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Structural Petrology of the Ôbokè Anticline in the Sambagawa Crystalline Schist Zone, Central Shikoku

By

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with 41 Text-figures, and 2 plates

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ABSTRACT: The structural geometry of Sambagawa crystalline schists in the Ôbokè district is investigated by statistical analysis of the preferred orientation of structural elements such as bedding schistosity, cleavages, and lineations. The Ôbokè Anticline is an asymmetrical antiform with various scales folds whose axes trend from N 85° E to N 85° W. The cleavages develop in harmonic relation to the folds. The quartz fabric of the sandstone schist is examined. The deformed quartz grains suggest a probability that the mechanism of quartz orientation is explained by the fracture hypothesis.

CONTENTS

I. INTRODUCTION

The Sambagawa metamorphic belt, which zonally occupies mountain ranges in Shikoku, has been studied under three main subjects, *i.e.* establishment of stratigraphy, structural analysis, and compilation of the metamorphic episode, by the "Members for scientific research of the crystalline schists in Southwestern Japan". Many painstaking reports treating these subjects have been published by many persons of this members and, at the same time, the presence of the minor structural elements, such as planar structures and lineations, became more and more to draw their attentions.

Now, the important problems, which attracted many structural petrologsits in Shikoku,will be summarized in the following two points: the first problem to be quoted is to confirm the peculiarity of each minor structural element which was successively imprinted on the rock during the time of intense dynamic metamorphism, and the second is to inquire into the mutual relations between the minor structural elements and the major structural elements such as anticline or syncline.

The greater part of the mountain chains of Shikoku, which runs through Central Shikoku in the direction of ENE-WSW, is occupied by the Sambagawa crystalline schist. At the westernmost region of Tokushima Prefecture, the Mountain Chains of Shikoku is crossed by the Yoshino River and the Iya River (a branch of the Yoshino River), along which two long transversal valleys, reaching a length of about 20 km and 8 or more km respectively, are developed in the direction of S-N. The famous sight such as "Ôbokè", "Kobokè" and "Iyakei" can be found in these valleys, and are the good exposures for the field investigation in this region.

This paper concerns mainly structural petrology of the Ôbokè andstone-schist, which is thick, distributed widely with the extension parallel to the Mountain Chains of Shikoku. Especially the sandstone schist in the districts of Ôbokè and Iyakei has been studied in detail. The writer intends to clarify the mutual relations of minor and major structural elements found in the "Ôbokè anticlinal zone", through megascopic and microscopic fabric analyses originated by B. SANDER,

Many authorities, such as T. OGAWA, K. KINOSHITA, J. SUZUKI et al., have studied the district in problem from, petrographical or geological standpoints of view, however reports dealt with structural petrology of the rocks in the district are very few.

R. SUGIYAMA (1943) stated from his studies in the field that the phyllitic sandstone in the Ôbokè district forms a synclinorium which had been explained as an anticline by many authors. Afterwards G. KOJIMA and C. MITSUNO (1950) pointed out that petrographic name of the Ôbokè-gneiss, which has been thus called by older geologists in Japan, is not suitable for the rocks in Ôbokè but is to be termed sandstone schist. Moreover they have clarified the stratigraphic situation of the Ôbokè sandstone schist, and asserted strongly as a working hypothesis that the sandstone schist forms a recumbent anticline. In the same year, I. NAKAYAMA also studied the sandstone-schist in problem, and examined his hypothesis which concerned the mutual relation between the preferred orientations of c-axes of quartz and the direction of differential movement.

G. KOJIMA (1951), K. HIDE and G. YOSHINO (1956) have successively published their substantial results of petrological and geological researches of the Sambagawa crystalline schist in Shikoku, and the stratigraphy and structural setting of the crystalline schist have increasingly been clarified by their contributions. Nowadays, no geologist in Japan doubts the proporsal of G. KOJIMA who pointed out the existence of the larger anticlinal zone in the district of Ôbokè.

Acknowledgements. Grateful acknowledgement is made to Professor G. KOJIMA, under whose guidance this study was made, for his constant and helpful criticism during the course of this work. The writer wishes to record his great indebtedness to Dr. K. HIDE and Dr. C. MITSUNO (Okayama University) for their cordial guidance in the field, and in particular, Dr. C. MITSUNO kindly offered his unpublished data collected from the region concerned. The writer is also indebted to the members of the "Petrologist Club" in his institute for their earnest discussion and criticisms. The cost in the field was covered in part by the Grant in Aid for Scientific reasarches from the Ministry of Education.

II. OUTLINE OF GEOLOGY

Sambagawa crystalline schist in Central Shikoku is distributed widely with about ten thousands meters in total thickness, and its stratigraphy is shown after G. KOJIMA, K. HIDE and G. YOSHINO (1956) as follows:

	(Group)	(Formation)
Yoshinogawa	Upper	Ôjoin
	Middle	Minawa Kobokè
	Lower	Kawaguchi Ôbokè

The geological structure is shown in FIG. 1.

The Ôbokè district has been recomended as a type locality of the Kobokè-, and Ôbokè formations. On the route along the Yoshino River, however, we can find an evidence that the sandstone schist of the Ôbokè formation joints with the sandstone schist of the Kobokè foramtion. Some significant problems concerning the stratigraphy and the structure are there. The writer considers from this evidence that in this district the formation named the Kobokè formation may be the same as the Ôbokè formation. The geological relations between the rock-facies and the structure are shown in FIG. 2.

The crystalline schists in the district consist mainly of sandstone schist, and subordinally of black schist, conglomerate schist, and belong to the green schist facies proposed by F. J. TURNER (1951). Petrographic descriptions of those rocks have been accomplished in detail by many authors, especially by J. SUZUKI (1932) and G. KOJIMA and C. MITSUNO (1950).

III. TECTONICS

A. Outline of Major Structure

The major axis of the anticline runs through Hibihara (the midstream of the River of Matsuo), Nemuri valley (the midstream of the Iya River), Dôtoko valley (the midstream of the Yoshino River) and the upper stream of the Shira

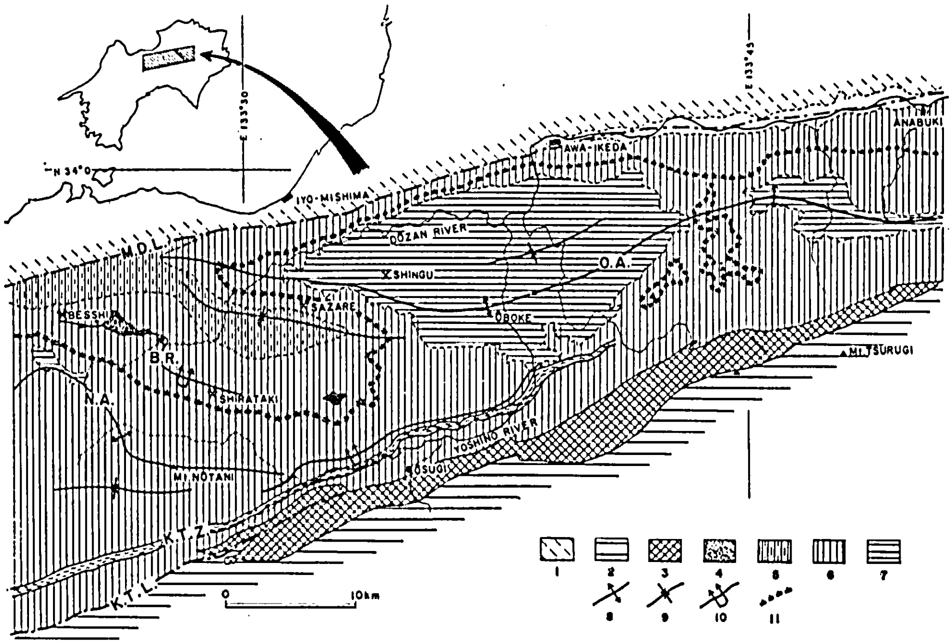

FIG. 1. Geological sketch map of the Sambagawa crystalline schists region in Central Shikoku.

1. Izumi Sandstone Formation.
2. Kamiyakawa Formation (Permain).
3. Mikabu Green-rocks.
4. Peridotite & Serpentinite.
5. Ôjôin Formation.
6. Minawa Formation.
7. Koboke, Kawaguchi and Ôbokè Formation.
8. Anticline Axis.
9. Syncline Axis.
10. Recumbent Fold Axis.
11. Boundary between Spotted Schist Zone and Non-spotted Schist Zone.

