Title	On New Occurrence of Aegirine Augite-Amphibole-Quartz-Schists in the Sambagawa Crystalline Schists of the Besshi-Shirataki District, with Special Reference to the Preferred Orientation of Aegirine Augite and Amphibole
Author(s)	KOJIMA, George; HIDE, Kei
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On New Occurrence of Aegirine Augite-Amphibole-Quartz-Schists in the Sambagawa Crystalline Schists of the Besshi-Shirataki District, with Special Reference to the Preferred Orientation of Aegirine Augite and Amphibole*

By

George KOJIMA and Kei HIDE

with 2 Plates and 22 Text-figures

ABSTRACT The present authors have collected in the Besshi-Shirataki district, Shikoku, three samples of aegirine augite-bearing quartz-schists, which have not been known from the Sambagawa metamorphic zone proper. Geological setting and petrographical properties of these rocks are described. They have been found in the spotted terrain characterized by the forming of porphyroblastic albite petrographically, and by the presence of recumbent type of folding and syntectonic intrusion of ultramafic rocks tectonically. The quartz-schists consist of aegirine augite, alkalic amphibole (especially of glaucophane-crossite series), garnet, muscovite, quartz, albite, and accessory minerals such as apatite, hematite, pyrite, sphalerite, and titanite. Petrofabric analyses have been carried out on aegirine augite, amphibole, muscovite, and quartz. Prisms of amphibole are oriented with the plane (100) parallel to the bedding-schistosity plane (*ab*), and with the crystallographic axis: c parallel to the *b*-lineation. In the quartz-schist at Shirataki the axis: c is parallel both to the tectonic axis: *b* and to *a*. Grains of aegirine augite are oriented with the plaine (010) parallel to the bedding-schistosity plane (*ab*), and with the crystallographic axis: c parallel to the tectonic axis: *b*. Quartz diagrams show the common pattern, which is not distinguishable from that of the other quartz-schists in the district. These petrofabric characteristics suggest that the quartz-schists in question have experienced the same history of deformation and crystallization as the normal quartz-schists in the district, and that the possible effect of metasomatism from serpentinites locally intruded late- or post-tectonically may be excluded.

CONTENTS

I. INTRODUCTION

In Japan, the occurrence of aegirine augite in crystalline schists has been reported from Hokkaidô (J. SUZUKI, 1931, 1933). These aegirine augite-bearing quartz-schists belong to or probably are derived from the Kamuikotan system, which represents the crystalline schist zone of the Hitaka orogenic zone. While from the Sambagawa meta-

*Addressed before the Geological Society of Japan at the 64th Annual Meeting in 1957 (Tokyo).

morphic zone proper in Southwestern Japan, which represents the axial crystalline schist zone of the *Varistziden* in Japan, no samples have been known carrying aegirine augite. Even in J. SUZUKI's all-inclusive paper of petrography on the Sambagawa crystalline schists (1930), aegirine augite was not reported. Y. HORIKOSHI (1934) has found a rim of aegirine augite enclosing titan-augite in a micro-meta-gabbro of the Kannagawa district, Kôzuké. The similar occurrence has also been reported by H. ASAI (1955) from the vicinity of Mt. Uhu, Aichi Rref. The last two localities belong in the so-called "Mikabu" zone, running along the southern margin of the Sambagawa metamorphic zone proper.

The present authors have examined a large number of sections of quartz-schists collected through their field survey during these eight years, and have found three specimens of crossite- or alkalic amphibole-quartz-schist carrying aegirine augite. In this paper the present authors intend to describe geological setting and petrographical properties of these newly found rocks, and along with this, to report on petrofabric behaviours of aegirine augute and amphibole, as the data may contribute both to the knowledge of petrofabrics of these minerals and to the genetical consideration of aegirine augite and alkalic amphibole.

II. GEOLOGICAL SETTING AND PETROGRAPHICAL PROPERTIES

Outline of geology of the Besshi-Shirataki district: In the Besshi-Shirataki district there

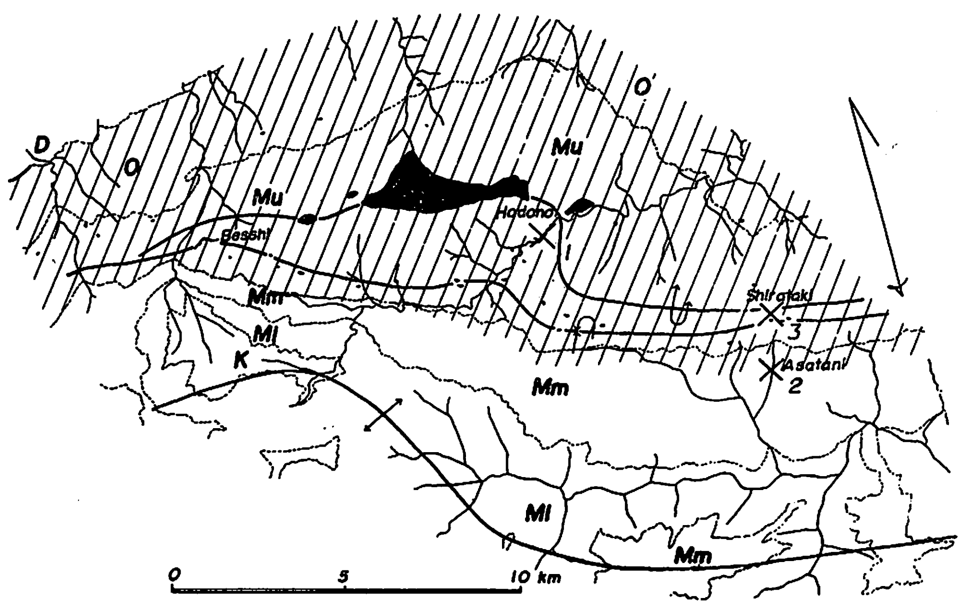

FIG.1. Geological map of the Besshi-Shirataki district (after K. HIDE, G. YOSHINO, and G. KOJIMA, 1956)

develop most typically the Sambagawa crystalline schists, which rerpesent the product of regional metamorphism in the orogenesis of the Late-Palaeozoic or/to the Early-Mesozoic in Japan. The northern half of the district (Fig. 1) is occupied with the so-called "spotted schists", which are characterized by the ubiquitous presence of porphyroblastic feldspar of albitic composition. Main constituents of the spotted schists are, besides porphyroblastic albite, muscovite, chlorite, epidote, common hornblende, and quartz, often accompanied by garnet, biotite, and tourmaline. In quartz-schists piedmontite and amphibole of glaucophane-crossite series are not rarely found. The metamorphism of the spotted schists in the Sambagawa crystalline schists can not unconditionally be correlated to any of the metamorphic facies as classified by P. ESKOLA (1939), but the present authors believe that the temperature condition, in which the spotted schists were soaked, could not have been lower than that of the epidote-amphibolite facies.

The southern half of the district consists of low-grade crystalline schists of non-spotted type. The metamorphic grade of these schists corresponds to the green-schist facies in the facies classification or the chlorite zone of the HARKER's normal case of regional metamorphism (1932). The mineral assemblages are represented by quartz-albite-(chlorite-) muscovite in pelitic rocks and albite-chlorite- (actinolitic amphibole-) epidote in green-schists. The grain-size of the non-spotted schists is far smaller than that of the spotted schists, and no porphyroblasts of albitic feldspar are found.

