Review

Recognition of the Shimanto HP metamorphic belt within the traditional Sanbagawa HP metamorphic belt: New perspectives of the Cretaceous–Paleogene tectonics in Japan

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ABSTRACT

The Sanbagawa metamorphic belt in SW Japan has been traditionally referred as a typical subduction-related high-pressure (HP) metamorphic belt. This belt extends E–W direction for more than 800 km from the Kanto Mountains to Kyushu Island. In part, protoliths of many HP metamorphic rocks formed as an accretionary complex after ca. 90–80 Ma and suffered a blueschist-facies metamorphism at 66–61 Ma. This metamorphic event clearly postdates the Sanbagawa metamorphism of 120–110 Ma. This newly recognized HP rocks occur extensively in the traditional Sanbagawa (HP-) metamorphic belt throughout Shikoku, Kii Peninsula and Kanto Mountains, thus it was named as the Shimanto (HP-) metamorphic belt. Thus, the traditional Sanbagawa metamorphic belt comprises two distinct HP metamorphic belts, and the Sanbagawa metamorphic rocks cover less than half of the areas for the traditional Sanbagawa metamorphic belt. Importantly, the metamorphic grade of the Shimanto metamorphic rocks ranges from the pumpellyite–actinolite to epidote–amphibolite facies, just like many Sanbagawa metamorphic rocks. The similarity between metamorphic rocks of these two belts, in spatial distribution, metamorphic grades, and metamorphic facies series, was the main reason why these two belts had not previously been differentiated.

A Pacific-type orogenic belt in general comprises a belt of accretionary complex and HP metamorphic belt on the ocean side, plus a fore-arc basin and a granite batholith belt on the continent side. In SW Japan, the Sanbagawa metamorphic belt is chronologically accompanied with the accretionary complex (Southern Chichibu belt), Lower Cretaceous fore-arc sediments, and the ca. 120–70 Ma Sanyo batholith belt with Ryoke low-pressure metamorphic rocks. Likewise, the Shimanto (HP-) metamorphic belt is accompanied with an Upper Cretaceous accretionary complex (Northern Shimanto belt), Campanian to Maastrichtian fore-arc sediments, and the San-in batholith belt. The opening of a back-arc basin (Japan Sea) at ca. 20 Ma extensively modified the primary spatial arrangements of the two Cretaceous–Paleogene orogenic belts. In particular, the southward thrusting of the Ryoke–Sanyo granitic batholith belt over the Sanbagawa metamorphic belt formed the present structural superposition of the Ryoke above the Sanbagawa and Shimanto metamorphic belts.

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1. Introduction

The Japanese Islands form a modern arc-trench system and also comprise several orogenic belts developed along oceanic plate convergent margins over more than ca. 500 Myr (e.g. Isozaki and Maruyama, 1991; Isozaki, 1996; Maruyama et al., 1997). Extensive investigations of the geotectonic subdivision of Japan have provided a comprehensive understanding of the geotectonic evolution of Japan, as well as allowing the orogenic evolution at past oceanic plate convergent margins to be established.

The crust of modern Japan is mainly composed of accretionary complex, high-pressure (HP) metamorphic rocks, and arc granites (e.g. Isozaki, 1996; Isozaki et al., 2010a). These are essentially divided and defined on the basis of differences in rock assemblage and formation age. For instance, a HP metamorphic belt is defined as a spatial distribution of HP rocks metamorphosed at wide P-T conditions ranging from the epidote–amphibolite (EA) facies to eclogite facies; these rocks have specific peak metamorphic ages. An accretionary complex belt is defined as a spatial distribution of weakly metamorphosed to non-metamorphosed rocks that essentially form an ocean plate stratigraphy of an accretionary complex (pelagic, hemipelagic and trench-fill deposits; Isozaki et al., 1990; Matsuda and Isozaki, 1991) with a specific accretionary age. The distribution and boundaries of these belts composed of accretionary complexes have largely been established based on field observation in previous investigations (e.g. Nishimura et al., 1989; Suzuki et al., 1990; Kawato et al., 1991; Isozaki et al., 1992; Sasaki and Isozaki, 1992; Masago et al., 2005).

The recent development of high-precision analytical equipments, such as the Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) and High Resolution Secondary ion mass spectrometer (HR-SIMS), has enabled to provide more precise age constraints for accretion and metamorphism of geological units than had previously been possible (e.g. Iizuka and Hirata, 2004; Rino et al., 2008; Takahata et al., 2008; Aoki et al., 2009). As a result it has become apparent that the traditional geotectonic subdivisions and definitions of geological units in Japan must be reevaluated. This is particularly apparent for unique units that lack high-resolution chronology. In this paper, we review the recent progress in understanding the world-renowned and referenced Sanbagawa HP metamorphic belt in SW Japan. In addition, we present a new account of the Cretaceous to Paleogene orogenic evolution of Japan.
important, because it provides the necessary records for unraveling the tectonic evolution.

