Dynamic Interpretation of the Simple Type of Calcite and Quartz Fabrics in the Naturally Deformed Calcite-Quartz Vein

By

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With 1 Table and 12 Text-figures

ABSTRACT The calcite and quartz fabrics in a deformed calcite-quartz vein found in the Sangun metamorphic formation at Hirose, Yamaguchi Pref., Western Japan, have been analysed, and the synchronization of both fabrics has been examined. The stress systems in the deformations, which produced the observed calcite fabrics, have been established in the light of what has been determined in the fabrics of experimentally deformed single crystals of calcite and marbles, and the quartz fabrics have been interpreted with reference to those stress systems. Small circle girdle pattern with angular radius of ca. 30° in the quartz lattice fabric in the vein has been clearly correlated with compressive stress directed parallel to the center of the small circle girdle, accompanied with almost equal amount of extension in all of the directions within the plane normal to the compression axis. It is pointed out that the c-axes of quartz may be stable at ca. 30° to the compression axis or at ca. 60° to the tension axis under such stress condition. The lamellae in quartz grains have been interpreted as the structure of late stage unrelated to the deformation which induced the lattice and dimensional fabrics of the quartz grains. The regular positional relationships between the c-axis of the host crystal and the corresponding lamellar pole and between the c-axis of the lamellar crystal and that of the corresponding host crystal have been recognized in the composite diagrams of those axial data for the quartz grains containing lamellae. It is pointed out that those relationships will be used to synthesize the stress system in the deformation related to the formation of lamellae.

CONTENTS

I INTRODUCTION

Since E. INGERSON and O. F. TUTTLE (1945) demonstrated that in the Ajibik quartzite and other rocks the pole of the lamellae in any quartz grain lies between the crystallographic c-axis of the host crystal in the same grain and the fabric axis *a* of the rock specmen concerned, similar regular relationship between the c-axis of the host crystal and the pole of lamellae in the composite diagram of these axial data has been noticed by N. A. RILEY (1947), J. PRESTON (1958), J. M. CHRISTIE and C. B. RALEIGH (1959) and others, and nowadays, this relationship seems to be regarded as an important attitude generally observed about lamellar structures of quartz, regardless of their types. INGERSON and TUTTLE considered that this relationship might be used to locate the fabric axes of the movement picture in the deformation which produced the lamellae. Recently CHRISTIE and RALEIGH have attempted speculatively to correlate this relationship with the stress system of the deformation related to the lamellae. They suggested that the axis which has been regarded by INGERSON and TUTTLE as the fabric axis *a* of the lamellae fabric coincides with the axis of maximum compression in the deformation. On the basis of these consideration, it seems to be very important to reanalyse the significance of this regular positional relationship between the c-axis of quartz and the pole of lamellae on a more favourable specimen.

Owing to the progress of experimental deformation of single calcite crystal and marble, much data have been provided for descriptive as well as dynamic analysis of naturally deformed calcite and calcite-bearing rocks (TURNER and CH'IH, 1951; BORG and TURNER, 1953; TURNER *et al.*, 1954; TURNER *et al.*, 1956). On the other hand, although so far experimental deformations on quartz and combinations of quartz and other minerals (GRIGGS, *et al.*, 1938; GRIGGS, 1941; GRIGGS *et al.*, 1960) and a remarkable amount of petrofabric analysis of naturally deformed quartz grains have been done, the mechanism, by which quartz orientation was developed, and even the lattice orientation favorable to simple stress system have scarecely been known.

The calcite fabrics of a calcite-quartz vein found in the Sangun metamerphic formation at Hirose, north of the Kawayama mine, Yamaguchi Pref., Western Japan, represent a simple type which can fully be interpreted in the light of what has been determined in the fabrics of experimentally deformed single crystals of calcite and marbles. Fortunately, in this specimen, lamellar structures in the associated quartz grains in the vein have been recognized. In the present work the author aims: 1) to interprete the calcite fabrics of the deformed calcite-quartz vein in terms of what has been determined experimentally for deformed single crystals and marbles; 2) to correlate the quartz fabrics of the vein with the stress system deduced from the calcite fabrics, and thereby to analyse the stress systems imposed upon the vein in the respective deformation stages when the c-axis fabric and the lamellae in the quartz grains have been produced; 3) to determine the positional relation of the c-axis of quartz to the stress system in the deformation which produced the c-axis fabric of quartz grains in the vein; and 4) to correlate the regular positional relationship between the c-axis of quartz grain and the pole of lamellae in the same grain in the composite diagram of these axial data with the stress system of the deformation which produced the lamellae.

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II Petrofabric Description and Dynamic Interpretation

A. General Features of the Rock

The host rock of the calcite-quartz vein in question is phyllite derived from sandy shale. The essential component of the host rock is white mica, quartz, and graphitic matter, accompanied by subordinate chlorite, calcite, and albite. The host rock shows a single schistosity defined by preferred orientation of platy minerals and elongation of quartz grains. Other planer structure is tiny cracks inclined to the schistosity plane at high angles, which are plane and open. They also cut across the calcite-quartz vein, and calcite and quartz grains in the vein are sharply cut showing neither associating granulation nor plastic deformation.

Within the schistosity surface are found two types of lineation formed in different stages: the older type is defined by distinct parallel striations and the younger type by indistinct parallel striations perpendicular to the older lineation. Tentatively in this paper the fabric axes have been set up in accordance with the schistosity plane and the older lineation, *i.e.*, the axis *b* coincides with the direction of the older lineation, the axis *a* is perpendiculer to the older lineation on the schistosity plane, consequently coinciding with the direction of the younger lineation, and the axis *c* is normal to the schistosity plane.

The calcite-quartz vein in question is generally straight with an average width of 0.7 mm., having a few swelling parts, and is slightly oblique to the schistosity plane. The vein consists almost exclusively of calcite and quartz grains. There is a tendency for swelling parts of the vein to consist almost only of quartz grains and for the remaining parts to be rather rich in calcite grains and partly to consist only of calcite grains. Those parts in which calcite or quartz grains are concentrated respectively are present side by side in a part of the vein. Data about calcite and quartz fabrics analysed in the following pages have been provided from those parts in the vein. In analysing the deformation picture of calcite and quartz grains in those parts may be negligible the influence of the attendant minerals ("Einfluss der Gefugegenossen", after Sander, 1950).