The schist complex of the Sambagawa metamorphic zone in Shikoku, including the district under consideration, is divided stratigraphically into the following formations in the descending order (HIDE, YOSHINO, and KOJIMA, 1956):

[GROUP]		[FORMATION]		[Abbr. in Fig. 1]
Yoshinogawa	Upper	Ojôin		O
	Middle	Minawa	Upper	Mu
			Main Green-schists	Mm
			Lower	Ml
		Koboké		K
	Lower	Kawaguchi		
		Oboke		

The main part of the Besshi-Shirataki district consists of schists belonging to the Minawa formation, comformably overlain by the Ojôin formation. The Koboké formation forms an inlier in the basins of Nakashichiban and Kômata, and the lower members of schists than the Koboké formation are concealed under the upper members. The fold structure of the schist formations shows a marked contrast between the spotted and the non-spotted terrains, as shown in Fig. 1. In the spotted terrain schist beds form over-turned folds with axial planes moderately dipping to N, the axial culmination of which extends from Besshi to Shirataki for about 20 km or more. While in the non-spotted terrain the axial plane of folds is nearly vertical, and the axial culmination is traced from Nakashichiban to Nôtaniyama for about 20 km in the mapped area, further extending both to E and to W. The contrast in fold structure is ascribed, after the present authors, to the difference in physical properties of material at the time of metamorphism, which is reflected in the petrographical difference of schists between the non-spotted and the spotted terrains.

As shown in Fig. 1, ultramafic rocks such as peridotite and serpentinite are distributed almost exclusively in the spotted terrain. The largest mass of ultramafic rocks (mainly dunite), the Higashiakaishiyama mass, occurs as a form of large tectonic inclusion (N. RAST, 1956) on the axis of culmination of the Shirataki recumbent fold. The smaller masses, mainly of serpentinite, are scattered throughout the whole region of spotted schists. After the authors' geological and petrological study on the occurrence of these ultramafic rocks, they are interpreted as intruded synkinematically with the deformation and mineralization of the spotted schists*.

Lastly, the quartz-schists, which are widely known owing to the presence of such uncommon minerals as piedmontite and alkali-amphibole of glaucophane-crossite series must be briefly mentioned, as only in these quartz-schists aegirine augite has been found in the Sambagawa crystalline schist zone proper. In the Sambagawa crystalline schists quartz-schists occur intimately associated with green-schists and amphibolites, which are metamorphic derivatives from basic lavas and tuffs extruded on the floor of geosyncline. The quartz-schists represent originally siliceous sediments deposited in connection with the submarine eruption in the geosyncline. In the non-spotted terrain they consist of mosaic aggregates of quartz and flakes of muscovite and /or chlorite, accompanied by actinolitic amphibole, epidote, garnet, stilpnomelane, hematite, and calcite. Piedmontite and alkali-amphibole of glaucophane-crossite series, which are not rarely found in the spotted quartz-schists, are rare. In the spotted terrain the grain-size is greatly increased, and muscovite, chlorite, epidote, piedmontite, amphibole (including glaucophane-crrossite series), and garnet are the common constituents of quartz-schists along with quartz and porphyroblastic albite.

The present authors examined a large number of sections of quartz-schists, spotted

* In several localities in the schist regions of Japan other than the spotted terrain of the Sambagawa zone, the development of porphyroblast of albitic feldspar at or near the contact with ultramafic masses is known, *e. g.* in the low-grade green-schists in the Peninsula of Saganoseki, Kyûshû, green-schists or amphibolites in the Sangun Mountainland, Hukuoka Pref., Kyûshû, green-schists in the Sangun crystalline schists to the north of Tokuyama, Yamaguchi Pref., Chûgoku, *etc.* In these schist regions the development of albite spots is only locally restricted, and its genetical relationship with the intrusion of ultramafic rocks (peridotite to serpentinite) is indisputable. In the Besshi-Shirataki district spotted schists are developed rather broadly, and the genetical connection between spotted schists and individual masses of ultramafic rocks is not detectable locally on the field. It may be clear, however, that the distribution of ultramafic rocks in the district is exclusively confined in the spotted terrain. This fact may suggests that, also in this district, porphyroblasts of albitic feldspar were developed genetically related to the synkinematic intrusion of peridotites and serpentininites.

and non-spotted, collected through their field survey during these eight years, and only three samples have been found to contain aegirine augite (or aegirinic augite) along with alkali- (or alkalic?) amphibole*. In the following, geological and petrographical properties of these three samples will be described.

Sample A

Sample no.: GHK56V24-2.

Rock name: Garnet-crossite-aegirine augite-quartz-schist.

Locality: Hodono, Besshiyama-mura, Uma-gun, Ehimé Pref.** (1 in Fig. 1)

Horizon: The upper member of the Minawa formation.

Structural position: at the lower wing of the Shirataki recumbent fold; in the spotted terrain.

Occurrence: as a thin seam in a quartz-schist bed, alternating with spotted black-schist and spotted hornblende-schist (amphibolite) beds. Beds are folded as shown in Pl. I Fig. 1, with an axial plane dipping to N at a high angle (67°). Lineation is parallel with fold-axis, plunging 21° to E. Isoclinal fold is commonly found.

Megascopic features: Seams rich in crossite are dark-bluish-green, while those rich in aegirine augite are yellowish-green. The rock has a marked schistosity and a distinct banding consisting of alternating layers of different mineral assemblage. Mutual ratios between crossite, aegirine augite, and garnet in respective layers are variable. Distinct lineation is shown on the schistosity plane.

Microscopic features: The rock consists of quartz, aegirine augite, garnet, crossite, hematite, pyrite, sphalerite, apatite, muscovite, and albite (Pl. 1, Figs. 2, 3). Compositional banding is distinct: the leucocratic layer is mainly composed of mosaic aggregates of quartz (0.3 mm in average diameter), and the mafic layer consists mainly of aegirine augite, crossite, and garnet.

TABLE 1

OPTICAL PROPERTIES OF AEGIRINE AUGITE IN QUARTZ-SCHISTS

Sample	A	B	C
$c \wedge X$ (mean)	15°	15°	22°
2V about X	78°	core margin 85° — 73° (max.) (min.)	core middle margin 81° — 87° — 83°
Opt. Character	negative	negative	negative
Dispersion	r<v strong	r<v strong, oblique	strong, oblique
Opt. Plane	//(010)	//(010)	//(010)
Pleochroism	X: light-green Y: light-yellowish-green Z: light-yellowish-green	X: pale-green Y: pale-yellow Z: pale-yellow	X: pale-green Y: light-yellowish-green Z: light-yellow
Absorption	X>Y≒Z		X>Y>Z

* In a crossite-quartz-schist, collected near the Ikadatsu mine, aegirine augite is included in albite porphyroblasts, but no grains of aegirine augite are found outside of the albite porphyroblasts.

** 愛媛県宇摩郡別子山村保土野

1) Aegirine augite: The outline is roughly prismatic, but prism faces are only poorly developed. Terminal faces are lacking. The long diameter of grain is 0.2 mm in general, attaining to 0.5 mm in maximum. Cleavage is parallel to (110). Cracks are common, roughly perpendicular to the crystallographic c-axis.* Interior of the grain is clear except rare inclusions of garnet and ores. Optical properties are shown in Table 1.

2) Crossite: The outline is prismatic, but no terminal faces are developed. The long diameter of grain is 0.2 mm on the average, attaining to 0.7 mm in maximum. Cleavage is parallel to (110). Cracks are common, roughly perpendicular to the c-axis. Inclusions of granules of hematite and garnet are rarely found. Optical properties of the mineral are shown in Table 2.

TABLE 2

OPTICAL PROPERTIES OF AMPHIBOLES IN QUARTZ-SCHISTS

Sample	A	B	C
c^Y or Z	c^Y 25.5°	core (c^Z) margin (c^Y) 18° —— 31°	c^Z 22°(mean)
2V about X	53°	core margin 58°—0°—81° (max.) (max.)	core margin 14°—49°
Opt. Character	negative	negative	negative
Dispersion	r<v strong		r<v strong, oblique
Opt. Plane	⊥(010)	core margin //(010) ⊥(010)	//(010)
Pleochroism	X:light-greenish-yellow Y:bluish-green Z: purplish-green	core: colourless margin: X: colourless Y: light-bluish-green Z: light-purple	X: colourless Y: smoky-green Z: light-bluish-green
Absorption	X<Y≑Z	X<Y≑Z (margin)	X<Z<Y

3) Garnet: The crystal form is rhombic dodecahedron or rounded. The diameter of grain is 0.1 mm on the average, attaining to 0.6 mm in maximum. Inclusions of granules of hematite are common, generally crowded in the core of crystal. Helicitic texture is also found.

