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Preferred Orientation of Tourmaline in Crystalline Schists from the Sazare Mine, in Central Shikoku, Japan

By

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With 1 Table and 3 Text-figures

Abstract: Two specimens of spotted quartz-schist and spotted greenschist rich in tourmaline were collected from the Sazare Mine in the Sambagawa metamorphic zone. In these specimens, dimensional orientation and lattice orientation of minerals have been analyzed. The longest dimension in these minerals is parallel to the fabric axis *b*, which is set up parallel to the high angle lineation developed at the horizon bearing the ore body of the Sazare Mine. The longest dimension of tourmaline coincides with [0001] and that of amphibole with *c*-axis. Orientation diagrams show that [0001]-axes of tourmaline are oriented parallel to the fabric axis *b*. For amphibole, it is inferred from the orientation diagrams for X, Y, and Z that *c*-axes are also oriented parallel to the fabric axis *b*. This coincidence of [0001] of tourmaline and *c*-axes of amphibole to the fabric axis *b* parallel to the high angle lineation, suggests that the fabrics of these minerals have been produced at the stage of deformation concerning the high angle lineation.

Contents

I. Introduction

Tourmaline has been reported as one of accessory minerals in crystalline schists of the Sambagawa metamorphic zone, Southwest Japan., by many authors (Suzuki, 1930; G. Horikoshi, 1937; G. Horikoshi and Katano, 1940; Hide, 1954, and 1961; Seki, 1961; Yamaoka, 1961).

The rule of preferred orientation of tourmaline crystals was presented by Fairbairn (1949, p. 9, Table 2-1). He showed that (0001) of tourmaline was parallel to the fabric axis *b*. Kamb (1959) discussed the preferred crystal orientation on the basis of thermodynamics, and showed that the *c*-axis of tourmaline is parallel to the uniaxial stress axis (p. 160, Table 1). Recently, a different view has been presented. Hide (1961, p. 31) has reported that the *c*-axis of tourmaline is parallel to the lineation concerning the first stage of folding in the tectonic history of the Sambagawa metamorphic zone in the Besshi-Shirataki district. Yamaoka (1961, p. 11) has recognized that the *c*-axis of tourmaline is coincident with the lineation of the other rock-forming silicate minerals. However, these observations have not so far been confirmed by the statistical analysis.

In the Sazare Mine district, approximately 20 km east of the Besshi Mine in central Shikoku, as shown in Fig. 1, rocks rich in tourmaline were collected by the present author. In this paper, he intends to describe the petrofabrics of two specimens of the tourmaline-bearing rocks, the rule of preferred orientation of tourmaline crystals, and discuss some problems concerning the lattice orientation of tourmaline.

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II. GEOLOGICAL SETTING

The Sazare Mine district is occupied by crystalline schists of the Sambagawa metamorphic zone. The apparent stratigraphy of these rocks in this district was divided by DOI (1959, and 1961) into the following formations in the ascending order: the Koboke formation, the Minawa formation, and the Tomisato formation. The Minawa formation, was subdivided into three members, i.e., the Lower, the Middle, and the Upper member.

The Sazare Mine is situated stratigraphically in the Middle member of the Minawa formation.

Rocks of the Koboke and the Lower Minawa formation which are distributed in the northern part of the district consist of non-spotted schists. The metamorphic grade of these rocks belongs to the greenschist facies, or the glaucophane-schist facies. Rocks of the formations from the Middle Minawa to the Tomisato formation in the southern part consist of spotted schists which belong generally to the epidote-amphibolite facies.

Structurally, the Sazare Mine is situated on the large limb between the Yakushi anticline and the Tsuneyama syncline, the axes of which trend approximately E-W with smaller inclination as shown in Fig. 1. In this district, b ($=B$)-lineation parallel or subparallel to these major structures are developed generally, while on the limb between these large scale folds, lineation with high angle plunge has been reported by many authors. TAKEDA (1954) called it the "Hinouchi (Ore-

