Eclogite and Related Metamorphism in the Sanbagawa Belt, Southwest Japan

Simon WALLIS [1*], Akira TAKASU [2], Masaki ENAMI [3] and Tatsuki TSUJIMORI [4]

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Abstract The Cretaceous Sanbagawa metamorphic belt is an exhumed convergent margin that locally contains evidence for eclogite facies metamorphism. The non-eclogitic units are characterized by strong orogen-parallel ductile deformation and associated thinning. This deformation overprints the formation of at least two large-scale nappes. The *P-T* paths of the higher-grade metamorphic units have open clockwise geometries. There is still no satisfactory tectonic model that can account for these *P-T* paths. The eclogite units are generally interpreted as disparate tectonic blocks in a tectonic melange. However, some workers suggest that these eclogite facies rocks formed as an integral part of the Sanbagawa belt.

Key words: Sanbagawa belt, petrology, structure, geochronology, eclogite.

HIGH-PRESSURE METAMORPHIC BELTS OF JAPAN

The Sanbagwa① belt of Japan is one of the best-studied and most easily accessible regions of subduction metamorphism in the world. Despite some speculation to the contrary, there is no evidence for the collision of microcontinents or island arcs during its evolution. The geological history of the Sanbagawa belt is dominated by subduction of oceanic crust, and studies of its structure and thermal history are, therefore, potentially very useful in placing constraints on how oceanic convergent margins evolve in general. The purpose of this review is to show what is known about the belt and to present the state of current debate on a number of important issues. The main focus will be on the high-grade rocks including the abundant eclogite units.

This review is about the Sanbagawa belt. However, it should be pointed out that the Phanerozoic development of the Japanese Islands can be largely thought of in terms of crustal growth along an active margin by addition of accretionary complexes and associated igneous domains (e.g. Isozaki, 1996) (Fig. 1). The presence of paleo-convergent margins in Japan is shown by the development of belts of relatively high-pressure low-temperature metamorphism (see summary in Banno, 1986). Outside of the Sanbagawa belt, probably the most significant advance in our understanding of the high P belts of Japan has been the division of the Sangun belt into the Renge and Suo belts on the basis of radiometric dating (Nishimura, 1998). In addition the discovery of eclogite facies rocks in the Renge belt, both as blocks in serpentinite melange (Komatsu, 1990; Nakamizu et al., 1989; Tsujimori and Itaya, 1999) and associated with regional blueschist facies rocks (Tsujimori et al., 2000) may help solve the regional tectonic problem of correlating geological units between Japan and China. Nevertheless, the main focus of research into high-pressure metamorphic belts in Japan remains on the Sanbagawa belt.

SANBAGAWA BELT : GENERAL OVERVIEW

The Sanbagawa belt is an elongate belt of relatively high *P/T* metamorphism that stretches throughout SW Japan for a length of roughly 800 km (Fig. 1). To the north the Sanbagawa belt is bounded by the Ryoke belt, which is characterized by high *T/P* metamorphism. Together these form perhaps the best known example of paired metamorphic belts (e.g. Miyashiro, 1973). The boundary between the

[1] *Department of Geology and Mineralogy, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan.*
[2] *Department of Geology, Faculty of Science, Shimane University, Matsue 690-8504, Japan.*
[3] *Department of Earth and Planetary Sciences, Graduate School of Science, Nagoya University, Nagoya 464-8602, Japan.*
[4] *Research Institute of Natural Sciences, Okayama University of Science, Okayama 700-0005, Japan.*

**Corresponding author.*
E-mail address: swallis@ip.media.kyoto-u.ac.jp (S. Wallis)

Note① : Both the spellings 'Sanbagawa' and 'Sambagawa' are commonly used. The difference arises from alternative representations of the Japanese letter ん, which is usually pronounced like an English 'n' but in some cases like an English 'm'. 'Sambagawa' is, therefore, a better representation of the actual pronunciation, but 'Sanbagawa' is preferred by those who would rather maintain a single transcription for any particular Japanese letter.

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Ryoke and Sanbagawa belts is a major strike-slip fault, the Median Tectonic Line (MTL), which is associated with ancient left-lateral and recent right-lateral motion (Ichikawa, 1980).

In the Sanbagawa belt the highest temperatures of metamorphism are recorded in rocks adjacent to the MTL and grade decreases to the south (e.g. Higashino, 1990). Isograds strike roughly parallel to the trend of the belt and dip to the north, defining an overall inverted metamorphic sequence. To the south the Sanbagawa belt grades into low-temperature metamorphic rocks, which preserve original sedimentary and volcanic features (Hashimoto, 1989). The southern boundary of the Sanbagawa belt is in contact with either the Paleozoic Chichibu belt or locally the Cretaceous Shimanto belt (Fig. 1). To the east, the Sanbagawa belt can be traced to the Kanto Mountains (e.g. Seki, 1958). The westward extension of the Sanbagawa belt is less clear, but may include the Nagasaki schists (Fig. 1) (Faure et al., 1988; Nishimura, 1998). The most accessible and well-developed outcrops of high-*P* metamorphic rocks occur in central Shikoku.

The main rock types of the Sanbagawa belt are mafic schist and meta siliciclastic rocks, which can be further divided into common graphitic metapelite, metapsammite and rare meta-conglomerate. The mafic schist and meta siliciclastic rocks are associated with lesser amounts of manganiferous quartz schist[②] derived from chert. Marble is relatively uncommon throughout the Sanbagawa belt.

The mafic schist locally shows gradations with the metapelite and meta chert suggesting it originated as sediments (Kawachi et al., 1982). Geochemistry of the mafic schists suggests an affinity with tholeitic ocean floor basalt (e.g. Hashimoto, 1989; Okamoto et al., 2000; Sano, 1999). The mafic schist and meta chert constitute a significant input of oceanic material in the Sanbagawa belt.

In constrast, the meta siliciclastic rocks suggest a continental source area. This is particularly clear in a large unit consisting of relatively low-grade meta pelite, metapsammite and locally meta conglomerate referred to as the Oboke unit (Fig. 2) (Kenzan-Research-Group, 1984). The Oboke conglomerate contains clasts of granitic material and the associated psammitic schists contain abundant zircon grains (Shinjoe and Tagami, 1994). Detrital zircon is also found in the high-grade units, but is overall quite rare. Detrital K-feldspar is also locally present throughout the Sanbagawa belt (Enami, 1994). However,the meta siliciclastic rocks mainly consist of graphitic schist, which originated as black shale. Cretaceous black shale are widespread in the world and probably formed in a variety of environments (e.g. Wignall, 1994). It is, therefore, difficult to use these rocks to draw clear conclusions about the sedimentary environment.

The mixing of oceanic mafic rocks and chert with continental materials is characteristic of active convergent margins and lends strong support to the interpretation of the Sanbagawa belt as a metamorphosed accretionary complex.

In addition to the above rock types, in the high-grade zone there are significant bodies of meta-gabbro and ultramafic rock with complex polymetamorphic histories (e.g. Kunugiza et al., 1986; Takasu, 1989) (Fig. 2). Distinct metagabbro and ultramafic rocks are also found in the low-grade southern part of the Sanbagawa belt within a prominent mafic igneous unit, the Mikabu belt. Athough this is categorized as a distinct geological unit by many workers, the Mikabu belt has undergone the Sanbagawa metamorphism and should be considered as a sub-unit of the Sanbagawa belt (e.g. Suzuki and Ishizuka, 1998) (Fig. 2).

