PRESSURE SOLUTION OF PLAGIOCLASE AND GARNET DURING NAGAHAMA FOLDING IN THE SAMBAGAWA BELT OF CENTRAL SHIKOKU

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Abstract It has been examined in this paper how plagioclase and garnet of the pelitic schist involved in the basal part of the Saruta nappe in the Sambagawa belt of Central Shikoku, Japan, were deformed during the Nagahama folding when the Sambagawa schists were emplaced as many nappes from the metamorphic field of high-pressure and low-temperature condition into the shallow tectonic position. It has been pointed out that pressure solution appears to have played an important role in deformation of plagioclase and garnet.

Introduction

The schists in the Sambagawa belt, Japan, occur as many nappes, whose formation is related to their emplacement from the metamorphic field of high-pressure and low-temperature condition into the shallow tectonic position, i.e. the deformation of Nagahama phase, (HARA, *et al.*, 1977; TAKEDA, *et al.*, 1981; HARA *et al.*, 1983). The schists involved in the basal parts of those nappes are commonly highly deformed in various styles during the Nagahama phase. In the basal part of the Saruta nappe of Central Shikoku (Fig. 1), they are strongly folded in minor scale associating the formation of distinct axial plane cleavage (HARA *et al.*, 1977, 1983). The microtextures of plagioclase and garnet in a minor fold of pelitic schist, which has been collected from the base of the Saruta nappe of the Shirataki district, Central Shikoku, (Fig. 1) and is of the Nagahama phase, will be described and discussed in this paper, in order to understand deformation

styles of those minerals during the Nagahama phase. The obtained data would indicate that pressure solution played an important role in deformation of plagioclase and garnet during the folding of Nagahama phase.

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Description and discussion of microtextures of plagioclase and garnet

1) Rock structure of examined specimen

The basal part of the Saruta nappe in the Shirataki district is placed on the southern limb of Shirataki recumbent fold (HIDE, 1961) (Fig. 1) and consists mainly of pelitic schists. Minor folds of Nagahama phase in the pelitic schists develop in tight form and with axial trends near NS, which are oblique at high angles to the axial trend of the Shirataki recumbent fold. One of them, which has been collected from the locality shown in Fig. 1, will be examined in this paper.

The minor fold of pelitic schist examined has a distinct axial plane cleavage (S_2). S_2 shows structural variation from differentiated crenulation cleavage (cf. WILLIAMS, 1972) to schistosity. The differentiated crenulation cleavage consists of two zones: 1) zones in which constituent minerals are dimensionally

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Fig. 1. Diagrams showing locality of the analysed specimen.

- 1) a, b, c and d : Saruta nappe [a and b : Saruta nappe II (a : garnet zone, b : biotite zone), c and d : Saruta nappe I (c : biotite zone, d : Shirataki hornblende-schists and associated quartz-schists)], e : Nagahama nappe (map after HARA, HIDE & MAEDA, 1983). arrow : locality of analysed specimen. Sa : Sazare, S : Shiragayama, x : Shirataki, RAS : River Asemi, RD : River Dozan. A-B : profile line of Fig. 1-2.
- 2) Structural profile along the A-B line of Fig. 1-1. f and g : Saruta nappe II (f : garnet zone, g : biotite zone), h and i : Saruta nappe I (h : biotite zone, i : Shirataki hornblende-schists), j : Nagahama nappe. arrow : locality of analysed specimen.

preferentially oriented parallel to S_2 forming a single set of schistosity (S_2 -schistosity) and 2) zones in which older schistosity (S_1 -schistosity) as relict structure develops. The pelitic schist consists mainly of quartz, plagioclase, muscovite, chlorite and garnet. The deformation styles of plagioclase and garnet grains in the S_2 -schistosity will be examined in the following paragraphs.

2) Microtextures of plagioclase

Plagioclase grains in the S_2 -schistosity are dimensionally preferentially oriented with their shortest axes normal to S_2 and their longest axes parallel to S_2 (Fig. 2). Fig. 3 illustrates the orientation pattern of the longest axes of plagioclase grains as measured on the section (B-section) normal to the axis

of the fold. They are much more preferentially oriented along S_2 as measured on the section (A-section) parallel to the fold axis and normal to S_2 . Fig. 4-a and b illustrates the degree of grain elongation [L (length parallel to S_2)/ S (length normal to S_2)] for plagioclase grains on the A-section and B-section respectively, showing that they are strongly elongated parallel to S_2 . The L/S ratio measured on the A-section is between 1.8 and 8.5 with mean value of 4.6, while that measured on the B-section is between 1.8 and 7.3 with mean value of 3.4. This data indicates that plagioclase grains in the S_2 -schistosity are much more strongly elongated in a direction parallel to the fold axis than in a direction normal to it.

