simple shear of a given part of the crystal lattice for a finite distance that can be computed. (3) This simple shear proceeds for a restricted distance, measurable as a fraction of the interatomic interval; therefore the orientation of the space lattice is changed in the sheared part of the lattice. In translation the movement is a whole multiple of the interatomic distance and is not necessarily homogeneous. The orientation of the space lattice is unchanged; therefore there is no optical means of recognizing the process except in those sections where the offset between the displaced portions of the grain may cause a perceptible irregularity in grain boundary or a fine lamellar structure.

The restricted amount of movement in twinning puts a definite limit upon the amount of extension or compression that can be attained by twinning alone. When the crystal is sheared throughout its whole extent nothing more can happen by twin-gliding. For this reason metallographers ascribe to translation the dominant role in metal deformation where the extension may be several hundred per cent of the length of the undeformed crystal. Twinning, however, plays an important auxiliary part. For example, in deforming a crystal of zinc in tension the deformation starts by translation along the basal plane when the shearing stress along that plane in a given direction has reached a certain critical value. The direction of the applied force remains constant; therefore, as the grain changes shape by gliding, the glide planes are gradually tilted towards the direction of extension and away from the direction of shortening in the crystal. This change finally brings the crystal glide plane into a position where the shearing stress on this plane is less than the critical value necessary for movement and the process slows down. At this stage the resolved shear stress on the twinning plane $\{10\bar{1}2\}$ comes into play and a part of the space lattice will snap by twinning for a limited distance into the position where the basal gliding plane can function once more. In a space lattice such as calcite, where one and the same crystal plane functions as a glide plane both for translation and for twinning, it is not so easy to sort out the difference in operation of the two processes. Even the comparatively low pressure of a knife blade upon the proper edge of a cleavage rhombohedron will produce simple shear in one direction upon the flat negative rhombohedron. This movement can only proceed in one direction sense, towards the crystal axis, whereas translation could proceed in the opposite sense. In order to prove that translation does operate as well as twinning, Bell deformed a calcite crystal by applying the force in such a way that the crystal could not yield by twinning. The calcite then moved in the same plane as before but in the opposite direction sense. Such movement must therefore be translation-gliding.

Griggs got some highly interesting and complex results by deforming a single crystal of Iceland spar. He obtained a homogeneous deformation of 7 per cent by applying a differential force of almost 2,800 kg./cm.[2] at room temperature to a crystal under a hydrostatic pressure of 10,000 atmospheres. The test cylinder was cut with the long axis parallel to an edge of the cleavage rhombohedron, in other words nearly parallel to one of the three possible flat rhombohedral glide planes. However, there is an ambiguity in the orientation, as the position of the crystal axis in the undeformed cylinder is not known. Four sets of glide planes were developed, with some indication that both twinning and translation had operated on at least three. But the lamellae pattern is somewhat too complex to justify far-reaching conclusions as to the mechanism of deformation, and although the crystal was selected to be free from all traces of twinning as far as could be judged from external appearance alone, there was no optical or X-ray study of the internal structure. This was in the nature of a preliminary experiment at a time when Griggs was establishing his high-pressure technique and there was no opportunity to repeat the experiment under more accurately controlled conditions. When it is repeated it would be desirable to change the crystal orientation of the test cylinder which was originally selected in order to facilitate the rather difficult operation of cutting the cylinders. In this cylinder, deformed by Griggs, one of the three potential glide planes was nearly parallel to the direction of applied force and therefore immobilized to slip as the resolved shear stress on this plane was zero. Movement could and apparently did occur on the other two potential glide planes. A simpler setup for the purposes of analysis would be a cylinder cut so that the crystallographic c-axis lies in the long axis of the cylinder. The resolved shear stress would then be equal on all the three glide planes, and the shearing stress on two other crystal planes that may possibly operate as glide planes in the calcite lattice, namely, the basal plane and the prism, would be zero, so that they should be unable to function. Moreover, with the crystal c-axis of calcite in the direction of a compressive force the three flat rhombohedral gliding planes should be unable to function by *twinning* as the movement on them would then have to proceed against the compressive force. Any movement on these planes ought therefore to be translation. Cylinders of similar orientation should then be tested in tension with the tensile force applied parallel to the cylinder axis. Such a stress plan is an ideal setup for yield by twin-gliding.

It would be particularly interesting to stop the deformation after it has proceeded a very short distance in order to see what happens in the early stage of the deformation and to compare it with deformation carried to a point where the stress-strain curve indicates considerable strain hardening. This comparison should be carried out on cylinders deformed under identical presure-temperature conditions in which the only variable would be the extent of the deformation. Later experiments should evaluate the effect of varying pressure and temperature conditions.

