U–Pb zircon dating of the Sanbagawa metamorphic rocks in the Besshi–Asemi-gawa region, central Shikoku, Japan, and tectonostratigraphic consequences

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Abstract

The aim of this study is to address unresolved issues associated with the depositional and metamorphic ages of the Sanbagawa metamorphic rocks (central Shikoku, Japan). We performed laser-ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) zircon U–Pb analysis on psammitic schists from the Sanbagawa metamorphic rocks (sensu stricto) in the Besshi–Asemi-gawa region. Young U–Pb ages of ca. 100–90 Ma were found in all analysed samples, regardless of the metamorphic grade. These results suggest that the Sanbagawa metamorphic rocks from the upper chlorite to oligoclase-biotite zones are metamorphic equivalents of the Cretaceous Northern Shimanto accretionary complex, which also underwent prograde metamorphism after ca. 90–80 Ma. Based on our results and previous geochronological data from the Sanbagawa metamorphic rocks, we suggest that the Sanbagawa metamorphic belt consists of three metamorphic units, which are characterized by different depositional and metamorphic ages. These three units, from old to young, are here referred to as the Besshi, Asemi-gawa, and Oboke units.

Key words: Sanbagawa, zircon, U–Pb, LA-ICP-MS

1. Introduction

Most Japanese basement rocks are composed of subduction-related geological units, such as accretionary complex, high-pressure part of accretionary complex (HP-AC), arc granites and arc-related basins. The lithologies are products of the numerous Pacific-type orogenic events that occurred along the western margin of the Paleo-Pacific Ocean throughout the past 500 million years (e.g. Uyeda and Miyashiro, 1974; Isozaki, 1996; Maruyama, 1997; Maruyama et al., 1997; Isozaki et al., 2010). The geology of Japan plays an important role in understanding the many tectonic processes that occur along convergent plate margins.

One such geologic unit in Japan is the Cretaceous Sanbagawa metamorphic belt, which is one of the most well-preserved HP-ACs in the world. Recently, the Sanbagawa metamorphic rocks have been the subject of numerous zircon U–Pb studies, using laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) techniques (e.g. Aoki et al., 2007; Otoh et al., 2010; Knittel et al., 2014). The LA-ICP-MS zircon method provides precise age constraints on the ages of deposition/accretion and metamorphism, as well as the spatial distribution of Sanbagawa metamorphic rocks, which previously has not been possible. Aoki et al. (2010b, 2011) compiled various geochronological (e.g. microfossil, K–Ar, Ar–Ar and U–Pb) analyses and lithostratigraphic data on the Sanbagawa metamorphic rocks, the Mikabu greenstones and the Jurassic–Cretaceous accretionary complexes (Sanbosan and Northern Shimanto belts). With these data, they proposed that the Sanbagawa metamorphic belt is composed of two types of metamorphic rocks, i.e. ca. 120–110 Ma metamorphic rocks.
and ca. 80–60 Ma metamorphic rocks; each rock is representative of the HP metamorphic parts of the Sanboso and Northern Shimanto accretionary complexes. However, Shimojo et al. (2011) and Knittel et al. (2014) reported detrital zircons younger than 100 Ma in 120–110 Ma metamorphic rocks, which poses a problem for the model of Aoki et al. (2010b, 2011). Accordingly, the protolith age of the Sanbagawa metamorphic rocks is now unclear. However, knowledge of the protolith age leads to an improved understanding of the tectonic evolution of the Sanbagawa metamorphic rocks, of the time of deposition, and of prograde metamorphism of the Sanbagawa metamorphic belt. Detrital zircon U–Pb data from meta-terrigenous rocks, are useful when attempting to constrain the timing of tectono-sedimentary and metamorphic events, because detrital zircons are less affected by later alteration (e.g. Clift et al., 2009; Dickinson and Gehrels, 2009; Isozaki et al., 2010; Aoki et al., 2012, 2014). Hence, our analyses of zircons, via U–Pb LA-ICP-MS, provide us with initial information on the formation age of their host rocks. In this study, we focus on the Besshi–Asemi-gawa region of central Shikoku, which is one of the type-localities of the Sanbagawa metamorphic belt. Detrital zircon U–Pb data from meta-terrigenous rocks, are useful when attempting to constrain the timing of tectono-sedimentary and metamorphic events, because detrital zircons are less affected by later alteration (e.g. Clift et al., 2009; Dickinson and Gehrels, 2009; Isozaki et al., 2010; Aoki et al., 2012, 2014). Hence, our analyses of zircons, via U–Pb LA-ICP-MS, provide us with initial information on the formation age of their host rocks. In this study, we focus on the Besshi–Asemi-gawa region of central Shikoku, which is one of the type-localities of the Sanbagawa metamorphic belt, from where we report new LA-ICP-MS zircon U–Pb ages. Moreover, we discuss the timing of deposition/accretion and metamorphism of the Sanbagawa metamorphic rocks in the context of their geological subdivisions. We will produce no further details about Sanbagawa tectonic evolution, nor the development of the Mikabu greenstones and the northern margin of the Chichibu composite belts, which underwent the same timing as the metamorphism of the Sanbagawa metamorphic rocks (e.g. Isozaki and Itaya, 1990; Suzuki et al, 1990; Aoki et al., 2007); we will discuss that elsewhere.