In the following we shall concentrate on the higher grade parts of the Sanbagawa belt looking at regions affected by both the eclogitic and non-eclogitic metamorphism.

NON-ECLOGITIC METAMORPHISM

Metamorphic Zonation

The estimated *P-T* conditions for formation of rocks in the Sanbagawa metamorphic belt covers a wide range of metamorphic facies including the prehnite-actinolite, blueschist, greenschist, epidote-amphibolite, and eclogite facies. Granulite facies rocks are also locally found, but these are considered by most workers to be relics from an event unrelated to the Sanbagawa subduction (e.g. Yokoyama, 1980).

The most widely used division of the Sanbagawa metamorphism, excluding eclogite facies rocks, is based on the appearance of characteristic Fe-Mg silicate minerals in metapelite (e.g. Banno and Sakai, 1989; Higashino, 1990). In order of increasing metamorphic grade these zones are: the chlorite, garnet, and biotite zones. The biotite zone is further divided into the albite biotite and oligoclase biotite zones (Enami, 1982) (Fig. 2). Bulk rock analyses show that there is little significant variation in the composition of the pelitic schists (with the possible exception of the oligoclase biotite zone in Besshi area) (Goto et al., 1996) and these mineral isograds can, therefore, be considered to closely approximate to surfaces of equal metamorphic grade. The most reliable indicator of metamorphic temperature is the Fe-Mg partitioning between chlorite and garnet (Banno and Sakai,

Note ②: There was once a flourishing copper mining industry in Shikoku. In general, the mineralization is concentrated along the boundary between quartz and mafic schists.

1989), but this is not used for regional mapping. Metamorphic zones can also be defined using the amphibole species in hematite-bearing mafic schist (Otsuki and Banno, 1990). With increasing grade the amphibole species shows the follow progressive changes: actinolite → winchite → crossite → barroisite → hornblend. Using the above two schemes for pelitic and mafic schists it has been possible to map the thermal structure of the higher-grade regions of the Sanbagawa belt (Banno et al., 1978; Higashino, 1990). These studies have shown that the metamorphic temperature is, in

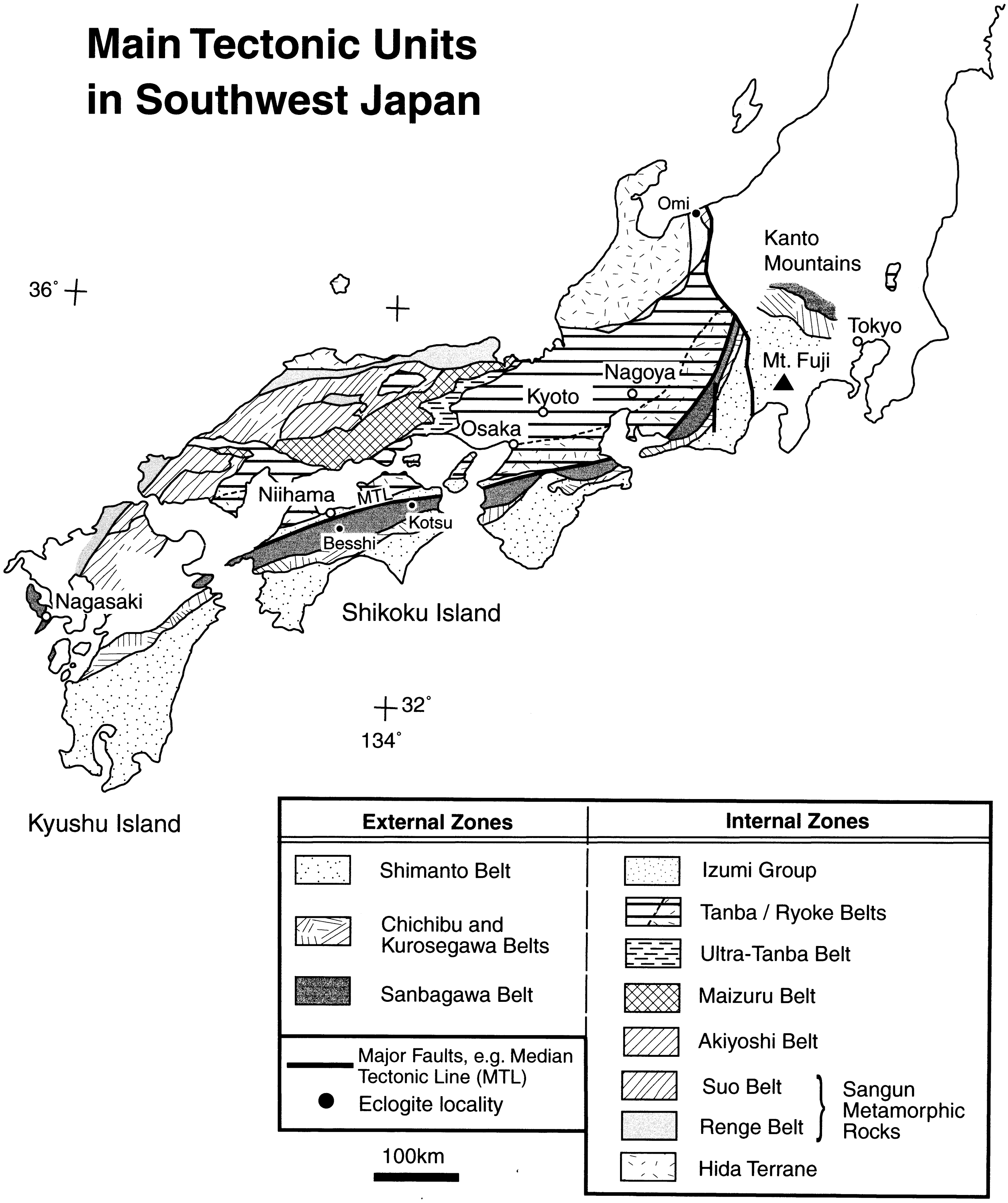

Fig. 1. Main tectonic units of southwest Japan (after Isozaki, 1990; Nishimura, 1998; Tujimori and Itaya, 1999). The eclogite-bearing Renge and Sanbagawa belts are shown in grey tones. In the Sanbagwa belt eclogite has been found in the Besshi and Kotsu regions.

