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Review

Evolution of the Sanbagawa and Shimanto high-pressure belts in SW Japan: Insights from K–Ar (Ar–Ar) geochronology

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ABSTRACT

The Sanbagawa belt *sensu lato* in Japan is one of the world's classical high-pressure (HP) metamorphic belts and has long been considered to be a coherent HP belt of the Cretaceous age. However, recent progress in detrital zircon geochronology together with the accumulation of abundant phengites K–Ar (Ar–Ar) ages revealed that the belt is comprised of two petrotectonic belts—Sanbagawa *sensu stricto* HP belt and Shimanto HP belt. These two belts have distinctly different ages of peak metamorphism and different P–T conditions of metamorphism. The Sanbagawa schists *sensu stricto* were metamorphosed in the conditions of the pumpellyite–actinolite facies through the epidote–blueschist to epidote–amphibolite facies and up to the eclogite facies during a prograde stage in a subduction zone at 120–115 Ma. Phengite K–Ar geochronology revealed that the subsequent exhumation after the peak metamorphism took place in a manner that the higher-grade rocks exhumed more rapidly in comparison with the lower-grade rocks; this is supported by a positive correlation between age and apparent metamorphic gradient that have formed during the post-metamorphic peak hydration/recrystallization. Moreover, the schists have experienced intense ductile deformation and long-term exhumation; it took longer than 31 m.y. to reset the phengite K–Ar system. In contrast, the Shimanto HP schists were metamorphosed in the epidote–blueschist/greenschist transitional facies to the epidote–amphibolite facies and have experienced a short-term deformation for less than 13 m.y. This short deformation formed a negative correlation between K–Ar age and apparent metamorphic gradient. These two contrasting age–temperature relationships suggest different exhumation processes between the two HP belts, most likely due to a change in subducting oceanic plates in the Cretaceous along the paleo-Japanese convergent margin.

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1. Introduction

Phengite is a main K-rich phase in high-pressure (HP) rocks and has been used to date approximate timing of subduction-zone metamorphism with K–Ar (Ar–Ar) method (e.g., Itaya and Takasugi, 1988; Tsujimori and Itaya, 1999; Nishimura et al., 2000). In SW Japan, more than 1000 phengite K–Ar (Ar–Ar) data have been collected from rocks of HP metamorphic belts and accretionary complexes (ACs) during last two decades; the results clearly suggest an episodic exhumation of HP belts during the orogen growth since the Early Paleozoic (Figs. 1 and 2). Many HP schists in SW Japan have suffered ductile deformation during exhumation and cooling of the HP belts. Therefore, the systematic K–Ar age mapping along a metamorphic gradient that characterizes the relationship

between temperature and deformation/recrystallization in a single metamorphic sequence provided critical information on exhumation processes (e.g., Itaya and Takasugi, 1988; Nishimura et al., 2000; Nuong et al., in press). Since there is no significant amount of excess argon in metamorphosed oceanic materials in Pacific-type HP metamorphic belts, systematic applications of K–Ar geochronology are, therefore, potentially very useful in placing constraints on how Pacific-type oceanic convergent margins evolve in general.

The Sanbagawa belt *sensu lato* that trends roughly E–W over 800 km in SW Japan is one of the best-studied and classical high-pressure (HP) metamorphic belts (Fig. 1). It has been considered that the Sanbagawa belt *sensu lato* consists of an 130–120 Ma accretionary complex that was subjected to subduction-zone metamorphism at peak P–T conditions ($P = 1.5\text{--}2.2$ GPa, $T = 500\text{--}750$ °C) at 116 Ma and retrograde metamorphism ($P = 0.7\text{--}1.1$ GPa, $T = 460\text{--}510$ °C) at around 86 Ma (e.g. Isozaki

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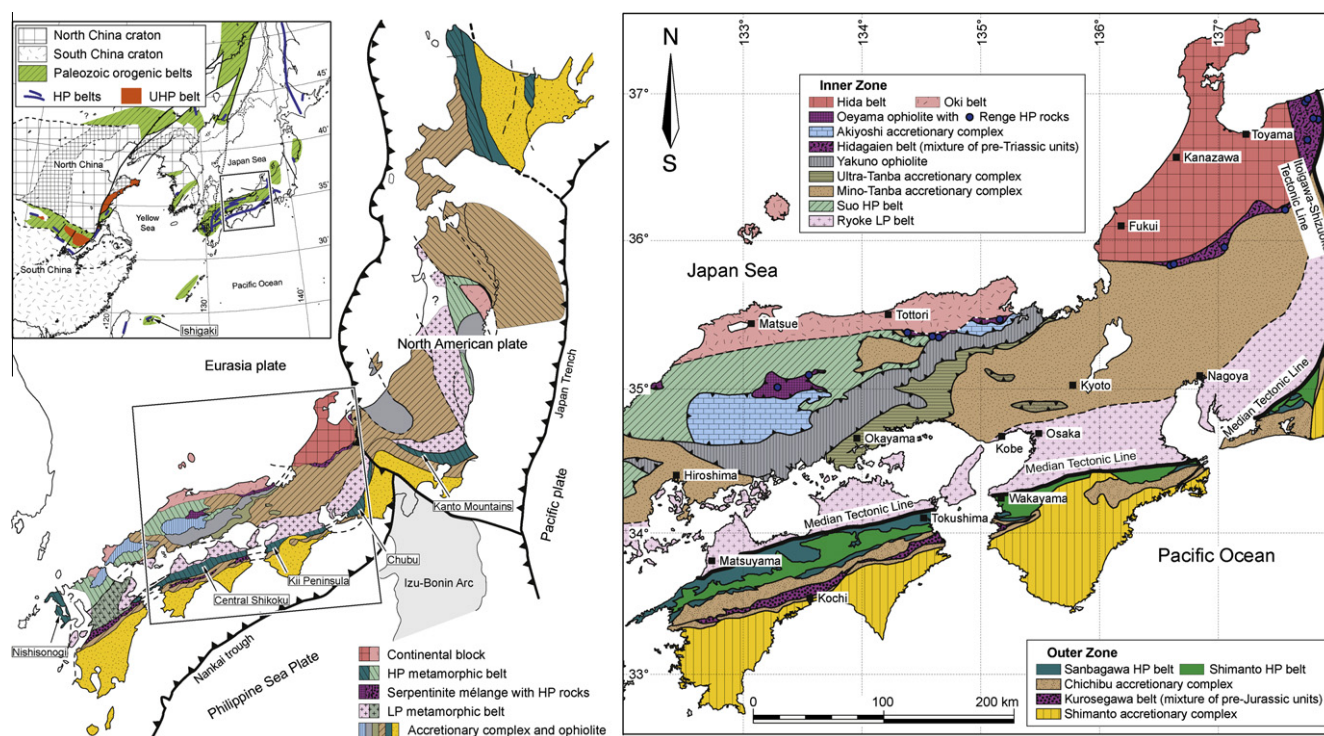


Fig. 1. Geotectonic subdivision of the Japanese Islands (modified after Ishiwatari and Tsujimori (2003) and Isozaki et al. (2010a)). The unit boundary between the Sanbagawa HP belt and Shimanto HP belt in Shikoku is compiled from Aoki et al. (2010a,b) and Isozaki et al. (2010a).

and Itaya, 1990; Okamoto et al., 2004; Aoki et al., 2009). The regional metamorphic mapping shows a systematic changes of the appearance of characteristic Fe–Mg silicate minerals in metapelite (Kurata and Banno, 1974; Higashino, 1975, 1990; Itaya, 1981; Enami, 1983; Banno and Sakai, 1989). In order of increasing metamorphic grade these zones are: the chlorite (Chl), garnet (Grt), and biotite (Bt) zones; the Bt zone is further subdivided into the albite–biotite (Ab–Bt) and oligoclase–biotite (Olg–Bt) zones (Enami, 1983). Metamorphic zones have also been defined using the amphibole compositions in hematite-bearing mafic schists (Otsuki and Banno, 1990); with increasing grade the amphibole species shows the follow progressive changes from actinolite through winchite, glaucophane, and barroisite to hornblende.

In spite of extensive and numerous investigations (cf. Banno et al., 1986; Isozaki and Itaya, 1990), timing of HP metamorphism has not been well constrained. Recent detrital zircon geochronology combined with K–Ar geochronology revealed that the Sanbagawa belt *sensu lato* should be subdivided into two HP belts—Sanbagawa belt *sensu stricto* and Shimanto belt (Aoki et al., 2007, 2009, 2010a, this issue; Isozaki et al., 2010a,b); the Shimanto HP belt is a newly-defined petrotectonic belt and differs from the Shimanto accretionary complex (Fig. 1). Moreover, the timing of Sanbagawa peak metamorphism (89–88 Ma Lu–Hf ages of garnet and omphacite pairs by Wallis and Endo (2010) vs. 120–110 Ma by Aoki et al. (2010b), for examples) remains to be debated.

In the present review article, we begin with a brief description of research history of the traditional “Sanbagawa” (*sensu lato*) belt. We then summarize the available geochronologic data of both the Sanbagawa *sensu stricto* and Shimanto HP belt. Finally, we discuss the phengite geochronology based mainly on our systematic K–Ar (Ar–Ar) dating of phengites from low- to high-grade rocks of these two HP belts. Our review also addresses a new idea of the closure temperature of phengite that is highly controlled by ductile deformation during exhumation of HP rocks.

2. Research history of the traditional Sanbagawa belt

2.1. General history

The Japanese Islands preserve multiple records of oceanward accretion/growth and landward erosion/denudation of a Pacific-type orogen (cf. Isozaki et al., 2010a,b); they are now composed of several petrotectonic units (Fig. 1); the major units of various ages consist of (1) subhorizontal and intermittent accretionary complexes and ophiolites with downward-younging growth, (2) episodic exhumation of HP metamorphic belts, and (3) emplacement of granitic batholiths with volcanics (e.g. Isozaki and Maruyama, 1991; Isozaki, 1996; Maruyama, 1997; Ishiwatari and Tsujimori, 2003; Isozaki et al., 2010a). All HP metamorphic belts are metamorphosed accretionary complexes that show a protolith suite of trench turbidites, oceanic crust, cherts, and minor ultra-mafic rocks.

After the first recognition of schists and gneisses in Japanese Islands by Nauman (1885), Koto (1989) of the Imperial University of Tokyo proposed the Sanbagawa series for crystalline schists crop out along the “Sanbagawa valley” in the Kanto Mountains. He correlated this unit with crystalline schists in Shikoku 800 km west of the Kanto Mtms and suggested a Precambrian age for this long and narrow metamorphic belt with Sanbagawa schists in Japan. During the period of 1895–1910, several geological maps (1:200,000) of “Sanbagawa” schists were completed in the Tokushima, Kochi and Matsuyama areas of Shikoku Island; a complete geological mapping of the Sanbagawa belt was made after the 2nd world war. In 1960s, Miyashiro (1961, 1973) postulated the concept of “paired metamorphic belts”, and considered that the Sanbagawa HP belt was paired with the Ryoke low-pressure (LP) belt. This significant contribution publicized the name “Sanbagawa” as a world-class metamorphic belt and emphasized the importance of paired metamorphic belts in our understanding of plate convergent processes.

