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Deformation and Recrystallization of Amphiboles in Sambagawa Schist with Special Reference to History of Sambagawa Metamorphism

By

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with 1 Table, 9 Text-figures and 2 Plates

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ABSTRACT: The amphibole grains in the Shirataki hornblende-schist, which has been collected from an outcrop in the biotite zone of the Sambagawa belt of the Shirataki district, Central Shikoku, are divided into three distinguishable populations which are different from each other in generation age: amphibole grains (S_i-amphibole) included in cores of plagioclase porphyroblasts, and their matrix amphibole grains which consist of two populations, old hornblende grains (porphyroblasts) and new hornblende grains. The S_i-amphibole grains, which recrystallized during growth of the cores of plagioclase porphyroblasts, belong to the actinolite — common hornblende group with Si content of 7.36–6.95, showing that the plagioclase cores grew during progressive increase of temperature. The old hornblende grains (Si content=6.97–6.66), which are of the same generation as the inner zones of mantles of plagioclase porphyroblasts, appeared under non-deformational condition and progressive increase of temperature until the highest tempeature. The new hornblende grains (Si content=6.87–6.79) grew during growth of the outer zones of mantles of plagioclase porphyroblasts and the deformation (S_e-deformation) of the beginning stage of retrogressive metamorphism. The lattice fabric of the old hornblende grains, which was produced by the S_e-deformation, is characterized by preferred orientation of crystallographic axes c forming a single set of lineation (L), though poles of (100) planes form a great-circle girdle normal to L. While that of the new hornblende grains, which grew during the S_e-deformation, is characterized by preferred orientation of c axes parallel to L and of (100) planes forming a single set of schistosity. On the basis of informations given by Hara *et al.* (1977), Takagi and Hara (1979), Hara *et al.* (1980), Maeda and Hara (1983a and b), Maeda *et al.* (1983) and Hara *et al.* (1983), as well as the present authors, the time-relationship between deformation and metamorphism in the biotite zone of the Sambagawa belt of Central Shikoku has been also briefly discussed in this paper, showing a result of Table 1 and that the deformation styles of the Sambagawa schists changed cyclically from ductile deformation (=folding and formation of schistosity) to brittle deformation.

CONTENTS

I. INTRODUCTION

Lattice fabrics of amphibole grains in the schists of the Sambagawa belt of Central

Shikoku, Japan, have been described by Kojima and Hide (1957), Oyagi (1964), Takagi and Hara (1979) and Hara *et al.* (1980). They in the schists with a single set of planar schistosity and of mineral lineation analysed by those authors will be explained as follows: 1) The amphibole fabrics (Type I) described by Kojima and Hide (1957, Figs. 3 and 10) and Hara *et al.* (1980, Figs. 3 and 6) are characterized by preferred orientation of crystallographic axes c parallel to the lineation and of crystallographic planes (100) parallel to the schistosity, 2) those (Type II) described by Oyagi (1964, Figs. 29 and 31) are characterized by preferred orientation of c axes parallel to the lineation though poles of (100) planes form a great-circle girdle normal to the lineation, and 3) Takagi and Hara (1979) had described an amphibole fabric of the intermediate type between Type I and Type II in which c axes are preferentially oriented parallel to the lineation and (100) planes show a weak tendency to be concentrated in and just near the schistosity.

Hornblende grains in the Shirataki hornblende-schist (Hide, 1954), which has been collected from an outcrop in the biotite zone of the Sambagawa belt of the Shirataki district, Central Shikoku, (Fig. 1) and shows a single set of schistosity and of mineral lineation, can be divided into two distinguishable populations, old grains and new grains. Their lattice fabrics will be described and discussed in this paper, showing that the fabric pattern for the old grains is of Type II and it for the new grains is of Type I. The microtextures of plagioclase, as well as amphiboles, will also be examined and, on the basis of the obtained data and of informations so far given by other authors, time-relationship between deformation and metamorphism in the biotite zone of the Sambagawa belt of

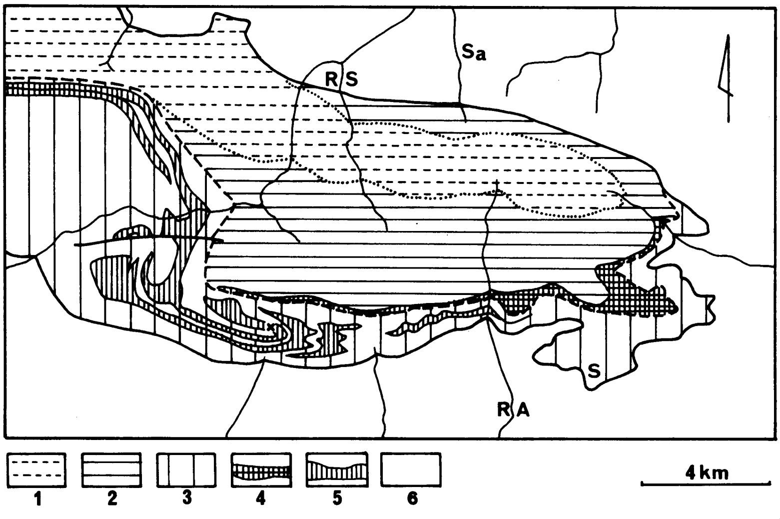

Fig. 1. Diagram showing the locality of the analysed specimen in the Sambagawa belt of Central Shikoku.

1, 2 and 3: Saruta nappe [1 and 2: Saruta nappe II (1: garnet zone, 2: biotite zone), 3: Saruta nappe I (biotite zone)], 4: 5th Shirataki hornblende-schist, 5: Shirataki hornblende-schists and associated quartz-schists, 6: Nagahama nappe [map after Hara, Hide and Maeda (1983)]. Sa: Sazare, S: Shiragayama, RS: River Saruta, RA: River Asemi, x: locality of analysed specimen.

Central Shikoku will be briefly discussed in this paper.