4) Muscovite: In this sample muscovite occurs only as an accessory ingredient, distributed as separate flakes in quartzose layers. The diameter of crystal is 0.3mm on the average.

5) Albite: Although the rock is situated in the midst of spotted terrain, porphyroblasts of albitic feldspar are rarely found. In the porphyroblast are included grains of garnet, aegirine augite, and opaque minerals. The porphyroblast attains to 0.5 mm in diameter.

Sample B

Sample no.: HK521011.
Rock name: Garnet-muscovite-amphibole-aegirine augite-quartz-schist.

* Parting or crack, roughly perpendicular to the c-axis, is commonly found in aegirine augite and amphibole in the district. As later shown, the c-axis of these minerals roughly coincides with the tectonic *b*-axis. So it may be infered that the crack has been formed during a tensional phase, in which tensional stress exerted along the *b*-lineation.

Locality: Asatani, Ôkawa-mura, Tosa-gun, Kôchi Pref.* (2 in Fig. 1)

Horizon: The main green-schists member of the Minawa formation.

Structural position: at the northern wing of the Nôtaniyama anticline; at the boundary between non-spotted and spotted terrains.

Occurrence: The quartz-schist is alternating with black-schists and green-schists with incipient porphyroblasts of albitic feldspar. The bed containing aegirine augite and alkalic amphibole is in contact with the bed of piedmontite-quartz-schist.

Megascopic features: The rock is dark-bluish-green in colour, speckled with dark-coloured mega-crystals of garnet. Porphyroblasts of aegirine augite are rather indiscernible owing to their light colour. Compositional banding is not distinct. Lineation of *b*-lineation type is developed on the bedding-schistosity plane, accompanied by a subordinate linear structure crossing the *b*-lineation.

Microscopic features: The rock consists of quartz, garnet, aegirine augite, muscovite, amphibole, titanite, apatite,albite, and opaque minerals (pyrite and hematite) (Pl. 1, Fig. 4, Pl. 2, Fig. 1). Quartz, forming the matrix of the rock, is 0.2 mm in average diameter, showing an intense effect of granulation.

1) Aegirine augite: It forms porphyroblastic mega-crystals of stout prism or ovoid in shape. Prism faces are rarely developed, and terminal faces are lacking. The long diameter of grain is 0.5 mm on the average, attaining to 2 mm in maximum. Cleavage is parallel to (110). Cracks are common, roughly perpendicular to the tectonic axis: *b*, and are often opened, keeping parts of one crystal apart from each other. Contorsion of cleavage traces is not uncommon. Granules of hematite and pyrite, not rarely of piedmontite, are included. Optical properties are shown in Table 1.

2) Amphibole: The outline is long prismatic to acicular. No terminal faces are developed. The long diameter of grain is 0.4 mm on the average, attaining to 1 mm in maximum. Cleavage is parallel to (110). Cracks are commonly found, roughly perpendicular to the c-axis. Inclusions are almost lacking. Crystals are often contorted. Optical properties of the mineral are shown in Table 2.

3) Garnet: The crystal shows an outline of rhombic dodecahedron or rounded form. The diameter of grain is 0.4 mm on the average, attaining to 1 mm in maximum. Inclusions of granules of hematite and piedmontite** are commonly found. Helicitic arrangement of inclusions is also observed.

4) Muscovite: It gathers in layers, winding around porphyroblasts. The diameter of flake is 0.4 mm on the average.

5) Albite: It shows an incipient stage of development of porphyroblast. Grains of opaque minerals are included. The diameter of the porphyroblast is less than 0.5 mm.

Sample C

Sample no.: HK 501111.

Rock name: Albite-spotted garnet-muscovite-amphibole-aegirine augite-quartz-schist.

Locality: Shirataki, Ôkawa-mura, Tosa-gun, Kôchi Pref.*** (3 in Fig. 1)

Horizon: The upper member of the Minawa formation.

Structural position: at the lower wing of the Shirataki recumbent fold; in the spotted terrain.

Occurrence: The rock occurs as a thin bed in spotted hornblende schist. Isoclinal folding is found.

Megascopic features: The rock is dark-bluish-green in colour. Compositional banding is marked owing to the alternation of layers of different mineralogical composition: layers rich in aegirine augite are yellowish-green and those rich in garnet are pinkish-gray. Distinct lineation parallel to the tectonic axis: *b* is developed on the bedding-schistosity plane.

Microscopic features: The rock consists of quartz, amphibole, garnet, aegirine augite, muscovite, apatite, and hematite (Pl. 2, Figs. 2, 3, 4). Quartz, forming the matrix of the rock, is 0.2 mm in average diameter,

* 高知県土佐郡大川村朝谷

** Piedmontite is found only as inclusions in porphyroblasts of garnet, rarely of aegirine augite. No grains of piedmontite are observed outside the porphyroblasts.

*** 高知県土佐郡大川村白滝

showing an intense effect of cataclasis.

1) Aegirine augite: stout prismatic or ovoidal in shape, rarely forming porphyroblasts. Crystallographic faces are poorly developed. The long diameter of grain is 0.2 mm on the average, attaining to 1.5 mm in maximum. Cleavage is parallel to (110). Cracks are commonly found, roughly perpendicular to the c-axis of the crystal. Inclusions are rare. Optical properties are shown in Table 1.

2) Amphibole: The outline is long prismatic, with distinct cleavage parallel to (110). Prism faces are developed, but no terminal faces are found. The length of crystal is 0.5 mm on the average, attaining to 1.5 mm in maximum. Inclusions are rare. Cracks are developed, roughly perpendicular to the c-axis of the crystal. Optical properties are shown in Table 2.

3) Garnet: The crystal shows an outline of rhombic dodecahedron or rounded form. The diameter of grain is 0.05mm on the average, attaining to 0.1mm in maximum. Inclusions of hematite are rarely found.

4) Muscovite: It is fairly abundant, forming isolated flakes dispersed in quartzose matrix. The diameter of flake is 0.3mm on the average.

5) Albite: It forms well-developed porphyroblasts. The size of porphyroblast is 2mm in average diameter, attaining to 4mm in maximum. The porphyroblast includes grains of hematite, garnet, aegirine augite, amphibole, and quartz, but no muscovite. Helicitic arrangement of inclusions is commonly observed, often showing a *si*-fabric of *Einschlusswirbel*.

Summarizing above descriptions, characteristics of the geological setting and petrographical properties of aegirine augite-bearing quartz-schists will be itemized in the following, attended with some discussions on their bearing on the genesis of aegirine augite.

1) Occurrence and mineral paragenesis: Aegirine augite has been found exclusively in quartz-schists, which occur alternating with or intercalated into green-schists or hornblende-schists (epidote-amphibolites) derived from basic effusives on the floor of geosyncline. The associated minerals are alkalic amphibole (especially of glaucophane-crossite series), garnet, muscovite, quartz, albite, and accessory minerals (apatite, hematite, pyrite, sphalerite, and titanite).

2) Stratigraphical horizon: They have been found in the Minawa formation : two from the Upper member, and one from the Middle Green-schists member. Although the number of samples is very small, the exclusive occurrence of aegirine augite in the Minawa formation may be concluded from the facts that the occurrence of glaucophane-crossite-bearing quartz-schists are restricted in the Minawa formation in the Sambagawa crystalline schists, and that no mafic alkalic minerals have been found in quartz-schists belonging to formations stratigraphically lower than the Minawa formation. This fact may suggests the original difference in chemical composition of siliceous sediments between the Minawa formation and the lower ones.*

3) Structural position: Two of them are situated at the lower wing of the Shirataki recumbent fold and one at the northern wing of the Nôtaniyama anticline near the recumbent fold. This structural position may represent the plot of orogenic compression, which has been called for by some authors in interpreting the forming of glau-

* The present authors, in co-operation with G. YOSHINO (1956), have suggested the similar fact through the study of stratigraphical horizon of *Kieslager* in the Sambagawa zone of Shikoku.

cophane-schists. In the Sambagawa zone, however, the occurrence of glaucophane-schists has no direct relationship with this structural position, but rather is to be depicted in terms of stratigraphical position. The occurrence of aegirine augite-bearing quartz-schists at or near the recumbent fold may be interpreted as an indirect representation of the relationship between mineralization of aegirine augite and metamorphic character expressed in the forming of albite porphyroblast.