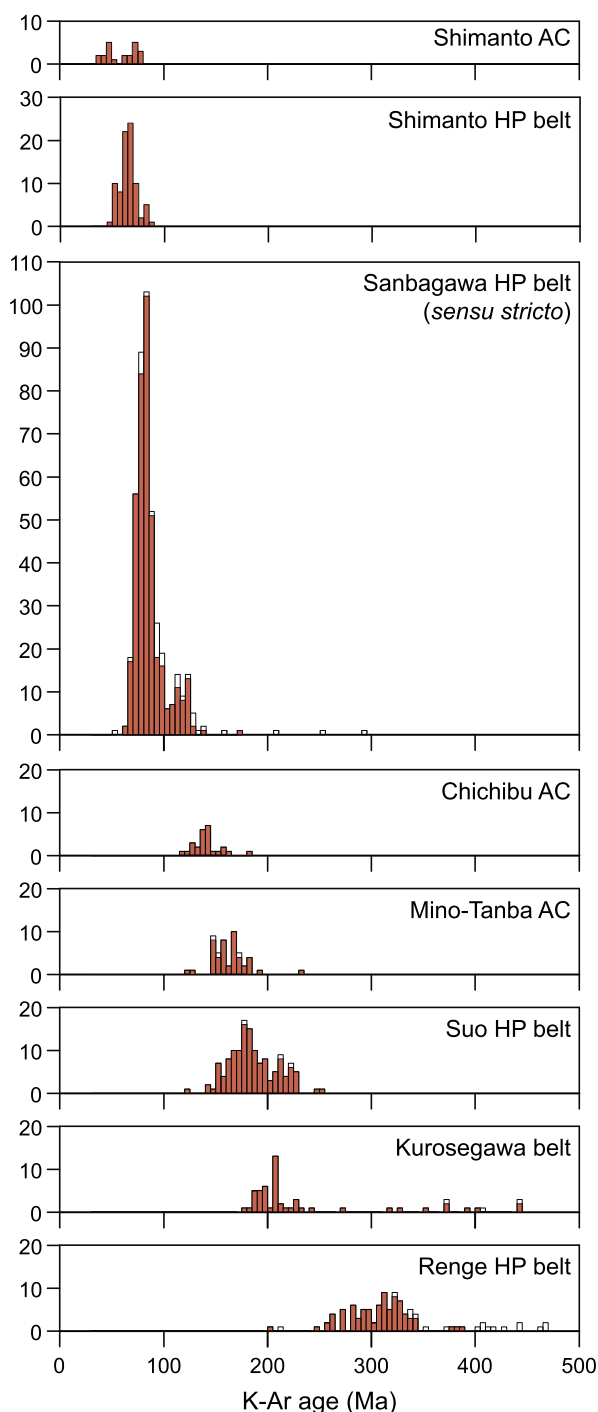


Fig. 2. K–Ar (Ar–Ar) age histograms showing various HP metamorphic belts and accretionary complexes in SW Japan (See references in Supplementary Material). Red bins—phengite and illite K–Ar ages of pelitic schists, White bins—whole-rock, paragonite, and amphibole K–Ar ages from psammitic, schist, mafic schist, amphibolite, eclogite.

2.2. Structural studies

Professor George Kojima and his colleagues of Hiroshima University conducted extensive structural studies of the Sanbagawa belt in Shikoku based on detailed distribution on protoliths of the schists (cf., Kojima et al., 1956; Hide, 1954; Hara et al., 1977, 1992). They recognized two deformation phases; the Nagahama–Ozu deformational phase is characterized by nappe formation with large-scale recumbent folds vergent towards the south, and the Hizikawa phase is characterized by the formation of large-scale upright folds

oriented in *en echelon* fashion. They also proposed that the Sanbagawa belt is situated to the south of the Ryoke LP metamorphic belt that is closely associated with granitic intrusives and to the north of the Chichibu AC (Fig. 1). In contrast, European structural geologists emphasized ductile flow for Sanbagawa structures (Faure, 1983, 1985; Wallis, 1990; Wallis et al., 1992) with the flow direction sub-parallel to the trend of belt eastward (Faure, 1983) or westward (Wallis et al., 1992). It was important that they demonstrated the ductile deformation microstructures such as strong stretching mineral lineation and sheath folding were formed post-metamorphic stage during the exhumation. Moreover, the tectonic boundary studies to define the domain of the Sanbagawa HP belt *sensu lato* were conducted by Isozaki and his students and K–Ar laboratory of Okayama University of Science (e.g. Suzuki et al., 1990; Kawato et al., 1991; Sasaki and Isozaki, 1992).

2.3. Petrologic studies

Study of mineral parageneses and major-element compositions from Sanbagawa HP schists began in the 1930s (Suzuki, 1930; Horikoshi, 1937). Metamorphic zones were mapped based on the appearance of index minerals and metamorphic facies established based on mineral assemblages and chemistry of characteristic minerals by Seki (1958), Iwasaki (1963) and Banno (1964); they delineated facies series and concluded that protoliths of the Sanbagawa belt has been subjected to HP metamorphism. A comparative study of subduction-zone metamorphic assemblages from the Sanbagawa belt and the Franciscan Complex of California Coast Range was conducted through a US–Japan project by Seki and Ernst (Ernst et al., 1970). The similarity of metamorphic zones led them to conclude progressive subduction of the oceanic lithosphere to greater depths. Banno and his colleagues made most intensive and detailed analyses of minerals from Sanbagawa HP schists in central Shikoku and applied precise analytical method to map the appearance of index minerals and mineral composition from regional to microscopic scales (Kurata and Banno, 1974; Higashino, 1975, 1990; Itaya, 1981; Enami, 1983; Banno and Sakai, 1989). Well-constrained P–T determinations of metamorphic zones combined with spatial zonal distribution led to establish a thermal structure of the Sanbagawa belt (e.g., Banno et al., 1978). They proposed a large-scale recumbent fold with south vergency; the highest-grade rocks occur in the middle part of apparent stratigraphy extend for more than 20 km. However, such thermal structure was not consistent with kinematic data obtained by structural geologists (Hara et al., 1992); hence a debate existed between metamorphic petrologists and structural geologists for the exhumation tectonics of the Sanbagawa belt as described in later section.

The metamorphic sequence of the Sanbagawa belt *sensu lato* in central Shikoku ranges in grade from the pumpellyite–actinolite through epidote–blueschist to epidote–amphibolite facies (Banno and Sakai, 1989). It has been known that some highest-grade rocks reached eclogite-facies conditions (e.g., Kunugiza et al., 1986; Ota et al., 2004). As P–T estimates of Sanbagawa eclogites differ significantly from those of the highest-grade schists, Takasu (1984, 1989) and Wallis and Aoya (2000) have considered that eclogite-facies rocks occur as tectonic blocks or nappes. Moreover, Aoki et al. (2009) recognized some relict eclogite-facies minerals from Ab–Bt/Olg–Bt zone rocks and suggested the present-day epidote–amphibolite-facies mineral parageneses were formed at retrograde conditions with an extensive hydration during exhumation. This suggestion is consistent with the occurrences of eclogite-facies rocks from the Ab–Bt zone in the Seba area reported by Aoya (2001) and Muori and Enami (2008). Aoki et al. (2009) also proposed the eclogite-facies metamorphism as an integral part of the Sanbagawa belt together with the surrounding schists under a specific thermal gradient at depth in the subduction zone.

2.4. Geochronology

Since 1965, radiometric ages of Sanbagawa schists *sensu lato* have been attempted with K–Ar (Ar–Ar) and Rb–Sr whole rock and mineral isochron geochronology (e.g., Banno and Miller, 1965; Hayase and Ishizaka, 1967; Yamaguchi and Yanagi, 1970; Ueda et al., 1977; Minamishin et al., 1979; Watanabe et al., 1982; Monie et al., 1987; Shibata and Takagi, 1988; Itaya and Takasugi, 1988; Dallmeyer and Takasu, 1991; Hirajima et al., 1992). The reconnaissance data yield Cretaceous ages, leading to suggest that the Sanbagawa metamorphism occurred in the Cretaceous (see review by Isozaki and Itaya (1990)).

2.5. Subdivision of the “Sanbagawa” belt

Recent study by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) on detrital zircon U–Pb geochronology by Aoki et al. (2007; also see the review by Aoki et al. (this issue)) from psammitic schists and meta-conglomerates of the Oboke area in central Shikoku showed that the depositional ages of host sediments were at 90–80 Ma. These ages are significantly younger than the 120–110 Ma that have been considered as peak ages of the Sanbagawa metamorphism. Based on these detrital zircon ages (Manabe et al., 1996; Aoki et al., 2008) together with the young K–Ar ages (66–61 Ma) for phengites from pelitic schist (Itaya and Takasugi, 1988; Aoki et al., 2008), Aoki et al. (2010a; also see the review by Aoki et al. (this issue)) and Isozaki et al. (2010b) proposed the separation of the Shimanto HP belt from the Sanbagawa HP belt *sensu stricto* (Fig. 1). Isozaki et al. (2010a) described that the relatively younger Shimanto HP belt (Aoki et al., 2007, 2008) occurs tectonically beneath the Sanbagawa HP belt *sensu stricto* in Shikoku, Kii, and Kanto regions and confirmed that the Sanbagawa belt *sensu stricto* is less than half in spatial distribution than has been previously regarded.

High-resolution ion-microprobe (SHRIMP II) U–Pb study of detrital zircons from psammitic schists from the Kanto Mtms also confirmed the youngest zircons of Late Cretaceous age (Tsutsumi et al., 2009); phengite K–Ar ages of pelitic schist from same area have been reported ranging from 82 to 60 Ma (Hirajima et al., 1992; Miyashita and Itaya, 2002). Moreover, Otoh et al. (2010) also found Late Cretaceous igneous zircons from psammitic schists in the Kii Peninsula. Reconnaissance detrital zircon U–Pb geochronology using LA-ICPMS and ion-microprobe to support this new subdivision has just begun. Recently Mori et al. (2011) reported LA-ICPMS U–Pb age of 126 ± 6 Ma relict igneous zircons in jadeitite from Nishisonogi metamorphic rocks in Kyushu. Using the same facility of Mori et al. (2011), Kouchi et al. (2011) reported 86 ± 2 Ma detrital zircons from psammitic schist from Nishisonogi metamorphic rocks and correlated Nishisonogi metamorphic rocks to the Shimanto HP belt. However, Yui et al. (2011) reported ion-microprobe (SHRIMP RG) U–Pb ages of 136 ± 2 Ma from same jadeitite of Mori et al. (2011). The age discrepancy resulting from systematic calibration difference between laboratories and facilities should be considered more seriously in future. Considering preexisting phengite K–Ar ages, the Sanbagawa belt *sensu lato*

likely extends to Nishisonogi metamorphic rocks in Kyushu, and the Shimanto HP belt extends to “Sanbagawa” schists in the Kii Peninsula and Chubu region, and Kanto Mtms (see the later section).

In central Shikoku, the newly defined Shimanto HP rocks contain the blueschist-facies mineral assemblages formed at 0.4–0.5 GPa and 240–270 °C (Aoki et al., 2008). In the Kanto Mtms, much higher-grade schists of Grt– and Ab–Bt zone are dominant; their metamorphic conditions reach to the epidote–amphibolite facies (e.g., Miyashita and Itaya, 2002). The paragonite + clinzoisite assemblage in prograde-zoned garnet of pelitic schist suggests a peak metamorphic condition at 0.8–1.1 GPa and $T = 340$ – 440 °C (Miyashita et al., 2009).

3. Lithology and ages of protoliths for the “Sanbagawa” metamorphic rocks

3.1. Sanbagawa HP belt (*sensu stricto*)

The Sanbagawa schists *sensu stricto* consist mainly of metabasites, pelitic and psammitic schists, and subordinate amounts of siliceous and calcareous schists; these were likely derived from basaltic–gabbroic greenstones, mudstones, siliciclastic sandstones, cherts and limestone, respectively. The protoliths of psammitic and pelitic schists are of continental affinity whereas those of metabasites, and siliceous and calcareous schists are oceanic in origin. Thin layers of serpentinite are common in pelitic/psammitic schist sequence. Mafic–ultramafic cumulate bodies (e.g., Iratsu and Higashi-akaishi bodies) occurs in central Shikoku and preserved eclogite-facies mineral assemblage (e.g., Kunugiza et al., 1986; Terabayashi et al., 2007); some HP-metamorphosed mafic cumulates are associated with recrystallized pelagic limestone and even contain relict granulite-facies mineral assemblage (Yokoyama and Itaya, 1990; Goto and Banno, 1996; Terabayashi et al., 2007). In the Iratsu and Higashi-akaishi body, the reconstructed oceanic plate stratigraphy in ascending order of peridotite, gabbro, basalt, limestone, minor chert, and pelite suggests that different parts of the protolith were derived from a mid-oceanic topographic high, an oceanic island or plateau, and an overlying trench turbidite; these oceanic sequences then have experienced the HP metamorphism in a subduction zone (Terabayashi et al., 2007). The lithotectonic assemblage of the Sanbagawa belt *sensu stricto* corresponds well to that of modern and ancient accretionary complexes, suggesting that the oceanic protoliths of Sanbagawa schists were accumulated and mixed at ancient trench sediments and subsequently subducted to greater depths for HP metamorphism (e.g. Okamoto et al., 2000; Terabayashi et al., 2007; Masago et al., 2007).

