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Structural and microstructural constraints on the mechanism of eclogite formation in the Sambagawa belt, SW Japan

Mutsuki Aoya*, Simon R. Wallis

Department of Geology and Mineralogy, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan

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Abstract

Eclogites in the Seba basic schist of the Sambagawa belt show contrasting textures. In one type of eclogite, coarse-grained omphacite is randomly oriented and cross-cuts the schistosity suggesting post-tectonic growth. In contrast, in the second type, fine-grained omphacite is preferentially aligned parallel to the schistosity suggesting pre- to syn-tectonic growth. The former type of eclogite has been regarded as a product of solid-state contact metamorphism after the formation of the schistosity while the latter type has been related to the Sambagawa regional metamorphism. The idea that eclogite can form by contact metamorphism is unconventional and, if true, could have major implications for the interpretation of eclogitic rocks in general. In the Seba basic schist, it has generally been assumed that the dominant schistosity formed during a single phase of deformation. However, field and microstructural studies show: (i) there are two different schistosities, one formed before and the other during eclogite formation; and (ii) the differences in eclogite texture reflect the strength of deformation during the second stage. Therefore, the various textural types of eclogite in the Seba basic schist all formed during a single phase of regional metamorphism and there is no need to invoke contact metamorphism.

1. Introduction

Eclogite forms at depth of between 30 and 100 km in regions of low geothermal gradients. Such high P–T conditions are generally associated with convergent margins where subduction of cold lithosphere produces an overlying anomalously cold region. Petrological studies of eclogite are an important source of information on the thermal structure of such subduction zones. However, Takasu (1984) suggests a radical alternative type of formation for eclogite. The facies boundary between the epidote amphibolite and eclogite facies is commonly drawn as a line with a negative $\mathrm{d}P/\mathrm{d}T$ slope (e.g. Velde, 1970; Fig. 1). Takasu (1984) suggests that, at least locally, eclogite in the Sambagawa belt of south-west Japan has formed from epidote amphibolite by contact metamorphism caused by the intrusion of a hot eclogitic body of metagabbro (the Sebadani metagabbro mass; Fig. 2). If true, this proposal has major implications for the interpretation of eclogitic rocks in general.

The main observations used by Takasu (1984, 1986) to support the idea that eclogite formed as the result of solid-state contact metamorphism are as follows:

1. Eclogite around the metagabbro body is localized to a region within 20 m of the contact.
2. Omphacite grows randomly cross-cutting an earlier foliation.
3. The metagabbro shows evidence for a two-stage metamorphic history. Estimates of the associated temperatures using core–core and rim–rim pairs of garnet and omphacite show a decrease in temperature from the first to second stages (Fig. 1). The temperature during the second stage is almost the same as that of the surrounding eclogite.
4. Garnet within pelitic schists adjacent to the metagabbro shows resorption followed by a second phase of growth.

Takasu's interpretation has been generally accepted by

* Corresponding author.
E-mail address: aoya@kueps.kyoto-u.ac.jp (M. Aoya)

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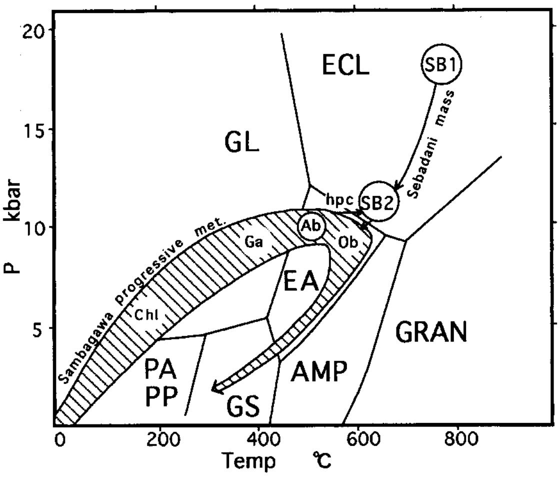

Fig. 1. Pressure–temperature diagram showing the metamorphic history of the Sebadani area proposed by Takasu (1984) (simplified from Takasu, 1986): SB1 = the first eclogite stage of the Sebadani metagabbro; SB2 = the second eclogite stage of the Sebadani metagabbro; hpc = high-pressure contact metamorphism. Sambagawa progressive met. = metamorphic field gradient of the Sambagawa regional metamorphism; Chl, Ga, Ab and Ob = chlorite zone, garnet zone, albite–biotite zone and oligoclase–biotite zone, respectively.

petrologists, particularly in Japan. There have, however, been no other reports of a similar phenomenon from other parts of the world. The present authors have, therefore, undertaken a series of studies to re-examine the phenomenon described by Takasu (1984) with the aim of testing the model and placing some constraints on the relationship between the eclogite facies rocks and the lower grade parts of the Sambagawa metamorphic belt.

There is a theoretical problem with Takasu's model. Thermal modelling by Aoya (1998) shows that solid-state contact metamorphism of the type proposed by Takasu (1984) requires a much larger intrusive body than there is evidence for and extremely high exhumation rates. In addition, recent field studies in the Sebadani area reveal the presence of schistose eclogite at a distance of up to 1 km from the metagabbro (Naohara and Aoya, 1997; Fig. 3a). Contact metamorphism cannot account for the formation of these distant eclogites (Aoya, 1998). Naohara and Aoya (1997) recognize this problem and suggest that two types of eclogite may be present in the region: one adjacent to the metagabbro formed by contact metamorphism and a second type formed by regional metamorphism under a low geothermal gradient. A distinct

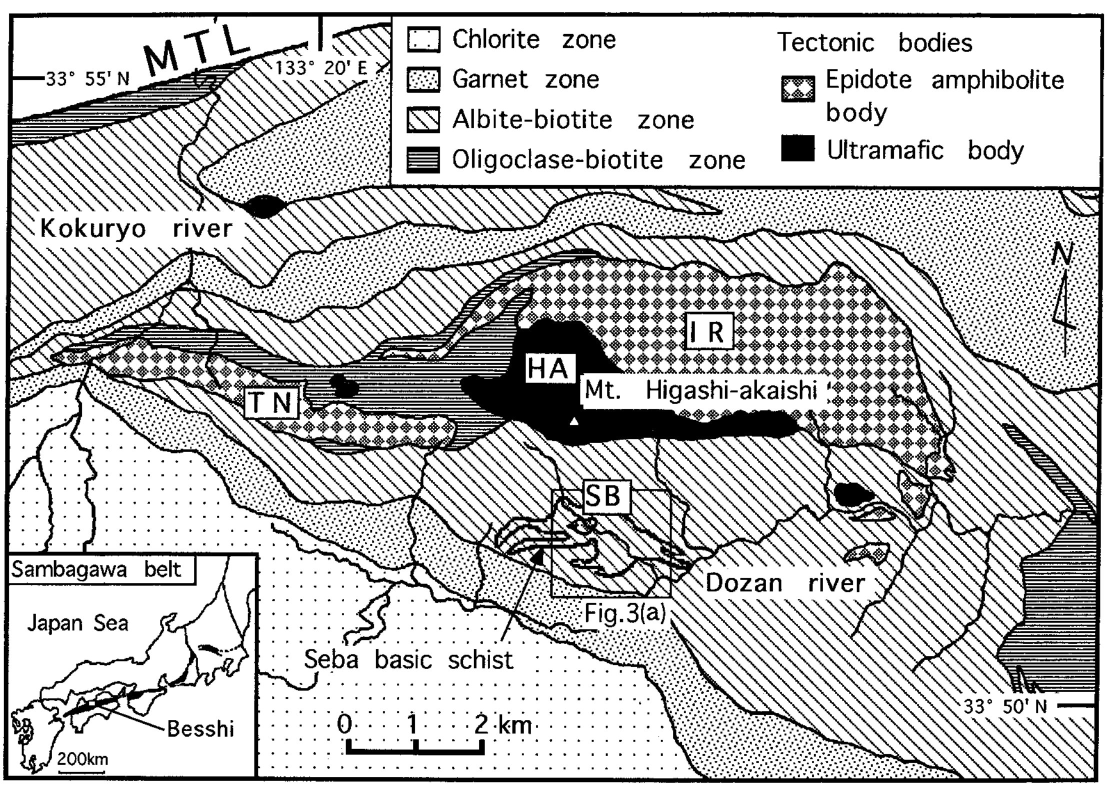

Fig. 2. Metamorphic zonation map of the Sambagawa belt in the Besshi district based on Higashino (1990) with distribution of Seba basic schist after Naohara and Aoya (1997). Eclogite-bearing bodies: SB = Sebadani metagabbro mass; IR = Iratsu mass; TN = Tonaru metagabbro mass; HA = Higashi–akaishi peridotite mass. MTL = Median Tectonic Line.