M. D. L; Median Dislocation Line.
K. T· Z; Kiyomizu Tectonic Zone.
O. A; Ôbokè Anticline.
N. A; Nôtaniyama Anticline.
B. R; Besshi Recumbent Fold.

River, with the trend of ca. N 80° E and the nearly horizontal plunge. The trend of the major axis curves towards WNW in the west of the Shira River. The anticline is an asymmetrical fold, and shows also some variations in structural characters along the major axis.

In the northern limb there is a synclinorium with the axis parallel to the anticline axis. On a route along the Matsuo River, by which the anticline is cut transversally, the extension of the southern limb of the anticline is restricted

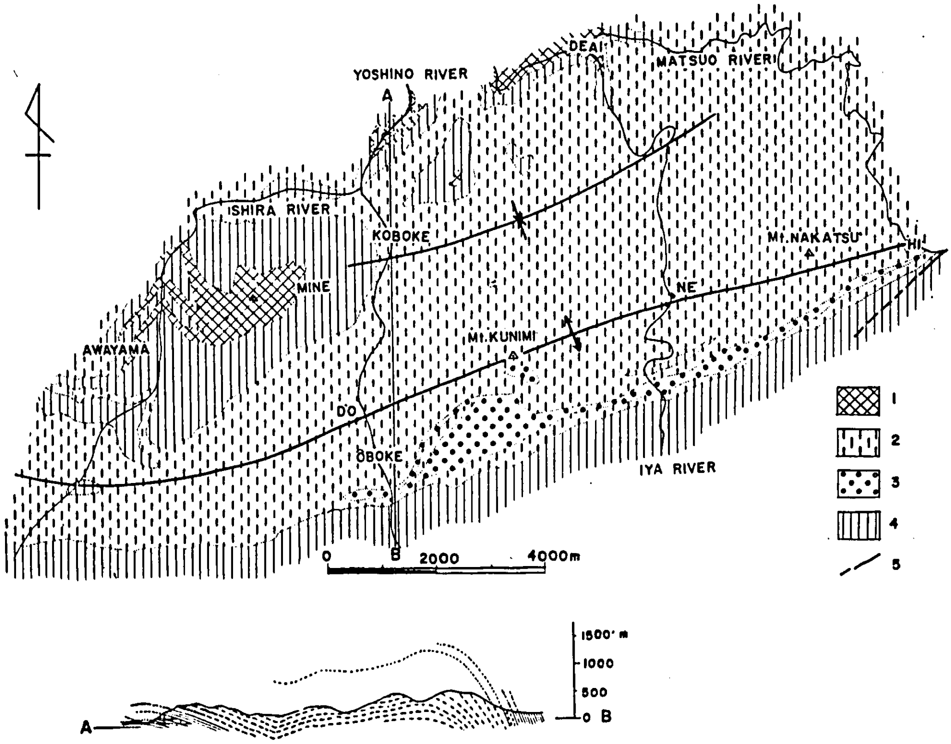

FIG. 2 Gelogical map of the Ôbokè district. (after George KOJIMA, Chiharu MITSUNO, 1950, partialy emended by NAKAGAWA, 1957)

1. Green schist
2. Sandstone schist
3. Conglomerate schist
4. Black schist
5. Fault

DO Dôtoko Valley
NE Nemuri Valley
HI Hibihara

by a fault and develops narrower. The bedding planes of the rocks at the southern limb are uniformly bent, without small-scale folds, while at the crest and the northern limb the bedding planes are strongly folded with the wave-lengths of several meters, inclining towards the north on the whole.

On a route along the Iya River, and the Yoshino River route, at the southern limb the bedding planes incline with angles about 60° towards the south without small-scale fold, while in the crest and at the northern limb the bedding planes show small-scale fold with various wave length, dipping slightly towards the north on the whole. The general inclination of the bedding plane in the northern-most area, the northern part of Deai, becomes nearly horizontal.

On a route along the River of Shirakawa, the S_1 of the southern limb is dipping 30° or more towards the south, and generally shows small-scale fold with various wave lengths. These small-scale folds are cut by one set of cleavage with high-angle dip, which develops with an interval of several mm. or less and by which the small-scale folds are changed to more complicated ones.

B. Megascopic Fabrics

1. *Planar structures*

The planar structure which is most predominantly found in the rocks of this district, is one set of schistosity plane parallel to the stratification of original rock, that is, bedding schistosity (S_1). All folding structures within the "Ôbokè Anticlinal Zone" are indicated by folding of the S_1.

As mentioned above, the S_1 at the southern limb of the anticline is uniformly bent, without small scale folds, while at the crest and at the northern limb the S_1 shows waves with wave-length of an order of centimeter. The relation between the latter minor type of folds and the former wave type shows two types of pattern. The one is indicated in the alternation of thin laters of black schist and sandstone schist among which the former is predominant, and the pattern of the minor fold of the alternation bed is asymmetrical with axial planes converging towards the crest of the wave. The other is indicated in the alternation in which sandstone schist is predominant, and the fold pattern of it is symmetrical with axial planes converging towards the center of the wave.

The trend of the S_1 is shown on an equal-area-projection of the S_1 poles in FIG. 3, FIG. 13, and FIG. 16. All the S_1 poles in each diagram fall in one girdle (π-circle by B. SANDER). β-Axes (by B. SANDER) determined for measured S_1 in each small selected area show a strong maximum respectively which strictly coincides with the pole of π-circle (FIG, 6, FIG. 9, FIG. 11, and Fig. 17). The fact may show a homogeneous character of folds in various scales in the district.

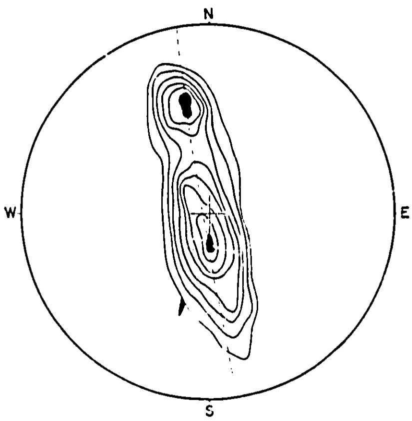

FIG. 3 400 poles of S_1 at the Yoshino River route. Max. : 19% Contours : 18-17.5-15-12.5-10-7.5-5-2.5-1%.

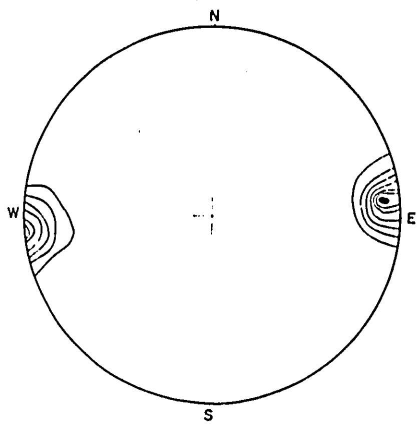

FIG. 4. 370 poles of L_{1-3} at the Ôbokè (Yoshino River) route. Max : 60%. Contours : 60-50-40-30-20-10%.

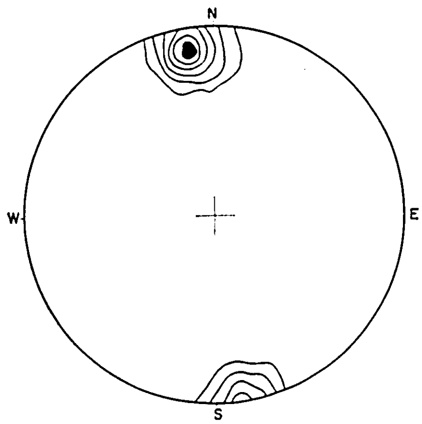

FIG. 5. 200 poles of S_3 at the Yoshino River route. Max : 43%. Contours : 40-30-20-10-1%.

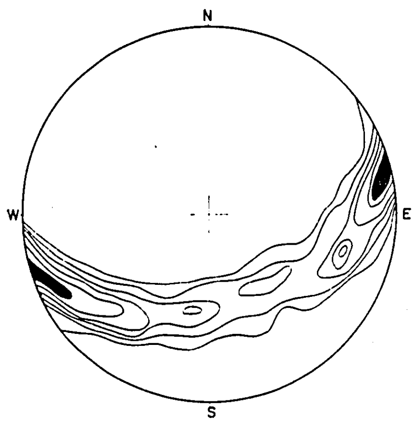

FIG. 6. β-diagram for S_1 on the southern limb at the Yoshino River route. Max : 135%. Contours : 12-9-6-3-1%.

