Title	Preferred Lattice Orientation of Quartz in Shear Deformation
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Citation	Journal of science of the Hiroshima University. Series C, Geology and mineralogy , 7 (1) : 1 - 10
Issue Date	1973-03-25
DOI	
Self DOI	10.15027/53047
URL	https://ir.lib.hiroshima-u.ac.jp/00053047
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Preferred Lattice Orientation of Quartz in Shear Deformation

By

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with 7 Text-figures and 1 Plate

(Received October 14, 1972)

ABSTRACT: The quartz fabrics of shear belts in granite of the Teshima district, Kagawa Pref., Japan, have been examined, in order to understand the nature of preferred lattice orientation of quartz developed by shear deformation. The strains in the shear belts are referred to the type of two dimensional strain with rotation. The stable pattern of the c-axis fabric of quartz in the shear belts appears in shear strain larger than ca. 1.80 and is characterized by two maxima with wide spreading on "pseudo-two-girdle", showing approximately orthorhombic symmetry whose symmetry planes are parallel to the principal planes of the strain ellipsoid of mean strain of the system concerned. The positions of two maxima coincide with the intersecting points of the "pseudo-two-girdle" which are situated on the plane containing the shortest and the intermediate principal axes of strain ellipsoid at the angle of ca. 30° to the latter axis. The one component girdle of the "pseudo-two-girdle" is a partial great-cicle girdle containing the two maxima and the intermediate principal axis, and the other component girdle would be regarded as two crossed small-circle-like girdles, which cut across the plane of the longest and the shortest principal axes of the strain ellipsoid at the angle of ca. 40° to the latter axis, and whose intersecting points correspond to the positions of the two maxima. It has been concluded that the c-axis fabrics of quartz in the shear belts are mainly determined by the principal strain.

CONTENTS

I. INTRODUCTION

In rotational strain the principal axis of strain rotates with process of deformation and so parallelism of the principal axes of stress and strain does not occur in larger deformation. Which determines the preferred lattice orientation of quartz developed in rotational strain, the principal stress or the principal strain? Is there any relationship between the preferred lattice orientation developed in non-rotational strain and that in rotational strain? Now, we have not yet any available answer to those questions.

The authors found shear belts (mylonite zones) in granite of the Teshima district, Kagawa Pref., Japan, which are commonly less than 10 cm in width and more than a few meter in length, and which occur in conjugate sets. Nature of preferred lattice orientation of quartz in those shear belts will be described and discussed in this paper. The obtained data may give an answer to the above-described questions.

Acknowledgements: The authors have benefited greatly from the continuous encouragement and interest discussion provided by Prof. G. KOJIMA.

II. ANALYSIS OF STRAIN PICTURE IN SHEAR BELTS

Shear belts in the Teshima granite occur in conjugate sets (Fig. 1–a). In those shear belts there is single set of schistosity, which is defined by preferred dimensional orientation of quartz and mica flakes, and on which a lineation defined by preferred orientation of mica flakes develops. The schistosity is oblique to the trend of the shear belt, forming a curviplanar structure (Plate 1). The axis of curvature is in a direction parallel to the intersecting line of the schistosity and the trend of the shear belt. The lineation is normal to the axis of curvature of the schistosity and also to the intersecting line of the conjugate sets of shear belts (Fig. 1–b).