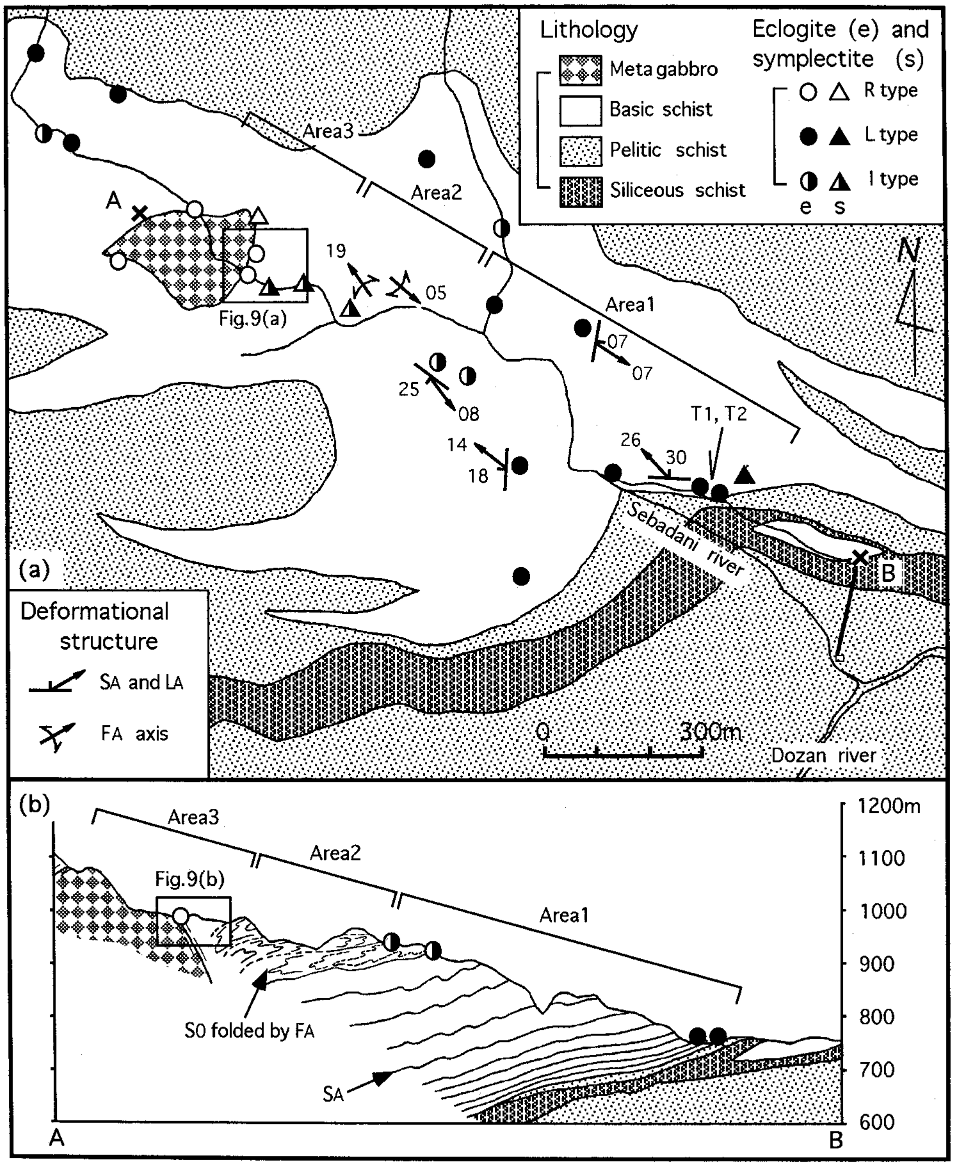

Fig. 3. (a) Geological map of the Sebadani area. (b) Cross-section along the line A–B shown in (a). Sample localities of eclogite (R, L and I types) and albite–hornblende symplectite in the Seba basic schist are shown. The divisions of the study area into Area 1, Area 2 and Area 3 are also shown. T_1, T_2 are the localities of outcrops showing best-preserved eclogite occurrences (see Table 1).

geological history for the two types of eclogite is suggested by their contrasting textures: eclogite distant from the metagabbro has a strong preferred orientation of fine-grained omphacite whereas the eclogite nearby the metagabbro shows a random development of coarse-grained omphacite (Fig. 4).

In this paper we study the look at the structural and microstructural development of the different types of eclogite and associated amphibolitic schists in the Sebadani region of the Sambagawa belt. Our main purpose is to establish the relationship between the growth of omphacite in basic schists and the deformational history of the region. Our studies show that the contrasting omphacite textures are related to the strength of syn- to post-eclogite facies deformation and that the texture of the omphacite forms no basis for proposing eclogite formation by contact metamorphism.

2. Geology of the Sebadani area

The Sambagawa metamorphic belt is one of the best documented subduction zone metamorphic complexes in the world (e.g. Banno and Sakai, 1989; Enami et al., 1994; Takasu et al., 1994; Wallis, 1998). The metamorphism is generally discussed in terms of four metamorphic zones based on the appearance of key

