anomaly) would hold the pieces together. It would be presumptuous, in the present lack of knowledge of the hydrogen-helium system, to calculate this tension. Nevertheless, the general model of the Red Spot and of its motion appears to have many attractive features.

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Quartz: Preferred Orientation in Rocks Produced by Dauphiné Twinning

Abstract. *X-ray analyses of quartz aggregates deformed in the laboratory and in nature show a striking difference in the preferred orientation of the positive and negative trigonal forms. These observations may be accounted for by mechanically induced Dauphiné twinning. This orienting mechanism is unusual in that it requires no permanent strain.*

It has long been known that naturally deformed and recrystallized quartz aggregates develop preferred orientations of their *c* axes (*1*). Only recently has it become possible for one to derive the preferred orientations of all planes and directions within deformed quartz aggregates, using spherical harmonic analysis of x-ray pole figures (*2*). A natural quartz mylonite revealed a pronounced difference in the preferred orientation of the positive and negative trigonal forms (*3*). Similar differences in orientation, most marked for the positive ($r = 10\bar{1}1$) and negative ($z = 01\bar{1}1$) unit rhombohedra, were also found in flints subjected to syntectonic recrystallization (*4*) at constant strain rate in a piston-cylinder apparatus with a solid confining medium (*5*). A satisfactory explanation for this asymmetry in the preferred orientation has not hitherto been found.

Recent x-ray analyses of experimentally deformed quartzites have shown that a difference in the preferred orientations of *r* and *z* also develops in the plastically deformed original grains, even in the absence of recrystallization. A typical inverse pole figure for a sample deformed in the alpha quartz field, where quartz has trigonal symmetry 32 (diffraction symmetry $\bar{3}\ 2/m$), is shown in Fig. 1a; the concentration of the poles to *r* parallel to the maximum compressive stress (σ_1) is more than 1.5 times that of a uniform distribution, whereas the concentration of the poles to *z* parallel to σ_1 is less than 0.5.

Despite the similarity of this inverse pole figure to some of those found by Green *et al.* (*4*) for recrystallized flints, the processes occurring in the two cases were apparently quite different. Thus attempts were made to explain this feature of the preferred orientation in terms of the slip processes known to have operated in the quartzites and thought to have been responsible for orienting the *c* axes (*6*).

Measurements on the universal stage of deformation lamellae in these deformed quartzites reveal that slip occurs primarily on basal (0001) and, to a lesser extent, on prismatic ($10\bar{1}0$) planes. Slip directions have been determined from tests on single crystals (*7*). If the critical resolved shear stress for slip on the prism parallel to *c* were significantly higher for one sense of shear than for the other, then a difference in the preferred orientation of *r* and *z* could develop. Two single-crystal experiments were performed to test this possibility. One cylindrical sample was cored with its length normal to *r* and the other with its length normal to *z*. A prism plane is very nearly in the orientation of maximum resolved shear stress for both orientations, but the sense of shear on it is crystallographically reversed. Both samples were subjected to axial compression at a temperature and strain rate (900°C and 10^{-5} sec^{-1} at a confining pressure of 14 kb) such that deformation was primarily by prismatic slip (*8*). Both crystals showed exactly the same strength (25 kb at the yield point) and essentially identical patterns of deformation lamellae and kinks as seen in thin section.

Further evidence in opposition to the theory that slip processes cause the difference in preferred orientation of positive and negative forms was obtained from analyses of quartzites plastically deformed in the beta quartz field, where quartz has true hexagonal $6/mmm$ symmetry. Inverse pole figures for such samples are indistinguishable from those for quartzites deformed in the alpha quartz field. Since differences between positive and negative forms, such as those displayed in Fig. 1a, are not allowed by the symmetry of the beta quartz field, the differentiation must have occurred during the brief interval in which the samples were under nonhydrostatic stress in the alpha quartz field at the termination of the experiments. Essentially no plastic deformation occurred during this interval; consequently, slip processes could not be responsible for the asymmetrical part of the preferred orientation.