Matsuda (1978) described middle-Upper Triassic conodont fossils in calcareous schist of the pumpellyite–actinolite (Pmp–Act) zone in southern margins of the Sanbagawa belt *sensu stricto* in Shikoku. His findings led other paleontologists to search fossils in Sanbagawa schists (Table 1). Kuwano (1979) and Suyari et al. (1980a,b) reported Upper Triassic conodonts in calcareous schists interleaved with mafic and pelitic schists of the Pmp–Act zone at several localities in Shikoku. Iwasaki et al. (1984) found Upper

Table 1
List of diagnostic fossils from the Sanbagawa HP belt *sensu stricto* in Shikoku.

| Rock type | Locality | Metamorphic grade | Age | Fossil | Reference |
|-------------------|--------------------|-------------------|-----------------------|------------|--------------------------|
| Volcanic mudstone | Okawara, Tokushima | Pmp–Act | Upper Jurassic | Radiolaria | Iwasaki et al. (1984) |
| Limestone | Doi, Kochi | Pmp–Act | Middle-Upper Triassic | Conodont | Suyari et al. (1980a) |
| Limestone | Ikegawa, Kochi | Pmp–Act | Middle-Upper Triassic | Conodont | Matsuda (1978) |
| Limestone | Tsuboi, Kochi | Pmp–Act | Middle-Upper Triassic | Conodont | Kuwano (1979) |
| Limestone | Sozu, Ehime | ? | Upper Triassic | Conodont | Suyari et al. (1980b) |
| Limestone | Yawatahama, Ehime | ? | Upper Triassic | Conodont | Suyari et al. (1980b) |
| Chert | Okuki, Ehime | Pmp–Act | Lower–Upper Jurassic | Radiolaria | Sakakibara et al. (1993) |

Jurassic radiolarians in a series of red volcanic phyllite interlayered with Mikabu greenstone complex—a subunit of Sanbagawa belt *sensu stricto*—of the Pmp–Act zone in east Shikoku. Sakakibara et al. (1993) reported upper Lower Jurassic radiolarian chert xenoliths in the Mikabu greenstone complex. Carboniferous, Permian and Triassic conodonts, and Jurassic radiolarians have also been found in weakly metamorphosed rocks associated with the Mikabu greenstone complex in Shikoku and Kanto Mtns (Fig. 1) (cf. Isozaki and Itaya, 1990). These fossils occur in schists with protoliths of oceanic affinity. For example, calcareous schist associated with metabasite was probably derived from reef limestone that formed at atoll or carbonate mound capping ancient seamounts. The red volcanic phyllite intercalated with thick greenstones is very fine-grained and completely devoid of coarse-grained terrigenous clastics. The bedded radiolarian chert is typical ancient pelagic sediment with unusually slow sedimentation rate (Isozaki, 1987; Matsuda and Isozaki, 1991).

The protolith ages of most metamorphosed igneous rocks are difficult to be determined because of their extensive metamorphic recrystallization. However, primary igneous mineral, if preserved, could be a candidate to determine the timing of magmatic event (Table 2). Relict igneous amphibole in picritic basalt of Kurouchi ultramafic mass of the Mikabu greenstone complex in the Kanto Mtns yielded K–Ar age of 199.4 ± 10.3 Ma (Ozawa et al., 1997a). Igneous hornblendes of gabbroic rocks from the Toba area, Kii Peninsula yield K–Ar ages of 153–142 Ma (Ozawa et al., 1997b). These results suggest that the protoliths of the Mikabu greenstone complex in the Toba area were Upper Jurassic basaltic extrusives on the oceanic floor.

The Bessi-type Cu deposits are strata-bound volcanogenic massive sulfide ores associated with mafic volcanic rocks or their metamorphic equivalents. These deposits are common in the Sanbagawa belt *sensu stricto*. Recently, Nozaki et al. (2010) carried out Re–Os isotopic analyses of sulfides from the limori deposit in western Kii Peninsula, giving 156.8 ± 3.6 Ma isochron age (Table 2). They described that the age is most likely the primary depositional age because the Re–Os closure temperature for the limori sulfide ores was higher than the metamorphic temperature (500 °C) estimated from mineral parageneses of associated epidote–amphibolite facies metamorphic rocks. This suggests that the deposition of volcanogenic sulfides at limori took place on ocean floor in the Upper Jurassic during magmatic crystallization of Toba gabbroic rocks.

3.2. Shimanto HP belt

The Shimanto HP schists also consist mainly of metabasites, pelitic and psammitic schists, and subordinate amounts of siliceous and calcareous schists. Lithologically and structurally, it is very difficult to distinguish the Shimanto HP schist from Sanbagawa HP schist. This was the main reason that both Sanbagawa *sensu stricto* and Shimanto HP belts have long been considered as a single coherent HP belt. On the other hand, the Shimanto HP belt can be petrologically distinguished from the Shimanto AC to the south (e.g., Taira et al., 1988; see Fig. 1 for its distribution) that is characterized by zeolite to prehnite–pumpellyite facies mineral assemblages; the K–Ar illites in the Shimanto AC in the Kanto Mtns yielded ages of 45–65 Ma (Hara and Hisada, 2007).

In the Shimanto HP belt, regional metamorphic mapping by several investigators shows almost identical changes of the appearance of characteristic Fe–Mg silicate minerals in metapelite

with those Sanbagawa schists; three mineral zones (Chl, Grt, and Bt zones) have been defined in order of increasing metamorphic grade in the Kanto Mtns (e.g., Hirajima et al., 1992; Miyashita and Itaya, 2002). In central Shikoku, psammitic schists are dominants and meta-conglomerate contains abundant granitic clast; these granitic clasts yield zircon U–Pb ages of 96–102 Ma (Manabe et al., 1996). The youngest detrital zircons are 92 ± 4 and 82 ± 11 Ma (Aoki et al., 2007); they also confirmed lithological difference of the Shimanto HP belt in central Shikoku.

4. Geochronologic consensus

4.1. Sanbagawa HP belt

4.1.1. Rb–Sr whole rock isochron ages of Sanbagawa schists

The Sanbagawa protoliths include a variety of rock types with long age span ranging from the Triassic to Early Cretaceous. These rocks were subjected to HP subduction-zone metamorphism and contain mineral assemblages from the pumpellyite–actinolite facies to epidote–amphibolite facies and up to eclogite facies. The ages of peak metamorphism of high-grade schists have been determined using a Rb–Sr whole-rock isochron method (Fig. 3a and Table 3).

Minamishin et al. (1979) determined Sr isotope composition from a Bt zone outcrop with three different lithologic units (A, B and C) in central Shikoku and presented a Rb–Sr whole-rock isochron age of 122 ± 12 Ma for unit-C pelitic schist (Fig. 4). Recalculated isochron ages using new decay constant of Rb for each unit are shown in Fig. 4. The Rb–Sr data include 5 unit-A pelitic schists, 10 unit-B psammitic and siliceous schists and 7 unit-C pelitic schists; the unit-B occurs as a 6–12 m thick layer below the unit A and above the unit-C. The unit-B psammitic/siliceous schists show similar linearity but yield larger error (115 ± 26 Ma). In contrast, unit-A pelitic schists having oxidized chlorite as a product of the latest greenschist-facies alteration (e.g., Higashino, 1975) do not yield a reasonable isochron age. It was considered that the Rb–Sr isochron clock was set soon after the peak metamorphism. Thus, we take the Rb–Sr isochron age of 122 ± 12 Ma from unit C pelitic schists as a timing of peak metamorphic condition in central Shikoku (Table 3). In the Kii Peninsula, Yamaguchi and Yanagi (1970) reported a whole-rock Rb–Sr isochron age of 107 ± 16 Ma (recalculated age) defined by three Bt zone schists (Table 3).

Recently, Institute for the Study of the Earth's Interior (ISEI), Okayama University applied multi-geochronology (U–Pb, Sm–Nd, Rb–Sr, K–Ar) for kyanite-bearing quartz eclogites from the Iratsuyu eclogite body. Ion-microprobe U–Pb age of metamorphic zircon yielded around 120 Ma. A Sm–Nd age of 120–115 Ma was obtained for the peak eclogite-facies metamorphism from Grt–Omp–glaucophanitic amphibole–whole-rock isochron and a Rb–Sr age of 109 Ma for epidote–amphibolite facies overprinting based on barroisitic amphibole–phengite–whole-rock isochron (ISEI, unpubl. data). These age constraints are consistent with the data described in this paper and shown in a P–T–time path of Fig. 3.

4.1.2. U–Pb zircon ages of eclogite

High-resolution ion-microprobe (SHRIMP, ims-1270, NanoSIMS, etc.) U–Pb dating of zircon separates from HP-ultra high-pressure (UHP) rocks has been extensively used to constrain the timing of subduction and exhumation of orogenic belts in the

Table 2
Radiometric ages showing protolith (igneous rocks and abyssal ore deposit) ages of the Sanbagawa HP belt *sensu stricto*.

| Rock type | Locality | Method | Age | Reference |
|-----------------|-----------------------|----------------|---------------------|----------------------|
| Picritic basalt | Kurouchi, Kanto Mtns | Amphibole K–Ar | 199.4 ± 10.3 Ma | Ozawa et al. (1997a) |
| Gabbro | Toba, Kii Peninsula | Amphibole K–Ar | 142–153 Ma | Ozawa et al. (1997b) |
| Cu deposit | limori, Kii Peninsula | Re–Os isochron | 156.8 ± 3.6 Ma | Nozaki et al. (2010) |

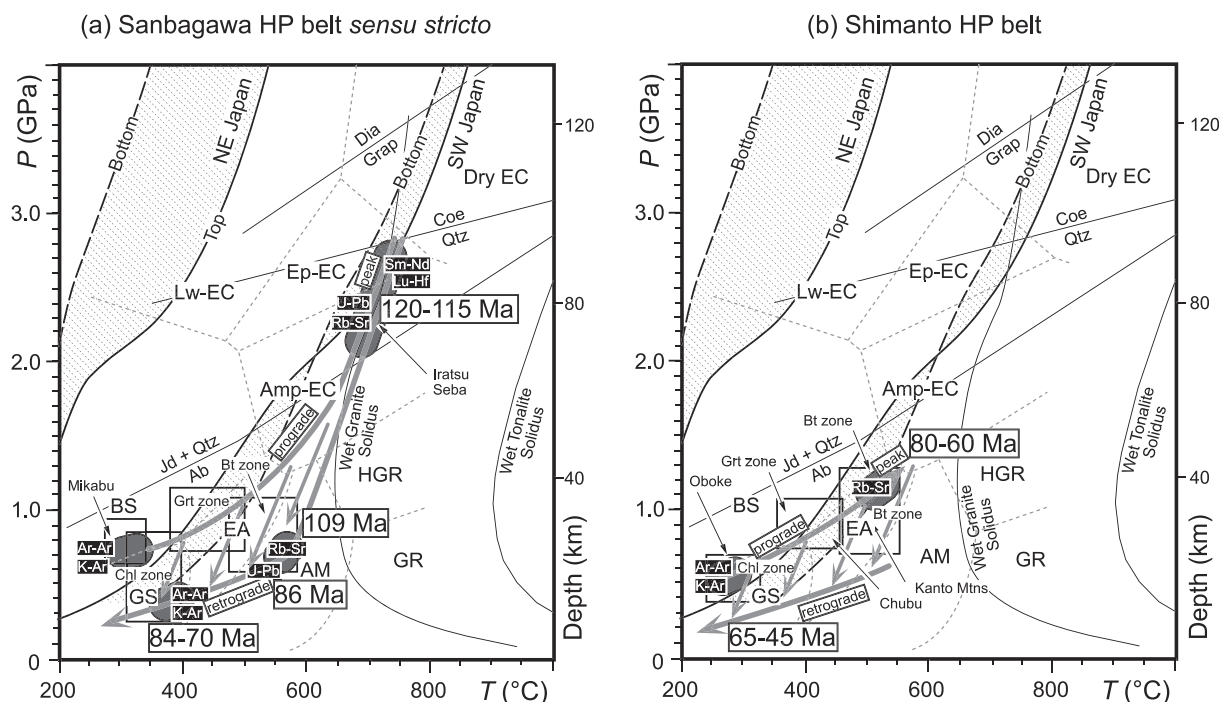


Fig. 3. Metamorphic P–T–t paths for rocks from low to high-grade zones during their exhumation in (a) the Sanbagawa HP belt *sensu stricto* and (b) Shimanto HP belt. The P–T path of the Sanbagawa HP belt *sensu stricto* is modified after Ota et al. (2004). The P–T path of the Shimanto HP belt is modified after Aoki et al. (2008) and Miyashita et al. (2009). Hatched areas represent the calculated P–T conditions for oceanic crust beneath present-day NE Japan (‘cold’) and SW Japan (‘warm’) subduction zones (Peacock and Wang, 1999); the gray solid/dashed lines show the top and bottom of oceanic crust. The metamorphic facies and their abbreviations are after Liou et al. (2004).