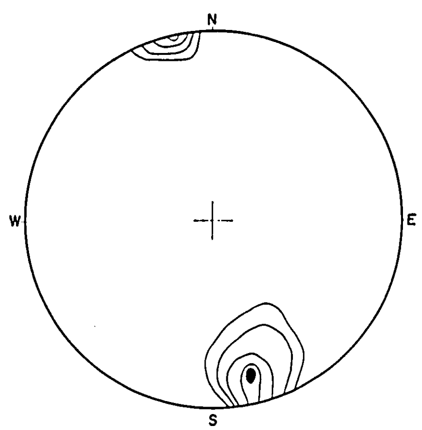

FIG. 7. 40 poles of S_3 on the southern limb at the Yoshino river route. Max : 42%. Contours : 40-30-20-10-1%.

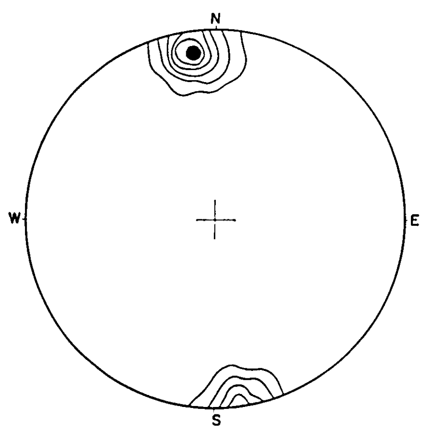

FIG. 8. 80 poles of S_3 on the crest at the Yoshino river route. Max. : 16.5%. Contours : 15-12-9-6-3%.

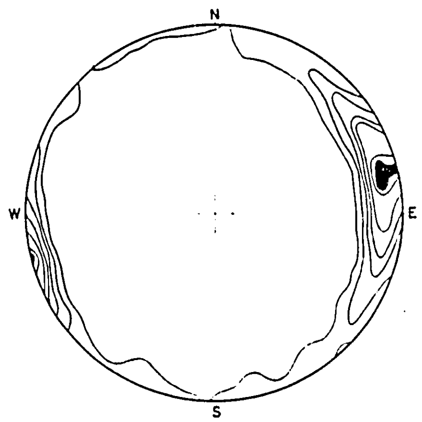

FIG. 9. β-diagram for S_1 on the crest at the Yoshino River route. Max.: 18%. Contours: 18-15-12--9-6-3-1%.

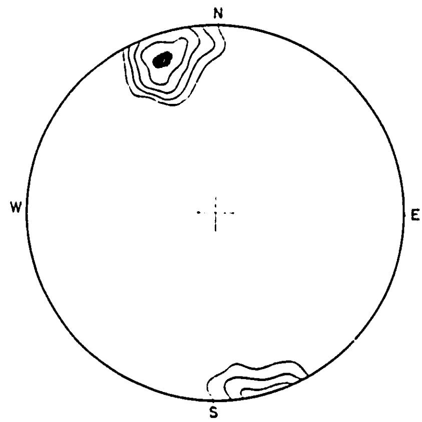

FIG. 10. 80 poles of S_3 on the northern limb at the Yoshino River route. Max.: 47%. Contours: 40-30-20-10-1%.

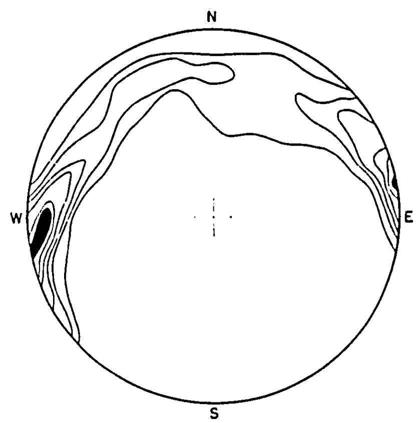

FIG. 11. β-diagram for S_1 on the northern limb at the Yoshino River route. Max. 20.5%. Contours: 20-16-12-8-4-1%.

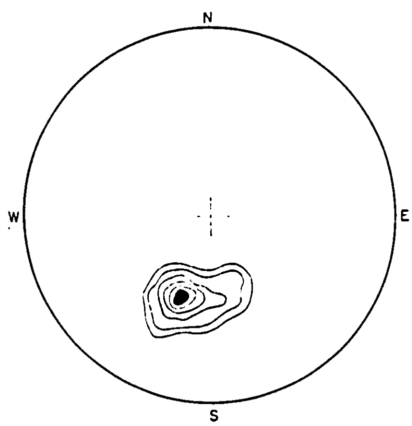

FIG. 12. 30 poles of elongation axes of tectonic inclusion at the Ôbokè.

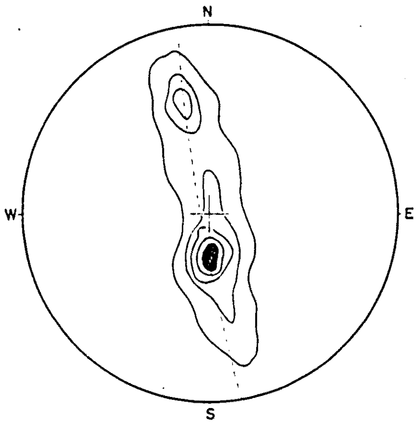

FIG. 13. 220 poles of S_1 at the Iya River route.
Max : 22.5%.
Contours : 20-15-10-5-1%.

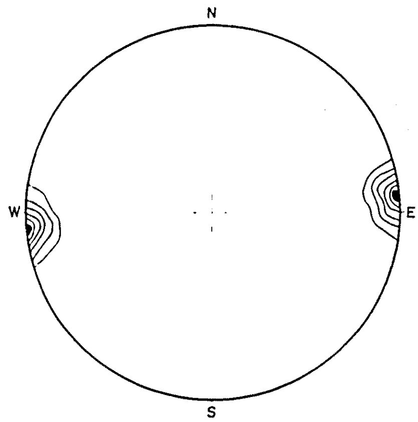

FIG. 14. 150 poles of L_{1-3} at the Iya River route.
Max : 68%.
Contours : 60-48-36-24-12-1%.

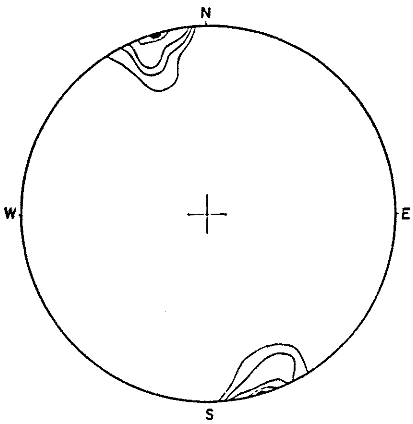

FIG. 15. 100 poles of S_3 at the Iya River route.
Max : 62%.
Contours : 60-48-36-24-12-1%.

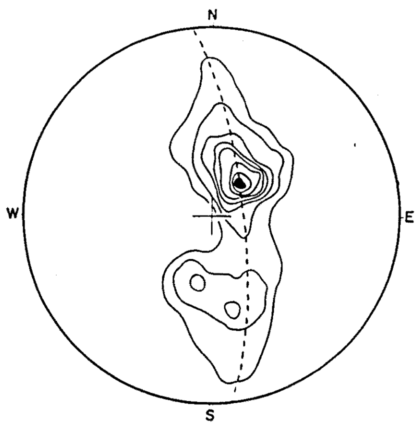

FIG. 16. 62 poles of S_1 at the Shira River route.
Max. : 37%.
Contours : 35-30-25-15-10-5-2.5%.

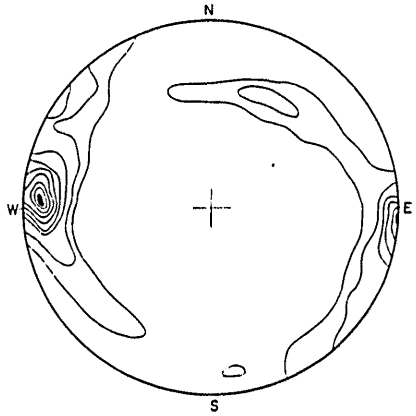

FIG. 17. β-diagram for S_1 at the Shira River route. Max : 24%.
Contours : 21-19-15-12-9-6-3-1%.

