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A Petrofabric Study of Shear Micro-fold

By

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with 15 Text-figures

ABSTRACT: Quartz and calcite fabrics of shear micro-folds in a phyllite and a crystalline limestone from the Sambagawa Metamorphic Zone at Tai and Motoyama in Central Shikoku, were analysed. Partial and collective diagrams were made from the orientation data of the c axes of quartz grains and of the c axes and the $\{01\bar{1}2\}$ twinned lamellae of calcite grains on the various sectors of the shear micro-folds. The patterns of fabric diagrams from the straight limb of fold are comparatively simple, while those from the knee of the fold are more complex. It is conceivable that in the knee the later shearing was too weak to obliterate completely the earlier fabric. The relationship between q-Richtungen and shear planes of a fold was also discussed.

CONTENTS

I. INTRODUCTION

It is possible, in general, to detect the process of folding from the form and the orientation of various structural elements in a rock. The method of petrofabric analysis which has been applied to the study of the tectonic history of fold, was first described by SANDER (1930, 1950). Subsequently, detailed analyses of more complicated folds have been made by various workers. Polygenetic folds, *e.g.*, shear folds followed by flexure ones, were analysed by ZOZMANN (1950), LADURNER (1954), JONES (1959), and BALL (1960). They interpreted the structure of these folds by reconstructing partially unfolded states. NUREKI (1960) examined micro-folds from banded chert and semi-pelite in the Ryôké Metamorphic Zone of Yanai, Southwestern Japan. He concluded that the pattern of quartz fabrics in folded banded chert is related to S_1, the bedding schistosity, and that in folded semi-pelite to the shear plane.

The quartz fabrics of the phyllites in the Kiyomizu Tectonic Zone, which was formed by remarkable thrusting shear movement, have been analysed on some representative specimens by KOJIMA and SUZUKI (1958). The calcite fabrics of the crystalline limestones in the Southern Marginal Belt of the Sambagawa Metamorphic Zone have been studied by the author (1962).

Based on these results, the analyses of shear micro-folds which would have occurred under the same geological conditions as reported above, will be described.

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II. METHOD OF PETROFABRIC STUDY

The method of petrofabric analysis is essentially the same as applied by LADURNER, ZOZMANN, JONES, and BALL. The folds are arbitrarily divided into several sectors throughout knees and limbs of the micro-folds. Optical orientations of quartz, calcite or sericite within each sector on thin sections were measured on the Leitz Five-Axis Universal Stage. The data so obtained were plotted on the standard SCHMIDT equal-area projection net and partial and collective diagrams based on each measurement were made.

III. THE FABRICS OF A QUARTZ-SERICITE-PHYLLITE

A micro-fold in a phyllite from the Kiyomizu Tectonic Zone is first analysed. The Zone is characterized by up-thrusting shear movement towards the south in Central Shikoku, consisting mainly of black-phyllitic rocks (KOJIMA and SUZUKI, 1958; SUZUKI, 1962).

Two types of S-planes, represented by the surfaces of mechanical inhomogeneity in rocks and inferred to have been developed during the main stage of the shear movement in the Zone, can be discriminated. The one is S_2, the surface of fracture-cleavage crossing the surface of bedding-foliation, S_1, at high angles. The axial plane of both minor and micro-fold is parallel to S_2. The other is S_{1-2}, the surface of schistosity-foliation plane of the papery schist that characterizing the Zone. It retains features of bedding-foliation, S_1, and its trend is parallel to S_2, which coincides with the axial plane of nearly recumbent folds.

The quartz fabric of the quartz-sericite-phyllite that can be inferred to have been formed during the phase of schistosity-plane, S_{1-2}, was analysed and a working hypothesis about the orientation of quartz in the rocks was presented by KOJIMA and SUZUKI (1958). In the present study, a petrofabric analysis of a phyllite characterized by a remarkable development of S_2 was carried out, and the result was compared with those regarding S_{1-2}. A rock possessing the following features was selected, that is, 1) the surface S_2, as flat and smooth as possible, 2) the micro-fold, both limbs of which are nearly parallel to each other, 3) the relic structure of bedding-foliation, S_1, and 4) no S_3, the surface of closely spaced shear cleavage, which was developed after the formation of S_2. These requirements were fulfilled by a black-phyllite collected in the Kiyomizu Tectonic Zone at Tai, Tosa, Kôchi Prefecture. The rock is quartz-sericite-phyllite, consisting of quartz, sericite, graphitic material and albitic plagioclase. The prominent planar structures are S_1 and S_2. No other planar element can be recognized. The linear structure marked distinctly on the foliation plane belongs to the *B*-lineation (L_{1-2}), representing the intersection of S_1 and S_2. A thin section cut perpendicular to the lineation (*ac*-section) was prepared. On the thin section, the author selected a micro-fold which has a symmetrical form with respect to S_2. The fold is small enough to be contained in single section. The outline of quartz grain is stretched along S_1, as shown in Fig. 1.

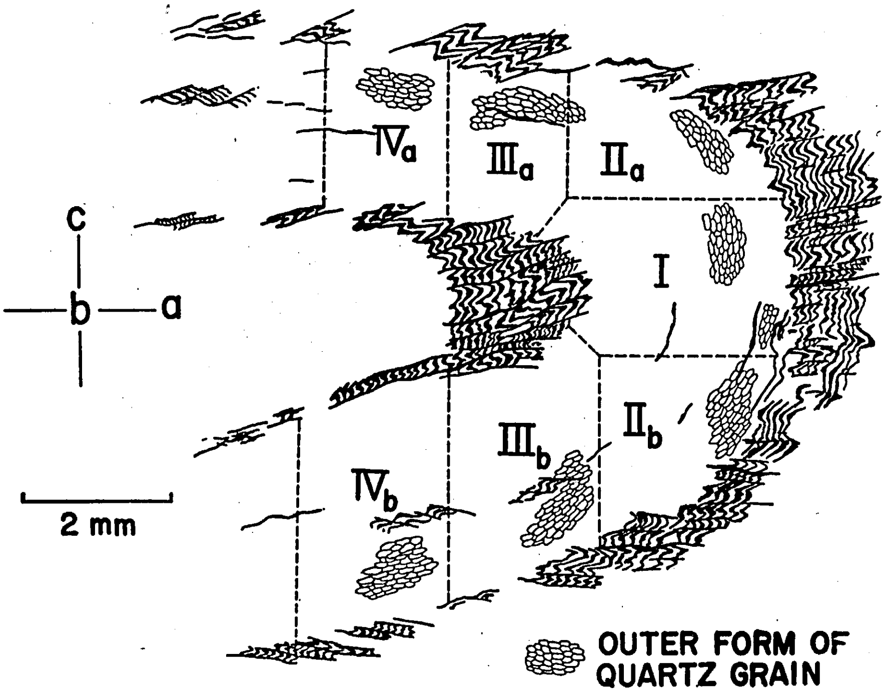

FIG. 1. Diagram of fold showing positions of seven sectors on the thin section from the quartz-sericite-phyllite at Tai.