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II. ANALYSIS OF MICROTEXTURES

The Shirataki hornblende-schist, whose microtextures will be analysed in this paper, has a single set of schistosity and of lineation and consists mainly of hornblende, epidote, chlorite, plagioclase and quartz. The schistosity (*S*) is quite even and the lineation (*L*) is quite straight within the analysed specimen.

Hornblende grains show great variation in size. Fig. 2 illustrates their size distribution as measured on the section (B-section) normal to *L*. The size is given by $\sqrt{AB}$, in which A is length of the longest axis for individual grains and B is length of its normal. The size distribution is bimodal. Such the microtextural characteristics is clearly observed in Plate 15–a, b and c. Hornblende grains with size of larger than 0.3 mm on the B-section are frequently associated with minute hornblende grains, showing their fragmentation (Plate 15–a). Plate 15–b shows fragmentation of a coarse-grained hornblende as observed on the section (A-section) parallel to *L* and normal to *S*. The minute hornblende grains

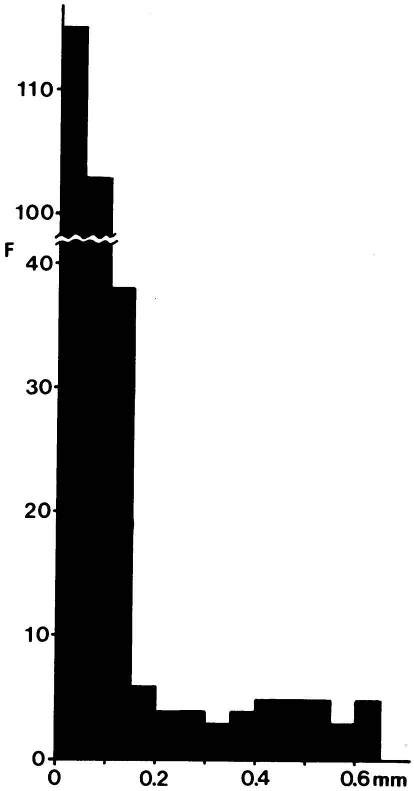

FIG. 2. Diagram showing the size distribution of hornblende grains as measured on the B-section, except for S_1-amphibole grains in plagioclase porphyroblasts.

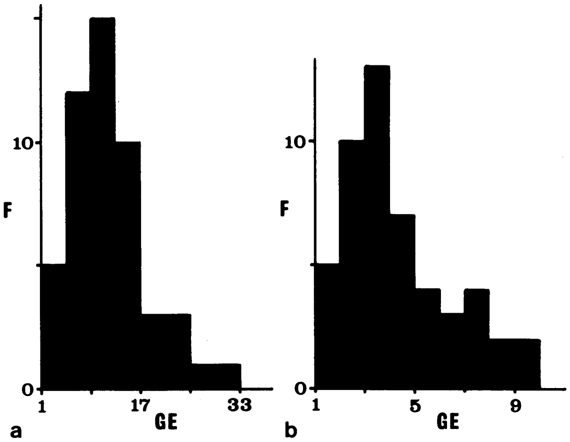

FIG. 3. Diagram showing the variation of elongation degree (GE) of hornblende grains as measured on the A-section.

a: data for new hornblende grains, b: data for old hornblende grains.

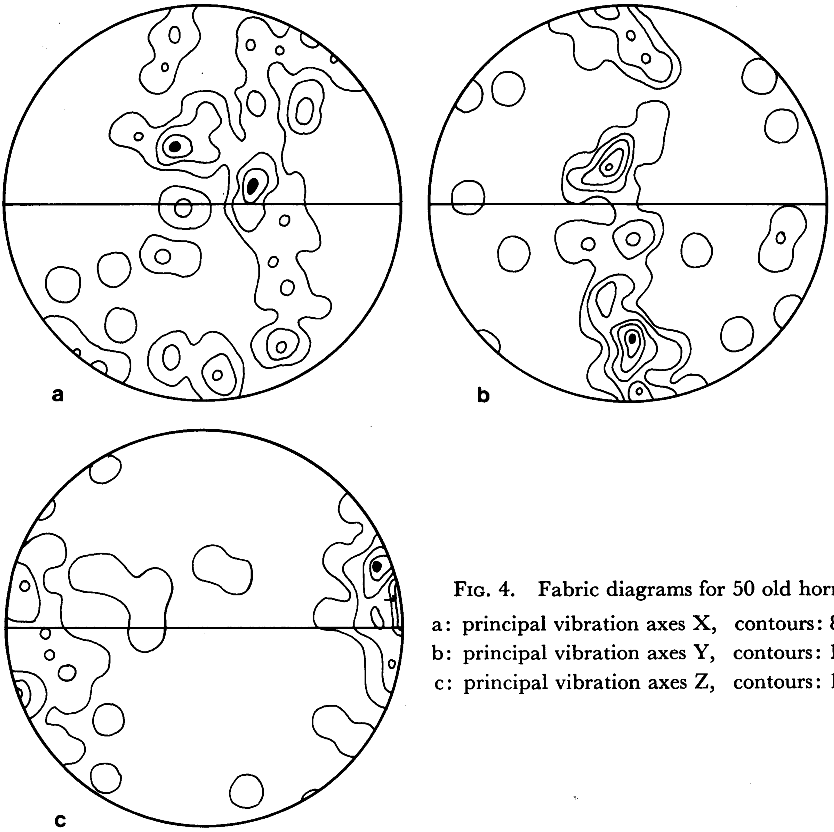

FIG. 4. Fabric diagrams for 50 old hornblende grains.

a: principal vibration axes X, contours: 8–6–4–2%,
b: principal vibration axes Y, contours: 12–10–8–6–4–2%,
c: principal vibration axes Z, contours: 18–14–10–6–2%.

are considered to belong to the group of fine-grained hornblendes of Fig. 2 with reference to their microtextural characteristics (Plate 15–a and b). It could be therefore said that hornblende grains are divided into two populations, old grains and new grains. Hornblende grains with size of larger than 0.3 mm on the B-section all appear to belong to the former, while most of them with size of smaller than 0.15 mm on the B-section to the latter. Hornblende grains with width (length normal to *S*) of larger than 0.2 mm on the A-section all appear to belong to the old grains, while most of them with width of smaller than 0.05 mm on the A-section to the new grains.