Two important factors in such a program are: (1) the homogeneity of the test crystal, which should be carefully studied to preclude the possibility of twinning in the original undeformed crystal; (2) a careful setup of the field of stress in its relation to the orientation of the glide planes that are known to be operative in calcite. If the initial orientation of the crystal lattice is known, it should be possible to predict the possibility of translation and of twinning on these planes and to plot the change in crystallographic orientation that would result from first, second and successive generations of twins if the deformation obeys the law of maximum resolved shearing stress. Comparison of the predicted and observed results should give a picture of the actual mechanism of deformation.

The same method of study should eventually be carried on in cylinders, in which the crystal setup is planned to put the maximum resolved shearing stress upon other potential glide planes in the crystal lattice.

Deformation of Polycrystalline Monomineral Aggregates

This problem can be studied in much the same way as in the single crystals. A way to determine what are the operative glide planes in such a rock constituent as calcite and how these planes carry the deforming movement is to deform a calcite fabric of simple pattern or a fabric of random orientation (if such can be found) and to measure all the linear elements in the deformed fabrics, grain by grain, and relate all the linear elements in each grain to the optic axis of that grain. We would then know which crystal planes have developed to the point of visibility in each grain and we would also know the orientation of these planes with respect to the stress plan that induced the deformation. It would also be possible to orient the stress field of the deformation in reference to the preferred position of potential glide planes just as was done in the study of the single crystal cylinder, and by checking the predicted against the experimentally acquired pattern we should be able to prove which are the operative glide planes and how they function. Of course this presupposes a simple pattern of strong preferred orientation to start with, which again emphasizes the necessity of most painstaking preliminary analysis of the material to be used for the tests.

Another interesting problem that should be studied in the deformation of polycrystalline aggregates is the relation of the degree of the preferred orientation to the amount of deformation in the test cylinder. If we get a certain degree of preferred orientation and a certain fabric pattern in a cylinder that has attained a 40-per cent deformation, how much would we get under similar conditions if the deformation were stopped at a 20-per cent shortening? One of the experiments in tension carried out by Griggs and Balsley suggests that there is a determinable relation between amount of strain and degree of preferred orientation.

In the experiments carried out by Griggs at Harvard the test cylinders were cut so that the tectonic slip plane of the fabric, which contains the maximum concentration of calcite lamellae, was parallel to the long axis of the cylinder in two of the three sets of test pieces. In the third set this planar structure was normal to the cylinder axis. Unfortunately, although this piece was shortened fully as much as the others, it was impossible to study it because the deformed cylinder crumbled to powder before it could be thin sectioned. The elastic recovery on this specimen was higher than in the other two, but probably the crumbling of the cylinder was not connected with this fact. Possibly the deformation was more intergranular in this specimen, more intragranular in the other two, or possibly the relief of pressure was more sudden in the specimen that crumbled than in the other two. This experiment of compression normal to the major slip plane of the fabric should be repeated.

Still more important experiments should be made upon cylinders cut so that the resolution of shear stress on the slip plane of the fabric should be a maximum, in other words at 45° to the tectonic slip plane, of the original fabric. Here the deformation should be a maximum.

Tensile Stress

Griggs and Balsley obtained marked deformation of as much as 24 per cent in Yule marble cylinders strained in tension under 10,000 atmospheres confining pressure. They used three test cylinders cut with the same orientation as the cylinders used in the compression tests. Their experiments attained a much higher degree of homogeneous deformation than the 9½ per cent extension that Böker had previously obtained in Carrara marble. I have had no opportunity to study these cylinders intensively, and one of the highly desired fields of investigation would be to repeat these experiments with very carefully oriented cylinders and to study the results more intensively than could be done from the single section cut from each cylinder deformed by Balsley.

Recrystallization

Griggs made an extremely important contribution to the technique of high-pressure deformation when he succeeded in producing a beautiful recrystallization texture in Yule marble, deformed at 150° C. in the presence of H_2O and CO_2. This experiment was, however, only of a preliminary nature, and it was only possible to cut one thin section from this cylinder instead of the three mutually perpendicular thin sections that are necessary for a comprehensive fabric analysis. There is also some ambiguity about the orientation of the one thin section that was made; therefore no report has been made upon the fabric. This interesting experiment should be repeated and the results restudied as intensively as possible.

Further Work

Finally, as the work progresses it should be possible to investigate the behavior of single crystals and monomineral aggregates in shearing stress and also to examine the behavior of polymineral aggregates made up of two or more constituents.

It must be strongly emphasized that, in order to get sound conclusions from the proposed experimental work, the investigation should be carried on systematically, and it is particularly important that work on single crystals and on the *simplest* polycrystalline fabrics that can be found should be carried on under the simplest possible stress plan until procedure can be formulated from the fundamental data as a basis for further investigation.

Research of this kind is slow and arduous, involving much drudgery before we can arrive at broad conclusions. Perhaps this fact should be emphasized to the geologist who is likely to think of research in terms of short programs. As geology becomes more and more an experimental science we are every day extending the scope of our investigations and in a day when much is heard about the necessity for organization of scientific research this should be recommended as one of major importance to geological science.