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Kinematic Interpretation of the Quartz Fabric of Triclinic Tectonites from Besshi, Central Shikoku, Japan

By

George KOJIMA and Kei HIDE

with 2 Plates and 13 Text-figures

ABSTRACT Three examples showing successive changes in quartz fabric pattern have been selected from triclinic tectonites from Besshi for geometrical and kinematic analyses of rock structure. After geometrical considerations, three sets of schistosity or cleavage surfaces have been discriminated, *i.e.*, the axial-plane-schistosity, the first and the second transversal-schistosities, the latter two consisting of conjugate sets of *s*-surfaces. Quartz fabric patterns of these tectonites show an unmistakable triclinic character with respect to the situation of principal maximum, and their girdle patterns show a tendency to lie on certain small circles. Types of quartz pattern of these examples have been interpreted successfully in terms of orienting movements along the analysed *s*-surfaces after a working hypothesis about the rule of quartz orientation proposed in the preceding paper (G. KOJIMA and T. SUZUKI, 1958). It has been revealed that the quartz pattern represents mainly the last phase of orienting movement, that is, the phase of the second transversal-schistosity. Geometrical and kinematic relations between several types of quartz pattern have been discussed. The tectonites in question belong to the category of $B \perp B'$-tectonites. Geological conditions and kinematic character of deformation of successive phases of development of these *s*-surfaces have been considered. The result emphasizes the necessity of phase analysis of metamorphism.

CONTENTS

I. INTRODUCTION

In the petrofabrics the symmetry of pattern of fabric diagram used to be defined with reference to the principal schistosity or foliation plane and the principal lineation within it, and the kinematics of rock deformation has been discussed based on this geometical system. This procedure of reference might be justified only for cases of simple *S*-tectonites and simple *B*-tectonites, the rock structure of which shows a rhombic or monoclinic fabric pattern formed during a single phase of deformation with a movement plan symmetrologically consistent with the initial anisotropic fabric. In most fabric diagrams of quartz the symmetry of pattern is triclinic rather than rhombic or monoclinic, if the position of maximum is taken into account. Regarding to the triclinic symmetry, F. J. TURNER (1957, p. 6) comments: "The (triclinic) symmetry is compatible with compound movements in two or more superposed unrelated deformations, or with deformation of an initially anisotropic fabric." The latter case has been analysed by L. E. WEISS (1955), who has interpreted the fabric of a triclinic tectonite from Anglesey in terms of one monoclinic deformation involving solid flow. Most tectonites, however, show complicated planar and linear structures, reflecting superposed deformations either related or unrelated. Because of the sensitive behaviour of quartz at the solid flow of rocks, the pattern of quartz fabric diagrams for these complex tectonites is generally very complicated. In these cases the kinematic interpretation of fabric pattern is hardly possible without an assumption as to the mechanisms by which quartz becomes oriented during flow and recrystallization.

The present authors have been engaged in the study of geology and rock structure in the Besshi district, Central Shikoku, where occur coarse-grained crystalline schists characterized by the presence of porphyroblast of albitic feldspar. They have carried out petrofabric analysis of various kinds of schists, among which a peculiar type of quartz fabric pattern with distinct triclinic symmetry has been found. The pattern is rather simple, and is to be easily correlated with *s*-planes developed in the rock. The development of the pattern has been kinematically analysed successfully based on the senior author's working hypothesis about the rule of quartz orientation with reference to the shear plane proposed in the preceding paper (G. KOJIMA and T. SUZUKI, 1958, p. 193). This line of interpretation has been extended to cases of somewhat complicated patterns. The result implies the usefulness of the senior author's hypothesis of quartz orientation for kinematic analysis of quartz fabric diagrams, and emphasizes the necessity of descriptive-geometrical analysis of rock structure before kinematic interpretation of fabric data will be tried, as concluded by WEISS (1955, p. 225).

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II. GEOLOGICAL SITUATION

The sample which shows a remarkable triclinic orientation pattern for quartz has been obtained from a quartz-schist bed just upper of the ore bed of Besshi. As the horizon of beds including the ore bed (*Kieslager*) of Besshi represents a special position in the geologic structure of the region, its geological situation will be outlined in the following (cf. K. HIDE, G. YOSHINO and G. KOJIMA, 1956; G. KOJIMA and K. HIDE, 1957, pp. 2–4).

The Besshi region in the Sambagawa crystalline schist zone of Central Shikoku is divided after petrographical characters into two sub-zones, that is, the spotted sub-zone and the non-spotted sub-zone (Fig. 1). The former, the northern terrain, is composed

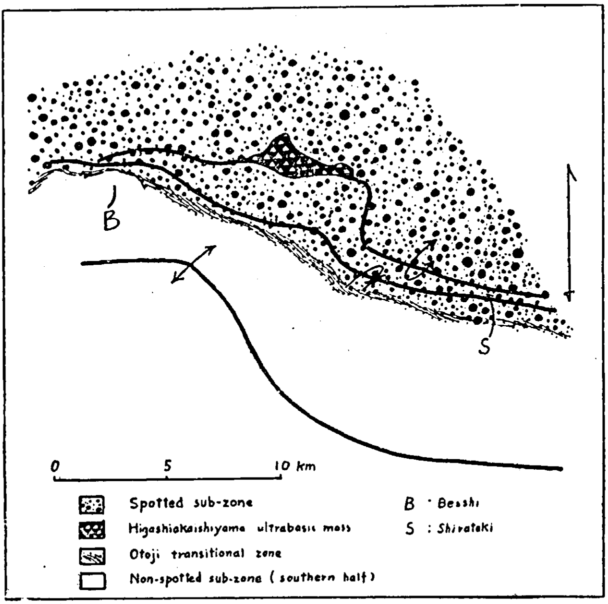


FIG. 1 Geological sketch-map of the Besshi-Shirataki district (after K. HIDE, G. YOSHINO, and G. KOJIMA, 1956)

of coarse-grained schists characterized by the ubiquitous presence of large porphyroblasts of albitic feldspar, while the latter, the southern terrain, consists of finer-grained, low-grade schists of regional metamorphic type, within which no porphyroblasts of feldspar can be found. The change in metamorphic behaviour across the boundary belt between these sub-zones is gradual.

Geologic structure shows a marked contrast between these two sub-zones. The inner part of the non-spotted sub-zone is characterized by gentle waving of schist formations, the dip (of bedding-schistosity or -foliation) of which rarely exceeds 50°. Thick beds of competent rocks such as sandstone-schist have been folded in the manner of flexure-fold, while within beds of black-schist derived from argillaceous sediment has been developed fracture-cleavage. These structures, formed in the earlier phase of deformation, have been penetrated by closely spaced shear-cleavage developed in the later phase, the dip of which is practically vertical throughout the sub-zone. On the surface of bedding-schistosity (-foliation) is developed a distinct lineation representing the line of intersection of the bedding-schistosity and the fracture- or shear-cleavage. The lineation is generally horizontal: the plunge rarely exceeds 15°. Its trend commonly coincides with that of regional fold-axis, *i. e.*, the regional *B*-axis, nearly parallel to the general trend of the Sambagawa metamorphic zone (WSW-ENE).

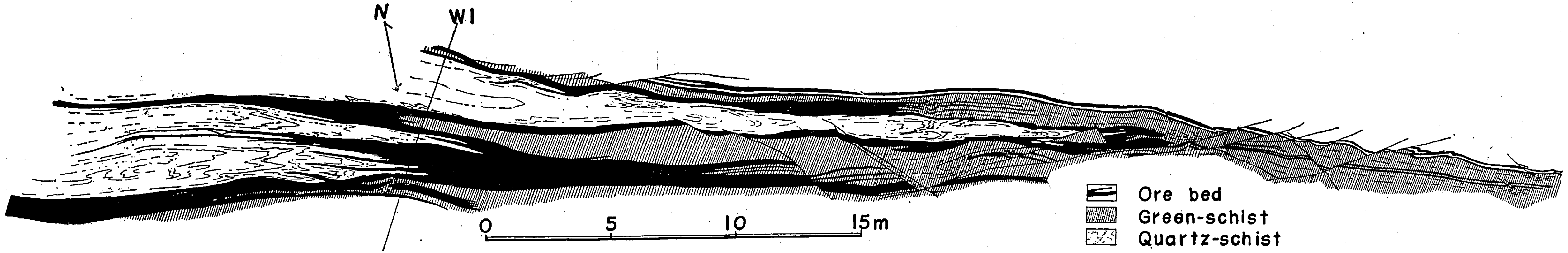
In the northern part of non-spotted sub-zone of the region, along the boundary to the spotted sub-zone, there occurs a distinct anticline, named the Nakashichiban (-Nôtaniyama) anticline. The axis of the anticline culminates at Nakashichiban, just to the south of Besshi, and gently sinks to the east. Rock structure in the anticline is the same as in the interior of the sub-zone. The lineation is also of *b*-type, coinciding with the fold-axis of the anticline in trend. The cross section of the anticline does not show a symmetrical form, *i.e.*: the southern wing is not distinct, merging into the waving terrain of the non-spotted sub-zone, while the northern wing consists of monoclinal formations of schists, the dip of which is fairly constant with angles near 50°. The lineation on the northern wing is also a type of *b*-lineation, its trend and plunge coinciding with those of the anticline axis. This asymmetrical form of the Nakashichiban anticline is to be attributed to the formation of a syncline and an anticline of recumbent type in the northern spotted sub-zone.

The spotted sub-zone of the Besshi district is framed with recumbent folds. The axis of recumbent anticlinorium can be traced from Besshi to Shirataki, its elongation attaining 40km or more. Its *Stirn* is protruded about 4km to the south in the Shirataki district. The axis of the anticlinorium culminates at Higashiakaishi-yama, where occurs a large mass of ultrabasic rocks (peridotite, including dunite and eclogite, and serpentinite). The southern wing of the anticlinorium is depressed, forming a recumbent synclinorium. Folds of recumbent or isoclinal types on a small scale predominate throughout the spotted terrain. These folds have characters of shear-fold, and parallel arrangement of flaky minerals defines the axial-plane-schistosity, which is overturned to the south, conforming to the vergency of the regional structure. The line of intersection of bedding- and axial-plane-schistosities defines the distinct *b*-lineation, which concides with the axes of folds on a small scale as well as the regional *B*-axis in direction. The plunge angle of the lineation is generally small, exceeding rarely 20°. Within the schists of the interior of spotted terrain linear elements of rock structure are more predominating than planar ones, and rocks split into rod-like pieces.

It is a remarkable fact that masses of peridotite and serpentinite are almost exclusively found in the spotted sub-zone. The largest one is the Higashi-akaishi-yama mass, which occurs as a large tectonic inclusion. In the present authors' view most of these ultrabasic masses represent synkinematic intrusions, whose physical and chemical agency played an essential role in the deformation and mineralization of the spotted schists (see KOJIMA and HIDE, 1957, p. 4, foot-note).

As outlined above, the non-spotted and the spotted sub-zones present a marked contrast not only in metamorphic behaviour but also in geologic as well as rock structures, the contrast reflecting the difference in physicochemical conditions at the time of metamorphism between these two sub-zones. It may be quite natural to suppose the presence of a zone of discontinuity between the non-spotted and the spotted sub-zones which show contrasted tectonic styles. The spotted sub-zone, which is characterized by the predominance of linear elements over planar ones, must have suffered more extensive elongation in the direction of fold-axis (the regional *B*-axis) and contraction in the plane perpendicular to the fold-axis (plane of cross section, *i.e.*, tectonic plane *ac*) than the non-spotted sub-zone, which, on the other hand, is characterized by the predominance of planar elements over linear ones. The marked difference in tectonic transport of material between these two sub-zones must have caused a strong differential movement mainly in the lateral direction along the boundary zone between them. The extent of lateral displacement of the spotted sub-zone relative to the non-spotted sub-zone may be expected to become greater towards the end of the fold of the spotted sub-zone. Are there any evidences of the lateral displacement inferred in the boundary zone?