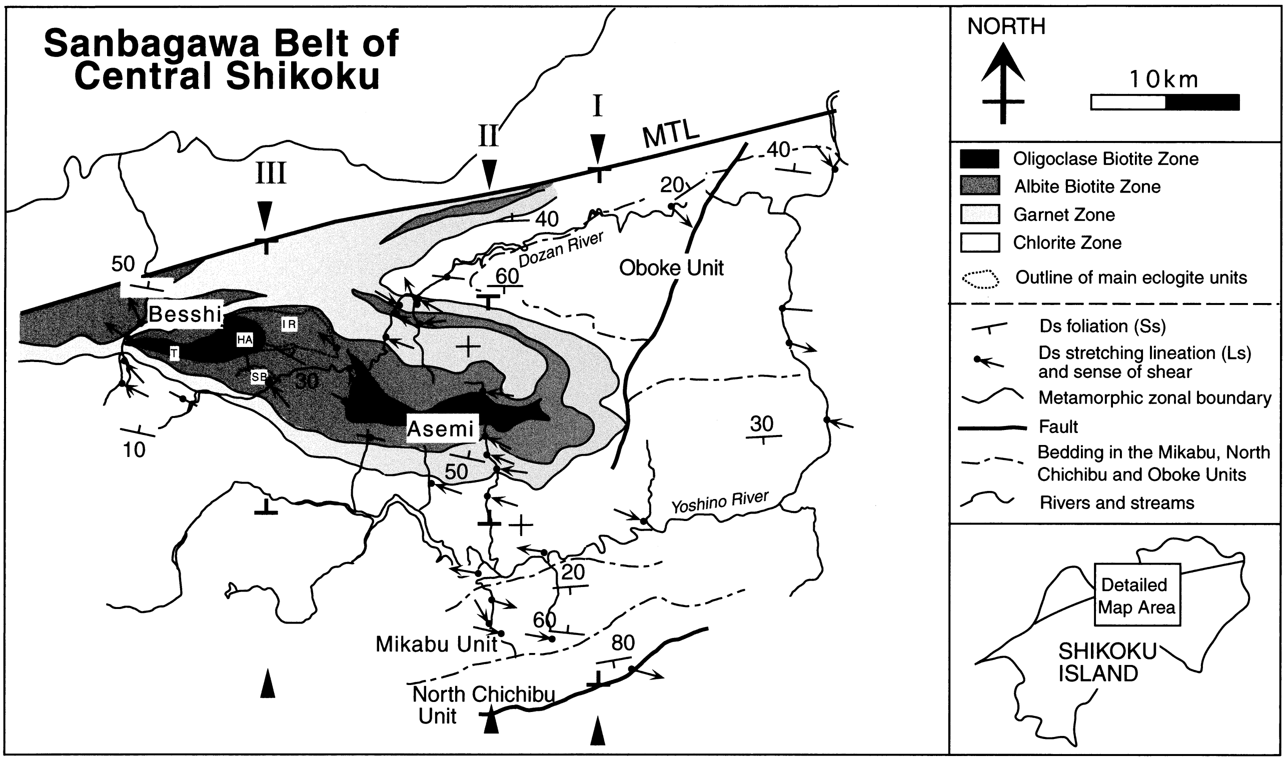

Fig. 2. Summary of the main features of the Sanbagawa belt in central Shikoku.
The sense of shear refers to the displacement direction of the structurally higher rocks with respect to the lower. Abbreviations for the eclogitic units are as follows: IR = Western and Eastern Iratsu masses, HA = Higashiakaishi mass, T = Tonaru mass, SB = Seba metagabbro mass and Seba mafic schist unit.

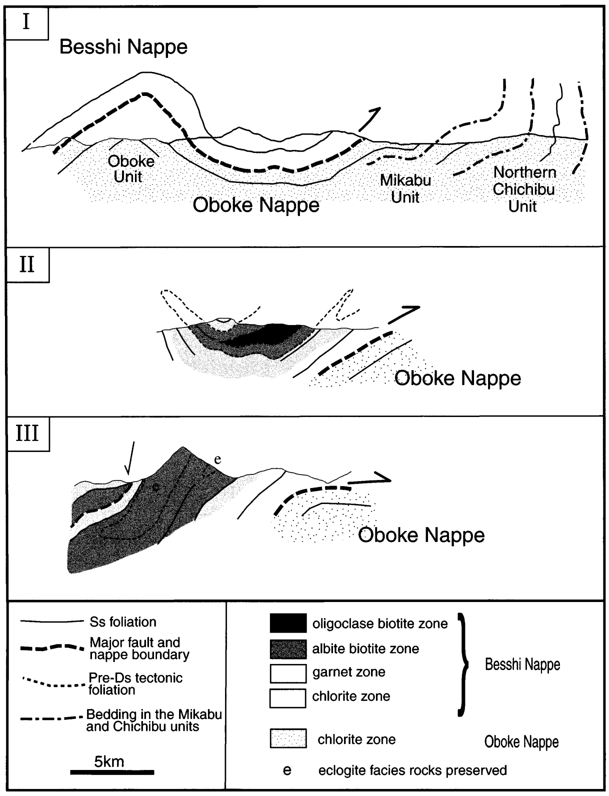

Fig. 3. Cross-sections of central Shikoku (after Wallis, 1998).
The locations of the sections are shown in Fig. 2.

general, highest close to the Median Tectonic Line, i.e. at the highest structural levels. There are, however, two exceptions. Firstly, in central Shikoku there is a complex thermal structure with the peak temperatures recorded at intermediate structural levels (Banno et al., 1978) (Figs. 2, 3). This structure reflects deformation that post-dates the peak of metamorphism. Establishing the nature of this deformation has been one of the goals of a number of structural studies in the region (e.g. Hara et al., 1990; Wallis et al., 1992). Secondly, in the Kanto Mountains the highest grade units are found at the structurally lowest levels (e.g. Yano and Tagiri, 1998).

The definition of the above metamorphic zones was a major advance in unravelling the thermal structure of the Sanbagawa belt. However, nearly all of the Sanbagawa metamorphic belt in fact lies within the chlorite zone, and the details of the metamorphic zonation in this region are, in general, unclear. One exception is central Shikoku where sliding equilibria in the pumpellyite-actinolite facies have been used to distinguish three subzones (Banno, 1998; Nakajima, 1982; Nakajima et al., 1977). A second shortcoming of the above scheme is that it cannot be applied to regions of eclogite metamorphism.

P-T Estimates

The estimates for the peak *P-T* conditions in the non-eclogitic Sanbagawa belt and the methods used are summarized in a number of papers (e.g. Banno and Sakai 1989; Enami et al., 1994) (Fig. 4). Pressure has been the most uncertain parameter, however, the discovery of very rare but widespread sodic pyroxene in equilibrium with albite and quartz has allowed good quantitative estimates of this parameter in a limited number of samples throughout central Shikoku (Enami et al., 1994).

		Estimates of Peak Metamorphic Conditions	
Metamorphic Zone		Temperature (˚C)	Pressure (kbar)
Oligoclase biotite zone		585 - 635 (gt - bi)	9 - 11 (modelling of zo+qtz +plag+gt assemblage)
Albite biotite zone	Saruta	505 - 575 (gt - chl) 480 - 560 (gt - bi) 540 - 570 (cc - dol)	10.5 - 11.0 (Na-px - qtz -ab)
	Asemi & Besshi	495 - 545 (gt - chl) 470 - 590 (gt - bi) 500 - 550 (cc - dol)	8.0 - 9.5 (Na-px - qtz -ab)
Garnet zone	Saruta	465 - 495 (gt - chl)	9.0 - 10.0 (Na-px - qtz -ab)
	Asemi & Besshi	425 - 455 (gt - chl) ~470 (gt - ardennite) ~460 (stable isotopes)	7.0 - 8.5 (Na-px - qtz -ab)
Chlorite zone		300 - 360 (see Enami et al, 1994)	5.5 - 6.5 (Na-px - qtz -ab)

Fig. 4. Peak *P-T* estimates for the different non-eclogitic metamorphic zones in central Shikoku (details given in Enami, 1994). Estimates are divided into two distinct regions, the Saruta area and the Asemi-Besshi area. Structural studies suggest the Saruta area was originally located to the north of the other areas (Enami, 1994).

P-T Paths

P-T paths give valuable information for constraining tectonic models of metamorphic belts. In the Sanbagawa belt, it has been suggested in a number of independent studies that from the oligoclase biotite zone to the garnet zone the prograde *P-T* path is shallower for higher grade, i.e. with a lower *P*/*T* gradient (Fig. 5). This conclusion is based on the following types of studies:

(1) modelling of Fe-Mg-Mn zonation in garnet (Banno et al. 1986);

(2) amphibole species within plagioclase porphyroblasts (Nakamura and Enami, 1994); and

(3) zoning of sodic pyroxene that grew in equilibrium with quartz and albite and garnet (Enami et al., 1994).