The old grains (hornblende grains with width of larger than 0.2 mm on the A-section) show lens-like shapes with rather ragged and ill defined grain boundaries (Plate 15–b and c). Their longest axes are preferentially oriented parallel to *L*. Fig. 3–b illustrates the elongation degree (A/B ratio) of the old grains as measured on the A-section. It is between 1.5 and 9.3 with mean values of 3.5. It can be said that the old grains are strongly elongated parallel to *L*. Many of old grains contain other metamorphic minerals (epidote, quartz, white mica, opaque minerals and so on) as inclusions which show preferred dimensional orientation forming a single set of schistosity (S_1) (Plate 15–a, b and d).

The lattice fabric of the old grains as measured on the A-section is illustrated in Fig. 4. The principal vibration axes Z are preferentially oriented on a small-circle with angular

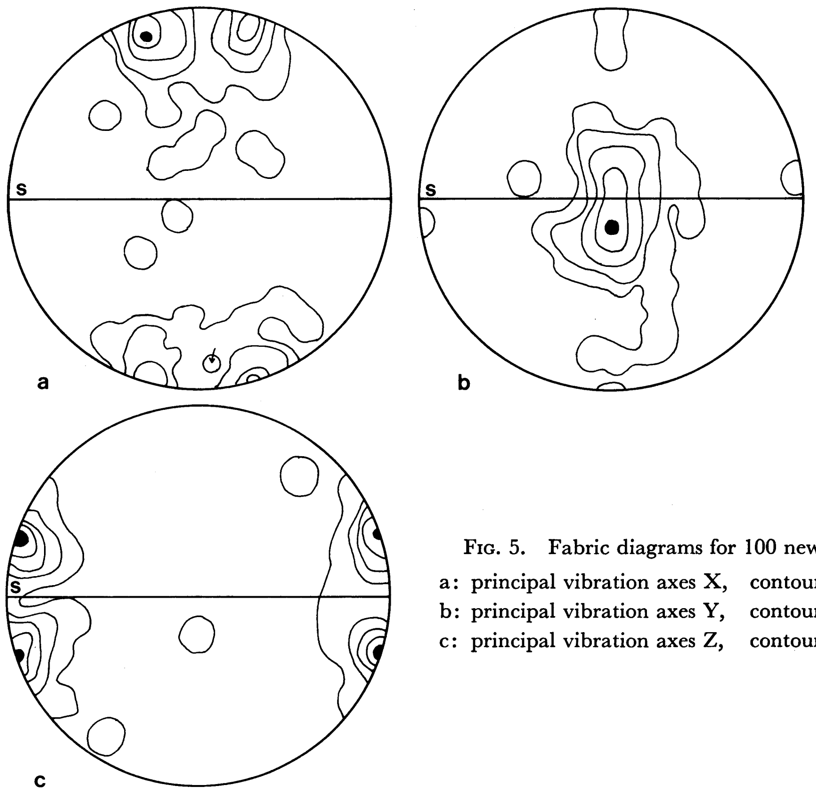

Fig. 5. Fabric diagrams for 100 new hornblende grains.
a: principal vibration axes X, contours: 16–12–8–4–1%.
b: principal vibration axes Y, contours: 16–12–8–4–1%.
c: principal vibration axes Z, contours: 20–15–10–6–1%.

radius of ca. 20° around *L*. The principal vibration axes Y are preferentially oriented on a great-circle normal to *L*, and the princiapl vibration axes X on two small-circles with angular radius of ca. 70° around *L*. The fabric data indicates that the c axes are preferentially oriented parallel to *L* and the poles of (100) planes are almost uniformly oriented on a great-circle normal to *L*. Thus, it can be said that the lattice fabric of the old grains is of Type II.

Fig. 5 illustrates the lattice fabric of the new grains (hornblende grains with width of smaller than 0.05 mm) as measured on the A-section. The fabric pattern clearly indicates that the c axes are preferentially oriented parallel to *L* and the (100) planes parallel to *S*. Namely, the lattice fabric of the new grains is of Type I, unlike in the case of the old grains.

The A/B ratio for the new grains as measured on the A-section is illustrated in Fig. 3–a. It is between 3.7 and 33 with mean value of 11.5. Thus, it can be pointed out that the new grains are much more strongly elongated than the old grains. *L* is defined by the dimensional orientation of the longest axes of the new grains, as well as the old grains. As observed on the A-section, the new grains are bounded on the two longest sides by planes parallel to the c axes (Plate 15–b, c and d).

Plagioclase grains develop as porphyroblasts with many other metamorphic minerals as inclusions (Plate 15–c and d). Fig. 6 illustrates the size distribution of plagioclase grains as measured on the B-section. It appears to be comparable with the size distribution of the old hornblende grains (Fig. 2). In Plate 15–c it would be understood that the old hornblende grains are as large as plagioclase grains in size.

Plagioclase grains show a zonal variation of inclusions defined by inclusion-free mantles and inclusion-rich cores, though matrix minerals are commonly partly incorporated in the outer zones of mantles (Plate 15–c and d), like in the cases described by Hara *et al.* (1977), Takagi and Hara (1979), Hosotani (1980) and Hara *et al.* (1980). The boundary between core and mantle is sharp (Plate 15–c and d).