The Japanese Islands represent an ongoing Pacific-type orogenic belt, which has developed on the eastern margin of Asia in the past 500 million years. In particular, SW Japan provides the type locality for the definition of geotectonic subdivisions, because bedrock in this area is well exposed compared with NE Japan. In SW Japan, four discrete HP-belts are discriminated on the basis of metamorphic age: the 440–400 Ma Oeyama belt (Isozaki and Maruyama, 1991; Tsujimori et al., 2000; Tsujimori, 2010; Kunugiza and Goto, 2010), the 330–280 Ma Renge belt (Nishimura, 1998; Tsujimori and Itaya, 1999; Tsujimori, 2010), the 230–160 Ma Suo belt (Nishimura, 1998), and the 120–110 Ma Sanbagawa metamorphic belt (Minamishin et al., 1979; Okamoto et al., 2004). As mentioned above, the presence of HP-rocks is indicative of orogeny. Thus, four orogenies have been recognized in SW Japan (e.g. Isozaki and Maruyama, 1991; Isozaki, 1996; Maruyama et al., 1997). However, recent studies have revealed that some crystalline HP-schists, which underwent discrete HP metamorphism from the classic Sanbagawa metamorphism, are widely distributed in the traditional Sanbagawa metamorphic belt (Aoki et al., 2007; 2008). This significant observation indicates the existence of a previously unrecognized, orogenic event in Japan. In order to understand, demonstrate and clarify the spatial distribution of the relevant geological units, we first analyze the tectonic framework of the Sanbagawa metamorphic belt.

3. A new aspect of the Sanbagawa metamorphic belt

3.1 Sanbagawa metamorphic belt

The Sanbagawa metamorphic belt in the traditional sense extends roughly E–W from the Kanto Mountains to Kyushu Island for more than 800 km from central to SW Japan (Fig. 1). Metamorphic grade varies from the pumpellyite–actinolite facies through blueschist transition facies, to epidote–amphibolite and eclogite facies (e.g. Banno and Sakai, 1989; Higashino, 1990; Enami et al., 1994; Aoya, 2001; Ota et al., 2004; Aoki, 2009; Aoki et al., 2009; Kouketsu et al., 2010); the highest-grade rocks occur at the intermediate structural level (Banno et al., 1978; Ota et al., 2004; Yamamoto et al., 2004; Terabayashi et al., 2005). The main Sanbagawa schists were derived from pelitic, psammitic and mafic protoliths. However, weakly metamorphosed greenstones, locally termed “Mikabu greenstones”, do occur intermittently along the southern margin of the belt.

Based on fossil, microfossil and SHRIMP zircon U–Pb ages (Isozaki and Itaya, 1990; Okamoto et al., 2004) it has been concluded that the Sanbagawa protoliths accumulated in a trench at 140–130 Ma. The age of the peak metamorphism occurred at ca. 120–110 Ma, based on Rb–Sr whole-rock isochron data (Minamishin et al., 1979) and SHRIMP zircon U–Pb data (Okamoto et al., 2004). In contrast, Wallis et al. (2009) reported that the Sanbagawa...
eclogites achieved peak metamorphism at ca. 90 Ma, based on garnet-omphacite Lu–Hf isochron dating of eclogites. On the other hand, Aoki et al. (2010a) found the eclogitic garnets are strongly zoned and their dated garnets and omphacites were not formed coevally. Thus, the so-called “garnet–omphacite Lu–Hf isochron ages” for the Sanbagawa metamorphism must be interpreted with caution. Moreover, the associated intermediate- to high-grade metapelitic rocks have phengite K–Ar and Ar–Ar ages between 88 and 65 Ma (Itaya and Takasugi, 1988; Takasu and Dallmeyer, 1990; Nuong et al., 2009). Nano-SIMS zircon analyses, in situ REE analyses and inclusion mineralogy in zircons (Aoki et al., 2009, 2010a) show that oligoclase-biotite zone metamorphic rocks, the highest-grade zone in the belt (Enami, 1982), underwent prograde eclogite-facies metamorphism and subsequent retrograde metamorphism, with

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**Fig. 2.** (a) Geotectonic subdivision and N–S cross-section of the Shikoku area (Aoki et al., 2010b after Aoki et al., 2007 and Otoh et al., 2010). (b) K–Ar phengite ages plotted along A–B cross-section (Itaya and Takasugi, 1988; Isozaki and Maruyama, 1991; Kawato et al., 1991; Aoki et al., 2008). (See Fig. 1 for abbreviations). SHRIMP and Nano-SIMS zircon ages from eclogite (Okamoto et al., 2004; Aoki et al., 2009) and mineral zones (Banno and Sakai, 1989) are also shown. The cross-section of Fig. 2b shows (1) a gently folded thin slice of the Sanbagawa metamorphic belt bounded on the bottom by the Shimanto metamorphic belt and on the top by the Jurassic Chichibu accretionary complex, and (2) the subhorizontal Sanbagawa unit with a symmetric thermobaric structure and deformation fabrics (see Osozawa and Pavlis, 2007); K–Ar ages of Sanbagawa metamorphic rocks (sl) are grouped into three with the youngest ones close to the lower boundary and the oldest ones at the southernmost lowest-grade part. Note that the K–Ar age of the southernmost group is similar to the peak SHRIMP zircon U–Pb age. Flow directions of late infiltrated fluid from underlying Shimanto metamorphic rocks are also schematically shown; such fluid has modified most K–Ar ages of Sanbagawa metamorphic rocks (Ak). Note that K–Ar ages of the southernmost group of Shimanto metamorphic rocks are older than those of the northernmost group.
extensive hydration at 85.6 ± 3.0 Ma, during exhumation. Therefore, we interpret the age of ca. 90–65 Ma age to reflect the time of retrograde recrystallization (Aoki et al., 2008, 2009; Maruyama et al., 2010). In summary, the protoliths of the Sanbagawa metamorphic rocks were formed as an accretionary complex in a trench of ca. 140–130 Ma, and subjected to progressive metamorphism at ca. 120–110 Ma, and retrogressive hydration-recrystallization at ca. 90–65 Ma. More details of the geochronology of Sanbagawa metamorphic rocks are given in Itoya et al. (this issue).