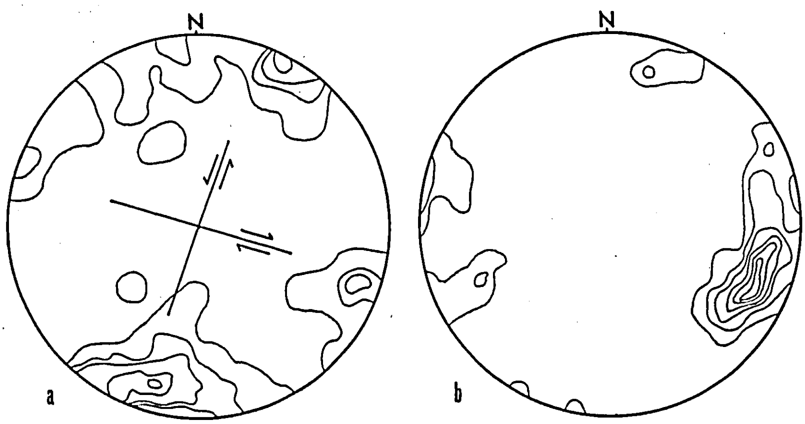

Fig. 1. Orientation data of shear belts in the Teshima granite.
a) Diagram for 75 poles of shear belts. Contours: 1.3–4–7–12–16%.
b) Diagram for 34 lineations in 34 shear belts. Contours: 3–6–9–12–15–18.
Arrows show sense of shear movement along shear belts.

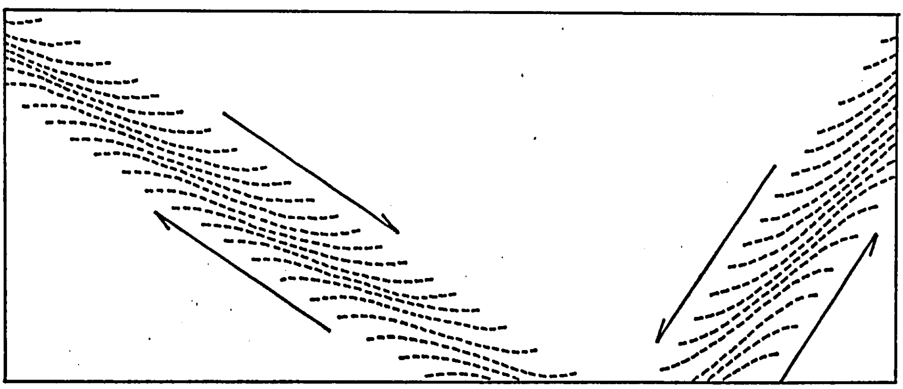

Fig. 2. The relationship between the schistosity and the sense of shear movement in the shear belts. Dashed lines: schistosity.

The features of structure in the shear belts will be further examined on the basis of statistical analysis of dimensional orientation of quartz, which is performed by the method of HARA (1966), in order to understand the strain picture in them. The results obtained from three small specimens (three shear belts), which show most of the features seen in the shear belts in the Teshima granite, will be described and discussed in the following paragraphs.

In the examined specimens the host granites show no preferred dimensional orientation of constituent minerals but isotropic fabric. Preferred dimensional orientation of quartz grains appears in the shear belts. Quartz grains in the belts appear to be commonly referred to as small secondary grains recrystallized in large quartz grains. As observed on the thin section (ac-section) normal to the schistosity and parallel to the lineation, the vector magnitude of grain orientation increases with positional change from the host granite to the center of the shear belt. The highest vector magnitude of grain orientation is generally measured in the center of the shear belt (Fig. 3–c). The boundary between the host granite and the shear belt is not so clearly defined. The trajectories of positions in which the statistically significant grain orientation first appears on the way passing from the host to the shear belt approximate to a straight line parallel to the trend of the shear belt. This line does not correspond to the outer limit of the shear belt but lies within the shear belt, because quartz grains outside the line appear to be deformed. For convenience's sake, the line will be named the apparent boundary of the shear belt. In the individual shear belts, the nature of the variation in vector magnitude of grain orientation with distance across the belt is approximately equal between different cross sections.

