Rock Structure and Quartz Fabric in a Thrusting Shear Zone: the Kiyomizu Tectonic Zone in Shikoku, Japan

By

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with 2 Plates and 24 Text-figures

ABSTRACT A remarkable thrusting shear zone has been found near the southern margin of the Sambagawa crystalline schist zone in Central Shikoku, representing a frontal zone characterized by thrusting shear movement towards the south, the movement having been caused by the horizontal compression and the consequent upward swelling of the metamorphic zone. The zone has been designated as the Kiyomizu tectonic zone. Rock structures, such as bedding-schistosity or -foliation, fracture-cleavage, closely spaced shear-cleavage, and the related lineations, have been geometrically analysed for rocks both in the tectonic zone and in the northern metamorphic zone proper. On the basis of these geometrical features, the history of development of the tectonic zone has been discussed. Then, the quartz fabric of rocks in the zone has been analysed. The pattern shows an intimate relation between the position of maximum and the direction and the sense of shear on the bedding-schistosity plane of papery schists characteristically found in the tectonic zone. From this definite relation has been deduced a working hypothesis about the orientation of quartz in the flow of rocks, especially in those cases of strong recrystallization or segregation under stress condition.

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I. INTRODUCTION

As the mineral quartz is one of the most predominant constituents of various types of metamorphic rocks and its petrofabric measurement is rather easy, a number of petrofabric diagrams have been put forth from many metamorphic regions of the world. Nevertheless, we have hitherto obtained no comprehensive theory which explains manifold situation of the maximum in quartz fabric diagams. In his typological treatment of fabric patterns of quartz, H. W. FAIRBAIRN (1949) has discriminated twelve types of patterns found in tectonites. However, he did not advance any theory to explain the mechanism of orientation of quartz crystal. According to the authors' view, the difficulty in interpreting the fabric pattern of quartz may be due to such reasons as that the mineral behaves very sensitively in orienting movement, and that the orientation of quartz responsible for every stage of deformation has been integrated into a single fabric diagram. For that reason, it is required for the analysis of fabric pattern of quartz that we have a clear knowledge on the geologic structure of the metamorphic region which allows us to deduce the precise movement plan and its change during a long history of metamorphism, and that the disposition of both primary and secondary *s*-surfaces must be exhaustively analysed. Moreover, as far as circumstances may permit, is desired to select rocks having a simpler planar structure, which may give rise to a simpler pattern of the fabric diagram. In that case we can obtain a clear correspondence of orientation of quartz to *s*-surface, *i. e.*, to the orienting movement. In this connection black-schist in the Kiyomizu tectonic zone offers a good example.

In August, 1951, the senior author (G. K.) made a cursory inspection of geology of a southern marginal area of the Sambagawa metamorphic zone in Central Shikoku along the highway from Saijô to Ino, and found a distinct thrusting shear zone which demarcates between the metamorphic zone proper to the north and the southern marginal belt of weak-metamorphic rocks. In November, 1954, he made the second survey in the vicinity of Kiyomizu along that highway.* After that, the junior author (T. S.) has started on the geological and structural-petrological studies of the tectonic zone in April, 1955. He has studied the area from Jizôji to Iwahara along the Yoshino River, which represents the eastern extension of the zone in the Kiyomizu district. Although his study is now in progress, and the complete results will be published in future, the authors have reached a conclusion about a rule of orientation of quartz in reference to the shear plane in a case of simpler tectonite. In this paper will be described an outline of geology and rock structure in and near the Kiyomizu tectonic zone and the quartz fabric of black-schist in the zone, in connection with which the behaviour of quartz crystal in shear movement will be inferred.

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II. OUTLINE OF GEOLOGY AND ROCK STRUCTURE

OUTLINE OF GEOLOGY

A greater portion of mountainous district in Central Shikoku is occupied by crystalline schists of lower metamorphic grade, named the Sambagawa crystalline schist system. It consists of beds of black-schist, sandstone-schist, green-schist, and quartz-schist, which attain to some ten thousands meters in total thickness. The geological structure of the schist region is generally characterized by a gentle folding of strata, the dip of which

* The result has been published in 1956 (G. KOJIMA, *etc.*), and in that paper the zone has been named the "Kiyomizu tectonic zone".

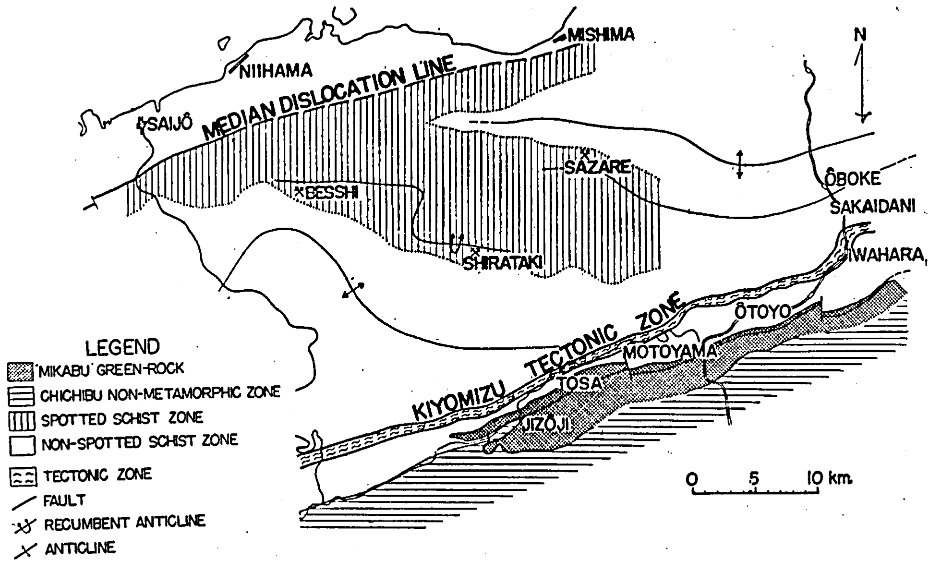

FIG. 1. Geological situation of the Kiyomizu tectonic zone.

rarely exceeds 50°. Cleavage structure is extensively developed throughout the schist region, cutting the bedding-schistosity or -foliation at high angles. The dip of the cleavage is close to vertical in most part of the low-grade schist region. The geology and rock structure of the Sambagawa schist zone proper change their character at the north of the Kiyomizu tectonic zone. As to the geological position of the tectonic zone, the reader is referred to the adjoining sketch-map (Fig. 1).

In the Jizôji-Motoyama district the tectonic zone is running through the terrain almost exclusively composed of black-schist which is correlated to a member of the Lower Sub-formation of the Minawa Formation. It is very difficult to discriminate the black-schist of the tectonic zone from that of the Sambagawa zone proper, especially for unfamiliar eyes. On the other hand, in the Iwahara-Iya district to the east of the above district, the tectonic zone runs through the schists belonging to the Koboke and the Minawa Formations which include, beside black-schist, layers of sandstone-schist, quartz-schist, and green-schist. Such geological situation in the district enables us to trace the changes in structure of beds differently characterized in competency in and near the tectonic zone.

To the north of Iwahara three beds of sandstone-schist belonging to the Koboke Formation in the Sambagawa schist zone proper are cut across by the tectonic zone as shown in the geological map (Fig. 2). Each bed has a thickness of 200m, 150m, and 100m, from the lower to upper one, and lies nearly horizontally. Whereas, just at the north of the tectonic zone, the beds have been bent, forming an asymmetrical fold, named the "Sakaidani anticline", with an axial plane overturned to the south. This type of folding characterized by the overturned axial plane presents a marked contrast