Microscopic measurements of calcite and quartz grains give the following average dimensions of grain parallel to the three fabric axes: for calcite grains *a* 0.13 mm., *b* 0.12 mm., and *c* 0.08 mm.; and for quartz grains *a* 0.37 mm., *b* 0.33 mm., and *c* 0.16 mm. Especially, quartz grains show remarkable lensoid babit, but this is not related to any lattice orientation. Boundaries of calcite grains are sharp in most grains, and marginal granulation is absent or, if present, slight. Undulatory extinction is generally absent, but it is slightly developed in some grains of calcite which show no sets of $(01\bar{1}2)$ lamellae. While, most grains of quartz show distinct undulatory extinction and internal and marginal granulation. Lamellar structure is developed in some grains of quartz, in which undulatory extinction and boundary deformation are relatively weak and are of the "plastic variety", that being in accord with the observation of WEISS (1954).

The calcite-quartz vein was formed in the late stage of metamorphism, namely, in the late kinematic stage, cutting across the younger lineation. The tiny cracks mentioned above are the expression of the later deformation stage than that having produced the undulatory extinction and the lamellar structures in calcite and quartz grains. The tiny cracks are generally filled with muscovite flakes in the vein. This fact suggests that even at the close of the deformation, when the cracks were formed, there occurred recrystallization in quartz and calcite crystals in the vein.

B. PREFERRED ORIENTATION OF c-AXIS OF CALCITE

Fig. 1 shows the preferred orientation of c-axis of calcite measured for 200 grains. The pattern is characterized by a girdle with maximum and submaxima spreading on a small circle about the fabric axis *c* with an angular radius of ca. 20°. Similar pattern of lattice orientation of calcite with a small circle girdle has been very distinctly produced in the calcite fabric of Yule marble deformed in the laboratory by compression under high confining pressure without associated recrystallization in most grains of calcite (TURNER *et al*, 1956). The c-axes of calcite are preferably oriented at 10°∼30° to the axis of compression. Accordingly, the analogous pattern of calcite lattice fabric of the calcite-quartz vein in question can be correlated with the compressive stress directed parallel to the fabric axis *c*.

Based on the experimental research, GRIGGS *et all.* (1960) said: "the c-axes of the calcite grains tend to remain in a plane in which lie the axis of tension and the direction of concentration of c-axes in the initial fabric. This is the deformation plane as deduced from the geometrical shape of the specimen.......... And even at strains exceeding 500 per cent the influence of the initial preferred orientation pattern upon evolution of the new fabric is still highly effective" (cf. TURNER *et al.*, 1956; TURNER, 1957). Therefore, the position and the difference in concentration of the maximum and submaxima of the calcite lattice fabric in question may probably be regarded as influenced by the pre-existing preferred orientation of calcite lattice in the vein, rather than by the stress configuration during the deformation which produced the present orientation of calcite lattice. Generally speaking, the symmetry of fabric of deformed rocks reflects the symmetry of movement responsible for the evolution of

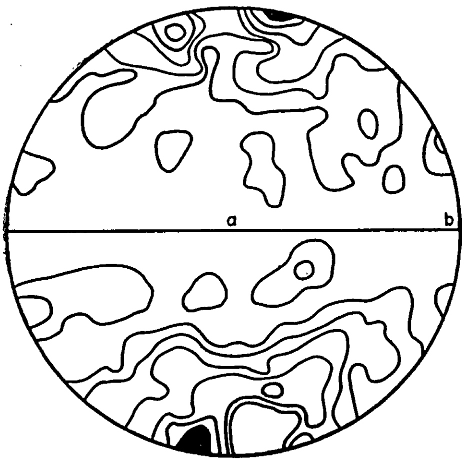

FIG. 1. 200 c-axes of calcite. Contours: 6-5-4-3-2-1 %

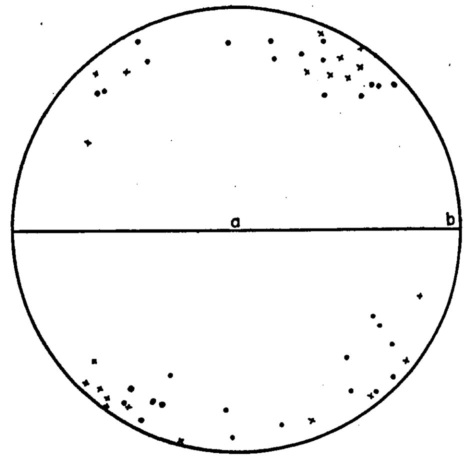

FIG. 2. Poles of twinned (crosses) and of nontwinned {01$\bar{1}$2} lamellae (dots) in 50 calcite grains.

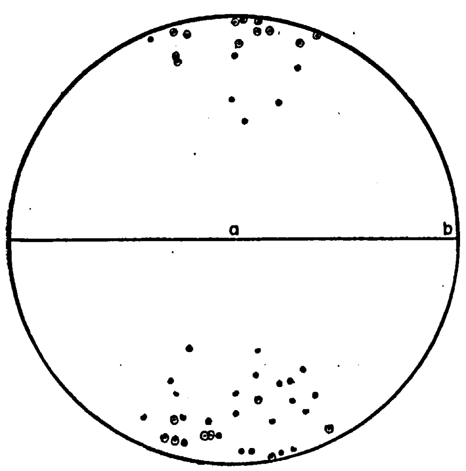

FIG. 3. c-Axes in 50 grains with twinned or nontwinned {01$\bar{1}$2} lamellae. Circled dots represent grains with twinned lamellae and dots represent grains with nontwinned lamellae.