Plagioclase grains are dimensionally preferentially oriented with their shortest axes normal to *S* and their longest axes parallel to *L*. Fig. 7–a illustrates the A/B ratio distribution for plagioclase grains as measured on the A-section, while Fig. 7–b that as measured on the B-section. Thus, it can be said that plagioclase grains are fairly strongly elongated parallel to *L*. Though plagioclase grains show such a preferred dimensional orientation, they do not have a preferred lattice orientation as seen in Fig. 8. Analogous fabric properties of plagioclase grains are also equally obvious in the specimens described by Takagi and Hara (1979) and Hara *et al.* (1983).

Mantles are absent or have a quite small width in the shortest axes of plagioclase

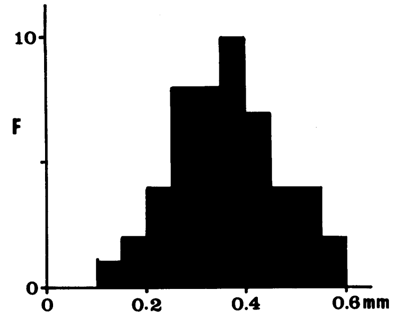

Fig. 6. Diagram showing the size distribution of plagioclase porphyroblasts as measured on the B-section.

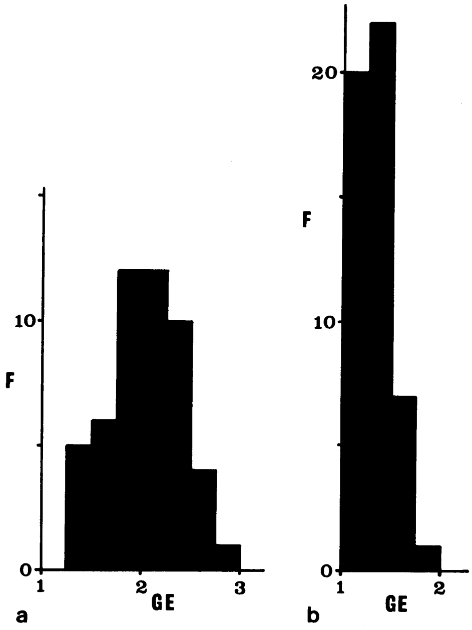

Fig. 7. Diagram showing the variation of elongation degree (GE) of plagioclase porphyroblasts.
a: data from the A-section,
b: data from the B-section.

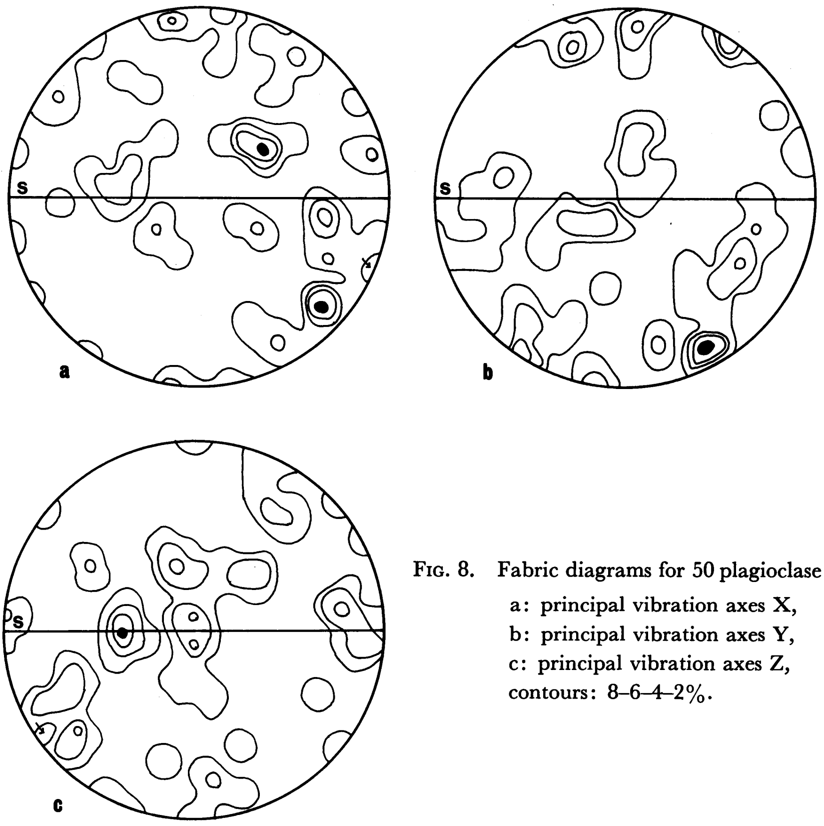

Fig. 8. Fabric diagrams for 50 plagioclase porphyroblasts.
a: principal vibration axes X,
b: principal vibration axes Y,
c: principal vibration axes Z,
contours: 8–6–4–2%.

grains. Their width is commonly maximum in a direction parallel to *S*, but it is much larger on the A-section (in the longest axes of plagioclase grains) than on the B-section.

Inclusions in the cores of plagioclase grains consist of minerals such as epidote, amphibole and opaque minerals. They show preferred dimensional orientation, defining a schistosity (S_i), as shown in Plate 15–c and d. S_i is even in many plagioclase grains, but it is sometimes folded. Amphibole grains in the S_i-schistosity (S_i-amphibole) are much finer-grained than the old and new hornblende grains (Plate 15–c and d).

As observed on the A-section, the new hornblende grains are deflected around plagioclase grains (Plate 15–c and d). They deflecting around a plagioclase grain may also abut against the boundary of the same plagioclase grain and the abutting new hornblende grains are partly incoporated into the outer zone of mantle, forming a fan-like arrangement, like in the cases described by HARA *et al.* (1977), TAKAGI and HARA (1979) and HARA *et al.* (1980). As is obvious in Plate 15–c, S_i is commonly oblique to *S*, showing that the new hornblende grains appeared after growth of the cores of plagioclase grains (cf. ZWART, 1962). Plate 15–d indicates that an old hornblende grain contacts with the core of plagioclase grain and is included within its inner zone of mantle, while the new hornblende grains contact with its outer zone of mantle showing such fan-like arrangement as mentioned above. Thus, it could be said that the amphibole grains in the present specimen are divided into three populations, S_i-amphibole, old hornblende and new hornblende grains, that the S_i-amphibole grains must have initially occurred before growth of the cores of plagioclase grains, and that the old hornblende grains appeared after growth of the cores of plagioclase grains and during growth of their inner zones of mantles, while the new hornblende grains appeared during growth of their outer zones of mantles.