The most noticeable fact is that in the boundary zone, named the Otoji transitional



PL. 27 Sketch of the folding in isoclinal fashion of alternating beds of quartz-schist, green-schist, and ore, at Sub-L. 15, No. WI, Besshi Mine. (Sketch by T. NISHI and K. HIDE, Sept. 1957)
The fold-axis coincides almost with the dip (NNE, 75°).

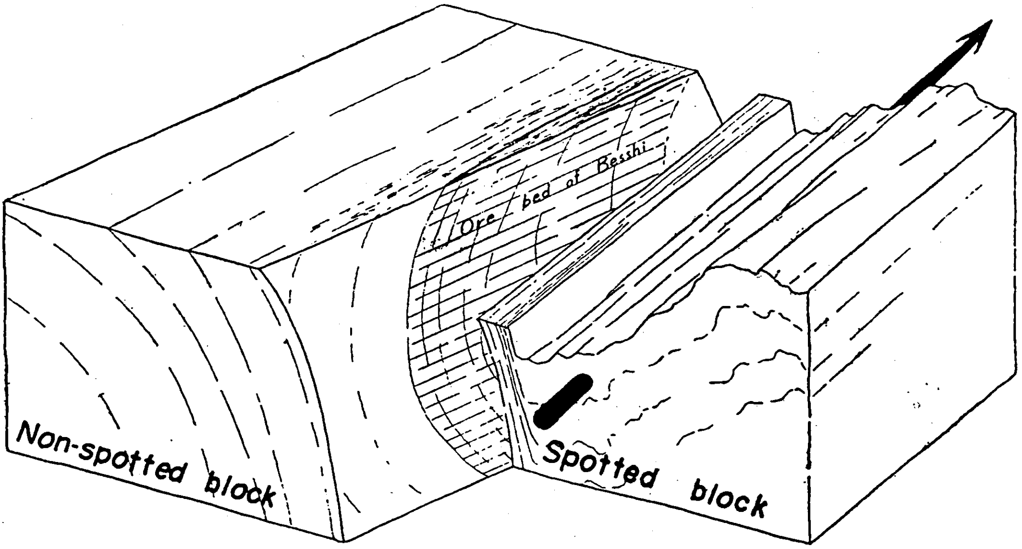


FIG. 2 Block-diagram, showing the geologic structure of the Besshi district. Arrow indicates the direction of lateral displacement of the spotted block relative to the non-spotted block.

zone (K. HIDE, G. YOSHINO and G. KOJIMA, 1956, p. 579), are found various types of linear structures, the plunge of which is distinctly higher than that of the lineations either in the non-spotted or in the spotted sub-zone. The linear structures in the Otoji zone comprise such features as 1) grooves or striations on the bedding-schistosity surface, which represent the megascopic expression of the line of intersection by shear-cleavage (transversal-schistosity) surfaces on the principal schistosity surface, 2) the axis of gentle waving of the schistosity surface, 3) rods of segregated quartz on the schistosity surface, and 4) the axis of fold of isoclinal character. These various types of linear structures concide in direction with each other in a single exposure. As geometrical and petrofabric studies on these linear elements carried out by the present authors have revealed their nature of *b*, the role of lateral movement in the formation of these high angle linear structures is to be inferred. The effect of the lateral movement is particularly distinct at Besshi, that is, near the western end of the main recumbent fold of the spotted sub-zone. The presence of one of the greatest copper mines in Japan enables us to trace the direction of linear structures: at higher levels the plunge is about 45° to E, becoming higher downward, coinciding with the dip at 14L. (about 150m above the sea), then changes to W. The ore beds are of a type of *Kieslager* (bedded cupriferous pyritic deposit), intervening conformably between crystalline schists. The beds of schists and ore have been folded in isoclinal fashion, as shown in Pl. 27. The axial trend of the folds coincides with that of the principal lineation on the schistosity surface. The geologic structure of the Besshi district is schematically shown in Fig. 2. It may easily be understood that the lateral component of movement of the folded block of spotted schists has played the most important role in forming these high-angle linear structures in the transitional zone.

On the importance of axial elongation of fold and lateral displacement of folded block in interpreting transverse linear structures——an additional remark: Recently, F. J. TURNER (1957, p. 4) has emphasized the relative importance of a component of movement acting parallel to the axis of regional folding in explaining transverse linear structures that commonly plunge steeply. He attributes this lateral component of movement to the tectonic stream, which might commonly be directed obliquely to the trend of the zone of crustal weakness (orogen), invoked by subcrustal convection. "In upper levels", he argues, "the deformed material is free to spill upward and outward; it yields by recumbent folding and thrusting across horizontal or gently plunging axes, with the principal direction of movement transverse to the trend of the deformed zone. But at deeper levels movement is constrained to directions more nearly parallel to the length of the orogen. Here transverse folds and related movements across axes that commonly plunge steeply characterize the movement plan" (p. 4). The component of movement acting parallel to the axis of regional folding, as pointed out by TURNER, may play an important roie in the structural geology of folded mountains, and TURNER's idea on the cause of this lateral movement seems to the present authors quite suggestive. In the authors' view, however, little interest has hitherto been taken in the axial extension as the counterbalance of compression in the direction of the force applied, namely, the elongation of folded block in the direction of regional B-axis.* The extent of elongation may depend on the physical properties of material being deformed and on the physicochemical conditons which exercise an essential influence on the mechanical properties of material. In other words, the extent of axial elongation must be different according to the difference in metamorphic grade or metamorphic behaviour of respective zones in a schist or gneiss region. This difference may give rise to a zone of strong lateral displacement, in which transverse linear structures will predominate. The senior author (G.K.) has found these zones characterized by strong lateral shearing at two districts, namely: at the Besshi district situated near the western end of the Besshi recumbent fold, and at the Sazare district near the eastern end of the fold, both representing the boundary between spotted and non-spotted sub-zones. The details will be described by the present authors and their collaborators in papers now in the course of preparation.

III. THE MOST REMARKABLE EXAMPLE——ROCK STRUCTURE AND PETROFABRICS

The sample which presents a remarkable triclinicity in quartz fabric pattern has been collected from a quartz-schist bed just upper of the Besshi ore bed in apparent

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* Recently, M. R. W. JOHNSON (1957) has explained E-W folds and lineations in the Moine Series of Coulin Forest as follows: "The regional B-axis (oriented nearly N.-S.) was a direction of low compressive stress and it is suggested that elongation in this direction gave rise to the folding about E.-W. axes" (p.263). I. NAKAYAMA (1958) has also suggested that "in the later stage of tectonic movement, the a-lineation and a-fold are formed as a result of local compression caused by the stretching of rock in the direction of the (regional) folding axis——the direction of the least resistance, and those a-structures (a-lineation and a-fold) are in reality b-structures" (p. 339).

stratigraphical succession near the entrance of the adit Taiheikō, 1100m above the sea. The bed trends to N40°W, dipping to NE at 40°. The sample number: GK 55 XI 17-1.

Lineation and joint of the bed: Within the surface of bedding-schistosity are found distinct parallel grooves or striations, which trend to E, plunging at an angle of 30°. This lineation corresponds to that high-angle type of lineation in the Otoji transitional zone mentioned in the preceding chapter. There is found still another lineation within the schistosity surface. This is represented by a weak ribbing or corrugation of micaceous seams in the quartz-schist, its continuation being apparently cut off by the lineation first mentioned. This second lineation trends to S55°E, and plunges at 5°, the direction being conformable to the general direction of lineation in the southern non-spotted sub-zone. From these points it may be inferred that the second type of lineation is a remnant of the lineation of the non-spotted zone. In addition to these types, there can be found the third type of lineation on the schistosity surface. This type is shown as very faint striations only perceptible for careful persons. Its direction is not so constant as the first and the second types, but these striations can be divided into two groups after the direction: one is nearly perpendicular to the most prominent lineation first stated, and another nearly coincides with the direction of dip, making angles near 40° with the first lineation. Its continuation is not good, but the striations have been overprinted on the grooved surface corresponding to the first lineation, that suggesting the later generation of the third type than the first and the second types. The structural meaning of these various types of lineation will be discussed in the section of the rock structure. The main system of joint is almost perpendicular to the most prominent lineation of the first type, and a less prominent system of joint is found nearly perpendicular to the relic lineation of the second type.

Megascopic and microscopic features: The rock is compact, and light-greenish in colour. It consists of alternating layers with different mineralogical composition, *i.e.*, highly quartzose layers and micaceous ones. The former consists of quartz almost exclusively, accompanied with muscovite, epidote, and hematite. While the latter consists of quartz, porphyroblastic albite, muscovite, chlorite, epidote, hematite, apatite, and garnet in some seams. The rock is fissil along the micaceous layer. The grain-size of main constituents is as follows: quartz 0.1–0.3mm, muscovite 0.2–0.5 mm, albite porphyroblast 2mm.

Principal s-surface and lineation: The planar structure of the rock has been examined on the sections cut perpendicular to the tectonic axes *a*, *b*, and *c*, respectively. The tectonic axes have been set up tentatively in accordance with the bedding-schistosity plane and the most prominent parallel grooves or striations, the lineation of the first type above mentioned, within the schistosity plane, *i.e.*: the axis *b* coincides with the direction of the most prominent lineation, the axis *a* is perpendicular to the principal lineation on the schistosity plane, and the axis *c* is normal to the schistosity plane. For

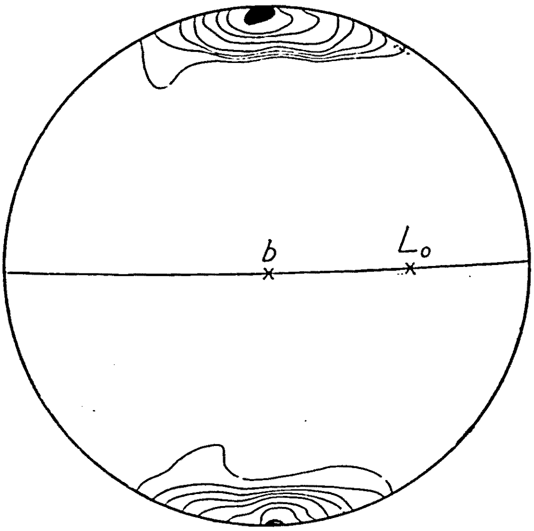

FIG. 3 150 [001] of muscovite and chlorite. *b* section of GK55XI17-1. No selection of grains was made. Max.: 49%. Contours: 45-35-20-10-5-3-2-1%.

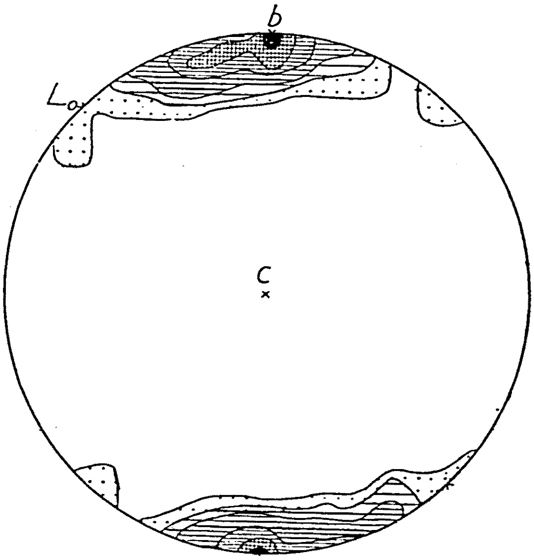

FIG. 4 150 b-axes of epidote. *c* section of GK55XI17-1. No selection of grains was made. Max.: 22%. Contours: 20-15-10-5-3-1%.

convenience in writing and reading, each section is designated by the letter representing the axis to which the section is normal. The sections are accordingly referred to as the *a*, *b*, and *c* sections.