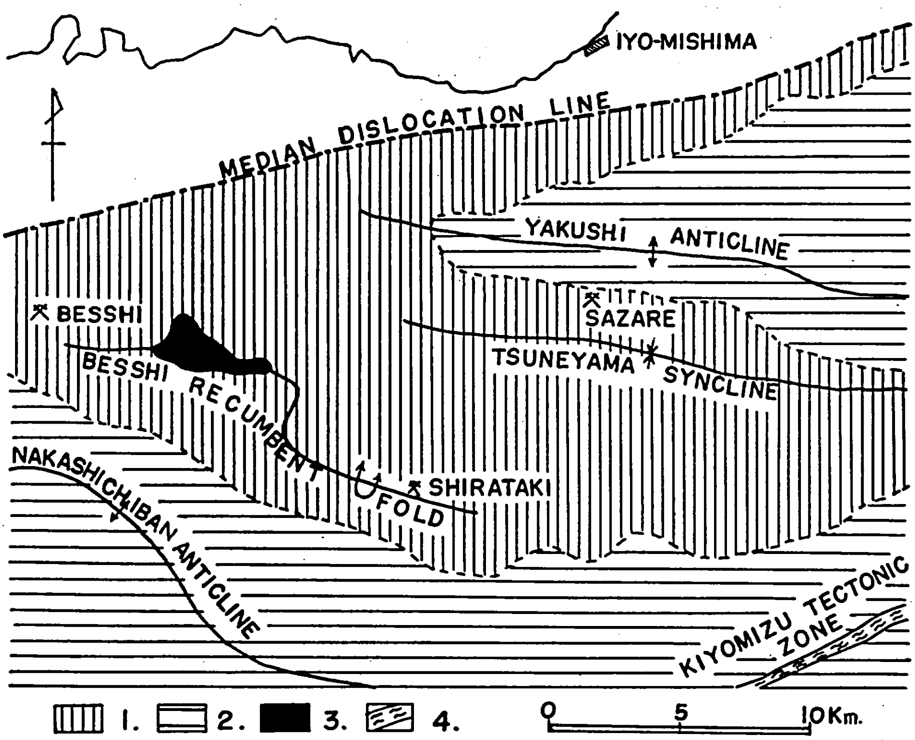


Fig. 1. Geological sketch map of the Besshi-Shirataki-Sazare district (after KOJIMA and SUZUKI (1958) and partially modified by the present author).
1. Spotted Schists 2. Non-spotted Schists 3. Ultra-Basic Rocks
4. Tectonic Zone

zone)-lineation", E. HORIKOSHI (1958) the "Abnormal lineation", and DOI (1959) the "L_2-lineation". The high anlge lineation is recognized in a zone called the high angle lineation zone with width from 300 m to 2000 m.

The ore deposit of the Sazare Mine is one of typical bedded cupriferous iron sulfide deposits (*Kieslager*), situated in spotted greenschists and in the high angle lineation zone.

To the west of the ore deposit, a fold of some peculiar style was discriminated by DOI (1959) and HIRATA (1959), named the Tomisato fold. The fold has a form of imperfect conjugate fold. The plunge of the fold axis is high, coinciding with the high angle lineation developed in this district. Specimens for petrofabric analysis were collected from the core and the wing of the Tomisato fold.

III. PETROGRAPHIC AND PETROFABRIC DESCRIPTIONS

A. SPECIMEN I.

Specimen number: NO58IX9-10.

Rock name: Spotted quartz-schist.

Locality: Shimpi ore body at the 6th sublevel of the Sazare Mine.

Structural position: Eastern wing of the Tomisato fold.

Horizon and occurrence: The specimen has several sets of planar structures. The most distinct set of these planar structures is the surface of compositional banding and parallel arrangement of cleavages of platy minerals. It is designated as S_1 after the nomenclature presented by KOIJMA and SUZUKI (1958) and KOJIMA and HIDE (1958). S_1-surface is modified by small scale folds, the wave length of which is about 4 cm and the amplitude 0.7 cm. On the surface of S_1 two sets of lineations are discernible. The lineation with high angle plunge is observed as distinct fine streaks. This type of lineation is parallel to the axis of small scale fold just mentioned above and parallel to the Tomisato fold. On the thin section cut normal to this lineation conjugate sets of planar structures with appearance of shear zones of micro-scale can be recognized. This type of lineation coincides with the intersection of S_1 and two sets of shear zones. Accordingly this lineation is also a type of b $(=B)$-lineation in the high angle lineation zone. The other set of lineation is observed as micro-corrugation or fold axis of micro-scale fold and has low angle plunge. This second type of lineation cut across the first type of lineation almost at right angle. Therefore, the second type of lineation must have been formed later than the first type of lineation. The rock belongs to the $B \perp B'$-tectonite. In this paper, the first type of lineation is called the high angle lineation and the second type the low angle lineation.