Table 3
Radiometric ages showing the metamorphic peak of the Sanbagawa HP belt *sensu stricto* and Shimanto HP belt.

| Rock type | Locality | Metamorphic grade | Age | Method | Interpretation | Reference |
|---------------------------|----------------------------|----------------------------|----------------|--------------------------------|----------------------|-----------------------------|
| <i>Sanbagawa HP belt</i> | | | | | | |
| Pelitic schists | Asemi, central Shikoku | Bt zone | 122 ± 12 Ma | Rb–Sr WR isochron | Peak | Minamishin et al. (1979) |
| Pelitic and mafic schists | Gojyo, Kii Peninsula | Bt zone | 107 ± 16 Ma | Rb–Sr WR isochron | Peak | Yamaguchi and Yanagi (1970) |
| Eclogites | W. Iratsu, central Shikoku | Eclogite-facies (Ky-grade) | 115–113 Ma | Sm–Nd WR–Grt–Omp–Amp isochrons | Peak | ISEI (unpublish. data) |
| Eclogites | W. Iratsu, central Shikoku | Eclogite-facies | 115.9 ± 0.5 Ma | Lu–Hf Grt–Omp isochrons | Pre-eclogite facies? | Endo et al. (2009) |
| Eclogites | Seba, central Shikoku | Eclogite-facies | 88.8 ± 0.6 Ma | Lu–Hf Grt–Omp isochrons | Peak? | Wallis et al. (2009) |
| Eclogites | Kotsu, eastern Shikoku | Eclogite-facies | 88.2 ± 0.5 Ma | Lu–Hf Grt–Omp isochrons | Peak? | Wallis et al. (2009) |
| Eclogites | W. Iratsu, central Shikoku | Eclogite-facies (Ky-grade) | 120–115 Ma | Zrn U–Pb | Peak | Okamoto et al. (2004) |
| Eclogites | W. Iratsu, central Shikoku | Eclogite-facies (Ky-grade) | 121–119 Ma | Zrn U–Pb | Prograde | ISEI (unpublish. data) |
| <i>Shimanto HP belt</i> | | | | | | |
| Pelitic schists | Bungui pass, Chubu | Chi zone | 69 ± 10 Ma | Rb–Sr WR isochron | Peak | Shibata and Takagi (1988) |

world. Okamoto et al. (2004) first applied this method to date zircon from quartz-kyanite eclogite in the Iratsu eclogite body of central Shikoku; the zircon rim yields age range of 120–110 Ma as the age of peak eclogite-facies metamorphism (Table 3) whereas the core yields various ages ranging from 148 to 135 Ma for possible protolith ages. This peak-stage age of 120–110 Ma was consistent with the Rb–Sr isochron age of pelitic schists by Minamishin et al. (1979) and the ion-microprobe U–Pb age for prograde zircon from Iratsu eclogite mentioned above. However, a debate continues after the report of the Lu–Hf analyses of eclogites described below.

4.1.3. Lu–Hf ages of eclogites

Lu–Hf system is a good chronometer for garnet-bearing metamorphic rocks that equilibrated at high-temperature metamorphic

condition. Wallis et al. (2009) reported Lu–Hf isotopic ages of 88.8 ± 0.6 and 88.2 ± 0.5 Ma respectively for strongly zoned garnet and omphacite separates from Seba eclogite in central Shikoku and Kotsu eclogite in eastern Shikoku (Table 3). Endo et al. (2009) also applied the same method to date Iratsu eclogite and obtained an age of 115.9 ± 0.5 Ma (Table 3). Their results pointed out that the two different types of eclogite blocks occur in close association with each other in central Shikoku, although Wallis and Aoya (2000) and Aoya (2001) have proposed that those two eclogite-bearing bodies represented a coherent large-scale eclogite nappe. They interpreted a pre-eclogite-facies metamorphism at 116 Ma and a peak eclogite facies metamorphism at 89 Ma. This is a challenging interpretation against many geologists who studied the Sanbagawa belt, providing a debate between them and others (Wallis and Endo, 2010; Aoki et al., 2010b).

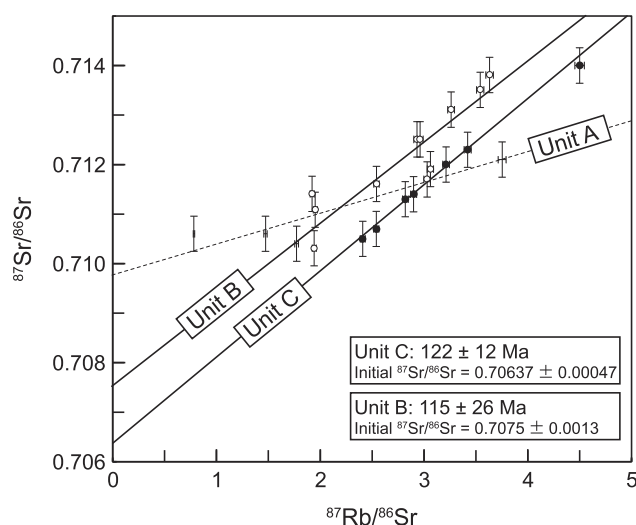


Fig. 4. Rb–Sr whole rock isochron diagrams for the Sanbagawa schists from the oligoclase–albite biotite zone in the Asemi area, central Shikoku. Original data of Minamishin et al. (1979) was re-calculated using a new decay constant of Rb.

We do not support the interpretation of Wallis et al. (2009, 2010) because the two-point isochron ages of garnet–omphacite pairs is easily affected by retrograde recrystallization described below, and two-point data always yield a linear equation that is not isochron.

4.1.4. Timing of retrograde metamorphism

Most Sanbagawa schists have been subjected to various degrees of retrograde metamorphism during exhumation; they contain chlorite after garnet (Higashino, 1975), composite aggregate of ilmenite, rutile and titanite (Itaya and Otsuki, 1978; Itaya and Banno, 1980) and monoclinic pyrrhotite formation (Itaya, 1975). These types of retrograde reactions have also been revealed in New Caledonia HP metamorphic belt (Itaya et al., 1985). However, it was not certain when such retrograde reactions took place because there was no valid method to date the timing of reaction.

Maruyama et al. (1996) pointed out that most UHP metamorphic rocks in a collision zone have been strongly affected by a Barrovian-type retrograde overprint with an extensive hydration that has obliterated most peak mineral assemblages. Similar extensive retrograde recrystallization has also been suggested to occur in Pacific-type HP metamorphic rocks although most blueschist-facies rocks do not contain syn-metamorphic zircons (Maruyama et al., 1996, 2004). Aoki et al. (2009) separated zoned zircon grains in pelitic schist from the Olg–Bt zone; they dated the rim with many phengite inclusions that have identical composition to matrix phengite with an ion-microprobe (Cameca Nano-SIMS) U–Pb method and obtained a concordia age of 85.6 ± 3.0 Ma (Table 3; Fig. 3) and discordia ages for the core. This age of 85.6 ± 3.0 Ma was interpreted as the timing of epidote amphibolite facies overprinting ($P = 0.7\text{--}1.1$ GPa, $T = 460\text{--}510$ °C) of the pelitic schist. The peak metamorphic condition lies within the eclogite-facies at $P = 1.5\text{--}1.9$ GPa and $T = 500\text{--}520$ °C; the peak and retrograde metamorphic conditions were calculated from associated garnet-rich clots preserved in Olg–Bt zone mafic schist using the P–T pseudo-section modeling. The observed mineral paragenesis was formed at retrograde conditions with an extensive hydration during exhumation. This suggestion is consistent with the occurrences of eclogite-facies rocks from the Ab–Bt zone in the Seba area reported by Aoya (2001) and Muori and Enami (2008). In other words, both eclogite and surrounding high-grade Sanbagawa schists have been subjected to coeval *in situ* eclogite-facies metamorphism and eclogites should not be considered as tectonic blocks or nappes as suggested by others (Takasu, 1984, 1989; Wallis et al., 2009).

4.1.5. K–Ar geochronology

Available phengite K–Ar (Ar–Ar) ages from pelitic schists of the Sanbagawa metamorphic belt *sensu lato* are shown in Fig. 5. A N–S traverses of phengite K–Ar ages in central Shikoku is also shown in Fig. 6. There are two distinct age groups recognized in the Sanbagawa HP belt *sensu stricto*. Rocks of the main part of the Sanbagawa HP belt *sensu stricto* yielded K–Ar ages around 81.6 Ma (weighted mean), suggesting timing of the exhumation/cooling at the mid-crustal levels (e.g., Itaya and Takasugi, 1988). These data are

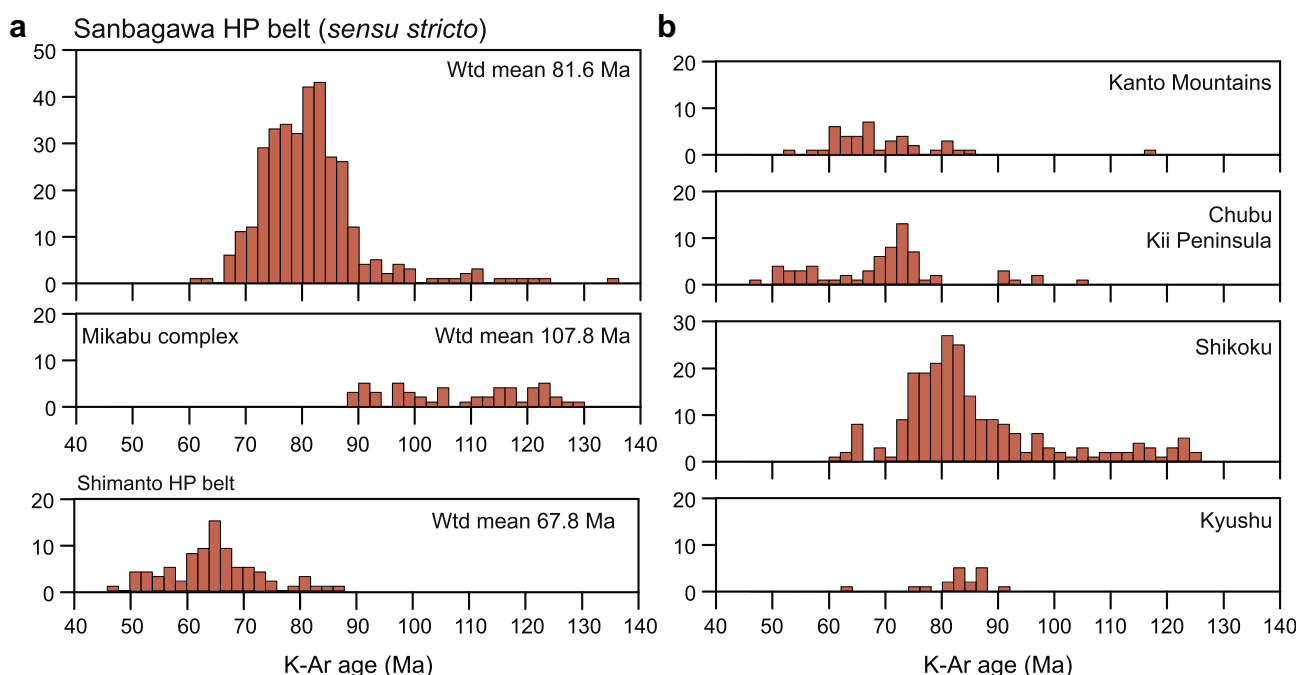


Fig. 5. Histograms of phengite K–Ar ages from pelitic schists from the Sanbagawa HP belt *sensu stricto* and Shimanto HP belt. (a) Sanbagawa HP belt *sensu stricto* vs Shimanto HP belt. (b) Aerial variations.

