[AMERICAN JOURNAL OF SCIENCE, VOL. 257, JUNE 1959, P. 385-407]

American Journal of Science

JUNE 1959

THE ORIGIN OF DEFORMATION LAMELLAE IN QUARTZ

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ABSTRACT. Fabrics of four quartzite specimens containing numerous quartz grains with deformation lamellae are described in detail. Patterns of preferred orientation of deformation lamellae in all four specimens are similar in that the poles of the lamellae define a small-circle girdle (about an axis designated A). The orientations and strengths of maxima within the girdle, however, are not consistent in different specimens. [0001]-axes of grains containing deformation lamellae also define a small-circle girdle about the same axis (A). In each specimen the great-circles containing [0001] and the pole of the deformation lamellae for individual grains pass through, or close to, the axis A of the small-circle girdles.

The deformation lamellae are shown to be late structures unrelated to the deformations which induced the preferred orientation of the quartz grains in the rocks. The lamellae are not parallel to rational crystallographic planes and they are considered to represent kink-bands resulting from shearing parallel to [0001] on irregular planes in the zone of [0001]. The shearing is probably controlled by imperfections in the crystal structure, which commonly exist parallel to [0001] in quartz.

According to this hypothesis the axis (A) of the small-circle girdle defined by poles of lamellae is the axis of maximum compressive stress during the deformation which produced the lamellae. This relationship may be used to obtain a dynamic interpretation of deformation lamellae in quartzose sedimentary and metamorphic rocks. The hypothesis is tested using data from the Baraboo Quartzite and it is demonstrated that the deformation lamellae in the rocks of this formation may be related to the folding of the Baraboo syncline.

HISTORICAL REVIEW

An extensive literature now exists on the nature and occurrence of lamellar structures in quartz grains in rocks of various types. There appear to be at least two or three different types of lamellae and there is considerable disagreement as to the character and the mode of origin of the lamellae.

Planar structures consisting of minute closely-spaced inclusions were first reported by Böhm (1883). Many writers have since described lamellar structures in the quartz grains of tectonites and they have frequently been designated "Böhm lamellae" or "Böhm striae" (Becke, 1892; Mügge, 1896; Sander, 1930). Intensive studies of the crystallographic orientation of these lamellae and their orientation in rock fabrics have been made by Sander (1930), Hietanen (1938), Fairbairn (1941), Ingerson and Tuttle (1945), Riley (1947), and Savul (1948). Becke (1892) described lamellae in quartz grains in a gneiss from the Central Alps; they were composed partly, but not entirely, of inclusions and showed a refractive index lower than that of the remainder of the crystal. Fairbairn (1941) also stated that the refractive index of lamellae in some cases appears to be lower than that of the grains in which they occur. Ingerson and Tuttle (1945), on the other hand, have described lamellae which are not composed of inclusions, but have refractive indices which are higher than those of the host crystals. They also recognize two other types—one consisting of planes of brown, sometimes liquid, inclusions, also showing a difference of refractive index, and the other consisting only of brownish granular material; they consider the latter to be 'relict' lamellae which have evolved from lamellae of the first type. Since many of the lamellae cannot be resolved microscopically into aggregates of discrete inclusions the practice of refering to all closely-spaced lamellae as 'Böhm lamellae' has been discontinued by many writers.

The lamellae are invariably found in quartz grains which show appreciable post-crystalline strain and it is now established that they are produced by deformation (Fischer, 1925; Fairbairn, 1941; Ingerson and Tuttle, 1945). There are several hypotheses as to the genesis of the lamellae: 1) Becke (1892) considered them to represent partially healed fractures in the quartz grains; 2) Judd (1888) and others, have suggested that they represent secondary twin-lamellae; 3) Mügge (1896), Fischer (1925), Sander (1930), Hietanen (1938), Fairbairn (1941), and Savul (1948) have all maintained that the lamellae are produced by translation-gliding; 4) Ingerson and Tuttle (1945) and Turner (1948) consider that they are microscopic shear-surfaces which are not parallel to rational planes in the quartz lattice.

A number of translation-mechanisms have been postulated to account for the deformation lamellae and there is a notable lack of unanimity among proponents of the translation-gliding hypothesis as to the actual glide-systems involved. Translation-gliding was first proposed by Mügge (1896) who showed that in basal sections of euhedral quartz crystals the traces of lamellae were neither parallel nor perpendicular to the sides of the hexagonal section, suggesting that they are not rational crystallographic planes; he, accordingly, considered that the translation took place on planes subparallel to the base. Sander, in his classic work of 1911, also maintained that the lamellae represent planes of translation-gliding. Fischer (1925) favored the view that translation takes place on $\{0001\}$, $\{10\bar{1}1\}$, $\{01\bar{1}1\}$ and perhaps more obtuse rhombohedra. Although Schmidt (1927) also postulated translation on $\{0001\}$, $\{10\bar{1}1\}$, and $\{01\bar{1}1\}$, he believed that visible lamellae need not develop parallel to the glide-planes. Sander later (1930) showed, with the aid of the universal stage, that the lamellae are inclined to $\{0001\}$ at angles varying from 6° to 30° and concluded that the planes of translation are $\{01\bar{1}3\}$ and $\{01\bar{1}2\}$.

Hietanen (1938) made a detailed study of the orientation of lamellae in different portions of individual grains with undulose extinction from the Finnish quartzites. She postulated several stages in the deformation of quartz grains. Initially, the grains undergo a limited amount of translation-gliding on $\{0001\}$, combined with bending of the glide-plane, which gives rise to feeble undulose extinction. In the next stage there is weak deformation of the lattice and the deformation lamellae are formed more or less parallel to the basal plane, the cavities in the striations being produced by breaking of the quartz-lattice. In a still later stage actual fractures are produced more or less parallel to the [0001]-axis and there is gliding parallel to the prism planes. Hietanen considered that some lamellae may also be relics of rhombohedral translation planes. But since the lamellae are never parallel to either the basal or the unit rhombohedral planes she postulated that they retained their initial orientation while the lattice was reoriented by a later deformational process in which one of the directions of closest packing of Si atoms in the grain lattices becomes oriented parallel to the *a* kinematic axis of the deformation. Hietanen also suggested that the early translation might take place on planes which diverge slightly from {0001}, in view of the 'screw-like' lattice structure of quartz.

Fairbairn (1941) and Ingerson and Tuttle (1945) have made extensive studies of the orientation of deformation lamellae in the Ajibik quartzite and other rocks. Fairbairn found that there was a stronger preferred orientation of the lamellae in the Ajibik quartzite than of the [0001]-axes, and inferred from this that the preferred orientation in the rock resulted from movements on the lamellae. The lamellae are inclined at variable angles to {0001}, but there is a strong maximum between 7° and 36°. The lack of a fixed crystallographic orientation for the lamellae obliged him to assume only a fixed glide-line [m:r], lying in the base, with variable glide-planes containing this line. Ingerson and Tuttle (1945) also demonstrated a conspicuous lack of crystallographic control in the orientation of the lamellae in the Ajibik quartzite, and their measurements show an even greater range of crystallographic orientation. These investigators also examined data for many grains with two or three sets of lamellae and concluded that these lamellae were not parallel to rational crystallographic planes. The angles between the lamellae and {0001} in the grains, however, did appear to be closely controlled by the orientation of individual grains in the fabric of the rock. Ingerson and Tuttle concluded that the lamellae are deformation-planes "such as would form in homogeneous material"; and that such crystallographic control as exists is only apparent, being actually dependent on the orientation of the grains with respect to the fabric axes. The poles of the lamellae in the Ajibik quartzite (as in many other rocks with quartz grains containing lamellae) form two strong maxima lying in the *ac* plane of the fabric and symmetrically oriented approximately 45° from the foliation. Ingerson and Tuttle claimed that in this and other specimens examined by them the pole of the lamellae in any grain lies between the [0001]-axis in the grain and the *a* fabric axis of the specimen. They suggested that this relationship might be used to locate the fabric axes in a rock, such as a massive quartzite, in which there is no other means of determining the fabric axes.

In his analysis of the microscopic structures in the Baraboo Quartzite, Riley (1947) found that deformation lamellae were extensively developed in rocks which showed very weak preferred orientations of the quartz grains. Applying the method suggested by Ingerson and Tuttle for locating fabric axes from the patterns of lamellae, Riley showed that the fabric axes thus obtained do not coincide with the fabric axes determined from megascopic data. He therefore inferred that, if the fabric axes determined from deformation lamellae are, in fact, related to the megascopic fabric axes in other areas, as Ingerson and Tuttle reported, the lamellae in the Baraboo Quartzite must date from a phase of deformation different from that which produced the foliation and folds.