The micro-fold was arbitrarily divided into seven sectors throughout the knee and the limbs (Fig. 1). In each sector, the crystallographic axes c of 150 quartz grains were measured without selection and several partial as well as collective diagrams based on each measurement were made. In all the diagrams the data have been plotted on the lower hemisphere of the equal-area projection and the center coincides with the fabric axis *b* (L_{1-2}). The horizontal line in the diagram is coincident with S_2 determined in the handspecimen, which is the most prominent planar structure representing the fabric plane *ab*, and the top is the normal to it.

The pattern of petrofabric diagram must be specialized by the situation and relation of girdle and maximum. In the present diagrams, the author noticed particularly 1) the difference between great circle- and small circle-girdle with respect to the girdle pattern, and 2) the maximum position of concentration and *q*-Richtungen, a straight line drawn through the main maximum and the center point of each diagram (LADURNER, 1954).

Before describing each partial diagram, the collective diagram of quartz axes will be noticed, which has been made by piling up seven partial diagrams with the fabric plane *ab* determined on the handspecimen as the common co-ordinate plane (Fig. 2). It is characterized by two girdles and two maxima in the first and third quadrant. The main girdle is a great circle-girdle which is nearly complete, including two maxima noted above. The other is a small circle-girdle which is incomplete, with lower concentration than the great circle-girdle, and its radius is 55°−75° with respect to the tectonic axis *b* (the center of the diagram), the width of the girdle being ca. 20°.

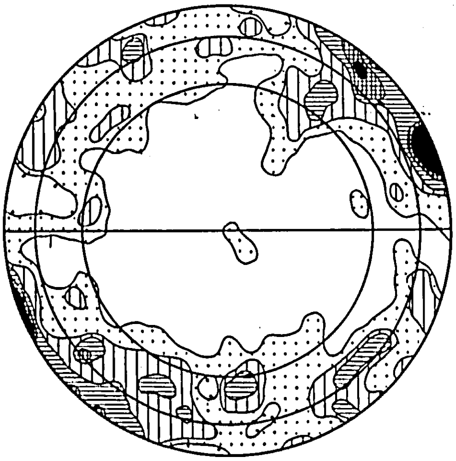

FIG. 2. Collective diagram of quartz fabrics in the folded state. 1050 c axes of quartz. Max.: 3.1 %. Contours: 3-2.5-1.5-1%.

The partial diagrams are also characterized by a great circle-girdle containing the main maxima, as shown in Figs. 3 and 4. In some of the partial diagrams a weak small circle-girdle is also developed, namely, in the sectors I, IIa and IIb with an angular radius of ca. 60° from the fabric axis *b*. There can be noticed a tendency of the small circle-girdle to appear clearer with approaching to the knee of the fold (Fig. 4) and to disappear towards the limbs, while the great circle-girdle becomes more distinct towards the limbs that are nearly parallel to S_1 to S_2,

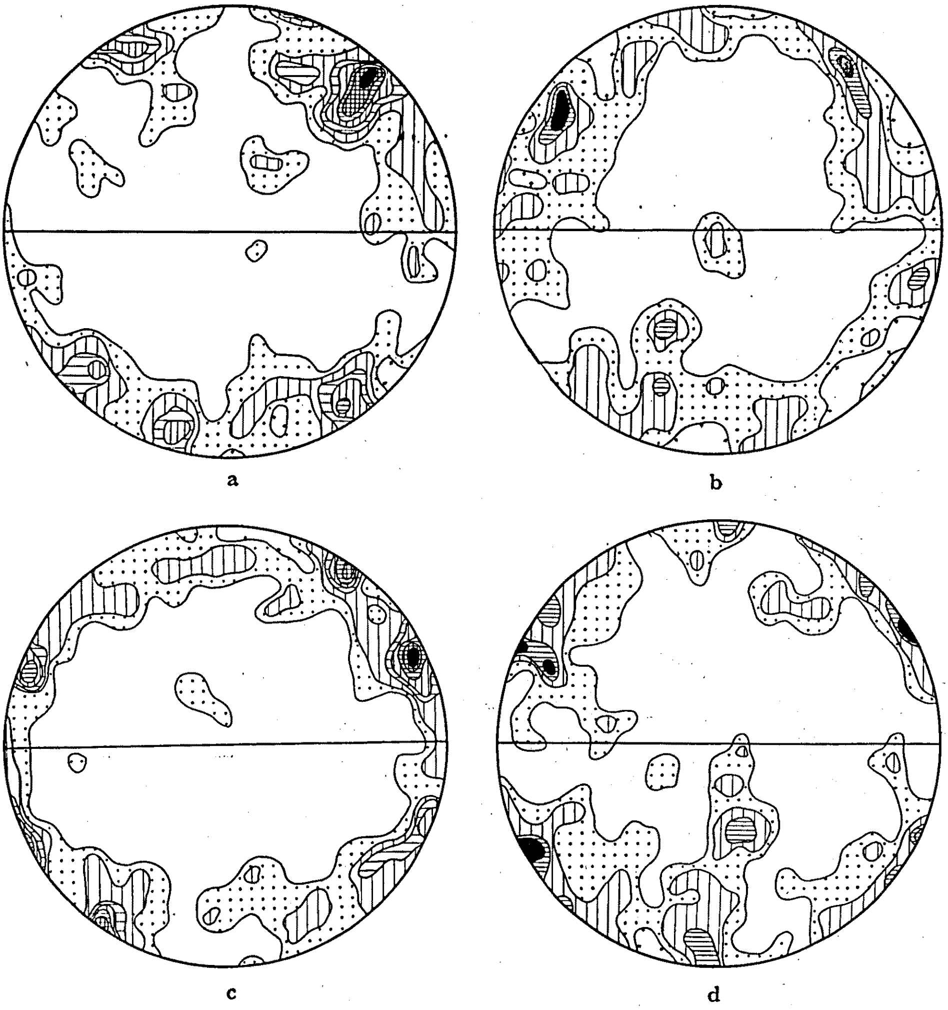

Fig. 3. Partial diagrams of quartz fabrics in the limbs of fold.

a) 150 axes from sector IVa. Max.: 7.3%. Contours: 7–6–5–4–3–2–1%.
b) 150 axes from sector IIIa. Max.: 4.7%. Contours: 4–3–2–1%.
c) 150 axes from sector IVb. Max.: 8%. Contours: 8–7–6–5–4–3–2–1%.
d) 150 axes from sector IIIb. Max.: 4%. Contours: 4–3–2–1%.

as sectors IVa and IVb (Figs. 3-a and -c). This tendency is more distinctly to be noticed, when diagrams collected from the sectors in the knee and those from the limbs are compared (Figs. 5 and 6).