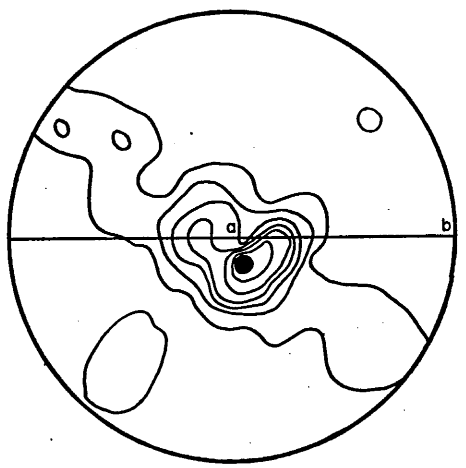

FIG. 4. β-diagram for twinned {01$\bar{1}$2} lamellae. Countours: 14-11-9-7-5-3-1 %.

the fabric (SANDER, 1948; TURNER, 1957). When the positions of maximum and submaxima are taken into account, the pattern of calcite lattice fabric in question shows triclinic symmetry with reference to the fabric planes. In fig. 1, however, a maximum (6 per cent) and two submaxima (5 per cent) are present on the same small circle with an angular distance of ca. 120° one another, and most of the remaining parts of the small circle has a higher concentration (4 per cent). Therefore, for the parts consisting only of calcite grains in the calcite-quartz vein, for which the fabric diagram of fig. 1 was made, the symmetry of movement with respect to the distribution of the c-axis of calcite seems to be approximately axial with reference to the assumed compression axis parallel to the fabric axis *c*.

This probability may be greatly strengthened by the following fact. As mentioned in the preceding page, the calcite grains show tabular habit with short dimension parallel to the fabric axis *c* and with long dimensions within the fabric plane *ab*. The mean grain dimensions parallel to the fabric axes *a* and *b* are almost equal. According to TURNER *et al.* (1956), "the fabric resulting from compression of Yule marble normal to the initial foliation is characterized by elongation of grains normal to the compression axis." A similar phenomenon has been observed in the experimental deformation of quartz sand by FAIRBAIRN (1950). Thus the lattice and dimensional fabrics of the calcite grains in question seem to be well correlated with the compression directed parallel to the fabric axis *c*, accompanied with almost equal amount of extention in all of the directions within the fabric pane *ab*. The stress and movement picture related to the vein is obviously different from unequal squeezing and /or extension in different directions within the schistosity plane inferred for the deformations which produced the older and younger lineation.

C. ANALYSIS OF {01$\bar{1}$2} LAMELLAE IN CALCITE GRAIN

{01$\bar{1}$2} lamellae are weakly developed, and are generally so widely spaced that only a few lamellae are observed in a single grain. They are recognized only in 25 per cent of measured grains. Twinning is optically recognizable in 10 per cent of the grains. In the remaining 15 per cent of the grains all sets of {01$\bar{1}$2} lamellae are nontwinned in the sense of BORG and TURNER (1953).

Twinned lamellae are a type of thin incomplete twin and are rationally oriented with respect to the crystal lattice. Therefore, it may be concluded that they represent the incipient twinning which has originated after the deformation which produced the lattice and dimensional fabrics described in preceding pages (TURNER, 1953 and MCINTYRE and TURNER, 1953).

c-Axes of twinned grains are distributed in sharply limited small area about the fabric axis *c* as shown in fig. 3, that being different from the lattice orientation for all measured grains shown in fig. 1. According to the method described by TURNER (1953), the direction of a applied stress which would have been most effective in causing twin gliding on each of the observed twinned lamellae was determined with the result shown in fig. 6. The mode of grouping of compression as well as tension axes is distinctly regular. Compression axes are concentrated about the fabric axis *b* and tension axes about the fabric axis *c*. Therefore, all the twinning observed in the measured grains could be correlated with a compressive stress applied in the direction of the fabric axis *b* or a tensile stress applied in the fabric axis *c*, or both stresses acting together, the stress having been imposed upon calcite grains in the calcite-quartz vein whose lattice had already been preferably oriented as shown in fig. 1.

Fig. 4 is the β-diagram for all sets of observed twinned lamellae. The diagram

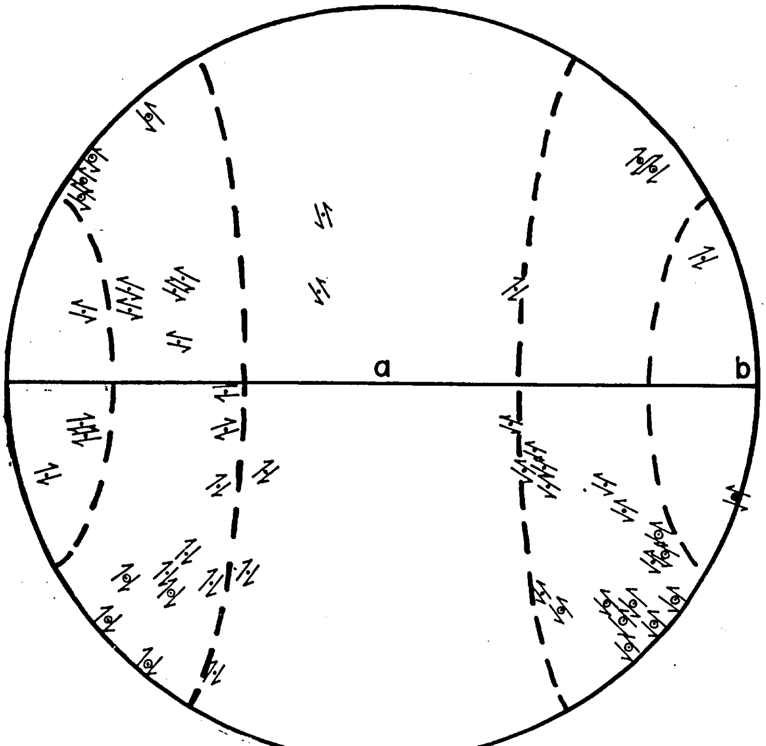

FIG. 5. Glide lines {01$\bar{1}$2}: (10$\bar{1}$1) and gliding sense along them in twinned and nontwinned grains of fig. 3. Circled dots represent glide lines in the former. Dots represent glide lines in the latter.