Several independent studies also indicate that the peak of temperature occurred after the peak of pressure in the higher-grade zones, resulting in open clockwise *P-T* paths (Fig. 5). The main studies suggesting this feature of the *P-T* paths are:

(1) modelling of garnet zonation including Ca in metapelitic samples (Enami, 1999);

(2) changes in amphibole composition in hematite-bearing mafic schist (Hosotani and Banno, 1986; Otsuki and Banno, 1990); and

(3) zoning of sodic pyroxene that grew in equilibrium with

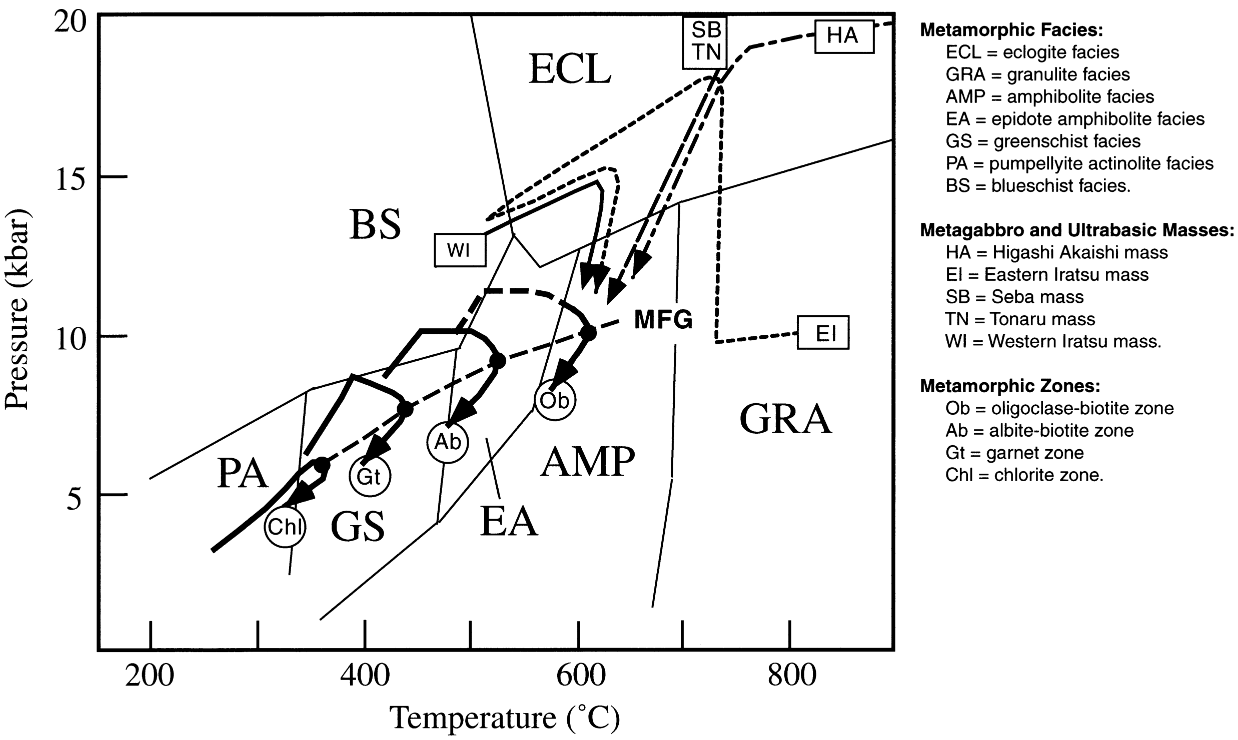

Fig. 5. *P-T* paths for the non-eclogitic units and eclogitic ‘ tectonic blocks ’(compilation based on Banno and Sakai (1989); Enami, (1994) and Takasu (1989). MFG = metamorphic field gradient of the non-eclogitic units.

quartz, albite and garnet (Enami et al., 1994).

In addition, detailed petrological studies using the amphibole species in hematite-bearing mafic schists and the jadeite content of Na-pyroxene in equilibrium with quartz and albite suggest that higher metamorphic pressures are recorded for the same temperature in the north of the Sanbagawa belt compared to the south (Enami et al., 1994; Nakamura and Enami, 1994). This suggests there was an original northward dip of the geotherms in the area, i.e. supporting the former presence of a northward dipping subduction zone.

Consensus View

The consensus view is, therefore:

(1) the prograde *P-T* paths in the non-eclogitic Sanbagawa belt are steeper (i.e. higher *P*/*T* ratio) at lower grades of metamorphism; and

(2) the P-T paths for the higher-grade zones have an open clockwise shape, i.e. the peak of temperature occurs after the peak of pressure.

There is good petrological evidence in support of these conclusions, however, locally textural evidence for non-equilibrium crystallization of some key minerals such as garnet and pyroxene is observed. In addition, an alternative to the consensus view has recently been proposed: an anticlockwise path with heating at low pressure, isothermal burial, and finally cooling and exhumation (Okamoto and Toriumi, 1999). This *P-T* path is based on modelling of amphibole using the Gibb's method.

STRUCTURE OF THE SANBAGAWA BELT

Main Charactersitics

Deformation in the Sanbagawa belt is characterized by high-strain ductile flow associated with the formation of an orogen-parallel stretching lineation and a penetrative foliation (Faure, 1985; Hara et al., 1992; Toriumi, 1982; Wallis, 1995; Wallis et al., 1992). This phase of orogen-parallel ductile flow is commonly referred to as Ds (or D_1). The Ds foliation, Ss, generally has a gentle northward dip, but is steeper close to the MTL and in the south of the Sanbagawa belt. Ss is folded by a series of large-scale upright folds referred to as Du (or D_3) (Figs. 2, 3). The major Du folds are arranged in an en-echelon fashion suggesting they formed associated with left-lateral motion (Hara et al., 1992, p.585). An independent phase of folding, Dt, can be defined on geometric grounds, however, this phase is only locally well developed and its significance is still unclear (e.g. Wallis, 1990).

Pre-Ds deformation is locally well developed especially in the high-grade zones. With the exception of deformation in the eclogite zones (see below), pre-Ds deformation is probably related to prograde subduction processes (Wallis, 1998). Several phases of such deformation can be defined using microstructures, however, most of these are only recognizable as inclusion trails in porphyroblasts and they have only limited value in tectonic studies. Bedding can be locally used to define early thrust and duplex structures (Okamoto et al., 2000). The presence of these early structures as well as the complexity of the later deformation implies that