The similarity in the inverse pole figures for quartzites plastically deformed in the alpha and beta fields and for flints recrystallized in the alpha field demands some previously unrecognized mechanism to account for the preferential orientation of the pole of *r* parallel to σ_1. The mechanism apparently involves neither slip nor recrystallization processes and must occur rapidly. Mechanical Dauphiné twinning, first reported in 1933 (*9*) and studied extensively 20 to 25 years ago (*10–12*) in a context unrelated to preferred orientation in rocks, satisfies these conditions.

Dauphiné twins are related to each other by a rotation of 180° about the *c* axis; the hand of the crystal is unchanged. The crystal axes remain parallel, but the polarity of the *a* axes is reversed; thus a positive form becomes a negative one, and vice versa. Twinning of this type is common in natural quartz, and the twinned parts are often intergrown in a complex manner (*13*). Several investigators (*9–12*) have shown that the twinning can easily be induced in quartz crystal plates in a variety of ways, which involve stresses of mechanical, thermal, or electrical origin within the alpha quartz field, and which produce no permanent strain. The maximum shear stresses necessary for twinning are very low, of the order of 20 bars at 400°C (*10*). The necessary stresses are so low because only a displacive rearrangement of the atoms occurs during twinning; no Si–O bonds are broken, as is the case in mechanical Brazil twinning (*14*).

The ease with which Dauphiné twinning can be induced in single crystals at low stresses and moderate temperatures implies that it should occur extensively in naturally and experimentally deformed quartz aggregates. The observations of Thomas and Wooster (*11*) permit specific predictions of the effect of this twinning on the preferred orientations developed in such aggregates. Irregularly twinned quartz plates of many different crystallographic orientations were subjected to torsion (*10*, *11*); for some crystal orientations the twin boundary moved so as to leave the crystal completely in one orientation, whereas in others it moved so as to leave the crystal in the twinned orientation. In all cases the movement of the twin boundary depended not on the sense of torsion but on the orientation of the crystal with respect to the applied stress: ". . . the twin boundary moved so that the whole crystal yielded [elastically] as much as possible under a given stress" (*11*), in accordance with Le Chatelier's principle (*15*).

This observation implies that in axially stressed single crystals and aggregates twinning will act to bring directions of greater compliance parallel to the unique stress axis (σ_1 in compression, or the minimum compressive stress σ_3 in extension). The variation of the compliance S_{11}' (the reciprocal of Young's modulus) (Fig. 1b) shows that the poles to positive forms consistently have greater compliances than the poles to corresponding negative forms. Because of the diffraction symmetry of quartz,

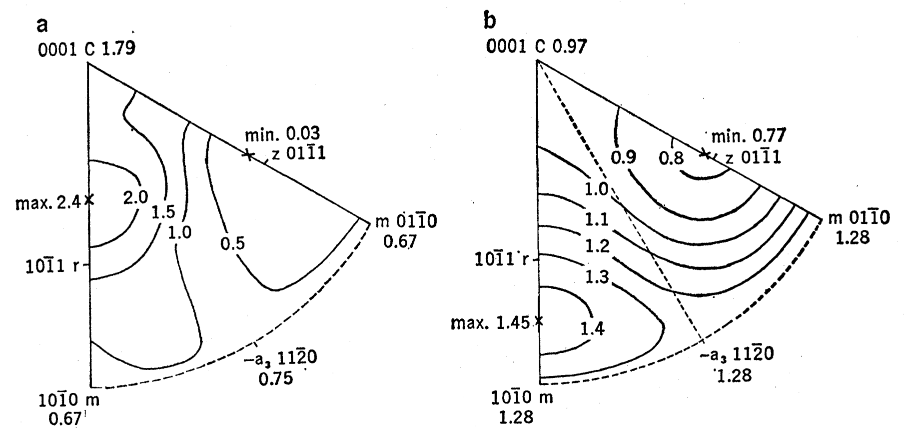

Fig. 1. Equal area projections showing that crystal directions which become parallel to σ_1 during axial compression tend to be those directions with greater compliance. (a) Inverse pole figure for specimen GB-202, a quartzite shortened 40 percent at a temperature of 600°C, a confining pressure of 15 kb, and a strain rate of 10^{-7} sec^{-1}. Inverse pole figures show the distribution of a variable with reference to the crystal axes; the value at any point in this figure gives the concentration of that crystal direction parallel to σ_1 in multiples of a uniform distribution. (b) Inverse pole figure showing the variation of the reciprocal of Young's modulus, S_{11}', with crystal direction at room temperature and atmospheric pressure, in units of 10^{-12} cm^2/dyne. The figure was calculated from the isothermal elastic constants determined by McSkimin *et al.* (*17*). Negative crystal forms are to the right of the dotted line; positive forms are to the left.