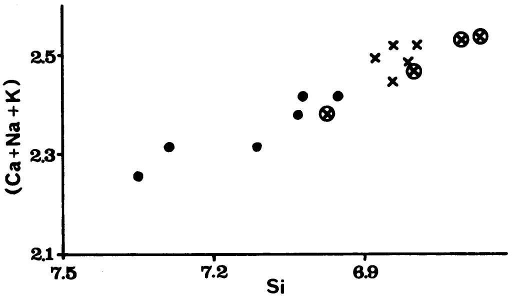

FIG. 9. Relationship between Si and (Ca+Na+K) in amphiboles.

solid circles: data for S_i-amphibole grains, circled crosses: data for old hornblende grains, crosses: data for new hornblende grains.

Chemical compositions of S_i-amphibole, new hornblende and old hornblende grains have been determined by JXA–5A microprobe. The data has been obtained from the central portions of individual grains. The new hornblende grains show little variation of chemical composition, while both S_i-amphibole and old hornblende grains show its greater variation, as shown in Fig. 9. The Si and (Ca+Na+K) contents of the new hornblende grains are between 6.87 and 6.79 and between 2.44 and 2.52, those of the old hornblende grains are between 6.97 and 6.66 and between 2.38 and 2.53, and those of the S_i-amphibole grains are between 7.36 and 6.95 and between 2.25 and 2.41 respectively. The S_i-amphiboles belong to the actinolite — common hornblende group, while both matrix amphiboles (old and new hornblendes) belong to the common hornblende group. Analogous relationship between the chemical composition of the S_i-amphiboles and that of matrix amphiboles is also equally obvious in the specimens described by Takagi and Hara (1979) and Hara *et al.* (1980), though most of matrix amphibole grains in them are considered to be comparable with the new hornblende grains in the present specimen with reference to their microtextural characteristics. And such a trend of decrease of Si content and concomitant increase of (Ca+Na+K) content as shown in Fig. 9 has been assumed to correspond to that of progressive metamorphism. On the basis of this assumption, here, it will be said that 1) the growth of plagioclase grains (cores) occurred including S_1-amphibole grains and stopped temporarily during the temperature increase (Takagi and Hara, 1979), 2) then the old hornblende grains (and the inner zone of plagioclase mantles) had grown during progressive increase of temperature until the highest temperature and 3) the new hornblende grains (and the outer zones of plagioclase mantles) grew at the temperature lower to some extent than the highest temperature, i.e. the deformation (S_e-deformation) related to the formation of S and L occurred during an earliest stage of the cooling phase of the Shirataki hornblende-schist.

III. Discussion

Though plagioclase grains are fairly strongly elongated (Fig. 7) and show a preferred dimensional orientation, they do not have a preferred lattice orientation (Fig. 8). Analogous fabric properties of plagioclase grains are also equally obvious in the specimens described by Takagi and Hara (1979) and Hara *et al.* (1983). Takagi and Hara said that the dimensional fabric of plagioclase grains was produced during the S_e-deformation, while Hara *et al.* clarified that the dimensional fabric of plagioclase grains was developed by pressure solution and probably concomitant growth in a direction normal to the axis of maximum compression during the deformation of later stage. Maeda and Hara (1983a) have described a specimen from the Sarutagawa district, Central Shikoku, in which the microtextures of plagioclase grains, as well as garnet grains, given when they appeared as porphyroblasts are well preserved, clarifying that the stage of the highest temperature of metamorphism, when plagioclase porphyroblasts (cores and mantles) and mantles of garnet grains grew, was a static stage. Plagioclase grains in Maeda and Hara's specimen show ameboid-like shapes coated with mantles and do not have a preferred dimensional orientation, owing to that the superposition of later deformations hardly occurred. They (1983b) have also clarified in another specimen from the Nikubuchi district, Central Shikoku, that plagioclase porphyroblasts grew under non-deformational condition. Tokuda and Hara (1983) have described a specimen from the Joshi district, Central Shikoku, in which epidote grains, together with plagioclase grains, grew as porphyroblasts under non-deformational condition. The present data indicates that the mantles of plagioclase grains must be divided into two zones, inner zones and outer zones, and that the growth of the inner zones of mantles had occurred during progressive increase of temperature until the highest temperature. Thus, it would be assumed that the cores and inner zones of mantles of plagioclase grains in the present specimen also grew under non-deformational condition. And it must be said that both lattice fabric of old hornblende grains and dimensional fabric of plagioclase grains were induced by the deformation (=S_e-deformation) related to the formation of the lattice fabric of new hornblende grains.

As mentioned in the preceding paragraph, the fabric pattern of old hornblende grains

(Type II) is essentially different from that of new hornblende grains (Type I). The former grains occurred before the S_e-deformation, while the latter grains grew during the S_e-deformation. Such the phenomenon must have been responsible for the difference in fabric pattern between them. NICOLAS and POIRIER (1976, p. 306) stated that "amphibole which is both brittle and needle shaped or prismatic can behave accordingly. MARCH's (1932) mathematical analysis of the orientation of rigid rods on a flowing medium can be applied here; it predicts that the rods tend to be aligned with their long axes parallel to the longest axis X of the strain ellipsoid in the surrounding medium." Even under non-deformational condition, generally, hornblende grains must grow as rod-like shapes with their longest axes parallel to c axes. NICOLAS and POIRIER's orientation mechanism of amphibole grains cited above may be therefore applicable to explain the Type II lattice fabric of the old hornblende grains. While the Type I lattice fabric of the new hornblende grains may be explained as a kind of growth fabric under stress condition.