The most prominent planar structure, which affords the rock a distinct fissility, is represented by the compositional banding and the dimensional orientation of muscovite, chlorite and epidote. The former is to be interpreted to inherit from the bedding and the lamination in a sedimentary bed, the contrast in both mineralogical and chemical compositions between each layers being, however, effected by metamorphic differentiation. The plane of dimensional orientation of mafic minerals strictly coincides with the plane of the compositional banding. Accordingly, the plane can be named the bedding-schistosity and the bedding-foliation as well.

The preferredo rientation of [001] of muscovite and chlorite jointly is shown in the petrofabric diagram of Fig. 3. The strong maximum (49 % in one percent area) strictly coincides with the tectonic axis *c*, namely, the normal to the bedding-schistosity plane. The diagram shows a spreading of axes in the *ac* plane, which may correspond to the development of grooves (lineation of the first type) on the schistosity plane. Furthermore, the one percent contour line reflects the existence of a subordinate girdle perpendicular to the relic lineation on the schistosity plane (lineation of the second type). In this non-selective diagram the influence of the third type lineation, situated about 40° to the left of *b* in Fig. 3, on the pattern can not be detected.

The prominent lineation is also represented by the dimensional orientation of epidote, as indicated in Fig. 4. It is a non-selective fabric diagram for the crystallographic b-axis, the longest axis of lath-shaped epidote.* The plane of projection of Fig. 4 refers to the bedding-schistosity plane. The distinct maximum (22% in one percent area) strictly coincides with the fabric axis *b*, the most distinct lineation. Contours of lower percentage show a spreading of axes towards the second type lineation on the schistosity plane, the plane *ab*, that corresponding to the presence of subordinate girdle normal to the relic lineation in the fabric diagram (Fig. 3) for muscovite and chlorite.

From the petrofabric diagrams above explained can be inferred that muscovite, chlorite, and epidote had been oriented in accordance with the older, now relic, *b*-lineation on the bedding-schistosity plane before the new phase of deformation and mineralization was set up in the Otoji transitional zone. As suggested in the section of lineation and joint, this older *b*-lineation has been formed under the movement plan conformable to that of the non-spotted sub-zone. Deformation and mineralization of the spotted sub-zone have been overprinted on the non-spotted schist under the movement plan induced in the zone by the lateral displacement of the northern spotted sub-zone, and during this phase of metamorphism such minerals as musovite, chlorite, and epidote, which had already been oriented preferentially, have been re-oriented in accordance with the new plan of movement.

On the basis of above discussion on the historical development of metamorphism, the schistosity planes and lineations of the quartz-schist are designated as follows:

The surface of the schistosity and foliation (compositional banding), both coinciding with each other, is to be interpreted to inherit from the bedding and the lamination of original sediment, which is designated as S_1 after the authors' system of designation on the schistosity and lineation (G. KOJIMA and T. SUZUKI, 1958, p. 177). As explained in the preceding chapter on geology, beds of the Otoji transitional zone have been folded in isoclinal fashion (Pl. 27), and axial plane of the fold coincides with the bedding (-schistosity) plane, except at the crest of fold, where the axial-plane-schistosity crosses the bedding. The surface of axial-plane-schistosity (or -cleavage) is named S_2, and the schistosity (or foliation) plane of the quartz-schist under consideration, which represents the surface of bedding of the original sediment as well as that of axial-plane-schistosity, is designated as S_{1-2} after the authors' system (KOJIMA and

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* The crystal habit of epidote in the quartz-schist in question is very characteristic. Grains of epidote in crystalline schist are usually prismatic in shape, elongated in the crystallographic b-axis, which coincides with the prominent lineation on the schistosity plane. Among the crystallographic planes, (100), (001), and $(10\bar{1})$ are developed. In many cases, it has been concluded that (001) or/and $(10\bar{1})$ coincide with the schistosity plane (C. B. CRAMPTON, 1957 ; J. LADURNER, 1951). In the quartz-schist in question, the epidote has a lath-shape, elongated in the crystallographic b-axis. Accordingly, on the *a* section epidote shows a slender form, while on the *b* section it is platy or a spindle form, oriented parallel to the schistosity plane. The surface of the plate is the plane $(10\bar{2})$, determined with the universal stage. For that reason, the optic elasticity axis X, which makes an angle of about 7° with the normal to $(10\bar{2})$, gathers at the tectonic axis *c* in the petrofabric diagram. The results by the present authors may be published in near future.

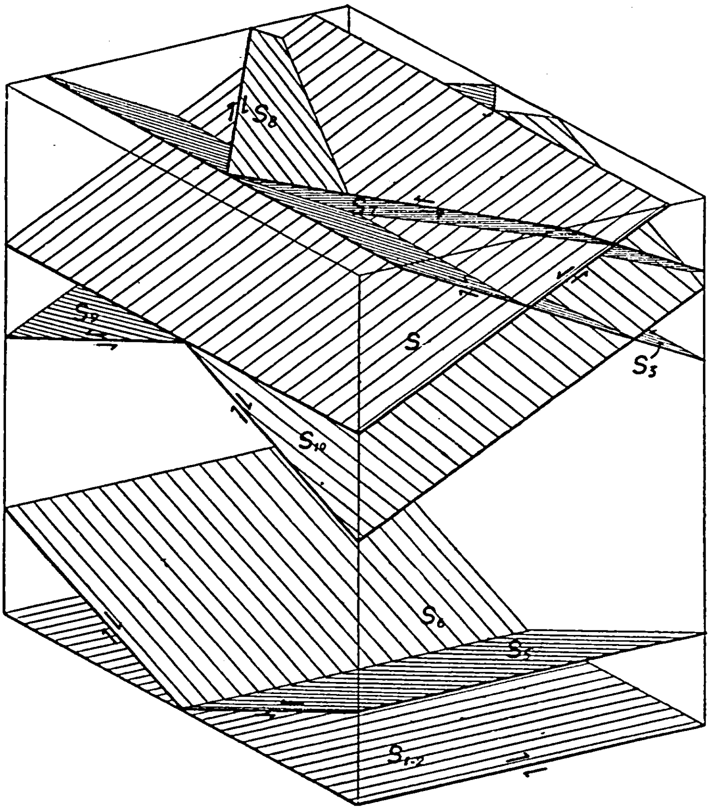

FIG. 5 Clinographic projection, showing the arrangement of *s*-surfaces.
Arrows parallel to each *s*-surface indicate the sense of shear along the respective surface. Hatching line indicate the direction of movement.

SUZUKI, 1958, p. 181).

Among lineations within the surface S_{1-2}, the oldest, relic one is designated as L_0. Other lineations are designated according to the subscript numerals of *s*-surfaces which mark their traces on the schistosity plane S_{1-2} as lineations by crossing it. For this reason, planar structure of the rock will be fully examined before the designation of other lineations is tried.

Subordinate s-surfaces and lineations——1) The first conjugate transversal-schistosity surfaces: Two sets of subordinate *s*-surfaces, one strong and another weak, can be detected on the *b* section. They are represented on the thin section by parallel sets of slip zones, and, as discussed by E. INGERSON (1936, p. 166) on a muscovite-biotite-schist from Niederthal, Tyrol, the direction of relative movement in the slip zone can be established where elongate or platy mica or chlorite crystals have been affected by the movement. The movement rotated mica and chlorite flakes in the slip zone internally to the direction of slip, but did not last long enough to bring the plates completely parallel to the slip plane. The angles between the principal schistosity plane S_{1-2} and each of these two sets of subordinate schistosity planes can be measured on the *b* section, which stands perpendicularly to these *s*-planes: the strong one is inclined at 30° to S_{1-2}, and the weak one at 24° to S_{1-2} on an average.

Between these two sets of subordinate *s*-surfaces, the strong one is designated as S_3, and the weak one as S_4.

The sense of slip movement on these subordinate schistosity planes is indicated diagrammatically in Fig. 5. The sense of internal rotation affected by the slip movement is reversed between S_3 and S_4, and they are almost symmetrically oriented to the principal schistosity plane S_{1-2}. These kinematic facts suggest that S_3 and S_4 represent a pair of shear planes formed by the contraction in the direction of tectonic axis *c* and the concomitant elongation in the direction of *a*, the axis *b* being the symmetry axis of this practically two-dimensional deformation. The deformation, however, was not the type of simple two-dimensional flattening, as suggested by unequal development of shear zones between S_3 and S_4. The latter fact is to be interpreted as reflecting the influence of rotational strain overlapped on the flattening. The sense of the internal rotation can be inferred from the disposition of strong and weak *s*-surfaces. In Fig. 6 is shown the relationship between compressional and rotational strains responsible for the development of S_3 and S_4, together with the sense of shear movement along S_{1-2}, which had operated before S_3 and S_4 were developed. It is a remarkable fact that the sense of the internal rotation of that rotational strain coincides with that of the shear movement along S_{1-2}, *i.e.*: S_3 is "*synthetisch*" (R. HOEPPENER, 1955, p. 30) with S_{1-2} with respect to the sense of shear movement.

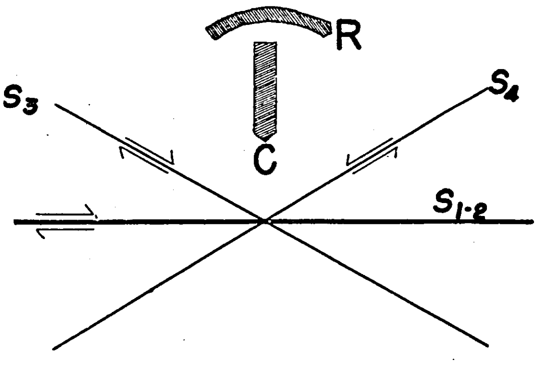

FIG. 6 Relation between the strain, *s*-surfaces, and the sense of shear along the *s*-surfaces.
C: compressional strain, R: rotational strain.

From these kinematic relationships between the principal and subordinate *s*-surfaces it may be inferred that the stress plan caused by the lateral displacement of the spotted sub-zone against the non-spotted sub-zone, which is now represented by the principal schistosity surface S_{1-2} or by the axial-plane-schistosity surface S_2 of quartz-schist in the Otoji transitional zone, remained unchanged in the successive phase of deformation, when the compressive stress has formed a pair of *s*-surfaces, S_3 and S_4.

The principal lineation, the most prominent one on S_{1-2}, has now revealed to be the trace of S_3 as well as of S_4 on the schistosity surface S_{1-2}. Accordingly, the tectonic axis *b* set up tentatively in the former section on the principal schistosity plane has also proven to be the real one. As mentioned above, after the authors' system of designation lineations are distinguished from each other by subscript numerals, which indicate the planes intersecting with each other. In this case, the principal lineation is designated as L_{2-3} or L_{2-4}, namely, the trace of S_3 on S_{1-2}, or the trace of S_4 on S_{1-2}. S_3 and S_4 are distinguished from other sets of transversal-schistosity (or -cleavage) surfaces, which will be described in the succeeding section, by naming "the first conjugate transversal-schistosity (or -cleavage) surfaces".

Subordinate s-surfaces and lineations——2) The second conjugate transversal-schistosity surfaces: One set of traces of strong *s*-surfaces is observed on the *a* section. On the section, *s*-surfaces are represented either by parallel sets of slip zones, as is the case for the first transversal-schistosity surfaces on the *b* section, or by the elongation of quartz grains in highly quartzose layers. It is quite distinct that these *s*-surfaces are of later genesis than the first transversal-schistosity surfaces. The traces of these *s*-surfaces on the *a* section are somewhat variable in direction, and the angles between the trace of the *s*-surfaces and that of the principal schistosity surface S_{1-2} range from 25° to 35°, the mean value being 31°. The fact that the traces of the *s*-surfaces cross the trace of S_{1-2} on the *a* section suggests that these *s*-surfaces are not (h0l). but that they must be either (0kl) or (hkl), or both. The distinction is hardly possible only on the *a* section. These *s*-surfaces, however, must leave their traces on the principal schistosity surface, namely, lineations not coincident with the *b*-lineation, the principal lineation L_{2-3}. As has been described in the first section of this chapter, there are two sets of faint striations on S_{1-2}, distinctly later than L_0 and L_{2-3}: one is perpendicular to the principal lineation, and another makes angles near 40° to L_{2-3}. The former must be the trace of the *s*-surface (0kl), and the latter the trace of the *s*-surface (hkl). Therefore, the cleavage or schistosity structure shown on the *a* section must be the trace of both (0kl) and (hkl), but it is hardly possible to discriminate between traces of each *s*-surface on the *a* section.