Savul (1948) measured the orientation of deformation lamellae and optic axes in different parts of individual deformed grains of quartz in a number of granitic rocks and quartz porphyries, selecting particularly grains with several sets of lamellae. On the basis of the angle between the poles of the lamellae and [0001], he distinguished 3 groups of lamellae; in one group the angles are between 8° and 36°, in the second, between 53° and 59°, and in the third, between 72° and 75°. These do not correspond to any of the common crystal faces in quartz. Savul superimposed the stereograms for measured quartz grains on a projection of a quartz crystal showing all the possible forms. This was also done for a number of quartz grains with several sets of lamellae and a few well-developed crystal faces. The lamellae, according to Savul, coincide most closely with the forms $\{10\bar{1}2\}$, $\{\bar{1}2\bar{1}6\}$, $\{3\bar{1}\bar{2}2\}$, and $\{10\bar{1}4\}$ and he considered them to be produced by translation-gliding on these planes.

In the majority of cases in which deformation lamellae have been investigated in quartz tectonites, they have been interpreted as visible traces of the deformations which oriented the grains in the rocks. But Turner (1948) drew attention to incompatibility between the patterns of preferred orientation of lamellae and of other elements in the fabric in many of the examples described in the literature. Continuity of lamellae across grain boundaries (Mackie, 1947) implies that the grains must have had their present orientation in the rocks before the formation of the lamellae. Turner therefore suggested that the lamellae probably represent, in most cases, late-stage structures unrelated to the preferred orientation of the lattices of the grains. The lamellae are commonly oriented so that their poles define two strong maxima between 60° and 90° apart, a relationship which would indicate that the formation of the lamellae "is favored by simple compression (as in a vise) with consequent relatively slight differential movement upon surfaces of maximum resolved shear stress so induced" (Turner, 1948, p. 567).

Weiss (1954) has described the orientation of deformation lamellae and the somewhat similar deformation bands (Riley, 1947) in the quartzitic rocks of the Barstow area in Southern California. Weiss also considered that the lamellae were of rather late origin, and unrelated to the movements which produced the preferred orientation of the grains in which they occur.

NEW DATA

Introduction.—Several authors have stated that deformation lamellae are of rather uncommon occurrence in rocks, but we have found that they are extensively developed in quartzites in metamorphic terranes in north-west Scotland (Christie, 1956) and Southern California. In the present paper the results of detailed microscopic analyses of four quartzite specimens are presented and an interpretation of the lamellar structures is proposed. Three of the specimens (I, II, III) are crystalline quartzites from the Orocopia Schists in the north-west corner of the Orocopia Mountains in Southern California, and the fourth (IV) is a deformed Cambrian quartzite collected a few feet below the outcrop of the Moine Thrust near the Stack of Glencoul, in the Assynt district of Scotland. The grains in all four specimens contain abundant deformation lamellae and other evidence of post-crystalline strain, such as undulose extinction.

Nature of the structures examined.—The planar structures whose orientations are described below may all be referred to as deformation lamellae. They are narrow, sub-planar structures which occupy a part or the complete area of a grain and generally are only found with one orientation in any grain. They are not all structurally similar when seen under the highest magnifications available: some consist entirely of minute brownish inclusions concentrated in planar zones; others cannot be resolved into individual inclusions and apparently have a different refractive index from the host grain; still others, intermediate between these two types, show a slight difference of refractive index and yet appear to consist in part of planes of inclusions (see Ingerson and Tuttle, 1945). Although the lamellae are gently undulating, they may all be measured on the U-stage, like cleavages and twin-lamellae in calcite and dolomite, by tilting them until they are parallel to the axis of the microscope. The maximum error involved is probably of the order of $\pm 2°$.

The above types of lamellae conform to the numerous descriptions in the literature, but it was noted that many of the lamellae have an extinction position which is slightly but markedly different from that of the neighboring part of the host grain. These lamellae are very conspicuous between crossed Nicols, particularly when the grain is close to the extinction position. The differences in the extinction position between lamellae and host grain are generally less than 3° (measured under high magnification on a flat stage) but an angle of 5° was noted in one grain.

Marked differences of optical orientation have been noted in the lamellar structures known as deformation bands (Riley, 1947; Weiss, 1954), but these are generally easy to distinguish from the more common deformation lamellae on the basis of the following criteria (Weiss, 1954):

1) Deformation bands are considerably broader than lamellae.
2) They are bounded by fractures which are not distinctly planar and whose orientation cannot be accurately measured with the U-stage; only the trend of the bands in the section can be measured.

The lamellae are generally, but not invariably, found in grains with marked undulose extinction in zones sub-parallel to the [0001]-axis, either with *continuous* or *discontinuous* change of extinction position ("plastic" and "ruptural" deformation of Hietanen, 1938).

Weiss (1954) found that the traces of deformation bands and deformation lamellae, when they occur in the same grain, are parallel, and he suggested that the two types of structure have the same genetic significance, the bands merely representing a more advanced stage of deformation than the lamellae. The present writers' discovery of small divergences of optic orientation between the material in deformation lamellae and in the parent grain is another point of similarity which supports Weiss' suggestion. The lamellae in which such differences of optic orientation may be observed do appear to be slightly broader than those in which differences are not detectable, but the lamellae are nevertheless well-defined and their orientation can be measured with the same accuracy as that of narrower lamellae. In a few of the grains examined the lamellae broaden into a wedge near the margin of the grain and differences of optic orientation are most readily seen in these wedges. No true deformation bands are present in the rocks.

Description of specimen I.—This specimen (fig. 1a) is a folded quartzite

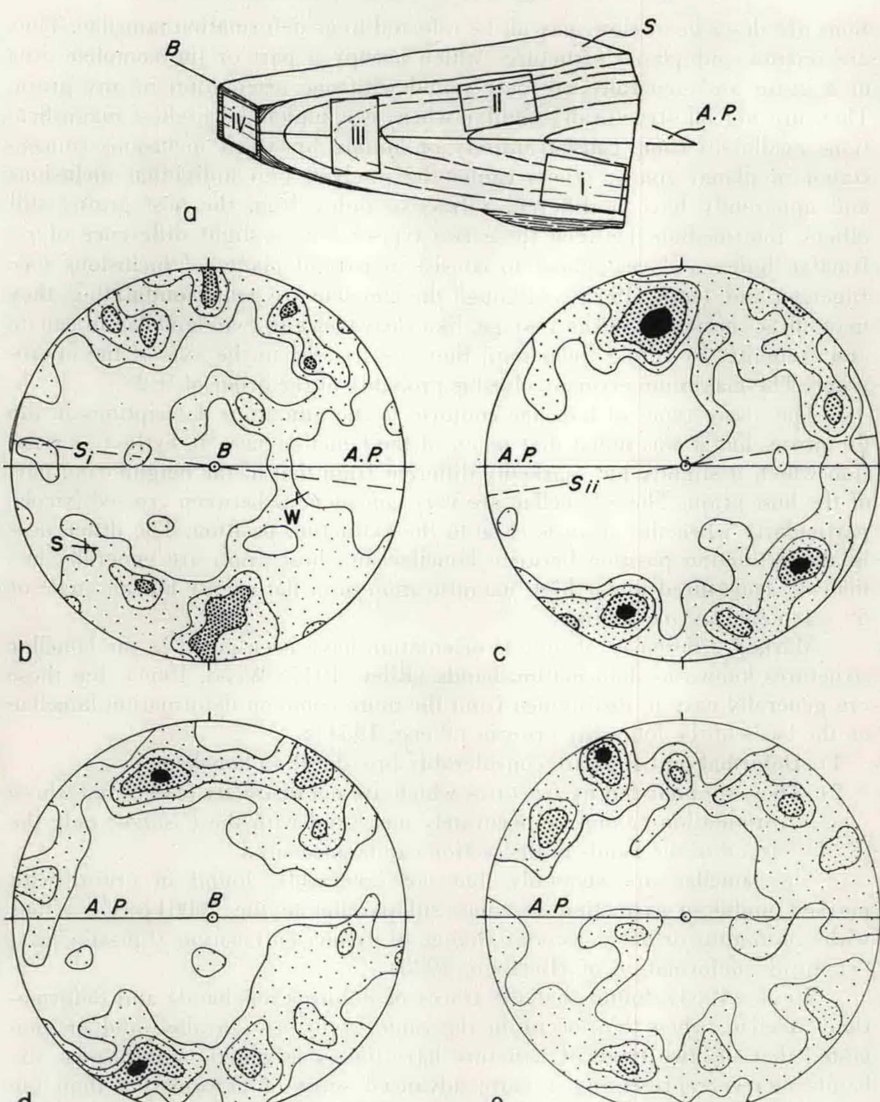

Fig. 1. Orientation data for specimen I.

a. Sketch of specimen I, showing the orientation and position of the thin-sections i, ii, iii and iv. *S* is the bedding-foliation, *B* is the fold-axis and *A.P.* is the axial plane of the fold.

b. [0001]-axes of 206 quartz grains in section i. Contours: 3, 2, 1% per 1% area.

c. [0001]-axes of 203 quartz grains in section ii. Contours: 5, 3, 2, 1% per 1% area.

d. [0001]-axes of 200 quartz grains in section iii. Contours: 5, 3, 2, 1% per 1% area.

e. [0001]-axes of 208 quartz grains in section iv. Contours: 5, 3, 2, 1% per 1% area.