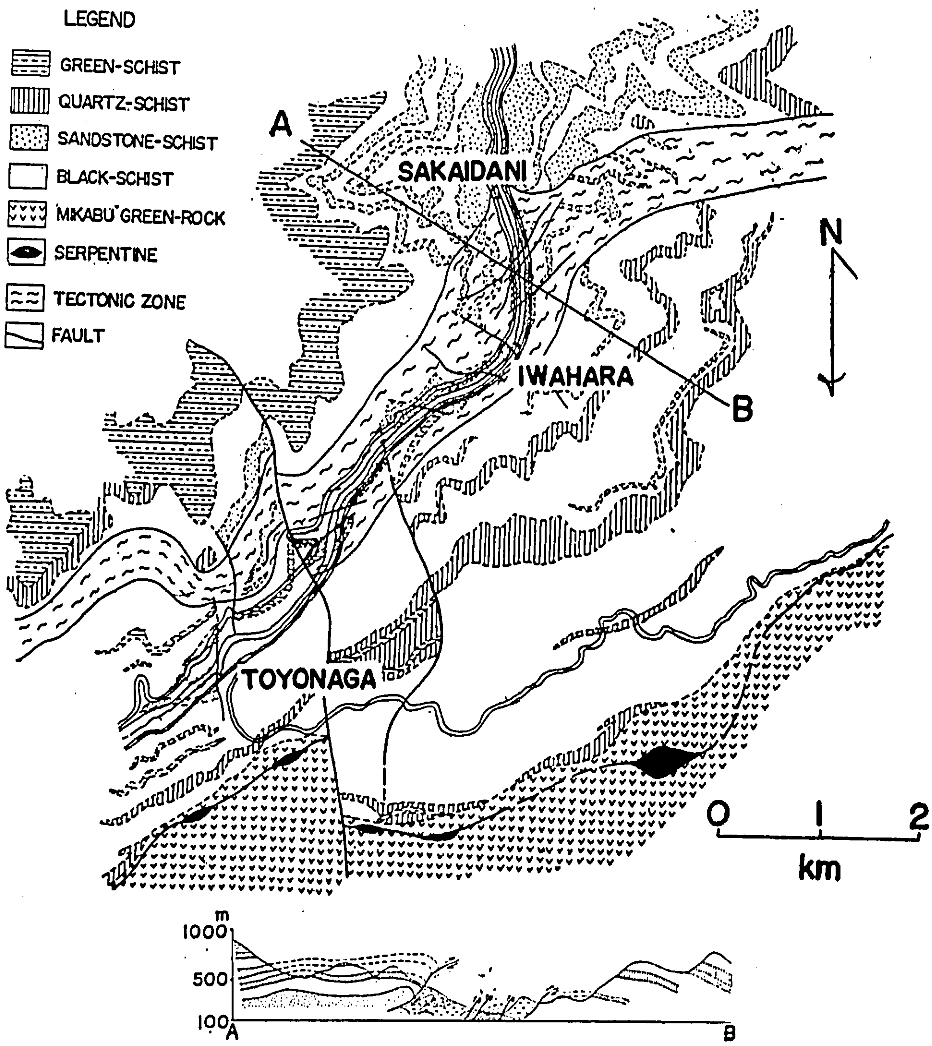

FIG. 2. Geological map of the Iwahara district.

to those found in the interior of the Sambagawa metamorphic zone proper, which have nearly vertical axial planes. Therefore, the occurrence of a southerly overturned fold at the boundary to the tectonic zone should be interpreted as an evidence of an over-thrusting movement of the northern metamorphic zone proper against the southern belt of weak-metamorphic rocks.

Just at the lower wing of the Sakaidani recumbent fold, there begins the zone of strong shear movement, the Kiyomizu tectonic zone. The zone is characterized by the predominance of a characteristic type of black-schist, which shows smooth schistosity surface with the strike and northerly dip consistent throughout the tectonic zone, and is easily exfoliated in thin papers of schist. As will be explained later, this type of schist represents a strong shear movement along the schistosity-foliation plane. The continuation of beds of competent sandstone-schist above mentioned into the tectonic zone is disturbed by the development of this papery schist, and each bed has been torn into lenticular bodies, as shown in the geological map (Fig 2).

PLANAR AND LINEAR STRUCTURES OF THE SAMBAGAWA METAMORPHIC ZONE PROPER IN THE IWAHARA DISTRICT

In rocks of the Sambagawa crystalline schist zone proper to the north of the tectonic zone can be discriminated three types of *s*-surface and lineations representing the intersections of these *s*-surfaces. The *s*-surfaces and lineations are classified as follows, using different subscript numerals:

S_1: the surface of bedding-schistosity and also, often, that of bedding-foliation, in the sense of A. HARKER (1932), *i. e.*, the surface of compositional banding. The surface is determined by the parallel orientation of sericitic mica flakes in black-schist and sandstone-schist, and especially in black-schist it coincides with the surface of compositional banding marked by the alternation of quartzose layers and dark-coloured ones composed of sericitic mica and graphitic matters. On the surface are found wrinkles, which are to be attributed to the formation of transversal cleavage structures, such as S_2 and S_3.

S_2: the surface of fracture-cleavage, in the sense of DE SITTER (1956 a), crossing the surface of bedding-schistosity, S_1, at high angles. It is mainly developed in black-schist, but lacking, in general, in competent beds of sandstone-schist. The thickness of microlithons bounded by adjoining cleavage surfaces is 2–3 cm, which coincides with the wave-length of micro-fold of S_1. The fracture-cleavage is generally formed on the flank of the micro-fold. The axial plane of both minor and micro-fold is parallel to S_2. The surface S_2 is sometimes traversed by a set of surfaces of closely spaced cleavage, S_3, showing wrinkles.

S_3: the surface of closely spaced shear-cleavage of the type of slaty cleavage. This type of cleavage is not restricted within black-schist, but also found in sandstone-schist. The interval between adjoining cleavage surfaces is of the order of 0.1 mm, but somewhat wide in sandstone-schist. It disappears within quartzose layers. The surface is smooth, and its continuation is good.

L_{1-2}: the lineation represented by the intersection of S_1 and S_2. It is shown as parallel streaks or ribs on S_1. As the axial plane of minor as well as micro-fold of S_1 is parallel to S_2, the axes of these folds coincide generally with the lineation L_{1-2}.

L_{1-3}: the lineation repesented by the intersection of S_1 and S_3. This is shown as fine crinkles overprinted on the wavy surface of S_1. The direction of them do not coincide with that of L_{1-2}, *i.e.*, the trend of axes of micro- or minor folds of S_1.

L_{2-3}: the lineation represented by the intersection of S_2 and S_3. This is shown as fine crinkles on the surface S_2.

In the following will be described geometrical relationship between these planar and linear elements.

The π-diagram for S_1 has been constructed by projecting poles of S_1 on the lower hemisphere of equiareal projection (Fig. 3). The concentration of the plotted points on the net of equiareal projection is expressed in percentage computed from the number of point in one percent area of the net. Poles of S_1 form a complete girdle (π-circle) on a great circle. Maxima and sub-maxima within the girdle reflect the bending of S_1 around the axis of the Sakaidani recumbent anticline.

The pole of the great circle girdle of S_1, the β-axis for S_1, is represented by the single maximum of the β-diagram for S_1 (Fig. 4). The diagram has been constructed after the method of B. SANDER (1948, p. 132).*

The azimuth and plunge of the β-axis for S_1, read from Fig. 4, are N77° E and 5°, respectively, which represent the trend of major fold-axis for S_1, namely the bedding-surface of schist beds.

The π-diagram for S_2, the surface of fracture-cleavage, is shown in Fig. 5. The diagram shows a marked maximum with some spreading on a great circle. The maximum corresponds to the constancy in the trend of S_2, which overturns to the south within the Sakaidani recumbent fold. The great circle, in which poles for S_2 spread, coincides practically with the π-circle for S_1, as shown in the synoptic diagram, Fig. 8. This fact indicates that S_2 is tautozonal with S_1, and further, that S_2 has been formed at the time of the folding of S_1 under the same stress-plan.

The lineation L_{1-2} has been plotted in Fig. 6, which shows a distinct maximum, the B-axis in the sense of B. SANDER. The azimuth and plunge of L_{1-2} are N77° E and 0°, respectively. Therefore, the trend of L_{1-2} coincides practically with that of the β-axis. That follows as a consequence of the tautozonality of S_1 and S_2, as mentioned just above.

The trend of the closely spaced shear-cleavage, S_3, is very constant throughout the region, as shown in Fig. 7. The surface is almost vertical with the strike of N88° E. It must be noted that the trend of S_3 deviates obviously from that of the tautozonal axis B or β for S_1 and S_2, as read from the synoptic diagram of Fig. 8. This fact suggests that closely spaced shear-cleavage has arisen under the stress condition independent of the folding and fracturing of schist beds. As shown in Fig. 1, Pl. 25, the fracture-cleavage S_2 is traversed by S_3, and folded after the type of cleavage-fold. The formation of S_3 is, therefore, clearly later than the main phase of folding and fracturing.**

* SANDER has defined β-axis as follows: "Unter einer β-Achse verstehen wir die Schnittgerade zweier oder mehreren Ebenen s oder eine statistische Häufung solcher Schnittgeraden. β ist also konstruktiv leicht erhältlich, wenn man auf der Lagenkugel (Netz) entweder die Ebenen, deren β interessiert als Ebenen (Grosskreise) einträgt oder die Lote dieser Ebenen".

** The number of measurement for L_{1-3} and L_{2-3} is not sufficient for constructing statistical diagrams. They are distributed in the diagram on the plane of S_3, with nearly E-W azimuth. The geometry of superposed deformation has been discussed lately for Dalradian rocks by L. E. WEISS and D. B. MCINTYRE (1957).

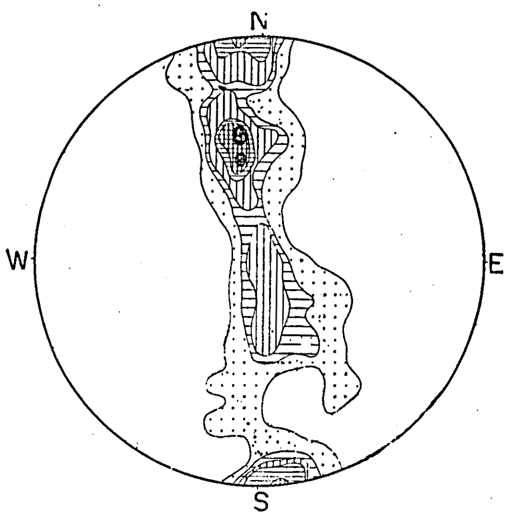

FIG. 3. π-diagram for S_1 of schists in the Sambagawa metamorphic zone proper of the Iwahara district. 81 points. Contours: 18-14-10-5-3-1%.