It has recently been reported that the traditional Sanbagawa metamorphic belt contains another HP unit, characterized by younger deposition and prograde metamorphic ages (e.g. Aoki et al., 2007, 2008). These data clearly show that the younger HP rocks post-dated the Sanbagawa metamorphism, and thus experienced a different metamorphic history to Sanbagawa metamorphic rocks. In view of this, the geotectonic subdivision of Japan requires a drastic revision (cf., Isozaki et al., 2010b). In the following section, we focus on the distribution of the Sanbagawa rocks of the traditional Sanbagawa metamorphic belt in Shikoku, Kii and Kanto.

3.2. Shikoku

In the Oboke area of central Shikoku, three distinct units traditionally called “Formations” occur: in structurally ascending order, they are Minawa, Koboke and Kawaguchi formations (Kojima, 1951; Kenzen Research Group, 1984). The Minawa Formation is composed of two subunits: the upper unit contains spotted schist and the lower unit does not have spotted schist. Because of their apparent lithological and structural similarities, they were traditionally regarded as parts of the Sanbagawa metamorphic belt.

Most sedimentary basins within convergent margins in subduction zones contain clastics related to igneous activity close to the time of deposition. Thus, the youngest age of detrital zircons in metamorphic rocks such as psammitic schist can be used to constrain the maximum age of deposition within the trench. Aoki et al. (2007) undertook a U–Pb study of many detrital zircons using LA-ICPMS, focusing on the youngest zircons. In the Oboke area, the older limits of the depositional age of the Koboke and Kawaguchi Formations are 92 ± 4 and 82 ± 11 Ma, respectively. Moreover, the older limits of depositional age of the upper and lower units of the Minawa Formation are 156 ± 7 and 71 ± 9 Ma, respectively (upper: Nakama et al., 2010; lower: Otoh et al., 2010). As mentioned above, ages of the accretion and peak metamorphic ages of the Sanbagawa metamorphic rocks are clearly older than those of the Koboke and Kawaguchi formations and the lower Minawa unit. Thus, the metamorphic rocks of the Koboke and Kawaguchi formations and the lower Minawa unit could not have existed at the time of the Sanbagawa metamorphism. Therefore, these rocks are distinctly different from Sanbagawa metamorphic rocks, but belong to independent metamorphic unit.

The Shimanto belt extends from the Kanto Mountains in central Japan to the Ryukyu Islands for over 1800 km along the Pacific side of SW Japan (Fig. 1). It evolved on the top of the subducting Philippine Sea plate during the Cretaceous accretion that was initiated by subduction of the Kula or Pacific plates. The Shimanto belt is traditionally divided into two sub-belts, the Cretaceous Northern Shimanto belt and the Paleogene to modern Southern Shimanto belt (Figs. 2–4). The Northern Shimanto belt is defined as an accretionary complex formed during the Upper Cretaceous (e.g. Taira et al., 1982; Kiminami et al., 1998, 1999).

Judging from their deposition ages and geological textures, protoliths of metamorphic rocks of the Koboke and Kawaguchi formations and the lower Minawa unit are equivalent to those in the Northern Shimanto belt, which is a Cretaceous accretionary complex that occurs as a tectonic window in central Shikoku (Aoki et al., 2007, 2008). Existence of the metamorphic rocks of the Northern Shimanto accretionary complex beneath the Sanbagawa metamorphic rocks was predicted (e.g. Isozaki, 1986; Isozaki and Maruyama, 1991). This relationship was initially suggested by Shinjoe and Tagami (1994), Manabe et al. (1996) and Kiminami et al. (1999), and has been confirmed by recent U–Pb geochronology of detrital zircons separated from metamorphic rocks (Aoki et al., 2007) and deep seismic profile data (Sato et al., 2005; Ito et al., 2009).
Furthermore, Aoki et al. (2008) demonstrated that these rocks underwent blueschist-facies metamorphism (*sensu lato*) at 66–61 Ma, much younger than the ages of peak metamorphism of Sanbagawa metamorphic rocks. In fact they are the youngest blueschist-facies rocks in SW Japan. According to their lithological similarities and lateral continuity, the spatial distribution of blueschist-facies rocks of the Northern Shimanto belt in Shikoku is shown in Fig. 2a (Aoki et al., 2008; Isozaki et al., 2010a; Otoh et al., 2010). Subsequently, Shimojo et al. (2010) demonstrated that the metamorphic rocks of the Northern Shimanto belt have a wider distribution than in the Shikoku.

3.3. Kii Peninsula

The Sanbagawa metamorphic belt in the Northeast Kii Peninsula is traditionally divided into three zones based on lithology, geological structure and metamorphic grade: non-spotted, spotted, and the Mikabu zone (e.g. Nakayama, 1983; Kurimoto, 1995), and overlies the Northern Shimanto belt (Sasaki and Isozaki, 1992; Masago et al., 2005). According to Otoh et al. (2010), detrital zircons separated from three psammitic schists in the non-spotted zone have LA-ICPMS U–Pb age limit of initial deposition at 80 ± 9, 77 ± 17 and 82 ± 22 Ma, respectively. Furthermore, Otoh et al. (2010) demonstrated that protoliths of non-spotted zone rocks were equivalent to those in the Northern Shimanto accretionary complex, by comparing the statistical evaluation of analyzed zircon U–Pb ages (Okamoto et al., 2004), K–Ar phengite ages (Kurimoto, 1995) and accretionary ages (e.g. Taira et al., 1982; Kiminami et al., 1998) (Fig. 3).