Diagrams from all four sections have the same orientation, shown by south (S) and west (W) directions in diagram b.

with well-defined foliation from the Orocopia Schists. It consists essentially of quartz (95 percent) with minor amounts of calcite, plagioclase, garnet, chlorite, muscovite, biotite and opaque ore. The impurities are concentrated in thin layers which probably represent a relic bedding-structure. Under the microscope the quartz shows granoblastic texture with little or no dimensional orientation; the micaceous minerals are oriented with their cleavages subparallel to the axial plane of the fold. All the minerals, but especially quartz, calcite and chlorite, show evidence of post-crystalline strain.

In order to test the homogeneity of the preferred orientation of quartz in

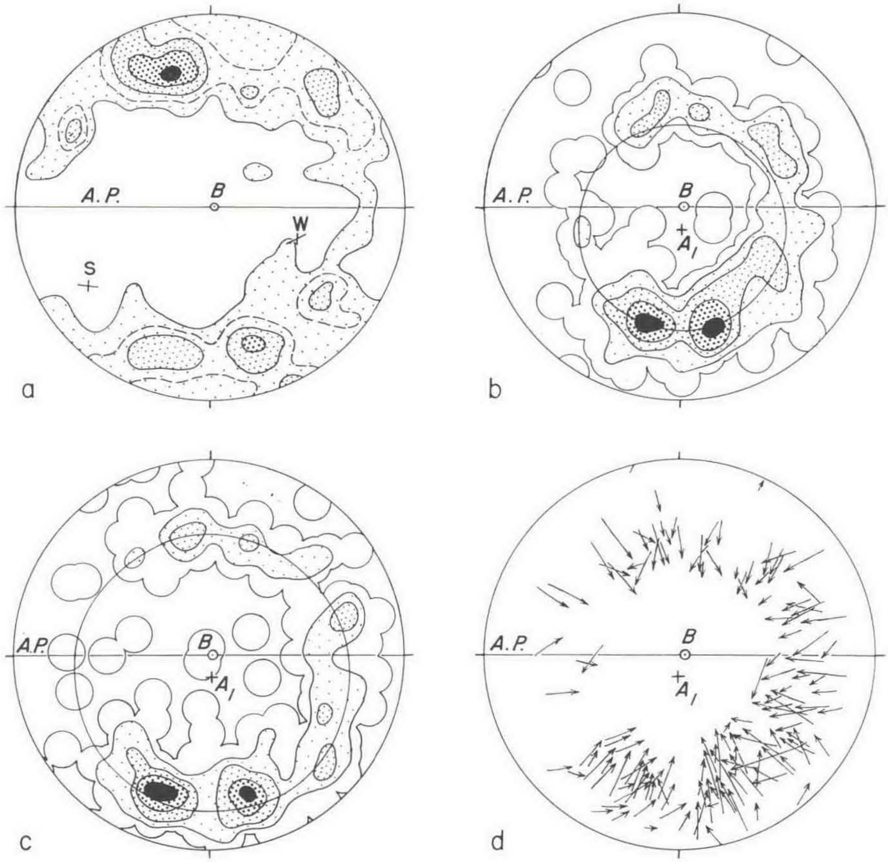

Fig. 2. Orientation data for specimen I.

a. Composite diagram: [0001]-axes of 817 quartz grains from the four sections. Contours: 4, 3, 2, 1½, 1% per 1% area.

b. Poles of deformation lamellae in 195 grains (195 sets of lamellae). Contours: 8, 5, 3, 1½, 1% per 1% area.

c. [0001]-axes of the same 195 grains containing deformation lamellae. Contours: 7, 5, 3, 1½, ½% per 1% area.

d. [0001]-axes (end of arrow) and poles of deformation lamellae (Point of arrow) in a representative number of grains from sections i-iv. A_1 is the axis of the small circle defined by the poles of lamellae and [0001]-axes of grains with lamellae. All four diagrams have the same orientation, shown by south (S) and west (W) directions in diagram a.

the specimen, analyses were carried out in four sections (fig. 1a). Three were cut parallel to the *ac* plane of the fold: one from each of the limbs (i, ii) and one from the hinge (iii). A further section was examined from a plan parallel to the fold axis (B) and approximately normal to the axial plane. The diagrams showing the orientation of [0001]-axes of quartz in the four sections are shown in figures 1b, 1c, 1d, 1e. The patterns of preferred orientation for all four sections are similar, indicating that the orientation of quartz is essentially homogeneous throughout the fold. The pattern of preferred orientation consists of a small-circle girdle, the axis of which is approximately normal to the axial plane of the fold (fig. 2a). The preferred orientation of micaceous minerals is also essentially homogeneous throughout the fold (diagrams not shown); the cleavage directions of the micas and chlorite are sub-parallel to the axial plane of the fold.

Deformation lamellae were measured in all the grains in which they were present and accessible for measurement with the U-stage. Each grain represented in the patterns of preferred orientation of quartz was carefully searched with the U-stage for lamellae, and it is therefore probable that in all the grains examined in each section all lamellae were measured except those inclined at low angles to the section and whose poles lie in the central "blind spot" in the diagrams. The partial diagrams showing the orientation of deformation lamellae in the individual sections show a strong similarity, indicating that there is homogeneity of this fabric element also throughout the specimen. The preferred orientation of the lamellae is such that the pattern obtained from the *ac* sections does not differ greatly from that obtained from the fold axis section; hence there must be few lamellae whose poles fall within the "blind-spots" in the diagrams.

The pattern of preferred orientation of the poles of lamellae (fig. 2b) is a small-circle girdle (about the axis A_1) containing two closely-spaced maxima and a number of sub-maxima. The poles of the lamellae therefore define (by their orientation) a cone with vertical axis A_1 and a semi-vertex angle of approximately 45°. The [0001]-axes of grains containing the deformation lamellae (fig. 2c) show a similar pattern of preferred orientation. They define a small-circle about the same axis A_1, but with a radius of approximately 60°; the small-circle contains maxima and sub-maxima which correspond closely with those in the pattern of lamellae poles (fig. 2b).

A striking feature of the grains with deformation lamellae is that the great-circle passing through [0001] and the pole of the lamellae generally passes through (or close to) the axis A_1 of the small-circle girdle. This is demonstrated in figure 2d, which shows the orientation of [0001] and the pole of lamellae in a representative number of the grains from all four sections.

Description of specimen II.—This specimen is a rather impure quartzite which is folded in a similar fashion to specimen I. The impurities comprise approximately 15 percent of the rock and include garnet, biotite, chlorite, muscovite and zircon. The garnets, zircons, and to some extent the micaceous minerals, are concentrated in layers defining the foliation, but the micas and chlorite are also disseminated throughout the purer layers of quartz. The micaceous minerals tend to lie parallel to the axial plane of the fold rather than the foliation. This tendency is most clearly observed in the hinge of the fold.