has been constructed after the method of B. SANDER (1948). The diagram is characterized by a single marked maximum close to the fabric axis *a*, indicating that the twinned lamellae are tautozonally oriented and correspond approximately to (*Okl*) planes with respect to the fabric axes. Glide lines and the sense of relative slip along them for twin gliding in all observed twinned lamellae show a marked preference as indicated in fig. 5. They are separately oriented in two distinctly limited areas, centers of which lie nearly in the fabric plane *bc* and stand at ca. 45° to the fabric axis *b* symmetrically. Most of those glide lines are inclined to the fabric axis *a* and β-maximum for twinned lamellae at angles between 65° and 90°. It may well be concluded, therefore, that the fabrics of twinned lamellae in question are consistent with the supposed biaxial strain with compressive stress directed parallel to the fabric axis *b* and tensile stress parallel to the fabric axis *c*.

The fabric of the non-twinned variety of {01$\bar{1}$2} lamellae will then be examined. This variety of lamellae, which appears as sharp lines that cannot be identified by optical means as applied to the twinned lamellae, may probably represent twinned lamellae of ultramicroscopic thickness, or it may belong to a certain type of defor-

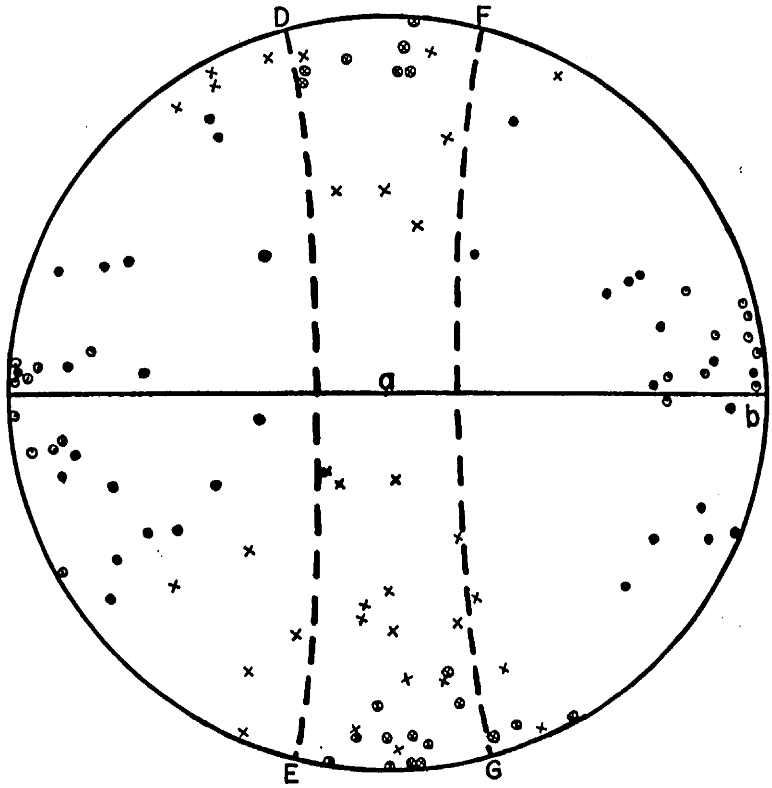

FIG. 6. Axes of compression and tension most favorably oriented to form twinned and nontwinned {01$\bar{1}$2} lamellae.

Circled dots and circled crosses represent axes of compression and of tension respectively for twinned lamellae. Dots and crosses represent those axes assumed for nontwinned lamellae respectively.

mation structure unillustrated at present (TURNER, 1953; BORG and TURNER, 1953).

Preferred orientation of c-axis of non-twinned grains is shown in fig. 3. They are preferably oriented in close periphery of the group of c-axes of twinned graines about the fabric axis *c* and at high angles to the compressive stress which is responsible to the fromation of the twinned lamellae. Assuming that the non-twinned lamellae had the same gliding behaviour as the twinned lamellae, the author determined with respect to all the sets of observed non-twinned lamellae directions of glide line and those of applied stress axes which would have been most effective in causing glide along them (figs. 5 and 6). The glide lines for non-twinned lamellae tend to spread into the annular broad zones making angles of between 30° and 60° with the direction of compressive stress assumed for the twinned lamellae. The similar orientation pattern of glide lines has been observed for twinned lamellae of the Yule marble (TURNER, 1953). The orientation of stress axes assumed for the non-twinned lamellae is shown in fig. 6. The compression axes tend to distribute in narrower zone close to the group for twinned lamellae. The tension axes show a larger dispersion around the group for the twinned lamellae. The tension axes, however, tend to spread in the zone bounded by the arcs DE and FG in fig. 6, which have angular distances of 15° to the fabric plane *ac*, except the vicinity of the fabric axis *a*.

The zonal arrangements of glide lines and tension axes are more clearly illustrated when combined for both twinned and non-twinned lamellae as shown in fig. 5 and 6, the figure being harmonic with the stress system assumed for the twinned lamellae described above.

ANDERSON (1948) analyzed the direction and magnitude of shear stress in selected points on the strain ellipsoids of two types of restricted flow with orthorhombic symmetry. Generally speaking, in experimental deformation of marbles the type of non-twinned lamellae develops in a zone of low resolved shear stress and that of twinned lamellae in a zone of high resolved shear stress with respect to the applied stress. The zonal arrangement of glide lines and tension axes for both twinned and non-twinned lamellae, and the spacial relations between glide lines for the former and those for the latter and between tension axes for the former and those for the latter, as shown in figs. 5 and 6, seem to be correlated with either one of ANDERSON's stress pictures for the two types of restricted flow with orthorhombic symmetry. Therefore, it may safely be said that the fabric of the twinned and non-twinned lamellae in question can be correlated with the restricted flow with orthorhombic symmetry with the maximum compression parallel to the fabric axis *b* and the maximum extension parallel to the fabric axis *c* and that the non-twinned lamellae represent deformation lamellae with the same glide direction and relative gliding sense with respect to the lattice structure of calcite as those determined for the twinned lamellae.