2. Geological background

The E-W Sanbagawa metamorphic belt extends for over 800 km in Japan from the Kanto Mountains to Kyushu Island (Fig. 1). The Sanbagawa metamorphic belt, which is tectonically overlain by Jurassic accretionary complexes (Chichibu composite belts) and underlain by a Cretaceous accretionary complex (Northern Shimanto belt), has the form of a subhorizontal, several km-thick tectonic slab (e.g. Isozaki and Itaya, 1990; Aoki et al., 2007). The Sanbagawa metamorphic belt has the structure of oceanic plate stratigraphy, being mainly composed of basalt, chart, and trench-fill and hemipelagic sediments (e.g. Isozaki and Itaya, 1990; Okamoto et al., 2000; Terabayashi et al., 2005; Isozaki et al., 2010). The Sanbagawa metamorphic rocks are widely distributed throughout Shikoku, Japan (Fig. 1), where the relatively good exposure and the well-preserved structures have led to numerous studies, which have significantly improved our understanding of the tectonic evolution of the Sanbagawa metamorphic rocks (e.g. Banno et al., 1978; Takasu, 1989; Aoya, 2001; Yamamoto et al., 2004; Terabayashi et al., 2005; Osozawa and Pavlis, 2007; Hattori et al., 2010; Osozawa and Wakabayashi, 2015, 2017). The metamorphic grade ranges from pumpellyite–actinolite facies through blueschist transition facies and epidote amphibolite facies to eclogite facies (e.g. Banno and Sakai, 1989; Higashino, 1990; Aoya and Wallis, 1999; Aoya, 2001; Ota et al., 2004; Aoki et al., 2009; Kouketsu et al., 2010; Taguchi and Enami, 2014). The Sanbagawa metamorphic rocks are
subdivided into four metamorphic zones in ascending order of their metamorphic grade, chlorite (Chl), garnet (Grt), albite–biotite (Ab–Bt) and oligoclase–biotite (Oli–Bt) zones, based on the present mineral parageneses in pelitic schists (e.g. Higashino, 1990; Enami et al., 1994). Metamorphic conditions range from 240–300°C at 4–6 kbar for the lower Chl zone to 585–635°C at 9–11 kbar for the Oli–Bt zone (e.g. Enami, 1983; Banno and Sakai, 1989; Enami et al., 1994; Aoki et al., 2008). Although their metamorphic conditions are lower than the eclogite facies condition, some eclogite facies rocks are reported from the Ab–Bt and Oli–Bt zones (e.g. Aoki et al., 2009; Taguchi and Enami, 2014). Metamorphic zircons separated from a pelitic schist in the Oli–Bt zone of the Asemi-gawa area have a U–Pb age of 85.6 ± 3.0 Ma (Aoki et al., 2009), and low- to high-grade schists have K–Ar and Ar–Ar mineral ages of ca. 90–60 Ma (e.g. Itaya and Takasugi, 1988; Takasu and Dallmeyer, 1990; Aoki et al., 2008). On the other hand, low-grade psammitic schists in the lower Chl zone have the youngest U–Pb detrital zircons of less than ca. 80 Ma (Aoki et al., 2007; Otoh et al., 2010; Knittel et al., 2014).