On the ac-section, the directions of grain orientation (=schistosity) are oblique to the apparent boundary of the shear belt (Plate 1). The angle θ between the former and the latter is generally smaller than 45° and decreases gradually towards the center of the shear belt. Near the apparent boundary, generally, θ is between 45° and 40°. In the individual shear belts, the nature of the variation in θ with distance across the belt is approximately equal between different cross sections. Decrease of θ, which corresponds to positional change from the host to the center of the shear belt, is correlated with increase of intensity of preferred dimensional orientation of quartz, which corresponds to increase of intensity of development of schistosity. Fig. 2 illustrates the relationship between the schistosity and the sense of shear movement in the shear belts of conjugate sets.

On the thin section parallel to the schistosity cut from the center of the shear belt, quartz grains show also preferred dimensional orientation. The orientation direction is parallel to the lineation. Therefore, it can be pointed out that the average shape of quartz grains in the center of the shear belt is referred to a triaxial ellipsoid with the longest axis parallel to the lineation, which lies on the plane containing the direction of shear and the normal to the belt, and the intermediate axis parallel to the axis of curvature of schistosity.

The nature of development of the schistosity in the shear belts in the Teshima granite appears to be essentially the same as the cases of RAMSAY *et al.* (1970). They (1970, p. 786) clarified the following points: "The schistosity appears to be formed perpendicular to the principal finite shortening (i.e. perpendicular to the shortest axis of the finite strain ellipsoid). Variations of the schistosity planes represent variations in the finite strain trajectories of XY plane in the strain states ($X \geqslant Y \geqslant Z$ ellipsoid axes). The