4) *Metamorphism*: Two of the samples have been found in the midst of the spotted terrain and one at the boundary between the spotted and the non-spotted terrains. In the latter case, however, incipient development of albite porphyroblast is microscopically detectable. No aegirine augite is found in glaucophane (or crossite)-quartz-schists outside the spotted terrain. This fact may suggest either direct or indirect relationship between the forming of aegirine augite in quartz-schists and the development of albite porphyroblast. As noted briefly at the beginning of this chapter, the spotted terrain is characterized by several facts such as *a*) the development of albite porphyroblast, *b*) increasing grain-size of component minerals, *c*) higher temperature of metamorphism, and *d*) synkinematic intrusion of ultramafic rocks. Which of these items is directly related to the forming of aegirine augite can not be stated definitely, because of the meagreness of datum. Probably *a*), *c*), and *d*) of the above items may be jointly responsible for the forming of aegirine augite in the quartz-schists having appropriate chemical composition*.

5) *Structure and texture*: Aegirine augite-bearing quartz-schists have distinct schistosity, characterized by the arrangement of mica flakes and prisms of amphiboles and aegirine augite with preferred orientation as described in the following chapter. The fissility of the rocks is also intensified by marked compositional banding, consisting of alternating layers of quartzose and mafic aggregates. Distinct lineation parallel to the tectonic axis: *b* is always marked on the bedding-schistosity plane. Modal ratios between component minerals are quite variable layer after layer, suggesting the lamination in the original sediment. Grain-size is fairly large in these quartz-schists as compared with those in the non-spotted terrain. Generally the grain-size of schist is represented by that of quartz forming granoblastic matrix, which ranges from 0.2 mm to 0.3 mm in diameter. Porphyroblastic growth of albite, aegirine augite, and garnet is met with in some samples.

* Recently H. M. E. SHÜRMANN (1956) has expressed an opinion, summarizing his observations on glaucophane-bearing rocks in the world, that glaucophane-schists occur nearly always together with ophiolites (serpentinites, *etc*.), which were originated from a geosynclinal magma, and that, after subsequent unilateral stress, ophiolites caused a Na metasomatism, by which the glaucophane was formed. While, in the succeeding chapter of the same paper, dealing with the Japanese glaucophane, he has regarded serpentinites in the Besshi district as intruded in the Younger Mesozoic long after the epizonal metamorphism of the Palaeozoic formations. Neither thefo rmer nor the latter opinion fits with the present authors' conclusion based on years of geological study in the same district.

6) *Aegirine augite*: It occurs as stout prismatic or ovoidal grains. Crystal faces are not developed in general. Optical properties are summarized in Table 1. Judging from values for c^X and 2V about X, the mineral must be members of the augite-acmite series, but the pale axial colour may suggest some mingling of jadeite molecule.

7) *Amphibole*: It occurs as long prisms or needles. Prism faces are developed, but no terminal ones are observed. Optical properties are shown in Table 2. In Sample A the amphibole is crossite with optical plane perpendicular to (010). In Sample B the amphibole is strongly zoned: the core is colourless with optical plane perallel to (010), while the margin is crossitic with optical plane perpendicular to (010). The range of 2V is very remarkable. In Sample C, zonal change of optical angle in the amphibole is somewhat abnormal.

III. PETROFABRICS

The authors have carried out petrofabric analyses on the preferred orientation of component minerals. The work has three meanings at the present state of knowledge.

Firstly, it may offer some important evidences in respect of the genesis of minerals in the rocks, especially of aegirine augite and alkalic amphiboles. As far as the authors are aware, there have been no petrofabric analyses attempting to clarify the phase relationship between the mineralization of these minerals and the differential movement of componental parts of rocks. If these alkalic minerals have grown keeping pace with the differential movement, petrofabric diagrams of these minerls may show characteristic patterns consistent with those of the other minerals. While, if they have crystallized under the effect of metasomatic agencies from the adjoining serpentinite, intruded generally in the declining phase of deformation, pattern of petrofabric diagrams may not show so marked preference in orientation as in the case of syn-kinematic crystallization.

Secondly, this work will contribute to the knowledge on structural petrology of the Sambagawa crystalline schists, on which we have only a poor knowledge of petrofabrics. Especially on the rule of preferred orientation of amphibole and pyroxene, nothing has been reported.

Thirdly, our knowledge is very poor on the lattice orientation of amphibole and pyroxene in crystalline schists, determined statistically using optic elasticity axes: X, Y, and Z, which are easily referable to crystallographic directions. In the Sambagawa crystalline schists amphiboles are commonly found in schists of basic composition, while pyroxene occurs only exceptionally in amphibolites. For this reason, we can hardly obtain a knowledge about the rule of preferred orientation of pyroxene in these crystalline schists except in the present case.

In the following, descriptions on characteristic features of pattern in each petrofabric diagrams will be given in the first place, and next, summarizing the descriptions, the rule of preferred orientation of amphiboles and aegirine augite will be discussed.

Sample A

Quartz: 400 c-axes of quartz were measured with the universal stage without selection of grains, and plotted on a Schmidt net. Contours were drawn after the usual practice (per cent of grains per one per cent area). The contoured diagram is shown in Fig. 2. The diagram shows a small circle girdle enclosing the tectonic axis: *c*, with maxima, which may be referable to II and IV of the average positions of known quartz

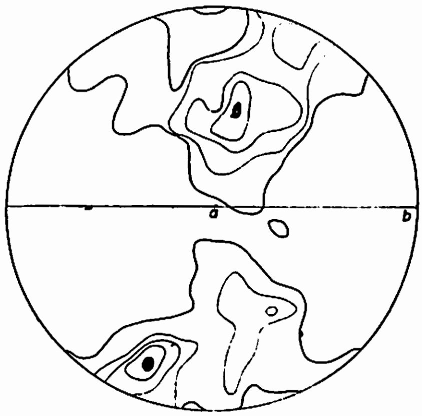

FIG. 2 400 c-axes of quartz from quartz-schist of Hodono (GHK-56V24-2A). No selection of grains was made. Max.: 5.5%. Contours: 5-4-3-2-1%.

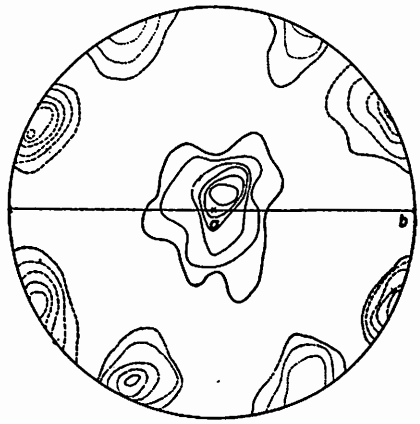

FIG. 3 130 optic elasticity axes of crossite from quartz-schist of Hodono (GHK 56 V 24-2 A). No selection of grains was made. Dotted lines: X, dashed lines: Y, full lines: Z. Max.: X 21.5%, Y 26.2%, Z 28.5%. Contours: 25-20-15-10-5-2%.

maxima by B.SANDER (1950. p.363, Fig. 48a). It must be noted that the maximum II is not developed symmetrically in respect of the bedding-schistosity plane (*ab*), and that concentrations of each maximum referable to IV in four quadrants are different. No traces of *b*-girdle pattern are shown. These features of petrofabric pattern of quartz diagram are common in quartz-schists in this district. As the authors are now preparing a paper dealing with the petrofabric behaviours of quartz in quartz-schists of the Sambawawa metamorphic zone. explanation of these features of pattern in quartz diagram is not treated in the present paper. It is suffice to say at this point of the present paper that the pattern of quartz diagram of this sample shows no special features distinguishable from the other quartz-schists.