The direction of relative movement along these s-surfaces can be established from the attitude of reoriented muscovite and chlorite plates in the slip zone, as discussed in the preceding section. The result is shown diagrammatically in Fig. 5. The disposition of these *s*-surfaces and the sense of slip movement along them suggest the presence of another *s*-surfaces complemental to each of these *s*-surfaces. If they exist, they may be represented on the *a* section by another slip zones complemental to those of (0kl) and (hkl) above mentioned. Unfortunately, they can not be detected in this case, but, as will be described in the succeeding chapter for other samples of triclinic tectonite from Besshi, weakly developed *s*-surfaces are found in the complemental position to the (0kl) and (hkl) *s*-surfaces in the present case. The indices of them are also (0kl) and (hkl), respectively. Accordingly, these *s*-surfaces with the indices of (0kl) and (hkl) compose "the second conjugate transversal-schistosity (or -cleavage) surfaces", which are distinctly of later genesis than the first. Their kinematic genesis may be interpreted as follows, on the same line of strain hypothesis as has been followed in the case of the first transversal-schistosity.

Contrary to the first transversal-schistosity, which has been interpreted as formed by the contraction in the direction of *c* and the concomitant elongation in *a*, accompanied by a rotational strain around *b*, the disposition of surfaces of the second transversal-schistosity suggests the elongation in the direction of the tectonic axis *b*. For (0kl) the contraction in the direction of *c* is responsible, but the presence of conjugate (hkl) surfaces does not permit to limit the direction of contraction only to *c*. That is, the movement plan in the phase of deformation in question must have been effectively influenced by the pre-existing heterogeneities. At the beginning of this phase of deformation the rock had been furnished with some additional heterogeneities other than the original bedding or lamination surface S_1 ; *viz.*, S_{1-2} (parallel to S_1), S_3, and S_4 (very weak) as planar elements, and L_{2-3} (parallel to *b*) as a linear element. The elongation in the direction of L_{2-3} caused the concomitant contraction in the direction perpendicular to L_{2-3}. If the rock had no planar heterogeneities, the deformation caused by the elongation in one direction might have an axial symmetry, characterized by the equal amount of contraction in any direction perpendicular to the direction of elongation, and cone-shaped shear surfaces must have been formed. In the present case, however, the movement plan has been conducted by the pre-existing *s*-surfaces which are parallel to the direction of elongation, the principal lineation L_{2-3}. The direction of maximum contraction, which must be perpendicular to the direction of maximum elongation, has been directed to those particular positions, namely, those perpendicular to S_{1-2}, S_3, and S_4, respectively. As has been discussed above, the set of *s*-surfaces (0kl) has been formed under the movement plan with the maximum contraction in the direction of *c* (perpendicular to S_{1-2}). While, two sets of conjugate *s*-surfaces characterized by the index (hkl) must have been formed under the movement plan with the maximum contraction in the directions perpendicular to S_3 and S_4.

All the *s*-surfaces inferred kinematically are shown in Fig. 13 ($\perp a$) as great circles. Two sets of *s*-surfaces (0kl) relating to S_{1-2} are designated as S_5 and S_6, those of *s*-surfaces (hkl) relating to S_3 are S_7 and S_8, and those of *s*-surfaces(hkl) relating to S_4 are S_9 and S_{10}. The tectonic axis *b* on the principal schistosity plane S_{1-2} becomes the axis *a* in the phase of deformation of the second transversal-schistosity, which is distinguished from the axis *a* of the foregoing phase as the axis a'. The tectonic axis *b* for the second transversal-schistosity must coincides with the lines of intersection of each set of conjugate *s*-surfaces, lying on S_{1-2}, S_3, and S_4, respectively. They are designated as b', b'', and b''', respectively, as shown in Fig. 13. Accordingly, the rock is a type of $B \perp B'$-tectonite.

In the ideal case, six parallel sets of *s*-surfaces of the second transversal-schistosity must be present as inferred kinematically. In the actual case, however, the intensity of development of *s*-surface is different between them. The difference is due to the difference in development between S_{1-2}, S_3, and S_4, as well as to the effect of rotational strain. In this case, the *s*-surfaces detected through the observation above mentioned correspond to S_5 and S_7 in the synoptic diagram of Fig. 13. S_9 may also be present in the rock, but with less intensity, because the related *s*-surface S_4 is less intensely developed than either S_{1-2} or S_3. If actually present, S_9 may be detected on S_{1-2} as a parallel set of striation, as the case for S_7. Unfortunately, the direction of the striation read from the diagram roughly coincides with the relic lineation L_0. Therefore, it is difficult to discriminate between them. S_5, S_7, and S_9 have been projected as great circles in Fig.8, together with S_{1-2}, S_3, and S_4.

Great circles representing the planes of the second transversal-schistosity, S_5, S_7, and S_9, can be drawn geometrically on the diagram of stereographic or equiareal projection, if we know positions of at least two points on respective great circle, *i.e.*, at least two directions on respective *s*-surface. One of them is afforded by the tectonic axis $b(b', b''$, and b''' for S_5, S_7, and S_9, respectively), which is inclined at 90° to $b=a'$ on respective *s*-surface. Another point can be given by the trace of *s*-surface on the *a* section. It may naturally be conceivable that the direction of the trace is different between these *s*-surfaces, but, as has been mentioned above in the text, it is hardly possible to discriminate the respective trace. Practically, however, it is sufficient in petrofabric analysis to adopt the mean value of the angle between the trace of the second transversal-schistosity plane and that of S_{1-2}, which has been estimated at 31° in this example.

The position of *s*-surface, drawn with this method, can be checked with the direction of lineation on the principal schistosity surface S_{1-2}.

After the authors' system of designation, lineations other than the principal lineation L_{2-3} on the schistosity surface S_{1-2} are to be designated as follows: the trace of S_5 as L_{2-5}, that of S_7 as L_{2-7}, that of S_9 as L_{2-9}, and so on. It may be noted that L_{2-5} corresponds to the *a* lineation. L_{2-7} and L_{2-9} are the type of oblique lineation, coinciding neither with *b* nor *a*.

Lastly, the authors will comment briefly on the one-sided development of the second transversal-schistosity. As has been discussed in the case of the first transversal-schistosity, it must have been due to the presence of a rotational strain accompanying the elongation in the direction of the principal lineation. From the geographical position of *s*-surfaces actually developed, the rotation must have occurred in the sense that the hanging block moves upward relative to the footwall, that is,the northern block of spotted schist has been thrust up on the southern block of non-spotted schist. This tendency of movement during the later phase of deformation is also indicated by the occurrence of a sheaf of high-angle thrust fault, which cut the ore bed into several slices.

Quartz fabric: For analysing the preferred orientation of quartz, a highly quartzose seam has been selected which shows strong preferred orientation with the gypsum test-plate. On the *a* section, the seam shows strong prevalence of blue interference colour at the position of addition with the test-plate. In contrast with seams studded with a fairly amount of muscovite, which do not show so strong prevalence of an interference colour, the seam is composed almost exclusively of coarser-grained, perfectly recrystallized quartz, accompanied by a few amount of muscovite, epidote, ect.

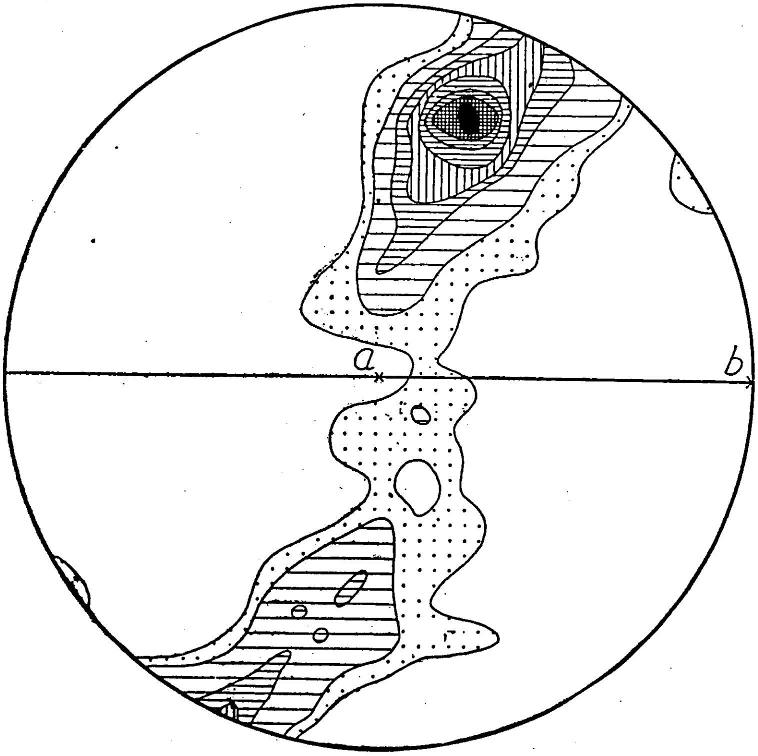

FIG. 7 350 c-axes of quartz. *a* section of GK55XI17-1. Grains were measured without selection within a highly quartzose seam in the section. Max. : 16%. Contours : 15-12-10-8-6-4-2-1%.

No porphyroblasts of albitic feldspar are found. The grain of quartz is not equant in shape, showing unmistakable preference of dimensional orientation on the *a* section, while on the *b* section, dimensional orientation of the mineral can not be detected (Pl.28).

On the basis of these provisional observations, it may be inferred that the essential part of preferred orientation of quartz of the seam must have been caused by the flow during the phase of the second transversal-schistosity, and that the orientation pattern in the petrofabric diagram will be interpreted independently by the rule of quartz orientation referring to the direction of flow and the shear plane regardless of the influence of the attendant minerals ("*Einfluss der Gefügegenossen*", B. SANDER, 1950, p. 114).

350 c axes of quartz in the highly quartzose seam in question have been measured without selection on the *a* section set on the four-axis universal stage. The data have been plotted on the lower hemisphere of an equiareal projection. Contours have been drawn after the usual practice (percent of points per one percent area). The maximum attains to 16%, the value being uncommonly high except certain cases of mylonitic rocks. The fabric diagram is shown in Fig. 7.

The diagram shows a very peculiar pattern with distinct triclinicity with reference to the principal schistosity plane S_{1-2}, the plane of preferred orientation of platy minerals (Fig. 3). Readers will see at a glance two unmistakable peculiarities of the pattern. One of them is that the circle on which points are distributed can not be regarded as a great circle, but that it is decidedly a small circle. Another noticeable point is that the maximum point on the small circle does not lie on the periphery of the diagram, the plane *bc*, *i.e.*, the maximum point does not coincide with the position of maximum III, but lies near maximum IV in SANDER's collective diagram of quartz maxima for *S*-tectonites (SANDER, 1950, p. 363, Fig. 48a).

In the next chapter, the pattern of quartz fabric diagram will be interpreted on the basis of kinematic analysis of the rock structure performed in this chapter.

IV. KINEMATIC INTERPRETATION OF QUARTZ FABRIC OF THE PRECEDING EXAMPLE

The occurrence of a small circle girdle in fabric diagram may well be interpreted by an assumption that a certain lattice plane which is not parallel to the c axis lies on a particular shear plane of the rock. Then, the angle between the small circle and the shear plane must be equal to the angle between the lattice plane and the c axis. Although we have had no definite theory about the attitude of quartz in orienting movement until now, the provisional observations mentioned in the preceding chapter suggest that the shear plane parallel to which a certain lattice plane of quartz is oriented must be a plane now represented by an *s*-surface of the second transversal-schistosity. Therefore, at the beginning will be sought the parallelism between the small circle and a certain *s*-surface of the second transversal-schistosity.