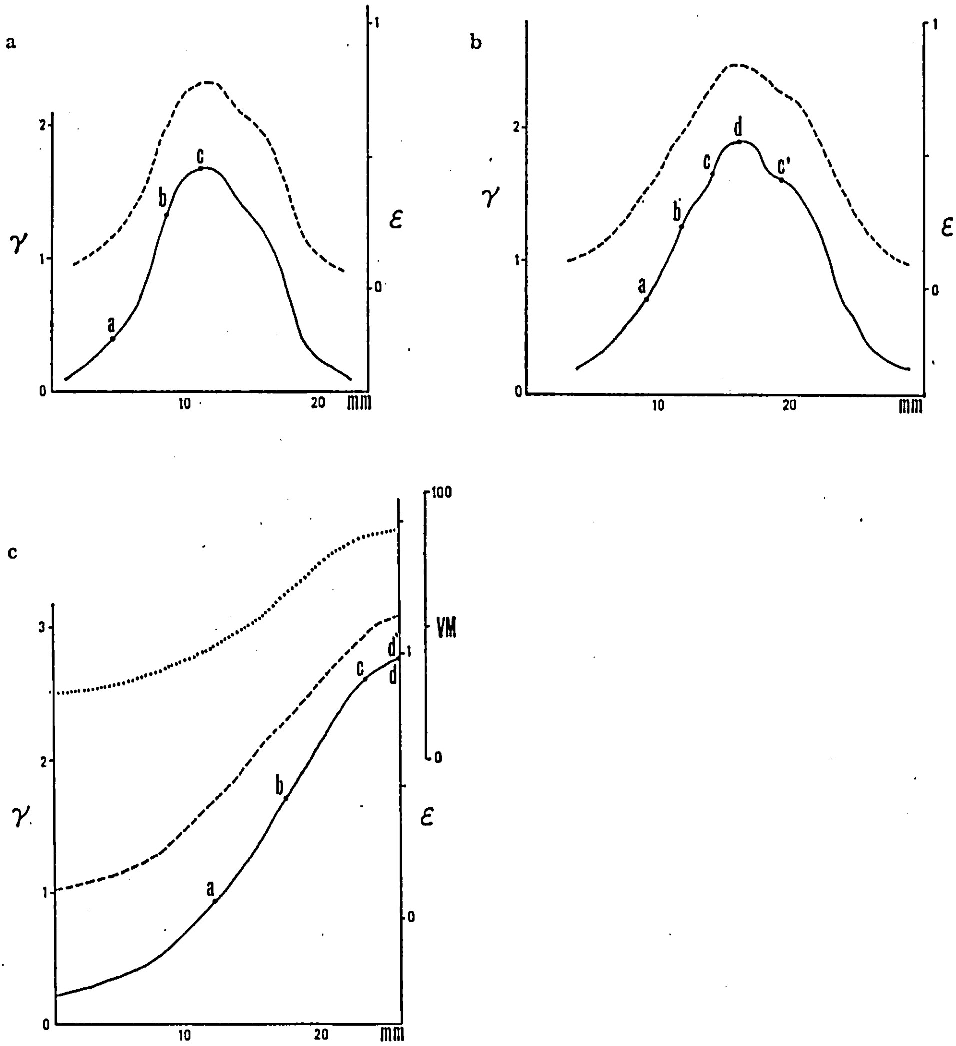

Fig. 3. Diagram showing the variation in γ, ε and VM (vector magnitude of grain orientation) with distance across shear belt for the three specimens (in diagram c, a half of shear belt).
Solid lines: γ. Dashed lines: ε. Dotted line: VM.
a, b, c, c′, d and d′: positions of measurement of c-axis fabric of quartz.

intensity of development of the schistosity is correlated with the values of the principal finite strains." And such the variation in deformation in the shear belt is accounted for by variable simple shear across the belt. Hara *et al.* (1968) and Hara *et al.* (1971) pointed out that the average shape of small secondary quartz grains recrystallized in large quartz grains during the deformation is conformable with the shape of strain ellipsoid of mean strain of the domain concerned. The vector magnitude of dimensional orientation of quartz grains in a homogeneously deformed domain increases with increase of the principal finite strain of the domain (HARA, 1966; HARA *et al.*, 1968). Thus, it will be said that the above-described structural features of the shear belts in the Teshima granite is clearly interpreted by Ramsay et al.'s terms cited above. The strain at a point in the shear belt will be referred to two dimensional strain with rotation, in which the longest principal axis X of the strain ellipsoid is parallel to the lineation.

The angle θ is a function of the amount of shear and the value of shear strain γ at a point in the shear belt is estimated by θ: $\tan 2\theta = 2/\gamma$ (RAMSAY *et al.*, 1970). The variation in θ with distance across shear belt for the present specimens is shown in Fig. 3. In the individual specimens it is approximately equal between different cross sections. In simple shear the principal finite strain increases with increase of shear strain γ:

$$\sqrt{\lambda_1},\ \sqrt{\lambda_2} = \sqrt{(\gamma/2)^2+1} \pm (\gamma/2), \qquad 2\in = l_n\sqrt{\lambda_1/\lambda_2},$$

where ε is the principal natural strain and λ_1 and λ_2 are the principal quadratic elongations of the strain (GAY, 1968). The variation in the principal natural strain with distance across shear belt for the present specimens is also illustrated in Fig. 3. The maximum values of the shear strain and the principal finite strain are found in the center of the shear belt.

The average size of quartz grains in the shear belts appears to decrease with positional change towards the center of them, reflecting the correspinding increase of intensity of shear stress. Biotite flakes in the shear belts show greenish tint, while those in the host granite brownish tint. The temperature at the stage when the deformation related to the formation of the shear belts occurred, appears to be lower than that at the stage when granitic magma consolidated, judging from the color of biotite flakes in the shear belts (cf. MIYASHIRO, 1965).

III. ANALYSIS OF PREFERRED LATTICE ORIENTATION OF QUARTZ

The finite strain state varies from place to place in the shear belt. Therefore, the c-axis fabric of quartz in the shear belt must be measured in very small domain in which the deformation related to the formation of the fabric approximates to a homogeneous strain, i. e. the value of shear strain is approximately constant.

In the host granite of the three examined specimens is not found any preferred orientation of c-axes of quartz, as shown in Fig. 4. While quartz grains in the shear belts show preferred orientation of c-axes (Figs. 5, 6 and 7), though near the apparent boundary the c-axis fabric approximates to the isotropic fabric. The intensity of preferred orientation of c-axes increases with positional change towards the center of the shear belt, which corresponds to increase of shear strain and principal finite strain, showing gradual change of fabric pattern.