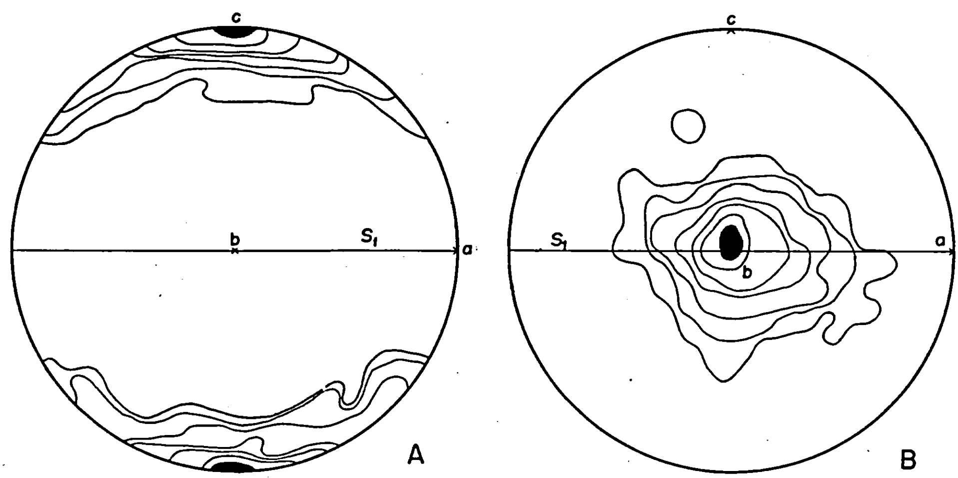
Fabric axis: In this specimen, three fabric axes are set up as follows: The fabric axis b is parallel to the high angle lineation, and the fabric axis a is normal to b on the surface S_1, and the fabric axis c is normal to a and b.

Petrographic properties: The rock consists mainly of quartz, muscovite, and chlorite, with subordinate amount of plagioclase, tourmaline, garnet, magnetite, hematite, pyrite, and chalcopyrite. In this specimen are found many layers of simple mineral assemblages; that is, quartz, chlorite-muscovite, tourmaline, tourmaline-quartz, tourmaline-quartz-muscovite-garnet, and garnet-chlorite-quartz. Quartz is fine-grained and shows distinct undulatory extinction. In muscovite recognized undulatory extinction near the micro-scale shear zones observed on the b-section and around micro-corrugation concerning the low angle lineation on the a-section. Chlorite is optically positive and shows also undulatory extinction. Tourmaline is abundant in this specimen, and found almost exclusively in the layers rich in tourmaline. Tourmaline shows a zonal structure consisting of five zones which can be discriminated with the variation of axial colour, namely, the colour of Z changes from the center to the margin of the crystal—greenish-brown—bluish-green—greenish-brown—green—greenish-browm, while, that of X is light-pink or colourless. Owing to the lack of chemical analysis, the composition of the tourmaline can not accurately be determined, but from the colour on thin section the mineral is inferred to belong to the dravite-schorlite series (EPPRECHT, 1953). The tourmaline is idiomorphic and occasionally is found that a single crystal is bent angularly or divided into two parts along (0001) parting and pulled apart from each other.

The average dimension of the tourmaline crystals to the directions of three fabric axes are *a*: 0.08 mm, *b*: 0.25 mm, and *c*: 0.08 mm, as shown in Table 1. Therefore, it is clear that the longest dimension of the tourmaline is parallel to the fabric axis *b*.

Fabrics: The orientation diagrams for [001]-axes of muscovite and chlorite shows a distinct *ac*-girdle the pole of which coincides with the fabric axis *b* (Fig. 2A).