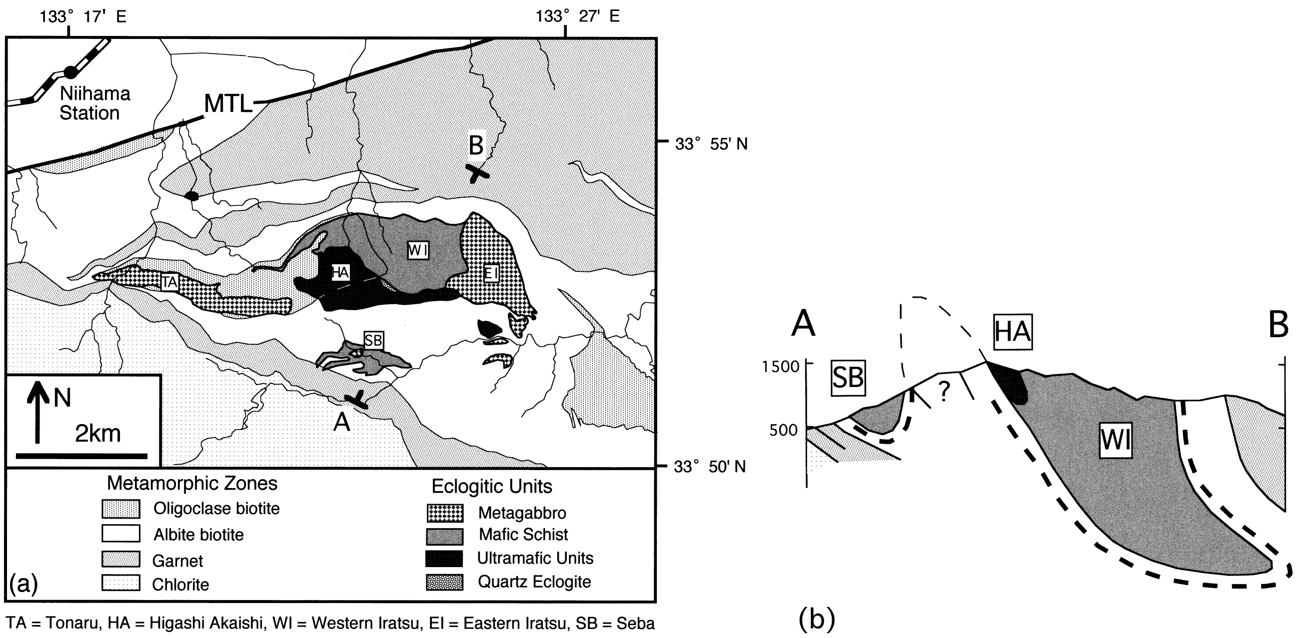

Fig. 6. Distribution of eclogitic units in the Besshi area and cross-section (after Wallis and Aoya, 2000). Eclogite facies mineral assemblages have not been verified in some of the smaller gabbro units. The thick dashed line represents the approximate location of a major tectonic boundary separating eclogitic rocks from non-eclogitic rocks.

no stratigraphic significance can be given to the present day structural sequence.

Large-Scale Structure

One of the main points of debate about the large-scale structure of the Sanbagawa belt is the extent to which it should be divided into discrete nappes. The first impression is of a continuous penetrative Ds fabric with no obvious post-metamorphic breaks and several studies treat the belt as a mechanical continuum. However, sudden changes in metamorphic and deformational history suggest that in central Shikoku two major nappes, known as the Besshi and Oboke nappes can be distinguished, with the high-grade Besshi nappe overlying the low-grade Oboke nappe (Takasu and Dallmeyer, 1990; Wallis, 1998) (Fig. 3). This division is now generally accepted and the distinction between the Oboke and Besshi nappes is supported by radiometric dating (Itaya and Takasugi, 1988; Takasu and Dallmeyer, 1990). However, it has proven very difficult to locate the boundary between the two units in the field.

In addition to the above nappe boundary, the Seba schistose eclogite unit has a major tectonic contact at its base, and this may form part of a third' eclogite nappe 'at the highest levels of the Sanbagawa belt (Wallis and Aoya, 2000) (Fig. 6). The nappes all formed before or during Ds and the boundaries are, therefore, overprinted by high-strain ductile deformation. Hara et al. (1990) suggest that both the Besshi and Oboke nappes can be subdivided into numerous sub-units each with a distinct metamorphic and deformational history.

In general, the highest-grade rocks are found at high structural levels in the Sanbagwa belt. However, metamorphic zonal mapping in central Shikoku has shown that the highest-grade rocks are located at intermediate levels, within the Besshi nappe described above. This distribution of metamorphic zones implies that the original metamorphic sequence has been strongly affected by post metamorphic deformation. Both thrusting and large-scale folding have been proposed to explain this distribution (Banno et al., 1978; Faure, 1985; Hara et al., 1990; Wallis et al., 1992). However, the largely continuous change in metamorphic grade both up and down section; the similar metamorphic ages and distribution of minor folds all favour the interpretation of this structure as a large fold (Wallis et al., 1992). Careful field studies (Hide 1956; Wallis and Aoya, 2000) and data from boreholes (Hara et al., 1992) show that such kilometer-scale folds are relatively common in the high-grade zones of central Shikoku. Microstructural relationships show that this folding took place during Ds (e.g. Aoya and Wallis, 1999).

Deformation Kinematics

Ductile deformation in the Sanbagawa belt is dominated by orogen-parallel movements (Faure, 1985; Toriumi, 1982; Wallis, 1995) (Fig. 2). The main exceptions are in the eclogite units, where there is a wide spread of lineation data and the main fabric-forming deformation is pre-Ds (Aoya and Wallis, 1999) and in the Nagasaki metamorphic belt, where the lineation data are orogen-normal (Faure et al., 1988). The dominant orogen-parallel flow can probably be related to a single phase of regional deformation, Ds. The dominant sense of shear associated with Ds is top to the west (Wallis, 1995; Wallis et al., 1992). Earlier suggestions of a uniform top to the east sense of shear have been found to be erroneous.

Estimates of the finite strain and rotational component of deformation along with the overall geometry can be used to show that Ds deformation caused a significant amount of ductile thinning of the Sanbagawa belt (Wallis, 1995). This conclusion is compatible with microstructural studies that suggest Ds took place during decompression or exhumation of the Sanbagawa belt (Hara et al., 1992; Takasu et al., 1994; Wallis et al., 1992). In the higher-grade zones Ds deformation began before peak temperature was reached (Wallis, 1998).

Because, Ds is associated with exhumation and not subduction it is not straightforward to relate the lineation orientation with plate direction. However, the dominantly orogen-parallel flow strongly suggests that the associated plate movement was oblique to the former plate margin. The sense of shear suggests a sinistral sense of oblique subduction and this is compatible with the predicted movement direction of the Izanagi plate during the mid to late Cretaceous (Engebretson et al., 1985).

AGE CONSTRAINTS

The Sanbagawa belt is overlain unconformably by the Eocene Kuma Group (Nagai, 1972). The maximum sedimentary age of the Kuma Group is 50 Ma (Narita et al., 1999) and this gives a clear lower limit on the age of metamorphism and ductile deformation in the Sanbagawa belt. A few rare fossil findings suggest a middle Triassic to late Jurassic age for some of the sedimentary units (see summary in Isozaki and Itaya, 1990).

The age of at least part of the thermal history of the Sanbagawa schists is well constrained by phengite K-Ar and Ar-Ar radiometric ages. The two methods are in good agreement and give 75−90 Ma for the Besshi nappe and 65−75 Ma for the Oboke nappe (Itaya and Takasugi, 1988; Takasu and Dallmeyer, 1990). Ar-Ar dating of amphibole gives ages of 80−95 Ma for the high-grade zones (Takasu and Dallmeyer, 1990). The closure temperature of white mica in the Oboke nappe is probably close to the maximum temperature achieved. The whole rock ages of 65－75 Ma may, therefore represent the peak age of metamorphism in this unit. The peak age in the Besshi nappe is, however, still unclear.

In addition to the above results, fission-track ages have been measured in the Oboke region and in the high-grade part of the Bessshi nappe. In both areas the estimated ages are around 65 Ma (Shinjoe and Tagami, 1994; Moriyama, pers. comm) suggesting that the two nappes were amalgamated before this time.