When the value of shear strain γ is smaller than 1.30, the fabric pattern appears to be different between different cross sections for the individual shear belts, showing that the fabric is not significant. When γ becomes slightly larger than 1.40 on the way passing from the host to the center of the shear belt, generally, the c-axis fabric begins to show such a fabric pattern as referred to the type of "pseudo-two-girdle" of SANDER (1950). The intersecting points (M_1 and M_2) of the "pseudo-two-girdle" lie on the plane containing the shortest principal axis Z and the intermediate principal axis Y of the strain ellip-

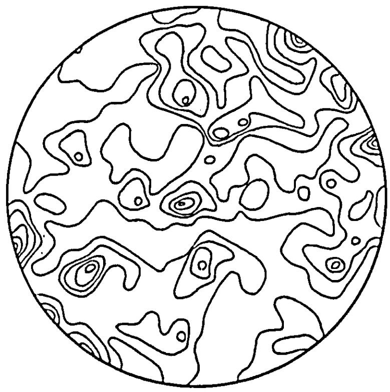

Fig. 4. c-Axis fabric of 200 quartz grains in the host granite.

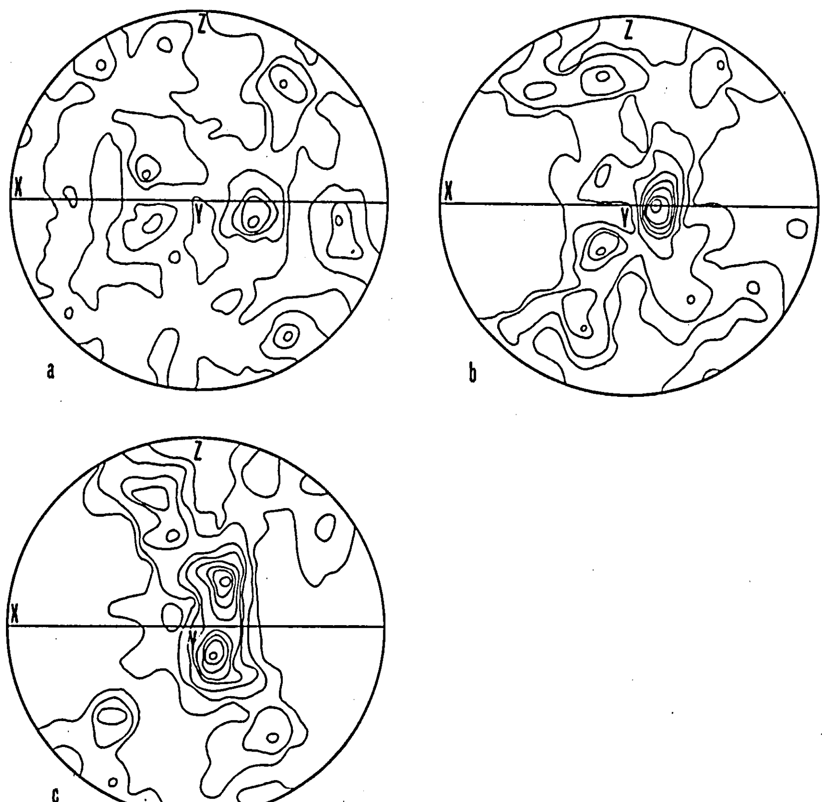

Fig. 5. c-Axis fabrics of quartz in the shear belt of Fig. 3-a.
a: Data from position a in Fig. 3-a. Contours: 1-2-3-4-5%.
b: Data from position b in Fig. 3-a. Contours: 1-2-3-4-5-6-7-8%.
c: Data from position c in Fig. 3-a. Contours: 1-2-3-4-5-6-7-8%.
X, Y and Z: the principal axes of strain.
In each position 200 quartz grains were measured.