The main maximum exists in the first and third quadrant on the great circle-girdle of each diagram, except the diagrams of the sectors IIIa and IIIb. Furthermore, the maxima in the diagrams of the sectors IVa and IVb which are characterized by a single distinct great circle-girdle, have remarkably higher concentra-

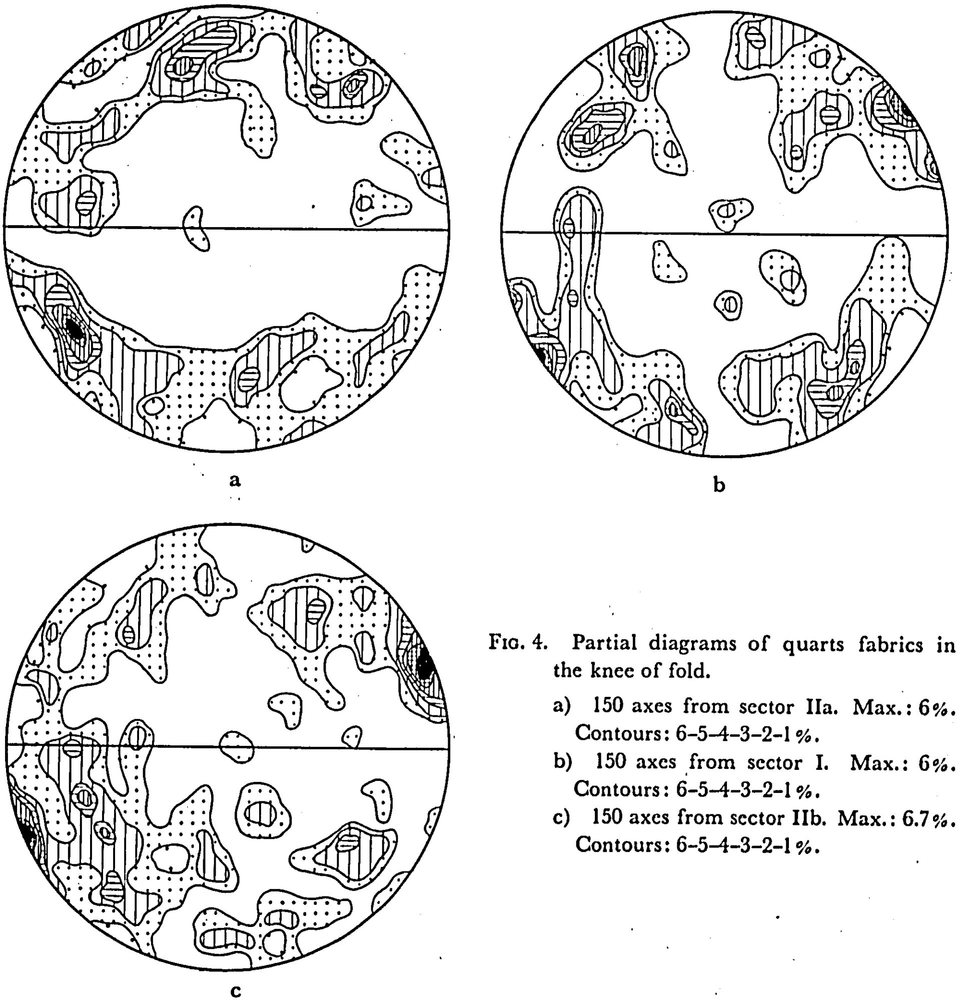

FIG. 4. Partial diagrams of quarts fabrics in the knee of fold.

a) 150 axes from sector IIa. Max.: 6%. Contours: 6-5-4-3-2-1%.

b) 150 axes from sector I. Max.: 6%. Contours: 6-5-4-3-2-1%.

c) 150 axes from sector IIb. Max.: 6.7%. Contours: 6-5-4-3-2-1%.

tion (in the sector IVa 7.3% and in the sector IVb 8%). For those cases of the sectors IIIa and IIIb, which show two q-Richtungen in the diagrams, one of the directions has been selected in accordance with the trend of q-Richtung in the other diagrams for convenience's sake. The difference of the maximum position between both limbs is the cause of the presence of two maxima in the collective diagram of Fig. 2; they are about 20° and 50° apart from the fabric axis a along the periphery. This difference becomes more distinct by comparing the collective diagram from the sectors of the upper limb (IIa, IIIa and IVa) with that of the lower limb (IIb, IIIb and IVb), as shown in Figs. 7 and 8; *viz.*, the q-Richtung in the upper limb and that of the lower limb are nearly constant in direction within respective part of the fold, and arranged asymmetrically to the fold co-ordinate ab. When the fold is completely unfolded, the angle between the q-Richtung and

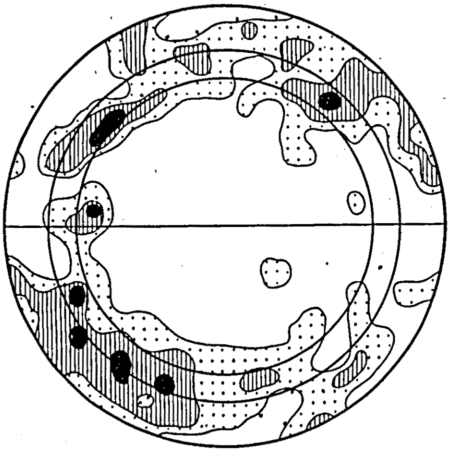

FIG. 5. Collective diagram of quartz fabrics from three sectors (I, IIa and IIb) in the knee of fold.

450 axes. Max.: 3.15%. Contours: 3-2-1%.