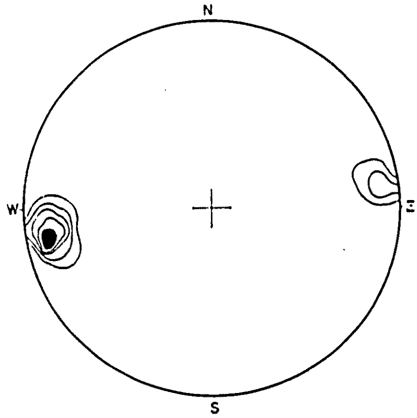

FIG. 18. 50 poles L_{1-3} at the Shira River route. Max : 50%.
Contours : 50-40-30-20-10%.

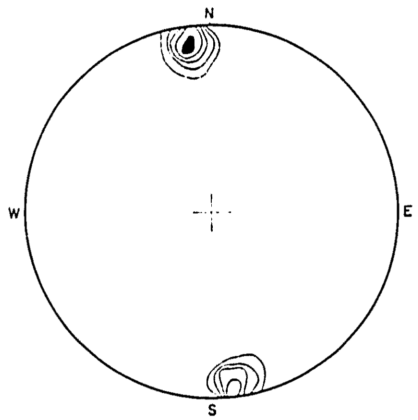

FIG. 19. 32 poles of S_3 at the Shira River route. Max : 56%.
Contours : 50-40-30-20-10%.

The other cleavage plane, which intersects the S_1 and which develops only in black-schist, is there. The cleavage plane is termed S_2. The S_2 is fanned out of fold, as shown in Pl. 32, Fig. 1. This relation of the S_2 to fold structure is the same through all types of fold with various scales. There occurred slipping along the S_2 plane toward the crest of fold, and the structures normal to the fabric axis *b*, are in part imprinted on the S_2. From those evidences, the S_2 may correspond to slip-cleavage. The preferred orientation of any minerals parallel to the S_2 can not be recognized.

In the sandstone-schist is found the third plane of cleavage type with high angle dip, which is termed S_3. The S_3 intersects the S_1 and develops with intervals of several mm or less.

On the southern limb of the anticline, in the Ôbokè, Iya, and Matsuo districts, the S_3 is weak or absent, and generally the S_3 dips at high angles towards the north. On the other hand, in the northern limb and at the crest of the anticline the small-scale folds are remakably developed. The S_3 is in general parallel to their axial planes, and is generally dipping at high angles towards the south. On the whole, the S_3 converges towards the center of the anticline. The trends of the S_3 are parallel to the small scale fold axes and the intersections of the S_1 and S_3 correspond to the B-lineation (by B. SANDER). Sometimes it can be found that the S_1 are slightly displaced along the S_3, especially in the adjacent of Kobokè.

The harmonic relation of the S_3 to the fold structure as described above can be recognized in the east of the Ôbokè route. The trends of the S_3 are slightly oblique to the axis of the Ôboké Anticline in the west of the Shira River route, reflecting change in direction of the axis to the west of Ôbokè.

2. *Linear structures*

Lineations found in the rocks of the district are divided into seven types, of which 2 types can be found in all rock types and 5 types are only rarely found here and there. These seven types of lineation are as follows:

(1) Parallel orientation of minerals. (L_1)
(2) Fold-axis of small scale fold. (present in all the rock types)
(3) Elongation axis of tectonic inclusion.
(4) Intersection of S_1 and S_2. (L_{1-2}, $S_1\hat{}S_2$)
(5) Striation on S_2. (L_2')
(6) Intersection of S_1 and S_3. (L_{1-3}, $S_1\hat{}S_3$) (present in all the rock types)
(7) Streak on the surface of some quartz-veins parallel to S_1.

In the following, characteristics of these linear structures will be described in the order of generation.

(1) Parallel orientation of minerals (L_1): Parallel orientation of minerals is found in the district of Kobokè, and is commonly oblique to the axes of small scale fold. The lineation belongs to the products prior to the fold of the S_1.

(2) Fold axes of small scale fold: Axes of small scale folds at the crest and on the northern limb of the Ôbokè anticline are strictly parallel to the axes of large scale folds: the fact is examined in the foregoing page, by using -diagrams.

(3) Elongation axis of tectonic inclusions: On the southern limb of the Ôbokè Anticline, in alternation beds of thin layers of sandstone-schist, which have been correlated with the uppermost member of the Ôbokè sandstone schist formation, is present a special linear structure. The lineations are in general divided into two sets, both of which are developed symmetrically to the tectonic a-axis of fold with small angles, in average, ca. 5 degrees (FIG. 12). The lineations are indicated by elogation axes of the tectonic inclusions, which are sandstone schist enclosed in black schist.

On sections perpendicular to the tectonic a-axes of the folds[1], the tectonic inclusions show a fusi-form, the major axis of which is generally 1 cm or more in length and the minor axis is 3 mm or less (Pl. 33 Fig. 3). The minor axes of the tectonic inclusions are nearly parallel to the planes of S_1, but none of them lie on the same horizon and each inclusion lies one by one within the black schist.

(4) Intersection of S_1 and S_2 (L_{1-2}): Lineation of this type may be found only in the black schist, and in every case it is strictly parallel to the axes of small scale fold.

(5) Striation on S_2 (L_2): Striation imprinted on S_2 represents also one set of linear structure, which is approximately perpendicular to the axes of small-scale fold.

(6) Intersection of S_1 and S_3 (L_{1-3}): Intersections of S_1 and S_3 are the most predominant lineation found in the district. In the east of the Ôbokè district the trend of the L_{1-3} is parallel to the axes of both small-scale and large-scale folds. While, in the district west of the Shirakawa River, trends of the lineation are in general oblique to the trends of the axes of various scale fold. In the neighborhood of Nemuri Valley, which belongs to the northern limb of the Ôbokè Anticline, the L_{1-3} is rarely found oblique within some degrees to the axes of small-scale fold.

(7) Streak on the surface of some quartz-veins parallel to S_1: On the surfaces of some quartz veins, which were segregated about parallel to the S_1, one set of lineations, that is approximately perpendicular to the L_{1-3}, is often found on the Ôbokè route. The lineation L_{1-3} is apparently filled by the quartz-veins in problem.

The trends of the L_{1-3} are shown on equal-area-projection of it measured in each small selected area. The diagrams determined for the Yoshino- and Iya River-route indicate one statistical maximum of the corresponding areas (FIG. 4 & FIG. 14). However, the diagram determined for the Shira River route shows, as expected from the relation of the L_{1-3} to the fold axes mentioned above, that one maximum of the L_{1-3} does not coincide with β-maximum (FIG. 18).

C. Kinematics and Dynamics

The writer has so far described mainly the mutual relations in the field between the major structure and the minor structural elements found in the district. The time-relation of them, i.e. the order of generation will be discussed here after.

In the foregoing section the writer pointed out a fact, that the axes of small

1) The terms of the fabric axes *a*, *b*, and *c* in this paper correspond to the difinition by B. SANDER.

scale folds are strictly parallel to the axes of large scale folds.

The L_1, which is shown by the preferred orientation of minerals, is folded about the axes of the small scale folds. The mineralization on bedding schistosity should, therefore, have taken place prior to the main stage of deformation by which the small scale and large scale folds were accomplished. And also it is reasonable to assume that the direction of movement of the L_1 phase might have been slightly oblique to that during the formation of the small- and large-scale folds.

The harmonic relations of the folds in various scales to the S_2 may, as described above, suggest that formation of the S_2 depends on movement by which the folds have been formed. No mineralization on the planes of the S_2 has been found, and mylonitic structure along the cleavage plane can not be found. Accordingly, it may be inferred that recrystallization was not so strong at the time when the S_2 has been formed. In other words, the stage during which the folds of various scales have been formed can probably not be referred to the main stage of mineralization.

The trend of S_3 is oblique to the trend of the major axis of the anticline on the route along the Shira River. Judging from the evidence, the writer believes that S_3 is not contemporaneous with the fold. However, from the harmonic relation of the S_3 to the folds in the east of the Ôbokè district it is inferred that the formation of the S_3 would not have been independent of folding of the S_1, but both might have been dynamically related to each other. The recrystallization at the time during which the S_3 has been formed does probably not correspond to the main stage of mineralization of the rocks in problem.

One set of streaks is found on some quartz-veins, which have been segregated along the S_1 and have been cut by the S_3.

Through the whole district in problem, joints of various trends can frequently be found, and some of them are strictly perpendicular to certain structural elements described above and the remainder is oblique to those.

Now the writer intends to deal with the genetics of the structural elements and their mutural relations hitherto described.