There are eclogite and peridotite bodies at Iratsu, Higashiakaishi, Seba, Kotsu and Bizan in Shikoku within Sanbagawa metamorphic rocks (Banno et al., 1978; Takasu, 1989; Aoya, 2001). Quartz-bearing eclogites on the boundary between the Iratsu eclogite and Higashiakaishi peridotite have metamorphic zircon U–Pb ages of ca. 120–110 Ma (Okamoto et al., 2004), whereas the Kotsu and Seba eclogites have Lu–Hf garnet–omphacite isochron ages of ca. 89–88 Ma (Wallis et al., 2009). Ideas about the tectonic setting of these eclogites are controversial: as tectonic blocks or nappes (Aoya and Endo, 2017, and references therein), or as metamorphic units conformable with the surrounding Sanbagawa metamorphic rocks (e.g. Ota et al., 2004; Aoki et al., 2009).

3. Sample description

To obtain detrital zircons, we collected fresh psammitic schists in the Besshi–Asemi-gawa region; three samples (SS16-24, SS16-62 and SS16-63) in the Oli–Bt zone, four (SS16-3, SS16-18, SS16-38 and SO55) in the Ab–Bt zone, two (SS16-27 and SS16-39) in the Grt zone, and one sample (SS16-83) in the upper Chl zone. After crushing and sieving approximately 300 g of rock samples, separation was performed by magnetic and heavy liquid techniques. The separated zircon grains were mounted on a 12-mm acrylic disc and polished. Internal zircon structures and any inclusions were checked with transmitted and reflected optical microscopy and cathodoluminescence (CL) imaging. The CL images were obtained using a JEOL JSM-5510LV scanning electron microprobe combined with a Gatan Mini-CL system at Yokohama National University.

Separated zircons have an average grain size of approximately 150 μm in length. Zircons in the upper Chl and Oli–Bt zones are euhedral to subhedral (Fig. 2). Zircons can be broadly separated into two types according to their CL images. The first type, which is mainly in the upper Chl and Grt zones, has oscillatory zoning patterns (Fig. 2). The second type, which is present in all metamorphic zones, has a light luminescent outermost rim (Figs. 2c, 2d). Aoki et al. (2009, 2010a) analysed both the internal structures and mineral inclusions in Sanbagawa zircons, and suggested that the light luminescent rims are metamorphic in origin. We observed that the luminescent rims in the separated zircons becomes wider with increasing metamorphic grade from the upper Chl zone to the Oli–Bt zone. This observation shows that the rims are related to the metamorphic grade, and supports the suggestion of Aoki et al. (2009, 2010a). Unfortunately, the rims are narrower than the laser spot size (< 15 μm) of LA-ICP-MS, or they contain mineral inclusions, therefore they could not be analyzed in this study. Consequently, in order to determine the maximum age of deposition of the host psammitic schists, we conducted LA-ICP-MS U–Pb analyses of

![Representative CL images of analysed zircon grains from the (a) Chl zone, (b) Grt zone, (c) Ab–Bt zone, and (d) Oli–Bt zone. Note the widening of the light luminescent rims with increasing metamorphic grades (from upper Chl to Oli–Bt).](image-url)
just the oscillatory zones in both types of zircons.

4. Zircon U–Pb age

4.1. Analytical procedure

In situ zircon U–Pb dating was carried out using a Nu Plasma II multi-collector ICP-MS (Nu instruments, Wrexham, UK) coupled to a TiS femtosecond laser ablation system (IFRIT, Cyber Laser, Tokyo, Japan) at the Geochemical Research Center, University of Tokyo. Analyses were also performed using an Agilent 8800 single-collector triple-quadrupole ICP-MS (Agilent Tech., Santa Clara, USA) coupled to a NWR-213 Nd:YAG laser ablation system (ESI, Portland, USA). The TiS femtosecond and Nd:YAG lasers were operated with a fluence of 4.8 and 2.2–2.3 J cm−2, a repetition rate of 10 and 5 Hz and a laser size of 300 μm2 and 78.5 μm2, respectively. 91500 zircon (Wiedenbeck et al., 1995, 2004) was used for Pb/U and Th/U fractionation correction in all measurements. The standard, NIST SRM610, was used to correct for Pb/Pb fractionation. The Plešovice (Sláma et al., 2008) and GJ-1 zircon (Jackson et al., 2004) standards were measured to monitor the analytical quality of the Nu Plasma II multi-collector ICP-MS and the Agilent 8800 single-collector triple-quadrupole ICP-MS, respectively. All uncertainties are reported at the 2-sigma level. 235U was calculated from 206Pb/238U and 207Pb/235U ages obtained from GJ-1 and SrRM610, was used to correct for Pb/Pb fractionation. The standard, NIST SRM610, was used to correct for Pb/Pb fractionation.