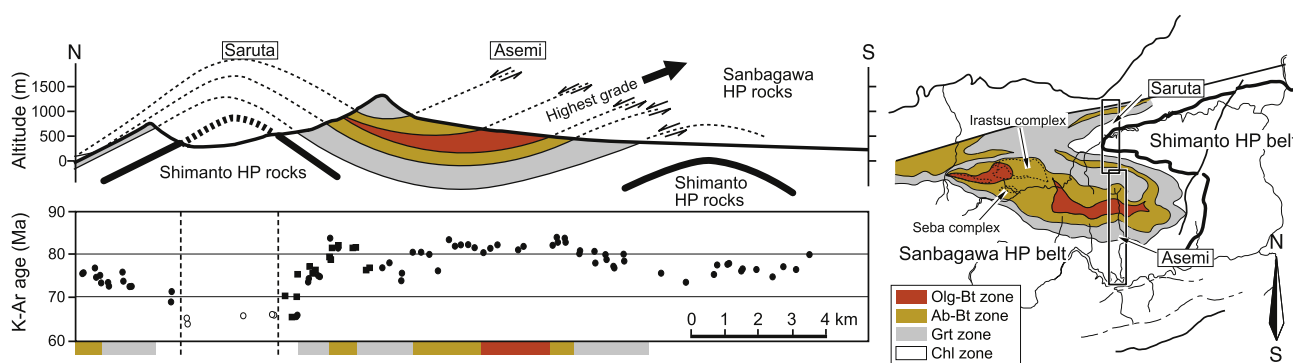


Fig. 6. A N–S traverse of phengite K–Ar ages from pelitic schists in central Shikoku (Itaya and Takasugi, 1988; Yagi, 2002). The Sanbagawa metamorphic sequence has a thermal structure that the highest grade rocks occur in the middle part of the apparent stratigraphy and a positive correlation in age– T relationship that the age becomes progressively older with increasing metamorphic temperature.

significantly younger than the peak ages (115–120 Ma), but they are related to regional exhumation tectonics as described in later sections. On the other hand, the low-grade zone of the Sanbagawa belt *sensu stricto* including the Mikabu greenstone complex and the associated pelitic schists yielded significant older K–Ar ages around 107.8 Ma (weighted mean). These portions of the Sanbagawa belt *sensu stricto* did not suffer extensive hydration/recrystallization during exhumation; in fact, these rocks preserve glaucophane- and rare lawsonite-bearing mineral assemblages (e.g., Suzuki and Ishizuka, 1998). The age variation is mainly due to significant argon depletion from phengites as their host rocks have experienced severe long-duration ductile deformation during exhumation as described below.

4.2. Shimanto HP belt

As described above, detrital igneous zircons from Shimanto HP schists yield about 80–90 Ma that is younger than the peak metamorphic ages of Sanbagawa HP belt *sensu stricto* (Aoki et al., 2007; Tsutsumi et al., 2009). Shibata and Takagi (1988) reported a Rb–Sr whole rock isochron age of 69 ± 10 Ma from seven low- to medium-grade pelitic schists (lower than the lowest Grt zone) in the Chubu region, central Japan. This Rb–Sr age is also significantly younger than the ages from those from Sanbagawa HP belt *sensu stricto* (Table 3). Fig. 5 shows the distribution of phengite K–Ar (Ar–Ar) ages from pelitic schists of the Shimanto HP belt; the data includes Shikoku, Kii Peninsula, Chubu region, and Kanto Mtns. The weighted mean age (67.8 Ma) is significantly younger than that of Sanbagawa HP belt *sensu stricto*. The K–Ar ages along a N–S traverse in central Shikoku show systematic changes between the Shimanto HP belt and Sanbagawa belt *sensu stricto* (Fig. 6). As described in later section, regional variations in phengite K–Ar ages are due to mainly significant argon depletion from phengite in the Sanbagawa schists of central Shikoku, of which the host rocks have experienced severe ductile deformation for long time during exhumation.

5. Phengite geochronology of the Sanbagawa (*sensu stricto*) and Shimanto HP belts

5.1. Closure temperatures

Since the early 1970s, the K–Ar system ages of minerals from metamorphic and igneous rocks have been widely interpreted as cooling ages recording the timing of closure, or cooling through the blocking temperature for argon retention in minerals (Dodson, 1973). The closure T of K-bearing minerals such as biotite, muscovite and hornblende have been examined theoretically (cf., Dodson, 1973) and determined by experimental and field studies (cf., Dodson and McClelland-Brown, 1985). The closure T of K–Ar

muscovite system has been long believed to be 350 °C in metamorphic rocks with slow cooling rate (Purdy and Jäger, 1976). In the last decade, some geochronologists have cast doubt on the closure T proposed by Purdy and Jäger (1976) (cf., Villa, 1998; Takeshita et al., 2004; Gouzu et al., 2006a,b; Itaya et al., 2009). Villa (1998) examined Jäger's calibration of the closure (or blocking) temperatures and proposed new closure T of 500 °C for muscovite. Takeshita et al. (2004) studied the resetting temperature of detrital white micas based on the systematic K–Ar analyses of phengites in calc-schists along the Chisone valley in western Alps. Their results strongly support the new closure T proposed by Villa (1998).

Itaya et al. (2009) carried out $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of biotite and muscovite in a Barrovian type pelitic schist in the eastern Tibetan plateau, of which the host lithologies have experienced polymetamorphism suggested by mutichronological study by Huang et al. (2003) and Wallis et al. (2003). The coexisting biotite and muscovite in sillimanite-grade pelitic schist ($T > 600$ °C) give consistent cooling ages of ca. 40 Ma. On the other hand, biotite and muscovite in the lower-grade zones ($T < 500$ °C) yield discordant ages that are due to excess argon inherited from pre-metamorphic phases. They suggested that muscovite and biotite in polymetamorphic terranes require higher metamorphic temperatures to completely reset the Ar isotopic system than generally thought. Therefore, it should be noted that most rocks in various metamorphic zones of the Sanbagawa belt were formed at temperatures lower than the closure T of muscovite K–Ar system that is applicable to the phengite system.

5.2. Excess argon-free schists

The presence of discordant and anomalously old K–Ar (Ar–Ar) ages in metamorphic rocks has been widely reported in the metamorphic belts of the world (Scaillet, 1996; Arnaud and Kelly, 1995; Li et al., 1994; Giorgis et al., 2000; Tonarini et al., 1993; Gouzu et al., 2006a; Ruffet et al., 1995, 1997; Inger et al., 1996; Sherlock and Arnaud, 1999; de Jong et al., 2001; Itaya et al., 2009). These results are likely due to the presence of excess ^{40}Ar trapped in the metamorphic minerals during recrystallization. The continental materials such as those from the Dora Maira massif (e.g. Chopin, 1984; Schertl et al., 1991) have experienced polymetamorphism and to some extents may retain radiogenic ^{40}Ar inherited from protolith; this would produce discordant ages if there were incomplete degassing and resetting of minerals during metamorphism. We have long considered that no significant amount of excess argon occurred in metamorphosed oceanic materials in the Pacific-type HP metamorphic belts because the systematic phengite K–Ar dating in the metamorphic belts in Japan and New Zealand yielded continuous age spectrum with increasing metamorphic temperatures since the first report by Itaya and Takasugi (1988) (Nishimura et al., 1989, 2000; Miyashita and Itaya, 2002; Nuong

et al., 2008, in press). Gouzu et al. (2006b) showed that the oceanic lithologies formed the excess argon free phengites during the UHP and HP metamorphism based on systematic laser probe Ar–Ar dating of phengites from the UHPM unit at Lago di Cignana, western Alps. This also indicates the phengites from HP rocks of the Pacific-type metamorphic belt such as the Sanbagawa and Suo in SW Japan are free in excess argon; K–Ar and Ar–Ar ages of phengites in these schists are identical (Takasu and Dallmeyer, 1990; Nuong et al., 2009), indicating that the phengite K–Ar ages are plausible and useful in critical discussion of regional tectonics.

5.3. Detrital micas

Most low-grade zone pelitic schists of the HP belts contain two types of white micas, the dusty and clear micas as observed in the southern part of the Sanbagwa belt in central Shikoku (Itaya and Fukui, 1994) and in Piemonte calcschists of western Alps (Takeshita et al., 2004). The dusty micas are neoblastic and metamorphic origin; they stretch along a mica layer associated with carbonaceous material. The clear micas are detrital ones and occur as coarser grain. Some detrital micas are extremely elongated along the stretching lineation and are poorer in Si content than dusty metamorphic micas. Both psammitic and pelitic schists contain detrital micas derived from terrigenous clastics; these micas yield ages older than the expected ages of 84–70 Ma in Sanbagawa schists (*sensu stricto*) (Itaya and Fukui, 1994) and ca 50 Ma in Piemonte calcschists of western Alps (Takeshita et al., 2004). In such a case, detail petrographic observation of micas as well as careful separations of different sizes of micas are essential, in particular for rocks metamorphosed at the P–T conditions lower than the pumpellyite–actinolite facies.

6. Discussion

6.1. Argon depletion of phengite by dynamic recrystallization

During exhumation of HP rocks after peak metamorphism, higher grade rocks cool through the closure T for retention of argon in phengite. The phengite K–Ar clock starts at the time when the rocks cool below probably ca. 500°C as mentioned above. If the K–Ar ages reset only at the closure T in the rocks with simple and conductive cooling histories, the same mineral from different lithologies within the same outcrop should have similar K–Ar ages as they would have experienced identical cooling histories. Moreover, K–Ar mineral ages should be younger in higher grade rocks than in lower grade rocks from the same metamorphic sequence, as the lower grade rocks cool through the closure T earlier.