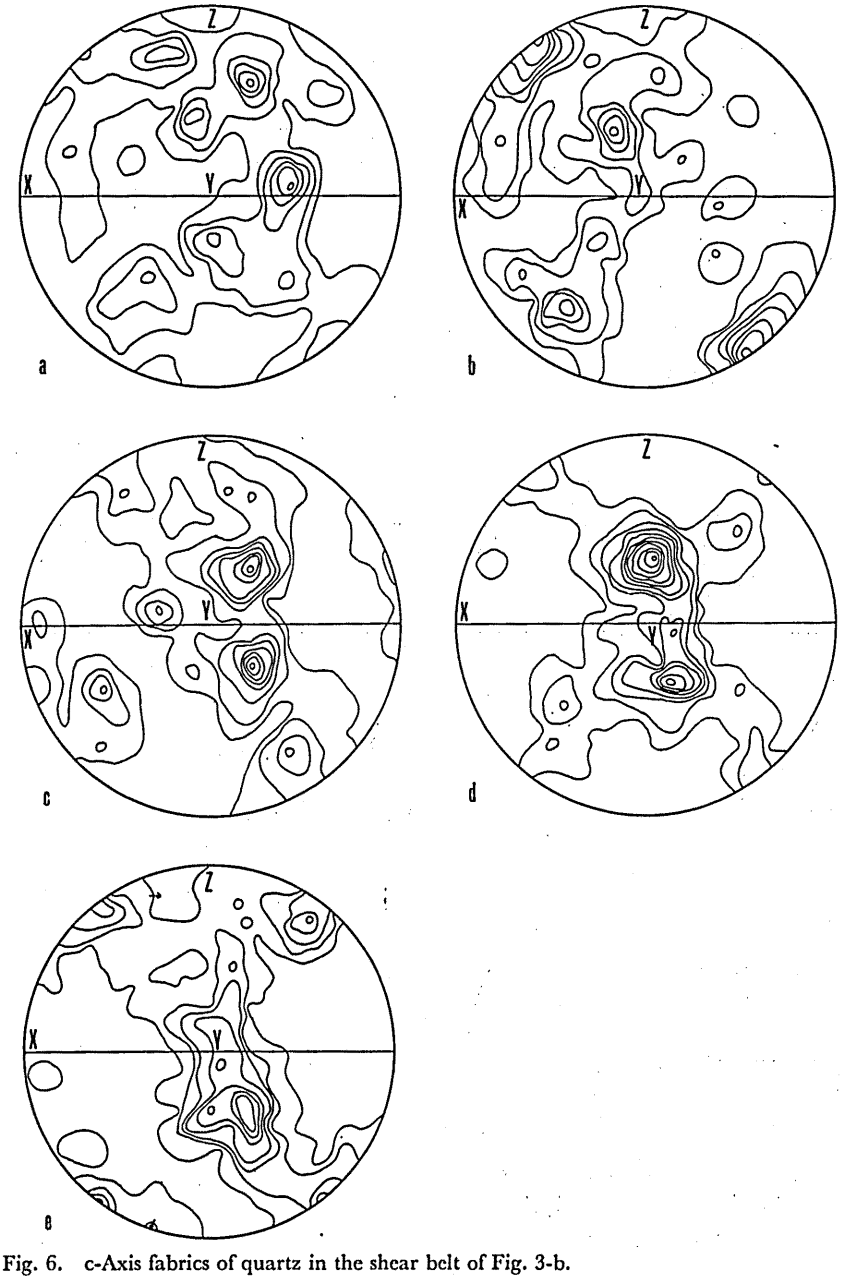

Fig. 6. c-Axis fabrics of quartz in the shear belt of Fig. 3-b.
a: Data from position a in Fig. 3-b. Contours: 1–2–3–4–5–6%.
b: Data from position b in Fig. 3-b. Contours: 1–2–3–4–5–6–7%.
c: Data from position c in Fig. 3-b. Contours: 1–2–3–4–5–6–7–8%.
d: Data from position d in Fig. 3-b. Contours: 1–2–3–4–5–6–7–8–10–11–12%.
e: Data from position c′ in Fig. 3-b. Contours: 1–2–3–4–5–6–7%.
X, Y and Z: the principal axes of strain.
In each position 200 quartz grains were measured.