the operation of Dauphiné twinning may be represented by a change in the orientation of σ_1 from one side of the dotted line (Fig. 1b) to the symmetrical position on the other side. Thus in axial compression grains oriented so that σ_1 lies to the right of the dotted line should tend to twin to the symmetrical position with σ_1 lying to the left side of the line. Grains initially oriented so that σ_1 lies to the left of the line should remain untwinned.

I have demonstrated this tendency both for single crystals and for aggregates loaded in axial compression tests. For the two single-crystal specimens mentioned above, one loaded normal to *r* and one normal to *z*, the orientations after deformation were checked by means of x-ray diffraction techniques. The relative intensities of reflection from several rhombohedral planes indicated that the specimen loaded normal to *z* had completely changed its orientation as a result of twinning, even in the colder ends, whereas the specimen loaded normal to *r* had remained unaffected by twinning. Since the twinning

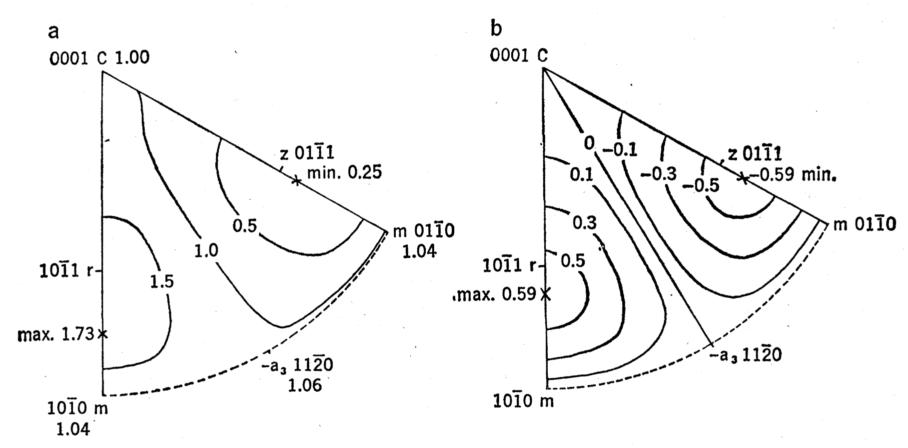

Fig. 2. Equal area projections showing that in an initially random aggregate subjected to axial compression the tendency for grains to twin is proportional to the increase in the value of S_{11}' due to twinning. (a) Inverse pole figure for specimen GB-353, a flint loaded at a temperature of 500°C and a confining pressure of 4 kb to a differential stress of 13 kb for 3 hours. Concentrations are in multiples of a uniform distribution. (b) Inverse pole figure showing the variation with crystal direction of the difference in S_{11}' between original and twinned orientations, in units of 10^{-12} cm^2/dyne.

probably occurred early in the deformation, the two crystals were of exactly the same orientation during the plastic deformation; thus it is probably impossible to test for asymmetric slip on the prism.

In an effort to test for the occurrence of twinning in aggregates, several samples of randomly oriented Dover flint were subjected to axial compression under conditions such that no other known orienting mechanism would operate (low temperature and small permanent strain). Two samples were loaded at 400°C; one remained under a differential stress of 3 kb for 20 minutes, the other under 13.5 kb for 3.5 hours. X-ray analyses revealed no preferred orientation and thus no evidence of twinning in the first sample, and only slight preferred orientation in the second.

A sample loaded at 500°C remained under a differential stress of 13 kb for 3 hours. Although the colder ends of the sample showed no evidence of twinning, the central 500°C region showed a significant amount of preferred orientation of the rhombohedral planes with no corresponding preferred orientation of the *c* axes, as would be expected from Dauphiné twinning alone (*16*). The inverse pole figure derived for this region is shown in Fig. 2a. In accord with the predictions made above, the more compliant directions have become aligned parallel to σ_1.