3.4. Kanto Mountains

The Kanto Mountains is the type locality of the Sanbagawa metamorphic belt; it is divided into two units based on lithology and stratigraphy: the lower Sanbagawa unit and the upper Mikabu unit (Makimoto and Takeuchi, 1992). *In situ* SHRIMP U–Pb isotope data for detrital zircon grains from three psammitic schists in the Sanbagawa unit yield the initial depositional age at 79 ± 1, 91 ± 2 and 95 ± 2 Ma, respectively (Tsutsumi et al., 2009). Integration of these data with previous zircon U–Pb ages (Okamoto et al., 2004), K–Ar phengite ages (Miyashita and Itaya, 2002), and the accretionary ages of the Northern Shimanto belt (e.g. Taira et al., 1982; Kiminami et al., 1998), we conclude that the Sanbagawa unit in the Kanto Mountains is a metamorphic part of the Northern Shimanto belt. Although the initial deposition age of the Mikabu unit cannot as yet be constrained, judging from the depositional
and K–Ar ages of the Mikabu greenstone in the Shikoku Island and Kii Peninsulas (Matsuda, 1978; Suyari et al., 1980; Iwasaki et al., 1984, 1988; Kurimoto, 1995), it is probable that the Mikabu unit belongs to the Sanbagawa metamorphic belt (Fig. 4).

4. New observation on the spatial distribution of HP metamorphic rocks in SW Japan

4.1. Geologic structure, metamorphic facies series and peak age of the Shimanto metamorphic rocks

Recent studies indicate that metamorphic rocks within the area traditionally considered as the Sanbagawa metamorphic belt in the Shikoku, Kii and Kanto underwent a HP metamorphism younger than the Sanbagawa metamorphism. These Shimanto (HP-) metamorphic rocks of Aoki et al. (2008) occur at the structurally lowest level in the traditional Sanbagawa metamorphic belt (Figs. 2–4). Moreover, Aoki et al. (2008, 2009) demonstrated that Sanbagawa metamorphic rocks were thrust over Shimanto metamorphic rocks after the Sanbagawa metamorphism. Thus these results suggest that Shimanto metamorphic rocks occur at a structurally higher level than Shimanto metamorphic rocks in the Shikoku, Kii and Kanto areas (Figs. 2–4).

We then compare metamorphic facies series and metamorphic age between these two distinct HP rocks. K–Ar phengite ages of some Shimanto mafic and pelitic schists in the Oboke area yielded blueschist-facies metamorphism at 66–61 Ma (Aoki et al., 2008). However, Shimanto metamorphic rocks with K–Ar phengite age of ca. 80–75 Ma (Itaya and Takasugi, 1988) in the Asemi-gawa area, Shikoku experienced a different thermotectonic history; these ages are clearly older than the initial depositional age of 71 ± 9 Ma (Otoh et al., 2010). As the depositional age cannot be younger than the metamorphic ages, the most likely explanation for this discrepancy is that these K–Ar ages are mixed ages affected by detrital phengites. Alternatively, the protoliths of Shimanto metamorphic rocks in the Asemi-gawa area were deposited and accreted earlier than those in the Oboke area, and later subjected to coeval subduction-zone metamorphism.

Shimanto metamorphic rocks in the Kanto Mountains are divided into three metamorphic zones; chlorite, garnet, and biotite zones in ascending order of metamorphic grade from the PA to EA facies (Seki, 1958; Toriumi, 1975; Hirajima, 1989; Makimoto and Takeuchi, 1992; Miyashita et al., 2009) (Fig. 5). These P–T conditions indicate that the highest-grade part of the Shimanto metamorphic rocks were recrystallized at a depth of 30–40 km. K–Ar phengite ages for chlorite-zone, garnet-zone and biotite-zone schists respectively are about 80–70, 80–60 and 70–60 Ma (Hirajima et al., 1992; Miyashita and Itaya, 2002). Hara and Hisada (2005) subsequently reported K–Ar illite ages of ca. 80–60 Ma from some weakly-metamorphosed rocks in the Northern Shimanto accretionary complex in the Kanto Mountains. Integration with these ages of initial deposition (Tsutsumi et al., 2009) with closure temperature of phengite, and P–T estimates of Shimanto metamorphic rocks in the Kanto Mountains, we conclude these rocks underwent a progressive metamorphism at about 80–60 Ma and these ages are much younger than the Sanbagawa metamorphism of 120–110 Ma.

Metamorphic grades of Shimanto metamorphic rocks in the NW Kii Peninsula range from the PA facies to blueschist facies (sensu lato) (Wang and Maekawa, 1997). The K–Ar phengite ages of most non-spotted zone Shimanto metamorphic rocks are 80–69 Ma (Kurimoto, 1993,1995). Thus, Shimanto rocks from this area suffered progressive metamorphism between 80 and 69 Ma. However, the reported K–Ar phengite ages of 97–83 Ma for southern non-spotted zone schists (Kurimoto, 1993,1995) are older than the initial depositional age by ca. 80 Ma (Otoh et al., 2010). These K–Ar ages may have been obtained from mixing neoblastic with detrital phengites. On the other hand, Kurimoto (1995) did not rule out the possibility that metamorphic rocks in the southern non-spotted zone do not extend to the northern and central parts of the non-spotted zone. Another possibility could be that the southern non-spotted zone rocks suffered earlier metamorphism than those from the northern and central parts of the non-spotted zone.

4.2. Existence of a new regional HP metamorphic belt in Japan

The Northern Shimanto belt was defined for the exposed areas of the Upper Cretaceous weakly to non-metamorphosed accretionary complexes (e.g. Taira et al., 1982; Kiminami et al., 1998). In this belt, most weakly metamorphosed rocks have been recrystallized at prehnite–actinolite and greenschist-facies conditions of the low-pressure type (Toriumi and Teruya, 1988; Miyazaki and Okumura, 2004; Harra and Hisada, 2007; Harra and Kurihara, 2010). However, as mentioned above, the metamorphosed Northern Shimanto belt (Shimanto metamorphic rocks) is far more extensively distributed in Japan than previously thought (Figs. 2–4). In addition, these rocks tectonically underlie the Sanbagawa metamorphic rocks, and have been subjected to HP metamorphism (Aoki et al., 2008). Furthermore, in the Kanto Mountains, metamorphic rocks ranging from low-grade (PA facies) to high-grade (EA facies) also exhibit younger peak metamorphic ages than the Sanbagawa peak metamorphic age of 120–110 Ma.