One of the significant structural characters of rocks in this district is that, as repeatedly described, the rocks on the southern limb of the anticline is uniformly bent without the small scale fold, and, on the contrary, those on the crest and on the northern limb are strongly folded on the small scale. The rocks at the crest and on the northern limb of the anticline consist of the alternations of black-schist and sandstone schist, while the sandstone schist is predominant on the southern limb. On the route along the Shira River the rocks in both limb of the anticline resemble to each other in facies and structural characters. At the present knowledge of research, the writer considers that such difference in structure may partly depend on differences in the main rock types composing both parts.

The sandstone schist in the district generally shows a flexural-slip symmetrical fold of the S_1. Slip movement along the S_2 might have taken place towards the crest of the small scale fold. The striations, which are in part imprinted on the S_2 and nearly perpendicular to axes of the small scale folds, may be referable to so-called a-lineation and may accordingly suggest slip movement along the S_2. The thickness of bed of the sandstone schist is in most cases constant either at the crest or on the limbs of a small scale fold, while that of black schist is much thicker at the crest and becomes thinner towards the limb of a small scale fold. Therefore, materials of the black schist might have been moved towards the crest of small scale fold, forming the ship plane (S_2) during the time when the sandstone schist were folded by flexural ship of the S_1. In other words, black schist might have been folded by slip movement of the S_2. L. U. de SITTER (1956) divides the fold patterns into two types, i. e. the concentric fold and the cleavage fold, and he discussed the genesis of each fold. He pointed out a theoretical possibility that a competent rock may be folded as a concentric fold, while an incompetent rock may result in a cleavage fold, when folding was exerted on a rock which consists of alternation of competent and incompetent beds. The writer considers that folding by slip of the S_2 of black schist corresponds to the cleavage fold by de SITTER.

Differences in geometry of the small scale folds found on the nortern limb of anticline shown in foregoing pages may depend on difference in rock facies. Asymmetric geometry of small scale folds of the alternations, in which black schist is more predominant than sandstone schist, can be explained as a special pattern of deformation of incompetent rock. It is considered that the formation of the asymmetrical fold may be due to the interference with the transport of rock materials along the slip plane (S_2) by thin leyers of intercalated competent sandstone schist in the black schist, and its axial planes converging towards the crest of the larger scale fold may be referable to the S_2 in ordinary black schist.

The harmonic relations of the folds to the S_3 may suggest that the formation of the S_3 is closely related to folding.

On the genesis of axial plane cleavage, many reports have been published. Especially, de SITTER (op. cit.) pointed out one type of folding which shows a transition from the concentric fold to the cleavage fold. It can not be considered that the S_3 in the district may correspond to cleavage plane of the cleavage fold, because, as de SITTER said, the cleavage fold may be genetrated in a rock, only when the rock could be more incompetently deformed than when it is concentrically folded under the same stress conditions. In the district there is no evidence to show that in the stage, when the S_3 was formed, rocks could be more incompetently deformed than in the stage when the deformation is indicated by the flexural slip of the S_1. It is unlikely that mineralization of the rocks was strong at the former stage than at the latter stage.

The main factor that decides the geometry of a concentric fold is, according to the opinion of de SITTER (*op. cit.*), the viscosity of a rock. In a case that the stress continuously acted after the rocks had concentrically folded within the go-ometrical limit of this knd of folding, the fold of this type must probably change into the other deformation pattern. In the southern limb of the anticline, where the S_1 is uniformly developed, the S_3 is very weak or absent. On the other hand, the S_3 is remarkably developed in close relation to the small scale folds in the crest and the northern limb.

D. Micropetrofabrics

The micropetrofabric investigation in the present district have been made by I. NAKAYAMA (1950) in an attempt to examine his hypothesis of the mechanism of quartz deformation. The writer's purpose of investigation of this type is to understand the internal deformation of rocks concerning each movement phase of the S_1 and the S_3 by dealing with deformed quartz as one of the constituent minerals.

The results of the laboratory investigation are recorded in the fabric diagrams. Before correlating those recorded data with the large scale features observed in the field, attention must be drawn to on what mechamism quartz orientation in this district are based.

1. The characters of quartz grains in worked specimens (sandstone and quartz vein within it)

Quartz grains in worked specimens are devided into following three types.

a) - type—coarse blast porphyritic quartz grains

They are relict minerals, as explained by I. NAKAYAMA (1950). Most of them show strong undulatory extinction and marginal granulation, and complete granulation of them is rare, but in the parts, where many quartz veinlets are present, most of them are completely granulated into elongated shapes parallel to the S_3 as well as quartz grains of quartz veinlet, and these granulated quartz grains show complete recrystallization and do not show cataclastic texture.

b) - type—divided into following two types by I. NAKAYAMA.

1) very small granulated products of the a)-type coarse grained quartz.

2) very small quartz grains as original sedimentation products. From incomplete granulation of the a)-type quartz grains, most of the b)-type quartz grains may belong to the latter. The quartz grains of this type in a sample are elongated parallel to the fabric axis *a* on the S_1 in the ac section.

c) - type—quartz grains constituting quartz veins or veinlets which might be segregated parallel to the S_1 after the deformation of the S_1 phase. The quartz grains of this type are very small, but under gypsum-plate they are grouped into larger units within which each of them show the same retardation color. Most of these very small quartz grains are strongly elongated and preferably oriented parallel to the fabric axis *a* on the S_3 in the ac section, but some of them are obliquely oriented to the S_3 and are oriented parallel to each other within the larger unit among which the quartz grains show the same retardation color.

Beside those very small elongated quartz grains there are a little coarse quartz grains which show undulatory extinction. Some of them are partly granulated, especially strongly in their marginal parts. The granulated small quartz grains in marginal parts of the coarse quartz grains are strongly elongated and, towards the inner part of these, elongated quartz grains decrease gradually and distribute in branches subparallel to the S_3 at intervals. Quartz grains occupying spaces between the branches are not so strongly elongated and each grain boundaries are not so clear. From those evidences mentioned above, the writer interprets that the very small quartz grains of this type may be granulated products of coarse quartz grains and that the larger units within which each of them show the same retardation color correspond to the original coarse quartz grains.

That the elongated quartz grains distributed in the branches and the surrounding quartz grains are in different extinction positions may mean the rotational movement of the former. Now it is question whether the elongated shapes and the elongation axes parallel to the S_3 of the former indicate the result of plastic translation of the latter, or the two features of the elongated quartz grains indicate the external rotation of the surrounding quartz grains, the slightly elongated shapes of the latter compared with the former in the ac section resulting from that the elongation axes of the latter are oblique to the ac section. It is favourable for the latter interpretation that the elongations of some strongly elongated grains are oblique to the S_3.

There are some quartz grains which changes radially their elongation trends, as shown by Pl. 32, Fig. 3. This evidence may deny the doubt if the trend of the elongation of the quartz grains oblique to the S_3 corresponds to a conjugate oblique plane of the S_3.

2. *The general features of the fabrics as determined by plotting poles of optic axes of the quartz grains of each type*

a) The fabrics as determined by a)-type quartz grain. The preferred orientations of quartz axes as shown by maxima or girdles on the diagrams are not strong in both FIG. 20 and FIG. 24, and are not so developed symmetrically in respect to any fabric axes, while the fabric diagrams of the c)-type quartz grains and the b)-type quartz grains undulatory extincting show the rotational movement of the optic axes about the fabric axis *b* (FIG. 21 and FIG. 25).

b) The fabrics as determined by the b)-type quartz grains. The fabric diagram is shown in FIG. 22. The diagram shows maxima, which may be referable to the maximum IV by B. SANDER and H. W. FAIRBAIRN, and a small circle girdle with the maxima parallel to the ac plane.

c) The fabrics as determined by c)-type quartz grains. The preferred orientations of the quartz axes on the whole diagrams show tendencies to concentrate maxima which may be referable to the maxima II, IV, and VIII by B. SANDER (1950) and H. W. FAIRBAIRN. The general features of each diagram prepared

Spl. no. MN56100602
Loc. Yoshino river route
Str. po. S limb uniformly bended
and S_3 invisible
Type of qu. a-type

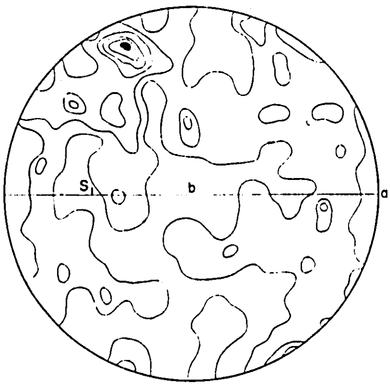

FIG. 20. 200 *c* axes of blast-porphritic quartz grains in sandstone schist. Max : 6.5% Contours : 6-5-4-3-2-1 %.