Fig. 2. Microphotograph of plagioclase in the S_2 -schistosity on the section parallel to the fold axis (under crossed nicols).

Figs. 5 and 6 are the data for plagioclase grains in the zones in which the S_1 -schistosity as relict structure develops. Fig. 5 indicates that their longest axes are preferentially oriented parallel neither to S_2 nor to S_1 . From Fig. 6 it can be said that they are nearly equiaxial (see also Fig. 7). The dimensional fabric of plagioclase grains in the S_1 -schistosity (Figs. 5, 6 and 7) is quite different from that of plagioclase grains in the S_2 -schistosity (Figs. 2, 3 and 4).

Plagioclase grains develop as porphyroblasts with other metamorphic minerals as inclusions (Figs. 2 and 7). The inclusions are not uniformly distributed within individual plagioclase grains, but are commonly absent from their outer zones (mantle). Namely, they show a zonal variation of inclusions defined by inclusion-free mantles and inclusion-rich cores (Figs. 2 and 7), like in the cases of plagioclase grains in the Sambagawa schists of other districts (HARA *et al.*, 1977; TAKAGI & HARA, 1979; HOSOTANI, 1980; HARA *et al.*, 1980; MAEDA & HARA, 1983a & b).

Fig. 8 illustrates the L/S ratio for the cores of plagioclase grains in the S_2 -schistosity as measured on the B-section. For all of measured grains L is longer than S, showing that the cores are strongly elongated parallel to S_2 . Mantles are commonly absent in a direction normal to S_2 and have maximum width in a direction parallel to S_2 . Thus, plagioclase grains (core+mantle) are much more strongly elongated parallel to S_2 than their cores are.

Fig. 9 illustrates the ratio of E (length parallel to the longest axis) to C (length normal to it) for the cores of plagioclase grains in the S_1 -schistosity. They are hardly elongated, unlike in the case of the cores of plagioclase grains in the S_2 -schistosity. And the mantles are commonly approximately uniformly developed around the cores.

Inclusions in the cores of plagioclase grains show preferred dimensional orientation, defining a schistosity (S_i), as shown in Figs. 2 and 7. S_i is approximately straight, though it is rarely slightly folded. The orientation direction of S_i within individual plagioclase grains is not controlled by their lattice direction. For plagioclase grains in the S_1 -schistosity S_i is commonly parallel to S_1 , while for them in the S_2 -schistosity S_i is randomly oriented but not parallel to S_2 . S_i is considered to be included S_1 . Thus, it is clear that the cores appeared before the deformation [S_2 -deformation=deformation of Nagahama phase (HARA *et al.*, 1977)] related to the formation of S_2 .

The cores of plagioclase grains in the S_1 -schistosity are nearly equiaxial. Thus, it can be assumed that they in the S_2 -schistosity were also nearly equiaxial before the S_2 -deformation. This assumption is harmonic with MAEDA and HARA's (1983a & b) conclusion that the cores of plagioclase grains in the pelitic and psammitic schists of the Saruta nappe appeared initially under non-deformational condition giving not rise to preferred lattice and dimensional orientation.

As clarified in the later page, garnet grains grew before the S_2 -deformation but were unstable during the S_2 -deformation. Namely, the pre- S_2 -deformation phase appears to have been under higher temperature condition than the S_2 -deformation phase. TAKAGI & HARA (1979) and HARA *et al.* (1980) have concluded that for plagioclase grains of the Saruta nappe their mantles grew either under higher temperature condition than their cores or under the same temperature condition as their cores did. Thus, it would be reasonable to assume that the mantles of plagioclase grains in the present specimen had already been produced before the S_2 -deformation. Because plagioclase (albite) was commonly

stable also during the Nagahama phase, however, the mantles may have partially been produced during the S_2 -deformation.

The above-described characteristics of the microtextures of plagioclase grains indicate that they in the S_2 -schistosity were highly deformed during the S_2 -deformation. However, they do not have preferred lattice orientation, as is obvious in Fig. 10.

Thus, the main mechanism of deformation of plagioclase grains in the S_2 -schistosity during the S_2 -deformation could be ascribed neither to intracrystalline slip nor to grain boundary slip but to pressure solution. Namely, the main mechanism of the shape change of plagioclase grains would be illustrated by Fig. 11. Removal of parts of plagioclase grain outside two dashed lines in Fig. 11, which occurs by pressure solution, produces the elongated shapes of (core+mantle) and core and the absence of mantle in a direction normal to S_2 . The pressure solu-

Fig. 3. Diagram showing the orientation pattern of the longest axes of plagioclase grains in the S_2 -schistosity as measured on the section normal to the fold axis.