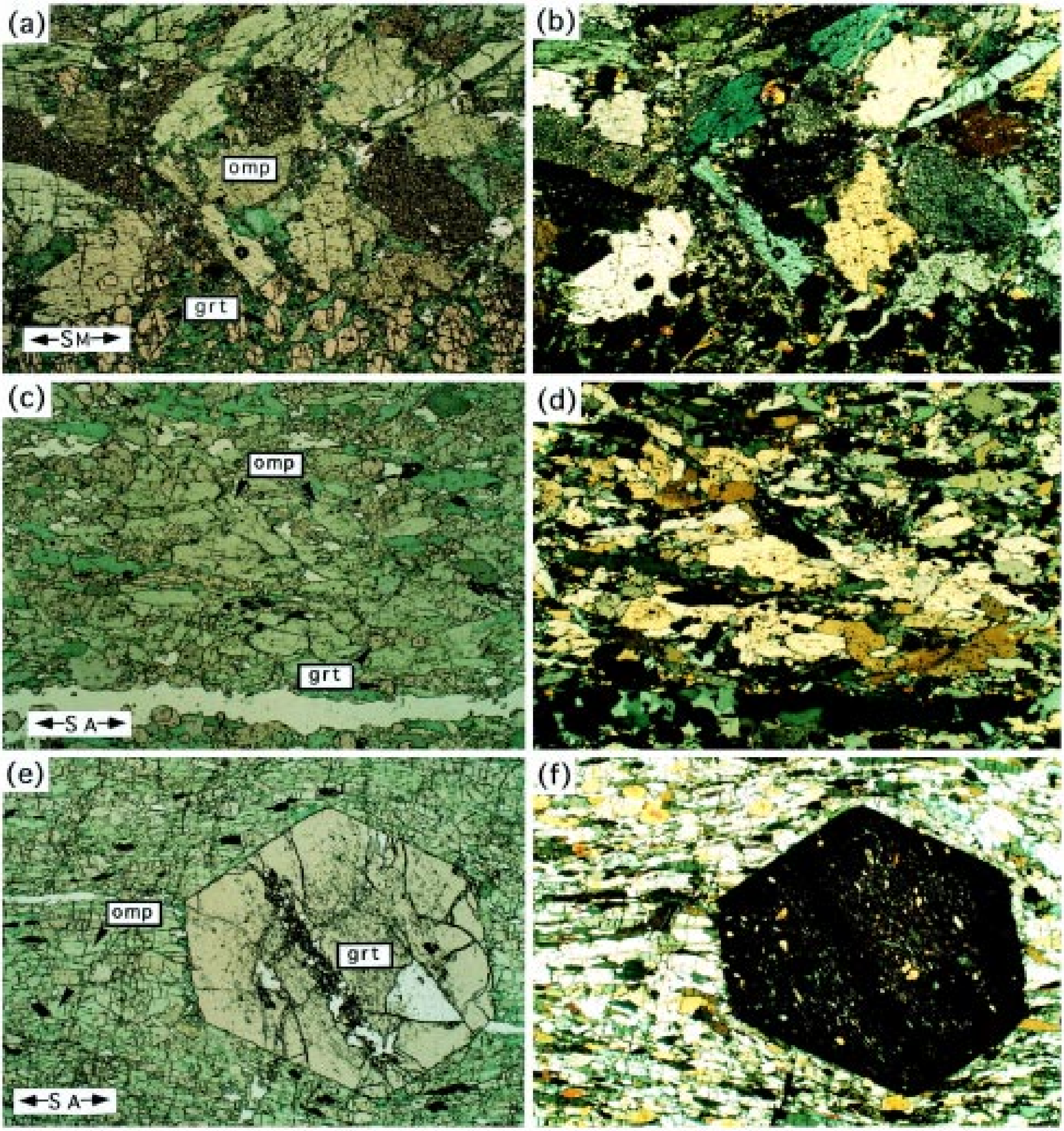

Fig. 4. Photomicrographs of eclogite from the Seba basic schist. Long axis all 3.4 mm. (a), (b) R-type eclogite [(b) cross polars of (a)]. Omphacite is randomly oriented cross-cutting S_M. (c), (d) I-type eclogite [(d) cross polars of (c)]. The majority of omphacite grains are aligned parallel to S_A but a significant proportion of omphacites are at a high angle to S_A. (e), (f) L-type eclogite [(f) cross polars of (e)]. Omphacite is fine grained and shows strong linear alignment within S_A.

metamorphic minerals in metapelite. In order of increasing grade these are the chlorite, garnet, albite–biotite, oligoclase–biotite zones. The Sebadani area occurs in the central part of the Besshi district of the Sambagawa belt and has been assigned to the albite–biotite zone by previous workers (e.g. Higashino, 1990; Fig. 2). The Sebadani area can be broadly divided into three distinct rock types: the Sebadani metagabbro mass, the Seba basic schist, and pelitic schist (Fig. 3).

The Sebadani metagabbro mass consists mainly of garnet–epidote amphibolite with local eclogite and has an outcrop dimension of 300×200 m^2 (Fig. 3a). Grain sizes of the constituent minerals in this lithology are generally larger than those in the surrounding basic

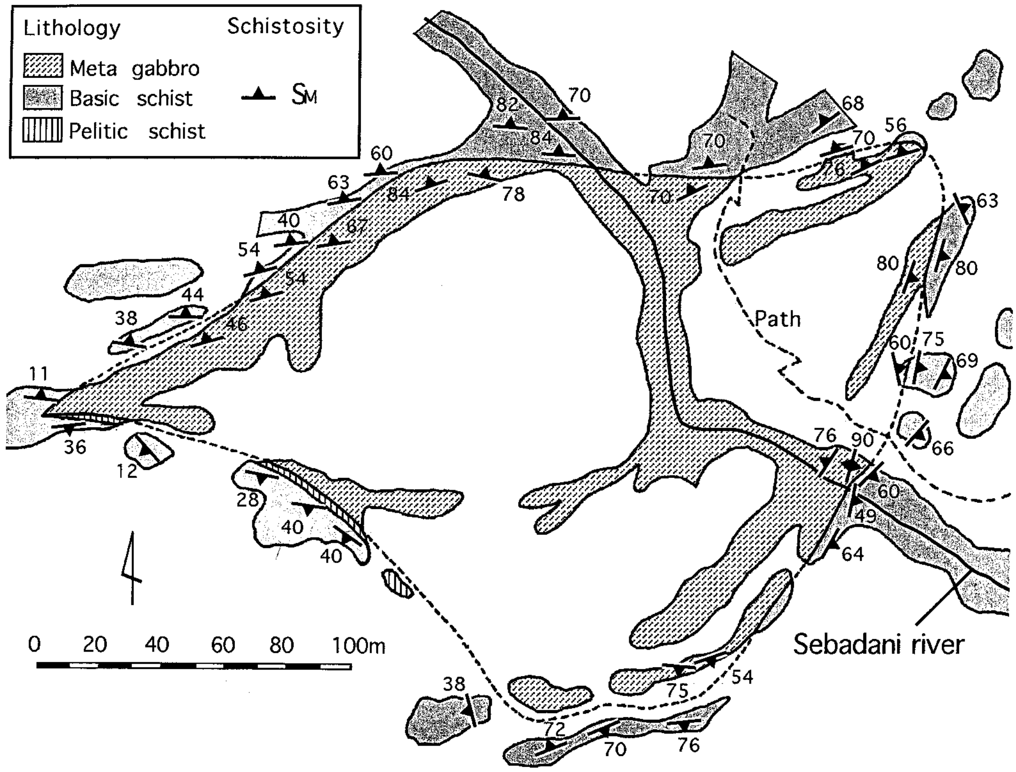

Fig. 5. Geological map of the Sebadani metagabbro mass.

schist and igneous banding is weakly preserved in the interior suggesting that the mass was originally layered gabbro (Takasu, 1984). A shear zone with a width of about 10 m is present along the margin of the Sebadani metagabbro mass. The mass is surrounded by basic schist (the Seba basic schist) although there is a thin (generally < 1 m) layer of pelitic schist between them (Takasu, 1986; Nomizo, 1992). Schistosities in the marginal shear zone, the thin pelitic schist and the Seba basic schist are, in general, all concordant and have steep dips subparallel to their boundaries (Fig. 5). The schistosities and the deformation that formed them will be referred to here as S_M and D_M (M = margin), respectively, following Aoya (1998). Takasu (1986) reported garnet with cores showing features of resorption within the thin pelitic schist between the Sebadani mass and the Seba basic schist and suggests these represent a two-stage growth history related to the Sambagawa regional metamorphism followed by contact metamorphism.

The Seba basic schist surrounding the Sebadani metagabbro mass forms a lenticular body of 3 km in length and has a maximum thickness of about 800 m in the central part (Fig. 2). The Seba basic schist is mainly composed of garnet epidote amphibolite, but also locally contains the assemblage omphacite + garnet (e.g. Takasu, 1984; Naohara and Aoya, 1997; Fig. 3a) characteristic of the eclogite facies.