Ar-Ar radiometric dating of amphibole from metamorphic clasts in the Kuma Group sediments gives ages of 130 Ma and 160 Ma. The clasts are very similar to the mafic schist in the high-grade part of the Sanbagawa belt. However, the ages are much older than any other recorded in the Sanbagawa belt and have been used to suggest the former existence of a Kuma nappe (Takasu and Dallmeyer, 1992). K-Ar dating of similar high-grade clasts by Yokoyama and Itaya (1990) gives phengite ages of 84.0 ± 1.8Ma, 98.7 ± 2.1 and a hornblende age of 118.7 ± 3.7 Ma. K-Ar dating of phengite in the Kanto Mountains suggests that the overall rage of cooling ages is the same as central Shikoku, but that the highest-grade units have the youngest age: the inverse to central Shikoku (Hirajima et al., 1992).

ECLOGITIC METAMORPHISM AND HIGASHI AKAISHI ULTRAMAFIC UNIT

Eclogite Types

Eclogite facies metamorphism of the Sanbagawa belt has only been recognized in central and east Shikoku. Two areas can be defined, the first around Besshi③ (Figs. 1, 2, 6) and the second around Mt. Kotsu④ (Fig. 1). Several distinct types of eclogitic rocks with different protoliths can be defined and these are described below. In the following sections we shall use a broad definition of eclogite that includes all rocks of mafic composition in which omphacite and garnet grew in equilibrium.

I. Besshi Metagabbro bodies (Tonaru, Eastern Iratsu and Seba⑤ Masses)

A number of Meta-gabbro bodies of 100 m to several km in size are distributed throughout the Besshi region (Figs. 2, 6). These are usually described as tectonic blocks and thought to have disparate metamorphic histories (Takasu, 1989). There are however, strong similarities in the protoliths and in the present contribution we discuss these units together.

The dominant mineral assemblage (amphibole, albite, phengite, paragonite, epidote, garnet, quartz) reflects metamorphism in the epidote amphibolite facies. However, earlier eclogite facies mineral parageneses have been recognized in the Tonaru, Eastern Iratsu, and Seba masses (Banno et al., 1976; Kohsaka and Toriumi, 1984; Takasu, 1984; Takasu, 1989; Takasu and Kohsaka, 1987). Kyanite also occurs locally in the Tonaru and Eastern Iratsu masses (Banno et al., 1976; Kunugiza et al., 1986; Takasu, 1989).

The presence of metamorphosed graded bedding and thick layers of kyanite-bearing zoisite rock (up to several meters) with a bulk composition of anorthosite (Banno et al. 1976), as well as the coarse grain size and bulk composition of these units suggests they originated as gabbro. Locally strong centimeter- to 10 centimeter-scale colour banding is observed. This banding is probably an original igneous layering consisting of pyroxene-rich and feldspar-rich domains. The pyroxene and feldspar have now been replaced by the metamorphic minerals amphibole and zoisite, respectively. Both the Eastern Iratsu and Tonaru masses contain lenses of ultramafic rock (e.g. Yokoyama, 1980). The tectonic setting for the original formation of the gabbro is unclear.

A foliation is only locally strongly developed in the matagabbro bodies and well-preserved areas of eclogite-facies metamorphism tend to be massive. Grain size can be large, with garnets up to 5 cm relatively common in the Eastern Iratsu mass. Abundant evidence for eclogite facies metamorphism is found in the Iratsu and Seba masses, but is very rare in the Tonaru mass (Kohsaka and Toriumi, 1984; Takasu et al., 1999). The dominant mineral assemblages in all these units formed during the final phase of metamorphism in the epidote amphibolite facies. The polymetamorphic history of these units has resulted in complex metamorphic textures; garnet in particular commonly shows chemical zoning patterns suggesting more than one stage of growth. Some workers use such zoning patterns and textural evidence to suggest there is evidence for two separate stages of eclogite metamorphism one at high T and one at lower T in both the Seba and Eastern Iratsu metagabbro masses (Takasu, 1984; Takasu and Kohsaka, 1987; Toriumi and Kohsaka, 1995). This is disputed, however, in the Seba mass (Aoya in press; Aoya and Wallis, 1999) because although garnet is zoned, omphacite is homogenous and cannot be in equilibrium with garnet of two different compositions.

Many of the details of the petrology of the metagabbro

Note ③ : Besshi is also written as Bessi and Kotsu as Kotu. The two different spellings arise from two different ways of representing the Japanese characters し and つ in Roman letters. The character し is pronounced in a similar fashion to the English word‘ she ’and the character つ as in the tsu of tsunami.

Note ④ : Photographs of the Sanbagawa eclogites are presented in an accompanying publication 'Illustrated Introduction to the Eclogite of Japan'.

Note ⑤ : Also known as the Sebadani Mass.

units are still unclear. The prevailing opinion is, however, that the principal metagabbro bodies show *P-T* paths that are distinct from each other and from those of the schistose eclogite units discussed below (Kunugiza et al., 1986; Takasu, 1989; Toriumi and Kohsaka, 1995) (Fig. 5). These *P-T* paths finally converge in the epidote amphibolite facies, which represents the metamorphism of the surrounding ‘normal’ non-eclogitic Sanbagawa schists. The main stages of metamorphism that have been distinguished for the different metagabbro masses can be given in terms of the associated metamorphic facies as follows.

(1) Tonaru Mass: epidote amphibolite → eclogite → epidote amphibolite.
(2) Eastern Iratsu Mass: granulite → high-temperature eclogite → blueschist → lower temperature eclogite → epidote amphibolite.
(3) Seba Mass: high temperature eclogite → low-temperature eclogite.

II. Garnet-Pyroxenite and Highashi Akaishi Peridotite

The Higashi Akaishi peridotite (Fig. 5) consists mainly of dunite with local thin (centimeter to 10 centimeter scale) garnet-clinopyroxene layers (Horikoshi, 1937; Mori and Banno, 1973; Yoshino, 1964). These garnet-clinopyroxene layers are not eclogite in the strict sense, but they are thought to have suffered metamorphism in the eclogite facies (Kunugiza et al., 1986). The dunite also locally contains chromite layers that were once mined commercially. The margins of the dunite have a well-developed cleavage lined with serpentinite, and the olivine lacks a crystallographic preferred orientation. In contrast, the core of the dunite unit lacks a cleavage but shows a strong crystallographic preferred orientation (Yoshino, 1964), reflecting deformation at high temperatures. The garnet clinopyroxenite layers are boudinaged and show strong deformation associated with grain-size reduction.

The Higashi Akaishi unit is generally interpreted to represent a cumulate that formed in the garnet lherzolite facies at pressures of 19−28 kbar (Kunugiza et al., 1986; Mori and Banno, 1973). Kunugiza et al. (1986) suggest that this unit subsequently suffered metamorphism in the eclogite and then epidote amphibolite facies. Enami (1996) estimates the peak metamorphic conditions to be T = 600−680°C and P = 18−25 kbar.