Crossite: Optic elasticity axes: X, Y, and Z were determined using the five-axis universal stage. As the concentration of maxima is fairly high, not so many grains are needed to be measured. The petrofabric diagram for 130 grains of crossite is shown in Fig. 3. Maxima for X and Y lie on the *bc* plane, and a single maximum for Z lies at *a*. As the crystallographic axis:b coincides with Z for crossite, the plane (010) is parallel to the *b*-lineation and perpendicular to the bedding-schistosity plane (*ab*). Maxima for Y lie at symmetrical positions in respect of *b*. The angle between two maxima for Y lying on both sides of *b* is about 50°, which corresponds to the angle 2c/Y for crossite. This indicates that the crystallographic axis: c of crossite coincides with the tectonic axis: *b*. It must be mentioned that the concentration of maxima for Y on either side of *b* is roughly the same.

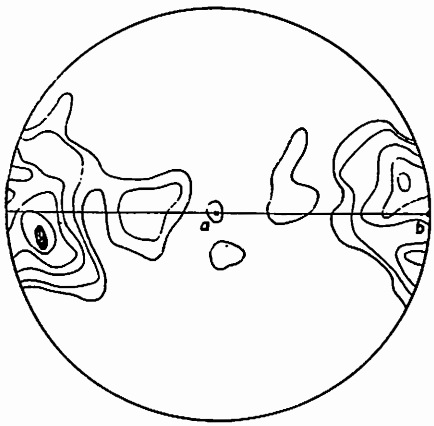

FIG. 4 130 X -axes of aegirine augite from quartz-schist of Hodono (GHK56V24-2A). No selection of grains was made. Max.: 10.8%. Contours: 10-8-6-4-2-1%.

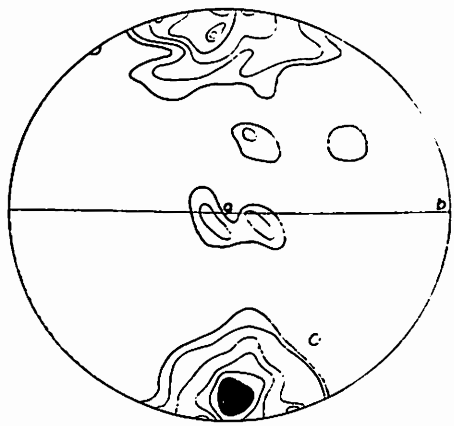

FIG. 5 130 Y-axes of aegirine augite from quartz-schist of Hodono (GHK56V24-2A). No selection of grains was made. Max.: 12.3%. Contours: 10-8-6-4-2-1%.

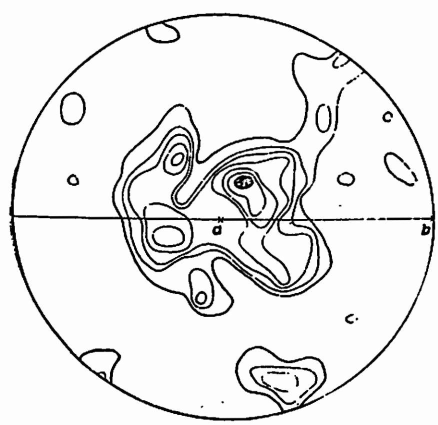

FIG. 6. 130 Z-axes of aegirine augite from quartz-schist of Hodono (GHK56V24-2A). No selection of grains was made. Max.: 9.2%. Contours: 7-6-5-4-3-2-1%.

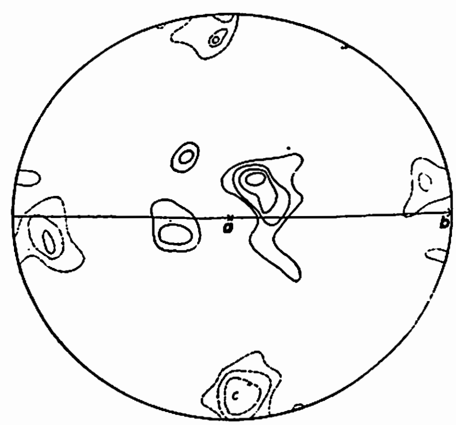

FIG. 7. Collective diagram of X-, Y- and Z-axes of aegirine augite from quartz-schist of Hodono (GHK56 V 24-2A) (Figs. 4, 5, and 6). Dotted lines: X, dashed lines: Y, full lines: Z. Contours: X 10-8-6%, Y 12-10-8-6%, Z 7-6-5-4%.

Aegirine augite: Optic elasticity axes: X, Y, and Z were measured. The petrofabric diagram for 130 grains of aegirine augite are shown in Figs. 4, 5, and 6. Maxima for X, Y, and Z are collected in a single diagram of Fig. 7. A single maximum for Y, which coincides with the crystallographic axis : b, lies nearly at *c*, and maxima for X and Z lie on the bedding-schistosity plane (*ab*), symmetrically arranged in respect of *a* and *b*. The angle between maxima for Z on either side of *a* and that for X on either side of *b* are about 30°, which corresponds to the angle 2c′ X for aegirine augite. From these features of petrofabric diagrams it is infered that grains of aegirine augite are arranged with the c-axis parallel to the *b*-lineation and with (010) parallel to the bedding-schistosity plane (*ab*). Comparing collective diagrams for crossite and aegirine augite with each other, the preference in orientation for aegirine augite is not so perfect as for crossite.

Sample B

Muscovite: 150 poles of cleavage flakes were measured and plotted with the result shown in Fig. 8. Marked dimensional orientation is shown with a strong maximum in *c*. Some poles are dispersed in a partial girdle parallel to *ac*, indicating an external rotation about *b*.

Quartz: 400 c-axes of quartz were measured without selection of grains. The petrofabric diagram is shown in Fig. 9. Four maxima may be observed at IV of the average positions of known quartz maxima by SANDER. This type of pattern in quartz diagram is commonly found in the Shirataki district, and no peculiarities for this diagram can be pointed out. The pattern shows no traces of rotation about *b*.

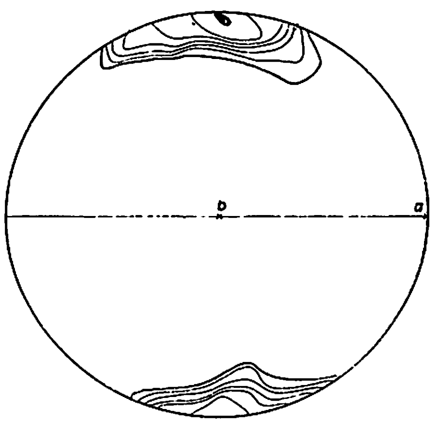

FIG. 8. 150 cleavage poles of muscovite from quartz-schist of Asatani (HK 521011 B). No selection of grains was made. Max.: 20.7%. Contours: 20-15-10-8-6-4-2%.

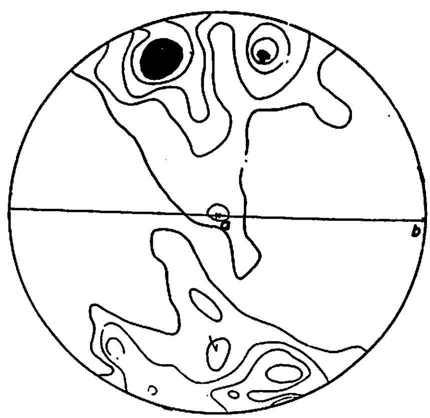

FIG. 9. 400 c-axes of quartz from quartz-schist of Asatani (HK 521011 A). No selection of grains was made, except finer unmeasurable grains. Max.: 6.3%. Contours: 5-4-3-2-1%

Amphibole: Optic elasticity axes were measured. The petrofabric diagram is shown in Fig. 10. As in Sample A, this crossitic amphibole is oriented with the crystallographic c-axis parallel to the *b*-lineation and with the plane (010) perpendicular to the bedding-schistosity plane (*ab*). The pattern for Z, which is parallel to the crystallographic axis: b, shows a maximum near *a*, with dispersion in a partial girdle parallel to *ac*, indicating an external rotation about *b*, as shown in the muscovite diagram.