Most regional HP metamorphic belts are defined on the basis of the following features: a wide distribution, occurrence of a series of metamorphic rocks from low- to high-grade, and a specific peak metamorphic age. In this regard Shimanto metamorphic rocks have all of these characteristics and thus define an independent HP metamorphic belt that is distinct from the Sanbagawa metamorphic belt. Accordingly, the traditional Sanbagawa metamorphic belt is no doubt composed of two independent HP
term the "Sanbagawa metamorphic belt" for the exposed areas of metamorphic belt is termed as the "Sanbagawa belt". We also morphic rocks sensu stricto the traditional Sanbagawa metamorphic belt from the "Sanbagawa metamorphic rocks" at structurally upper part of Murakami (1979). (a) Distribution of main geological units in the Shimanto orogenic belt, (b) Distribution of main geological units in the Sanbagawa orogenic belt. (See Fig. 1 for abbreviations). The present distribution of the units in these two orogenic belts records the primary relation of their spatial distribution at the time of orogeny. However, one unusual geological structure is observed in the Sanbagawa orogenic belt – the Sanbagawa metamorphic belt is in direct contact with the Ryoke–Sanyo batholith belt across the MTL.

4.3. Boundary between the two belts

The boundary between the Sanbagawa and Shimanto metamorphic belts has not yet been formally confirmed and defined. However, at present, we speculate that a distinct discontinuity fault at the boundary defines a major age gap between these two belts. In the Oboke area of central Shikoku, the Shimanto metamorphic belt occurs as a tectonic window in a domal uplift below the Sanbagawa metamorphic belt (Aoki et al., 2007); these two belts are in

Fig. 6. Spatial distribution of orogenic belts in the Chugoku, Shikoku and Kii regions, SW Japan. The boundary lines of granitic batholiths are after Ishihara (1971) and Murakami (1979). (a) Distribution of main geological units in the Shimanto orogenic belt, (b) Distribution of main geological units in the Sanbagawa orogenic belt. (See Fig. 1 for abbreviations). The present distribution of the units in these two orogenic belts records the primary relation of their spatial distribution at the time of orogeny. However, one unusual geological structure is observed in the Sanbagawa orogenic belt – the Sanbagawa metamorphic belt is in direct contact with the Ryoke–Sanyo batholith belt across the MTL.

Fig. 7. A schematic cross-section of SW Japan from the Japan Sea coast to the Nankai Trough and depicts the crustal structure between the volcanic front and the trench of a mature island arc system in SW Japan (partly modified after Kuramoto et al., 2000; Sato et al., 2005; Aoki et al., 2008, and Ito et al., 2009). Note the sharp contrast between the Japan Sea side and Pacific side separated by the MTL. The former is composed mainly of arc-related granitic batholiths that intruded into the pre-Cretaceous accretionary complexes with the HP metamorphic units as roof pendants. On the other hand, the latter consists almost entirely of a subhorizontal stack of post-Jurassic accretionary complexes and HP metamorphic units with downward and oceanward younging polarity. The pre-Cretaceous accretionary complex and HP metamorphic units on the Japan Sea side also have the same structure, suggesting an overall growth pattern of accretion and HP metamorphism in an oceanic subduction-related orogeny.

metamorphic belts: a belt of the Sanbagawa metamorphism at structurally higher level and the other belt of the Shimanto metamorphism at the structurally lower level.

Isozaki and Itaya (1990) have shown that the Jurassic accretionary complex of the northernmost part of the Chichibu belt underwent the Sanbagawa metamorphism, whereas the main part suffered much older metamorphism. These Sanbagawa metamorphic rocks including the northernmost part of the Chichibu belt have been called the “Sanbagawa metamorphic rocks sensu lato (sl)” (Isozaki and Itaya, 1990). In this paper, in order to differentiate the “Sanbagawa metamorphic rocks” at structurally upper part of the traditional Sanbagawa metamorphic belt from the “Sanbagawa metamorphic rocks (sl)”, we term the former to be “Sanbagawa metamorphic rocks sensu stricto (ss)”. The traditional Sanbagawa metamorphic belt is termed as the “Sanbagawa belt”. We also term the “Sanbagawa metamorphic belt” for the exposed areas of Sanbagawa metamorphic rock (ss) and the “Shimanto metamorphic belt” for the areas covered by Shimanto metamorphic rocks.

The geotectonic subdivision of the Japanese Islands, including the above new names, is under revision. For further details, refer to Isozaki (1996) and Isozaki et al. (2010b) to compare the traditional and renewed schemes.
direct contact by a high-angle fault (e.g. Aoki et al., 2008; Okamoto et al., 2009). However, this fault is likely of secondary origin after the formation of the primary boundary fault, because the geological units dip at a shallow angle. Judging from a dominant low-angle structure (Isozaki and Maruyama, 1991; Isozaki, 1996) and pattern of distribution of the Shimanto metamorphic belt (Fig. 2-a), the primary boundary of these two belts is most likely a subhorizontal low-angle fault.