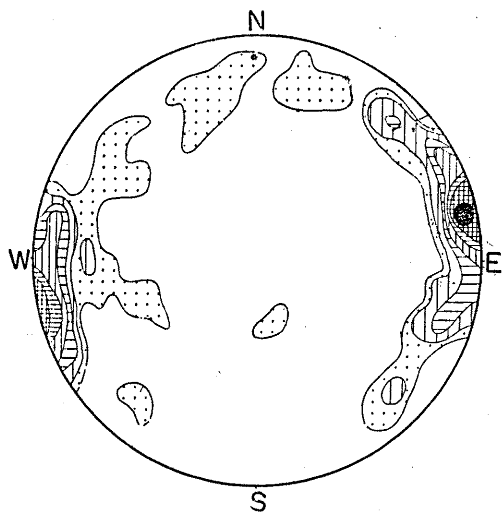

FIG. 4. β-diagram for S_1 of schists in the Sambagawa metamorphic zone proper of the Iwahara district. 276 points. Contours: 24-18-13-8-4-2-0.35%.

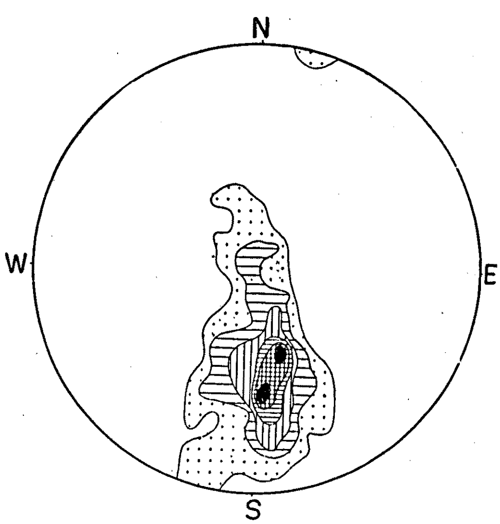

FIG. 5. π-diagram for S_2 of schists in the Sambagawa metamorphic zone proper of the Iwahara district. 125 points. Contours: 21-18-15-10-5-1%.

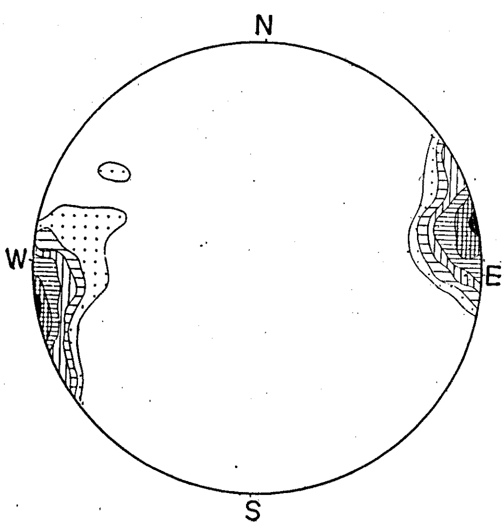

FIG. 6. L_{1-2} of schists in the Sambagawa metamorphic zone proper of the Iwahara district. 57 points. Contours: 30-20-12-7-5-2%.

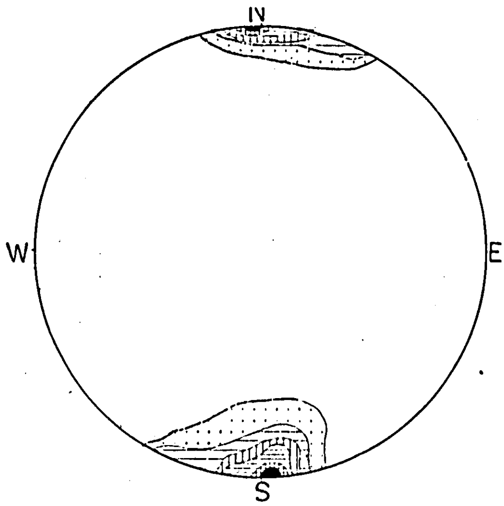

FIG. 7. π-diagram for S_3 of schists in the Sambagawa metamorphic zone proper of the Iwahara district. 30 points. Contours: 26-20-15-10-5-1%.

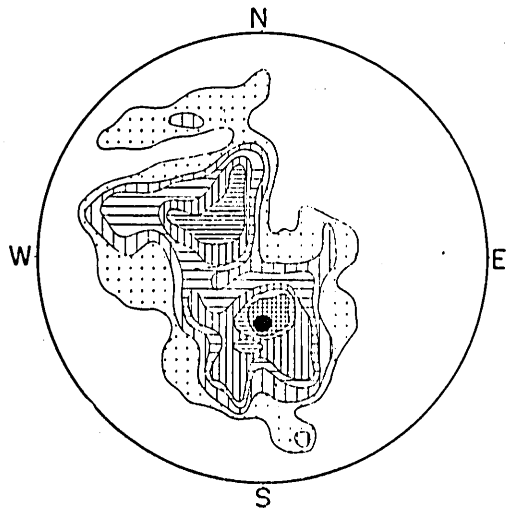

FIG. 9. π-diagram for S_2 and S_{1-2} of schists in the Kiyomizu tectonic zone of the Iwahara district. 95 points. Contours: 15-10-7-4-3-2-1%.

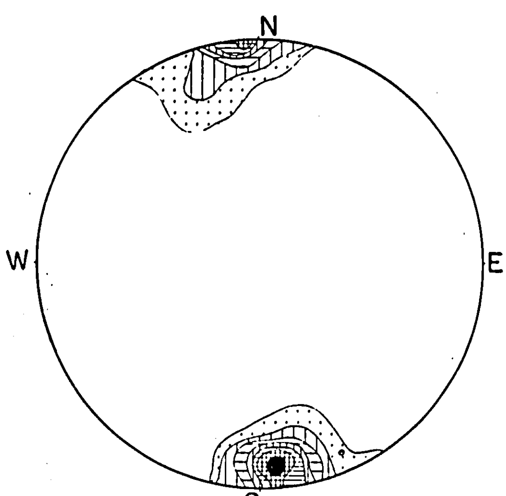

FIG. 10. π-diagram for S_3 of schists in the Kiyomizu tectonic zone of the Iwahara district. 100 points. Contours: 25-20-15-10-5-3-1%.

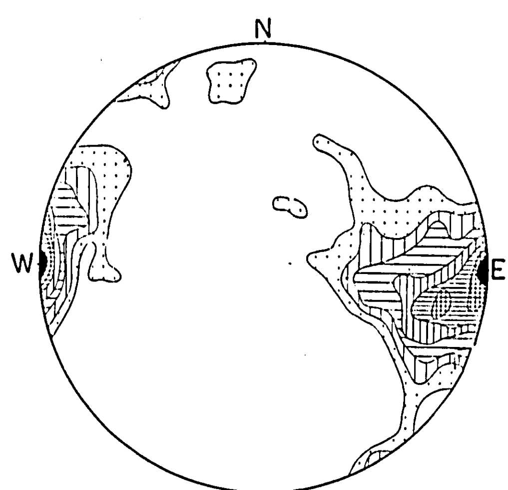

FIG. 11. L_{2-3} of schists in the Kiyomizu tectonic zone of the Iwahara district. 80 points. Contours: 13.5-11-8-6-4-3-1%.

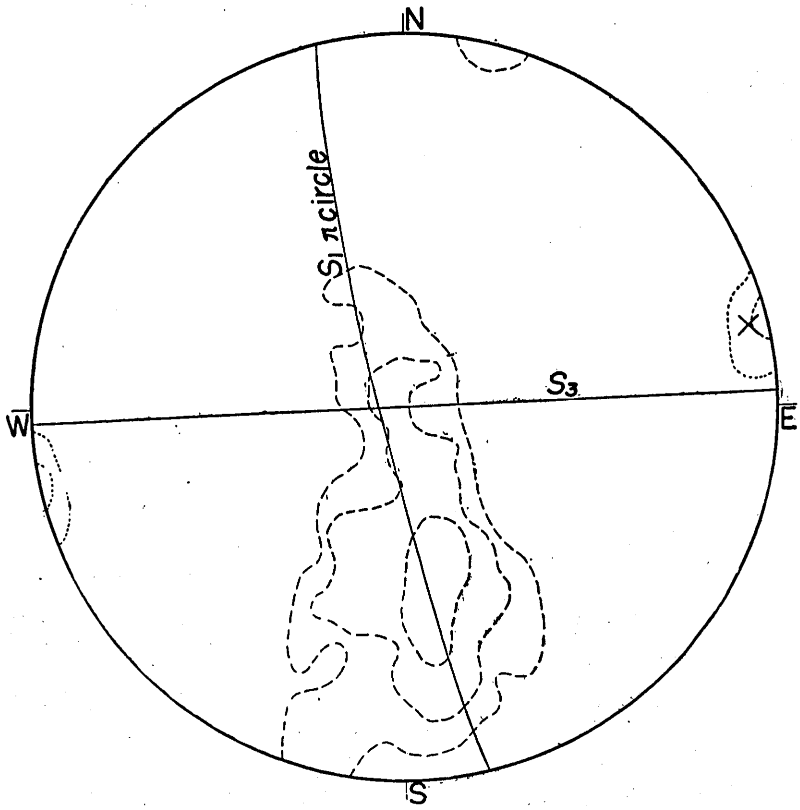

FIG. 8. Synoptic diagram of structural elements of schists in the Sambagawa metamorphic zone proper of the Iwahara district. Dashed contours for S_2: 15-5-1%. Dotted contours for L_{1-2}: 30-20%. Cross presents β-axis for S_1.