In the basic schists of the biotite zone of the Sambagawa belt of Central Shikoku are frequently found three populations of amphibole grains which are comparable with S_1-amphibole, old grains and new grains in the present specimen respectively. In most of them, however, most of old amphibole grains are replaced by new amphibole grains. Old amphibole grains contain sometimes other metamorphic minerals as inclusions which show preferred dimensional orientation forming a single set of S_1-schistosity (Plate 16), like in the case of the present specimen. It is clear that such the old amphibole grains are one of metamorphic minerals. Plate 16 illustrates an old amphibole grain and new amphibole grains deflecting around it in the 5th Shirataki hornblende-schist from the River Asemi (Fig. 1) (HARA, MAEDA and MIYAOKA, in preparation).

The deformation of the schists of the Sambagawa belt of Central Shikoku occurs in three main phases, pre-Nagahama phase, Nagahama-Ozu phase and Hizikawa phase (HARA *et al.*, 1977): The deformation of the pre-Nagahama phase is what the Sambagawa schists sufferred under progressive-metamorphic condition of high pressure and low temperature. During the Nagahama-Ozu phase appeared many nappes of the Sambagawa schists, whose formation is related to their emplacement from the high-pressure field into the shallow tectonic position. The deformation of the Hizikawa phase is upright folding in en echelon fashion. The metamorphism during the Nagahama-Ozu phase and Hizikawa phase is of retrogressive type. The data from the present specimen appears to present an important information to understand processes of deformation and metamorphism during the pre-Nagahama phase to the Nagahama-Ozu phase, which have not yet been clearly explained as pointed out by MAEDA and HARA (1983a).

Table 1 is an understanding about the processes of deformation and metamorphism during the pre-Nagahama phase to Nagahama-Ozu phase in the biotite zone of the Sambagawa belt of Central Shikoku, which would be given by the data of HARA *et al.* (1977), TAKAGI and HARA (1979), HARA *et al.* (1980), MAEDA and HARA (1983a and b), MAEDA *et al.* (1983), HARA *et al.* (1983) and the present authors. In the biotite zone of Central Shikoku there are two types of basic schists which are distinguished from each other on the basis of relationship between S_1-amphiboles and matrix amphiboles (new amphibole grains) with respect to Si and (Ca+Na+K) contents: For the one type (Type I), the Si content of S_1-amphiboles is different from and larger than that of matrix amphiboles, while, for the other type (Type II), the former is equal to the latter (HARA

TABLE 1. RELATIONSHIP BETWEEN DEFORMATION AND METAMORPHISM.

Deformation	Metamorphism		
S_{1c}-deformation ⋮		↑	↑
⋮ ↓		growth of garnet cores (MnO: ca. 15⟶4%)	⋮
Fracturing		⋮	⋮
S_1-deformation		⋮	growth of initial S_1-amphiboles
B_1-deformation		⋮ ↓	⋮ ↓
static stage	growth of plagioclase cores (porphyroblasts)	growth of garnet mantles MnO: ca. 4% |	recrystallization of S_1-amphiboles (Si: 7.36–6.95)
R-deformation	growth of outermost zones of cores of plagioclase	|	| ↓
static stage	growth of inner zones of mantles of plagioclase	↓ MnO: ca. 0.6%	growth of old hornblende (porphyroblasts) (Si: 6.97–6.66)
S_e-deformation	pressure solution of plagioclase		growth of new hornblende (Si: 6.87–6.79)
Fracturing			
B_1-deformation	pressure solution of plagioclase	pressure solution of garnet	
Fracturing			
B_2-deformation (Hizikawa phase)			

et al., 1980). Table 1 illustrates the deformational and metamorphic history of the basic schists of Type 1 and associated pelitic-psammitic schists.

The S_{1c}-deformation is defined by a S_1-schistosity of inclusion minerals in garnet cores in which MnO content decreases from ca. 15% in their center to ca. 4% in their edge for the specimen described by MAEDA and HARA (1983a). The chemical zonation of the garnet cores appears to be approximately explained by isothermal fractionation model (MAEDA *et al.*, 1983). The S_1-deformation is defined by a S_1-schistosity in plagioclase cores and garnet mantles in which MnO content decreases from ca. 4% in their innermost part to the minimum value in their rim for the specimen described by MAEDA and HARA (1983a). The B_1-deformation is observed as folds of S_1-schistosity in garnet mantles and plagioclase cores (MAEDA and HARA, 1983a; the present data). The S_1-amphiboles belong to the actinolite — common hornblende group (TAKAGI and HARA, 1979; the present data). The plagioclase cores with actinolite inclusions must have generated in an earlier stage than those with common hornblende inclusions (TAKAGI and HARA, 1979). Namely, the S_1-amphibole grains should have been recrystallized changing their chemical composition throughout the process of growth of plagioclase cores until they had been completely included into the plagioclase cores. Because the plagioclase cores grew under non-deformational condition, the now-observed S_1-schistosity would be inferred to be a secondary one which was produced by mimetic recrystallization. The S_1-amphiboles in the initial S_1-schistosity must have been of the actinolite group.

The S_e-deformation is shown by the above-described microtextural relationship between plagioclase grains and their matrix (new hornblende grains) (HARA *et al.*, 1977; TAKAGI and HARA, 1979; HARA *et al.*, 1980; the present data). Its stage appears to correspond to the beginning stage of retrogressive metamorphism (the present data) and so to the earliest stage of the uplifting. It may be said that the most prominent characteristics of structures and microtextures for many of schists of Central Shikoku was produced by the S_e-deformation.