The orientation diagram for [0001] of tourmaline measured for 200 non-selected grains in the tourmaline-rich layer on a single *b*-section, is shown in Fig. 2B. A



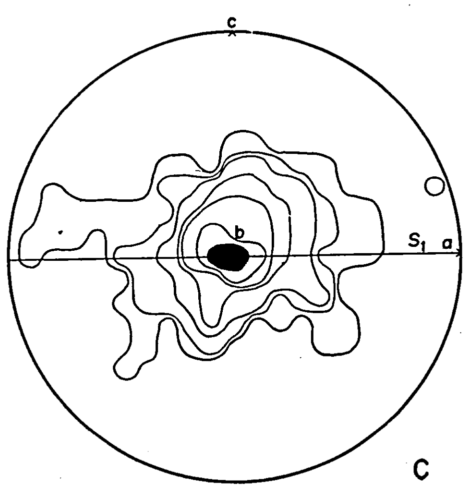


Fig. 2. Orientation data for the specimen I from the Shimpi ore body at the 6th sublevel.
A. 200 [001]-axes of muscovite and chlorite measured in the *a*-section. Contours: 15-10-8-6-4-2-1 %.
B. 200 [0001]-axes of tourmaline measured in the *b*-section. Contours: 15-11-7-5-3-2-1 %.
C. 200 [0001]-axes of tourmaline measured in the *a*-section. Contours: 12-9-7-5-3-2-1 %.

strong maximum of [0001] coincides with the fabric axis *b*. The pattern is elongated somewhat on the *ab*-plane (*ca.* 106°) and less evidently on the *bc*-plane (*ca.* 80°). In the fabric pattern of [0001] of tourmaline can not be recognized any appreciable difference between two orientation diagrams measured on the *a*- and the *b*-section respectively (Fig. 2B, and C). Therefore, in this case, the *Schnitteffekt* is negligible.

B. SPECIMEN II.

Specimen number: NO58IX18-2.
Rock name: Spotted greenschist.
Locality: Tomisatomuke prospecting gallery at the 12th level of the Sazare Mine.
Structural position: Core of the Tomisato fold.
Horizon and occurrence: This spotted greenschist belongs to the western part of country rocks of the ore deposit.

Rock structure: A single set of distinct planar structre in the specimen is identified as S_1-surface. Two sets of lineations are recognized on the surface S_1. Of these lineations, the lineation with high angle plunge is distinct and parallel to the axes of micro-scale isoclinal folds, which is also parallel to the axis of the Tomisato fold. The other set of lineation cuts across the former one with right angle. These two types of lineations are identical with those of the specimen I. Fabric axes for the specimen II are defined in the same way as for the specimen I.

Petrographic properties: The rock consists mainly of bluish-green amphibole, epidote, chlorite muscovite, plagioclase, with subordinate amount of quartz, calcite, tourmaline, rutile, and titanite.

Bluish-green amphibole has following optic properties: $Z \wedge c = 18°$, $2Vx = 44°$, pleochroism X light yellow, Y green, and Z bluish-green. Amphibole crystals show often undulatory extinction around micro-folds concerning the later low angle lineation.

Small grains of tourmaline are observed abundantly in thin layer in this specimen. Tourmaline shows idiomorphic crystal form and zonal structure consisting

TABLE 1. AVERAGE DIMENSIONS OF MINERALS IN DIRECTIONS OF THE FABRIC AXES, *a*, *b*, AND *c*.

Specimens	Minerals	Average Dimensions (mm)		
		d_a*	d_b	d_c
I	Tourmaline	0.08	0.25	0.08
II	Tourmaline	0.03	0.17	0.03
	Amphibole	0.15	0.55	0.04
	Epidote	0.03	0.06	0.02
	Plagioclase	0.07	0.17	0.06

* d_a, d_b, and d_c represent average dimensions parallel to the fabric axes, *a*, *b*, and *c*.

of three zones which can be discriminated with the variation of axial colour, namely, the colour of Z changes from the center to the margin of the crystal light brownish-green—greenish-brown—light greenish-brown, while that of X is light brownish pink.