PLANAR AND LINEAR STRUCTURES OF THE KIYOMIZU TECTONIC ZONE IN THE IWAHARA DISTRICT

Several *s*-surfaces and lineations have been discriminated in rocks of the Kiyomizu tectonic zone. They are classified as follows, using respective subscript numerals which correspond to those of the Sambagawa metamorphic zone proper:

S_1: the surface of bedding-schistosity or -foliation.

S_2: the surface of fracture-cleavage. (S_1 and S_2 have the same characteristics as those of the metamorphic zone proper above described.)

S_{1-2}: the surface of schistosity-foliation plane of the papery schist characteristic in the tectonic zone. At the lower wing of recumbent folds of small scale, which are numerous within the tectonic zone and bounded by belts of papery schist, rocks have suffered extension and strong shear movement along the bedding-surface, that resulting in the production of the characteristic papery schist. The surface of the schistosity-foliation retains features of bedding-foliation, that is S_1, and, on the other hand, its trend is parallel to S_2 of the nearby recumbent fold. The belts of papery schist must be interpreted as representing the loci into which the thrusting shear movement has been focused. The surface is smooth with silky luster, but, when S_3 is present, it shows fine crinkles owing to the slip along the surface of closely spaced shear-cleavage, S_3.

S_3: the surface of closely spaced shear-cleavage of the type of slaty cleavage. This type of cleavage is generally found throughout the tectonic zone irrespective of rock-species and structure. Its characteristic features are the same as those in the metamorphic zone proper above described.

L_{1-2}: the lineation represented by the intersection of S_1 and S_2. In the tectonic zone this type of lineation is found in the folded parts bounded by the belts of papery schist. The characteristic features of the lineation are the same as those in the northern metamorphic zone proper.

L_{1-3}: the lineation represented by the trace of S_3 on the surface S_1.

L_{2-3}: the lineation represented by the trace of S_3 on the surface S_2 or S_{1-2}. It is shown as fine crinkles on the surface S_{1-2} of the papery schist.

Geometrical relationship between these planar and linear elements will be described in the following.

The π-diagram for S_2 and S_{1-2} is shown in Fig. 9. The pattern of the diagram may be interpreted as indicating a two-girdle arrangement. The main girdle is represented in the synoptic diagram, Fig. 12, as a great circle, the pole of which has the azimuth and plunge of N71° E and 8°, respectively, the direction being very close to the B-axis of the northern metamorphic zone proper; namely, the tautozonal axis for S_1 and S_2. From this may safely be concluded that the pole of the main girdle in the π-diagram for S_2 and S_{1-2} is also the zone-axis for S_2 and S_{1-2}, *i.e.*, the B-axis, at the phase of deformation when the folds of recumbent type and shear-zones have been formed.

The π-diagram for S_3 (Fig. 10) shows a very similar pattern as that of the metamorphic zone proper (Fig. 7). The trend of S_3 is very constant throughout the tectonic zone as indicated by the single maximum of high concentration in the diagram. No spreading of points of girdle type can be found. From the position of the maximum point in Fig. 10, the strike and dip of S_3 are determined to be N86° E and 81° N, respectively. This direction coincides nearly with that of S_3 of the northern metamorphic zone proper. In the tectonic zone, also, the direction of S_3 deviates obviously from that of the B-axis, the fact suggesting that the closely spaced shear-cleavage has arisen during the later phase of shear movement under the stress condition independent of the folding and shearing of schist beds in the tectonic zone. Furthermore, the coincidence of trend of S_3 between the tectonic zone and the metamorphic zone proper suggests the simultaneous formation of the shear-cleavage under the stress-plan identical through both zones.

On the surface S_{1-2} there is often observed a lineation in the form of fine crinkles,

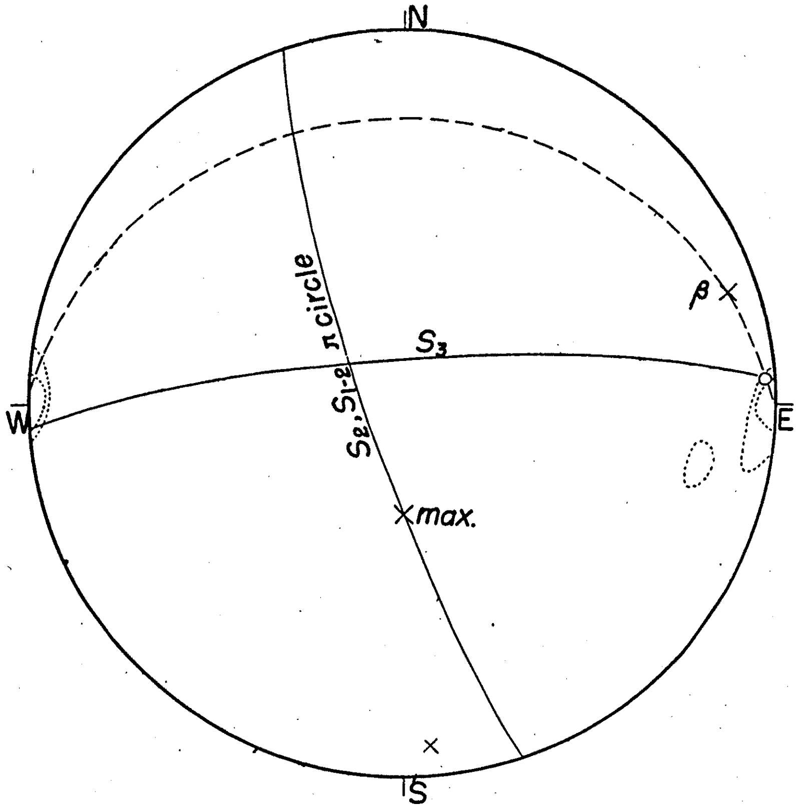

FIG. 12. Synoptic diagram of structural elements of schists in the Kiyomizu tectonic zone in the Iwahara district. Dotted contours for L_{2-3}: 13.5–11%.

designated as L_{2-3}, which have been formed by slip movement along the shear-cleavage S_3. The direction of L_{2-3} is to be inferred geometrically from the directional data for S_{1-2} and S_3. An example is shown in the synoptic diagram, Fig. 12. In the diagram great circles for S_{1-2} and S_3 have been drawn, which correspond respectively to the maximum points of S_{1-2} (S_2) in Fig. 9 and S_3 in Fig. 10. The point of intersection of these two great circles is L_{2-3} in this case. Because of the spreading of poles of S_{1-2} (S_2) in girdles, the position of intersection of S_{1-2} and S_3 is not fixed. However, as the trend of S_3 is fairly constant, the points of intersection must lie nearly on the great circle of S_3 in Fig. 12. In Fig. 11 are shown the tendency of concentration of L_{2-3} measured within tectonic zone. The single maximum nearly coincides with the derived point of intersection of S_{1-2} and S_3 in the synoptic diagram, Fig. 12; namely, the observed L_{2-3}, corresponding to the maximum point in Fig. 11 is 0° to E, while the derived L_{2-3} is 2° to N86°E. Furthermore, the spreading of L_{2-3} coincides roughly with the great circle of S_3 maximum.

In the foregoing paragraph the authors have noticed a two-girdle arrangement of pattern in the π-diagram for S_2 and S_{1-2}. One of these two great circle girdles has been interpreted as the π-circle with the zone-axis B. Through the above discussion on L_{2-3}, it becomes now clear that another great circle girdle is related to L_{2-3}, *i.e.*, this latter π-circle reflects the folding of S_{1-2} of the type of cleavage-folding by slip movement along the shear-cleavage S_3 (Figs. 2 and 3, Pl. 25).

DEVELOPMENT OF THE GEOLOGY AND ROCK STRUCTURE OF THE KIYOMIZU TECTONIC ZONE

From the above discussion on the geometrical relationship between various planar and linear elements of rock structure in and near the Kiyomizu tectonic zone, the following three points may be picked up as important facts in considering the development of the geology and rock structure of the tectonic zone.

1) The fold-axis of S_1, the zone-axis of S_2 and S_{1-2}, and the lineation L_{1-2} coincide in trend with each other both in the metamorphic zone proper and in the tectonic zone. This trend defines the B-axis of the folding in the earlier phase of deformation. Besides, it must be noted that the B-axis in the tectonic zone has the same direction as that in the metamorphic zone proper. From this may be inferred that the folding of recumbent type and the thrusting shear movement characterizing the tectonic zone have been occurred under the same stress-plan in the earlier phase of deformation of the Sambagawa metamorphism.