Itaya and Takasugi (1988) obtained K–Ar analyses of 70 phengite separates from Sanbagawa schists in the Chl, Grt and Bt zones along a N–S traverse including the Asemi and Saruta areas in central Shikoku (Fig. 6). They found that phengite K–Ar ages are older in higher-grade zone rocks of the Sanbagawa belt. Similar age– T relation has also been observed in the Suo HP belt of the Ishigaki islands, southern Ryukyu Arc, Japan (cf., Nuong et al., 2008, in press) (Fig. 7). In contrast, Hirajima et al. (1992) and Miyashita and Itaya (2002) reported a reversed age– T relation—younger ages in the higher grade metamorphic zones—from the Shimanto HP schists in the Kano Mtns (Fig. 8). Similar age– T relation has been also known in the Otago schist in New Zealand (Nishimura et al., 2000). Itaya and Fujino (1999) examined the age–lithology relation in the central Shikoku. They dated phengite K–Ar ages from different lithologies from same outcrops, and found discordancy among different lithologies. Considering all regional scale age–metamorphic gradient relationships, we conclude that the K–Ar phengite

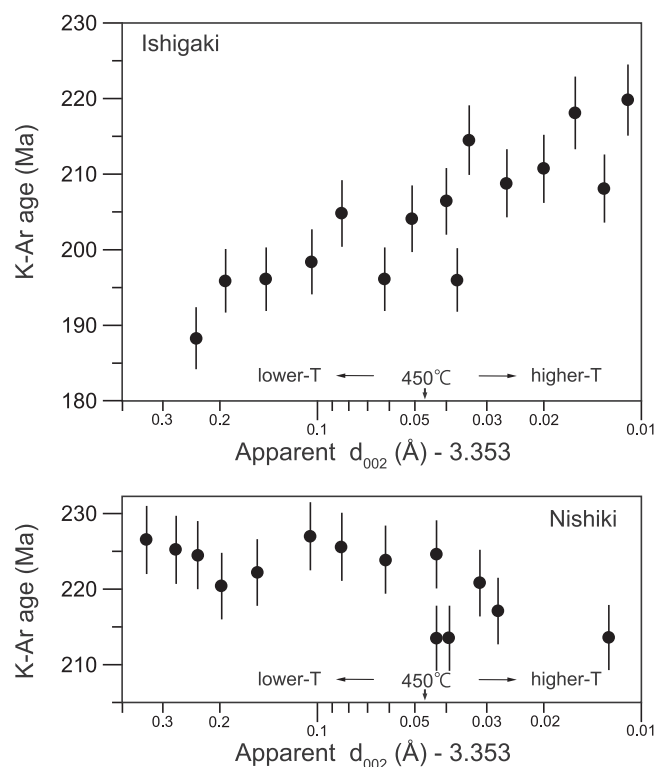


Fig. 7. Age–temperature relations of the Ishigaki and Nishiki metamorphic sequences of the Suo HP schist belt (Nuong et al., 2008). The Ishigaki metamorphic sequence indicates that the age becomes progressively older with increasing metamorphic temperature and the thermal structure is inverted so that the highest-grade zone occurs in the upper most parts of the apparent stratigraphic succession. The Nishiki metamorphic sequence displays younger ages in higher-grade metamorphic rocks and a thermal structure in which the higher-grade zone is in the lower part of the apparent stratigraphic succession.

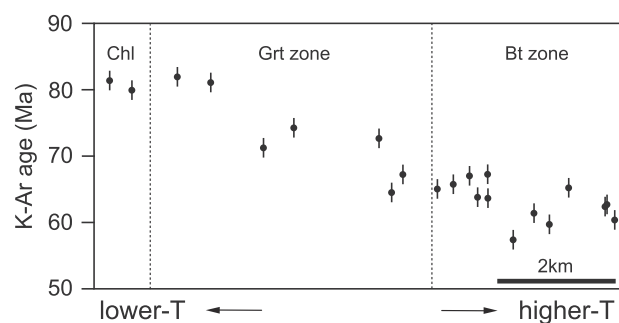


Fig. 8. A transect of phengite K–Ar ages from Shimanto HP pelitic schists in the Kanto Mountains, showing a negative correlation between age and metamorphic grade (Miyashita and Itaya, 2002). Note that the higher-grade zones occupy a structurally lower portion.

ages of HP schists may have been reset not only at the theoretical closure T for thermal retention of argon but also by other processes.

Since the closure T depends on the radius of diffusion (Dodson, 1973) and the average grain size becomes coarser in higher-grade schists, the closure T for phengite should become lower in lower grade schists. This hypothesis, however, was not suitable for the case in central Shikoku, because phengites yielding the youngest age in the Chl zone was not significantly finer, if we compared the average size of phengites in the Grt and Bt zones. Moreover, two pelitic schist samples from a same outcrop with different grain size yielded a same age within error. Thus, Itaya and Takasugi (1988) addressed that argon in phengite was depleted during low- T deformation, and the extent of argon depletion depends on

the intensity and duration of the deformation. Although, this idea has not been accepted by scientists who have considered only the theoretical closure T by Dodson (1973), we postulate that the argon depletion from phengites during low- T deformation is a common phenomena in schistose HP rocks.

The HP schists of the Sanbagawa and Shimanto HP belts have been strongly deformed as documented by microstructural features that include a strong stretching mineral lineation and sheath folding (Faure, 1983; Faure et al., 1988; Wallis, 1990). Wallis et al. (1992) demonstrated that the microstructures were formed during a post-metamorphic stage, suggesting that the ductile deformation took place during the exhumation and cooling of the HP schist belts. Itaya and Fujino (1999) observed that most phengites of pelitic schists occur as fine-grained aggregates both in matrix and at domains close to rigid garnet (Fig. 9). These microstructures indicate the size reduction of phengite by strain-induced recrystallization or dynamic recrystallization during deformation accompanied by exhumation. Strain-induced recrystallization promotes retrograde reaction of phengites because matrix phengite is different in chemistry from that included in garnet, the former being

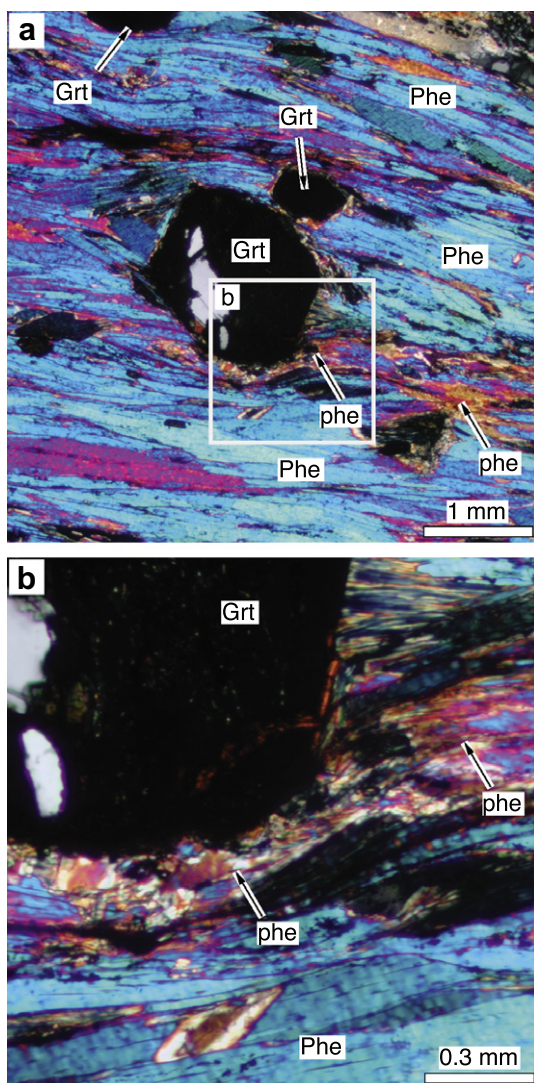


Fig. 9. Photomicrographs of an oligoclase-albite biotite zone pelitic schist in central Shikoku. (a) Phengite defining a penetrative schistosity of matrix (b) Fine-grained phengite aggregates at pressure shadow of a garnet porphyroblast. These microstructures suggest the grain size reduction of phengite by strain-induced recrystallization during ductile deformation of pelitic schist during exhumation (see text).

Table 4

Compositional characteristics of phengites in a pelitic schist sample (302P) from Sanbagawa HP belt (Itaya and Fujino, 1999).

| | Matrix | Inclusion in garnet |
|---------------------------|----------------------------|---------------------|
| Sip.f.u. for O = II | 3.25–3.42 (majority –3.31) | 3.38–3.43 |
| Na/(Na + K) atomic ratio | 0.06–0.18 | <0.02 |
| Mg/(Mg + Fe) atomic ratio | 0.63–0.73 | 0.55–0.58 |

more heterogeneous and lower in Si content, and higher Mg/Fe and Na/K ratios in comparison with the later (Table 4). The similar chemical features have been documented in UHP schists of Lago de Cignana in western Alps (Gouzu et al., 2006b). Recrystallization with significant re-arrangement of major elements such as Al and Si in phengite crystals should involve argon release from phengite as the trapped argon is not favored in the K site of phengite, and easily diffuses out from phengite crystal structure. In contrast, the phengite inclusion in rigid garnet has high Si value and does not release argon as documented by Gouzu et al. (2006b). The phengites in matrix and as inclusion in garnet show different crystal form. The former has been stretched by deformation during exhumation, whereas the included phengite crystal has a granular form and has been protected from ductile deformation of the host rock (Fig. 10). They dated both matrix phengites and inclusion phengites in garnet in coesite-bearing pelitic schists from Lago di Cignana in western Alps by Ar–Ar spot analysis method. The results reveal that the phengite (44 Ma) included within garnet is significantly older than that (36 Ma) in the matrix and the former age is consistent with SHRIMP zircon age (44 Ma) from the same unit by Rubatto et al. (1998). The Sanbagawa garnet does not contain coarse-grained phengites to be dated by our present Ar–Ar analytical system. However, we suggest that the Sanbagawa schists have also suffered the same manner that the phengites included in garnet did not release out the radiogenic argon, as observed in UHP schist from Lago de Cignana.

We interpret that the K–Ar ages are related directly to the ductile deformation history of the matrix phengite during exhumation and cooling of HP rocks. The resetting phenomena must have taken place during deformation at temperatures below the closure T (ca. 500 °C) for thermal retention of argon in phengite. According to this model, the argon depletion ceases and the phengite K–Ar system closes, when the ductile deformation of phengite stopped. The argon closure system of phengites in HP metamorphic rocks is controlled by the onset of brittle deformation in the low-grade sequence, because the brittle deformation zone or the fault zone absorbs the strain of the whole sequence; as a result, the ductile deformation and associated recrystallization of phengite in the high-grade zone is restricted. If the higher-grade rocks are still at temperatures above the argon closure T at the time when the low-grade rocks reach the ductile/brittle boundary, they will continue to lose argon from phengite. This process will continue until the rocks cool below the closure T and thereafter will only lose argon if the rocks are subjected to ductile deformation.

Most mafic rocks such as metagabbro and amphibolite are rigid in comparison with the associated pelitic schists. In Sanbagawa belt *sensu lato*, moreover, most phengites in amphibolites occur as coarse-grained crystals (Fig. 11) in comparison with pelitic phengites (Fig. 9). Thus they could be relatively resistant to strong deformation of a metamorphic pile and phengites of mafic rocks could be protected from deformation. Nuong et al. (2009) confirmed that mafic rocks yield significantly older phengite K–Ar (Ar–Ar) ages than pelitic schists from the Sanbagawa HP belt *sensu stricto* in central Shikoku (Fig. 12). The laser-probe Ar–Ar dating using a single phengite crystal yields plateau ages of 102.9 ± 2.5 and 117.2 ± 1.6 Ma from amphibolites (Nuong et al., 2009); these ages are significantly older than the phengite age (83.8 ± 1.8 Ma)

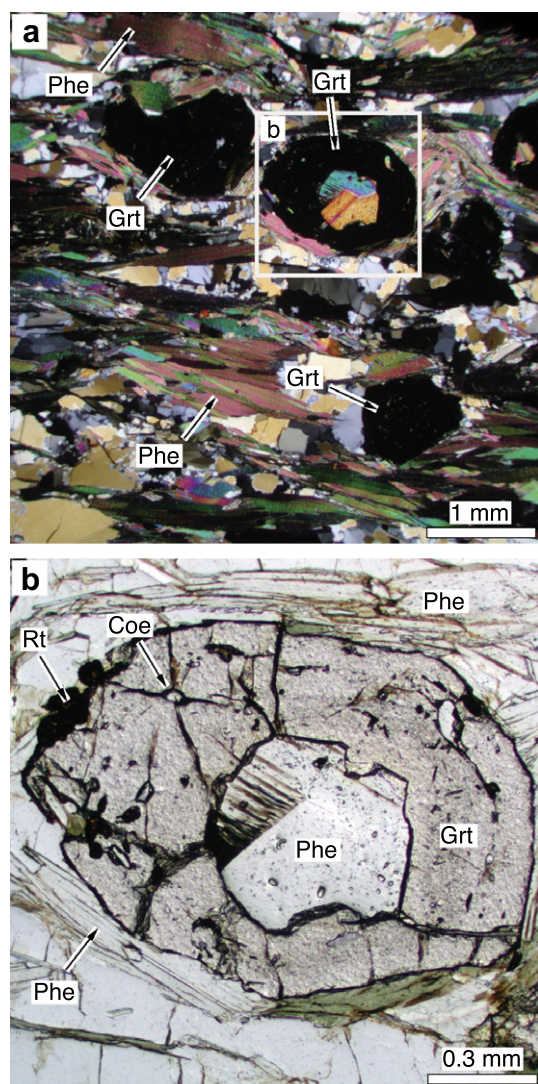


Fig. 10. Photomicrographs of phengite in a UHP pelitic schist of the Lago di Cignana, Western Alps (Gouzu et al., 2006b). (a) Matrix phengite (36.4 ± 1.4 Ma) defining a penetrative schistosity. (b) Phengite inclusions (44.4 ± 1.5 Ma) within coesite-bearing garnet. The Ar–Ar age of phengite inclusion is coeval with zircon U–Pb age (44.1 ± 0.7 Ma) reported from the same unit by Rubatto et al. (1998).

of the biotite zone pelitic schist. This implies that the mafic rocks are likely to have suffered insignificant argon loss during exhumation. Moreover, the plateau ages (103 and 117 Ma) of phengites from amphibolites may indicate the timing of the early exhumation, probably close to the metamorphic age as the closure T of phengite K–Ar system was 500°C mentioned above (Villa, 1998; Gouzu et al., 2006a, b; Itaya et al., 2009).