D. PREFERRED ORIENTATION OF c-AXES OF QUARTZ

The preferred orientation of c-axes of quartz measured in 300 grains is illustrated in fig. 7. The pattern is characterized by a girdle with maximum and submaxima spreading on a small circle with an angluar radius of ca. 30° about the fabric axis *c*. Similar small circle girdle pattern about the fabric axis *c* in the quartz fabric diagram has been recognized by many workers (*cf.* FAIRBAIRN, 1949).

Recently, kinematic interpretation of this type of quartz fabric has been tried about that of the quartz schist from Besshi, Japan, by KOJIMA and HIDE (1958). It is based on the transversal schistosity surfaces (*Okl*) and (*hkl*), from observed relative slip directions on which the maximum compression about the fabric axis *c* was assumed, and on KOJIMA and SUZUKI's hypothesis on the orientation of quartz in reference to the shear plane (KOJIMA and SUZUKI, 1958). However, in the calcite-quartz-vein and the host rock in question no sets of such the visible effective transversal schistosity surface are there.

B. KAMB (1959) and F. W. BRACE (1960) have predicated the formation of small circle girdle pattern of lattice orientation of quartz under nonhydrostatic stress field on the basis of the thermodynamic theory. However, angular radius (ca. 30°) of the small circle girdle in the fabric diagram in question does not coincide with that (70°) for stably oriented low quartz calculated by BRACE. This fact and the presence of maximum and submaxima in the fabric diagram suggest orienting mechanism based on mechanical plastic flow, which cannot be illustrated by their predications.

The quartz grains show remarkable tabular habit with short dimension parallel to the fabric axis *c* and with long dimension within the fabric plane *ab*, just as well as the calcite grains. The mean grain dimensions parallel to both fabric axes *a* and *b* are nearly equal. Swelling parts of the vein, which consist only of quartz grains, show nearly equal longer dimensions parallel to both fabric axes *a* and *b* and shorter dimension parallel to the fabric axis *c*. Therefore, according to the experimental evidences after FAIRBAIRN (1950) and TURNER *et al.* (1956) cited in preceding page, the dimensional fabric of quartz grains is tentatively correlated with compressive stress directed parallel to the fabric axis *c*, accomparied with nearly equal amount of extension in all of the directions within the fabric plane *ab*.

The dimensional fabric is unrelated to the deformation which produced undulatory extinction bands, internal and marginal granulations and lamellar structure in quartz grains, those tending to break down original grain shape and lattic orientation. The lattice fabric and dimensional fabric of quartz grains concerned may be synchronous. Therefore, it is attempted to correlate the quartz c-axis fabric with compressive stress directed parallel to the fabric axis *c*, accompanied with nearly equal amount of extension in all of the directions within the fabric plane ab. The small circle girdle pattern of c-axes of quartz about the the fabric axis *c* is harmonic phenomenon with respect to the assumed stress system. However, the presence of maximum and submaxima on the small circle girdle gives the pattern a triclinicity with reference to the fabric planes, which may be disharmonic with respect to the assumed stress system. However, a maximum (4 per cent) and three submaxima (3 per cent) distribute radially on the small circle in fig. 7, and also in most of the remaining parts on the small circle is recognized nearly equal concentration (2 per cent) of c-axes of quartz. Therefore, if the c-axes of quartz grains has been oriented in one phase of deformation, in parts consisting only of the quartz grains in the calcite-quartz-vein, from which the c-axes fabric diagram of fig. 7 has been established, the symmetry of movement with respect to the distribution of c-axes of quartz might have been approximately axial with reference to the fabric axis *c*. The presence, position and relative strength of the maximum and submaxima in the quartz fabric concerned may be regarded as influenced by the pre-existing preferred orientation of quartz lattice in the vein, rather than by the stress configuration during the deformation which produced the present orientation of quartz lattice, according to the experimental evidences after GRIGGS *et al.* (1960) cited in preceding page. Thus the lattice and dimensional fabrics of quartz grains seem to be clearly correlated with compressive stress directed parallel to the fabric axis *c*, accompanied with nearly equal amount of extension in all of the directions of the fabric plane *ab*, which have been deduced tentatively from

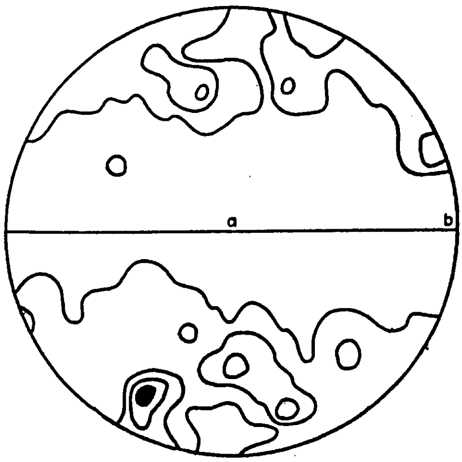

FIG. 7. 300 c-axes of quartz. Countours: 4-3-2-1%.

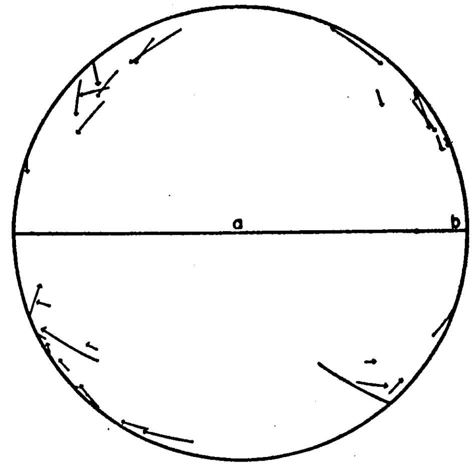

FIG. 8. Poles of lamellae (point of arrow) and c-axes of host crystals (end of arrow) in the quartz grains containing lamellae out of 300 grains examined.