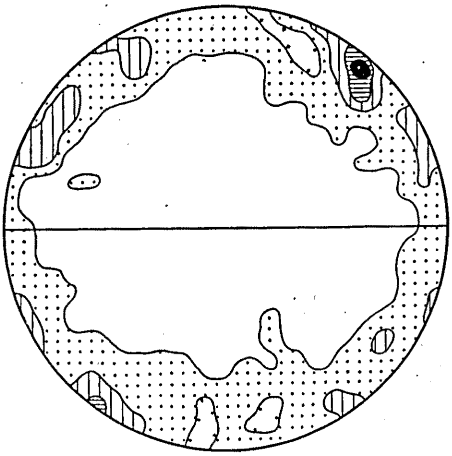

FIG. 6. Collective diagram of quartz fabrics from four sectors (IIIa, IIIb, IVa and IVb) in the limbs of fold.

600 axes. Max.: 4%. Contours: 4-3-2-1%.

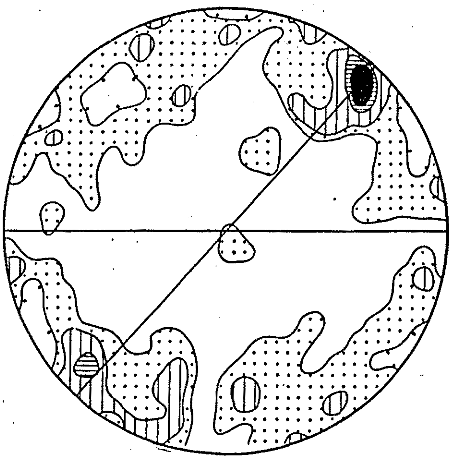

FIG. 7. Collective diagram of quartz fabrics from sectors IIa, IIIa and IVa.

450 axes. Max.: 4.2%. Contours: 4-3-2-1%.

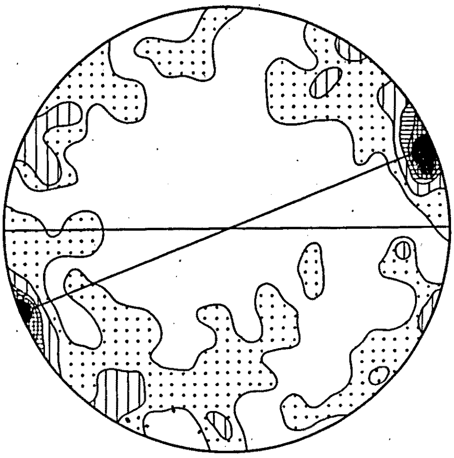

FIG. 8. Collective diagram of quartz fabrics from sectors IIb, IIIb and IVb.

450 axes. Max.: 5.7%. Contours: 5-4-3-2-1%.

the tangent of the fold is not constant as shown in Fig. 9; therefore, the fold is "non-unrollable", or "unabwickelbar" after ZOZMANN (1950).

This fact indicates that the q-Richtung was developed after the bending to form a heterogeneous fabric and the later shear has obliterated the fabric of the earlier flexure. It is worthy of attention, however, that the collective diagram in the un-

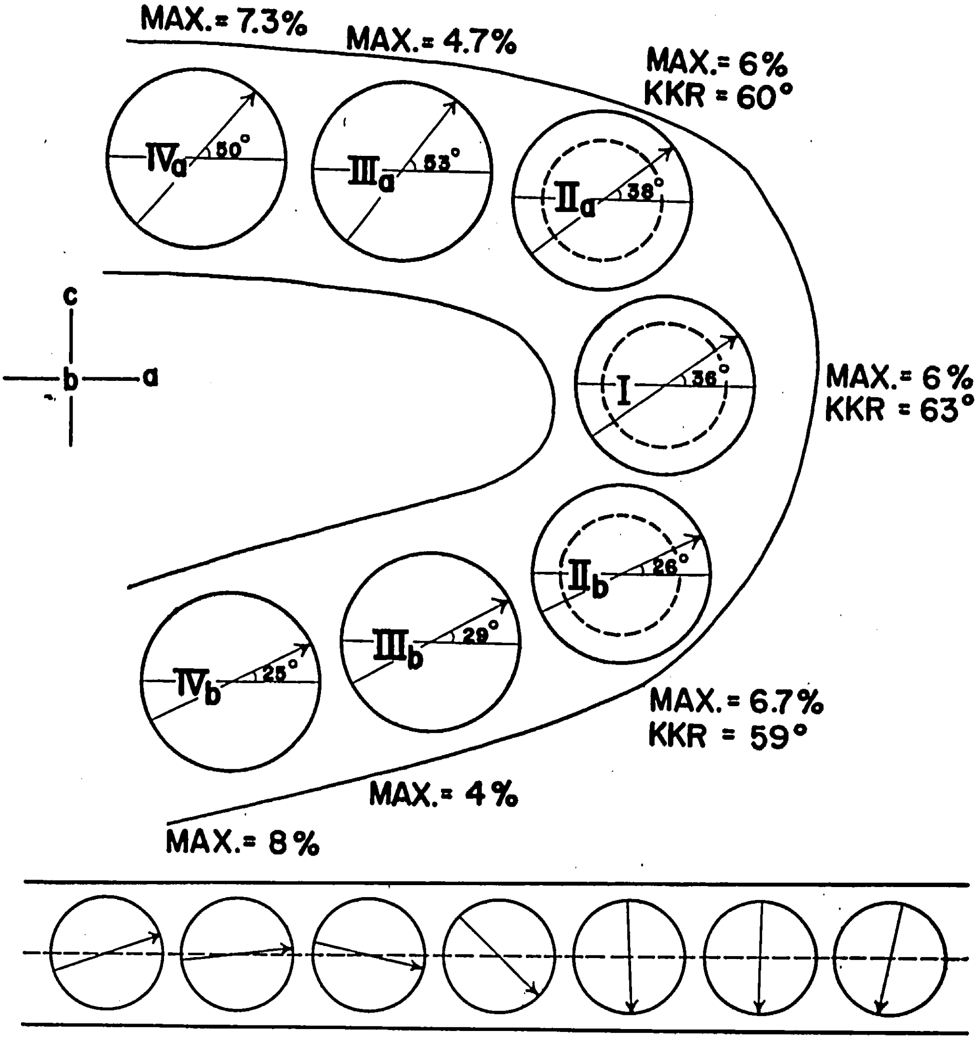

FIG. 9. Relationship of q-Richtungen to the fold.
KKR = the small circle-girdle (Kleinkreis)
Lower figure shows the q-Richtungen in the completely unfolded state.

folded state (Fig. 10) shows two distinct maxima on the small circle-girdle. The tendency is that the small circle-girdle is remarkable in the knee of the fold and disappears in the limbs as described above. It is conceivable that the small circle-girdle represents a relic fabric imprinted before the shear movement along S_2, from the following reasons. That is,