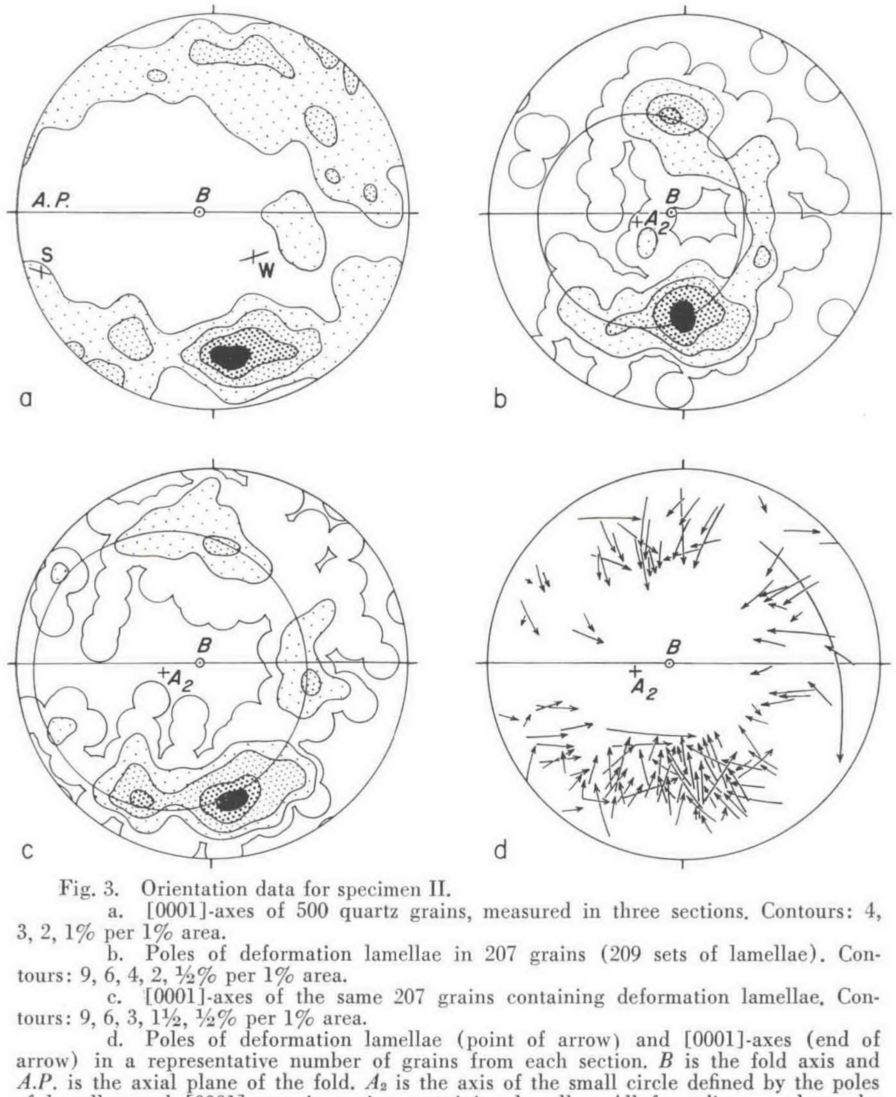

Fig. 3. Orientation data for specimen II.

a. [0001]-axes of 500 quartz grains, measured in three sections. Contours: 4, 3, 2, 1% per 1% area.

b. Poles of deformation lamellae in 207 grains (209 sets of lamellae). Contours: 9, 6, 4, 2, ½% per 1% area.

c. [0001]-axes of the same 207 grains containing deformation lamellae. Contours: 9, 6, 3, 1½, ½% per 1% area.

d. Poles of deformation lamellae (point of arrow) and [0001]-axes (end of arrow) in a representative number of grains from each section. *B* is the fold axis and *A.P.* is the axial plane of the fold. A_2 is the axis of the small circle defined by the poles of lamellae and [0001]-axes in grains containing lamellae. All four diagrams have the same orientation, shown by south (S) and west (W) directions in diagram a.

Analyses were made of the orientation of [0001]-axes and deformation lamellae in quartz in two *ac* sections of the fold, one from the hinge and one from a limb, and a *bc* section from one of the limbs.

The orientation of [0001]-axes of quartz is homogeneous throughout the fold, as in specimen I. The preferred orientation of [0001]-axes is shown in the composite diagram (fig. 3a). The pattern consists of a diffuse girdle normal to the fold-axis B, incomplete near the axial plane of the fold, and cleft at the pole of the axial plane; the girdle contains maxima inclined at high angles to the axial plane.

The poles of deformation lamellae (fig. 3b) in the quartz grains define a portion of a small-circle girdle which contains two maxima of unequal strength. The axis of the small-circle is A_2 and the radius is approximately 44°. The [0001]-axes of grains containing these deformation lamellae (fig. 3c) are oriented in a well-defined small-circle about A_2 and the small-circle contains a number of maxima which correspond more or less in orientation to those in the pattern of poles of lamellae (fig. 3b). The radius of the small-circle defined by [0001]-axes is approximately 60°. The great-circles containing poles of deformation lamellae and [0001]-axes in individual grains (fig. 3d) generally pass through the axis A_2, as in specimen I.

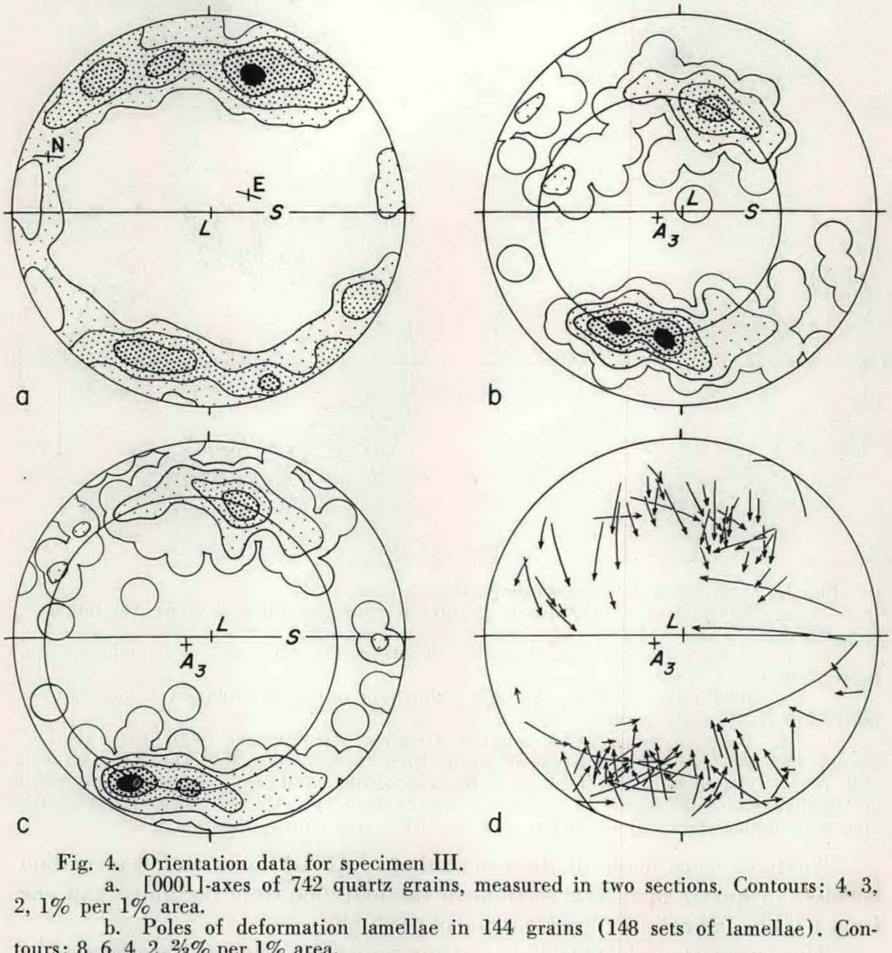

Fig. 4. Orientation data for specimen III.

a. [0001]-axes of 742 quartz grains, measured in two sections. Contours: 4, 3, 2, 1% per 1% area.

b. Poles of deformation lamellae in 144 grains (148 sets of lamellae). Contours: 8, 6, 4, 2, ⅔% per 1% area.

c. [0001]-axes of the same 144 grains containing deformation lamellae. Contours: 8, 6, 4, 2, ⅔% per 1% area.

d. Poles of deformation lamellae (point of arrow) and [0001]-axes (end of arrow) in a representative number of grains from each section. S is the foliation and L the lineation. A_3 is the axis of the small circle defined by the poles of lamellae and [0001]-axes in grains containing lamellae. All four diagrams have the same orientation, shown by north (N) and east (E) directions in diagram a.

Description of specimen III.—This specimen is a quartzite containing as impurities less than 10 percent of garnet, chlorite, biotite and opaque ore. It has a well-developed planar foliation (S), defined by layers of the above minerals, and a very weak lineation (L = B). Many of the quartz grains are slightly flattened in the plane of the foliation and there is some elongation parallel to the lineation.

The analysis was carried out on two thin sections cut normal to the foliation, one parallel and the other perpendicular to the lineation (*bc* and *ac* respectively). Approximately 350 grains were examined in the *ac* section and 390 in the *bc* section. Partial diagrams of 200 grains each from the two sections are almost identical, indicating a very high degree of homogeneity in the field of this specimen.

The pattern of preferred orientation of [0001]-axes (fig. 4a) consists of a girdle more or less normal to the lineation; the girdle is cleft near the pole of the foliation and the main maxima are inclined to the foliation at angles greater than 45°. The poles of the deformation lamellae (fig. 4b) define two maxima of unequal strength and tend to spread into a small-circle girdle about the axis A_3. The angular radius of the small-circle is approximately 52°. The preferred orientation of [0001]-axes of grains with lamellae is again similar to that of the lamellae poles, the radius of the small-circle being approximately 64°.

Description of specimen IV.—This specimen is a pure quartzite with a crude planar foliation and no lineation. The rock is a deformed sedimentary quartzite in which the original clastic grains are recognizable. The grains are considerably flattened in the plane of the foliation and show intense undulose extinction and moderate marginal granulation; zones of crushed quartz in the specimen are inclined to the foliation, which is defined only by the dimensional orientation of the large quartz grains.