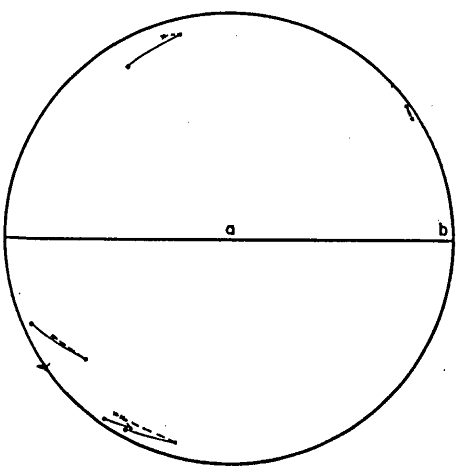

FIG. 9. Poles of lamellae (circles) and c-axes of lamellar (croses) and of host crystals (dots) in the quartz grains, in wich the relative positions of c-axis in lamellar and host crystal could be approximately measured.

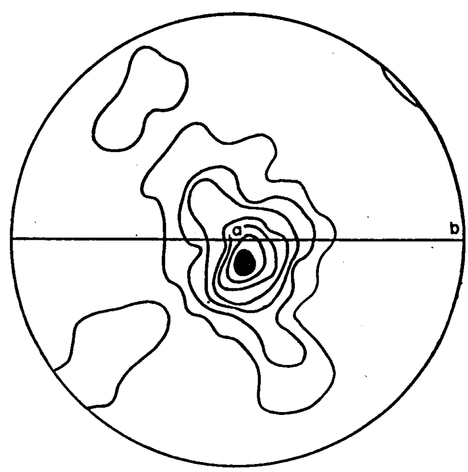

FIG. 10. β-diagram for lamellae of Fig. 8. Countours: 23-20-15-10-5-3-1%.

the dimensional fabric as mentioned above.

E. Analysis of Lamellar Structures in Quartz

Development of lamellae is insignificant. They are recognized only in 9 per cent of the measured grains. Also the lamellae themselves are fairly weak displayed. The lamellae are defined by slightly higher refractive index and slightly different extinction position, terminating within the grain boundaries. However, the relative positions between the c-axis of the lamellar crystal and that of the host crystal could not be measured in most grains containing lamellae and has been approximately measured in only five grains. The angular distances between the c-axis of the lamellar crystal and that of the host crystal in those five grains are approximately 22°, 17°, 14°, 7° and 3° respectively. The crystallographic location of the lamellae with respect to lattice direction of quartz was determined with the U-stage, though that in those five grains seems to be fairly ambiguous. It is shown in fig. 11. The histogram in fig. 11 shows that, except one of all observed lamellae, they are inclined to (0001) at angles varying from 0° to 20° This result about crystallographic locations of the lamellae is not dissimilar to that noticed by SANDER (1930), FAIRBAIRN (1941), INGERSON and TUTTLE (1945), PRESTON (1958) and CHRISTIE and RALEIGH (1959).

The c-axes of quartz grains containing lamellae distribute in two sharply restricted areas, centers of which lie approximately in the fabric plane *bc* and stand with angular distances of ca. 40° to the fabric axis *b* symmetrically (fig. 8). A similar restricted orientation of the poles of lamellae is equally obvious, occupying the same area in the diagram as that of the corresponding c-axes, as shown in fig. 8. The patterns of preferred orientation of both the c-axes of grains containing lamellae and the poles of lamellae in fig. 8 are almost perfectly orthorhombic together and the two symmetry planes coincide approximately with the fabric planes *bc* and *ab* together. As described in preceding page, the pattern of preferred orientation of the c-axes in all measured grains of quartz is triclinic with reference to the fabric planes (fig. 7). Thus it is safe to conclude that the lamellae represent late-stage structure unrelated to the present lattice orientation of quartz grains, as INGERSON and TUTTLE (1945), RILEY (1947), TURNER (1948), WEISS (1954) and CHRISTIE and RALEIGH (1959) have pointed out.

Fig. 10 is the β-diagram for all sets of observed lamellae. The diagram is characterized by a single maximum of high concentration close to the fabric axis *a*, in-

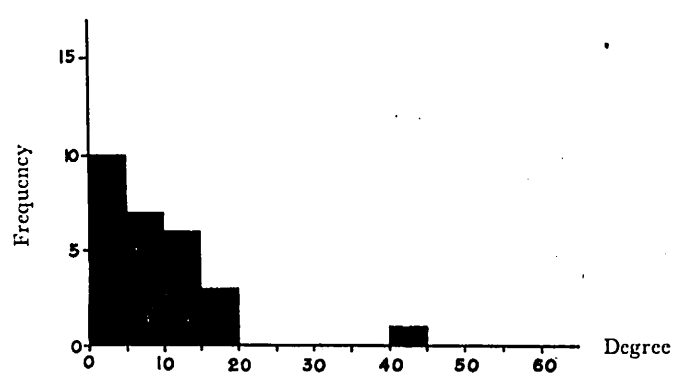

FIG. 11. Histogram showing the variation in the angle between c-axis of host crystal and the pole of lamellae in the quartz grains of Fig. 8. The frequency is given by number of grains.

dicating that they are tautozonally oriented and approximately correspond with the (*Okl*) planes with respect to the fabric axes. Thus the lamellae in question seem to be correlated with biaxial strain under compressive stress directed parallel to the fabric axis *b* and tensile stress directed parallel to the fabric axis *c* or under tensile stress directed parallel to the fabric axis *b* and compresive stress directed pallalel to the fabric axis *c*.