6.2. Relationships between K–Ar age and metamorphic gradient

As described above, two contrasting age– T –structure relationships have been observed in the HP schist belts in SW Japan (Itaya and Takasugi, 1988; Miyashita and Itaya, 2002; Nuong et al., 2008, in press). The Sanbagawa HP schists in central Shikoku exhibits a thermal structure that the highest grade rocks occur in the middle part of the apparent stratigraphy and a positive correlation in age– T relationship that the ages are progressively older with increasing metamorphic temperature (Fig. 6). In contrast, the Shimanto HP schists in Kanto Mtns, where the thermal structure for the higher-grade zone is in the lower part of the apparent stratigraphic

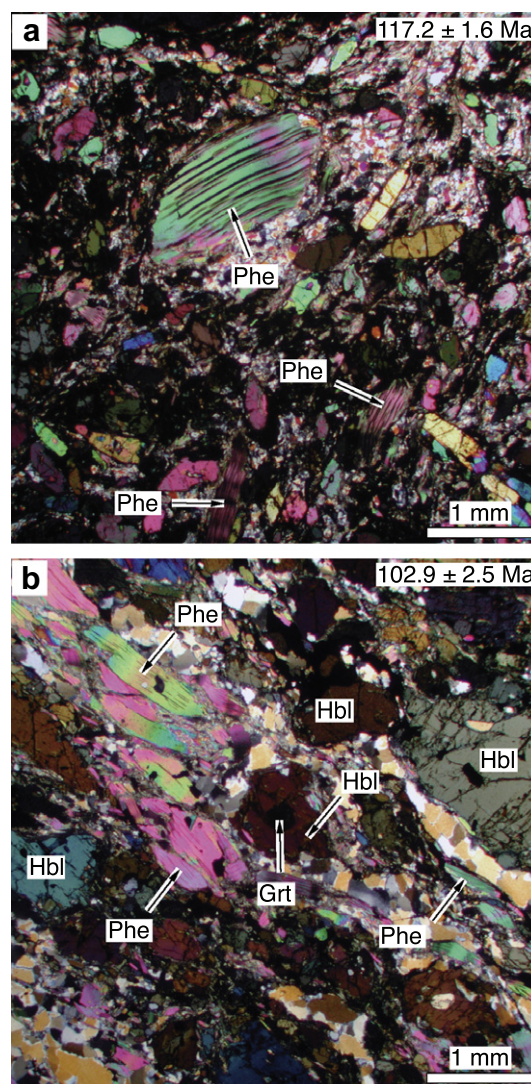


Fig. 11. Photomicrographs of amphibolite pebbles of the Kuma Formation. The laser-probe Ar–Ar dating of a single crystal yields plateau ages of 102.9 ± 2.5 Ma for garnet–amphibolite and 117.2 ± 1.6 Ma for amphibolite that are significantly older than the phengite age (83.8 ± 1.8 Ma) of biotite zone pelitic schist (Nuong et al., 2009). The plateau ages (103 and 117 Ma) of phengites from the amphibolites indicates the timing of the early stage of the exhumation (see text).

succession, displays a negative correlation that younger ages are in higher-grade metamorphic rocks (Fig. 8).

In the Suo HP metamorphic belt, the Ishigaki schists show that the ages are progressively older with increasing metamorphic temperature and the thermal structure is inverted so that the highest-grade zone occurs in the upper most parts of the apparent stratigraphic succession (Fig. 7). In contrast, the Nishiki schists display younger ages in higher-grade metamorphic rocks; the higher-grade zone is located in the lower part of the apparent stratigraphic succession (Fig. 7).

As we postulated, the argon closure system of phengites in a whole metamorphic sequence, which has been deformed during exhumation and cooling of rocks, is controlled to a large extent by the onset of brittle deformation in the low-grade sequence. This is because the brittle deformation zone or the fault zone absorbs the strain of the whole sequence and the ductile deformation in high-grade zone rocks is restricted. Nuong et al. (2008, in press) showed two possible resetting mechanisms during the cooling history of a metamorphic pile, which has been deformed during cooling and also shows two different ductile/brittle boundaries to

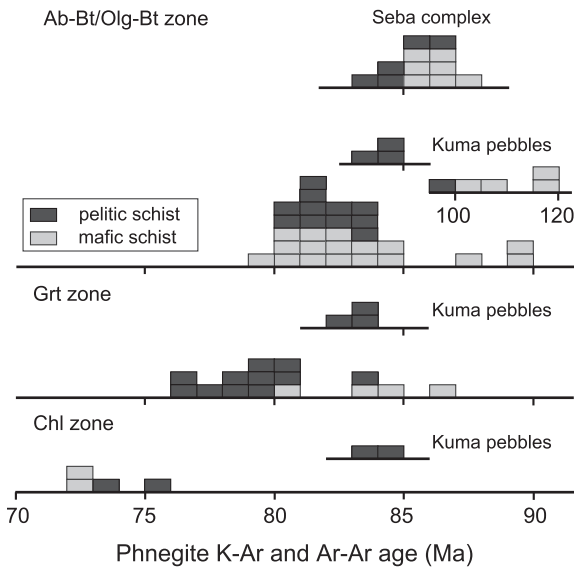


Fig. 12. Histograms of phengite K–Ar and Ar–Ar ages reported from Kuma Formation pebbles (Nuong et al., 2009) and the Asemi area of the Sanbagawa HP schists (*sensu stricto*) in central Shikoku.

explain the two contrasting age–*T*–structure relationships observed in the Ishigaki and the Nishiki areas of the Suo HP belt of SW Japan (Fig. 13). The position, or in this case the temperature, of the ductile/brittle boundary in the metamorphic succession depends on a number of variables including lithology, pressure, strain rate and the presence or absence of fluids. The higher temperature boundary requires that higher-grade rocks have younger ages than the lower-grade rocks, as seen in the Nishiki metamorphic sequence. The lower temperature boundary requires an evolution whereby all rocks from high to low grade experience deformation related to argon depletion and have a comparatively long duration of deformation. This is required to have the age relationships similar to the Ishigaki where the lowest grade rocks record the youngest ages. This resetting model is consistent with the contrasting thermal structures of the Ishigaki and the Nishiki areas of the

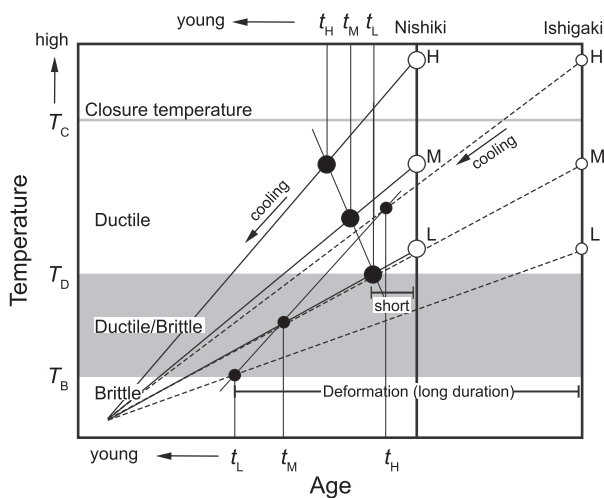


Fig. 13. Generalized temperature–age diagram showing a possible mechanism to form negative and positive K–Ar age–*T* relationships in regional HP belt. t_L —K–Ar age of low-*T* portion, t_M —K–Ar age of moderate *T* portion, t_H —K–Ar age of high-*T* portion. T_C —closure *T* of phengite, T_D —maximum *T* of ductile/brittle boundary, T_B —minimum *T* of ductile/brittle boundary. Long duration of deformation forms a positive correlation (e.g. Ishigaki, Suo HP belt, SW Japan), whereas short duration yields a negative correlation (e.g., Nishiki, Suo HP belt, SW Japan).

Suo HP belt, and of the Sanbagawa HP belt *sensu stricto* in central Shikoku and the Shimanto HP belt in Kanto Mtns.

The coherent schist unit having an inverted thermal structure with large-scale recumbent folds is possible to have undergone ductile deformation for a longer time at lower temperature; in this case, it is expected a relatively low strain rate for deformation of metamorphic pile. A high strain rate would require ductile deformation at higher temperatures, which would not allow deformation of the low grade rocks to continue for a sufficiently long time to produce an inverted thermal structure with large-scale recumbent folding. This interpretation for exhumation process is consistent with the estimated time span between the peak age of metamorphism and the apparent resetting time of phengite argon system in the Sanbagawa HP belt *sensu stricto* in central Shikoku and the Shimanto HP belt in Kanto Mtns.

A schematic cooling pattern of highest grade zone (Olg–Bt/Ab–Bt zone) rocks of the Sanbagawa HP belt *sensu stricto* is shown in Fig. 14; the cooling patterns of lower grade zone rocks (Grt and Chl zones) are also drawn according to the pattern of the Olg–Bt/Ab–Bt zone. This diagram shows the estimated time duration of deformation is longer than 31 m.y. using the oldest ages (84 Ma) in the Bt zone (Fig. 6) and the peak ages (115–120 Ma).

For the comparison, the K–Ar ages of the Shimanto HP belt in Kanto Mtns are shown in the same diagram. If we consider the youngest detrital zircon age for Kanto Mtns schists by Tsutsumi et al. (2009), we obtain an estimate of the duration of deformation shorter than 13 m.y. for the Shimanto HP belt.