III. Quartz eclogite

A distinct eclogitic lithology occurs as a small (< 100 m) unit along the eastern margin of the Higashi Akaishi Ultramafic body (Enami, 1996; Takasu, 1989) (Fig. 2, 6). This is a quartz-rich lithology locally with mafic clots and layers. This unit has a distinct protolith from the other eclogite bodies. The mafic domains may represent original sedimentary features, and bulk-rock analyses (Table 1) are compatible with an origin as a wacke. Because of its high modal quartz content this lithology is commonly referred to as quartz eclogite. The eclogitic paragenesis is garnet, omphacite, quartz, rutile, kyanite, epidote, phengite (Enami, 1996). Paragonite also occurs as inclusions in garnet and replacing kyanite. Other minerals include zircon and amphibole. The amphibole probably developed after the eclogitic metamorphism. Enami (1996) estimates the peak *P-T* conditions to be around T = 700−750°C and P = 19−24 kbar using thermodynamic modelling of the assemblage garnet-omphacite-kyanite-epidote-phengite-quartz. This agrees broadly with the above estimates for the Higashi Akaishi peridotite with which it is associated. The quartz eclogite has a weak tectonic foliation.

Table 1. Quartz eclogite bulk-rock chemical analyses.

	GO1701c	GE1502	GO1701a	QE9601-2	ME75043008
SiO_2	56.13	57.07	63.32	66.15	68.01
TiO_2	0.62	1.06	0.51	0.52	0.47
Al_2O_3	14.13	13.7	13.36	13.14	13.97
Fe_2O_3*	10.18	11.93	8.71	8.48	6.91
MnO	0.16	0.18	0.14	0.13	0.1
MgO	6.89	6.16	4.73	4.3	2.24
CaO	7.27	6.33	5.3	4.53	4.42
Na_2O	2.17	2.29	1.89	1.89	2.35
K_2O	0.89	0.7	1.25	1.16	1.01
P_2O_5	0.07	0.14	0.08	0.09	0.09
Total	98.51	99.56	99.29	100.39	99.57

* Total Fe as Fe_2O_3

IV. Schistose mafic eclogite (Seba, Kotsu, Western Iratsu)

In addition to the above weakly-foliated metagabbro and quartz eclogite bodies, strongly-foliated eclogite occurs in several kilometer-sized units consisting dominantly of mafic schist. These are the Western Iratsu, Seba (Fig. 5) and Kotsu units (Aoya and Wallis, 1999; Naohara and Aoya, 1997; Takasu, 1984; Takasu, 1989; Takasu and Kaji, 1984; Wallis and Aoya, 2000). A smaller unit of schistose eclogite has also been reported from an outcrop to the north of the Eastern Iratsu mass in the Gazo area (Sakurai and Takasu, 1999). In addition to mafic schist, these units also contain significant amounts of pelitic and quartz schist both of which grade into the more mafic rock types. Locally marble is also found in the Western Iratsu unit (Banno et al., 1976; Kunugiza et al., 1986). These observations suggest that in contrast to the metagabbro units, eclogite in the mafic schist units is of sedimentary origin and formed close to the earth's surface. This is supported by the presence of detrital garnet in the mafic schist (Wallis and Aoya, 2000).

The schistose eclogite outcrops show a variety of different textures. For instance, omphacite may be coarse and randomly oriented cross-cutting the foliation or it may be fine grained with a strong grain-shape preferred orientation. The interpretation of these differences in textures has been the focus for debate on the origin of eclogite in the Seba region (see section below). Detailed microstructural studies have only been carried out in the Seba unit. In this area Aoya and Wallis (1999) suggest that the strongly aligned omphacite fabrics developed during exhumation.

Garnet-omphacite geothermometry in all the schistose eclogite units suggests similar peak temperatures of around 600−650°C (Aoya, in press; Takasu, 1984; Wallis and Aoya, 2000; Sakurai and Takasu, 1999). Metamorphic pressure is less easy to estimate, but minimum values can be obtained from the jadeite content of omphacite in equilibrium with quartz. In the Seba and Kotsu regions this is a maximum of 38 % suggesting a minimum pressure of 12−13 kbar. In the Gazo outcrop and the Western Iratsu unit the jadeite content reaches a maximum of 45−50 % giving somewhat higher minimum pressures. An upper limit for the pressure of around 24 kbar is given by the estimates of peak temperatures and the presence of paragonite in both the Kotsu and Seba units.

The various schistose eclogite units are petrologically very similar. However, the amphibole associated with eclogite in the Kotsu region is glaucophane (Hosotani and Banno, 1986; Iwasaki, 1963; Wallis and Aoya, 2000) and clearly distinct from the Seba and Western Iratsu eclogite units in the Besshi region where the associated amphibole species is barroisite (e.g. Aoya, in press; Takasu, 1984). Preliminary data suggest there is no significant difference in bulk composition between the two areas and the difference may reflect a cooler retrograde path in the Kotsu region.

In the Seba unit, Aoya (in press) uses a combination of microstructural and petrological methods to place constraints on the *P*-*T* path. The results of this work suggest significant cooling after eclogite metamorphism and a second temperature peak associated with the epidote amphibolite facies metamorphism. This type of *P*-*T* path with a double thermal peak has also been suggested for the quartz eclogite unit (Enami, pers. comm) and can explain why the thermal structure of the surrounding schists cross cuts the distribution of eclogite units (Figs. 2, 6)

Large-Scale Structure of Eclogite Units - Tectonic Mélange or Nappe?

The most significant point of dispute in the interpretation of the eclogite units is the extent to which they must be treated as tectonic blocks with disparate and incompatible histories. These units formed from a number of different protoliths and in some sense the Higashi Akaishi peridotite and metagabbro units must be exotic blocks in a matrix of schist derived from sediment. However, the schistose eclogite units were derived from sediments indistinguishable to the lower-grade ‘normal’ Sanbagawa schists. It is, however, unclear when the various units took on a common history. Two extreme opinions have been expressed in the literature. Takasu (e.g. 1989) emphasizes the differences between the eclogite units and describes them as tectonic blocks in a schist matrix forming a tectonic mélange. Takasu (1989) suggests that this mélange formed when the Besshi nappe was close to maximum burial and became accreted to the hangingwall of the former subduction zone. Takasu (1989) proposes that the blocks were entrained in low-density serpentinite diapirs and that the rise of these units caused the emplacement of the blocks in the surrounding lower-grade schists.

In contrast, (Wallis and Aoya, 2000) suggest that the available petrological and structural data allow most, if not all of the eclogite units to have a common history after attaining the eclogite facies. These workers propose the existence of an eclogite nappe linking the eclogite units into a single once continuous sheet (Fig. 6). An important area for studying this problem is the contact between the eclogitic units and the surrounding schist. Aoya (in press) and Wallis and Aoya, (2000) use structural, petrological and lithological arguments to suggest that the base of the Seba schistose eclogite is a major tectonic boundary developed during exhumation of the eclogite. This contact is decorated with lenses of serpentinite and other related rocks, which may help trace the contact into other areas. The resolution of this dispute will require more field-based structural studies and petrological work including textural studies.

Origin of the Seba Eclogite Unit

The schistose eclogite of the Seba region immediately adjacent to the Seba metagabbro body deserves particular mention both because eclogite in this area has been extensively studied and because it has been the focus for contrasting opinions about its formation history. The eclogite consists of coarse crystals of omphacite (up to 1cm) randomly oriented and cross-cutting the foliation. Takasu (1984) makes the provocative suggestion that this eclogite formed as the result of contact metamorphism with the Seba metagabbro that intruded as a hot solid-state eclogitic body. In support of this suggestion Takasu (1984) cites petrological evidence for an early hot and later cooler phase of eclogite re-equilibration in the metagabbro. The second stage has similar estimated *P*-*T* conditions to those of the surrounding schistose eclogite. In addition, metapelitic layers within the schistose eclogite contain garnet with unusual textures suggesting resorption, which Takasu (1984) relates to the contact metamorphic event.