θ : angle between S_2 and the longest axis of grain.

Fig. 4

Fig. 5

Fig. 6

Fig. 4. Diagram showing the distribution of the ratio (GE) between length parallel to S_2 and length normal to S_2 for plagioclase grains in the S_2 -schistosity.

a : data from the section parallel to the fold axis and normal to S_2 , b : data from the section normal to the fold axis.

Fig. 5. Diagram showing the distribution of the ratio (GE) between length parallel to S_2 and length normal to S_2 for plagioclase grains in the S_1 -schistosity as measured on the section normal to the fold axis.

Fig. 6. Diagram showing the distribution of the ratio (ED) between length of the longest axis and length of its normal for plagioclase grains in the S_1 -schistosity as measured on the section normal to the fold axis.

Fig. 7. Microphotograph of differentiated crenulation cleavage showing elongated plagioclase grains in the S_2 -schistosity and equiaxial plagioclase grains in the S_1 -schistosity (under crossed nicols).

Fig. 8. Diagram showing the distribution of the ratio (GE) between length parallel to S_2 and length normal to S_2 for the cores of plagioclase grains in the S_2 -schistosity as measured on the section normal to the fold axis.

Fig. 9. Diagram showing the distribution of the ratio (ED) between length of the longest axis and length of its normal for the cores of plagioclase grains in the S_1 -schistosity as measured on the section normal to the fold axis.

tion of plagioclase grains may have been associated with their concomitant overgrowth in a direction normal to the axis of the maximum compression (Fig. 11), because they (albite) were stable during the S_2 -deformation.

3) Microtextures of garnet

Fig. 12 illustrates the orientation pattern of the longest axes of garnet grains in the S_2 -schistosity as measured on the B-section. Garnet grains are also dimensionally preferentially oriented with their shortest axes normal to S_2 and their longest axes parallel to S_2 , though some grains have the longest axes inclined at high angles to S_2 .

The L/S ratio for garnet grains in the S_2 -schistosity as measured on the B-section is illustrated in Fig. 13. It is between 0.92 and 3.9 with mean value of 1.92. It can be said that many garnet grains in the S_2 -schistosity are fairly elongated parallel to S_2 . While garnet grains in the S_1 -schistosity are nearly equiaxial (Fig. 14).

Garnet grains also develop as porphyro-

Fig. 10. Fabric data for plagioclase grains in the S_2 -schistosity (50 grains).

a : Principal vibration axis X, b : Principal vibration axis Y, c : Principal vibration axis Z, contours : 8-6-4-2%.

Fig. 11. Diagram illustrating the shape changes of plagioclase grains in the S_2 -schistosity which were produced by pressure solution. heavy solid lines : original shape of grain, dotted lines : original shape of core, stippled area : new shape of grain. Material outside two dashed lines was removed by pressure solution, and the removed material may have migrated to form overgrowth (stippled area with heavy dots) in a direction parallel to S_2 .

Fig. 12. Diagram showing the orientation pattern of the longest axes of garnet grains in the S_2 -schistosity as measured on the section normal to the fold axis.
 θ : angle between S_2 and the longest axis of grain.

Fig. 13. Diagram showing the distribution of the ratio (GE) between length parallel to S_2 and length normal to S_2 for garnet grains in the S_2 -schistosity as measured on the section normal to the fold axis.

Fig. 14. Diagram showing the distribution of the ratio (ED) between length of the longest axis and length of its normal for garnet grains in the S_1 -schistosity as measured on the section normal to the fold axis.

blasts with other metamorphic minerals as inclusions (Fig. 15). The inclusions show preferred dimensional orientation, defining a schistosity (S_1), and are commonly uniformly distributed within individual grains (Fig. 15). S_1 is approximately straight, though it is rarely folded. Fig. 16 illustrates the orientation pattern of S_1 of garnet grains in the S_2 -schistosity as measured on the B-section.

Fig. 15. Microphotograph of garnet in the S_2 -schistosity showing orientation of S_1 -schistosity and fractures (under open nicol) and microprobe traces for MnO, MgO and FeO along line a-b and line c-d.

Fig. 16. Diagram showing the distribution of the angle (θ) between S_1 and S_2 for garnet grains in the S_2 -schistosity as measured on the section normal to the fold axis.