The analysis was carried out on three mutually perpendicular sections, one of which was parallel to the foliation, and approximately 200 grains were measured in each section. The [0001]-axes of the quartz grains show a weak preferred orientation (fig. 5a). The pattern consists essentially of a diffuse small-circle girdle about the pole of the foliation, but there is also a strong maximum lying close to the foliation. This maximum is present in the partial diagrams from each of the three sections and must therefore be significant. The partial diagrams are otherwise similar only in that they all show the small-circle pattern referred to above; maxima in this girdle are not reproducible in the samples of 200 points. This is considered to reflect the weakness of the preferred orientation rather than lack of homogeneity of the fabric.

There is a very strong preferred orientation of deformation lamellae in the rock (fig. 5b). The pattern of preferred orientation consists of two strong maxima spreading into a small-circle girdle about the axis A_4, the radius of the small-circle being approximately 38°. The [0001]-axes of grains containing deformation lamellae also define a small-circle girdle about the axis A_4 with a radius of approximately 50°. Great-circles containing the pole of the lamellae and [0001] in individual grains (fig. 5d) commonly pass through the axis A, as in the other three specimens.

Crystallographic orientation of lamellae.—The histograms in figure 6

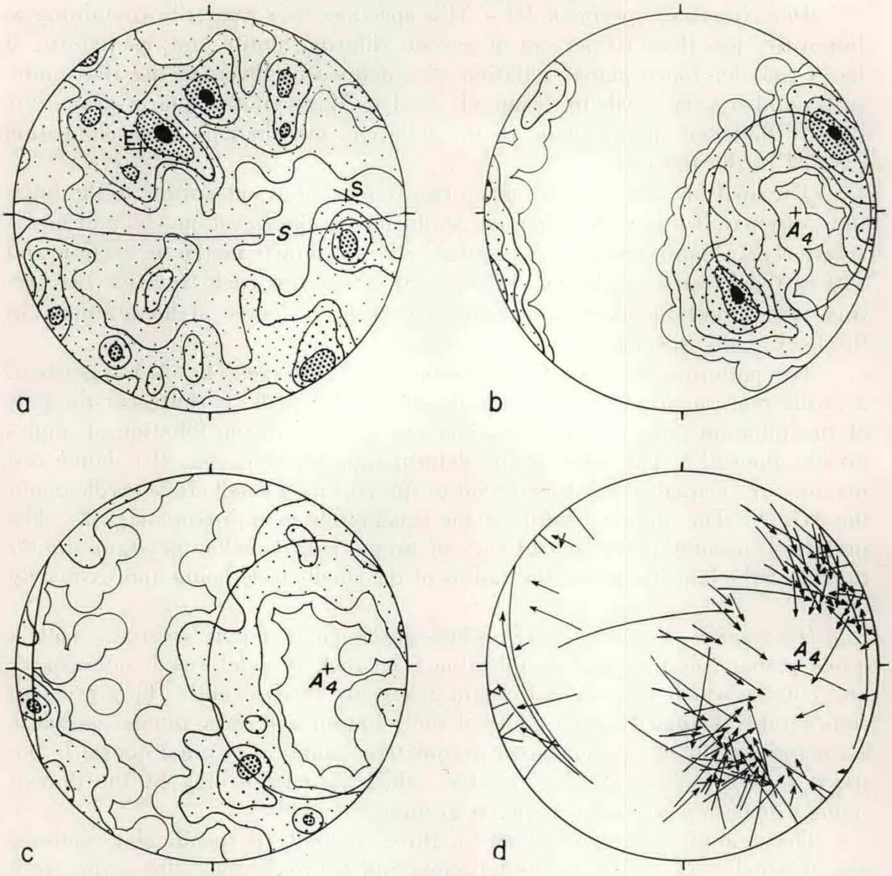

Fig. 5. Orientation data for specimen IV.

a. [0001]-axes of 607 quartz grains, measured in three sections. Contours: 2½, 2, 1½, 1, ½% per 1% area.

b. Poles of deformation lamellae in 204 grains (205 sets of lamellae). Contours: 10, 7½, 5, 2½, 1, ½% per 1% area.

c. [0001]-axes of the same 204 grains containing deformation lamellae. Contours: 4½, 3, 1½, ½% per 1% area.

d. Poles of deformation lamellae (point of arrow) and [0001]-axes (end of arrow) in a representative number of grains from each section. *S* is the foliation and A_4 is the axis of the small circle defined by the poles of lamellae and [0001]-axes in grains containing lamellae. All four diagrams have the same orientation, shown by east (E) and south (S) directions in diagram a.

show the angles between the pole of the deformation lamellae and the [0001]-axis ($C \wedge \perp L$) in the grains containing lamellae in each of the four specimens. The frequency distribution of these angles is similar in all the specimens: in the majority of the grains in each specimen the angle is between 0° and 40°, with a strong maximum in each case between 8° and 18°. The histograms are not dissimilar to those obtained by Fairbairn (1941) and Ingerson and Tuttle (1945) for the Ajibik quartzite, but there is a much greater variation in the ($C \wedge \perp L$) angle in the grains of the Ajibik rock. It is, of course, impossible to determine the orientation of the lamellae with respect to the horizontal crystallographic axes of quartz in rocks of the type described above, but it is evident that the crystallographic orientation is highly restricted.

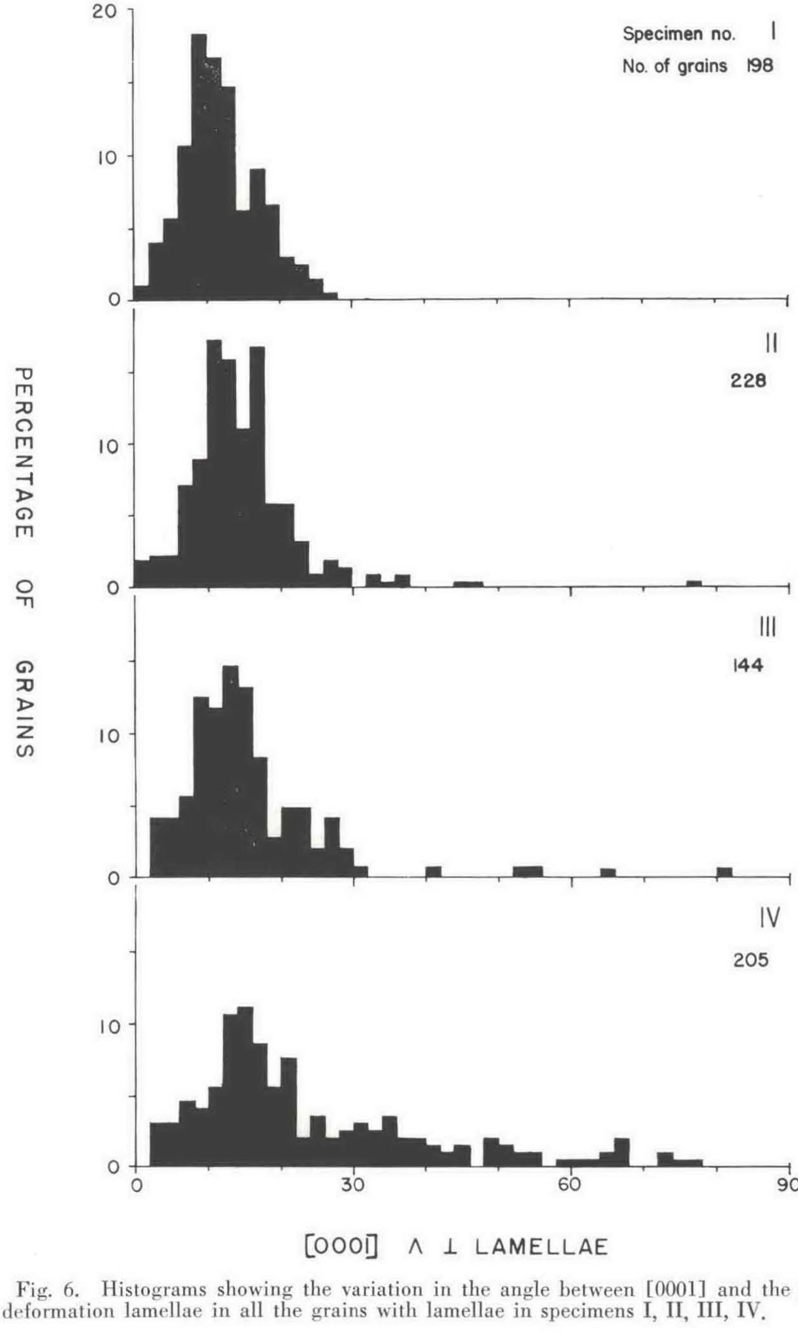

Fig. 6. Histograms showing the variation in the angle between [0001] and the pole of deformation lamellae in all the grains with lamellae in specimens I, II, III, IV.

Summary.—The orientation patterns of deformation lamellae in each of the four specimens described above are strikingly similar. In specimens II, III and IV, the poles of the lamellae from two distinct maxima 80° to 90° apart, indicating that the lamellae statistically define two surfaces; this is the type of pattern most commonly described in the literature (Turner, 1948). However, in all the specimens there is a more or less definite small-circle girdle containing the maxima. This distribution is also reflected by the [0001]-axes of the grains which contain the lamellae. The small-circle pattern of poles of lamellae was also noted by Riley (1947, fig. 8) in two samples of Baraboo quartzite. By comparison with the small-circle girdles, the maxima appear to be of minor importance.