2) The folded surface of bedding-schistosity or -foliation (S_1) and the surface of fracture-cleavage (S_2) as well as that of schistosity-foliation (S_{1-2}) of the papery schist in the tectonic zone have been crossed by closely spaced shear-cleavage (S_3) both in the metamorphic zone proper and in the tectonic zone. Those earlier surfaces have often been displaced by slip movement along the cleavage-plane S_3, showing typical cleavage-folds. The formation of this closely spaced shear-cleavage is distinctly later than the main folding and fracturing described in the upper paragraph.

3) The direction of the closely spaced shear-cleavage shows no significant difference between the metamorphic zone proper and the tectonic zone. The surface S_3 has roughly E-W strike with nearly vertical dip, the direction bearing no direct relation to that of the B-axis of the earlier folding. This fact suggests that the closely spaced cleavage has been formed under the stress-plan independent of the earlier folding and fracturing of schist beds.*

* Recently, interesting discussions have been reported on the journal, "*Geologie en Mijnbouw*" (Journal of Royal Netherlands Geological and Mining Society) about the relation between cleavage and folding. After M. G. RUTTEN (1955), "There is no correlation (of cleavage) with larger or smaller folds nor with the axial planes...... The dip of the schistosity [cleavage in the sense of the present authors] planes is distributed on a pattern of its own coinciding with the axial planes in some places but divergent in others." Responding to the criticism by RUTTEN, P. FOURMARIER (1956) insists: "la schistosité (cleavage), malgré la diversité de ses aspects est en relation étroite avec le plissement...... En conclusion, selon moi, le développement de la schistosité est dû aux mêmes efforts qui ont produit le plissement,

Based upon these fundamental facts, the history of development of the Kiyomizu tectonic zone may be outlined as follows.

Geosynclinal sediments consisting of mud, sand, siliceous matter, basic tuff and lava, which attain to some ten thousands meters in thickness, have been put in folding at a certain time between the Late Permian and the Early Triassic. The style of the folding in the earlier phase of tectogenesis is characterized by the flexure of beds accompanied with slip along the bedding-surface or the lamination in bed, which becomes the surface of bedding-schistosity and -foliation in the course of metamorphic recrystallization and differentiation. At a certain stage of folding fracture-cleavage has begun to form in less competent parts of the fold, especially in the portion of black-schist, while, the competent beds such as of sandstone-schist have continued their flexuring.

In most parts of the Sambagawa metamorphic zone proper folds of this earlier phase of tectogenesis have almost horizontal fold-axes and nearly vertical axial planes, while, near the southern margin of the metamorphic zone proper the fold-axial plane tends to overturn to the south, where many recumbent folds of smaller scale occur bounded by belts of the characteristic papery schist formed by extension and strong shear movement along the bedding-surface. That is the Kiyomizu tectonic zone. The parallelism in fold-axis and shear-surface between the metamorphic zone proper and the tectonic zone indicates the contemporaneity of folding, fracturing, and shearing in these two zones. In Fig. 13 is shown the schematic relation in structure, both geologic and petrofabric, between the northern metamorphic proper, the middle tectonic, and the southern weak-metamorphic marginal zones, as vertical and horizontal sections. As the closely spaced shear-cleavage is omitted from the figures so as to avoid confusion, the sections in Fig. 13 represent the relation in this earlier phase of tectogenesis. As explained in the above sections, the *B*-axis plunges to ENE at small angles. Therefore, the horizontal section shows the similar pattern as the vertical one. The notice-

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à condition qu'il y ait eu charge statique suffisante au moment de la tectogenèse,......"; that is, according to FOURMARIER, cleavage is due to the same process as and contemporaneous with the folding in an orogenic belt. L. U. DE SITTER (1956b) says in the postscript to the discussion, supporting FOURMARIER's conception of the cleavage, that "the direct connection between cleavage and folding is a feature sustained by so many authors and in such divers conditions that it can be no doubt that almost invariably the folding is due to the cleavage." In spite of these counterpleas, however, RUTTEN has not abandoned his opinion, saying: "The non-parallelism between schistosity and axial fold planes elsewhere is to my mind a decisive argument against contemporaneity of origin. But to FOURMARIER this non-parallelism is not of great importance, because 'de três nombreuses exceptions locales peuvent exister.'...... a two-step origin is proposed by way of an earlier folding period followed by a later formation of schistosity (cleavage)". RUTTEN's conclusion is quite consistent with the present authors' result on the disposition and the phase of formation of the closely spaced cleavage in relation to the main folding. In the present case, fracture-cleavage is parallel to the fold-axis *B* of the main fold and, therefore, contemporaneous with the main folding, but the closely spaced shear-cleavage is not parallel to the main fold-axis, representing a later formation than the main folding. It is quite important, after the authors' view, to discriminate between the two types of cleavage with different disposition and properties and of different stage of formation.

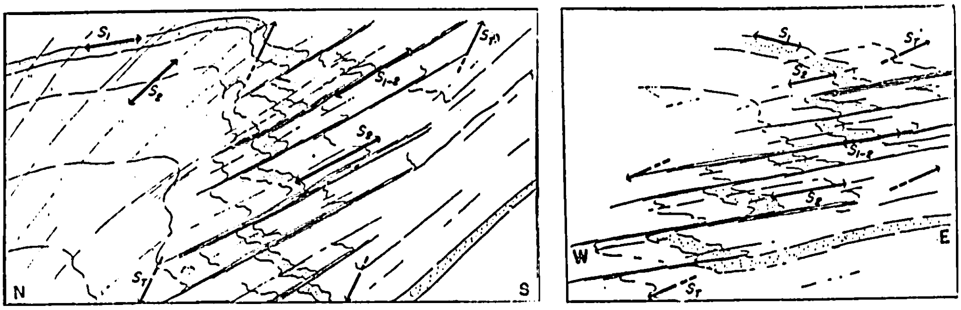

FIG. 13. Schematic vertical (left) and horizontal (right) sections of the Kiyomizu tectonic zone. See in the text about S_1, S_{1-2}, and S_2. S_T denotes the boundary surface of the tectonic zone.

able fact that the trend of the tectonic zone crosses the strike of shear-surface in the zone may be explained by the vertical section, *i.e.*, the boundary surfaces (S_T in Fig. 13) of the tectonic zone make an angle with the shear-surface (S_{1-2}), dipping to the north at a higher angle than the latter.

This disposition of the boundary surface (S_T) of the tectonic zone and the shear-surface (S_{1-2}) within the zone may be explained kinematically after the strain hypothesis. Compressive stress acting vertically to the boundary surface S_T may give rise to two conjugate sets of shear-planes: the one is represented by S_{1-2} and the another is shown as S' in Fig. 14. While, the upward thrusting movement of the northern zone relative to the southern one has exerted a rotation to the tectonic zone, clockwise in Fig. 14. Because the sense of internal rotation of S_{1-2} and S' formed in the course of flattening by the compressive stress normal to S_T is reversed between S_{1-2} and S', namely, anticlockwise for S_{1-2}, while clockwise for S', on the section of Fig. 14, the composite effect by the flattening and the thrusting movement keeps, on the one hand, S_{1-2} active, while, S' formed at every stage of deformation is shifted by rotation from the position of maximum shear, and become inactive.

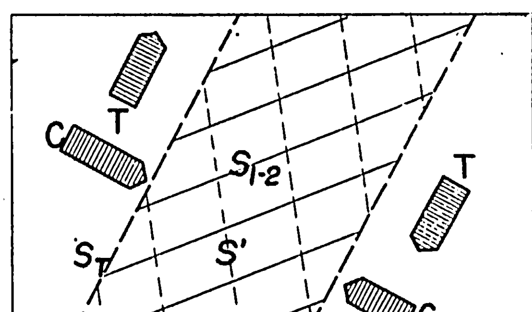

FIG. 14. Schematic illustration of the relation between *s*-surfaces and stress components.
C : compressive stress; T : shear by thrusting; S_T, S_{1-2} and S' : see in the text.

The folding in the earlier phase of tectogenesis was accompanied by flattening owing to the compressive stress in the horizontal direction normal to the fold-axis, and this flattening caused the increase of curvature of fold and the flattening of microlithons bounded by surfaces of fracture-cleavage. This type of deformation, however, can not proceed unlimitedly, because in the course of folding and metamorphism both physical and chemical conditions of the environment become changed; *i.e.*, the increase in confining pressure caused by the thickening of materials, the increase in temperature, the presence of fluidal phase, the change in mechanical properties of rocks, etc. All these factors must have acted in increasing the plasticity of rocks, and so, the closely spaced shear-cleavage has arisen. In this phase of deformation there existed no difference in competency between various rock-types, as suggested by the fact that the cleavage is found in every type of rocks with fairly constant trend. Beds have been folded in the type of cleavage-fold, and the flattening of microlithons bounded by the newly formed cleavage-surfaces is also detectable. The deformation of this phase, however, has exerted no significant changes to the geologic structure of larger scale both in the metamorphic zone proper and the Kiyomizu tectonic zone.