The intermediate stage between the stage of the B_1-deformation and that of the S_e-deformation corresponds to the main stage of the Sambagawa metamorphism. From MAEDA and HARA's (1983a and b) data, this stage is inferred to be a static stage. The data from the present specimen is harmonic with this inference. In TAKAGI and HARA's (1979) specimen and HARA *et al.*'s (1980) specimens, however, the outermost zones of cores of plagioclase grains have frequently curved S_i, indicating that shear deformation occurred immediately before the formation of their mantles and after the formation of their central zones of cores. The stage of the formation of the central zones of cores and that of the formation of the outermost zones of cores have been called the C-stage and the R-stage respectively (HARA *et al.*, 1980; The Reasearch Group of the Sambagawa Belt, 1981). The C-stage when the most parts of cores of plagioclase grains grew appears to be a static stage (TAKAGI and HARA 1979). In the biotite zone of Central Shikoku there are two types of basic schists, Type I and Type II, as mentioned in the preceding page. Because inclusion amphiboles in plagioclase cores of basic schists of Type I commonly contain Si content of larger than 6.89 and some of them belong to the actinolite group, it may be said that, during the C-stage, the basic schists of Type I were placed under the metamorphic condition of garnet zone. While the basic schists of Type II are considered to have been placed under the metamorphic condition of biotite zone already during the C-stage, because inclusion amphiboles all belong to the common hornblende group, (The Research Group of the Sambagawa Belt, 1981). In the biotite zone are randomly distributed basic schist bodies of Type I and those of Type II, suggesting that their mixing occurred immediately after the C-stage and probably during the R-stage (HARA *et al.*, 1980). Namely, the shear deformation of R-stage may be related to the mixing of basic schist bodies of two types. However, it must be questioned why plagioclase grains in the basic schists of Type II had not grown as porphyroblasts until the metamorphic temperature corresponding to biotite zone but not to garnet zone had appeared, unlike in the case of those in the basic schists of Type I. The authors have not, at present, any available data and idea to discuss this problem.

HARA *et al.* (1983) have clarified that the Nagahama folding (B_1-deformation) occurred under a physical condition where garnet grains were deformed by pressure solution but had not shown their concomitant growth in a direction normal to the axis of maximum compression, because they were unstable, and plagioclase grains were also deformed by pressure solution associated probably with their concomitant growth in a direction normal to the axis of maximum compression.

MAEDA and HARA (1983b) have described a fold (B_1-fold) of pelitic schist which was produced by the B_1-deformation. In the pelitic schist are found quartz veins which are approximately parallel to the schistosity of surrounding schist and also involved in the B_1-fold (MAEDA and HARA, 1983b, Plate 13). The quartz veins indicate that the pelitic schist was fractured along its schistosity before the B_1-folding. It has not been yet exactly clarified whether the fracturing responsible for the formation of the quartz veins occurred at the stage between the S_1-deformation and the B_1-deformation or immediately before the S_1-deformation. In Table 1, however, it is assumed to have occurred immediately before the S_1-deformation. The fracturing is of the phase of progressive metamorphism and may be ascribed to increase of pore fluid produced by metamorphic reactions. HARA *et al.* (1977) clarified that quartz veins were developed in vast volume immediately before the folding of the Nagahama-Ozu phase and also before the folding of the Hizikawa phase. The fracturings of the Sambagawa schists which were responsible for the formation of those quartz veins are also plotted in Table 1. This table illustrates cyclic change of deformation style [from ductile deformation (folding and formation of schistosity) to brittle deformation] of the Sambagawa schists.

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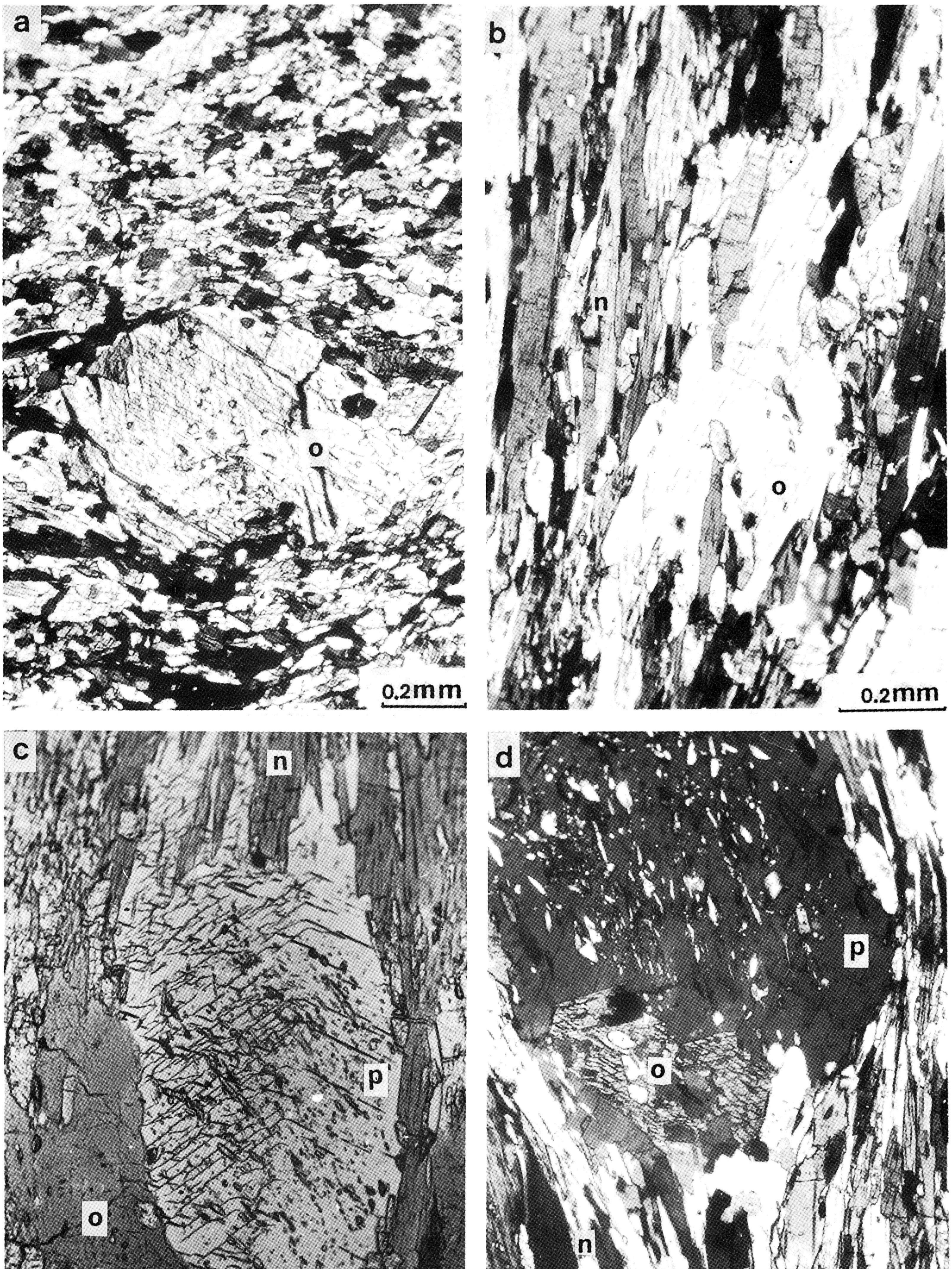
EXPLANATION OF PLATE XV