Two points will be noticed: 1) the small circle is arranged symmetrically to the center of the diagram, namely the tectonic axis *a* (or *b'*), the fact suggesting the small circle to be parallel to a certain *s*-surface which includes *a*, and 2) the most distinct *s*-surface among those of the second transversal-schistosity is S_5, which is parallel to *a*. Therefore, the authors have drawn a small circle parallel to S_5 by way of trial, as shown in Fig. 8. In this trial, the angle between the small circle and S_5 was assumed to be 38°, *viz.* the angle between the c axis and the plane of unit rhombohedron, either positive: $(10\bar{1}1)$ —— *r* or negative: $(01\bar{1}1)$ —— *z*, or both, of quartz crystal. The result of this trial is astonishingly satisfactory. The girdle in the diagram coincides with the assumed small circle. The coincidence suggests that the lattice plane $(10\bar{1}1)$ or $(01\bar{1}1)$, or both, of quartz has been oriented parallel to the shear plane S_5 during flow.

The next point to be noticed is that, whereas there can be drawn two small circles on both sides of S_5, the girdle occupies a single small circle among them. This fact may be explained by assuming that there exists a definite sense of displacement between lattice layers parallel to the unit rhombohedron conforming to the sense of shear movement within the shear plane in the rock, the fact having been established

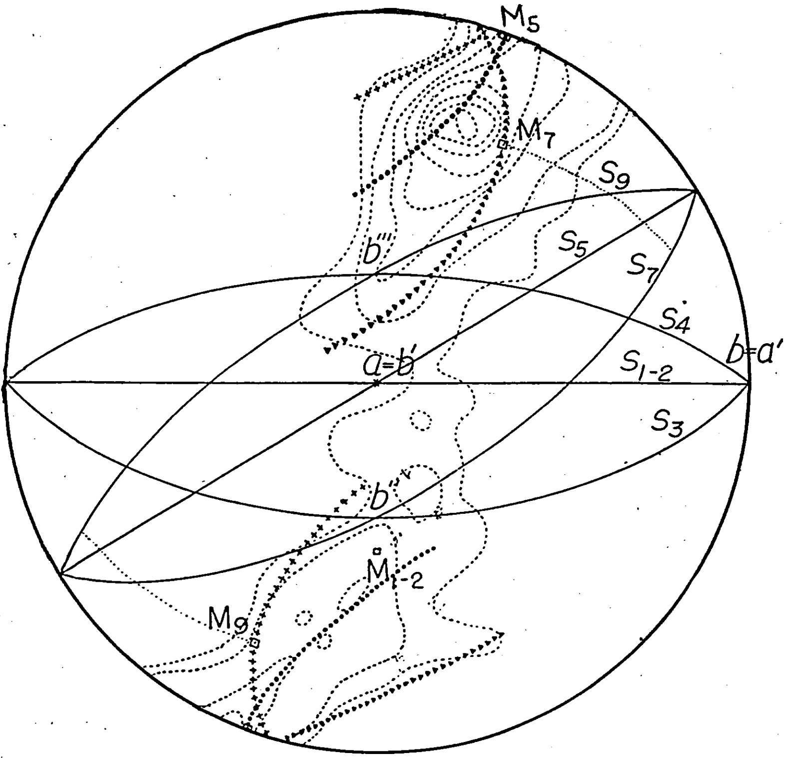

FIG. 8 Analysis for Fig. 7. (see in the text)

for calcite (F. J. TURNER, D. T. GRIGGS, and H. HEARD, 1954). This point of problem will be discussed after the meaning of maximum point in the diagrm is considered.

That the maximum point deviates from the periphery of the diagram gives the pattern a remarkable triclinicity. Because the movement plan for S_5 is monoclinic with reference to the principal schistosity plane S_{1-2}, the presence of a single maximum at the point which bears no relationthip with the plan of symmetry elements can not be explained simply by the shear movement along S_5. Then, the deviation of the maximum point is to be interpreted as indicating the effect of orienting movement along other shear planes such as those represented by S_7 or S_9. In Fig. 8, therefore, small circles at the angle of 38° to S_7 and S_9, respectively, have been drawn on the same side of each *s*-surface as for S_5. Then, it becomes clear that the maximum point is situated between the small circle for S_5 and that for S_7. This fact may well be explained on the basis of a hypothesis on the orientation of quartz in reference to the shear plane as follows.

The senior author (G. K.) and T. SUZUKI (1958, p.192) have shown that a cetain rule must exist concerning the preferred orientation of quartz sufficiently recrystallized during flow of a rock. The rule has been stated as follows:

1) *r* $(10\bar{1}1)$ and/or *z* $(01\bar{1}1)$ of quartz lie on the shear plane, and
2) the sense of displacement of upper layers on these lattice planes is downward

from the c axis.

According to this rule, it is to be inferred that, if the pattern of quartz fabric diagram in Fig. 7 were brought about solely by the orienting movement along S_5, the maximum point must be situated at the point representing the direction of intersection between the plane $a' c$, *viz.* bc, and the small circle for S_5, *i. e.*, the point inclined at 38° to S_5 on the plane $a'c$. While, if a certain part of quartz grains has been oriented in reference to S_7, the pattern of petrofabric diagram must show a spreading of axes on a small circle inclined at the angle of 38° to S_7, and a subordinate concentration at the point representing the intersection of the small circle and the plane perpendicular to b'', namely, the plane $a' c''$. These inferred points of axes concentration on the small circles are marked in Fig. 8 with squares, designated as M_5 and M_7 for S_5 and S_7, respectively. In the same way, a small circle and a point of axes concentration (M_9) are drawn for S_9, another subordinate *s*-surface of the second transversal-schistosity, less distinct than S_7.

On the basis of above analysis, the fabric pattern in Fig. 7 may be explained as follows.

The most part of the area occupied with axes projected lies between two small circles relating to S_5 and S_7, and the maximum is situated between M_5 and M_7. These facts suggest that the preferred orientation of quartz has been brought about mainly by the shear movement along S_5 and S_7, while the effect of S_9 might have been negligible. The effect of shear on S_{1-2} is traceable in the center of the lower half of the diagram.

This line of interpretation will be extended to further examples of triclinic tectonites from the Besshi district.

V. FURTHER EXAMPLES OF TRICLINIC TECTONITES FROM BESSHI

A. A TRICLINIC TECTONITE WITH QUARTZ FABRIC PATTERN OF CROSSED SMALL CIRCLE GIRDLES

The sample has been collected from a quartz-schist bed just upper of the Besshi ore bed (A-bed) in apparent stratigraphical horizon at Level 20, No. E7–8, 230m below the sea level. The bed trends to N 58°W, dipping to NNE at 55°. The sample number: GHK 56V 26–3.

Rock structure: The rock is highly compact, and light-bluish-green in colour. It consists mostly of quartz, accompanied with a small amount of muscovite, chlorite, calcite, epidote, garnet, apatite, and hematite. Modal percentages of these accessory minerals are variable layer after layer. Although the rock intervenes between spotted schists, albite porphyroblasts are lacking in this very sample. The grain-size of main constituents is as follows: quartz 0.1–0.2mm, muscovite and chlorite 0.1–0.3mm. The planar structure of the rock has been analysed with the method explained in the preceding example. Angles necessary for reconstructing and checking *s*-surfaces in the diagram are as follows:

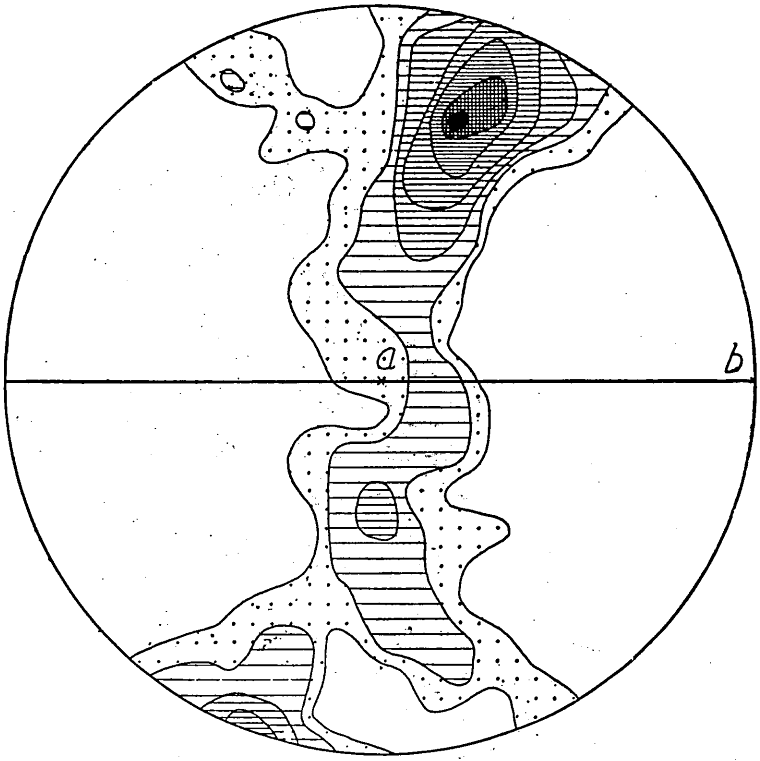

FIG. 9 350 c-axes of quartz. *a* section of GHK56V26-3. Grains were measured without selection within a highly quartzose seam in the section. Max.: 10.3%. Contours: 10-9-7-5-3-2-1%.

$S_3 \wedge S_{1-2}$	25°
$S_4 \wedge S_{1-2}$	26°
Trace of S_5, etc. $\wedge$ tr. of S_{1-2} on the *a* section	32°
Tr. of S_6, etc. $\wedge$ tr. of S_{1-2} on the *a* section	28°
$L_{2-3} \wedge L_{2-7}$ on S_{1-2}	45°
$L_{2-3} \wedge L_{2-8}$ on S_{1-2}	46°

Direction of relative movement can also be established from the attitude of reoriented flakes of muscovite and chlorite in the slip zone.

From these data the following *s*-surfaces have been established.

The principal schistosity surface: S_{1-2}

The first conjugate transversal-schistosity surface: S_3 and S_1
(S_3 is strong, while S_4 is weak)

The second conjugate transversal-schistosity surfaces: S_5 and S_6 (with reference to S_{1-2}: S_5 strong, S_6 weak); S_7 and S_8 (to S_3: S_7 strong, S_8 weak); and, S_9 and S_{10} (to S_4: both weak)

The disposition of these *s*-surfaces is shown in Fig. 10. The most noticeable point in contrast with the preceding example (see Fig. 8) is that there occur complementary

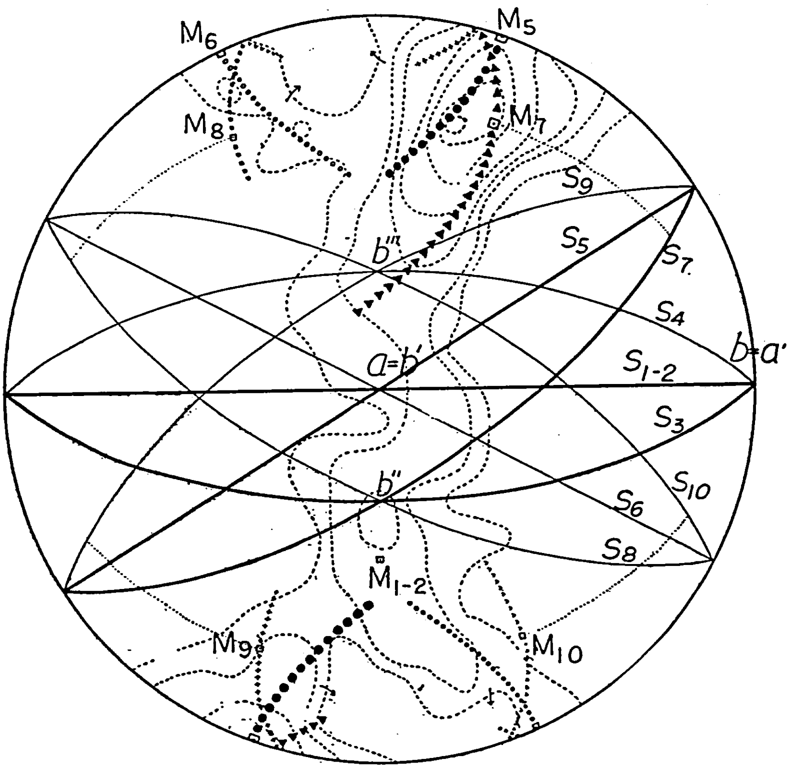

Fig. 10 Analysis for Fig. 9 (see in the text)

s-surfaces (S_6, S_8, and S_{10}) of the second transversal-schistosity to those found in the preceding example (S_5, S_7, and S_9), although the intensity of development of these complementary *s*-surfaces is weak.