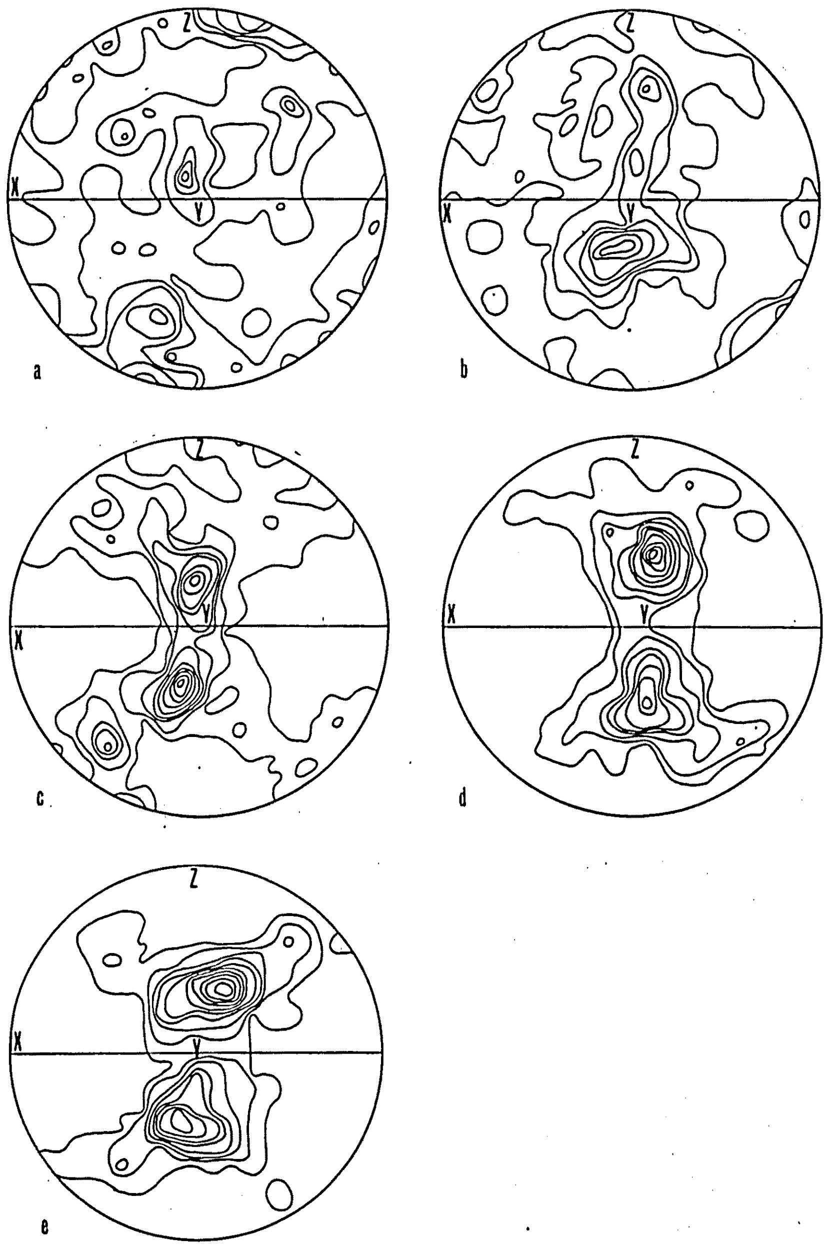

Fig. 7. c-Axis fabrics of quartz in the shear belt of Fig. 3-c.
a: Data from position a in Fig. 3-c. Contours: 1-2-3-4-5%.
b: Data from position b in Fig. 3-c. Contours: 1-2-3-4-5-6-7%.
c: Data from position c in Fig. 3-c. Contours: 1-2-3-4-5-6-7-8-9%.
d: Data from position d in Fig. 3-c. Contours: 1-2-3-4-5-6-8-10-13-16%
e: Data from position d′ in Fig. 3-c. Contours: 1-2-3-4-5-6-7-8-9-10%.
X, Y and Z: the principal axes of strain.

soid of mean strain in the domain concerned. With further increase of γ, the c-axis fabric shows more and more clearly the property of "pseudo-two-girdle", accompanying the higher concentration of c-axes at the points M_1 and M_2. When γ becomes larger than 1.80, two maxima on the points M_1 and M_2 become the most important property of the fabric, though the property of "pseudo-two-girdle" remains in it (Fig. 7). Those two maxima lie on the YZ-plane at the angle of ca. 30° to the Y-axis. The one component girdle of the "pseudo-two-girdle" is a partial great-circle girdle containing the points M_1 and M_2 and the Y-axis, and the other component girdle would be regarded as two crossed small-circle-like girdles, which cut across the XZ-plane at the angle of ca. 40° to the Z-axis, and whose intersecting points coincide with the points M_1 and M_2. The fabric pattern is approximately orthorhombic in symmetry, showing the symmetry planes parallel to the principal planes of the strain ellipsoid. This type of the c-axis fabric of quartz will be regarded as the stable one developed in the shear belts of the Teshima granite.

Now, it may be concluded that the stable pattern of the c-axis fabric of quartz produced under two dimensional strain with rotation is such a fabric pattern as shown in Fig. 7–e, having approximately orthorhombic symmetry, and that the fabric is mainly determined by the principal strain.