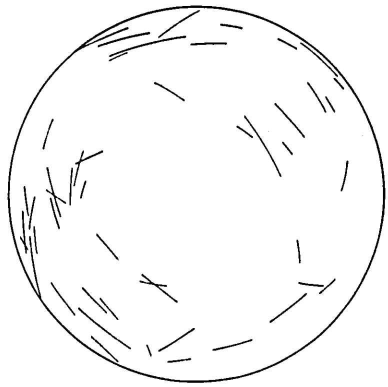

FIG. 21. Trend lines of optic axes within individual blast-porphyritic quartz corresponding to FIG. 20.

Spl. no. MN56100602
Loc. Yoshino river route
Str. po. S limb uniformly bended
and S_2 invisible
Type of qu. b-type.

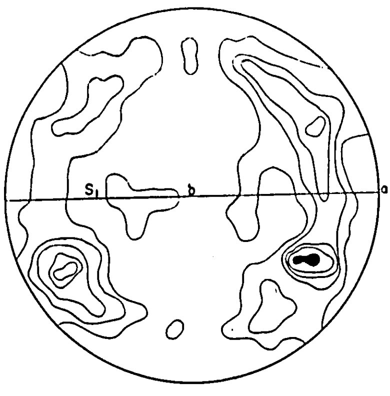

FIG. 22. 400 *c* axes of quartz having their longest dimensions in S_1 (sandstone schist). Max : 5.5% Contours : 5-4-3-2-1 %

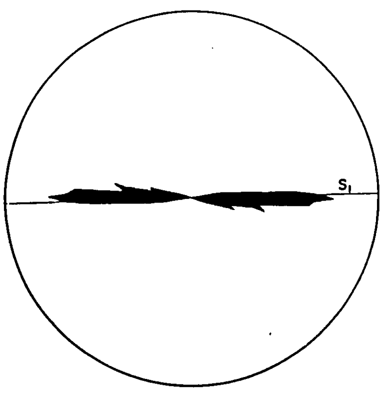

FIG. 23. Frequency of elongation trends of quartz grains corrensponding to FIG. 22.

Spl. no. MN 57052102
Loc. Iya river route
St. po. Crest of minor fold in N limb of major fold
Type of qu. a-type

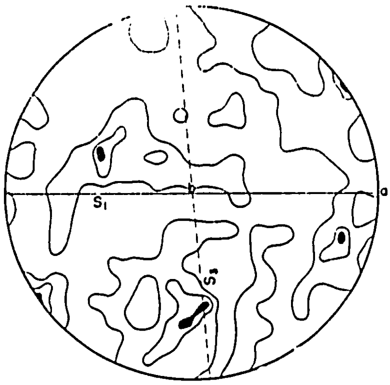

FIG. 24. 150 *c* axes of blast-porphyritic quartz grains in sandstone schist. Max : 3% contours : 3-2-1%.

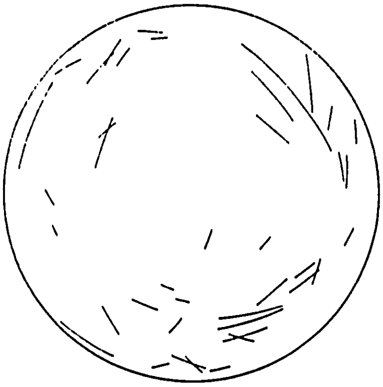

FIG. 25. Trend lines of optic axes within individual blast-porphyritic quartz grains corresponding to FIG. 24.

Spl. no. MM 57052102
Loc. Iya river route
Str. po. Crest of minoir fold in N limb of major fold
Type of qu. c-type

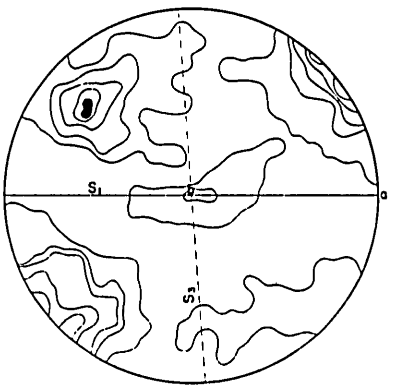

FIG. 26. 500 *c* axes of quartz having their longest dimensions in S_3 (quartz vein). Max : 5% Contours : 5-4-3-2-1%

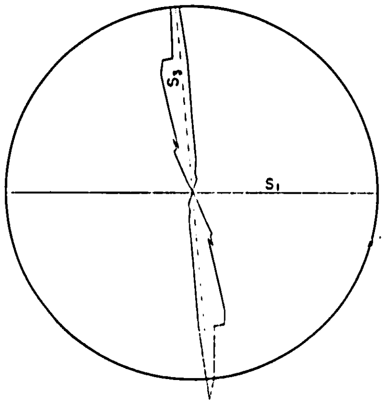

FIG. 27. Frequency of elongation trends of quartz grains corresponding to Fig. 26.

Spl. no. MN 57051001
Loc. Yoshino river route
Str. po. N limb of minor fold in crest of major fold.
Type of qu. c-type

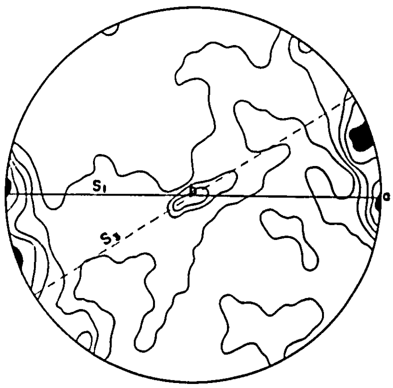

FIG. 28. 400 *c* axes of quartz having their longest dimensions in S_3 (quartz vein). Max : 5.2% Contours : 5-4-3-2-1%.

Spl. no. MN 57051001
Loc. Yoshino river route
Str. po. Crest of minor fold in crest of major fold
Type of qu. c-type

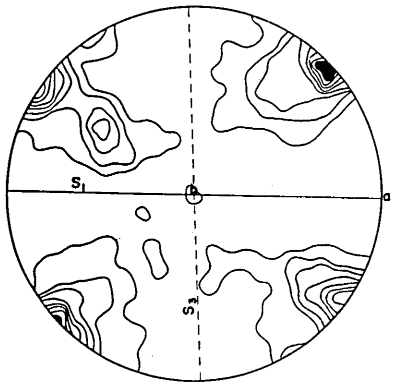

FIG. 29. 400 *c* axes of quartz having their longest dimensions in S_3 (quartz vein). Max : 8.1% Contours : 8-7-6-5-4-3-2-1%.

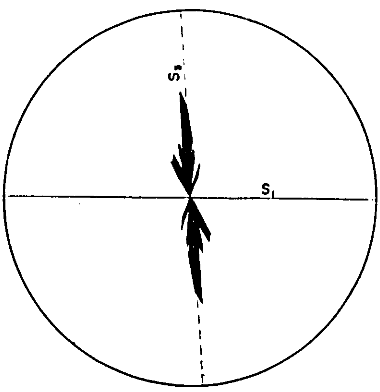

FIG. 30. Frequency of elongation trends of quartz grains corresponding to FIG. 29.

Spl. no. MN 56100502
Loc. Yoshino river route
Str. po. S limb adjacent ot crest of major fold
Type of qu. c-type.

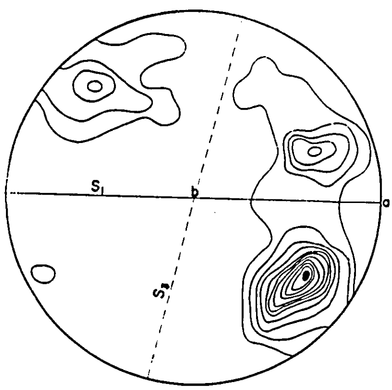

FIG. 31. 500 *c* axes of quartz having their longest dimensions in S_3 (quartz vein). Max : 11.2% Contours : 11-10-9-8-7-6-5-4-3-2-1%.

Spl. no. 56100502
Loc. Yoshino river route
Str. po. S limb adjacent to crest of major fold
Type of qu. c-type

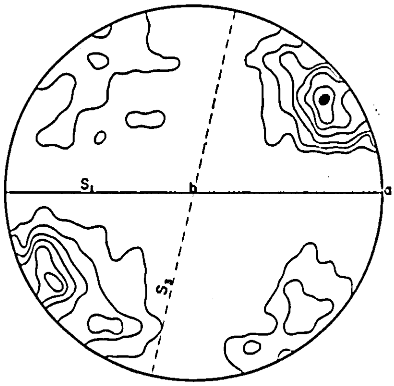

FIG. 32. 500 *c* axes of quartz having their longest dimensions in S_3 (quartz vein). Max: 7.6% Contours: 7-6-5-4-3-2-1%.