4.2. Results

The LA-ICP-MS U–Pb dating of individual zircon grains provided 4, 8 and 2 concordant data from samples SS16-24, SS16-62 and SS16-63 in the Oli–Bt zone; 16, 9, 8 and 23 concordant data from samples SS16-3, SS16-18, SS16-38 and SO55 in the Ab–Bt zone; 5 and 14 concordant data from samples SS16-27 and SS16-39 in the Grt zone and 9 concordant data from sample SS16-83 in the upper Chl zone. All concordant measurements are listed in the supplement material (Appendix Table). All data have high Th/U ratios over 0.1, showing that the analysed zircons are igneous in origin (e.g. Hoskin and Black, 2000; Rubatto and Gebauer, 2000). To avoid analytical bias due to lead loss or addition, discordant measurements (over 5% discordance) or 204Pb intensities significantly higher than the gas blank were removed. Figure 3 shows 206Pb/238U–205Pb/237U concordia curves of zircon grains made with Isolot/Ex 4 (Ludwig, 2003, and its update). Results are summarised as follows. In this study, we take the youngest zircon 206Pb/238U age to constrain the deposition/accretion age of each sample. The geologic time scale follows the classification of Grandstein et al. (2012).

Upper Chl zone: We analysed 28 zircon grains from sample SS16-83, and obtained nine concordia data; eight ca. 124–90 Ma (mid-Cretaceous) grains, and one 252.0±5.0 Ma grain (Permian–Triassic). The youngest age is 93.0±2.3 Ma.

Grt zone: We analysed 14 zircon grains from sample SS16-27 and 28 zircon grains from sample SS16-39. Five concordia ages of ca. 118–103 Ma (mid-Cretaceous) were obtained from sample SS16-27. The youngest age is 102.7±1.8 Ma. From sample SS16-39 fourteen concordia data have ages of: Middle–Early Cretaceous (ca. 130–96 Ma; ten grains), Early Jurassic–Permian (ca. 284–175 Ma; three grains) and Proterozoic (2127.3±35.9 Ma; one grain). 97.7±2.1 Ma is the youngest age.

Ab–Bt zone: We analysed 28 zircon grains from sample SS16-3, 28 from sample SS16-18, 28 from sample SS16-38 and 54 zircon grains from sample SO55. Sixteen concordia data were obtained from sample SS16-3, yielding an age of Middle Cretaceous (ca. 119–101 Ma; thirteen grains) and Triassic–Permian (ca. 280–249 Ma; three grains); the youngest age is 103.4±2.3 Ma. For sample SS16-18, concordia data yield a Middle Cretaceous age (ca. 125–98 Ma; six grains) and a Jurassic–Permian age (ca. 270–175 Ma; three grains), the youngest age being 100.2±2.1 Ma. We obtained both a Middle Cretaceous age (ca. 129–93 Ma; four grains) and a Permian–Triassic age (three grains) for sample SS16-38; the youngest age was 93.3±3.0 Ma. Sample SO55 gave an age of Middle Cretaceous–Jurassic (ca. 197–90 Ma; 15 grains). Four concordia data were Triassic–Carboniferous in age (ca. 333–213 Ma); we also found some Cambrian and Paleoproterozoic ages, and the youngest age was 95.6±6.2 Ma.