Average dimensions of grains of minerals in the directions of three fabric axes are shown in Table 1. In tourmaline, the longest dimension is parallel to the fabric

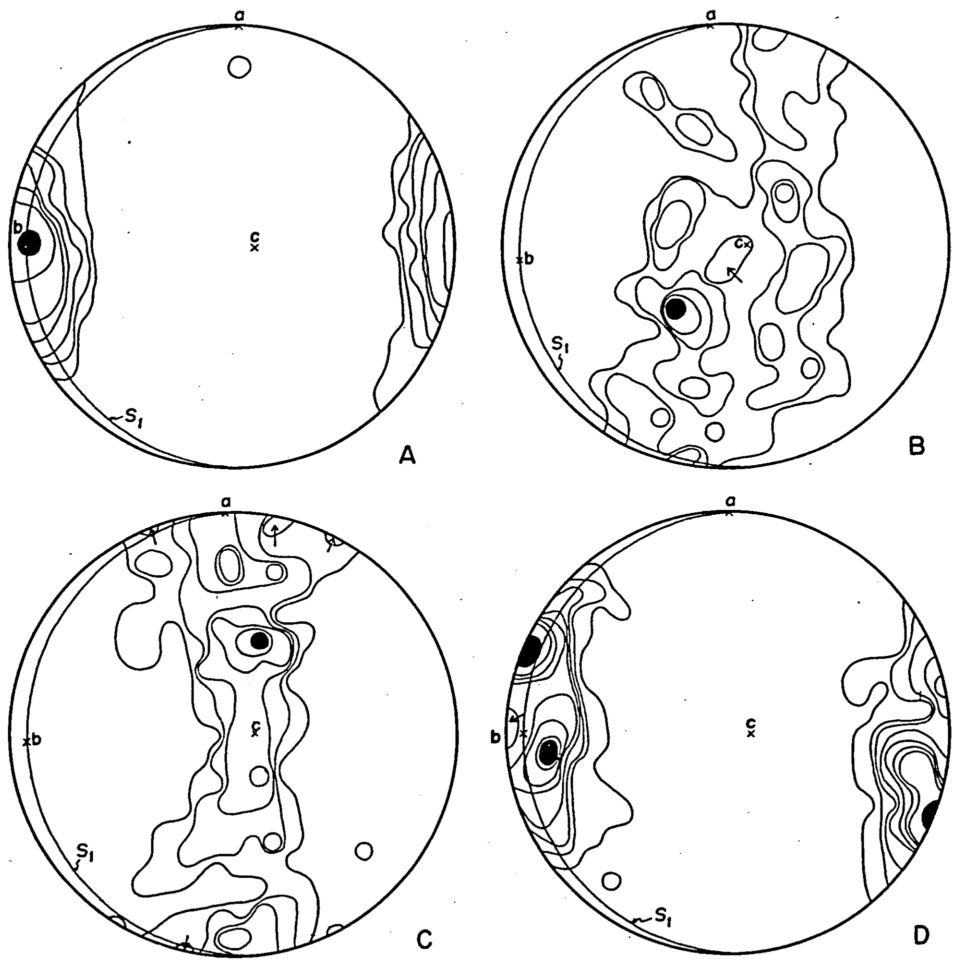


Fig. 3. Orientation data for the specimen II from the Tomisatomuke prospecting gallery at the 12th level.
A. 200 [0001] axes of tourmaline measured in the *c*-section. Contours: (17-15)-11-7-5-3-2-1 %.
B. 200 X-axes of amphibole measured in the *c*-section. Contours: 5-4-3-2-1 %.
C. 200 Y-axes of amphibole measured in the *c*-section. Contours: 6-5-4-3-2-1 %.
D. 200 Z-axes of amphibole measured in the *c*-section. Contours: (9-8)-7-6-5-4-3-2-1 %.

axis *b* and the dimensions parallel to the fabric axis *a* and *c* are the same. While in amphibole, epidote, and plagioclase the longest dimension is parallel to *b*, the intermediate to *a* and the shortest to *c*.

Fabrics: 200 [0001] axes of tourmaline crystals are shown in Fig. 3A. The pattern is characterized by a strong maximum with slight dispersion on *ab*-plane amounting to *ca.* 90°. This maximum coincides with the fabric axis *b*. Dispersion of concentration on *bc*-plane is not recognized.