If the c-axis fabric of quartz developed by rotational strain is mainly determined by the principal strain, there may be a close correlation between the quartz fabric by non-rotational strain and that by rotational strain. Hara *et al.* (1971) examined the stable c-axis fabric of quartz produced under two dimensional strain without rotation. The stable fabric appears to be characterized by two crossed small-circle-like girdles, which cut across the XZ-plane at the angle of ca. 35° to the Z-axis and whose two intersecting points are situated on the YZ-plane at the angle of ca. 35° to the Y-axis, showing orthorhombic symmetry. The stable fabric for two dimensional strain with rotation appears to be well correlated with that for two dimensional strain without rotation, though the concentration of c-axes at the intersecting points of the girdles on the YZ-plane is much higher for the former than for the latter.

In most parts of geologically deformed rock bodies, strain appears to belong to the type of rotational strain. For the natural quartz fabrics, however, Turner *et al.* (1963) pointed out, "the symmetry of quartz orientation patterns so commonly is approximately, though seldom perfectly, orthorhombic". This may be because the c-axis fabrics of quartz developed by geologic deformation of rotational type are commonly mainly determined by the principal strain as well as in the present case.

The c-axis fabrics of quartz (Type I) in mylonites of the Moine thrust zone described by Christie (1963) are quite similar to those in the shear belts of the Teshima granite with reference to the fabric pattern and the orientational and symmetrical relations of the fabric to the principal finite strain of the domain concerned. According to the principle of symmetry, Christie considered that the deformation related to the formation of the quartz fabrics involved no translative movement. According to the present data, however, Christie's conclusion may be questioned. The nature of deformation (rotational strain or non-rotational strain) of a system will be clearly understood by the analysis of the spatial variation in the strain state and in the pattern and symmetry of the lattice and dimensional fabrics of constituent minerals in the system.

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EXPLANATION OF PLATE I

Photograph (in reverse) of a shear belt in the Teshima granite. ×2.5