Oli–Bt zone: We analysed 14 zircon grains from sample SS16-24, 28 from sample SS16-62 and 28 from sample SS16-63. Four concordia data were obtained from sample SS16-24, yielding a Middle Cretaceous age (ca. 110–93 Ma), the youngest age being 96.0±2.6 Ma. For sample SS16-62, concordia data yielded Middle–Early Cretaceous ages (ca. 134–102 Ma; five grains). Additionally, we obtained ages of 232.3±5.2, 455.5±10.1 and 1953.2±38.0 Ma from sample SS16-62, and the
youngest age was 107.6±5.6 Ma. Sample SS16-63 yielded two concordia data with ages of 97.7±3.4 and 2689.7±26.4 Ma.

5. Discussion

5.1. Constraints on the timing of deposition/accretion and metamorphism

U–Pb age histograms with probability age frequency curves from analysed rocks are commonly used to constrain the provenance source of terrigenous rocks. However, we could not use such histograms, due to small amounts of concordia data, but we are able to place an upper limit on the time of host rock deposition/accretion in the trench by using the youngest U–Pb zircon age (e.g. Aoki et al., 2007; Dickinson and Gehrels, 2009). Combining our youngest U–Pb ages with metamorphic ages previously reported provides useful deposition/accretion and metamorphic ages of the Sanbagawa metamorphic rocks.

The youngest U–Pb ages, ranging from ca. 100 to 90 Ma (Fig. 3), obtained from each sample are nearly identical regardless of metamorphic grade. This finding shows that the protoliths of the analysed Sanbagawa samples were deposited in a trench after ca. 100–90 Ma, and that the rocks underwent prograde metamorphism for the duration of subduction. To find a prograde metamorphic age, systematic K–Ar and Ar–Ar ages of the Sanbagawa rocks were obtained in Shikoku (Itaya and Takasugi, 1988; Takasu and Dalmeyer, 1990). However, these results are regarded not as prograde but as retrograde or cooling ages (e.g. Aoki et al., 2008; Maruyama et al., 2010; Itaya et al., 2011). As mentioned above, we were unable to analyse the metamorphic rims of the separated zircons. Aoki et al. (2009) found that the Oli–Bt zone rocks underwent retrograde metamorphism at 85.6±3.0 Ma after prograde eclogite metamorphism using nano-Secondary Ion Mass Spectrometry (SIMS) on zircons extracted from Sanbagawa pelitic schists in the Asemi-gawa area. Taking into account the systematic change of mineral assemblages observed in the Asemi-gawa area (Fig. 1) and the similarity of our youngest ages of each sample, the Sanbagawa metamorphic rocks from the upper Chl zone to the Oli–Bt zone record the same tectono-metamorphic evolution. Hence, we may say that their protoliths began to subduct after ca. 100–90 Ma and underwent prograde metamorphism before 85.6±3.0 Ma. Moreover, this discovery also shows that the duration of the prograde Sanbagawa metamorphism was much shorter than previously proposed by Aoki et al. (2011; i.e. approximately 20–10 million years). Minamishin et al. (1979) interpreted ca. 120 Ma whole-rock Rb–Sr isochron ages (122±12 and 115±26 Ma: calculated by Itaya et al., 2011) from the Oli–Bt and Ab–Bt zones rocks in the Asemi-gawa area as the time of peak metamorphism. This unlikely conclusion may be because the isochron age was obtained from a pseudo-isochron in the Rb–Sr system.

5.2. Two types of eclogite rocks

Aoki et al. (2009, 2011) considered that the high-grade Sanbagawa “proper” rocks and the eclogites in the Iratsu and Seba bodies have the same coeval tectono-metamorphic history, and that the accretionary age and peak metamorphic age of the rocks were at ca. 140–130 Ma and ca. 120–110 Ma, respectively. However, as mentioned above, our results clearly demonstrate that the age definition of Aoki et al. (2011) cannot apply to the high-grade Sanbagawa “proper” rocks. In consequence, one question arises: do ca. 120–110 Ma metamorphic rocks not exist in the Sanbagawa metamorphic belt? The presence of ca. 120–110 Ma metamorphic rocks was strongly suggested by metamorphic U–Pb zircon ages obtained from eclogites in the Iratsu and Tonaru bodies (Okamoto et al., 2004; Nagata et al., 2015). As the ages are obtained from Sensitive High Resolution Ion MicroProbe (SHRIMP) and LA-ICP-MS analyses, the reliability of their geochronological value increases. Thus, ca. 120–110 Ma metamorphic rocks surely exist in the Sanbagawa metamorphic belt.