Aegirine augite: Optic elasticity axes were measured for 150 grains of the mineral. The petorofabric diagrams are shown in Figs. 11, 12, and 13, and also collectively in

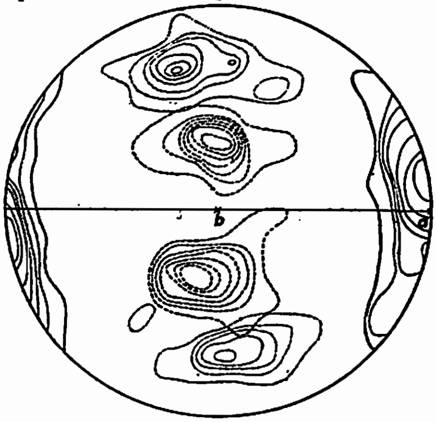

FIG. 10. 130 optic elasticity axes of crossite from quartz-schist of Asatani (HK521011B). No selection of grains was made. Dotted lines: X, dashed lines: Y, full lines: Z. Max.: X 14.6%, Y 19.2%, Z 17.7%. Contours: 14-12-10-8-6-4-2%.

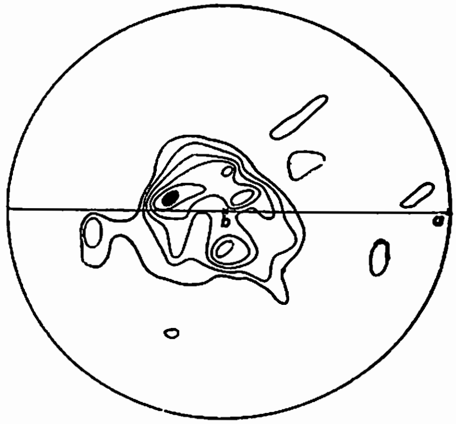

FIG. 11. 150 X-axes of aegirine augite from quartz-schist of Asatani (HK521011B). No selection of grains was made. Max.: 8%. Contours: 7-6-5-4-3-2%.

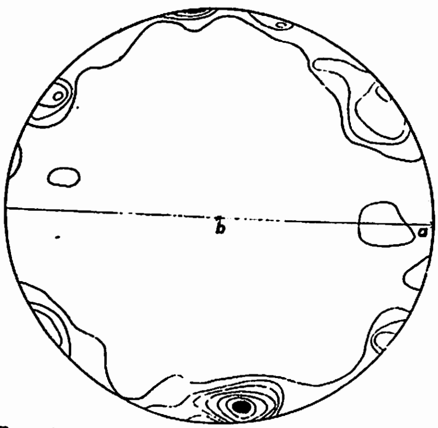

FIG. 12. 150 Y-axes of aegirine augite from quartz-schist of Asatani (HK521011B). No selection of grains was made. Max.: 9.3%. Contours: 8-7-6-5-4-3-2%.

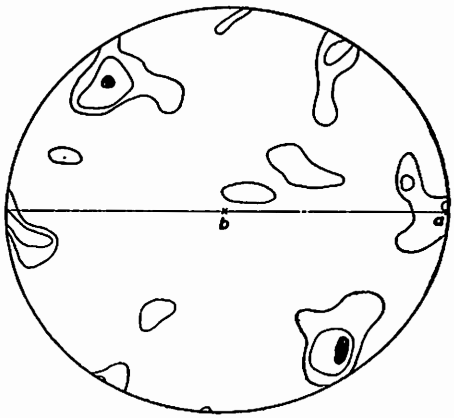

FIG. 13. 150 Z-axes of aegirine augite from quartz-schist of Asatani (HK521011B). No selection of grains was made. Max.: 4.7%. Contours: 4-3-2%.

Fig. 14. X axes are distributed around *b* forming a small circle girdle, the diameter of which is near the value of 2c^X (30°) of the mineral. X and Z axes are distributed on *ac*, showing an intense effect of rotation about *b*.

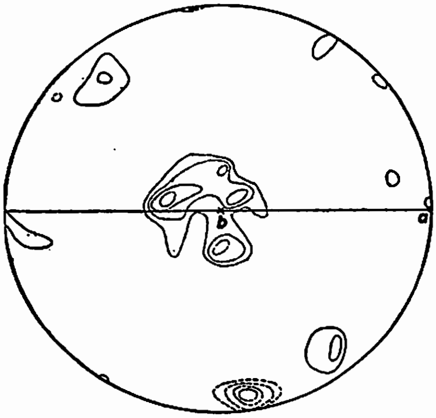

FIG. 14. Collective diagram of X-, Y-, and Z-axes of aegirine augite from quartz-schist of Asatani (HK521011B) (Figs. 11, 12, and 13). Dotted lines: X, dashed lines: Y, full lines: Z. Contours: X 7-6-5-4%, Y 8-7-6-5%, Z 4-3%.

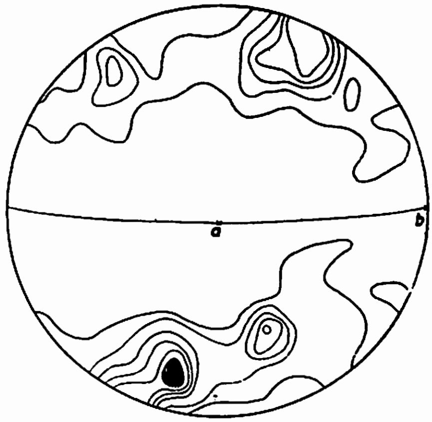

FIG. 15. 400 c-axes of quartz from quartz-schist of Shirataki (HK 501111 A). No selection of grains was made, except finer unmeasurable grains. Max. : 7 %. Contours: 6-5-4-3-2-1 %.

Sample C

Quartz: 400 c-axes of the mineral were measured and plotted. As in this sample grains of quartz are rather severely crashed by post-crystalline deformation, prevailing in the Shirataki district, pre-kinematic grains of 0.2 mm in average diameter embedded in the matrix of granulated quartz are selected for determination. The pattern of quartz diagram (Fig. 15) shows four maxima referable to IV of the average positions by SANDER. A small circle enclosing *c* is also shown. No traces of girdle about *b* or *a* are detectable. These features are commonly found in quartz diagrams of schists in this district. No peculiarities are shown in the quartz pattern.

Amphibole: Optic elasticity axes were measured for unselected grains of amphibole. The petrofabric diagrams for X, Y, and Z are shown in Figs. 16, 17, and 18, respectively. It is a remarkable fact that c-axes of amphibole prism are oriented in two directions, which are perpendicular to each other: *i. e.* the one in *b* as commonly met with, and the other at *a*. This is clearly shown in Z pattern in Fig. 18. Four maxima in the diagram form two pairs, the one of which is at *a*, and the other at *b*. The Y (// crystallographic b-axis) pattern also shows two maxima, which correspond to two positions of pair of maxima in Z diagram. The pattern of the X diagram (Fig. 16) may be read in terms of two directions in orientation of amphibole prism. The meaning of the peculiarity in amphibole orientation will be discussed at some length in the later section.