Lastly, the geological significance of the Kiyomizu tectonic zone in the Palaeozoic terrain, both metamorphic and non-metamorphic, in Central Shikoku will be mentioned briefly. The Palaeozoic terrain is divided into two zones, namely, the Sambagawa metamorphic zone and the non-metamorphic Chichibu zone. The Kiyomizu tectonic zone is running through the Sambagawa zone near the southern border, dividing the metamorphic zone into two parts: the metamorphic zone proper to the north and the southern marginal zone. The latter is a narrow (<4 km in width) belt consisting of weak-metamorphic rocks such as black-schist, sandstone-schist, quartz-schist, and green-schist. This zone represents the transitional one between the metamorphic zone proper and the non-metamorphic Chichibu zone, viewed on the standpoint of metamorphism and lithology. From the geological setting above outlined the Kiyomizu tectonic zone is to be interpreted as representing the frontal zone of the Sambagawa metamorphic zone proper, characterized by thrusting shear movement towards the south, the movement having been caused by the horizontal compression and the consequent upward swelling of the metamorphic zone.

III. Quartz Fabric

In rocks of the tectonic zone, in general, three kinds of *s*-surfaces are developed; namely, S_1, the surface of bedding-schistosity or -foliation, S_2, the surface of fracture-cleavage, and S_3, the surface of closely spaced shear-cleavage. They represent not only the surfaces of mechanical inhomogeneity in rocks, but also they are the surfaces along which shear movement has occurred at respective phases of deformation. It is highly conceivable that each phase of deformation has printed rocks with respective pattern of quartz fabric. Accordingly, patterns of quartz fabric in rocks with all these *s*-surfaces must be too complicated. For that reason, the present authors have selected for quartz fabric analysis those rocks characterized by S_{1-2} with or without S_3; namely, the black-schist of papery appearance in the tectonic zone. As described in the foregoing chapter, S_{1-2} represents a kind of schistosity-foliation plane derived from the bedding- or lamination-plane of the original sediment, along which strong shear movement occurred at the phase of thrusting shear of the tectonic zone. Therefore, it is very profitable to be able to decide the sense of shear movement on the rock specimen geographically oriented. As for S_3, the sense of slip movement is also easily determinable on the thin slice from the feature of displacement of schistosity-plane by the slip along S_3. Such being the case, the fabric pattern for quartz of these rocks can be interpreted in terms of slip movement on S_{1-2} and S_3.

CHARACTERISTIC FEATURES OF QUARTZ FABRIC PATTERNS

In the following, the pattern of fabric diagram of quartz will be studied starting from a more typical example to rather indistinct ones.

The first example is offered by a rock collected at Motoyama. The rock is quartz-sericite-phyllite, consisting of quartz, sericite, chlorite, graphitic material, and albite. The schistosity and compositional banding (foliation) are very distinct. The schistosity-foliation surface is plane, but fine crinkles are seen as the intersection of S_{1-2} and S_3, designated as L_{2-3} (see the fabric of mica in Fig. 15). Micaceous layers, consisting of parallel flakes of sericitic mica, chlorite, and graphitic matter, are crossed by the closely spaced S_3. The interval between the adjacent cleavage surfaces, *i.e.*, the thickness of microlithon, is 0.1mm on an average. It must be noted that no cleavage penetrates into quartzose layers, which consist of fine aggregates of quartz and accessory albite of 0.01mm in average diameter with finely divided sericite. This feature may be interpreted as showing different behaviours of material to shearing stress between plastic quartzose layers and less plastic micaceous ones, *i.e.*, the former has been deformed *en masse*, while the latter discontinuously by cleaving.

The orientation of the c-axis of quartz has been measured on the universal stage for grains in a coarser-grained layer consisting exclusively of quartz, 0.05 mm in diameter, concordant to S_{1-2}. The data have been projected on the lower hemisphere of equiareal projection. The contoured diagram is shown in Fig. 16. The center of the diagram coincides with L_{2-3}, as is the case also in the following diagrams. It must be borne in mind that L_{2-3} coincides necessarily, in general, neither with the b-axis on S_{1-2} nor with that on S_3, because S_{1-2} and S_3 have been formed at different phases of deformation under different stress-plans (cf. L. F. WEISS, 1955).

In Fig. 16, c-axes of quartz are focused on two separate areas, both nearly lying on the periphery of the diagram: one in the first and the third quadrants, and another in the second and the fourth ones. The former shows the most distinct maximum. Provided that these two areas of concentration correspond respectively to the monoclinic positions of quartz axes, the position II after SANDER, in respect to S_{1-2} and S_3, the former is to be correlated with slip on S_{1-2} and the latter on S_3. They are designated in this paper as M_{1-2} and M_3, respectively, in compliance with the subscript numerals of the correlative s-surfaces. In the diagram of Fig. 16, are marked the positions inclined to S_{1-2} and S_3, respectively, at 38°, the angle between the c-axis and $r(10\bar{1}1)$ or $z(01\bar{1}1)$ of quartz crystal. M_{1-2} and M_3 roughly coincide with these hypothetical positions.

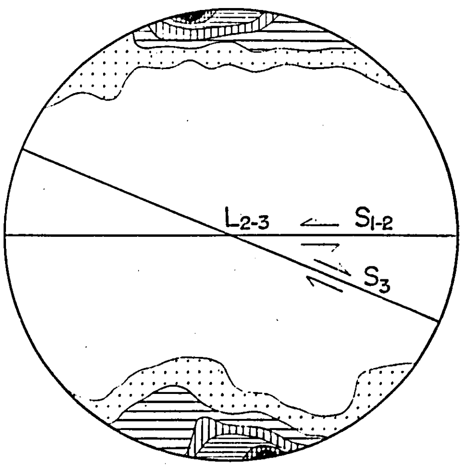

FIG. 15. 100 [001] of sericitic mica of quartz-sericite-phyllite from Motoyama (T S31052603). No selection of grains was made. Max.: 24%. Contours: 24–20–14–8–4–1%.

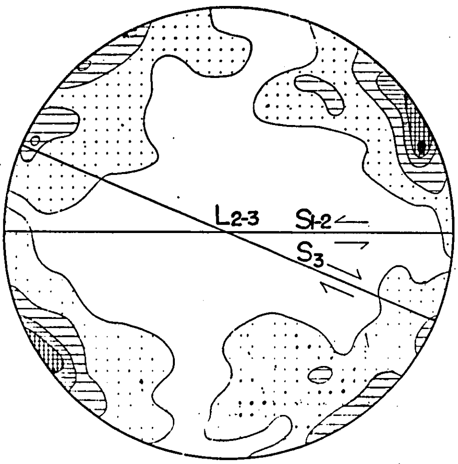

FIG. 16. 500 c-axes of quartz in a quartzose concordant layer in quartz-sericite-phyllite from Motoyama (TS31052603). No selection of grains was made within the layer. Max.: 5.2%. Contours: 5-4-3-2-1%.

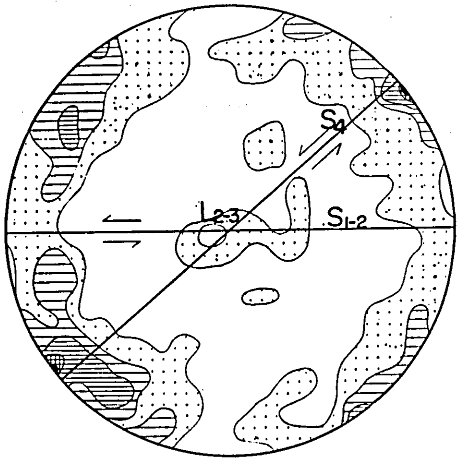

FIG. 17. 500 c-axes of quartz in a quartzose concordant layer in quartz-sericite-phyllite from Ôtoyo (TS32051002). No selection of grains was made within the layer. Max.: 4.5% Contours: 4.5-4-3-2-1%.

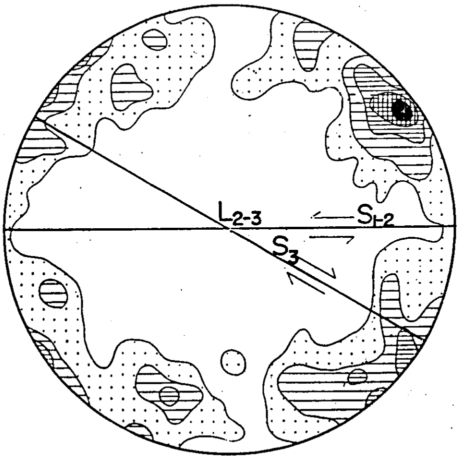

FIG. 18. 400 c-axes of quartz in a quartzose concordant layer in quartz-sericite-phyllite from Ôtoyo (TS32110301). No selection of grains was made within the layer. Max: 5%. Contours: 5-4-3-2-1%.