The Seba basic schist is surrounded by pelitic schist (Fig. 3a) consisting of quartz, white mica, chlorite, garnet and albite with a small amount of biotite. The pelitic schist belongs to the albite–biotite zone with estimated P–T conditions of 520 ± 25°C, 8–9.5 kbar,

Table 1
Modal mineralogy of eclogite and amphibolite samples from T_1, T_2 outcrops

	Eclogite (a)	Eclogite (b)	Eclogite (c)	Amphibolite
omphacite	31	55	33	0
garnet	11	13	27	10
amphibole	8	2	5	49
epidote	9	tr.	tr.	2
calcite	12	7	7	0
quartz	tr.	tr.	14	9
mica	23	15	8	19
sphene	4	4	3	2
rutile	tr.	tr.	tr.	tr.
albite	1	2	tr.	9
ore	tr.	tr.	2	tr.
chlorite, apatite	tr.	0	tr.	0
point No.	8000	3000	3000	3000
grt + omp	42%	69%	61%	10%

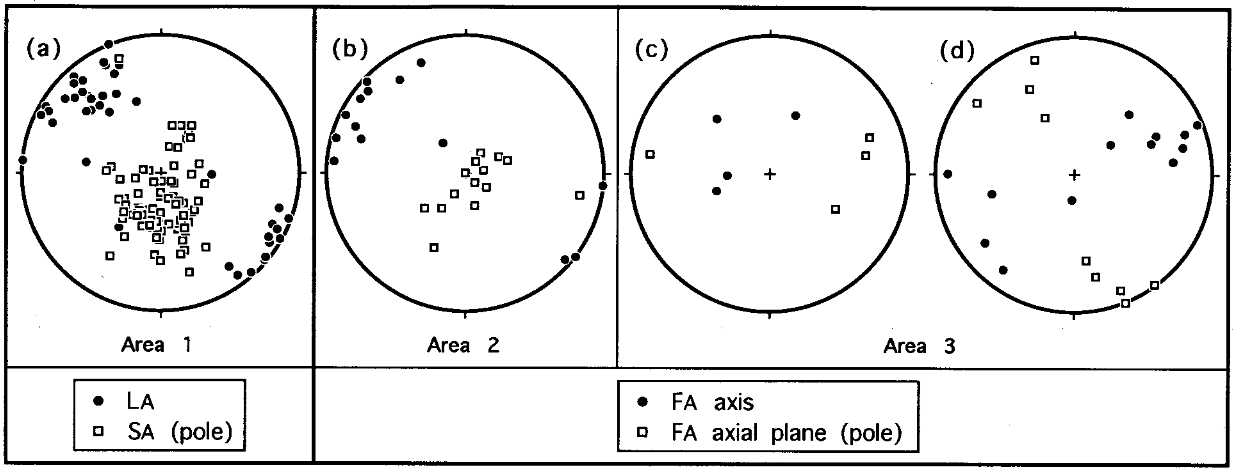

Fig. 6. Mesoscopic orientation data from the cross-sectional area shown in Fig. 3. (a) L_A and S_A from Area 1. (b) F_A axes and F_A axial planes from Area 2. (c), (d) F_A axes and F_A axial planes from Area 3. In Area 3, the trend of F_A shows a progression (b) → (c) → (d) from the eastern end of the area to the Sebadani metagabbro mass.

which correspond to the epidote amphibolite facies (Enami et al., 1994).

3. Textural classification and distribution of eclogites in the Seba basic schist

The Seba basic schist epidote amphibolite is mainly composed of barroisitic amphibole, epidote, white mica (phengite) and lesser amounts of garnet. Omphacite is rare but widespread. Very well-developed eclogites have recently been found in the south-eastern part of the Seba basic schist (localities T_1 and T_2 in Fig. 3a). In a sample from these localities the proportion of garnet + omphacite is nearly 70% (Table 1) thus qualifying as 'eclogite' even in the narrowest definition (e.g. Carswell, 1990). Other samples contain less omphacite, although the common development of garnet means that samples of the Seba basic schist that contain omphacite can be termed eclogite in a broad sense and distinguished from other non-eclogitic parts.

In general, eclogites in the Seba basic schist can be divided into two types with reference to the occurrence of omphacite.

1. R (random) type: In R-type eclogite, omphacite is randomly oriented and cross-cuts a pre-existing schistosity (S_M). In general, the omphacite is relatively coarse grained (up to 10 mm in length) whereas the associated garnet is relatively fine grained (about 0.2 mm in diameter) (Fig. 4a, b). This type corresponds to the eclogitic basic schist of Takasu (1984).
2. L (lineated) type: In L-type eclogite, omphacite is fine grained (0.1–1 mm in length) and shows a strong linear alignment within the dominant mesoscopic schistosity. This type commonly contains coarse garnet (up to 7 mm in diameter) with abundant inclusions (Fig. 4e, f). Most of the newly discovered eclogites (Fig. 3a) belong to this type.

R-type eclogites have been found only in the area adjacent to the Sebadani mass, while L-type eclogites are widespread in parts of the Seba basic schist some distance away from the Sebadani metagabbro mass (Fig. 3a).

Albite–hornblende symplectites are generally considered to form from omphacite, and can be regarded as indicating the original existence of omphacite. Localities of those epidote amphibolite samples which contain albite–hornblende symplectite are shown in Fig. 3(a). The same classification (R type, L type) as for eclogites has been applied to omphacite pseudomorph occurrences.

4. Deformation phases and their distribution

The main study area is along a traverse stretching from the Sebadani metagabbro to the T_1 and T_2 outcrops (A–B in Fig. 3a). Field studies have focused on mesoscopic structures, and several discrete deformation stages are recognized.

4.1. D_A deformation

The main structures formed during deformation stage D_A are a strongly developed schistosity (S_A) and associated stretching lineation (L_A). The main L_A forming minerals are barroisitic amphibole and white mica, and their alignment on the S_A plane can be observed with the naked eye. In eclogitic parts, omphacite grains are also oriented parallel to L_A. S_A and L_A are dominant in the south-eastern part of the