From this figure it is clear that for most of garnet grains S_1 is oblique to S_2 , as, for example, seen in Fig. 15. S_1 is not included S_2 . Thus, the growth of garnet grains is considered to have occurred before the formation of S_2 and so to have been unstable during the S_2 -deformation.

As analysed by a three channel JEOL X-ray microprobe analyser (JXA-5A), garnet grains show zonation of chemical composition in which the MnO content decreases from the central part to their rim while the FeO and MgO contents increases (Fig. 15), like in the cases of garnet grains in the Sambagawa

schists previously described by other authors (BANNO, 1965 ; BANNO & KURATA, 1972 ; HIGASHINO, 1975 ; ITAYA, 1978 ; HARA *et al.*, 1983 ; MAEDA & HARA, 1983a).

For garnet grains in the S_1 -schistosity which are nearly equiaxial, their rims have MnO content smaller than 2% in all directions. Fig. 17 illustrates the zonal structures for MnO of three elongated garnet grains in the S_2 -schistosity. From this figure and Fig. 15 it can be pointed out that the outer zones (mantle with low MnO content) of zonal structures, which are developed in a direction parallel to S_2 , are absent in a direction normal to S_2 . Therefore, the MnO content measured at grain boundaries of the longest axes of garnet grains, which are parallel to S_2 , is commonly nearly constant and smaller than 2%, but that measured at grain boundaries of the shortest axes, which are normal to S_2 , is not commonly constant but between 1.5% and 10%.

It has been pointed out in the preceding paragraph that the garnet grains, as well as the cores of plagioclase grains, were produced before the S_2 -deformation. MAEDA & HARA (1983a) have clarified that the mantles (with MnO content of ca. 4% - ca. 0.6%)

Fig. 17. Diagram showing the zoning pattern for MnO (wt%) in three garnet grains in the S_2 -schistosity as measured on the section parallel to the fold axis and normal to S_2 .

of garnet grains in the pelitic schist of the Saruta nappe are of the same generation as the cores of plagioclase grains and grew under non-deformational condition. The garnet grains in the S_1 -schistosity are nearly equiaxial and uniformly coated with rims of MnO content smaller than 2%. Thus, it would be reasonable to assume that, before the S_2 -deformation, they in the S_2 -schistosity also occurred as nearly equiaxial grains uniformly coated with rims of MnO content smaller than 2%.

Thus, it can be pointed out that the garnet grains in the S_2 -schistosity were elongated parallel to S_2 as a consequent of the S_2 -deformation removing fairly large volume of their mantles in a direction normal to S_2 . The main mechanism of the shape change of garnet grains in the S_2 -schistosity during the S_2 -deformation could be regarded as cor-

Fig. 18. Diagram showing the orientation pattern of prominent fractures of garnet grains in the S_2 -schistosity as measured on the section parallel to the fold axis and normal to S_2 .

θ : angle between fracture and S_2 .

responding to the removal of parts of their mantles in a direction normal to S_2 . In garnet grains are commonly found fractures (Fig. 15). The orientation pattern of prominent fractures is illustrated in Fig. 18. They are preferentially oriented oblique at high angles to S_2 . The fractures are also developed in garnet grains of the S_1 -schistosity. Thus, the removal of parts of mantles of garnet grains in the S_2 -schistosity which occurs in a direction normal to S_2 can not be related to fracturing and displacement along fractures. It seems most probable to consider that the garnet grains in the S_2 -schistosity were mainly deformed by pressure solution during the S_2 -deformation.

References

- BANNO, S., 1965 : Notes on rock forming minerals (34) Zonal structure of pyrospite garnet in Sanbagawa schist in the Besshi area, Sikoku. *Jour. Geol. Soc. Japan*, **71**, 185-188.
- and KURATA, H., 1972 : Distribution of Ca in zoned garnet of low-grade pelitic schists. *Jour. Geol. Soc. Japan*, **78**, 507-512.
- HARA, I., HIDE, K., TAKEDA, K., TSUKUDA, E., TOKUDA, M. and SHIOTA, T., 1977 : Tectonic movement in the Sambagawa belt. In K. HIDE (ed), The Sambagawa Belt. Hiroshima Uni-