Maruyama et al. (1996) suggested that many exhumed HP metamorphic belts are bounded by a low-angle normal fault on the top and a reverse fault at the bottom as HP units extruded from deeper crustal levels toward the surface. The highest-grade part of the Sanbagawa metamorphic belt was exhumed from a mantle depth over 40–50 km and juxtaposed over the Shimanto metamorphic rocks (Aoki et al., 2008, 2009). Thus, the primary boundary between these two belts is considered to be a low-angle thrust. Subsequently, the highest-grade part of the Shimanto metamorphic belt was exhumed to the surface from depths >30–40 km based on metamorphic P–T estimates (e.g. Hirajima, 1989); such a low-angle contact should be a normal fault.

In summary, the tectonic boundary between the Sanbagawa and Shimanto metamorphic belts can be divided into three types: a low-angle thrust formed at the time of exhumation of the Sanbagawa metamorphic rocks, a low-angle normal thrust formed at the time of exhumation of the Shimanto metamorphic rocks, and a high-angle normal fault formed by secondary domal uplift. Until now, there have been no reports of these three boundaries in the area. However, confirmation of the tectonic boundary is very important in order to identify the spatial distribution of the metamorphic rocks, as well as to understand the exhumation tectonics of the Sanbagawa and Shimanto metamorphic belts. Clearly the documentation of the nature of these boundaries will require detailed additional field observation.

5. Cretaceous–Paleogene Orogeny in Japan

To explain the geotectonic evolution of Japan, several orogenies have previously been proposed (e.g. Kobayashi, 1941; Gorai, 1955; Minato et al., 1965; Horikoshi, 1972). The definition of each orogeny was different and inconsistent, mainly because the precise ages of rock units were poorly constrained prior to the 1980s. During the 1990s, the geotectonic evolution of Japan was explained in the plate tectonic framework (e.g. Isozaki and Maruyama, 1991; Isozaki, 1996; Maruyama, 1997). They emphasized that the Pacific-type orogeny had a clear rhythm of ca. 100 million years that was tuned by the episodic subduction of mid-oceanic ridge, and that each cycle spanned from one ridge-subduction to the next one. Moreover, they concluded that one set of an orogenic belt consists of accretionary complex, HP metamorphic belt, batholith belt and fore-arc basin, and that an orogenic peak was driven by ridge-subduction when a HP metamorphic belt was exhumed and a large granite batholith formed (Isozaki and Maruyama, 1991; Isozaki, 1996; Maruyama et al., 1996, 2010; Maruyama, 1997). On the basis of these new concepts, Isozaki and Maruyama (1991) distinguished four major orogenies in Japan that occur at about 450–300, 300–220, 220–75 Ma, and on-going orogeny. The third orogeny was named as the Miyashiro orogeny after the great contribution in the orogenic study in Japan by late Akiho Miyashiro (Isozaki and Maruyama, 1991; Isozaki, 1996). In this framework, the Sanbagawa belt has been generally regarded as a major product of the Miyashiro orogeny.

As described above, recent studies have shown that the (traditional) Sanbagawa belt contains evidence for two HP metamorphic belts including the Sanbagawa and Shimanto metamorphic belts. This distinction indicates that another orogeny occurred between the Sanbagawa metamorphism and prior to the current orogeny. In other words, the Miyashiro orogeny of Isozaki and Maruyama (1991) comprises two distinct orogenies. In this paper, we strictly use “Sanbagawa orogeny” and “Sanbagawa orogenic belt” for the orogeny that gave rise to the Sanbagawa metamorphic belt and for its overall products, whereas we use “Shimanto orogeny” and “Shimanto orogenic belt” for the one that formed the Shimanto metamorphic belt and for its products. In the following, we list components of these two orogenic belts on the basis of the compiled data mainly from SW Japan.

5.1. Components of an orogenic belt

Most Pacific-type orogenic belts consist of the following four major components: accretionary complex and HP metamorphic belt on the ocean side, plus fore-arc basin and batholith belt on the continent side; these components develop parallel along the entire arc-trench system (e.g. Maruyama, 1997). In this regard, both the Sanbagawa and Shimanto orogenic belts retain a full set of these four components.

5.1.1. Sanbagawa orogen

The peak age of the Sanbagawa metamorphism is estimated to be ca. 120–110 Ma (Isozaki and Itaya, 1990; Okamoto et al., 2004).
The Suo HP metamorphism, the next older HP event in SW Japan, occurred between 230–160 Ma (Nishimura, 1998; Isozaki et al., 2011). Thus, the main geologic units of the Sanbagawa orogenic belt formed after ca. 160 Ma and before 120 Ma. The accretionary complex of the Southern Chichibu belt sensu stricto (the Sanbosan and Togano units of Matsuoka et al., 1998) in SW Japan was formed during the Middle Jurassic to Early Cretaceous (ca. 160–125 Ma); these units chronologically correspond to the components of the Sanbagawa orogenic belt.

Cretaceous granite batholiths are widespread in SW Japan; they are divided into three belts on the basis of lithology, bulk composition, and magnetic susceptibility: the Ryoke, Sanyo, and San-in belts from south to north (Ishihara, 1971; Murakami, 1979; Iizumi et al., 1985). However, in all cases mutual boundaries are obscure on the surface. The granitic rocks of the Ryoke and Sanyo belts formed between 120–70 Ma, representing the batholith belt of the Sanbagawa orogeny. Remnants of the coeval fore-arc basin unconformably overlying the pre-Jurassic rocks are preserved in the Chichibu belt (Lower Cretaceous Ryoseki–Monobegawa Group) in SW Japan (Suzuki et al., 1990).