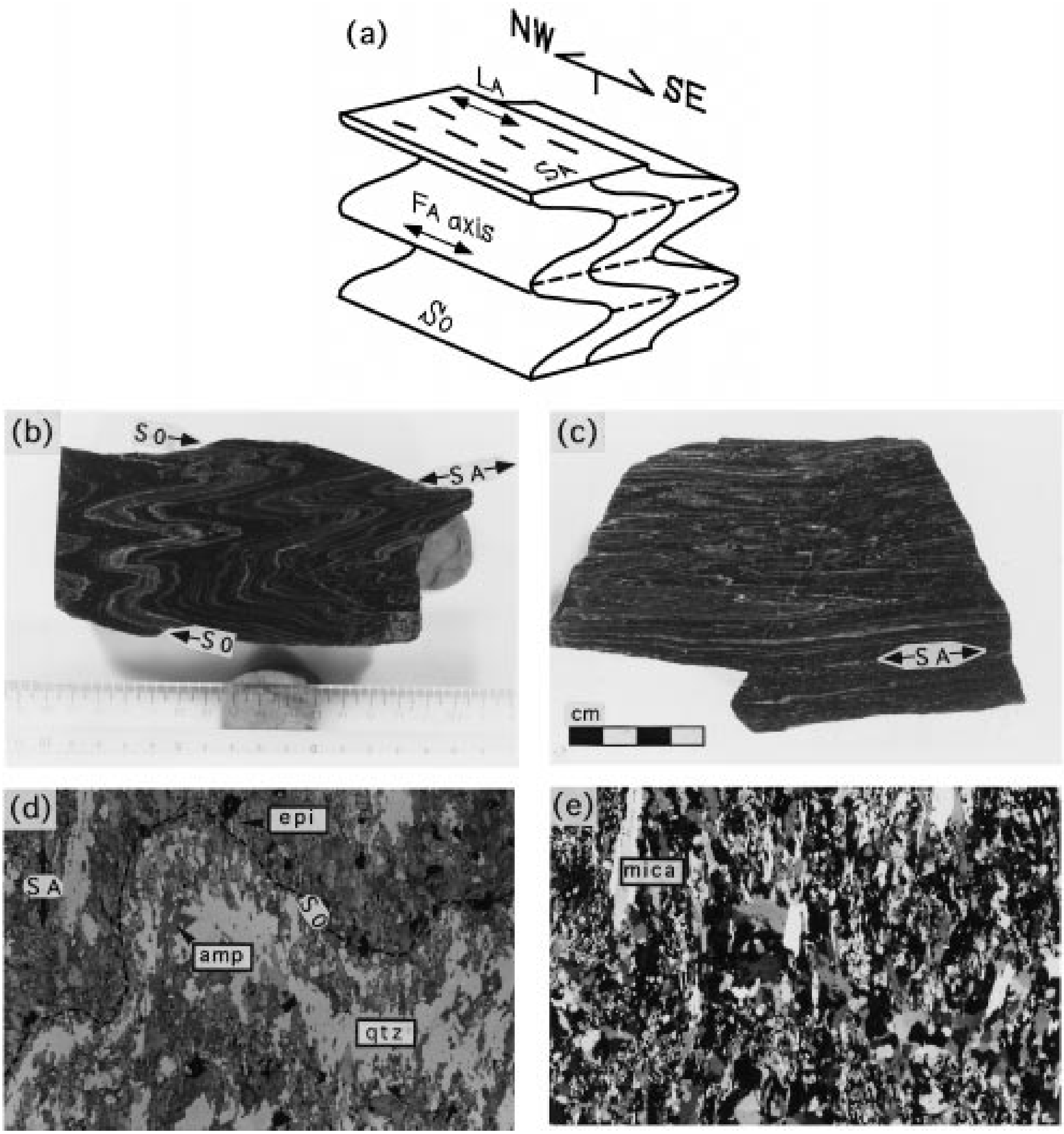

Fig. 7. F_A folds and S_0–S_A relationships. (a) Schematic illustration of F_A folds in Area 2 and their associated structures. (b), (c) Photographs of epidote amphibolite samples from Area 2 with tightly developed F_A folds. (d), (e) Photomicrographs of epidote amphibolite from Area 3 showing S_0–S_A relationship [(e) cross polars of (d)]. Although S_0 is recognizable in (d) as compositional layering, most mineral grains are aligned parallel to F_A and are clearly oblique to S_0 in (e). Long axes 6.7 mm.

study area, and this south-eastern part will hereafter be called 'Area 1' (shown in Fig. 3). The orientation data of S_A and L_A from Area 1 are plotted in Fig. 6(a). L-type eclogites in the cross-sectional area are all found in Area 1.

Mesoscopic folds formed during D_A (referred to as F_A) are dominantly found in the north-western part of the study area (Areas 2 and 3 in Fig. 3; Fig. 7). F_A folds are generally tight with an orientation trend as shown in Fig. 6(b). These folds are regarded as forming during D_A because: (i) with the exception of Area 3, the folds have flat lying axial planes and NW–SE-

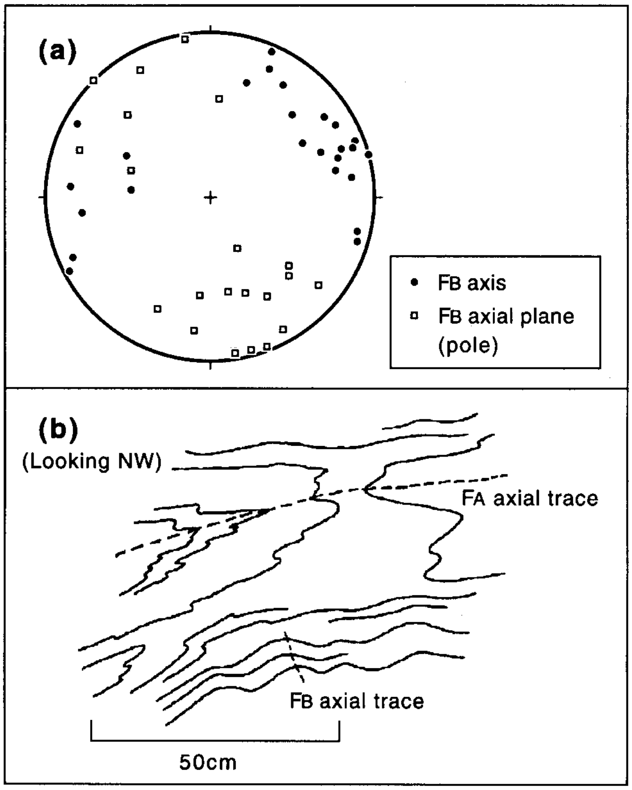

Fig. 8. (a) Mesoscopic orientation data of F_B folds. (b) A field sketch of a fold interference structure where both F_A and F_B folds can be recognized. From an outcrop located in the north-westernmost part of Area 1.

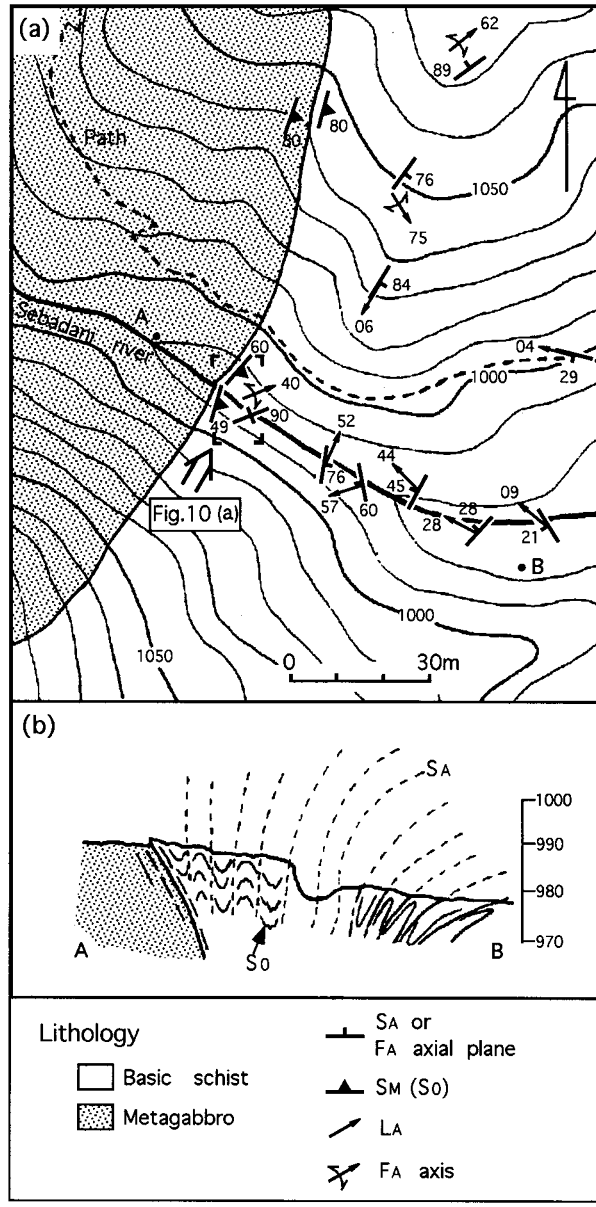

Fig. 9. (a) Geological map of the eastern part of Area 3. (b) Cross-section along the line A–B shown in (a).

trending axes, and the orientations of these structures are the same as those of S_A and L_A in Area 1 (Fig. 6a, b); and (ii) a newly formed schistosity ($=S_A$) is commonly observed subparallel to the axial planes of the folds and the stretching lineation on it is parallel to the fold axes (Fig. 7a). It is widely recognized that, irrespective of the original orientation, folds associated with high strain will tend to have their axes parallel to the maximum finite stretching direction and their axial planes will be parallel to the new schistosity (e.g. Williams, 1978). If deformation is sufficiently strong, a newly formed schistosity may become very strongly developed and earlier fold structures will no longer be clearly recognizable (Fig. 7c). Area 3 is the north-westernmost part of the study area and closest to the Sebadani metagabbro. In Area 3, the orientation of F_A in the Seba basic schist gradually changes (Fig. 6c, d). This change will be further discussed later.

4.2. D$_B$ *deformation*

D_B is a post-D_A phase of deformation recognized most readily by kink-like mesoscopic folds that fold S_A. This type of fold, generally on a centimetre to 10 m scale, is termed F_B. F_B axes are gently plunging with a NE–SW to E–W trend and they are mostly associated with steeply dipping axial planes (Fig. 8a). In Area 1, for example, most of the F_B crenulations (about 1 cm wavelength) on the S_A plane are oblique to L_A, and L_A is clearly folded by the F_B crenulation. Moreover, interference structures between F_A and F_B can be locally observed (Fig. 8b).