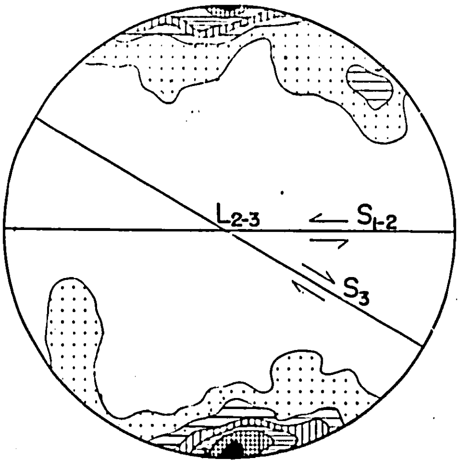

FIG. 19. 100 [001] of sericitic mica of quartz-sericite-phyllite from Ôtoyo (TS321-10301). No selection of grains was made. Max.: 20%. Contours: 20-16-12-8-4-1%.

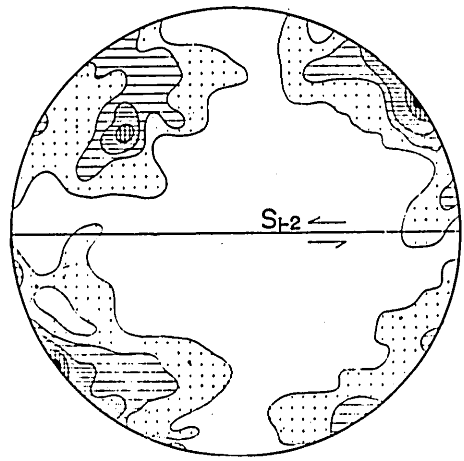

FIG. 20. 500 c-axes of quartz in a quartzose concordant layer in quartz-sericite-phyllite from Ôtoyo (TS32050901). No selection of grains was made within the layer. Max.: 5.6%. Contours: 5-4-3-2-1%.

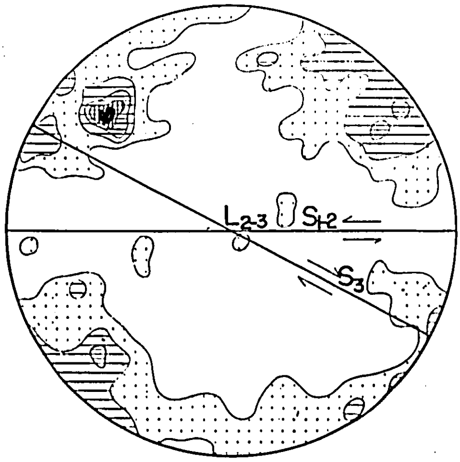

FIG. 21. 500 c-axes of quartz in a quartzose concordant layer in quartz-sericite-phyllite from Tosa (TS31052803). No selection of grains was made within the layer. Max.: 5.2%. Contours: 5-4-3-2-1%.

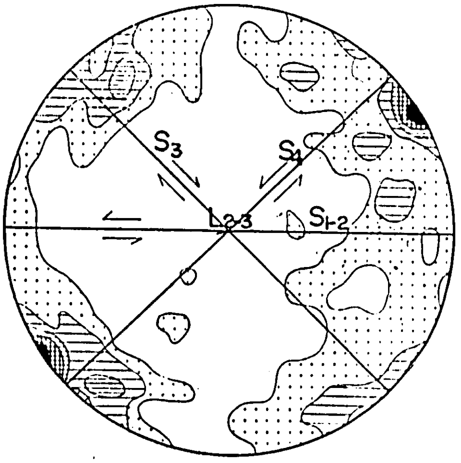

FIG. 22. 500 c-axes of quartz in a quartzose concordant layer in quartz-sericite-phyllite from Ôtoyo (TS31101404). No selection of grains was made within the layer. Max.: 5%. Contours: 5-4-3-2-1%.

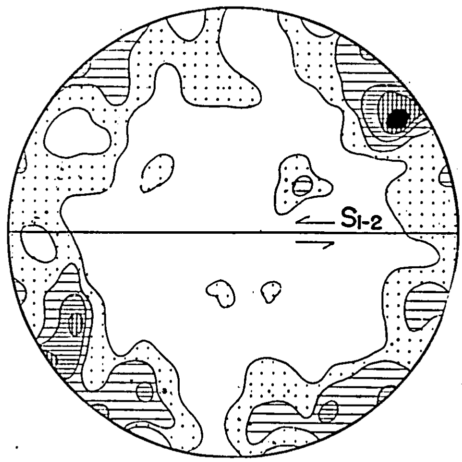

FIG. 23. 300 c-axes of quartz in a quartzose concordant layer in quartz-sericite-phyllite from Jizôji (TS30073002). No selection of grains was made within the layer. Max.: 5%. Contours: 5-4-3-2-1%.

It must be noted that both M_{1-2} and M_3 stand at the identical relation with the sense of slip movement on the respective *s*-surfaces.

The next example is a quartz-sericite-phyllite from Ôtoyo. Petrographic characters of the rock are very similar to the above one, except that, instead of the nearly vertical cleavage S_3, there develops a nearly horizontal cleavage, designated as S_4, which is to be taken as complementary to S_3. The fabric diagram has been constructed for quartz of coarser-grained (0.05mm in diameter) aggregates in a quartzose seam, concordant to S_{1-2}(Fig. 17). The concentration of axes is also roughly peripheral, namely, normal to L_{2-3}. M_{1-2} is fairly distinct, roughly coinciding with the hypothetical position in respect to S_{1-2}. The position of M_{1-2} has the same relation with the sense of slip movement on S_{1-2} as in Fig. 16. The orientation of axes corresponding to S_4 is indistinct.

The third example is a quartz-sericite-phyllite from Ôtoyo. There develops distinct S_{1-2} and S_3. The orientation of quartz axes has been measured for grains in a coarser-grained (0.05mm in diameter), concordant quartzose seam in the rock, with the result shown in Fig. 18. The concentration of axes is nearly peripheral. M_{1-2} is distinct, roughly coinciding with the hypothetical position in respect to S_{1-2}. It stands in the same relation with the sense of slip movement on S_{1-2} as in the examples above described. The orientation of axes in respect to S_3 is indistinct.

The fourth example is also a quartz-sericite-phyllite from Ôtoyo. Platy S_{1-2} is distinct, while neither S_3 nor S_4 is developed. The measurement was carried out for quartz grains (0.05mm in diameter) in a concordant quartzose seam. The fabric diagram is shown in Fig. 20. M_{1-2} is distinct, coinciding with the hypothetical position in respect to the sense of slip movement on S_{1-2}. The concentration in the second quadrant is difficult to interpret.

The last three examples are also quartz-sericite-phyllites from Tosa, Ôtoyo, and Jizôji. Fabric diagrams for quartz in quartzose seams concordant to S_{1-2} are shown, respectively, in Figs. 21, 22, and 23. It is shown in common in them that M_{1-2} is fairly distinct, coinciding with the hypothetical position in respect to the sense of slip movement on S_{1-2}, while that the orientation of axes in respect to S_3, or, if present, to S_4 is indistinct.

Summarizing the characteristic features of quartz fabric patterns of the examples above described, the following points are significant in considering the behaviour of quartz in tectonic movement.

1) There is a distinct concentration of axes with constant relation to S_{1-2} and the sense of slip movement on it, designated as M_{1-2}. M_{1-2} lies very close to the point which is inclined at 38° to S_{1-2}. Furthermore, M_{1-2} is situated on the definite side of S_{1-2} in constant relation to the sense of slip movement on S_{1-2}, as shown in figures.

2) The orientation of quartz axes in respect to the closely spaced cleavage (S_3, or S_4) is indistinct.

INTERPRETATION —— A RULE OF QUARTZ ORIENTATION IN REFERENCE TO THE SHEAR MOVEMENT

Quartz axes measured on concordant quartzose seams show a distinct concentration in a definite relation to the slip movement on the schistosity plane S_{1-2}, as mentioned just above. The concordant quartzose seams in question are coarser-grained than the leucocratic seams which construct the foliation structure (compositional banding) together with micaceous seams, and they almost lack such common minerals of black-phyllite as sericite, albite, etc., other than quartz. These petrographic features suggest their origin by lateral segregation during the shear movement along the schistosity plane. Grains of quartz in such concordant quartzose seams have, therefore, crystallized newly under the stress condition in the phase of formation of S_{1-2}. The genesis of these quartzose seams may account for the distinct concentration of quartz axes with respect to S_{1-2} in fabric diagrams.