Aegirine augite: Optic elasticity axes are measured for 150 grains of aegirine augite, and petrofabric diagrams are shown in Figs. 19, 20, and 21. Positions of principal maxima for X, Y, and Z in respective diagrams suggest that the crystals are mostly oriented according to the general rule of orientation as discussed in Sample A: the crystallographic c-axis is parallel to the *b*-lineation, and the plane (010) is parallel to the bedding-schistosity plane (*ab*). Positions of subordinate maxima or dispersion of

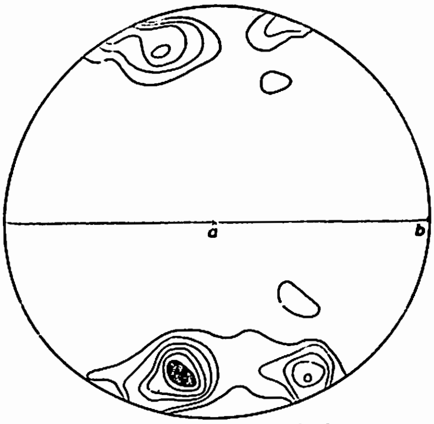

FIG. 16. 150 X-axes of amphibole from quartz-schist of Shirataki (HK501111A). No selection of grains was made. Max.: 16%. Contours: 12-10-8-6-4-2%.

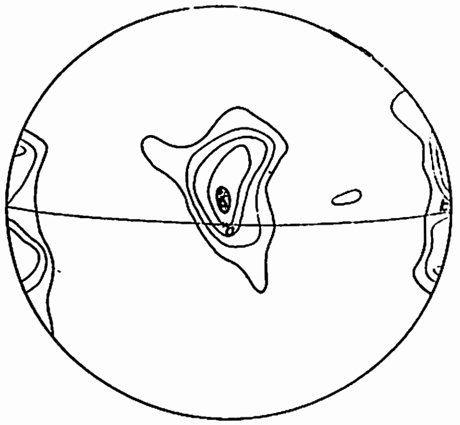

FIG. 17. 150 Y-axes of amphibole from quartz-schist of Shirataki (HK501111A). No selection of grains was made. Max.: 10%. Contours: 10-8-6-4-2%.

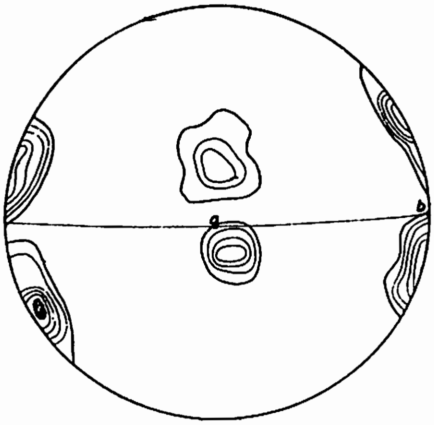

FIG. 18. 150 Z-axes of amphibole from quartz-schist of Shirataki (HK501111A). No selection of grains was made. Max.: 13.3%. Contours: 12-10-8-6-4-2%.

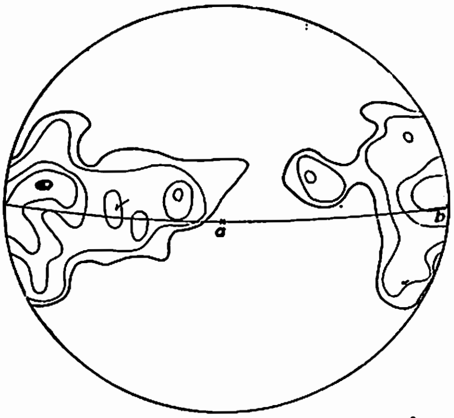

FIG. 19. 150 X-axes of aegirine augite from quartz-schist of Shirataki (HK501111A). No selection of grains was made. Max.: 8%. Contours: 8-6-4-2-1%.

point show, however, some deviations from the ordinary orientation. Some grains are oriented with their plane (010) perpendiculer to *ab*, as illustrated by a sub-maximum in *a* in the Y diagram (Fig. 20). Dispersion of X and Z in a partial girdle parallel to *ab* indicates that the crystallographic c-axis does not perfectly coincide with *b*, but that some grains are irregularly oriented on the bedding-schistosity plane. The latter feature suggests that the orienting mechanism, which gave rise to the coincidence of c-axis of amphibole with both *b* and *a*, worked also for aegirine augite, but the preference in orientation of the c-axis to *a* is not so strong for aegirine augite as for amphibole.

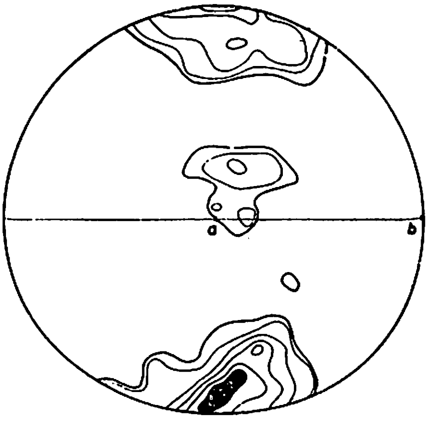

FIG. 20. 150 Y-axes of aegirine augite from quartz-schist of Shirataki (HK 501111A). No selection of grains was made. Max.: 12%. Contours: 10-8-6-4-2-1%

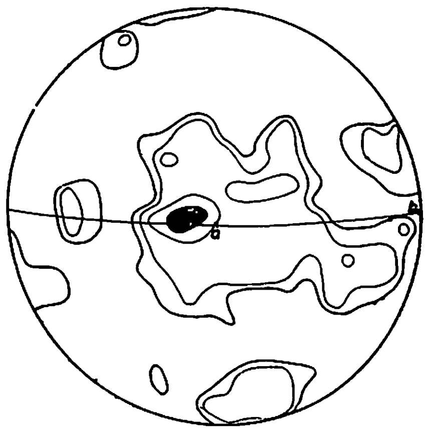

FIG. 21. 150 Z-axes of aegirine augite from quartz-schist of Shirataki (HK501111A). No selection of grains was made. Max.: 7.3%. Contours: 6-4-2-1%.

Summarizing above descriptions, the general rule of preferred orientation of amphibole and aegirine augite and the genetical significance of petrofabric characteristics of aegirine augite-bearing quartz-schists will be discussed in the following.

1) ***Rule of preferred orientation of amphibole***: More than thirty years ago, J. SUZUKI (1924) has reported that prisms of glaucophane are oriented with their long axis (c) and crystallographic axis: b parallel to the schistosity plane in crystalline schists, but his description did not based on statistical measurement. Recently K. ISHIOKA and K. SUWA (1954) have plotted poles of (100) and c-axes of hornblende in a schistose amphibolite from the region of Kurobe-gawa. After them prisms of hornblende are oriented with their plane (100) (rarely plane (110)) parallel to the plane *ab*, and with their crystallographic axis:c parallel to *b*. This rule of preferred orientation for amphibole confirms the result by B. SANDER (1930), who plotted poles of cleavage plane of hornblende in gabbro-amphibolite. While, in his collective table showing the mineral orientation in tectonites, H. W. FAIRBAIRN (1949, p.9, Table 2-1) regards the plane (110) of hornblende as parallel to *ab*. This type of orientation is referable to the rare case mentioned by ISHIOKA and SUWA.* All of these authors measured cleavage planes of hornblende, but by this method those planes which lie near the plane of section can not be measured, resulting in some blind area near the center of diagram. The present authors have measured optic elasticity axes: X, Y, and Z of amphibole, which are easily referable to crystallographic axes or planes of the mineral. The authors' results on the rule of preferred orientation of amphiboles are summarized as follows.

a) Prisms of amphibole show a parallel orientation, with their c-axis parallel to the tectonic axis: *b*, which is represented by the principal lineation on the bedding-schistosity plane. The plane (100) is parallel to the schistosity plane. No cases are found, in which the cleavage plane (110) of hornblende is parallel to the schistosity plane, as abvocated by FAIRBAIRN and ISHIOKA-SUWA**. The orientation of amphibole is diagammatically shown in Fig. 22 (left) for crossite.

b) In Fig. 22 (left) two alternative positions are shown as hatched planes for the optical

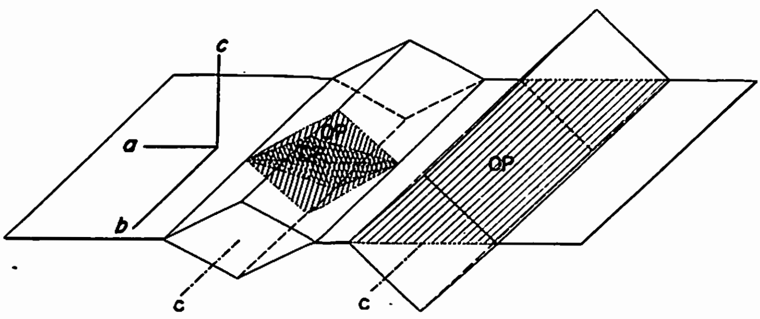

FIG. 22. Preferred orientation of crossite and aegirine augite. OP: optical plane, c: crystallographic axis, *a. b. c*: tectonic axes.