1) The collective diagram in the unfolded state has more distinct small circle-girdle and more remarkable maxima on the girdle than that for the fold in its present form (compare Figs. 2 and 10).
2) The small circle-girdle in the partial diagrams appears distinctly in the

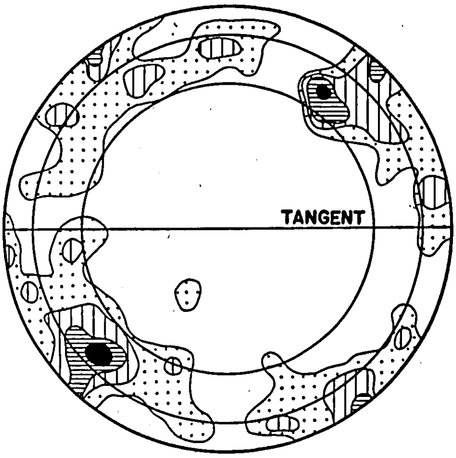

Fig. 10. Collective diagram of quartz fabrics in the completely unfolded stage. Tangential plane of S_1 is right and left. 1050 c axes. Max.: 2.75%. Contours: 2.5–2–1.5–1%.

knee in which the shear movement may have been relatively weak.

3) The fabric diagram of quartz in the black-schists of the Sambagawa Metamorphic Zone Proper near the Kiyomizu Tectonic Zone shows a pattern having a small circle-girdle with maxima at the IV and VI positions regarding the bedding-foliation, S_1, after Fairbairn's notation (1949).

It is doubtless that the main maxima of the partial diagrams represent the fabric with regard to the formation of S_2, because quartz axes show a distinct concentration with a definite relation to the shear movement on S_2. Although the outline of quartz grain is stretched parallel to S_1 not only in the limbs but also in the knee, as shown in Fig. 1, its fabric has a close relationship with S_2. Accordingly, it is obvious that quartz axes have rotated internally during the main stage of the shear movement in the Kiyomizu Tectonic Zone.

The author has applied to this example the working hypothesis about orientation of quartz in the flow of rocks by Kojima and Suzuki (1958); r$(10\bar{1}1)$ and/or z$(01\bar{1}1)$ of quartz lie on the shear plane and the sense of displacement of upper layers on these lattice planes is downward from the c axis. As shown in Fig. 1, closely spaced shear planes, arranged more or less divergent from the knee of the fold, are well developed in each sector. Accordingly, they are oblique in some degrees to the fold co-ordinate *ab*, parallel to S_2. Moreover, it is noticed that they are distinctly oblique to the longest dimension of the stretched quartz grain. They are termed S'_2. On the other hand, the common orientation rule for micas is that its (001) cleavage plane lies on the *S*-plane, with the c axis normal to the *S*-plane (Sander, 1930). Although the sericitic mica diagram in the knee is disordered and has several maxima in the complete *ac*-girdle (Fig. 11-b), in both limbs it has a maximum near the pole of bedding-foliation, S_1, on the incomplete girdle (Figs.

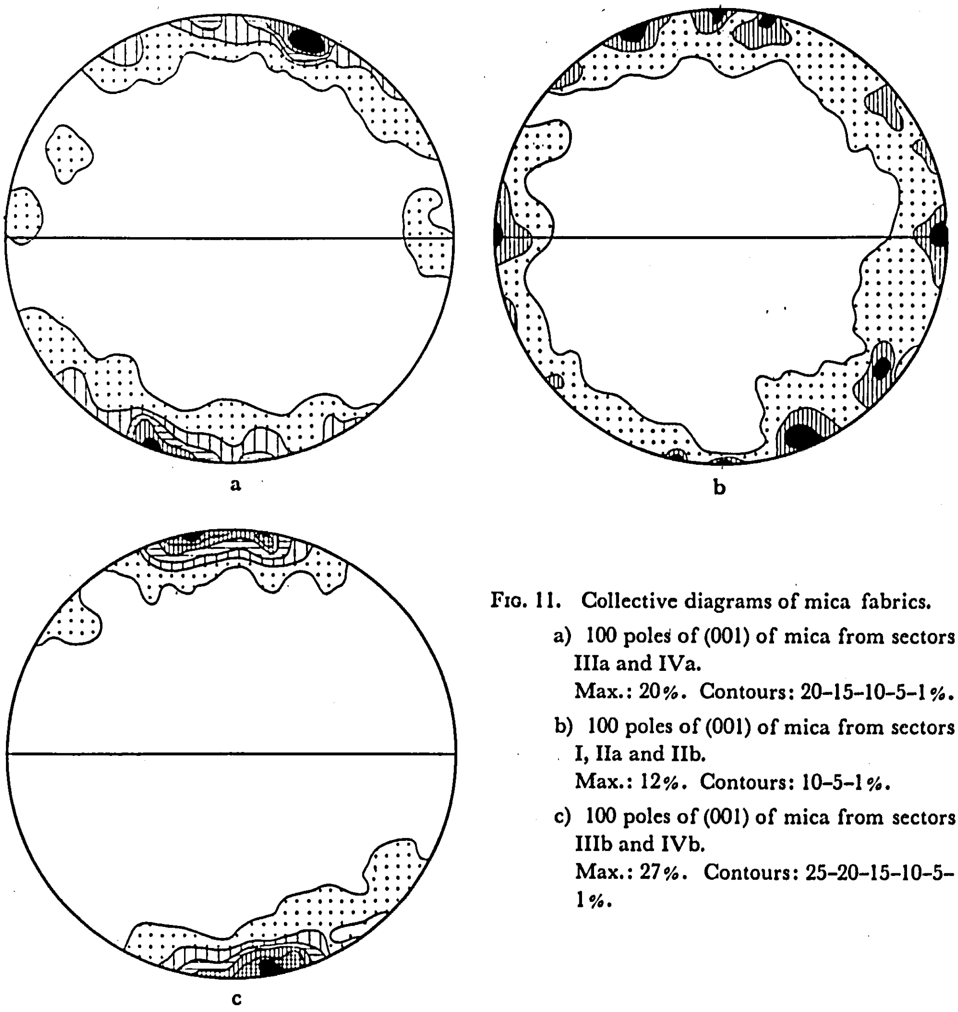

Fig. 11. Collective diagrams of mica fabrics.

a) 100 poles of (001) of mica from sectors IIIa and IVa.
Max.: 20%. Contours: 20–15–10–5–1%.

b) 100 poles of (001) of mica from sectors I, IIa and IIb.
Max.: 12%. Contours: 10–5–1%.

c) 100 poles of (001) of mica from sectors IIIb and IVb.
Max.: 27%. Contours: 25–20–15–10–5–1%.