4.3. D$_0$ *deformation*

D_0 is a pre-D_A phase deformation recognized by a schistosity, S_0, that is folded by F_A (Fig. 7). Since F_A folds are mainly recognized in Areas 2 and 3, S_0 is preserved mainly in these two areas. The mesoscopic and microscopic relationships between S_0 and S_A can be

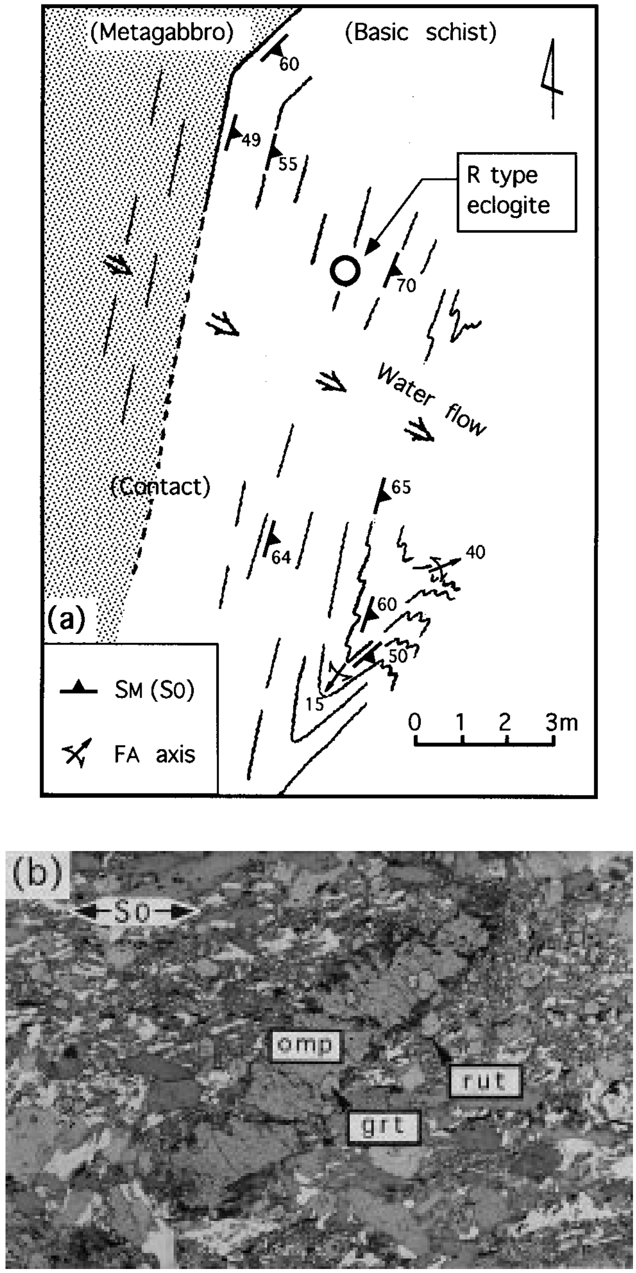

Fig. 10. (a) Large-scale map of an outcrop located on the south-eastern boundary of the Sebadani metagabbro mass. The sample locality of R-type eclogite in this outcrop is shown. S_M is folded by F_A with steeply dipping axial planes. (b) Photomicrograph of R-type eclogite, sampling point of which is shown in (a). Omphacite porphyroblast has grown cross-cutting S_M (recognized by arrangement of rutile). Long axis 3.4 mm.

most easily observed around the hinges of F_A folds with S_0 at a high angle to S_A that is developed along F_A axial planes (Fig. 7d, e).

4.4. Distribution of deformation

The distribution of deformation in the study area can be summarized as follows (see also cross-section Fig. 3b): (i) The effect of D_A is strongest in Area 1, which is structurally the lowest part with reference to S_A. In rocks structurally overlying Area 1 (Areas 2 and 3), the effect of D_A was relatively weak and the schistosity formed by the pre-D_A phase deformation (S_0) is preserved. (ii) Post-D_A phase deformation (D_B) is recognized throughout the region.

5. Relative timing of omphacite formation

R-type eclogite has been found only in Area 3 and contains randomly oriented omphacite that cross-cuts the schistosity surrounding the Sebadani metagabbro mass (S_M). S_M is developed both in the Sebadani mass and the adjacent Seba basic schist and is subparallel to the contact between the two units. The fact that S_M is observed in both lithologies implies that the emplacement of the Sebadani mass into the Seba basic schist occurred simultaneously with or before the D_M phase of deformation (Aoya, 1998). Omphacite of the R-type eclogite overgrows the S_M schistosity. To determine the relative timing of the formation of the R- and L-type eclogites, it is important to determine the relationship between S_M and the deformation phases defined above: D_0, D_A, D_B.

In Area 2, the axial plane of F_A is parallel to the flat-lying S_A seen in Area 1 (Fig. 6a, b). However, in Area 3, studies along a well-exposed stream section show F_A axial planes steepen towards the Sebadani metagabbro (Fig. 9). Accompanying this, the orientation of the F_A axes changes from a NW–SE trend with a gentle plunge to almost vertical and finally to a NE–SW trend with various plunges (Figs. 6b–d and 9). The important point is that although there is a change in orientation, the dominant folds in Area 3 are still due to D_A deformation.

Fig. 10(a) is a large-scale map of the boundary between the Seba basic schist and the Sebadani metagabbro mass in Area 3 with the location shown in Fig. 9(a). R-type eclogite has been reported from this locality by Takasu (1984) and was confirmed in this study (Fig. 10a, b). The map highlights the following two points: (i) S_M is folded by F_A (with nearly vertical axial planes) in the Seba basic schist, and is identical to S_0. (ii) The schistosity that is cut by randomly oriented omphacite in R-type eclogite is S_0 (Fig. 10a, b) showing that the random omphacites grew after the D_0 phase.

L-type eclogites occur in Area 1 where D_A deformation dominates (Fig. 3). These eclogites have fine-grained matrix-forming minerals including omphacite that are preferentially aligned along S_A (Fig. 4c). This implies that omphacite in the L-type eclogite grew simultaneously with or earlier than the D_A deformation. It is, therefore, possible that the growth of omphacite in