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* After this paper was sent to the printer, the authors have been able to read J. LADURNER's paper entitled "Deformation, Wachstum und Regelung der Epidote als Gefügekorn und Einkristall" (*Neues Jahrb. f. Miner.*, Abh., 82, (3), 317-412, 1951), by courtesy of Dr. LADURNER. He has measured grains of hornblende in a gabdro-amphibolite of Gröller Joch, Südtirol, and has found "die Einregelung hauptsächlich von (100), aber auch von (110) in $s = (ab)$ des Gefüges" (p. 325). Also recently, C. B CRAMPTON (Regional study of epidote, mica, and albite fabrics of the Moines, *Geol. Mag.*, 94, (20), 89-103, 1957) has measured [010]-axes and [001]-axes of hornblende in quartz-mica-epidote-hornblende-schist of the North-West Highlands of Scotland, and has found that [010]-axes were oriented within two sub-maxima situated at a small angles one either side of the foliation and that [001]-axes are parallel to the lineation (pp. 92-93; Text-fig. 3).

** The present authors are doubtful if the plane (110) of hornblende be oriented parallel to schistosity planes. They have tried petrofabric analyses on several samples of schistose amphibolites in this district, and have found in some instances that the plane (100) is oriented parallel to several *s*-planes, in which are included conjugate transversal schistosity planes inclined about 30° to the bedding-schistosity plane. In this case the plane (110) might be mistaken as parallel to the bedding-schistosity plane. The present authors insist that the schistosity or clavage structure of schist must be clearly analysed before the petrofabric analysis is tried.

plane of crossite. It corresponds to the occurrence of two maxima on both sides of the tectonic axis: *c* for X of crossite in Fig. 3. The fact that these two maxima show roughly the same concentration suggests no preference between these alternative positions.

c) It is quite remarkable that prisms of amphibole are oriented parallel to two directions perpendicular to each other in a quartz-schist at Shirataki: *i. e.* the one group is parallel to the tectonic axis: *b* as in the usual case, while the other parallel to *a*. To understand this peculiar fabric may require further information on petrofabric features in the district, but here the following fact must be noted that the Sample C was collected at the lower wing of the Shirataki recumbent fold, which represents the sliding sole of protruded over-fold, as shown by the protrusion of the recumbent fold axis to S in Fig. 1.

2) Rule of preferred orientation of aegirine augite: As far as the authors are aware, petrofabric behaviour of aegirine augite in crystalline schists has not been analysed. The present authors have measured optic elasticity axes: X, Y, and Z of aegirine augite, which are easily referable to crystallographic axes and planes of the mineral. The results are summarized as follows.

a) Prism faces of aegirine augite are rarely developed, and no terminal faces are shown. Grains are oriented with the plane (010) parallel to the bedding-schistosity plane (*ab*), and with the crystallographic axis: c parallel to the tectonic axis: *b*.

b) The preference in orientation for aegirine augite is not so perfect as for crossite. In Sample B is shown an intense effect of rotation about the tectonic axis: *b*. In Sample C some grains are oriented with the plane (010) perpendicular to *ab*, and some are rotated on *ab* keeping the crystallographic axis: c parallel to *ab*.

3) Genetical significance: In some rocks which are believed to bear some genetical relationship with adjoining ultamafic rocks, alkali-amphibole and aegirine augite do not show any preference in orientation, as judged from illustrations in such papers by J. SUZUKI (1933), or by G. FISCHER and J. NOTHHAFT (1954). In the quartz-schists in question amphibole and aegirine augite show a remarkable preference in orientation. Symmetrological charactristics of each petrofabric diagrams are consistent with each other. Quartz diagrams show common pattern, which is not distinguishable from that of the other quartz-schists of the district. These petrofabric characteristics suggest that the quartz-schists in question have experienced the same history of deformation and crystallization as the normal quartz-schists in the district, and that the possible effect of metasomatism from serpentinites locally penetrating late- or post-tectonically may be excluded.

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EXPLANATION OF PLATES

PLATE 1

FIG. 1. Fold structure of quartz-schist beds, in which garnet-aegirine augite-crossite-quartz-schist was found. Hodono.

FIG. 2. Garnet-crossite-aegirine augite-quartz-schist of Hodono (GHK56V24-2). The section was cut parallel to the *b*-lineation and perpendicular to the bedding-schistosity plane. Lower nicol only. G :garnet, C: crossite, A: aegirine augite.

FIG. 3. *ibid.* The section is perpendicular both to the bedding-schistosity plane and the *b*-lineation. Lower nicol only. G: garnet, C: crossite, A :aegirine augite.

FIG. 4. Garnet-muscovite-amphibole-aegirine augite-quartz-schist of Asatani (HK521011). The section is parallel to the *b*-lineation and perpendicular to the bedding-schistosity plane. Lower nicol only. G: garnet, C:amphibole, A: aegirine augite.

FIG. 1

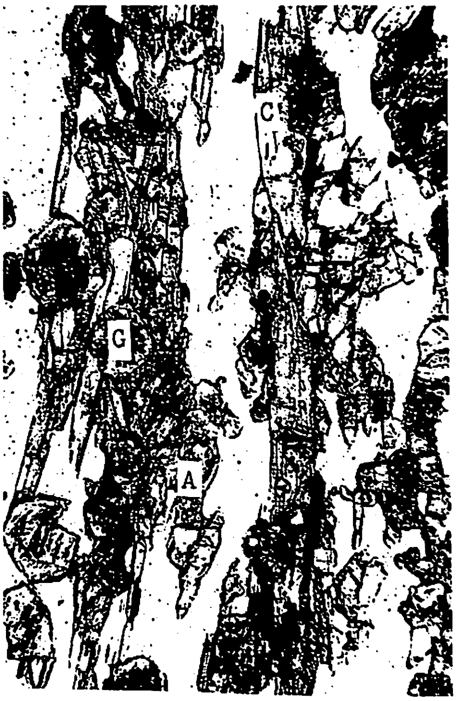

FIG. 2

FIG. 3

FIG. 4

EXPLANATION OF PLATE

PLATE 2

FIG. 1. Garnet-muscovite-amphibole-aegirine-augite-quartz-schist of Asatani (HK521011). The section is perpendicular both to the bedding-schistosity plane and the *b*-lineation. Lower nicol only. G: garnet, C: amphibole, A: aegirine augite.

FGI. 2. Albite-spotted garnet-muscovite-amphibole-aegirine-augite-duartz-schist of Shirataki (HK-501111). The section is parallel to the *b*-lineation and perpencicular to the bedding-schistosity plane. Lower nicol only. G: garnet, C: amphibole, A: aegirine augite.

FIG. 3. *ibid.* The section is perpendicular both to the *b*-lineation and the bedding-schistosity plane. Lower nicol only. G: garnet, A: aegirine augite, C: amphibole.

FIG. 4. *ibid.* The section is parallel to the bedding-schistosity plane. Prisms of amphibole are arranged parallel to two directions perpendicular to each other.

FIG. 1

FIG. 2

FIG. 3

FIG. 4