6.3. K–Ar constrains for exhumation process

The phengite K–Ar ages of Grt and Bt zone pelitic schists in the Saruta (northern part) and Asemi areas are different (Figs. 6 and 14); the former (77–72 Ma) is younger than the later (84–77 Ma) and the Mikabu greenstone complex and associated HP schists (125–90 Ma in the Pmp–Act zone) are significantly older than the Chl zone (79–73 Ma in the Asemi area) of the Sanbagawa belt *sensu stricto* (Fig. 5). Nuong et al. (2009) dated phengite K–Ar and Ar–Ar ages from schist pebbles of the Chl, Grt and Bt zones from Early

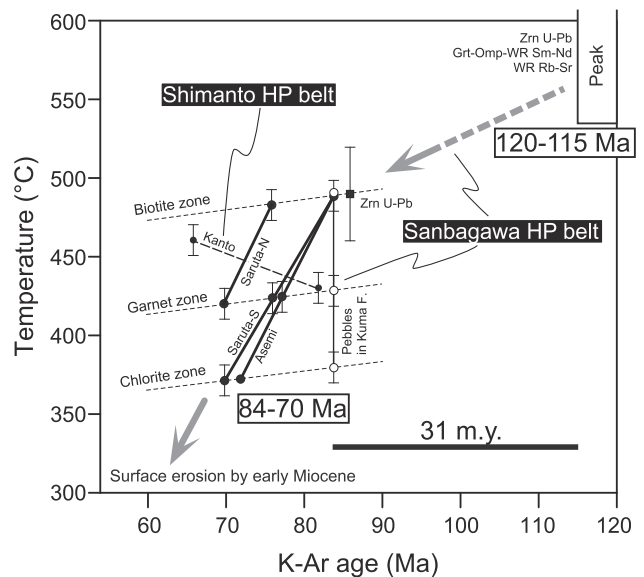


Fig. 14. Age–temperature patterns of the chlorite, garnet and biotite zones of the Sanbagawa HP schists *sensu stricto* in central Shikoku. Different areas show different age–*T* relationships suggesting different duration of deformation during exhumation. For comparison, age–*T* patterns of garnet and biotite zone of the Shimanto HP schists of Kanto Mtns are also shown. Note that minimum duration of deformation is longer than 31 million years in the Sanbagawa HP belt *sensu stricto*.

Miocene Kuma Group sediments in central Shikoku (Fig. 12). They revealed that all pelitic schist pebbles yielded similar phengite ages (84–82 Ma) regardless of metamorphic grade; the K–Ar ages of schist pebbles are older than those from Sanbagawa schists in the Asemi area (Fig. 12). This implies the monotonous older ages of the “Kuma unit” irrespective of metamorphic grade than those from outcrops in the Asemi area. The “Kuma unit” was exhumed earlier than the Asemi area, and the relationships between K–Ar age and metamorphic gradient might have been intermediate between those of the Kanto Mtns and the Asemi area of central Shikoku.

No age–metamorphic grade relationship in pebbles of the “Kuma unit” suggest that high-grade rocks formed in the deeper part of the subduction zone were exhumed more rapidly than low-grade rocks. During a series of exhumation processes of the Sanbagawa HP metamorphic pile, the argon closure of phengites in pelitic schists was attained first in the “Kuma unit” schist and subsequently in the schist that now exposed in the Asemi area; in the Asemi area, the closing (resetting) periods are 84–82 and 81–77 Ma for the Grt and Bt zones, respectively (Fig. 14). Then finally, the schists of the North Saruta area reached the argon closure of phengite, at 77–72 Ma (Figs. 6 and 14). The present-day apparent geological structure formed at later stage of deformation after the argon closure of phengite of the whole Sanbagawa metamorphic sequence.

The lowest grade rocks of the Sanbagawa HP belt *sensu stricto* in central Shikoku occur in the Mikabu greenstone complex. As described above, rigid mafic rocks are relatively resistant to strong deformation of the metamorphic pile. Pelitic schists intercalated within the Mikabu greenstone complex could be protected from

the deformation. This means that the phengite of pelitic schists have suffered insignificant argon loss during the exhumation of the metamorphic pile. However, the phengite K–Ar system in the Mikabu greenstone complex did reset in the early stage of exhumation without the experience of long deformation because host rocks existed at the shallow part of the subduction zone (Fig. 15).

6.4. Evolution of Sanbagawa belt (*sensu stricto*)

On the basis of the all available data, the Sanbagawa HP belt *sensu stricto* in central Shikoku consists of rocks of the Early Cretaceous accretionary complex that was metamorphosed at P–T conditions of the pumpellyite–actinolite through epidote–blueschist to epidote–amphibolite facies and up to the eclogite facies during a prograde stage in a subduction zone at 120–115 Ma. The subsequent exhumation after the peak metamorphism took place in a manner that higher-grade rocks exhumed more rapidly in comparison with lower-grade rocks (Fig. 15). This requires different P–T–t paths for rocks from low to high-grade zone during their exhumation as seen in Fig. 3. The Bt zone schists and the Iratsu eclogite have recorded epidote–amphibolite facies overprinting at 86 and 109 Ma, respectively, suggesting their exhumation rates are 0.1 and 0.9 cm/y, respectively. The Chl and Grt zone schists should exhume with the rates lower than 0.1 cm/y, making it possible to suggesting the low strain rate during rock deformation discussed above. However, the Mikabu greenstone complex and associated HP schists of the Sanbagawa HP belt *sensu stricto* exhumed without intense deformation/recrystallization to result in resetting the phengite K–Ar system in earlier stage of exhumation of the whole Sanbagawa belt.

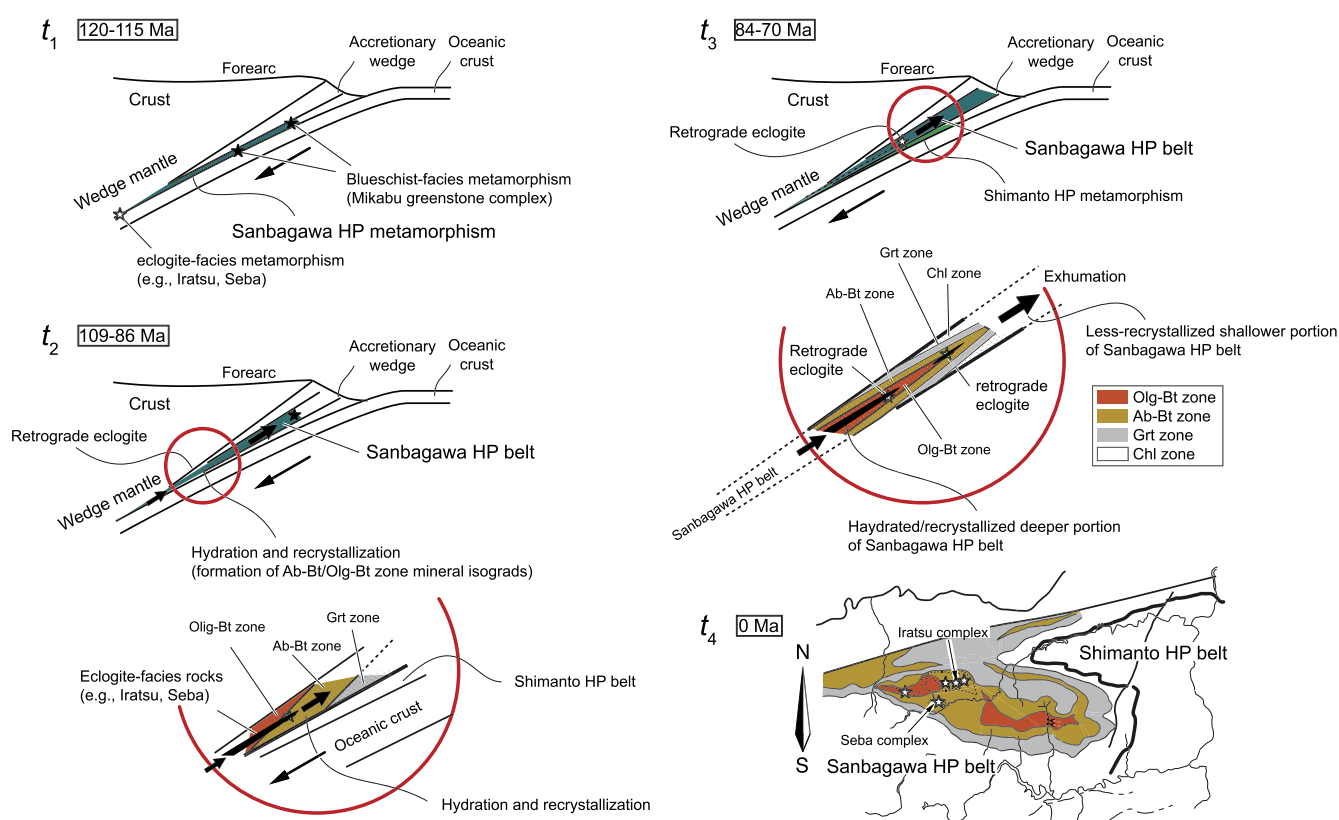


Fig. 15. Evolution of the Sanbagawa HP belt *sensu stricto* in central Shikoku. t_1 —prograde and peak metamorphism at 120–115 Ma. Eclogite-facies rocks (e.g. Iratsu and Seba bodies) and low grade blueschist-facies rocks in the Mikabu greenstone complex represents deeper and shallower portions of a subducting accretionary complex, respectively. t_2 —retrograde metamorphism at 109–86 Ma. Exhumation started and the exhumed deeper portion of the metamorphosed accretionary complex (e.g. Iratsu and Seba bodies) suffered intense hydration at the middle crustal depth; this recrystallization event formed biotite-bearing apparent metamorphic gradient. t_3 —wedge extrusion at 84–70 Ma. The high-grade rocks (Olg–Bt/Ab–Bt zone rocks) including partially retrograded eclogite (e.g., Iratsu and Seba bodies) were exhumed more rapidly than the low-grade rocks. This exhumation process is based on K–Ar phengite geochronology and the wedge extrusion model proposed by Maruyama et al. (1996). t_4 —present-day apparent thermal structure in central Shikoku showing distribution of eclogite-facies rocks.

Engelbreton et al. (1985) documented that five independent oceanic plates (Farallon, Izanagi, Kula, Pacific and Philippine Sea) have interacted with to SW Japan along the eastern margin of the Asian continent. The mid-ocean ridge between the Kula and Pacific plates was subducted beneath SW Japan as recorded in the ocean plate stratigraphy (Matsuda and Isozaki, 1991) of the Shimanto AC (Taira et al., 1988). This suggests that the exhumation of the HP schists was triggered off by the ridge subduction (Maruyama et al., 1996; Aoya et al., 2003; Aoki et al., 2008). Although all the boundaries between the two neighboring oceanic plates among these five oceanic plates have not yet been documented as mid-oceanic ridges, the exhumation of the Suo, Sanbagawa *sensu stricto* and Shimanto HP belts in SW Japan could be correlated with subduction events of the plate boundaries between the Farallon and Izanagi plates, Izanagi and Kula plates and Kura and Pacific plates, respectively, as predicted by Isozaki and Maruyama (1991) and Aoki et al. (2011, this issue). The different natures of subducted plate boundary may have caused different exhumation processes of metamorphic belts as observed in the Sanbagawa *sensu stricto* and the Shimanto HP belts.

7. Conclusions

The traditional Sanbagawa HP belt *sensu lato* can be subdivided into (1) the Sanbagawa *sensu stricto* and (2) the Shimanto HP belt. The HP rocks of the Sanbagawa belt *sensu stricto* contain phengites with significantly depleted radiogenic argon during intense ductile deformation; duration of exhumation is estimated to have been longer than 31 m.y. This long-term deformation formed the unique thermal structure, in which the highest-grade rocks occur in the middle part within the apparently thick and coherent schist body and the positive correlation in age-temperature relationship that the age becomes progressively older with increasing metamorphic temperature. In contrast, the Shimanto HP schists have experienced much shorter-term deformation less than 13 m.y. This short-term deformation formed the thermal structure, in which the higher-grade zone occurs in the lower part of the apparently thick succession and the negative correlation that younger ages are in higher-grade metamorphic rocks.

This review has encouraged reevaluation and reconsideration of the existing geochronology data in the Pacific-type of HP metamorphic belts. The issues to be addressed in future include: (1) integrated multiple-geochronology of the rocks from low to high-grade zone, (2) experimental study for argon depletion mechanism of phengite, (3) formulating more advanced model for the exhumation of metamorphic belts. Further development of new techniques; for instance, more sophisticated Ar–Ar analysis for zoned amphiboles using fine-beam laser will help in extending our knowledge on the tectono-metamorphic process of HP metamorphic belts.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jseae.2011.06.012.

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Supplementary Material

References of K-Ar and Ar-Ar age data used in Figures 2.

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