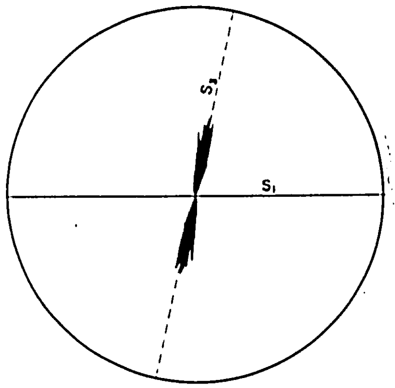

Fig. 33. Frequency of elongation trends of quartz grains corresponding to FIG. 32.

Spl. no. MN 57051003
Loc. Yoshino river route
Str. po. Nl imb adjacent to crest of major fold
Type of qu. c-type

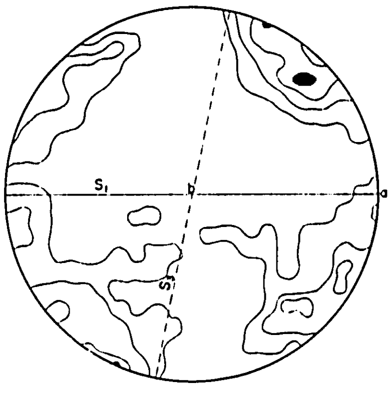

FIG. 34. 500 *c* axes of quartz having their longest dimensions in S_3 (quartz vein). Max: 5% contours: 5-4-3-2-1%.

Spl. no. 57110707
Loc. Shira river route
Str. po. N limb or minor fold in N limb of major fold
Type of qu. c-type

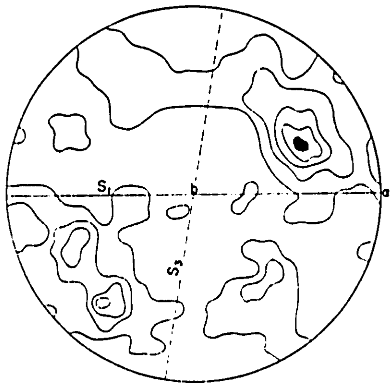

FIG. 35. 500 *c* axes of quartz having their longest dimensions in S_3 (quartz vein). Max: 5.2% Contours: 5-4-3-2-1%.

are represented in Table 1.

3. Interpretation of mechanism of the quartz orientation

As mentioned above, the features of the c)-type quartz grains may mean a mecanical granulation of the coarse-grained quartz. Accordingly, at least at initial stage of quartz orientation, mechanical granulation of quartz grains might had played a role to it.

The fracture hypothesis, advocated by B. SANDER, GRIGGS anb BELL, is based on the assumptions that 1) upon initial deformation quartz grains are fractured into elongated fragments parallel to certain crystallographic directions, 2) during continued deformation the needles of quartz are rotated so that elongation axes are parallel to the direction of movement, 3) one of the banding plane of each needle lines in the plane.

It is considered that the needles may be composed of combinations of cleav-

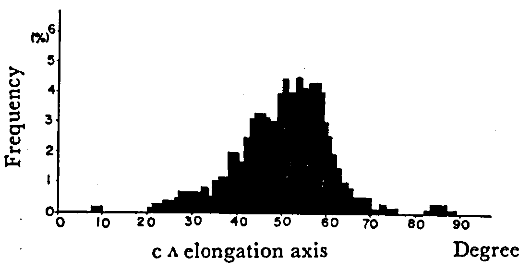

FIG. 36. Corresponding to the maximum areas in the 2nd and 4th quardrand of FIG. 31.

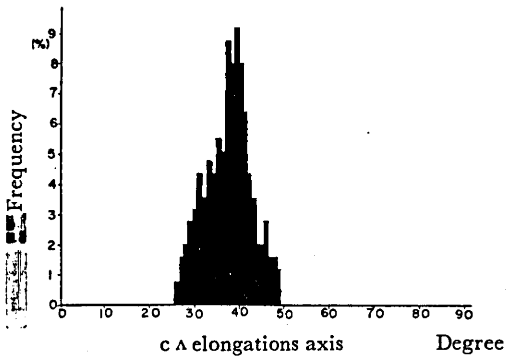

FIG. 37. Corresponding to the maximum aseas in the 1st and 3rd quardrand of FIG. 29.

Angles between optic axes and elongation axes of the quartz grains corresponding to the maximum areas in each diagrams.

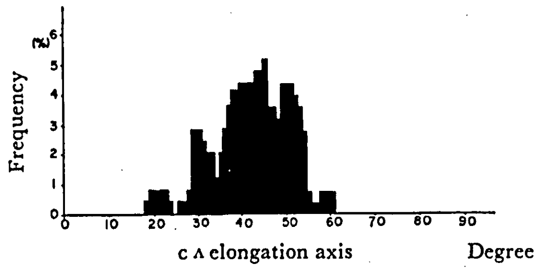

FIG. 38. Corresponding to the maximum areas in the 2nd and 4th quardrand of FIG. 29.

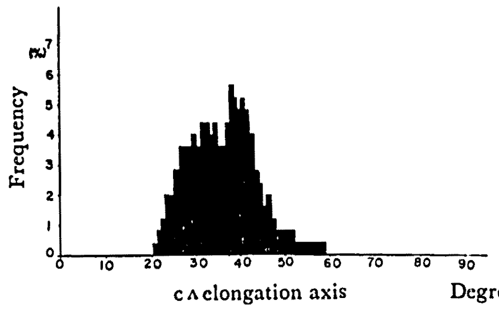

FIG. 39. Corresponding to the maximum areas in the 2nd and 4th quardrand of FIG. 26.

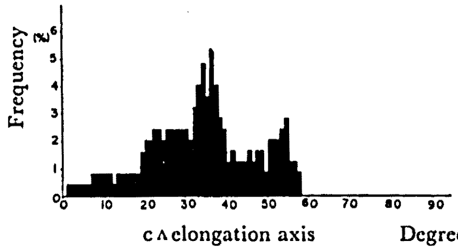

FIG. 40. Corresponding to the maximum areas in the 1st and 3rd quardrand of FIG. 26.

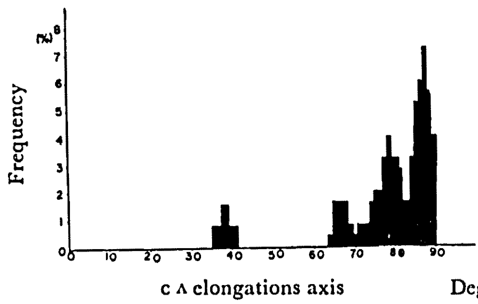

FIG. 41. Corresponding to the maximum areas in the central part of FIG. 26.

ages. According to H. W. FAIRBAIRN (1936), in quartz crystal $r(10\bar{1}1)$ and $z(01\bar{1}1)$ should exhibit the best cleavage, with $m(10\bar{1}0)$, $c(0001)$ and $a(11\bar{2}0)$ as the second best. Thus, as H. W. FAIRBAIRN (1949) explained, if the needles are composed of those cleavage, the maxima II, IV, VI and VIII should be determined by conditions in FAIRBAIRN's table (1949, p. 121) respectively.

The c)-type quartz grains show strong elongation in ac section. According to the fracture hypothesis, it it considered that the elongation axes may correspond to the axes of the needles and therefore angle between the optic axis and the elongation axis of quartz grain should be about 38° in the elongation quartz grains corresponding to maxima referable to the maximum II, about 42° in the other corresponding to maxima referable to the maximum VI, about 50° in a third corresponding to maxima referable to the maximum VI and 90° in a fourth correspond to maxima referable to the maximum VIII.

In order to examine those relationships the writer measured the angle between the optic axes and the elongation axes of the c)-type quartz grains, and correlated the angle with the maxima on the diagram of the corresponding quartz grains. The results may accord with the relationships expected from the fracture hypothesis. The results are shown in FIG. 36–41. The fabric diagram shown in FIG. 26 were prepared from the measurment of the c)-type grains sketched in Pl. 32, FIG. 3.