In contrast, other workers suggest that the Seba metagabbro and surrounding schistose eclogite have a common metamorphic history (Aoya, 1998; Aoya and Wallis, 1999; Nomizo, 1992). Aoya (1998) tests the solid-sate intrusion model of Takasu (1984) by using thermal calculations to place constraints on the required size of the gabbro body and the associated exhumation rates. The results of this modelling suggest both parameters would have to be outside the range of generally accepted values to account for the observed metamorphism. A further important discovery is the presence of eclogite at distance of up to 1 km away from the metagabbro body (Aoya and Wallis, 1999; Naohara and Aoya, 1997). In contrast to the eclogite adjacent to the metagabbro, the distal eclogite has a strong grain-shape fabric which could be taken as indicating a distinct origin. However, (Aoya and Wallis, 1999) use structural data to suggest this difference is due to increasing strength of post-eclogitic ductile deformation with increasing distance from the metagabbro body. This ductile deformation is related to decompression of the eclogite units, but took place before Ds, the dominant orogen-parallel ductile flow of the Sanabagawa belt (Aoya, in press; Aoya and Wallis, 1999). These workers conclude that there is no need to invoke solid-state contact metamorphism to account for the formation of the Seba eclogite adjacent to the Seba metagabbro and that this eclogite is best understood as representing a high-grade part of the normal Sanbagawa metamorphism.

Radiometric Dating of Eclogite

Ar-Ar and K-Ar age determinations of phengitic mica have been carried out throughout the Sanbagawa belt of central Shikoku (Itaya and Takasugi, 1988; Takasu and Dallmeyer, 1990). Both methods give cooling ages of around 75–85 Ma. However, there have been very few successful attempts to date the eclogitic rocks.

The peak of metamorphism has remained particularly elusive despite several attempts to date coexisting clinopyroxene and garnet using the Sm-Nd method. Perhaps the best indication of the peak of metamorphism is given by SHRIMP dating of zircon grains from the quartz eclogite unit (Okamoto et al., 1999). The results suggest an age of 110–120 Ma. Ar-Ar isotope correlation ages for amphibole of the Seba metagabbro mass and surrounding schistose eclogite are reported by Dallmeyer and Takasu (1991). These are given as 83.4 ± 0.5 Ma, 83.6 ± 0.5 Ma in the schistose eclogite and 93.7 ± 1.1 Ma , 96.5 ± 0.7 Ma in the metagabbro. These data suggest that the metagabbro cooled before the rocks adjacent to it. This result could, therefore, be taken as evidence against the idea that the Seba metagabbro intruded into the surrounding schist and caused contact metamorphism. However, Dallmeyer and Takasu (1991) explain the difference in the derived ages as the result of a higher closure temperature for the relatively Mg-rich amphibole from the metagabbro. The same samples of schistose eclogite give Ar-Ar ages of 87.9 ± 0.3 Ma and 89.3 ± 0.4 Ma and paragonite from the metagabbro mass gives an Ar-Ar age of 93.7 ± 2.7Ma.

A new set of K-Ar ages of phengite and paragonite from various eclogite units is presented in figure 7. The results from the Seba area in very close agreement with those from the surrounding non-eclogitic schist (Dallmeyer and Takasu 1991; Itaya and Takasugi 1988) and suggest cooling to 350–400℃ by around 85 Ma. The ages from the other areas show considerable variation.

SUMMARY: THE KNOWNS, UNKNOWNS AND DISPUTES

The Sanbagawa belt represents the deeply exhumed part of the active margin that existed off eastern Asia in the

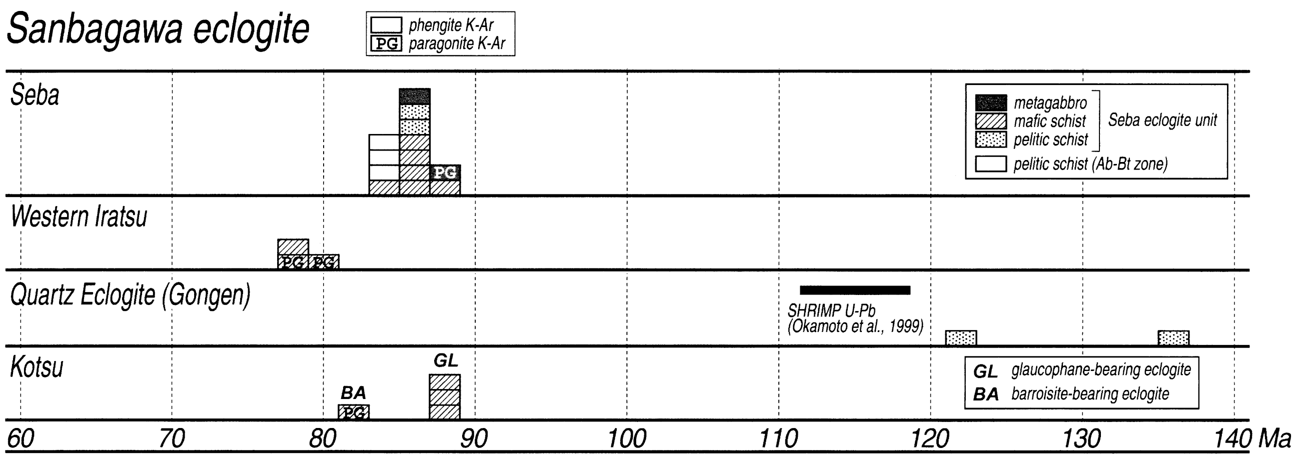

Fig.7. Compilation of new K-Ar ages of eclogite units. Both paragonite and phengite were used for age determinations. The results of SHRIMP dating of zircon rims from the quartz eclogite unit are shown for comparison.

Cretaceous. Kinematics of ductile deformation in the region suggests its formation was associated with major left-lateral movements, compatible with plate reconstructions for this period. At least two large-scale nappes can be defined. Both nappes and their boundary have been penetratively deformed by the dominant ductile flow that caused orogen-parallel stretching and thinning. In general, the metamorphic grade increases with structural level although in central Shikoku this has been modified by post-metamorphic deformation. In the Kanto Mountains the maximum metamorphic grade is seen at low structural levels. The maximum metamorphic grade generally observed is in the epidote amphibolite facies. However, substantial units that locally contain eclogite mineral assemblages are also found. *P-T* paths of the non-eclogitic but relatively high-grade zones are thought to have an open clockwise geometry with peak pressure before peak temperature. Radiometric dating gives good constraints on the cooling history of the region, but the peak of metamorphism is still unclear. The thermal history of the Sanbagawa belt is in general compatible with that predicted for convergent margins. There is, however, as yet no thermal modelling that can explain the more detailed aspects of the *P-T* paths in terms of the known large-scale structure and kinematics.

Compared to the rest of the belt, the eclogite units have been relatively poorly characterized. There is, therefore, still considerable debate about their evolution. It is known that they were derived from both sedimentary and plutonic protoliths. The eclogite facies metamorphism has been strongly overprinted by metamorphism in the epidote amphibolite facies. Locally granulite facies metamorphism that predates the formation of eclogite has also been recognized. The age of eclogite metamorphism is unknown and its relationship to the lower-grade Sanbagawa units is still disputed. The prevailing view is, however, that all the eclogite units have separate and distinct metamorphic histories from each other. These units are, therefore, treated as tectonic blocks in a regional tectonic mélange. An alternative view that at least some of these bodies represent outliers of a once continuous eclogite unit has also been proposed. The resolution of this dispute will require more careful field work and studies of metamorphic textures.

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