The definite relation of quartz maximum (M_{1-2}) to the sense of slip movement on S_{1-2} suggests that quartz has been oriented with a certain lattice plane on the shear plane S_{1-2} and with a certain lattice direction to the direction of shear. From the facts that M_{1-2} lies very close to the point inclined at 38° to S_{1-2}, and that M_{1-2} is located on the definite side of S_{1-2}, in constant relation to the sense of slip movement on S_{1-2}, the relation between the lattice plane and translation direction of quartz and the shear plane and shear direction can be schematically shown in Fig. 24. The rule may be stated as follows:

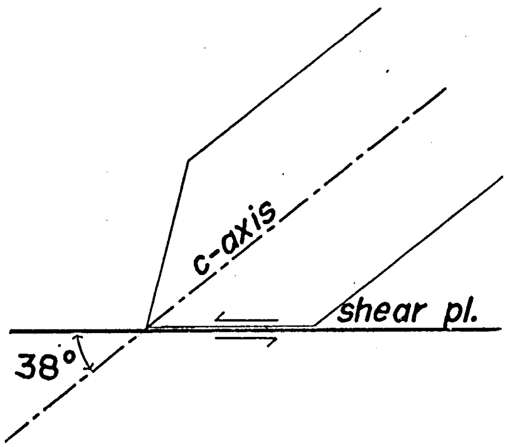

FIG. 24. Orientation of quartz crystal in reference to the shear plane and the sense of shear movement.

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.

It must be noticed that this rule of the orientation of quartz may well be applied to newly crystallized quartz under stress condition, because the orientation of recrystallized quartz must show a certain influence of the original preferred orientation of the mineral, unless the recrystallization proceeds so far as to obliterate the original anisotropy. In the present case, the concordant quartzose seams have been deformed *en masse* in the phase of formation of cleavage S_3, but the recrystallization accompanying the deformation has not been so strong as to make the fabric pattern show direct and distinct relationship with the slip movement on the cleavage plane. In several examples, *e. g.* Figs. 16, 18, and 21, however, some sub-maxima may be found lying near the hypothetical positions in respect to the cleavage plane S_3.

It is desired that this working hypothesis about the orientation of quartz in the flow of rocks will be tested both factually and experimentally.

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Explanation of Plate

Plate 25

FIG. 1. A relation between the bedding-schistosity (S_1), the fracture-cleavage (S_2), and the closely spaced shear-cleavage (S_3), seen to the north of Iwahara. Notice the cleavage-folding of S_2 by the closely spaced cleavage, S_3. (Photo. by Ch. MITSUNO)

FIG. 2. Cleavage-folding of S_{1-2} by the closely spaced cleavage, S_3, at Iwahara. T. I. denotes the tectonic inclusion of sandstone-schist, arranged with its longer axes along S_{1-2}.

FIG. 3. Cleavage-folding of S_{1-2} by the closely spaced cleavage, S_3, to the north of Iwahara. (Photo. by Ch. MITSUNO)

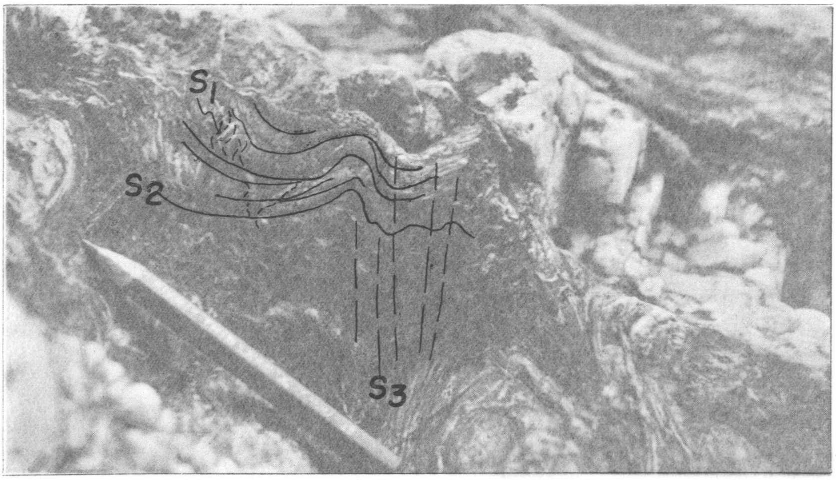

FIG. 1

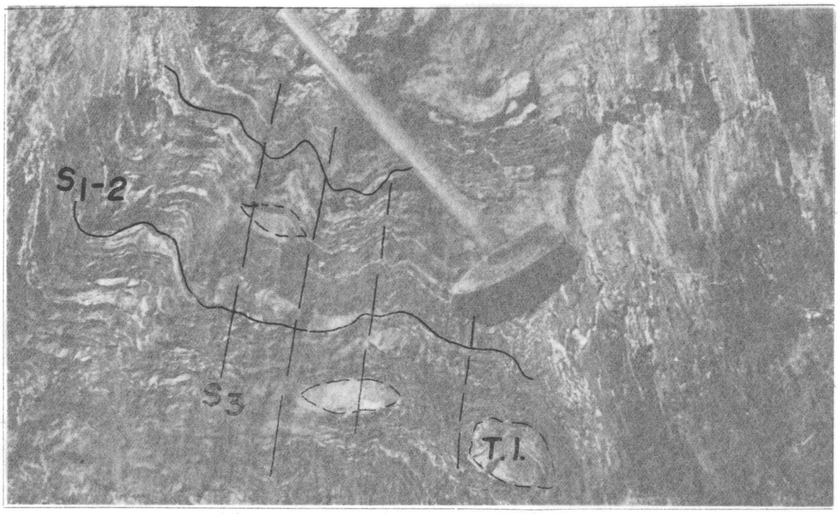

FIG. 2

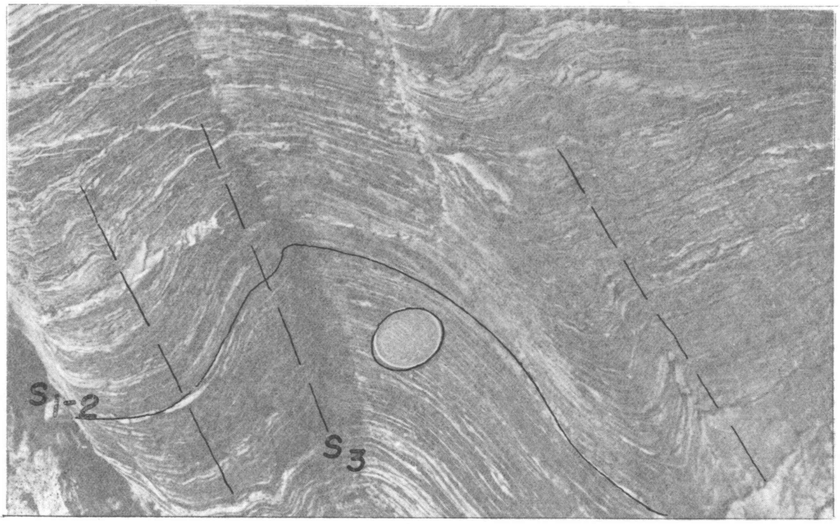

FIG. 3

FIG. 1

FIG. 2

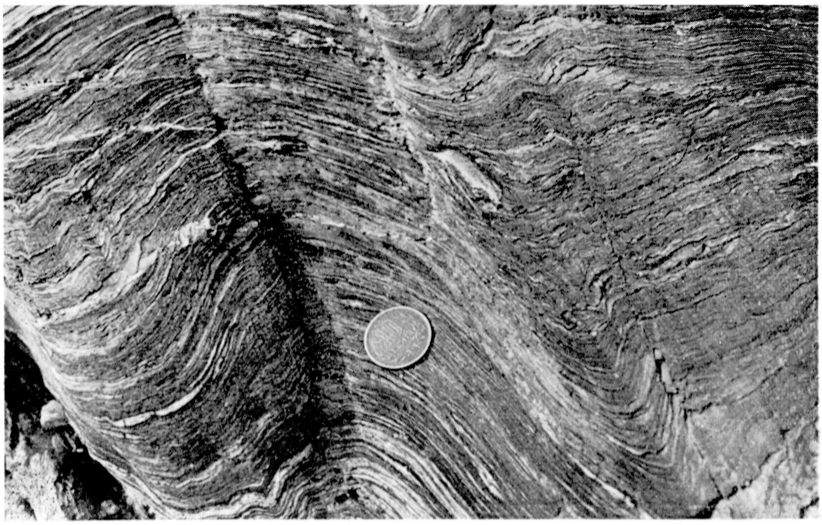

FIG. 3

EXPLANATION OF PLATE

PLATE 26

FIG. 1. Quartz-sericite-phyllite from Motoyama. Sample no. TS31052603. The banding represents the bedding-schistosity, which, at the same time, coincides with the plane of shearing, *i.e.*, S_{1-2}. The leucocratic layer of the right half is a highly quartzose one, segregated along S_{1-2}, on which the petrofabric analysis has been made. The closely spaced shear-cleavage, S_3, is crossing S_{1-2}. Lower nicol only. $\times 70$.

FIG. 2. *ibid.* Under crossed nicols. $\times 70$.

FIG. 3. Cleavage structure of black-phyllite from Iwahara. The compositional banding represents S_1, being crossed by the closely spaced cleavage, S_3. Lower nicol only. $\times 41$.

FIG. 4. Cleavage structure of black-phyllite from Iwahara. The compositional banding represents S_1, being crossed by the fracture-cleavage, S_2. Notice that the original bedding or lamination structure, S_1, was intensely displaced by the shear movement along S_2. (Compare with FIG. 3). Lower nicol only. $\times 10$.

FIG. 1

FIG. 2

FIG. 3

FIG. 4