The orientations of the great-circles containing the poles of the lamellae and the [0001]-axes in the quartz grains of all the specimens are similar. These great-circles (figs. 2d, 3d, 4d, 5d) intersect in, or close to, the axis A of the small-circle of lamellae-poles.

INTERPRETATION OF DATA

Discussion of fabrics.—The folds in specimens I and II are "homogeneous" with respect to the orientation of quartz and mica (Sander, 1930, p. 260-262) and are therefore not unrollable.

When the grain orientation in such folds is symmetrologically related to the axial-plane of the folds they are commonly interpreted as shearfolds in which the folded surfaces are mechanically insignificant and the grain orientation has been produced by shear or flow on surfaces parallel to the axial-plane foliation (Sander, 1930). But a homogeneous grain fabric, particularly in the case of quartz, may also be produced by a strong imprint imposed on a fold of any origin (Sander, 1934, p. 44).

The patterns of preferred orientation of [0001] in specimens I, II and III are triclinic, if considered in detail, but there is a close approach, especially in specimens I and III (figs. 2a, 4a), to symmetry of a higher order—monoclinic or even orthorhombic. The closely appressed, almost isoclinal form of the folding (specimens I, II) precludes the possibility that the folds were formed purely by inhomogeneous slip on surfaces parallel to the axial-planes. Their development would require considerable flattening perpendicular to the axial planes to rotate the limbs almost into parallelism. Furthermore, there is good independent evidence, from the twinning of calcite in the rocks, that the folds have undergone strong compression normal to the axial planes late in their development.

The foliation in the quartzites is defined by zonal concentrations of accessory minerals in a framework of quartz grains and was therefore probably quite passive throughout the deformation. But the quartzites are thin and surrounded by comparatively incompetent greenschists, so that the boundaries were mechanically significant and evidently functioned as slip surfaces. We consider that the folds originated by flexural-slip, the slip being concentrated along the boundaries of the quartzite layers, and developed subsequently by rotation of the limbs resulting from compression along an axis normal to the axial planes. The quartz was undergoing recrystallization and reorientation throughout this deformational sequence. The main features of the patterns of preferred orientation are considered to date from the late imprint of this deformation, when the strain had orthorhombic or higher symmetry, but the patterns preserve certain traces inherited from the earlier monoclinic movement.

The fabric of specimen IV differs from that of the other three specimens in that there is no evidence of complete crystallization of the quartz grains: the grains are relics of the clastic grains of the original sediment. The symmetry of the strain appears, however, to have been similar to that of the late paracrystalline imprint in the other specimens. Although recrystallization may have played a part in achieving the flattening of the rock, it was not sufficiently strong to obliterate the original texture. Plastic strain within the grains and intergranular shear appear to have been more important mechanisms of deformation.

The origin of the deformation lamellae.—Examination of the patterns of preferred orientation of the lamellae and of [0001]-axes in grains containing lamellae shows that in each rock these two elements show identical symmetry. But, as Turner has pointed out for other examples described in the literature (1948), the preferred orientation of the lamellae does not correspond in symmetry with that of the [0001]-axes in the rocks. This is particularly noticeable in the patterns for specimen IV; the pattern of preferred orientation of lamellae poles is almost perfectly orthorhombic and the three symmetry axes do not coincide with any of the fabric axes evident in the pattern of [0001]-axes (the 'flattening-foliation', S, and the axis of flattening, $\perp$ S). This lack of correspondence is also seen in the other specimens to a lesser extent; the symmetry of the pattern of lamellae poles is different from that of the [0001]-axes in each case.

From this we infer that the lamellae are secondary structures, dating from a late stage in the deformation of the rocks, and unrelated to the preferred orientation of the lattices of the quartz-grains (see Turner, 1948). They are not present in grains with all orientations in the general pattern of [0001]-axes. The patterns of preferred orientation of lamellae poles are not, however, so simple as those previously represented in the literature: although two maxima of poles, approximately 90° apart, are developed in the patterns for three of the specimens, a more constant feature of the patterns is the small-circle girdle about the axes designated A in the diagrams. The axial distribution of the lamellae poles in the specimens suggests that the lamellae have been produced by a simple compression (or tension) parallel to the axis A, as proposed by Turner (1948), but the surfaces of maximum shearing strain appear to be conic surfaces rather than two intersecting plane surfaces.

Before a further discussion of the origin of deformation lamellae is attempted, the nature of the structures must be considered. Several theories have been proposed to account for the orientation of deformation lamellae in the lattice of quartz: the lamellae have been considered as

a) Planes of twin-gliding (Judd, 1888) or translation-gliding parallel to rational crystallographic planes (Sander, 1930; Fischer, 1926; Schmidt, W., 1927; Savul, 1948)

b) Intragranular shear-surfaces with limited crystallographic control on the orientation (Fairbairn, 1941; Turner, 1948; and to some extent Hietanen, 1938)

c) Intragranular shear surfaces with no direct crystallographic control on their orientation (Ingerson and Tuttle, 1945).

The histograms in figure 6 show that the orientation of the lamellae in the lattices of the grains is rather highly restricted, but certainly not to the extent that $\{01\bar{1}2\}$ twin-lamellae are restricted in the lattice of calcite. A great variety of rational indices have been assigned to deformation lamellae by previous writers (Savul, 1948) but the following facts lead us to conclude that the lamellae are not parallel to rational planes in the quartz lattice:

a) The angle between the lamellae and the base {0001} varies *continuously* in any single specimen from 0° to 40°, and larger angles also occur.

b) There are slight variations in the position of the main maximum in histograms for different specimens.

The lamellae therefore are not parallel to rational crystallographic planes, but their orientation in the lattice is otherwise restricted, as Fairbairn (1941), Ingerson and Tuttle (1945) and Turner (1948) have maintained.

Ingerson and Tuttle (1945) accounted for the apparent crystallographic control over the orientation of deformation lamellae in the grains of the Ajibik Quartzite by demonstrating that the angle between the [0001]-axis and the pole of the lamellae in the grains varies systematically with the inclination of the [0001]-axes to the *B*-axis of the fabric; they concluded that the crystallographic control was only apparent and due to the fact that i) lamellae were cozonal with the B-axis and ii) the [0001]-axes were generally inclined at high angles to the B-axis. It is impossible, however, to account for the restricted crystallographic orientation of the lamellae in specimens I-IV in this way. Examination of diagrams 2d, 3d, 4d and 5d shows that the angle between [0001] and the pole of the lamellae in any grain is not controlled by the relationship between [0001] and any of the fabric axes defined by the foliation and fold-axis; nor is there any evidence from the patterns (figs. 2d, 3d, 4d, 5d) that the angle between the lamellae and [0001] varies systematically with the inclination of the [0001]-axes to the symmetry axes of the quartz [0001]-patterns. The restriction in the crystallographic orientation of the lamellae in these specimens is therefore not merely apparent (and controlled by the orientation of the grain lattices in the fabrics). It must be accounted for in some other fashion.

A striking and hitherto unexplained feature of the diagrams (figs. 2d, 3d, 4d, 5d), showing the relationship between the lamellae and the [0001]-axes in individual grains in the rocks, is the fact that, in each specimen, the great-circles containing the pole of the lamellae and [0001] pass through, or close to, the axes (A_1, A_2, A_3, A_4) of the small-circles defined by lamellae poles. This feature is so consistently evident (see also Riley 1947, fig. 8) that it must have some significance. The control of quartz orientation and, more particularly, the development of undulose extinction in zones sub-parallel to [0001] has commonly been attributed to limited bend-gliding on the surfaces represented by the deformation-lamellae (Johnsen and Becke in discussion of Schmidt, 1927; Hietanen, 1948). But the radial arrangement of the zones containing

[0001] and the poles of lamellae in the grains of quartz-tectonites would suggest that the reverse relationship may be correct: that the deformation lamellae originate as a result of movements parallel to the [0001]-axes of the grains. There is a mechanism, demonstrated by experimental studies, by which gliding movement on one set of surfaces may give rise to subsidiary movement along a plane inclined at steep angles to the glide-surface, namely, the formation of "kink-bands" (Turner, et al., 1954, p. 896-897). These kink-bands are slightly irregular zones, bounded by sub-parallel planes, in which the lattice of the mineral has a different orientation from that of the parent grain; they are inclined at high angles to the active slip-plane in the crystal and may or may not be parallel to a rational crystallographic plane.