11-a and -c). In the diagrams of both limbs there are sub-maxima near the pole of the divergent *S*-planes, S'_2, described above. Accordingly, the definite relationship between the *q*-Richtungen and the divergent S'_2 is explicable according to the working hypothesis and the asymmetrical arrangement of the *q*-Richtung in the both limbs can also be understood.

IV. THE FABRICS OF A CRYSTALLINE LIMESTONE

Petrofabric studies on the crystalline limestones from the Southern Marginal Belt of the Sambagawa Metamorphic Zone in Central Shikoku were reported by the present author (SUZUKI, 1962). The specimens analysed in his paper, however, are unfolded ones with no planes other than the bedding-foliation, S_1. In order to study the relationship between calcite orientation and fold, a folded crystalline limestone was selected from the Southern Marginal Belt at Motoyama, Nagaoka-gun, Kôchi Prefecture.

The specimen is characterized by a shear micro-fold of more larger scale than that of the quartz-sericite-phyllite described above. The fold is symmetrical in form with respect to the axial plane, to which the closely spaced shear cleavage, S_3, is parallel. The interval between adjoining cleavage surfaces is of the order of 0.2 mm. The bedding-foliation plane has been displaced in some degree by the slip movement along S_3, that showing the style of typical cleavage fold. The cleavage plane S_3 is almost vertical as shown in Fig. 12.

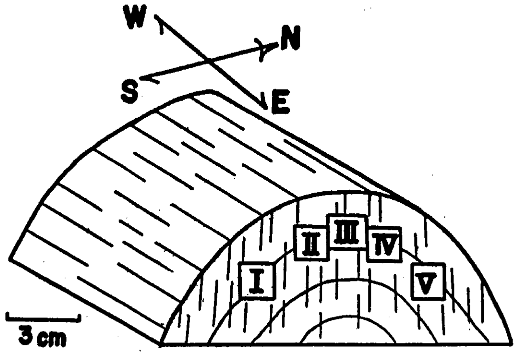

FIG. 12. Location of five sectors selected from three thin sections of the crystalline limestone at Motoyama.

Three specimens were collected from three parts of the fold. The sampled part of the southern limb of the fold strikes N 88° W and dips 44° to S, and that of the northern limb N 67° E and 50° to NW. The lineation representing the intersection of S_1 and S_3 develops distinctly on S_1 and its trend is nearly S 80° W and it plunges to the west with a low angle (about 10°). Three thin sections cut perpendicular to the lineation were prepared from the limbs and knee. The micro-fold on the thin section made from the knee was arbitrarily divided into three sectors (Fig. 12)*.

The rock is grayish and consists almost exclusively of monomineralic aggregate of calcite with accessory amounts of quartz, albite, sericite and chlorite. Orientations of the optic axes and the poles of visible completely twinned $\{01\bar{1}2\}$ lamellae of calcite from each thin section were directly measured. The axes of compression and tension most favourably oriented with respect to the orientation of each $\{01\bar{1}2\}$ twin (HANDIN and GRIGGS, 1951; TURNER, 1953; SUZUKI, 1962) were diagrammatically determined on the SCHMIDT net from the measured data. In all

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* After K. A. JONES (1959), "Experience suggests that the fabric of the straight flanks of a fold is homogeneous and only one diagram need be made in these areas. However, the curved axial area of a knee of a fold should be as finely sub-divided as possible".

the diagrams the center coincides with the lineation and the diagrams are so located as one looks westward. Geographical orientation is given by the horizontal curve of dashed line in the diagram.

In each sector, the crystallographic axes c of 160 to 300 calcite grains were measured without selection and five diagrams were prepared from each sector (Fig. 13). The general characters of each diagram are also exhibited by a complete great circle-girdle including a maximum or two maxima. In the case of flexure fold, main maxima must be approximately co-linear when the fold is unfolded. In the present case, no correspondence exists in the position of the equivalent maxima with respect to the common tangent. Accordingly, the fabric is "non-unrollable" ("unabwickelbar" after ZOZMANN, 1950). Moreover, although the individual *q*-Richtung lies nearly symmetrically to the axial plane of the fold at the completely unfolded state, they are divergent from the knee of the fold. So it is impossible to interpret the fabric of the fold by reconstructing in partially unfolded state.

In the diagrams of both limbs (Figs. 13-d and -e), the positions of maximum on the *ac*-girdle are nearly perpendicular to the closely spaced shear cleavages S_3 and their patterns are comparatively simple. On the other hand, the patterns in the diagrams of the knee are more complex, though they show *ac*-girdle including maxima and sub-maxima. Namely, the maximum in the diagram of the top of the fold (sector III) shows lower degree of concentration, 7.4% for the maximum from the sector III, while in other sectors the maximum concentration amounts to 11 to 14%, and it lies near the pole of curved S_1 (Fig. 13-a). Furthermore, there are sub-maxima in the positions near the poles of curved S_1 and S_3. The diagrams from the II and the IV sector, which belong to the same thin section along with the sector III (Figs. 13-b and -c), indicate that the areas showing high degree of concentration lie between poles of S_1 and S_3 in the *ac*-girdle and the maxima or sub-maxima are present near the poles of S_1 and S_3.

Judging from the facts mentioned in this paper and the results of the former paper of the author (SUZUKI, 1962), it is conceivable that each maximum and sub-maximum represent the fabrics related to the planer elements perpendicular to them. It is of course possible that the shear folding was preceeded by flexural slip and that the later shear has largely obliterated the fabric of the earlier flexure in the limbs, as verified in the other cases already studied.