The units neighbouring to each other which may correspond to original coarse quartz grains as mentioned above show respectively maxima referable to the maxima II, IV, and VIII, and also FIG. 39–41 show that quartz grains within the units corresponding to each maxima are composed of the same conbination of the cleavages. GRIGGS and BELL (1938) investigated that the predominating cleavage faces developed in single crystal quartz deformation were dependent on the orientation of the test cylinder used. Thus the writer considers that those different combinations of cleavages of the quartz grains may be dependent on the relations of the c axis of the original quartz to the deformation planes of the S_3 phase, as within such small area probably each grain might have been under the same condition. All those evidences may indicate a probabillty that mechanism of deformation of those quartz grains may be explained by the fracture hypothesis.

Also the following evidences may favor the fracture hypothesis.

a) The fabric diagram of the c)-type quartz grains show the tendencies to concentrate to the maxima referable to II, IV, VI and VIII.

b) The elongation axes of same c)-type quartz grains are oblique to S_3.

On the contrary, the other following evidences may be unfavorable to the fracture hypothesis,

a) the change into the strongly elongated from of the slightly elongated form may be the result of the plastic translation of the latter.

b) in ab section on the S_3 the ratio a:b of the c)-type quartz grains in length may be not so different, and some of them is rather longer in b than the a on the S_3.

Those two evidences may show the intragranural plastic deformation.

c) the small circle girdle parallel to the ac plane as shown on the diagram of b)-type quartz grains (FIG. 22).

d) some of the c)-type quartz grains show undulately extinction. These four evidences may be reasonablly explained by the translation hypothesis advocated by SCHMIDT and B. SANDER.

Now it is question whether during continued deformation the external rotation was followed by the translation-gliding, or the whole processes could be explained by the translation gliding. And now the writer must start his career over again.

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Explanation of Plate XXXII

Fig. 1 and Fig. 2. Quartz grains in the sandstone schist. Coarse granular grains of quartz, whos e-axes demonstrate a random orientation, and surrounding fine tabular grains of quartz, whose c-axes demonstrate a preferred orientation. $\times$ 10

Fig. 3. A deformed quartz vein in the black schist. The elongation axes of quartz grains are preferably oriented parallel to the S_2-surfaces in the black schist. $\times$ 10

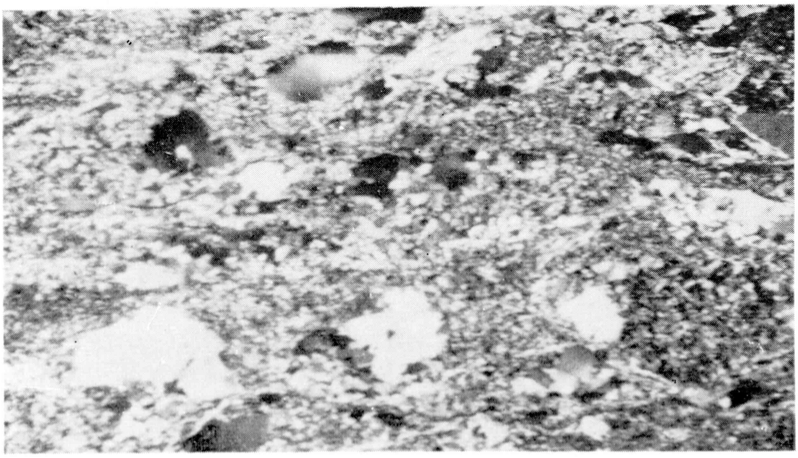

FIG. 1.

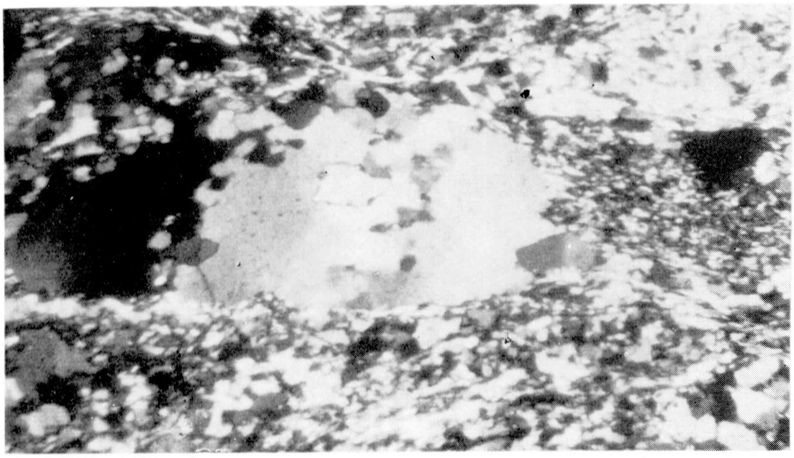

FIG. 2.

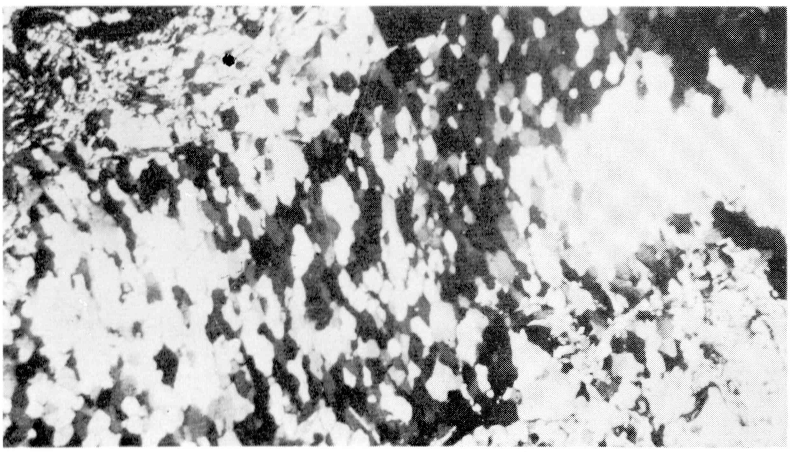

FIG. 3.

Explanation of Plate XXXIII

Fig. 1. The S_2-surfaces in the black schist. $\times 4$

Fig. 2. The photo shows a relationship between the transversal slip cleavages in the black schist and sandstone schist. $\times 3$

Fig. 3. Deformed pebbles photographed in plane of the ac-thin section. $\times 10$

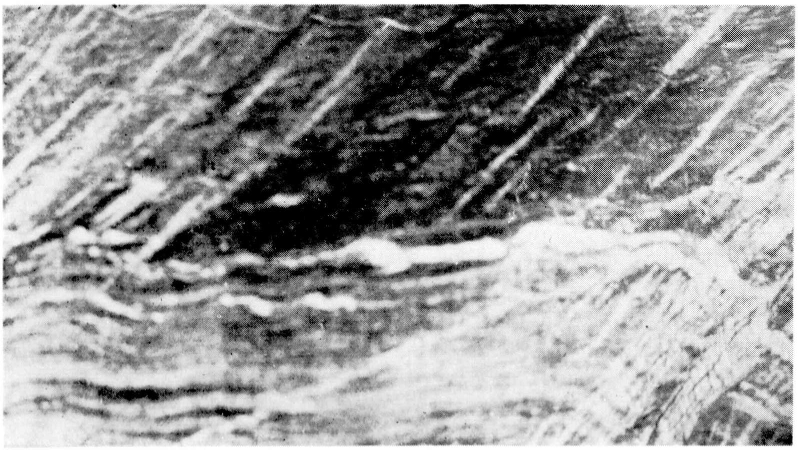

FIG. 1.

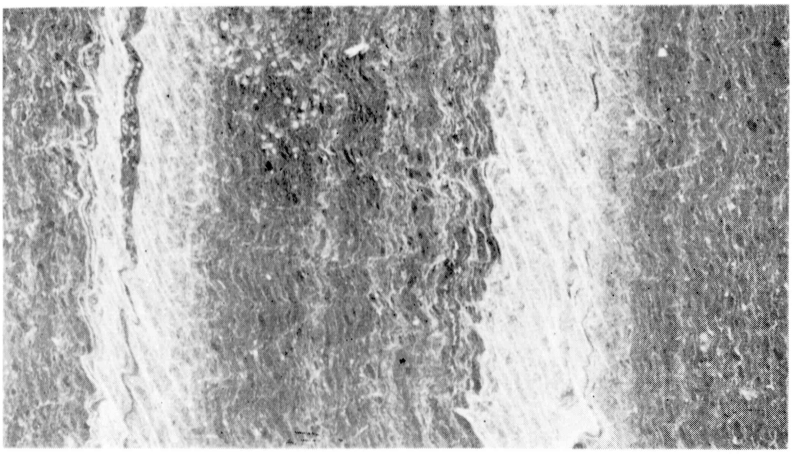

FIG. 2.

FIG. 3.