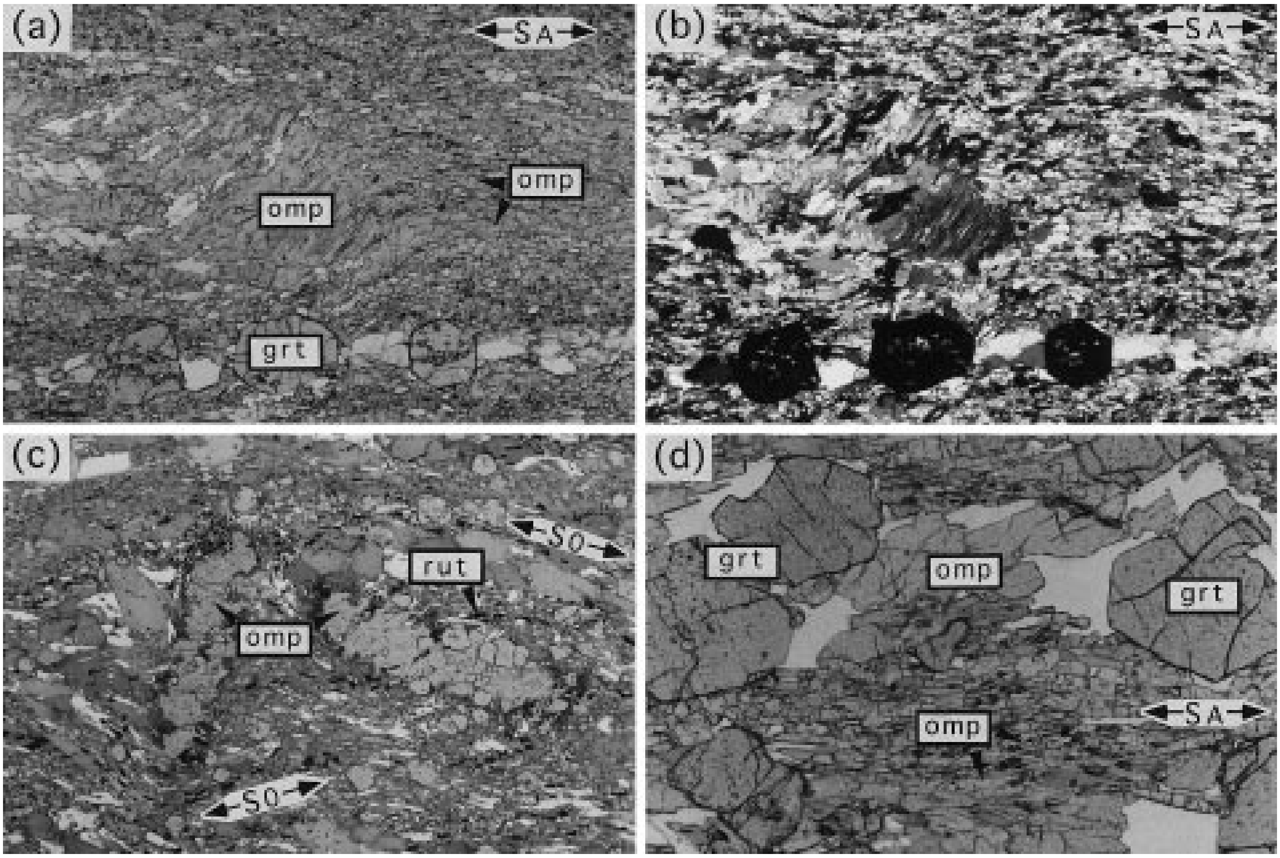

Fig. 11. Photomicrographs of eclogite showing textural evolution caused by D_A deformation. (a), (b) I-type eclogite [(b) cross polars of (a)]. Lenticular aggregates of coarse-grained omphacites wrapped by layers of fine-grained S_A-forming minerals including omphacites are preserved. Long axis 3.4 mm. (c) R-type eclogite. Coarse-grained omphacite cross-cutting S_0 is slightly rotated. The rotation is recognized by arrangement of S_0-forming rutile. Long axis 3.4 mm. (d) L-type eclogite. Coarse-grained omphacite is preserved within strain shadow of garnet while other matrix forming omphacites are fine-grained. Long axis 2.1 mm.

both the R and L types took place sometime after D_0 and before the completion of D_A. In this case the textural difference between L- and R-type eclogite could be explained simply by differences in the strength of D_A deformation without need to consider two different origins.

6. Microscopic evidence for textural evolution

If, as we suggest, the change from coarse-grained random omphacite fabrics to fine-grained aligned fabrics is due to increasing D_A strain, it should be possible to discover eclogite samples with intermediate fabrics (I-type eclogite). Two different types of such fabrics have been identified.

1. The first type of I-type eclogite is recognized at two sites in the structurally middle part of the cross-sectional area (Fig. 3a, b). In this type of eclogite, the omphacite grains are generally aligned parallel to S_A, but a significant proportion of the grains have their long axes oriented at a high angle to S_A (Fig. 4b). These features suggest that omphacite grains initially with a random distribution became reoriented by porphyroblast rotation during the D_A phase deformation. The associated D_A finite strain was, however, not sufficient to cause a complete alignment of the omphacite.
2. A second I-type eclogite is found away from the line of the cross-section (Fig. 3a). This type shows almost the same texture as the L-type eclogite with a well-developed S_A, but also contains lenticular aggregates of coarse-grained omphacites wrapped around by layers of fine-grained matrix-forming omphacites (Fig. 11a, b). This type of texture indicates that initially coarse-grained omphacite underwent grain-size reduction by recrystallization during D_A. In this case, however, the D_A deformation was not sufficiently strong to completely reset the omphacite grain size.

Both types of intermediate eclogite fabrics are found where the mesoscopic structures show that the D_A strain is also intermediate. This supports the idea that the textural difference between L- and R-type eclogite

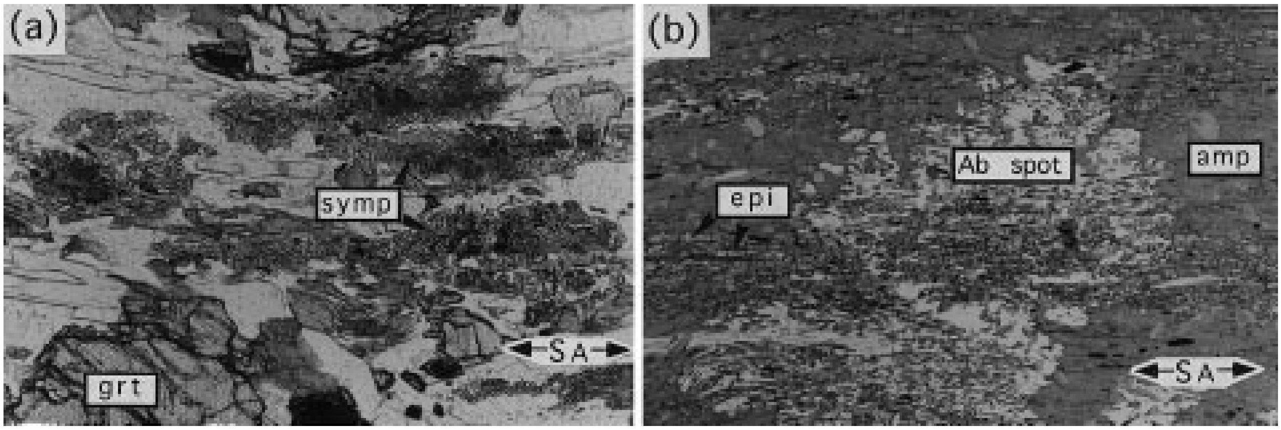

Fig. 12. Photomicrographs showing occurrence of albite in the Seba basic schist amphibolite. (a) L-type albite–hornblende symplectite. Long axis 1.4 mm. (b) Albite spot with highly irregular outlines across S_A. Long axis 3.4 mm.

depends on differences in the strength of D_A deformation. Careful observation shows that the initial stages of rotation of omphacite grains are locally also preserved in the R-type eclogite. This is shown by the deflection of S_0 as it passes through omphacite grains (Fig. 11c). A second important observation is that coarse-grained omphacite is preserved in the strain shadow of garnet in L-type eclogite (Fig. 11d). This feature can be interpreted either as the result of syn-D_A growth of omphacite or preservation of pre-D_A omphacite in a low strain region. In either case, this microstructure strongly supports the idea that preservation of coarse omphacite occurs where D_A strain is relatively low.

7. Discussion

7.1. Tectonic interpretation of D_0 and D_A

To relate the D_0 and D_A deformation phases to major tectonic events requires knowledge of the metamorphic history and how it is linked with the structures described in this paper. A detailed discussion of the metamorphic evolution of the study area is beyond the scope of the present paper. We can, however, make some qualitative statements as outlined below.

One of the clearest indications of metamorphic conditions in the Seba basic schist is the eclogite stage described in this paper. The Seba basic schist is gradational with pelitic rock types and locally contains pillow structures. These features imply the Seba basic schist formed close to the earth surface and then suffered prograde metamorphism up to the eclogite facies. D_0 occurred before the eclogite facies metamorphism and is, therefore, associated with prograde metamorphism and subduction.

The eclogite facies metamorphism is overprinted by epidote amphibolite facies metamorphism, during which omphacite is partially replaced by albite. This change implies a phase of decompression (Fig. 1). Although rare in eclogitic parts of the Seba basic schist, albite is relatively common in epidote amphibolite parts. Two modes of occurrence can be defined: (i) a constituent mineral of albite–hornblende symplectites (Fig. 12a); and (ii) porphyroblasts with highly irregular outlines that grew across S_A (Fig. 12b). These textures indicate that albite is a secondary phase in the Seba basic schist and its growth took place after D_A. Post-D_A growth of albite, therefore, suggests that D_A can be related to the early stages of exhumation (decompression) from eclogite to epidote amphibolite facies conditions. (N.B. Takasu, 1984, uses the reaction curve albite = jadeite + quartz as an upper bound for the pressure of formation of eclogite, but this approach does not seem appropriate because there is no evidence for the co-existence of omphacite and albite.)