Next, optically recognizable twinned lamellae on $\{01\bar{1}2\}$ was studied on five sectors of the fold. The applied stress axes most favourably oriented to effect the observed twinning were diagrammatically determined on 35 to 43 grains with the $\{01\bar{1}2\}$ twinned lamellae from each sector, and plotted as shown in Fig. 14. As the c axes of the calcite crystals show a remarkable tendency to orient themselves normal to the lineation as shown in Fig. 13 and the angle between the pole of $\{01\bar{1}2\}$ lamella and the c axis of calcite crystal is rather small ($26\ ^1/_4°$), the majority of $\{01\bar{1}2\}$ lamellae must be situated on the measurable positions on the

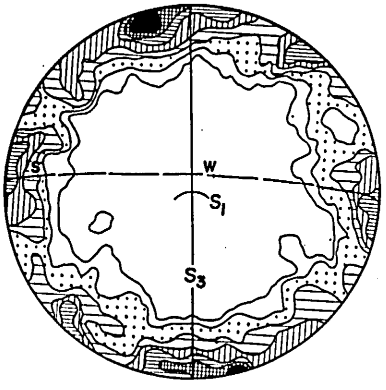

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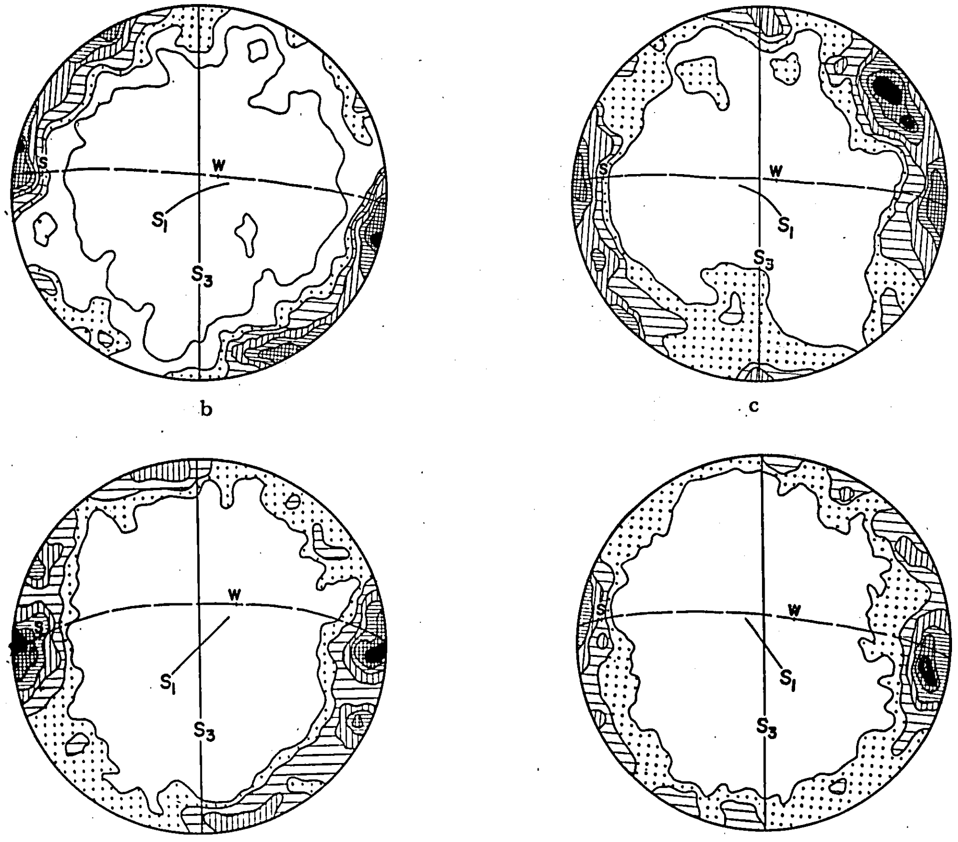
Fig. 13. Partial diagrams of calcite fabrics in five sectors. The geographically horizontal plane through south (S) and west (W) is shown by dashed curves.
a) 300 c-axes of calcite from sector III.
Max.: 7.4%. Contours: 7-6-5-4-3-2-1%.
b) 160 c-axes of calcite from sector II.
Max.: 13%. Contours: 12-10-8-6-4-2-1%.
c) 200 c-axes of calcite from sector IV.
Max.: 11%. Contours: 10-8-6-4-3-1%.
d) 200 c-axes of calcite from sector I.
Max.: 14%. Contours: 12-10-7-5-3-1%.
e) 210 c-axes of calcite from sector V.
Max.: 13.5%. Contours: 13-10-8-5-3-1%.



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universal stage, only when the *ac*-section perpendicular to the lineation is used.

The concentrated positions of the compression and the tension axis in each diagram do not show constant relationship with the direction of the bedding-foliation