In fig. 8, the pole of lamellae in any grain is closer to the fabric axis *b* than the c-axis of the host crystal in the same grain. This relationship is similar to that noticed by INGERSON and TUTTLE, RILEY, PRESTON and CHRISTIE and RALEIGH. Analogous positional relationship between the c-axis of the lamellar crystal and that of the host crystal is equally obvious, as shown in fig. 9. The c-axis of the lamellar crystal in any grain is closer to the fabric axis *b* than that of the host crystal in the same grain. This relationship has been traced ambiguously by comparison of extinction positions in the lamellar and host crystal in most grains, in which the c-axis of the lamellar crystal could not be measured accurately. While, both c-axis of the lamellar crystal in any grain and the pole of lamellae in the same grain show no regular positional realtionship between them in fig. 9. In one grain the c-axis of the lamellar crystal is closer to the fabric axis *b* and in another grain that is closer to the fabric axis *c* than the pole of the corresponding lamellae. The pole of lamellae, the c-axis of the lamellar crystal and that of the host crystal in any grain seem not always to lie on a single great circle together, though error of measurement on them, especially on the former two, comes into question (fig. 9).

III. SYNCHRONIZATION OF THE QUARTZ FABRICS WITH THE CALCITE FABRICS

Synchronization of the quartz fabrics with the calcite fabrics, which have been analyzed in preceding pages, will now be examined. The calcite-quartz vein in question originated after the deformation which produced the younger lineation running parallel to the fabric axis *a*. Thereafter, calcite and quartz grains in the vein had experienced respectively the deformation which produced the lattice and dimensional fabrics shown in figs. 1 and 7. In the next stage, deformation, which both calcite and quartz grains had experienced, was what produced lamellar structures in those grains respectively. In the last stage, the calcite and quartz grains had yielded to the deformation which produced the tiny cracks sharply cutting those grains, as mentioned in preceding page. Therefore, judging only from respective sequence of deformation structures observed on the calcite and quartz grains, the calcite fabrics and the quartz fabrics seem to be clearly synchronized as shown in Table 1. However, for difference in stress sensitivity between the quartz and calcite crystal might be error this synchronization in Table 1. Therefore, this synchronization must be in more detail discussed.

Comparison of the lattice fabric of the quartz grains (fig. 7) with that of the calcite grains (fig. 1) shows that the pattern of preferred orientation is well similar to

Table 1 Tectonic sequence

tectonic phase		I	II		III	IV	V
host rock		Older lineation within the schistosity S_l / monoclinic symmetry	Younger lineation within the schistosity S_l / monoclinic symmetry	segregation of calcite-quartz vein (slightly oblique to the S_l)			tyny cracks at high angle to the S_l
calcite-quartz vein	calcite				lattice and dimensional fabrics / axial symmetry (nearly)	twinned and nontwinned lamellae / orthorhombic symmetry	tyny cracks at high angle to the vein
	quartz				lattice and dimensional fabrics / axial symmetry (nearly)	deformation lamellae / orthorhombic symmetry	tyny cracks at high angle to the vein
stress picture		maximum compression within the fabric plane ac	maximum compression within the fabric plane bc		compressive stress parallel to the fabric axis c, accompanied with almost equal amount of extension in all of the directions within the fabric plane ab.	maximum compression parallel to the fabric axis b and maximum extension parallel to the fabric axis c,	

one another with an axis of axial symmetry parallel to the fabric axis *c*. Both quartz and calcite grains show sharp lensoid form, though it is more remarkably displayed in the former, showing the same attitude with respect to the fabric axes together. Therefore, the strain and movement pictures correlated with the lattice and dimensional fabrics of the quartz and calcite grains would be symmetrically of similar style to one another. The stress picture correlated with the lattice and dimensional fabrics of the calcite grains, that has been analyzed in preceding pages in the light of what has been determined in the fabrics of experimentally deformed marbles, has been illustrated as compressive stress directed parallel to the fabric axis *c*, accompanied with almost equal amount of extension in all of the directions within the fabric plane *ab*. This stress picture is in accord with that tentatively assumed for the lattice and dimensional fabrics of the quartz grains (see p 44).

As illustrated in figs. 4 and 10, the twinned lamellae in the calcite grains and the lamellae in the quartz grains correspond approximately with the fabric plane (*Okl*) with respect to the fabric axes together. Superposition of fig. 2 on fig. 8 shows that the poles of those lamellae distribute in the similar areas in the diagrams together. The patterns of preferred orientation of both the poles of the twinned lamellae in the calcite grains and those of the lamellae in the quartz grains are almost perfectly orthorhombic and the two symmetry planes coincide approximately with the fabric planes *bc* and *ab* together in figs. 2 and 8. Therefore, the stress pictures correlated with the twinned lamellae in the calcite grains and with the lamellae in the quartz grains would be of similar style to one another. Therefore, the lamellae in the quartz grains seems to be clearly synchronized with the twinned lamellae in the calcite grains.

It is impossible to synchronize the lamellae in the quartz grains with the lattice and dimensional fabrics of the calcite grains, because the symmetry of the lamellar fabric of quartz in fig. 8 and of the movement picture in the deformation related to the lamellae is perfectly disharmonic with that of the lattice and dimensional fabrics of the calcite grains (fig. 1) and of the movement picture in the deformation, which produced these fabrics, and because the stress system for these calcite fabrics analyzed in preceding page seems to favor annular arrangement of the poles of the lamellae of quartz about the fabric axis *c*, judging from the orientation pattern of the c-axes of quartz shown in fig. 7. It is also impossible to synchronize the lattice and dimensional fabrics of the quartz grains with the twinned and nontwinned lamellae in the calcite grains, because the symmetry of the former is perfectly disharmonic with that of the latter fabric and the attitude of lensoid forms of quartz grains with respect to the fabric axes described in prededing page does not correspond with the stress system for the twinned and notwinned lamellae in the calcite grains analyzed in preceding pages. Undulose extinction and boundary deformation observed in both calcite and quartz grains are synchronous with the lamellar structures in those grains.

Thus the lattice and dimensional fabrics of the quartz grains could be clearly synchronized with those of the calcite grains. And the lamellae in the quartz grains could be clearly synchronized with the twinned and nontwinned lamellae in the calcite grains. Remarkable lensoid form of quartz grains shows that generally quartz crystal changed more sensitively its shape than calcite crystal under physico-chemical condition which covered the calcite-quartz vein in this deformation stage. Now the dimensional and lattic fabrics of quartz grains in question must be illustrated in term of compressive stress acting parallel to the fabric axis *c*, accomparied with almost equal amount of extension in all of the directions within the fabric plane *ab*, which is the stress system for the lattice and dimensional fabrics of the calcite grains. Thus, dynamic interpretation on the lattice and dimensional fabrics of the quartz grains in preceding page is confirmed.