In all the reported cases of minerals or metals in which kink-bands are considered to develop, they do so in response to gliding on a rational crystallographic glide-plane. There is no evidence, either from petrographic studies or from a consideration of the crystal structure of quartz (Griggs and Bell, 1938; Fairbairn, 1939) that such planes exist in quartz. However, there is good evidence that there is a linear weakness parallel to [0001]: the most obvious and common indication of post-crystalline deformation in quartz is the appearance of undulose extinction in zones sub-parallel to [0001]; when the strain is slight, the variation in extinction is continuous over a grain, but when the strain is more intense the grain is divided into distinct zones bounded by sharp surfaces of discontinuity. These boundaries are not distinctly planar and their orientation cannot be measured with the U-stage, indicating that they are not rational crystallographic planes but rather curved or irregular surfaces. The available data on the experimental deformation of quartz at high temperature and pressures (Griggs and Bell, 1938) show that quartz exhibits a strong tendency to break into needles parallel to the [0001]-axis. Examination of the crystal structure of quartz shows that none of the prism planes have the characters necessary to act as glide-planes, but it has been suggested (Griggs and Bell, 1938; Fairbairn, 1939) that imperfections in the crystal lattice, known as lineage structures (Buerger, 1934), which are known to exist parallel to [0001] in quartz, may be important in controlling the deformation. Griggs and Bell (1938, p. 1740) demonstrated that the needles parallel to [0001] are irregular and not bounded by prism planes.

Differential movement along [0001] of irregular blocks or rods elongate parallel to [0001] is part of the "Frontwendung" hypothesis of Hietanen (1938) and similar gliding movement is postulated by Weiss (1954). But in both of these hypotheses the deformation lamellae are considered to be the first indication of strain, representing planes of limited translation-gliding parallel to the basal pinacoid or rhombohedral planes. This is not in agreement with the actual crystallographic orientation of the lamellae. The following mechanism, which we consider to be the simplest and most rational means of accounting for the crystallographic orientation of the lamellae and their orientation in the fabric, is proposed:

Certain grains in the rocks have deformed by gliding parallel to the [0001]-axis, and the lamellae represent kink-bands inclined at high angles to the glide-surface and glide-direction. The type of gliding envisaged is not normal translation-gliding on a rational crystallographic plane; it may be "*linear gliding*" involving differential movement of rods sub-parallel to the [0001]-axis (such as might be illustrated with a sheaf of pencils) or the gliding may take place on irregular surfaces of high resolved shear stress in the zone of [0001], involving differential movement of platy elements defined by these irregular surfaces.

In addition to explaining the restricted but non-rational orientation of the lamellae, this hypothesis accounts for most of the features observed in the patterns of preferred orientation of the fabric elements in the specimens. In a quartzite with random orientation of [0001]-axes, subjected to strong axial compression, gliding parallel to [0001] (or on non-rational surfaces in the zone [0001]) will take place only in grains with an orientation such that there is high resolved shear stress suitable for gliding parallel to [0001]; the [0001]-axes of these grains define (in projection) a uniformly-covered small-circle girdle about the axis of compression. The stress in this instance is axial and the resulting strain will also be axial. However, if a rock with a strong preferred orientation of [0001]-axes is subjected to a similar axial compression, the grains oriented so that there is high resolved shear stress parallel to [0001] will again deform by gliding, but the pattern defined by the [0001]-axes of these grains will not be a complete and evenly-covered small-circle about the axis of compression: the pattern will be modified by the pre-existing preferred orientation. Although a small-circle may still be defined by the [0001]-axes of the deformed grains, it will contain maxima where the small-circle coincides with concentrations in the pre-existing pattern of [0001]-axes. (Although the stress in such a case is axial, the resulting strain, by this mechanism alone, would not be axial, but would have some lower symmetry controlled by the pre-existing anisotropy of the fabric.) An examination of figures 5a and 5c, for example, shows that the maxima of [0001]-axes in grains with deformation lamellae (fig. 5c) occur where the small-circle in this diagram crosses areas of high concentration in the pattern of preferred orientation of [0001] in the rock as a whole (fig. 5a). A similar relationship may be seen, though it is less evident, in specimens I (figs. 2a, 2c) and III (figs. 4a, 4c).

Kink-bands probably originate in response to some external influence which prevents unlimited deformation by gliding on a set of glide-planes with high resolved shear stress. In the case of deformed cylinders of calcite this influence is the constraint caused by clamping the ends of the cylinders, and thus preventing external rotation of the cylinder (Turner, et al., 1954). In the case of an aggregate of calcite or quartz grains, the constriction of any grain is probably imposed by the neighboring grains in the aggregate. This is illustrated for quartz in figure 7, assuming the mechanism postulated above, namely, gliding on non-rational surfaces of high resolved shear stress in the zone of [0001]. The development of kink-bands (represented by deformation lamellae and bands) in quartz may be explained as follows: When the aggregate of quartz grains (quartzite) is deformed by strong compression (fig. 7c) only grains which are suitably oriented for gliding parallel to [0001] (grains X and Y in fig. 7) will deform by gliding. As gliding proceeds these grains will become elongated and will rotate externally with respect to the axis of compression (figs. 7b, c). These processes are, however, impeded by the surrounding grains, which are not suitably oriented to deform by gliding. But

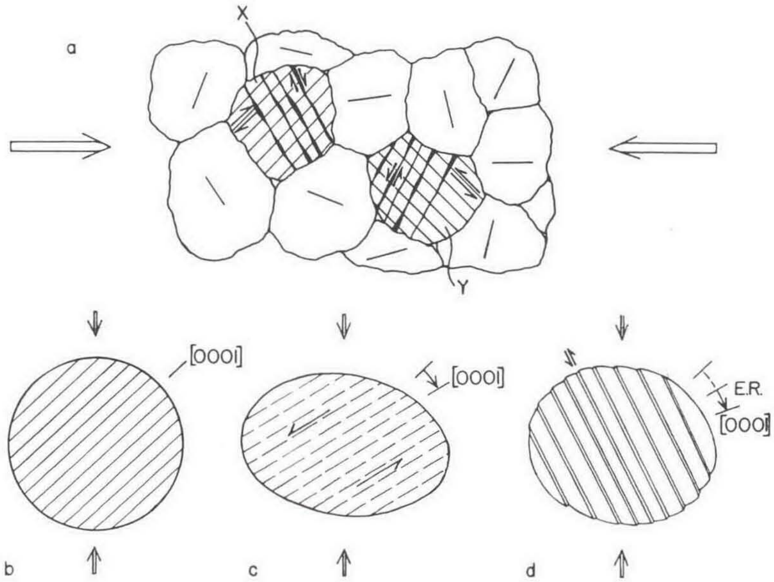

Fig. 7. Diagrammatic representation of the process of formation of deformation lamellae.

a. Aggregate of quartz grains, represented in two dimensions; uniform parallel lines in grains X and Y and short lines in other grains indicate the orientations of the [0001]-axes; irregular lines in grains X and Y represent deformation lamellae.

b,c,d. Change of shape of a grain of initially circular cross-section as a result of 1) shearing on surfaces parallel to [0001] and 2) kinking along planes inclined at a high angle to [0001]. The external rotation (E.R.) of the grain is shown qualitatively. Thick opposed arrows represent the direction of compression. For fuller explanation see text.

the production of kink-bands (fig. 7d) has the effect of correcting, at least to some extent, the change of shape induced by the gliding. Thus, if kink-bands are produced, gliding parallel to [0001] may take place with less change of shape than would be necessary in the absence of kinking.

It is probable that the undulose extinction and deformation lamellae are produced with a relatively small amount of post-crystalline strain, since in most of the specimens (I, II, III) there is no marginal granulation or marked elongation of grains. Moreover, the amount of strain in a grain containing kink-bands is reflected in the degree of external rotation of the kink-bands (that is, in differences of extinction position between the lamellae and host grain). These differences are very slight in deformation lamellae so that the strain must also be slight. It is significant that in highly deformed quartzites containing large amounts of granulated quartz and with very strong undulose extinction in the porphyroclastic relics, deformation lamellae are absent.[1] It is probable, in our opinion, that when deformation is so intense that differential movement and external rotation of grains occur, the restriction on individual grains is removed and deformation lamellae are no longer produced.

We do not wish to suggest that the mechanism postulated above is the

[1] This was noted by one of the writers (J.M.C.) in intensely deformed quartzites of the Assynt region.

only one which is operative in the deformation of quartz, or that it plays an important part in the development of preferred orientations in tectonites. There can be little doubt that solution and recrystallization are important in the reorienting of quartz and other mechanisms of plastic deformation may yet be demonstrated under conditions not yet attainable in the laboratory. However, the evidence described above leads us to conclude that it is significant in the initial stages of post-crystalline deformation of quartz and leads to the production of deformation lamellae.