Quartz fabric: 350 c axes of quartz grains were measured from a highly quartzose seam on the *a* section without selection of grains. The petrofabric diagram is shown in Fig. 9. Viewed from the distribution of concentration, the pattern is decidedly triclinic, but, if the unsymmetrical distribution of maximum and sub-maxima is neglected, the pattern is rather orthorhombic in symmetry. That owes to the presence of complementary small circle girdles in the second and the fourth quadrants of the diagram symmetrically arranged to the small circle girdles in the first and the third quadrants. The latter represents the main girdle, the meaning of which has been discussed in the preceding chapter. The pattern and the situation of maximum and sub-maxima can be interpreted as follows.

In Fig. 10, the respective small circle has been drawn referring to every *s*-surface on its inferred side, as explained in the preceding chapter. Inferred points of axes concentration on these small circles have also been marked with squares, designated as M_5, M_6, M_7, M_8, M_9, and M_{10}, respectively. Small circles corresponding to S_5 and S_6

well explain the trend of girdles. The deviation of maximum point from M_5 must be due to the subordinate concentration of axes at M_7. The distribution and concentration of axes conform well to the intensity of development of each *s*-surface, *i. e.*, the small circle girdle of higher concentration in the first and the third quadrants corresponds to S_5 and S_7, *s*-surfaces of stronger intensity, and the small circle girdle of lower concentration in the second and the fourth quadrants refers to S_6, an *s*-surface of lesser intensity. *s*-Surfaces other than S_5, S_7, and S_6, have left no detectable effects on the diagram. A sub-maximum near the center of the lower half of the diagram may correspond to the shear movement along S_{1-2}, the point of axes concentration of which is marked in the diagram as M_{1-2}.

It may be worth notice if FAIRBAIRN's two-girdle arrangement of axes with the girdles (of great circle type) intersecting in *a* (FAIRBAIRN, 1949, Fig. 2–1, (g)) could include such cases of crossed small circle girdles as illustrated here. The similar pattern of quartz fabric of a quartzite from Rensenspitze, Provinz Bozen, quoted by SANDER (1950, p. 178ff.) as an example of A. V. A., may also be explained on the basis of the present authors' system of analysis.

B. A TRICLINIC TECTONITE WITH QUARTZ FABRIC PATTERN OF ANNULAR CONCENTRATION AROUND *c*

The sample of the last example was collected from a quartz-schist bed in the spotted schist zone proper at a cross-cut of Level 20, No. E6, of the Besshi Mine, 230m below the sea level. The bed trends to N65°W, dipping to NNE at 62°. The sample number: GHK 56V 26–2.

Rock structure: The rock is light-greenish-gray in colour, laminated, and compact. It consists mostly of quartz, accompanied with variable amount of muscovite, chlorite, garnet, epidote, apatite, and hematite. Albite porphyroblasts are also present in some micaceous layers. Modal percentages of accompanying minerals are variable layer after layer. The grain-size of chief constituents is as follows: quartz 0.1–0.3mm, muscovite 0.3–0.6mm, chlorite 0.5–1.0mm, garnet 0.2mm, albite porphyroblast 1–2 mm.

Angles necessary for reconstructing and checking *s*-surfaces in the diagram are as follows:

$S_3 \wedge S_{1-2}$	31°
$S_4 \wedge S_{1-2}$	21°
Trace of S_5, etc. $\wedge$ tr. of S_{1-2} on the *a* section	29°
Trace of S_6, etc. $\wedge$ tr. of S_{1-2} on the *a* section	23°
$L_{2-3} \wedge L_{2-7}$ on S_{1-2}	49°
$L_{2-3} \wedge L_{2-8}$ on S_{1-2}	42°

Direction of relative movement along surfaces of transversal-schistosity can be determined from the attitude of reoriented flakes of muscovite and chlorite in the slip zone.

From these data the following *s*-surfaces have been established:

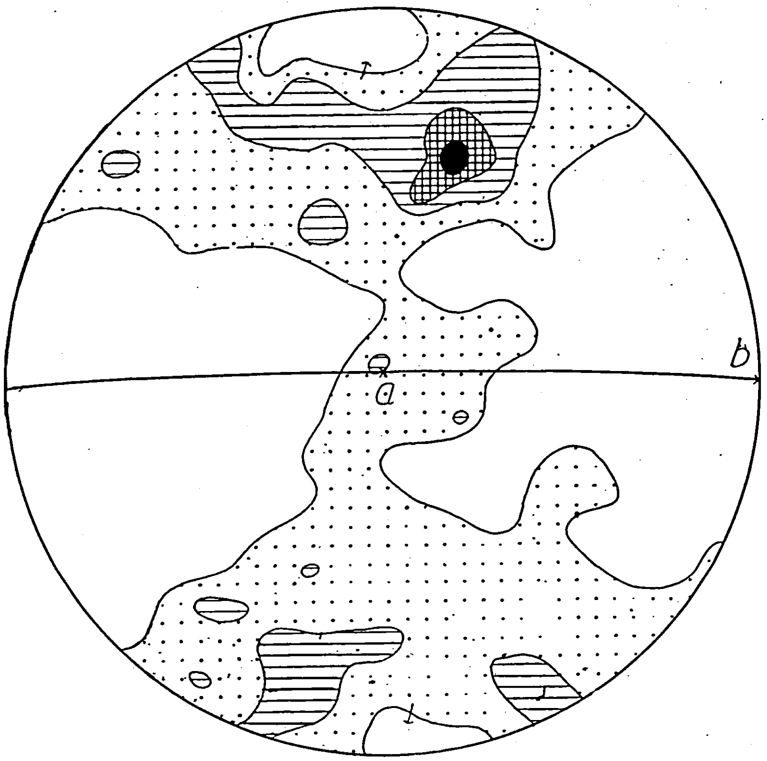

FIG. 11 500 c-axes of quartz. *a* section (nearly perpendicular to *a*) of GHK56V26-2. No selection of grains was made. Max.: 4.6%.Contours: 4-3-2-1%.

The principal schistosity surface: S_{1-2}
The first conjugate transversal-schistosity surfaces: S_3 and S_4
(S_3 is strong, while S_4 is weak)
The second conjugate transversal-schistosity surface: S_5 and S_6 (with reference to S_{1-2}: S_5 strong, S_6 weak); S_7 and S_8 (to S_3: S_7 strong, S_8 weak); and, S_9 and S_{10} (to S_4: both weak)

The disposition of these *s*-surfaces is shown in Fig. 12. The disposition is quite similar to the preceding example (Fig. 10).

Quartz fabric: 500 c axes of quartz grains were measured from a highly quartzose seam on the *a* section without selection of grains. The fabric diagram is shown in Fig. 11. The pattern is characterized by an annular arrangement around the fabric axis *c*. If the situation of maximum and sub-maxima is neglected, therefore, the pattern is rather orthorhombic in symmetry. The occurrence of a single maximum in the first quadrant bestows the diagram a triclinic character. The pattern is somewhat different from the preceding case, but it can be interpreted as follows with the authors' hypothesis.

As has been done in the preceding cases, the corresponding small circle was drawn

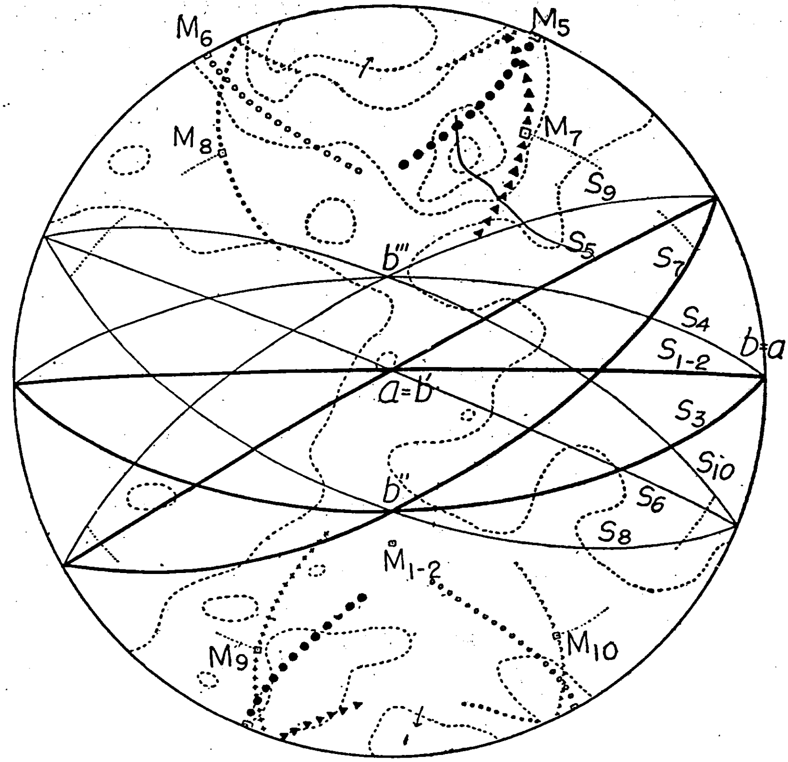

FIG. 12 Analysis for Fig. 11 (see in the text)

for every *s*-surface on the side inferred from the sense of shear along it, the result being shown in Fig. 12. Inferred points of axes concentration on these small circles have been marked with small squares, designated as M_5, M_6, M_7, M_8, M_9, and M_{10}, respectively. It is a remarkable fact that the small circles corresponding to S_5 and S_6 well explain the annular arrangement of axes around *c*. The maximum point in the first quadrant may also be explained as influenced by an axes concentration at M_7, which refers to one of stronger *s*-surfaces, S_7. Accordingly, the annular arrangement of quartz axes around *c* can be fully explained in the same way as in the case of the pattern of crossed small circle girdles. The chief difference between them is that in the latter case the concentration of axes is fairly different between the group of small circles for S_5, S_7, and S_9, and that for S_6, S_8, and S_{10}. That difference is not essential, but only superficial.

The annular arrangement of axes around *c* in the quartz fabric diagram has been noticed by many workers (cf. FAIRBAIRN, 1949, p. 12, and Fig. 2–1, (f)), as is the case with the pattern of crossed small circle girdles. Transitions between these two cases have been suspected by several authors.

Lastly, several words may be added about the geological meaning of the presence of annular pattern in this example. In the preceding two examples, the rocks were collected from the zone of strong lateral displacement, the Otoji transitional zone intervening between the non-spotted and the spotted sub-zones. As has been explained above, the elongation in the direction of fold axis (or the principal lineation) was accompanied by a rotational strain caused by thrusting movement of the northern spotted block upward relative to the southern non-spotted block. This tendency of movement in the later phase of recrystallization has bestowed the rocks a marked one-sided character with respect to the development of *s*-surfaces and to the quartz fabric pattern. On the other hand, the last example explained in this section represents the fabric pattern of rocks in the spotted zone proper. From both the geological and the petrofabric points of view, the spotted zone is characterized by an intense elongation in the axial direction of folds, which is inclined at low angles, forming a marked contrast to the high-angle character of the folds in the Otoji transitional zone. Therefore, the thrusting movement as mentioned above had no influence upon the development of the second transversal-schistosity during the phase of axial elongation. Nearly equal development of small circle girdles of both sides that leads to the annular pattern about *c* conforms to the above statement. The slight unbalance indicated by the presence of a single maximum at a point bearing no relation to the symmetry plan of the rock may show a slight effect of rotational strain caused by the difference in amount of axial elongation between subordinate units of rock within the spotted sub-zone.*

VI. CONCLUDING REMARKS

In the preceding pages three examples of triclinic tectonites from Besshi have been analysed geometrically as well as kinematically, with special reference to the quartz fabric. Through the discussion the authors have made clear that 1) successive systems of *s*-surfaces have been developed in the rocks in keeping pace with the successive change of conditions of material and environment, and that 2) the patterns of quartz fabric can fully be understood with the authors' hypothesis on the preferred orientation of quartz. The results will be summarized in the following, attended with some geological and petrological meanings deducible from them.