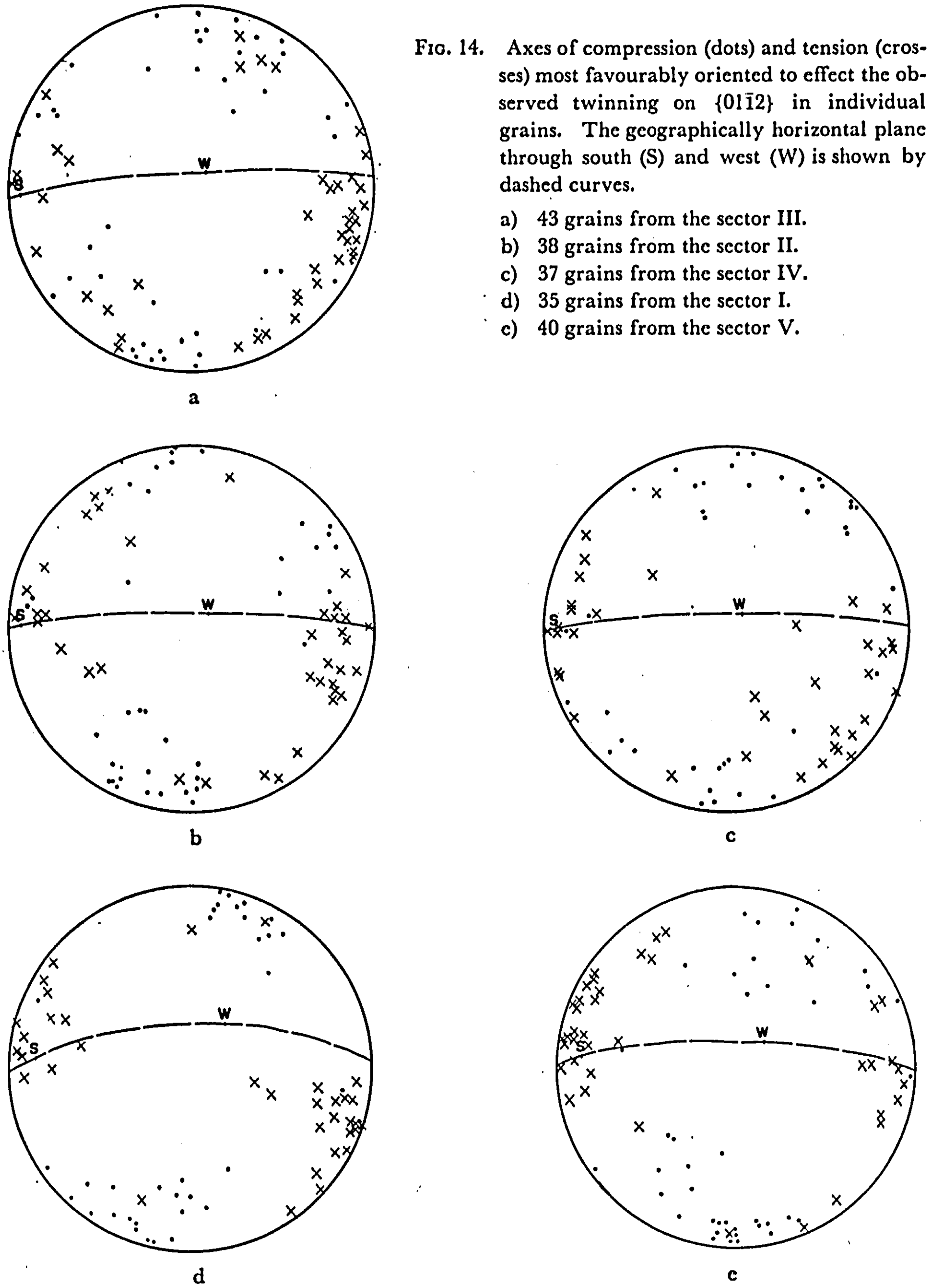

FIG. 14. Axes of compression (dots) and tension (crosses) most favourably oriented to effect the observed twinning on {01$\bar{1}$2} in individual grains. The geographically horizontal plane through south (S) and west (W) is shown by dashed curves.

a) 43 grains from the sector III.
b) 38 grains from the sector II.
c) 37 grains from the sector IV.
d) 35 grains from the sector I.
e) 40 grains from the sector V.

(S_1). It is, however, obvious that there is a remarkable relationship between the concentrated positions of the applied stress axes and the geographical co-ordinates, namely, the position of the compression axis is nearly perpendicular to the horizontal plane or makes a high angle with it, while, that of the tension axis is parallel to the horizontal plane or lies at a small angle to it. The tendency becomes more distinct in the diagrams rotated as the primitive circle of the diagram coincides with the geographical horizontal plane. Fig. 15 has been made by plotting all the compression and tension axes in five sectors of the fold. Although the diagrams show an incomplete great circle-girdle parallel to *ac*, the maximum position of the compression axis is nearly perpendicular to the horizontal plane, the azimuth being S with the plunge angle of 80°, while, that of the tension axis lies in N-S direction within the horizontal plane. This tendency is almost coincident with the pattern of crystalline limestones from the Motoyama-Jizôji area (SUZUKI, 1962).

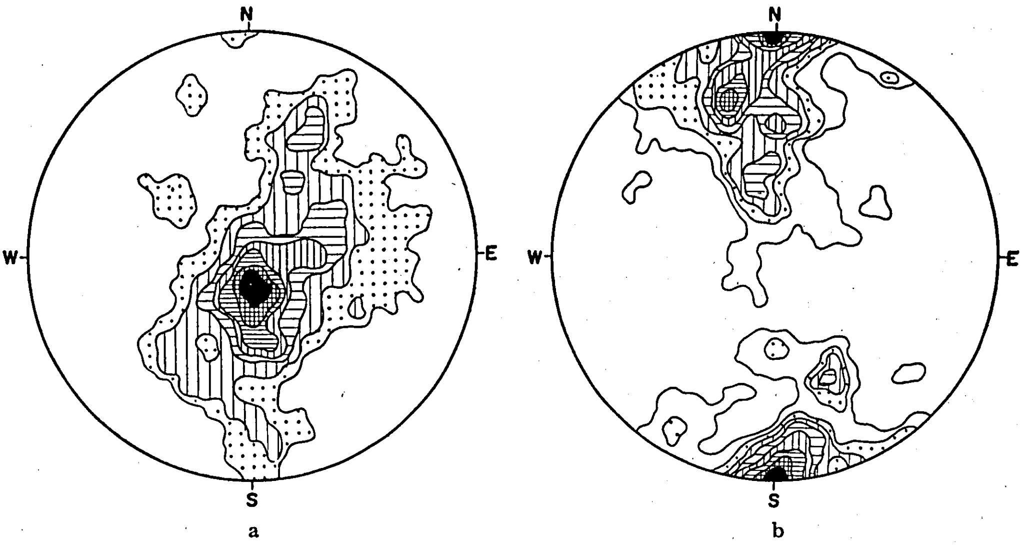

FIG. 15. Stress axes diagrams rotated into the geographically horizontal plane. Plane of projection is geographically horizontal.

a) 192 axes of compression.
Max.: 11.5%. Contours: 10-8-6-5-3-2-1%.

b) 192 axes of tension.
Max.: 12.5%. Contours: 10-8-6-5-4-3-2-1%.

Judging from the facts described above, it can well be concluded that the fabrics show remarkable homogeneity with respect to the direction of stress axes at the stage of formation of the {01$\bar{1}$2} twinned lamellae within the scale of the fold studied. Furthermore, it is evident that the twinning on {01$\bar{1}$2} is related to the later phase of movement after the folding. It can also safely be said that the fabric axis *b* has remained the same during deformation.

Although the concentration of the applied stresses appear to have intimate relation with the direction of the closedly spaced shear cleavage, S_3, namely, the maximum in the diagram of compression axis lies near or within S_3 and that of tension axis almost perpendicular to S_3, the coincidence can not be explained neither with the shear on S_3 nor with the compression perpendicular to S_3, as suggested by the style of the closely spaced cleavage. Therefore, it is most probable that the twinned lamellae have been formed at a later phase of stress than the cleavage.

V. Concluding Remarks

The author has divided a fold into several sectors and analysed the fabric within individual sectors. It is proved to be rather successful for understanding the essential features of fabric pattern of a fold to make collective diagram by piling up partial diagrams.

From the analyses of two samples described, complex pattern of the diagrams from the knee of the fold is regarded as indicating the complexity of movement at the knee. Shear movement is difficult to occur along the bedding-foliation surface at the later stage of deformation, because the bedding-foliation is often cut by cleavage S'_2 or S_3. Therefore, it is conceivable that the fabrics in the knee of the fold indicate superposition of the relic fabrics at the earlier stage of folding and the fabrics with respect to shear movement along S'_2 or S_3 which was formed at the main stage of folding.

On the other hand, the pattern of the diagrams from the limbs of a fold is rather simple. It is considered to show that the shear movement along S'_2 or S_3 was so intense that the earlier fabrics were completely obliterated.

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