Orientation diagrams for optic elasticity axes, X, Y, and Z, in 200 grains of amphibole, are shown in Fig. 3B, C, and D. Z-axes distribute on a small circle girdle with the radius of 18° which corresponds to the extinction angle of amphibole ($Z \wedge c = 18°$) in this specimen (Fig. 3D). Y-axes distribute on a great circle the pole of which coinides with the center of the small circle girdle for Z (Fig. 3C). X-axes distribute on a small circle girdle with the radius of 72° which corresponds to the angle of $X \wedge c$ of this amphibole (Fig. 3B). The center of this small circle girdle coincides with the center of the small circle girdle for Z-axes and the pole of the great circle girdle for Y-axes. Therefore, it is inferred that *c*-axes of amphibole are concentrated to the fabric axis *b*, as recognized by many authors (FAIRBAIRN, 1949; ISHIOKA and SUWA, 1945; and KOJIMA and HIDE, 1958).

IV. SUMMARY AND DISCUSSION

As a summary of above descriptions, general rule of preferred orientation of tourmaline crystals and related problems will be discussed in the following.

The longest dimension of grains of tourmaline, amphibole, epidote, and plagioclase is parallel to the fabric axis *b*. For amphibole, epidote, and plagioclase, the intermediate dimension is parallel to *a* and the shortest is parallel to *c*. For tourmaline, however, the difference in dimension of crystal between parallel to *a* and to *b* can not be recognized. When the dimensions with respect to three axes, *a*, *b*, and *c* are shown as d_a, d_b, and d_c, respectively, for tourmaline $d_b > d_a = d_c$, and for amphibole, epidote and plagioclase $d_b > d_a > d_c$. Accordingly, the relation between the values of axial dimensions of these component minerals will be written as $d_b > d_a \geqq d_c$.

Therefore, the high angle lineation in the present specimens coincides with the dimensional orientation of component minerals.

[001]-Axes of muscovite and chlorite show distinct *ac*-girdle in the fabric diagram. [0001]-Axes of tourmaline have maximum concentration parallel to the fabric axis *b* with slight dispersion on *ab*-plane.

From the orientation diagrams for X-, and Y-, and Z-axes of amphibole, it can be inferred that *c*-axes of amphibole were concentrated parallel to the fabric axis *b*. Therefore, it has been proved that [0001]-axes of tourmaline are oriented parallel to *c*-axes of amphibole, both being parallel to the fabric axis *b*. In this case, the dimensional orientation of these minerals means the lattice orientation.

The observations by HIDE (1961) and YAMAOKA (1961), who reported the orientation of the c-axis of tourmaline to be parallel to the lineation, are supported by these results mentioned above.

FAIRBAIRN (1949) showed in his synoptic table of mineral orientation in tectonites (p. 9, Table 2-1) that (0001) of tourmaline was parallel to the fabric axis *b*. However, his presentation is not the case for present specimens[1]. KAMB (1959) predicted on the basis of thermodynamics that the c-axis of tourmaline is oriented parallel to a single stress axis under uniaxial (compressive) stress. Because, in the present case, dynamic interpretation of the fabrics is not possible, direct correlation of the results can not be performed. However, in the general view that the direction of fold axis is not the maximum compressive axis, his presentation is not conformable to the results mensioned above.

Although the presence of low angle lineation parallel to *a* suggests compression parallel to *b* in later phase of deformation, it is evident that the tourmaline did not recrystallized at the stage of the formation of the low angle lineation, as shown by its deformed feature of crystal bent angularly about the low angle lineation.

Fabric diagrams of tourmaline and amphibole show the same monoclinic symmetry (Fig. 3A, B, C, and D). This fact suggests that these minerals have recrystallized under the same tectonic condition. [0001]-Axes of tourmaline and *c*-axes of amphibole are parallel to the high angle lineation. This evidence suggests that preferred orientation of these minerals was performed at the stage of formation of the high angle lineation in the tectonic history. However, this does not neccessarily implies simultaneous recrystallization of these minerals at the stage of high angle lineation. Furthermore, such fabrics as characterized by so strong preferred orientation can not be interpreted by mimetic recrystallization, that suggesting these minerals not to be recrystallized after the stage of the high angle lineation. Therefore, crystallization of the tourmaline crystals may have took place either during or before the stage of the high angle lineation.

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