The c-axes of most grains of calcite show a stable orientation with reference to the stress system, as mentioned in preceding page. Then, it may be concluded that also the c-axes of most grains of quartz in fig. 7 had been stably oriented with reference to the stress system, because of sensitive behaviour of quartz to the stress that many authors pointed out. On the basis of these consideration, it may be pointed out that the c-axis of quartz is stable at ca. 30° to the compression axis or at ca. 60° to the tension axis under the stress condition as mentioned above. According to BRACE (1960), the most elastically compliant ditrection for low quartz is at about 70° to the c-axis. Therefore, it may be noted that the quartz grains in question are oriented with their most elastically compliant direction subperpendcular to the inferred compression axis.

The lamellae in the quartz grains must be accounted for by the stress system which has been established with respect to the twinned and non-twinned lamellae in the calcite grains in preceding pages following the method described by TURNER (1953). Also regular positional relationships among the pole of lamellae, the c-axis of the lamellar crystal, that of the host crystal and the fabric axes, described in preceding pages, must be accounted for by the stress system.

IV PROBLEM SETTING ON THE ORIGIN OF THE LAMELLAR STRUCTURES IN QUARTZ

From preceding discussions, we could clearly correlate the lamellae in the quartz grains in question with the stress system imposed upon the calcite-quartz vein in the deformation stage, when they were produced. Therefore, mechanism of formation of the lamellae and of the associated deformation in the quartz grains must be illustrated with reference to this stress system.

The sense of rotation in the lamellar crystal in any grain can be determined by the relative position between the c-axis of the lamellar crystal and that of the host crystal in fig. 9. This examination shows that the sense of rotation in the lamellar crystal is that of external rotation with respect to the applied stress system. This relationship has been traced ambiguously by comparison of extinction positions in the lamellar and host crystal in most grains, in which the c-axis of the lamellar crystal could not be measured accurately. Generally, external rotation of crystal in such a

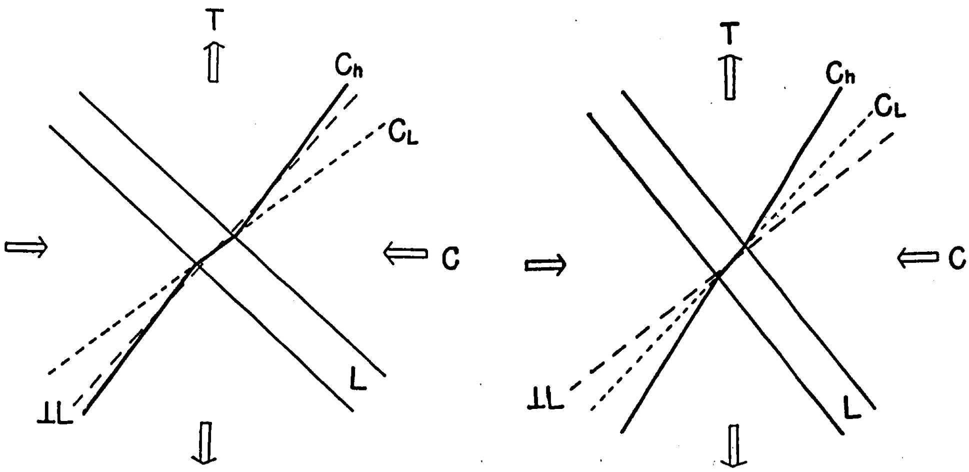

FIG. 12. Schematic sketch of relation of lamellar (L), pole of lamellar (⊥L), c-axis of lamellar crystal (CL), c-axis of host crystal (Ch), compression (C), and tension axis (T).

narrow band as the lamellar of quartz has been observed in deformation band and kink band formed in experimental deformation of metals and minerals. In fig. 12 is shown the schematic relation among the c-axis of the lamellar crystal, that of the host crystal, the pole of lamellae and the stress axes. This relationship is distinctly similar to that between the active glide line (c-axis) and deformation band or kink band (lamellar). Therefore, the lamellae in quartz in question may be correlated with deformation band or kink band inclining at high angles to the active glide line parallel to the c-axis, as CHRISTIE and RALEIGH have speculatively pointed out.

From X-ray studies of quartz grains containing undulatory extinction, deformation lamellae, marginal granulation and fracturing in naturally deformed rocks, BAILEY *et al.* (1958) have noticed that "most of the quartz has deformed plastically by bend gliding. One of the three crystallographic a axes is always the major axis of bending, but no unique glide direction or glide plane has been established.........". However, as shown in fig. 9, the pole of lamellae, the c-axis of the lamellar crystal and that of the host crystal in any grain seem not always to lie on a single great circle together, though error of measurement on them comes into question. Therefore, it is suggested that crystal within the lamellae does not rotate always about an axis perpendicular to the c-axis and so about the a-axis of quartz. Then it is comes into question whether the active glide line is parallel to the c-axis or not and also whether the boundaries parallel to the lamellae are pure tilt boundaries or of other style. However, those problems will be in details discussed in other paper.

Lastly, on the basis of actual evidences mentioned in preceding pages, it is noted in general terms that: 1. the pole of the lamellae in any grain is closer to the direction of the compressive stress than the c-axis of the host crystal in the same grain: 2. the c-axis of the lamellar crystal in any grain is closer to the direction of the compressive stress than the c-axis of the host crystal in the same grain; 3. two groups of the poles of lamellae, distributed separately in angular distance of ca. 90 in the diagram for them, lie together on the plane containing the compression and tension axes; 4. the compression and tension axes are located to points which lie midway between two groups of the poles of lamellae on the great circle, on which these lie together. These relationships will be used to lacate the stress system imposed upon rocks concerned in the deformation stage, when had been produced the lamellae in quartz grains.

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