System of s-surfaces——geometry of the rock structure: The planar structure of the rocks

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* Most diagrams of quartz fabric in rocks of the spotted sub-zone show similar patterns of annular concentration around *c*. Other examples of similar pattern can be seen in some figures of a previous paper by the present authors (1957, Figs, 2 and 15). They represent the fabric pattern of quartz of aegirine augite-alkali amphibole-quartz-schists in the spotted sub-zone of the Besshi-Shirataki district. There can not be detected any essential differences in the pattern of quartz fabric as well as in other fabric features between the quartz-schists with alkaline mafics and those lacking them. This fact suggests that the history and the geological condition of metamorphism of quartz-schists in the spotted sub-zone were independent of whether they carry alkaline mafics or not. On the basis of these fabric as well as geological facts, the present authors (*ibid.*, pp. 9 and 19) have interpreted the quartz-schists with alkaline mafics as derived from certain siliceous sediments somewhat alkaline in original composition under the same condition of metamorphism as in the case of the other quartz-schists lacking alkaline mafics.

has been analysed by observing directions of slip zones on the oriented sections, *viz.* *b* and *a* sections. To begin with, the principal schistosity surface is noticed as the plane of dimensional orientation of such flaky minerals as muscovite or chlorite. The surface coincides with the plane of laminated structure set forth by the variable modal proportion of constituent minerals, which is to be interpreted as reflecting the original planar heterogeneity of sediments, such as bedding or lamination, named S_1. In the present cases, the plane coincides with that of the axial-plane-schistosity of the isoclinal fold of high-angle, which have been formed by the lateral displacement of the spotted sub-zone relative to the non-spotted one. Therefore, according to the authors' system of designation, the surface is designated as S_{1-2}, that is, the surface represents S_1 as well as S_2, the surface of axial-plane-schistosity.

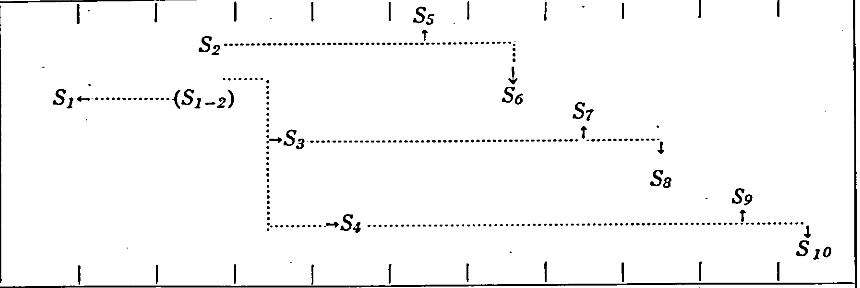
Then, two *s*-surfaces, complementary to each other, can be discriminated by observing the *b* section. They are represented on the section as two sets of slip zones, and they cross the schistosity surface S_{1-2} at a common direction, the principal lineation on S_{1-2}. Accordingly, the direction of the principal lineation must be selected as the tectonic axis *b*, the direction perpendicular to the principal lineation on S_{1-2} the axis *a*, and the normal to S_{1-2} the axis *c*. The angles between these transversal-schistosity (or -cleavage) surfaces and S_{1-2} can be directly measured on the *b* section. This set of transversal-schistosity is designated as the first transversal-schistosity, and the surfaces are designated as S_3 and S_4.

Thirdly, the second sets of transversal-schistosity have been recognized. They are represented as traces of slip zones on the *a* section on the one hand, and as faint striations oblique to and younger than the principal lineation on S_{1-2} on the other. One conjugate set of the second transversal-schistosity is the *s*-surfaces (0kl), occurring in reference to the planar heterogeneity of S_{1-2}, and the other sets, also conjugate, are the *s*-surface (hkl), formed in reference to those of S_3 and S_4. The former is designated as S_5 and S_6, the latter as S_7, S_8; S_9 and S_{10}. Faint striations on S_{1-2} can be correlated with these *s*-surfaces of the second transversal-schistosity, *i. e.*, those normal to the principal lineation, namely a type of *a* lineation, with (0kl), and those oblique to it with (hkl). The direction of intersection of each conjugate set of *s*-surfaces defines the tectonic axis *b* in that phase of deformation, *i. e.*, the intersection of S_5 and S_6 defines b' $(=a)$, that of S_7 and S_8 b'' (on $S_3, \perp b$), and that of S_9 and S_{10} b''' (on $S_4, \perp b$). Accordingly, the tectonites may be named $B \perp B'$-tectonites. *s*-Surfaces of the second transversal-schistosity can be drawn into the diagram approximately by using the mean values of angles between the traces of these *s*-surfaces and the trace of S_{1-2} on the *a* section.

Lineations on S_{1-2} are designated by adopting the subscript numerals of *s*-surfaces crossing S_{1-2} at respective lineations.

s-Surfaces, their related lineations, and tectonic axes are summarized in Table 1. The arrangement of these linear and planar elements of rock structure is shown diagrammatically in Fig. 13.

TABLE 1 *s*-SURFACES, LINEATIONS, AND TECTONIC AXES

Phase		Sedimentation.	Non-spotted metam.	Spotted metamorphism				
				Folding: axial-plane-schistosity	First transversal-schistosity (Elongation in *a*)	Second transversal-schistosity (Elongation in *b*)		
s-surface		 						
Tectonic axes	*a*		a_0	*a*	*a*	$a'(=b)$	$a'(=b)$	$a'(=b)$
	b		b_0	*b*	*b*	$b'(=a)$	$b''(\perp b$, on $S_3)$	$b'''(\perp b$, on $S_4)$
	c	*c*	c_0	*c*	*c*	*c*	$c''(\perp S_3)$	$c'''(\perp S_4)$
Lineation on S_{1-2}			L_0	L_{1-2}	L_{2-3} | (L_{2-4}) (//*b*)	L_{2-5} | (L_{2-6}) (//*a*)	L_{2-7} | L_{2-8} (not parallel either to *a* or to *b*)	L_{2-9} | L_{2-10}

It must be noted that the intensity of development of these *s*-surfaces is different between the sets complementary to each other.

Kinematic interpretation of quartz fabric: Fabric diagrams of quartz of the triclinic tectonites from Besshi are characterized by the following two points: 1) the presence of small circle girdles, and 2) the occurrence of a single maximum at a point not related symmetrically to the symmetry plan established with reference to the principal schistosity plane and the principal lineation. The first point confers a symmetry of orthorhombic or monoclinic character upon the diagram, while the second point lowers the order of symmetry to a triclinic one.

The pattern of quartz fabric diagram has been successfully explained on the basis of a working hypothesis presented by the senior author (G. K.) and T. SUZUKI in the preceding paper of this journal (1958, p. 192) concerning the preferred orientation of quartz sufficiently recrystallized during flow of a rock. The hypothesis states as follows:

1) r $(10\bar{1}1)$ and/or z $(01\bar{1}1)$ of quartz lie on the shear plane, and

2) the sense of displacement of upper layers on these lattice planes is downward from the c axis.

According to this working hypothesis, the pattern of quartz diagram can be predicted, provided that the disposition of *s*-surfaces and the sense of shear movement

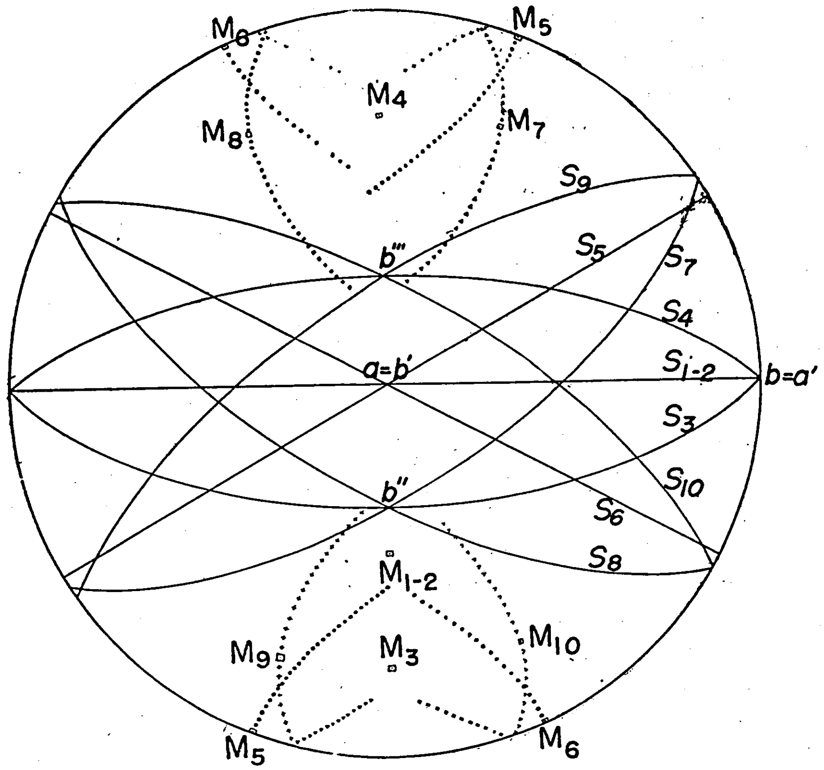


FIG. 13 Schematic diagram showing the disposition of *s*-surfaces, related small circles and points of axes concentration, and tectonic axes. ($\perp a$)

along these surfaces are known. As a matter of fortune, we can establish the sense of shear along each *s*-surface by observing the attitude of reoriented flakes of muscovite and chlorite within the slip zones. The quartz pattern predicted after this hypothesis must have the following characters:

1) from the first item of the hypothesis, it follows that c axes of quartz must lie on the small circles inclined at 38° to respective *s*-surfaces, and
2) from the second item of the hypothesis, it is inferred that i) the axes lie on the small circles of the definite side of respective *s*-surfaces (defined by the sense of shear along respective surfaces), and that ii) the axes are concentrated to the points of intersection of the small circles and the tectonic planes *ac* defined for each conjugate set of *s*-surfaces.

It is to be inferred, furthermore, that the concentration of axes to the predicted points is dependent on the number of quartz grains oriented with reference to the corresponding *s*-surfaces, the latter being proportional to the intensity of development of respective *s*-surfaces. Therefore, the actual point of maximum must represent the resultant effect of concentration of axes with reference to *s*-surfaces with greater intensity of development. This effect induces the triclinic character of symmetry into the diagram. The small circles and the points of axes concentration (M_{1-2}, M_3, M_4,... refer to S_{1-2}, S_3, S_4,..., respectively) corresponding to every *s*-surface are drawn in Fig. 13.

In this paper the authors have begun with the case of distinct triclinic symmetry and proceeded to those of less triclinic symmetry. As shown in the analytical diagrams, Figs. 8, 10, and 12, the pattern of quartz diagrams has been clearly explained, the result suggesting the validity of that hypothesis on the preferred orientation of quartz, at least in those cases of sufficient recrystallization accompanying the flow.