5.1.2. Shimanto orogen

The Shimanto metamorphic belt (progressive metamorphic age: 80–60 Ma) and the Upper Cretaceous accretionary complex of the Northern Shimanto belt belong to the Shimanto orogenic belt. In addition, granitic rocks of the San-in belt have similar age and are also interpreted as components of the Shimanto orogenic belt (Iizumi et al., 1985; Nakajima et al., 1990; Kagami et al., 1992, 1995; Osanai et al., 1993; Sawada et al., 1994; Kiji et al., 2000; Nishida et al., 2005; Imaoka et al., 2011). Nishida et al. (2005) systematically analyzed Rb–Sr whole-rock isochron age of granitic rocks and associated volcanic rocks in the San-in belt, and demonstrated that these rocks formed in three stages at ca. 80 Ma (Late Cretaceous; Mochigase stage), 75–50 Ma (Late Cretaceous to Early Paleogene; Inbi stage), and 44–30 Ma (Late Paleogene; Tamagawa stage). Most of San-in granitic rocks likely belong to the Shimanto orogenic belt, whereas much younger granitic rocks of the Tamagawa stage, as well as the Paleogene Accretionary complex of the Southern Shimanto belt, belong to the on-going orogeny.

Thick Upper Cretaceous (Campanian to Maastrichtian; ca. 84–65 Ma) turbidites (the Izumi Group) cover unconformably mid-Cretaceous Ryoke granitic rocks (e.g. Matsumoto, 1953; Suyari, 1973; Hashimoto and Ishida, 1997). These sedimentary rocks filled the Cretaceous fore-arc basin developed during the Shimanto orogeny.

5.2. Spatial arrangement of orogenic components

Within the Sanbagawa orogenic belt, the Late Jurassic–Early Cretaceous accretionary complex (Southern Chichibu belt) and its HP metamorphosed part (Sanbagawa metamorphic rocks) occur on the ocean side of the coeval Ryoke–Sanyo granite batholith belt (Fig. 6b). Likewise in the Shimanto orogenic belt, the Late Cretaceous accretionary complex (Northern Shimanto belt) and its HP

Fig. 9. (a) Original configuration of the Cretaceous Sanbagawa orogenic belt in SW Japan (ca. 100 Ma), (b) Removal of granite crust and old orogenic belts by contraction–erosion due to the opening of the Japan Sea (ca. 20 Ma) (modified after Isozaki, 1996). The juxtaposition of the Sanbagawa metamorphic belt and the Ryoke (+ Sanyo) belt was caused by the movement of the low-angle paleo-MTL that likely formed as a mid-crustal detachment in the fore-arc during the Miocene back-arc (Japan Sea) spreading.
metamorphosed part (Shimanto metamorphic rocks) occur on the ocean side of the coeval fore-arc deposits (the Izumi Group) and San-in batholith belt (Fig. 6a) Thus, the present distribution of the components basically reflects their primary arrangement in the two distinct orogenic belts that formed in Cretaceous to Paleogene time.

In the Sanbagawa orogen, however, there is a strange mode of occurrence of orogenic components; i.e. the Sanbagawa HP metamorphic rocks occur in direct contact with the coeval Ryoke–Sanyo batholith belt along the Median Tectonic Line (MTL). As pointed out by previous researchers (e.g. Uyeda and Miyashiro, 1974), these two belts should not have originally formed adjacent to each other on the basis of their P–T relationships. Therefore, their current distribution indicates their juxtaposition by secondary processes.

In the Kii Peninsula and Shikoku of SW Japan, the Sanbagawa metamorphic belt and the Ryoke–Sanyo batholith belt are bounded by the MTL, a vertical right-lateral strike-slip fault on the surface. In the deeper crust, however, these two units are bounded by a much gently northward dipping fault as clearly demonstrated by recent seismic profiles (Sato et al., 2005; Ito et al., 2009; Fig. 7). Thus along this major boundary fault, the Ryoke–Sanyo belt structurally overlies the Sanbagawa metamorphic belt. On the basis of the surface geological mapping in SW Japan, Isozaki and Maruyama (1991) and Isozaki and Itaya (1991) suggested this structural relationship between the two major components, and emphasized the significance of a low-angle boundary fault (Paleo-MTL) with respect to the younger lesser important strike-slip fault (Neo-MTL) (Fig. 8). They interpreted the Paleo-MTL to have formed during a Miocene back-arc spreading that opened the Japan Sea.

We follow this interpretation and suggest that the Ryoke–Sanyo batholith belt was thrust southward to overlie the Sanbagawa metamorphic belt by reactivation of a mid-crustal low-angle fault in the arc crust during opening of the Japan Sea. The subsequent strike-slip movement of Neo-MTL occurred later when the Nanakai fore-arc sliver became activated. For further details of the opening of the Japan Sea, refer to Tamaki (1985), Otofuji and Matsuda (1987), Jolivert et al. (1994) and Yanai et al. (2010).

Given the overthrusting of the Ryoke–Sanyo batholith belt over the Sanbagawa metamorphic belt, we need to estimate the original distance between these two belts before the across-arc shortening. The Ryoke–Sanyo batholith belt formed immediately below the volcanic-front at the time. The Sanbagawa metamorphic rocks (sl) were exhumed sometime in the Late Cretaceous and were exposed on the surface at the non-volcanic outer arc near the trench by the Paleogene (ca. 50–40 Ma) (e.g. Isozaki and Itaya, 1990).