a: Microphotograph of old and new hornblende grains on the B-section. o: old hornblende grain. Lower nicol only.
b: Microphotograph of old and new hornblende grains on the A-section. o: old hornblende grain. n: new hornblende grain. Crossed nicols.
c: Microphotograph of old hornblende (o), new hornblende (n), plagioclase porphyroblast (p) and S_1-schistosity. Lower nicol only.
d: Microphotograph of plagioclase porphyroblast (p), old hornblende (o), new hornblende (n) and S_1-schistosity. Old hornblende is placed within the inner zone of plagioclase mantle. Crossed nicols.

EXPLANATION OF PLATE XVI

Microphotograph of old (o) and new amphibole grains in the 5th Shirataki hornblende-schist from the River Asemi. Crossed nicols.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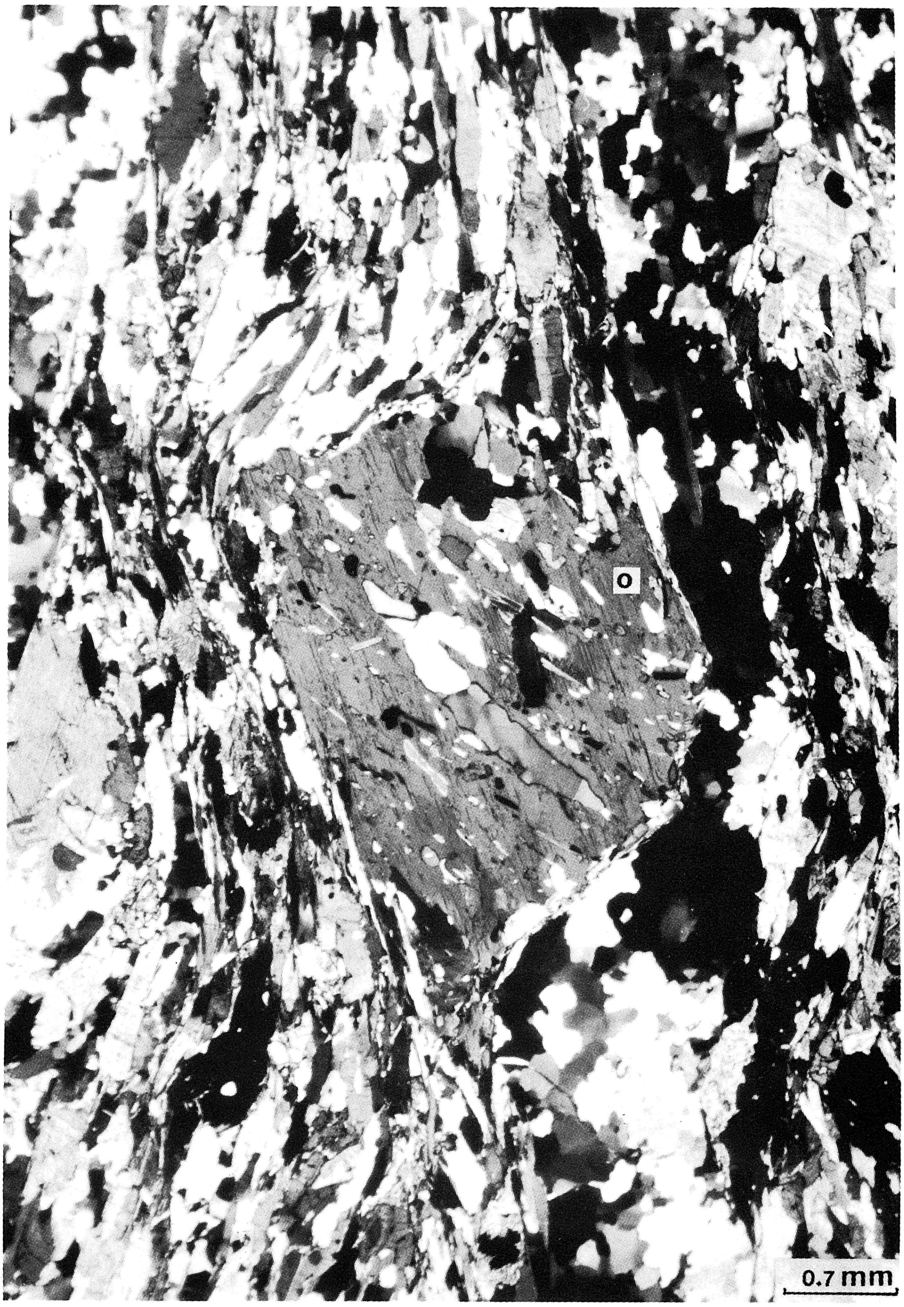
o
0.7 mm