This inverse pole figure is very similar in form to that in Fig. 2b, which shows the difference in compliance between twinned and original orientations. Under constant axial deviatoric stress, this difference in compliance $\Delta S_{11}'$ is directly proportional to the difference in elastic strain energy ΔE between twinned and original orientations.

$$\Delta E = \tfrac{1}{2}(\sigma_1 - \sigma_3)^2 \, \Delta S_{11}'$$

The similarity of the inverse pole figures (Fig. 2, a and b) thus tends to confirm Thomas and Wooster's theory (*11*) that twinning occurs more readily for grains in which the strain energy difference is larger, and is compatible with the idea that the stress in the flint sample is approximately homogeneous.

The effect of Dauphiné twinning on the preferred orientation of axially compressed aggregates can be removed by averaging the concentrations in symmetrical positions on either side of the *c-a* line in the inverse pole figure, and then plotting the points again with the *c-a* line as a mirror plane. Any remaining preferred orientation must be due to some other process.

For the inverse pole figure of Fig 2a, all of the preferred orientation is removed as a result of such averaging. For the plastically deformed quartzite of Fig. 1a, there remains a tendency for the *c* axes to lie at moderate angles to σ_1. However, the averaging produces not only mirror symmetry about the *c-a* line, but also complete rotational symmetry about *c*. Such averaging produces nearly the same rotational symmetry for almost all the recrystallized flints described by Green *et al.* (*4*), even though the flints show several distinct patterns of preferred orientation of the *c* axes, with the particular pattern dependent on the temperature and strain rate. This implies that the other operative orienting mechanisms do not strongly depend on differences in elastic strain energy.

Mechanically induced Dauphiné twinning appears to have a unique importance for quartz petrofabrics. Its operation is strongly indicated in almost all axial compression tests on quartz aggregates, at conditions ranging from 500°C at a strain rate of 10^{-4} sec^{-1} to 900°C at a strain rate of 10^{-7} sec^{-1}. Also, although the different patterns of preferred orientation of the *c* axes in recrystallized flints have probably been produced by different orienting mechanisms, twinning has operated in conjunction with almost all of them. Thus it is expected that twinning will occur extensively in naturally deformed quartz aggregates. Since the pattern of twinning is related to the symmetry of the imposed stress, the preferred orientations of positive and negative forms may aid one in determining the recent stress history of the rock.

Dauphiné twinning is also of importance in thermodynamic theories of the development of preferred orientation in quartz aggregates subjected to nonhydrostatic stress. This well-defined orienting mechanism is responsible for a definite part of the preferred orientation in almost all experimentally deformed quartz aggregates. The rate of Dauphiné twinning must be fast relative to the rates of the other operative orienting mechanisms. Thus for a given state of stress, twinning would overwhelm the effects of any mechanism tending to minimize the elastic strain energy and would reduce the driving potential for other mechanisms tending to maximize the strain energy. To my knowledge Dauphiné twinning is the only orienting mechanism in which no permanent strain occurs and no interatomic bonds are broken.

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15. Thomas and Wooster (*11*) observed in their constant-stress experiments that twinning acted to maximize the elastic strain energy. Ida [*J. Geophys. Res.* **74**, 3208 (1969)] has recently questioned this conclusion, on the basis of Thomas and Wooster's use of a negative value for S_{14}. This might imply that they had incorrectly associated compliances with crystal orientations. However, their choice of a coordinate system is consistent with a negative value for S_{14}, just as the coordinate system described in the "Standards on Piezoelectric Crystals" [*Proc. Inst. Radio Eng.* **49**, 1378 (1949)] is consistent with a positive value for S_{14}. Thus Thomas and Wooster used the correct elastic constants, and the twinning in their experiments *did* act to maximize the elastic strain energy. Ida's theory, which predicts minimization of elastic strain energy, is based on a recrystallization process and does not apply to the coherent process of twinning. If strain instead of stress were held constant, the elastic strain energy of the crystal would decrease with twinning.
16. Preliminary results show that Arkansas novaculite becomes more completely twinned at 200°C than flint loaded to the same differential stress at 500°C. Novaculite and flint are similar except that novaculite has a lower content of clays, carbonates, and water than flint. Thus these results are consistent with Thomas and Wooster's findings that impurities seem to inhibit twinning in single crystals (*11*).
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