![Fig. 10. Schematic illustration of the modification of the arc-trench setting of the SW Japan segment in East Asia by tectonic erosion before (a) and after (b) ca. 90–80 Ma. Tectonic erosion tectonically eroded older fore-arc crustal materials and buried them in the mantle at 90–80 Ma. As a result, Position of both the trench and volcanic front retreated landward. Therefore, the San-in batholith was positioned landward of the Ryoke–Sanyo batholith belt.](image-url)
Thus, the Ryoke–Sanyo batholith belt must have been subhorizontally overthrust from the volcanic front toward the trench to override the Sanbagawa metamorphic belt. The present volcanic front is located about 100–150 km above the top of the subducting oceanic slab, regardless of the subduction angle (e.g. Hirose et al., 2008; Hasegawa et al., 2008; Nakajima et al., 2009). The distance between the trench and volcanic front changed as follows: e.g. more than 100–150 km in case of a subduction angle of less than 45 degrees, or less than 100–150 km in the case of a subduction angle higher than 45 degrees. Although precise value is unavailable for the past, the subduction angle should have been less than 30–50 degrees, according to the present examples in NE Japan; i.e. 30–50 degrees where an oceanic plate of ca. 100 Ma is being subducted. Thus, we can estimate that the Sanbagawa metamorphic belt and Ryoke–Sanyo batholith belt were originally separated by more than 100 km.

The low-P/T metamorphic rocks of the Ryoke belt (P = 3–6 kbar and T = 500–800 °C) are accompanied with intrusions of granitic rocks (Hokada, 1996; Okudaira, 1996; Brown, 1998; Kawakami, 2001; Ikeda, 2004). The depth of low-P/T metamorphism based on pressure conditions corresponds to a mid-crustal level (ca. 10–20 km deep), which accommodates the brittle–ductile transition boundary of continental crustal rocks. Thus, it is likely that continental crust was detached along this boundary when the back-arc spreading occurred in the Miocene. It is probable that a large amount of the fore-arc crust as well as the Ryoke–Sanyo batholith belt were eroded during horizontal shortening. These eroded materials were carried to the trench forming a huge Miocene accretionary complex (Fig. 9).

5.3. Modification by tectonic erosion

Although Pacific-type orogenic belts were previously considered to grow unidirectionally ocean-ward with time (Isozaki and Maruyama, 1991; Isozaki, 1996; Maruyama, 1997), this model does not explain the present distribution of the relatively older Ryoke–Sanyo batholith belt on the ocean side with respect to the younger San-in batholith belt (Figs 6 and 7).

Recent age spectrum analyses of detrital zircons from the Paleozoic to Cenozoic sandstones and psammitic schists in Japan have shown that major tectonic erosion has occurred at least four times during the 500 Ma history of the Japanese Islands (Isozaki et al., 2010a, 2011; Nakama et al., 2010; Suzuki et al., 2010). In this regard, it is noteworthy that one of such tectonic erosion episodes occurred just between the Ryoke–Sanyo and San-in batholith emplacements.

The processes of tectonic erosion can bury older fore-arc crustal material into the mantle (e.g. Nasu et al., 1980; von Huene and Lallemant, 1990; von Huene and Scholl, 1991, 1993; Lallemant, 1996; Clift and Vannucchi, 2004; Kukowski and Oncken, 2006; Scholl and von Huene, 2009; Yamamoto, 2010). Consequently, both positions of trench and volcanic front of the arc retreat toward continent; that is the opposite direction to continental growth. Thus the secondary across-arc shortening can explain why the relatively younger San-in batholith belt developed on the continent side of the older Ryoke–Sanyo batholith belt (Fig. 10) without any contradiction in the overall tectonic scenario. For further discussion of the tectonic erosion recognized in the Phanerozoic Japan, refer to Isozaki et al. (2010a, 2011), Nakama et al. (2010) and Suzuki et al. (2010).

6. Conclusion

The role of ridge subduction has been extensively used to explain an orogenic peak activity within the context of a Pacific-type orogenic event that starts from one ridge-subduction and ends with subduction of the next ridge by Isozaki and Maruyama (1991), Isozaki (1996) and Maruyama et al. (1996, 1997). This general framework clearly explains the overall growth history of the Japanese Islands; however, in the case of the Late Cretaceous–Paleogene tectonics in Japan, the distinction of orogenic cycle is not straightforward because of the existence of two discrete orogenies, i.e. the Sanbagawa and Shimanto, which occurred within a short time interval. The duration of ca. 15 million years between the two orogenies was too short for previous age analyses to differentiate. This explains why the Shimanto orogenic belt was not previously recognized. However, recent techniques, particularly high-resolution chronology, provide a means to document the specific orogenic history of ancient subduction-related orogenic belts exposed on land.
Fig. 11 summarizes formation ages of the main components of the Sanbagawa and Shimanto orogenic belts. In the case of the Shimanto orogeny, the progressive HP metamorphism occurred in ca. 80–60 Ma, and the exhumed metamorphic rocks are widespread in SW Japan (Aoki et al., 2008, 2009), whereas nearly coeval granitic rocks of the main San-in belt formed at about 75–50 Ma. By analyzing relative motions around Japan, Maruyama and Seno (1986) clarified that the subduction of the Pacific plate beneath Japan started around ca. 70 Ma. According to the scheme mentioned above, the peak activity of the Shimanto orogeny was triggered by the subduction of the Kula/Pacific ridge sometime around 70 Ma in SW Japan. On the other hand, the Sanbagawa progressive HP metamorphism occurred at ca. 120–110 Ma, and then metamorphosed rocks suffered the retrogressive metamorphism with hydration during the exhumation by ca. 85–70 Ma (e.g. Aoki et al., 2008, 2009), whereas the granites of the Ryouke–Sanyo batholith belt formed at ca. 120–70 Ma. As the subduction of the Kula plate started by 85 Ma (Maruyama and Seno, 1986), the peak of the Sanbagawa orogeny was probably induced by the subduction of the Izu-nagi/Kula ridge sometime around 85 Ma in SW Japan.

This type of approach with high-resolution chronology can be applied to the studies of tectonics elsewhere in the world, in particular, the orogenic belts with composite aspects that likely formed through multiple tectonic episodes.

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