- versity Press, 307-390.
- , ———, TOKUDA, M., TAKAGI, K. and SHIOTA, T., 1980 : Relationship between deformation and metamorphism in the Sambagawa belt, Central Shikoku, (A preliminary report). *Studies on Late Mesozoic Tectonism in Japan*, **2**, 1-14.
- , ——— and MAEDA, M., 1983 : Internal structure of Saruta nappe in the Sambagawa belt of Central Shikoku. *90th Ann. Meet. Geol. Soc. Japan*, Abstract, 350.
- , ———, SEO, T. and MAEDA, M., 1983 : Discontinuously zoned garnet in Sambagawa schist from Central Shikoku, Japan. *Jour. Sci. Hiroshima Univ.*, Ser. C, **8**, 51-58.
- HIDE, K., 1961 : Geologic structure and metamorphism of the Sambagawa crystalline schists of the Besshi-Shirataki mining district in Shikoku, Southwest Japan. *Geol. Rep. Hiroshima Univ.*, **9**, 1-87.
- HIGASHINO, T., 1975 : Biotite zone of Sanbagawa metamorphic terrain in the Siragayama area, Central Shikoku, Japan. *Jour. Geol. Soc. Japan*, **81**, 653-670.
- HOSOTANI, H., 1980 : Growth stage of albite porphyroblast in pelitic schist of the Sambagawa metamorphic belt. *Jour. Geol. Soc. Japan*, **86**, 537-543.
- ITAYA, T., 1978 : Notes on petrography and rock-forming mineralogy (5) Reverse-zoned garnet in Sanbagawa pelitic schists in Central Shikoku, Japan. *Jour. Jap. Assoc. Min. Pet. Econ. Geol.*, **73**, 393-396.
- MAEDA, M. and HARA, I., 1983a : Pre-Nagahama fold in the Sambagawa belt of the Sarutagawa district, Central Shikoku. *Jour. Geol. Soc. Japan*, (in press).
- and ———, 1983b : Growth condition of plagioclase porphyroblasts in Sambagawa schist from Central Shikoku, Japan. *Jour. Sci. Hiroshima Univ.*, Ser. C, **8**, 131-134.
- TAKAGI, K. and HARA, I., 1979 : Relationship between growth of albite porphyroblasts and deformation in a Sambagawa schist, Central Shikoku, Japan. *Tectonophysics*, **58**, 113-125.
- TAKEDA, K., HIDE, K., MAKISAKA, S. and SONODA, K., 1981 : Depositional environment of the original rocks of Sambagawa metamorphic rocks. In I. HARA (ed), *Tectonics of Paired Metamorphic Belts*, Tanishi-Print Kikaku, Hiroshima.
- WILLIAMS, P. F., 1972 : Development of metamorphic layering and cleavage in low grade metamorphic rocks at Bermagui, Australia. *Am. Jour. Sci.*, **272**, 1-47.
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四国中央部三波川帯の長浜褶曲作用における斜長石・ざくろ石の PRESSURE SOLUTION

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(要 旨)

三波川変成岩類はナップ群として変成場から解放されている。四国中央部三波川帯にはこのようなナップの一つとして猿田ナップが発達している。猿田ナップ形成期にナップのベースの変成岩類に顕著な軸面へき開の形成を伴う褶曲作用が起こっている。ここでは、白滝地域の猿田ナップの基底部の泥質片岩を試料として、この褶曲過程に泥質片岩中の斜長石とざくろ石がどのような様式で変形したかを解析した。褶曲過程に形成されたへき開は differentiated crenulation cleavage ないし片理 S_2 である。 S_2 -片理中の斜長石とざくろ石は形態定向配列と極めて著しい伸長を示す。これは differentiated crenulation cleavage の古期片理 S_1 残存部の斜長石とざくろ石が伸長性を示さないのと著しく対照的である。斜長石は平滑な片理 S_1 を形成する包有物を含む核とそれを含まないマントルに分かれ累帯構造を示す。Si は一

般に S_2 に斜交している。Si は S_1 を包有したものであり、核の形成は S_2 形成前である。 S_1 -片理中の斜長石の核は伸長性を示さないが、 S_2 -片理中で核は S_2 方向に著しく伸長している。斜長石は S_2 形成期に著しく変形したことは明らかであるが、格子定向配列を示さない。ざくろ石にも平滑な片理 Si を形成する包有物が粒内全体を通して認められる。Si は S_2 に一般に斜交している。Si は S_1 を包有したものであり、ざくろ石の成長は S_2 形成前に終わっている。ざくろ石の化学組成の累帯構造の解析によれば、 S_2 方向への著しい伸長を示すざくろ石においては、一般に S_2 に垂直な側で、累帯構造外縁部(低 MnO, 高 FeO・MgO)が大きく後生的(S_2 形成期)に消滅せしめられている。上記のような組織特性から、斜長石とざくろ石は S_2 の形成を伴う褶曲過程に pressure solution によって変形したものと結論された。