7.2. A note on the composition of amphibole

S_0 was formed before eclogite facies metamorphism and in principle the compositions of minerals such as amphibole formed during this stage could be used to constrain the prograde P–T path. S_0-parallel amphiboles, however, do not seem to preserve chemical compositions established before eclogitic metamorphism. In R-type eclogite, some coarse-grained amphiboles show the same texture as omphacite, i.e. cross-cutting S_0, indicating post-D_0 growth. Chemical compositions of S_0-forming, fine-grained amphiboles, however, are the same as those of the post-D_0 amphiboles, both having barroisitic compositions (unpublished data). This suggests that although S_0 can be structurally recognized as an older foliation pre-dating the eclogite facies metamorphism, the petrological features of minerals formed during D_0 have been thoroughly overprinted by subsequent metamorphic events.

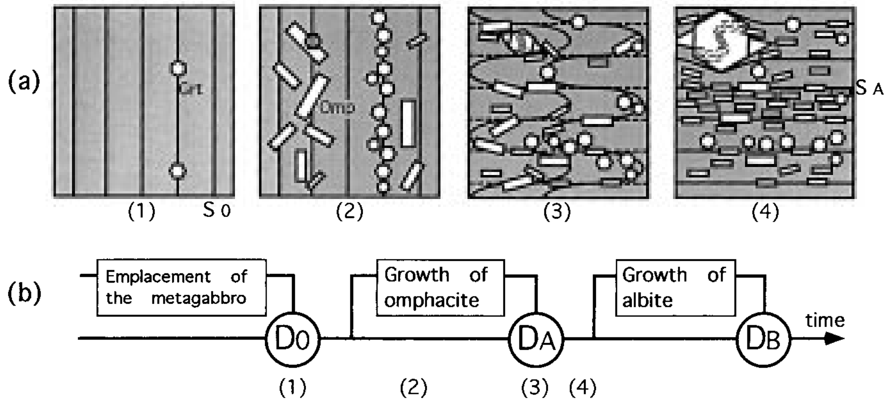

Fig. 13. Metamorphic history of eclogite in the Seba basic schist. (a) Progressive textural changes from R- to L-type eclogite; (1) D_0 phase (main matrix-forming minerals = amphibole, epidote); (2) non-deformational period coinciding approximately with attainment of peak metamorphic pressure; (3) during the D_A phase; (4) just after the D_A phase. The textural features of (2), (3), and (4) correspond to R-, I- and L-type eclogite, respectively. (b) Time sequence showing metamorphic history of eclogite in the Seba basic schist.

7.3. Metamorphic history of eclogites in the Seba basic schist

A single metamorphic history for all the eclogites in the Seba basic schist can now be proposed as follows (Fig. 13). (1) The Sebadani metagabbro mass was emplaced into the Seba basic schist which was undergoing prograde metamorphism with increasing pressure during subduction. (2) D_0 phase deformation occurred simultaneously with or later than emplacement of the Sebadani metagabbro and S_0 was formed both in the Sebadani mass and in the host basic schist. (3) Subsequent to D_0, the Seba basic schist and the Sebadani metagabbro were subjected to eclogite facies conditions as a single coherent unit. There may have been a significant period after D_0 when deformation did not take place. Growth of omphacite in the Seba basic schist began and randomly oriented omphacite cross-cutting S_0 was formed. (4) D_A deformation represents the onset of decompression and, therefore, exhumation. The main growth of omphacite during D_A is recognized. Eclogite in the Seba basic schist was affected by D_A phase deformation to varying degrees resulting in the formation of a variety of textural types. In the structurally lower part (Area 1), the effect of D_A was strong and omphacites correspondingly show a strong grain-shape preferred orientation forming the L-type eclogite. In contrast, in the area immediately adjacent to the Sebadani mass where the effect of D_A was weakest, randomly oriented omphacite cross-cutting S_0 is preserved. (5) The latest phase of ductile deformation recognized in the present study, D_B, took place after D_A and caused local disturbance of the D_A structures.

7.4. Eclogite-forming stage of the Sebadani metagabbro—comparison with other studies

Previous petrological studies have emphasized the presence of two stages of eclogite metamorphism in Sebadani metagabbro. In contrast, we consider that there is only evidence for one phase and that the associated metamorphic conditions are the same as those of the Seba basic schist. The most significant differences in interpretation of the available petrological data are summarized below.

Eclogitic garnet within the Sebadani metagabbro described in Takasu (1984) shows remarkable chemical zoning characterized by an abrupt compositional change from a high-Mg core to a low-Mg rim. Takasu (1984) interprets the zoning pattern as having formed by *re-equilibration* of high-Mg garnet by low-Mg garnet along cracks and rims accompanied by rapid cooling caused by exhumation of the Sebadani metagabbro. However, diffusional processes cannot by themselves form abrupt, kink-like chemical changes as observed in the garnet from the metagabbro. In addition, although not clearly recognizable by optical microscopy, backscattered electron images show the high-Mg garnet is cross-cut by a network of interconnecting bands consisting of low-Mg garnet (fig. 8 in Takasu, 1984). This observation suggests that cracks or some similar feature were filled by *growth* of low-Mg garnet.

If contact metamorphism at high pressure had occurred, the temperature of the Sebadani metagabbro should monotonously decrease throughout the whole of the subsequent metamorphic history (Aoya, 1998). It is then difficult to explain *growth* of the low-Mg rim of garnet. Instead it is proposed here that emplacement of the Sebadani metagabbro occurred during prograde metamorphism of the Seba basic schist (Fig. 13). According to Takasu (1984), the estimated temperature of the metagabbro eclogite using rim–rim pairs of garnet–omphacite is almost the same as that of the Seba basic schist eclogite. The growth of the low-Mg rim of garnet in the Sebadani metagabbro can then be accounted for by the prograde metamorphism after its emplacement into the Seba basic schist.

Takasu (1984) used both core–core and rim–rim pairs of garnet–omphacite for *P–T* estimates of eclogite in the Sebadani metagabbro, but at least one of those estimates will be erroneous because omphacite in the eclogite has no clear chemical zoning implying either a single-stage growth or later homogenization by diffusion. Our proposed history suggests that the temperature estimated using rim–rim pairs is reliable for the eclogite forming stage of the metagabbro. This further implies that the Sebadani metagabbro was already metamorphosed to form the Mg-rich core to the garnet prior to its emplacement into the Seba basic schist.

8. Conclusions

Detailed field study and textural analysis allow us to draw the following conclusions about the metamorphic history of widely distributed eclogite in the Seba basic schist.

1. The timing of growth of omphacite in all types of eclogite cannot be distinguished. In all samples, omphacite growth occurred post-D_0 to syn-D_A.
2. Differences in eclogite texture depend on how strongly D_A deformation affected the particular eclogitic rocks. In the Seba basic schist, the distribution of D_A recognized from observations of meso-structures is concordant with the distribution of the resulting eclogitic textures.
3. Emplacement of the Sebadani metagabbro mass as a metamorphic block into the Seba basic schist took place during subduction (syn- or pre-D_0 phase). Subsequent to emplacement, the Sebadani mass was metamorphosed under the same eclogite facies condition as the surrounding Seba basic schist.

These conclusions imply that there is no need to invoke high-pressure contact metamorphism to explain the development of eclogite facies metamorphism in the Sebadani area. The presence of various eclogites in the Seba basic schist (R, L and I type) can be accounted for by a single regional metamorphic episode. This, then, also indicates that the Sambagawa prograde metamorphism achieved regional eclogite facies conditions in the Sebadani area. Pressure–temperature estimates from this region can, therefore, be used as representative of the physical conditions within the former Sambagawa subduction zone.

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