It has generally been accepted that quartz is the most sensitive mineral to orienting movement among rock-forming minerals. The present study also confirms this empirical fact. The essential part of the pattern of quartz fabric diagrams can be exhaustively explained with the preferred orientation of quartz performed in the phase of the second transversal-schistosity, the latest phase of deformation reflected upon the micro-fabric. Only a trace of the effect induced by the shear movement along S_{1-2}, the earliest, but very distinct, phase of deformation, is detectable as an indistinct submaximum in the diagram. The effect of the first transversal-schistosity on the fabric pattern, which may theoretically be predicted as M_3 and M_4 in Fig. 13,could not be distinguished from the girdle concentration referring to the second transversal-schistosity.

Such being the case, it seems to be questioned to interpret the fabric pattern of quartz in terms of the type of fabric pattern of *S*-tectonites, such systems of typology as proposed by SANDER (1950, p. 143ff.) and FAIRBAIRN (1949, p. 9ff., Fig.2–1). In the present examples, the principal schistosity plane, the base plane in the consideration of *S*-tectonites, leaves only an indirect effect in the fabric diagram of quartz as one of planes of heterogeneity which have conducted the trend of the succeeding cleaving of the second transversal-schistosity. It is beyond dispute that there are also true *S*-tectonites, the fabric pattern of which can fully be explained in terms of orienting movement referring to a single *s*-plane. It must be admitted, however, that most tectonites are not simple *S*-tectonites, but they show a certain linear structure, along which must have occurred a certain amount of extension or elongation in the later phase of deformation. Therefore, according to the present authors, the fabric pattern of quartz in the tectonites having more or less distinct linear structure should not be tried to interpret in terms of orienting movement referring only to the principal schistosity plane, but it can be explained successfully in terms of penetrative movement caused by the axial elongation in the later phase of metamorphic history.* For

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* In those cases, to which the authors' hypothesis on the orienting mechanism of quartz can be applied, the situation of maxima and the trend of girdles in the fabric diagram mainly relate to the presence or absence of the second transversal-schistosity. It may be inferred that the presence of that schistosity deviates maxima from the plane *ac*, and gives the pattern a triclinic character with reference to the position of a single maximum, as shown in the present examples. If the second transversal-schistosity is absent, on the other hand, maxima lie on the plane *ac*. The latter case has been illustrated by the senior author and T. SUZUKI (1958) referring to highly sheared rocks of the Kiyomizu tectonic zone. The latter case is rather rare as compared with the former. That may explain the fact that most maxima of quartz axes do not lie on *ac*, as noted by FAIRBAIRN (1949, Fig. 9–4, (a)) and SANDER (1950, Diagr. 49–53).

this reason, the present authors insist on the importance of systematic analysis of rock structure based on the dialectical development of rock deformation.

History of development of s-surfaces: *s*-Surfaces developed in the rocks have been divided into several sets generated under different conditions of material as well as of the environment. The correlation between sets of *s*-surfaces and phases of deformation is summarized in Table 1. Geological conditions and kinematic characters of deformation of these phases will be summarized as follows.

1) **The pre-metamorphic phase:** Sedimentation on the floor of geosyncline. The formation of bedding and lamination, the surface of which is designated as S_1. This surface has been preserved as the most distinct surface of heterogeneity in the rock throughout the whole history of metamorphism.

2) **The phase of non-spotted metamorphism:** The rocks had been metamorphosed in the fashion of low-grade schists generally found in the non-spotted subzone, before the spotted metamorphism began. The rock structure imprinted in this phase can be read from palimpsest structure within the rock: relic lineation L_0, dimensional orientation of epidote parallel to L_0, dimensional orientation of flakes of muscovite and chlorite parallel to S_1 and rotation about L_0, etc. These palimpsest structures suggest that the rock had similar structural features as those observed in the quartz-schists now present in the non-spotted sub-zone.

3) **The phase of folding — axial-plane-schistosity (spotted metamorphism):** Spotted metamorphism began with the introduction of albite. Schist beds were folded together with syntectonic intrusives of ultrabasic rocks. The folding about nearly horizontal axis was accompanied by the intense elongation of rock masses in the axial direction, which caused extensive lateral displacement of spotted schists block relative to the unaffected non-spotted block, especially near the end of a large-scale fold of recumbent type of the Besshi-Shirataki district. The zone suffering this intense lateral displacement is named the Otoji transitional zone. Within this zone the movement caused folds of isoclinal type with high-angle axes. Under the condition of spotted metamorphism, *i. e.*, probably, of higher temperature, and of higher plasticity (pseudoviscosity) owing to the addition of fluid, beds were folded attended by the axial-plane-schistosity, S_2. Within the rocks folded in isoclinal fashion, the axial-plane-schistosity is observable only at the crest of fold, and at the wing the axial-plane-schistosity coincides with the original bedding or lamination, S_1, showing the bedding-schistosity, S_{1-2}. The grain-size of muscovite, chlorite, epidote, and probably garnet, apatite, and hematite, already formed in the phase of non-spotted metamorphism, increased, and furthermore, they were reoriented with reference to the newly established tectonic axes, *a*, *b*, and *c*. Growing porphyroblasts of albite were rotated about *b*. The movement plan of this phase must be characterized by the extensive elongation in the direction *a*.

4) **The phase of the first transversal-schistosity (spotted metamorphism):** The extension and shear movement in the direction *a* during the preceding phase proceeded

along with complete recrystallization of quartz. This process can not proceed unlimitedly, because the recrystallization of quartz reoriented in accordance with the stress plan must cause the hardening of rock material, a phenomenon similar to that known to metallurgists as work-hardening. Then, the way of yielding in response to the stress, unchanged in respect to its plan, must be changed. The rock was cleaved, forming the first transversal-schistosity (S_3 and S_4, complementary to each other). The schistosity (or cleavage) is represented as sets of slip zones, and pre-existing minerals such as muscovite or chlorite have been rotated internally in the sense of the shear movement along the slip zone. Conjugate sets of *s*-surfaces of the first transversal-schistosity intersect each other at *b*, and accordingly, the resultant movement plan by these *s*-surfaces implies the extension in *a*, that representing the continuation of the movement in the preceding phase. Moreover, the one-sided development of the sets of *s*-surfaces indicates the effect of a rotational strain, the sense of which has been the same as that of the internal rotation caused by the shear movement along S_{1-2} in the preceding phase. This fact also affirms the idea that the movement plan of this phase corresponds to the continuation of the deformation of the preceding phase. However, the condition of the material and the environment must have been changed with the entrance of this phase: there are no decisive evidences suggesting the lowering of temperature, but most minerals other than quartz and albite ceased their crystallization, and the rock became less plastic owing to the hardening.

5) **The phase of the second transversal-schistosity (spotted metamorphism):** The last phase of deformation is characterized by the extension in the direction of *b*. At the beginning of this phase, the rock had three sets of planar heterogeneity, namely S_{1-2} (the bedding-schistosity), S_3 and S_4 (the first transversal-schistosity), which have conducted the trend of cleaving in response to the stress plan causing the extension in *b*. Accordingly, three conjugate sets of *s*-surfaces have been formed with the symmetrological *b* axes perpendicular to the axis *b* of the preceding phases ($S_5, \cdots\cdots, S_{10}$). These *s*-surfaces are represented generally by sets of slip zones within the rock, but in cases characterized by the one-sided development of the system, strong dimensional orientation of elongated quartz grains parallel to the *s*-surfaces can be observed. The one-sided character of the second transversal-schistosity implies the effect of a rotational strain on the extension in *b* (with concomitant compression perpendicular to *b*).

The cause of that sudden transition from the phase of elongation in *a* to that of elongation in *b* is a difficult problem. It may naturally be conceivable that also in the preceding phases subordinate stretching (E. CLOOS, 1946, p. 22ff.) in the direction of *b* had accompanied the principal movement in *a*, but, contrary to the cleaving by the principal movement, no cleaving had occurred in response to the subordinate stretching. This fact suggests that the stretching in *b* was insignificant in amount as compared with the principal extension in *a* in the preceding phases. On the contrary, at this phase, the stretching in *b* must have become the principal movement. After the view of the present authors, the transition in the direction of principal movement must have been caused by the change in the mechanical property of rock, *i. e.*, the deformability in the direction of *a* had been diminished stepwise with the progress of deformation (and mineralization), and finally, when the value of deformability in *a* became below that value in *b*, the movement plan of the rock changed its direction, causing the elongation in *b*.

In the phase of the second transversal-schistosity, femic minerals ceased their crystallization, and were split apart or cracked nearly perpendicular to *b* owing to the streching of quartzose matrix in *b*. The growth of snowball-type porphyroblasts of albite was continued, and their rotation about *a* can be observed in the *a* section of rock. The physical as well as chemical conditions of the material and the environment must have been degraded gradually from the preceding phase towards this phase, *i.e.*, becoming less plastic, less amount of fluidal material, and temperature lowered.

Phase analysis of metamorphism: One of the most important contributions to petrology made by petrofabrics must be the recognition of the presence of various phases in metamorphism, each being characterized by respective modes of deformation and mineralization. At this stage of development of metamorphic petrology we can not stand on the side of BECKE and GRUBENMANN, who presumed that crystalloblastic fabric was attributed to simultaneous growth of all the component crystals. In his description on the application of the mineral facies principle, ESKOLA (1939, p. 341) has established the "*Hauptphase der Mineralbildung der Fazies*", when the critical minerals of a certain mineral facies crystallized. Furthermore, he discriminated in a rock between these syngenetical, critical minerals and other "*proterogen*" or "*hysterogen*" ingredients. In this connection, H. H. READ (1948, p. 165) says, "it is clear, however, that complete interpretation of all the detail seen in a facies must lead to conclusions regarding the metamorphic history of a rock—that is, to genetic conclusions—except in those rare cases where equilibrium is completely reached. ESKOLA (1939, pp. 341–3) himself realizes this and decides that the study of unstable relics, posterior products and non-equilibrium associations will supply the history of the rocks. *This, of cause, will be of much greater geological importance than the study of true equilibrium facies*" (italicized by the present authors). The last sentence of this quotation seems to the present authors of utmost importance to metamorphic petrology at present. As has been described in the preceding sections, the metamorphism, including both re- or neo-crystallization and deformation, must have proceeded stepwise, keeping pace with the change in both physical and chemical conditions of the material and the environment. At present, it is necessary to collect precise and sufficient knowledges about the historical development of metamorphism, that is, the phase analysis of metamorphism. The logical background of phase analysis must be the dialectic of metamorphic process, which is expressed in the process as discontinuous steps in the development.

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EXPLATION OF PLATE

PLATE 28

FIG. 1. Quartz-schist (GK 55 XI 17-1). *a* section. Lower nicol only. × 76.

FIG. 2. *ibid.* Crossed nicols.

FIG. 3. Quartz-schist (GK 55 XI 17-1). *b* section. Lower nicol only. × 76.

FIG. 4. *ibid.* Crossed nicols.

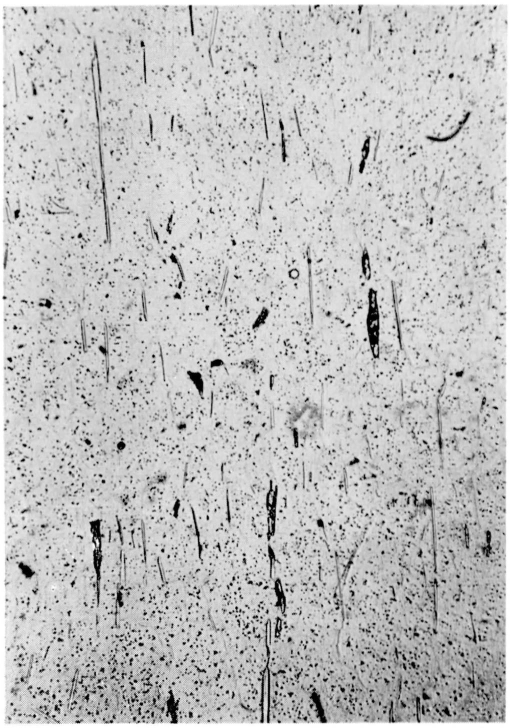

FIG. 1

FIG. 2

FIG. 3

FIG. 4