A few deformation lamellae in the specimens may not have originated as kink-bands in the manner outlined above. Numerous cases are recorded, in specimens described herein and in the literature, of grains in which the lamellae are not inclined at high angles to the [0001]-axis. These lamellae may be shear-planes "induced" in a grain by the deformation of neighboring grains in the aggregate, either by gliding parallel to [0001] or by production of deformation lamellae in a neighboring grain. This view is supported by the existence of lamellae which pass more or less uninterrupted from one grain to another (Mackie, 1947, and present writers' observations). Moreover, some lamellae, particularly those which obviously consist of discrete inclusions and do not differ in refractive index from the host grain, may be relics of earlier fractures or deformation lamellae which have survived recrystallization of the grains (Hietanen, 1938).

Summary of hypothesis.—The deformation lamellae do not date from the deformation which produced the strong preferred orientations of the quartz grains in the rocks, but from a late penetrative deformation which has caused only slight strain and has had little or no effect on the preferred orientation. The grains have deformed by gliding on irregular surfaces in the zone of [0001] parallel to the direction [0001] and the lamellae are interpreted as kink-bands produced by this gliding. The strong preferred orientation of the lamellae is controlled by the preferred orientation of the grains in which such gliding has taken place, these grains being the ones which are oriented so that there is high resolved shear stress suitable for gliding parallel to [0001].

In the specimens described the [0001]-axes in grains with deformation lamellae define a small-circle girdle, representing a circular cone. The glide-surfaces are probably tangential to this cone and the poles of the induced kink-bands (deformation lamellae) also define a small-circle about the same axis. The orientation of the fabric elements suggests that the deformation was produced by a compression parallel to the axis of these small-circles. Two maxima are recognizable in some of the patterns of preferred orientation of lamellae, but the orientation and relative strengths of these maxima appear to be influenced by the existing preferred orientation in the rock before the production of the lamellae, rather than by the stress configuration during the deformation which produced the lamellae.

APPLICATION OF THE HYPOTHESIS

Significance of the proposed hypothesis.—If the above hypothesis is reliable it should be of direct application to the *dynamic* interpretation of the microfabric of deformed rocks.

The axis of the small-circle girdles defined by poles of deformation lamellae and [0001]-axes in grains with lamellae ('A' in figs. 2, 3, 4, 5) is the axis of maximum compression in the deformation which produced the lamellae. It is not the *a*-axis of the movement picture in this deformation, as claimed by Ingerson and Tuttle (1945). The patterns of preferred orientation of lamellae poles are not invariably small-circle girdles (Fairbairn, 1941; Ingerson and Tuttle, 1945; Riley, 1947) but in cases where this is not so, the axis A may be determined statistically as the intersection of the great-circles containing [0001] and the pole of lamellae in individual grains in the rock; in all the fabrics described in the literature, the pole of the lamellae in any grain is closer to the axis A than the [0001]-axis in the same grain (Ingerson and Tuttle, 1945). The orientation of the axis of compression (A) should be most easily determined in rocks showing little or no preferred orientation of the grain lattices, such as pure sedimentary quartzites and sandstones. But even in rocks with a strong preferred orientation of the quartz, such as schists and gneisses, it should be possible to identify the axis A using the above criteria.

By examining numerous specimens of quartzose rocks with deformation lamellae from an area it should be possible to obtain a reliable dynamic picture of the deformation which produced the lamellae. This should have more or less the same significance as the dynamic data obtained from studies of twinning in marble fabrics (e.g. Turner, 1953). For a terrane consisting of deformed crystalline rocks with strong preferred orientations of quartz, the inferred axes of compression will probably reflect only the last stage of the main deformation or some late imprint which has affected the rocks after the main phase of deformation and crystallization. However, for a terrane containing unrecrystallized quartz-rich sediments, the inferred axes of compression may reflect the main phase of deformation which has affected the rocks.

Certain precautions should be observed in the measurement and evaluation of data employed for such a dynamic interpretation:

1. Measurements should be made in two or three sections cut with different orientation from a specimen, to determine the real pattern of preferred orientation of lamellae.
2. The investigator should determine, if possible, that any lamellae found in sedimentary rocks are of post-diagenetic origin, and not relic structures which were present in the clastic grains of the sediment. The consistency of data, assessed by comparing successive samples of data from a single specimen, may indicate whether the lamellae are relics or have originated after the formation of the rock in which they are measured. Other criteria may also be found, such as the continuation of lamellae from a clastic grain in a quartzite into a peripheral region of secondary enlargement (Riley, 1947, p. 463).

Application to data from the Baraboo Quartzite.—The only regional study in which the orientation of deformation lamellae has been investigated is Riley's (1947) excellent study of the Baraboo Quartzite in Wisconsin. Riley made analyses of the orientation of [0001]-axes, deformation lamellae and other microstructures in the quartz grains of a large number of specimens from the Baraboo syncline. His detailed descriptions of the structures indicate that the deformation lamellae are identical with those described in the present work. The poles of deformation lamellae in most of the rocks define two strong

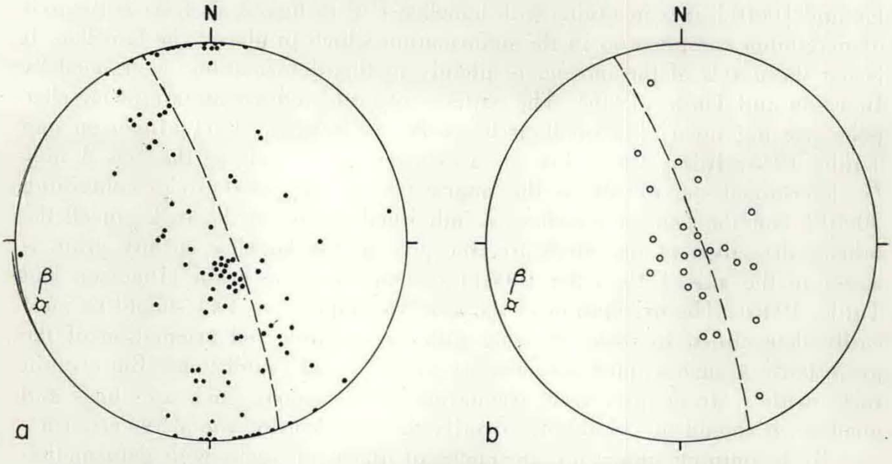

Fig. 8. Data from the Baraboo Quartzite (after Riley, 1947).

a. Poles of planar structures (bedding, shear-surfaces, etc.) in the Baraboo syncline. β represents the regional fold-axis.

b. Compression axes ("*a*-axes" of Riley) deduced from the orientation of deformation lamellae in specimens of the Baraboo Quartzite. In both diagrams the primitive circle is horizontal with north (N) at the top.

maxima but in a number of the specimens they are oriented in a small-circle girdle, similar to those illustrated above (figs., 2b, 3b, 4b, 5b). Riley determined, according to the method suggested by Ingerson and Tuttle (1945), *a*-, *b*- and *c*- fabric axes from the patterns of preferred orientation of lamellae. These axes, however, showed no consistent relationship to the fabric axes determined in the field from megascopic structures such as foliation and folds, nor was there any obvious regional consistency in the orientations of *a*-, *b*- and *c*- axes determined from the patterns of deformation lamellae (Riley, 1947, fig. 14). Riley considered that the fabric axes thus determined might be either a) strain axes of a different deformation from that which produced the megascopic structures, or b) local strain axes of the deformation, independent of the movement along bedding surfaces.

If the patterns of preferred orientation of deformation lamellae are interpreted according to the theory proposed by the present writers, the axes designated "*a*-axes" by Riley (after Ingerson and Tuttle) are no longer to be considered as the directions of slip in planar deformations, but as *axes of compression* during the deformation which produced the lamellae. Figure 8b shows the orientation of these "*a*-axes" (compression axes) reproduced from Riley (1947, fig. 14). These axes lie in a vertical plane with NNW strike and many of the axes plunge steeply. Figure 8a is a π-diagram, also constructed from Riley's data, showing the orientation of the bedding surfaces in the area. The diagram shows a well-developed π-circle about the regional fold-axis which trends ENE. The shear-surfaces, axial plane cleavages and small folds agree in symmetry with this picture. It is evident that the axes of compression, determined from the deformation lamellae, lie in the *ac*-plane of the regional structure and also, therefore, in the deformation plane of the large-scale movements. Thus the deformation lamellae may be related genetically to the movements which produced the large-scale folding of the Baraboo syncline. Although the movements may have been complex when considered in detail, as Riley has maintained, it is not impossible to incorporate the deformation lamellae and the folding in a single movement-picture.

ACKNOWLEDGMENTS

This paper reports the results of work carried out at Pomona College, Claremont, California, as part of a research project financed by the National Science Foundation; this support is gratefully acknowledged. We are indebted to Professor D. B. McIntyre for helpful discussion during the course of the study and the preparation of the manuscript. We are also very grateful to Professor F. J. Turner, who read the manuscript and made several very valuable suggestions; and to Professor D. T. Griggs, Professor G. Tunell and Dr. L. E. Weiss for helpful criticism and advice regarding the manuscript.

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