Aoki et al. (2009) revealed that the whole rock package in the Oli–Bt zone in the Asemi-gawa area once reached eclogite facies and underwent retrograde metamorphism under epidote amphibolite facies conditions during exhumation at 85.6±3.0 Ma. Wallis et al. (2009) interpreted a Lu–Hf garnet-omphacite isochron age of ca. 89–88 Ma as the time of eclogite metamorphism of the Kotsu and Seba eclogites, although Aoki et al. (2010a) and Itaya et al. (2011) pointed out that the petrography of the measured garnets and omphacites suggested they were not coeval. However, our current study suggests that the isochron age reported from Wallis et al. (2009) does have a geological meaning, because the age is consistent with our Sanbagawa prograde metamorphic age, demonstrating that the Kotsu-Seba eclogites are equal to the eclogites in the Asemi-gawa area. Hence, the Kotsu-Seba eclogites are not tectonic blocks, but integral parts of the high-grade Sanbagawa tectonic belt that includes the Asemi-gawa eclogites.

In summary, the inconsistency in age between the high-grade Sanbagawa metamorphic rocks including the Seba and Kotsu eclogites, and other eclogites such as the Iratsu and Tonaru can be used to indicate that each rock has a different deposition/accretionary and meta-
Fig. 3. U–Pb concordia curves for analysed zircon grains, and information on the youngest age (YA) of each sample.
morphic history. Therefore we conclude that there are two kinds of eclogite in the Sanbagawa metamorphic belt in Shikoku.

5.3. Subdivision of the Sanbagawa metamorphic belt

This study demonstrates that the Sanbagawa metamorphic belt can be subdivided into two units. In the first, metamorphic rocks were subducted after ca. 140–130 Ma and underwent prograde metamorphism at ca. 120–110 Ma. In the second, metamorphic rocks were subducted after ca. 100–90 Ma and underwent prograde metamorphism at ca. 90–88 Ma. According to the lithostratigraphy proposed by the Kojima et al. (1956) and Kenzan Research Group (1984), the first unit is equivalent to the upper part of the Minawa Formation, and the second belongs to the middle and upper Minawa Formation and the Ojoin Formation. The lithostratigraphic relationship between them is confusing. One possibility is to assume that first unit is a distinct lithostratigraphic unit from other formations. Another possibility is that it is equivalent to the upper part of the Ojoin Formation. Although there is still room for the lithostratigraphic relationship, the first unit can be regarded as a different unit from the second one. Moreover, Aoki et al. (2008, 2010b, 2011) demonstrated the existence of metamorphic rocks, whose deposition/accumulation and prograde metamorphic ages are ca. 80 Ma and ca. 80–60 Ma, respectively, in the Sanbagawa metamorphic belt. Structurally these rocks belong to the lower part of the Sanbagawa metamorphic belt, and to the lower Chl zone. Takeshita et al. (2011) reported a fission-track age of ca. 92.6±6.2 Ma from the lower Chl zone, which they interpreted as the time of peak metamorphism. However, the fission-track age is clearly older than the youngest detrital zircon age of ca. 80 Ma obtained from the lower Chl zone (Aoki et al., 2011; Nagata et al. 2016). Thus, we consider that the analyzed zircons are not metamorphic but magmatic in origin, and the fission-track age represents the cooling age of magmatism. The lower Chl zone rocks belong to the lower Minawa Formation, the Koboke Formation, and the Kawaguchi Formation (Kenzan Research Group, 1984). Integration of these results clearly shows that the Sanbagawa metamorphic belt is composed of three independent metamorphic units (Knittel et al., 2014; Aoki, 2015), which have distinct and different tectono-metamorphic histories. In this study, each unit is called conveniently the Besshi, Asemi-gawa and Oboke units in ascending time order (Figs. 4, 5). Each unit boundary is likely situated within the upper Minawa Formation and/or the upper part of Ojoin Formation, and between the lower and middle Minawa Formation, respectively. The precise position and formation process of each unit boundary remains at the moment unknown. Further investigations of these questions are required.

5.4. Contrast to an accretionary complex

According to Aoki et al. (2011, 2012), the Asemi-gawa and Oboke units are the metamorphic equivalents of the Jurassic–Early Cretaceous Sanbosan and Cretaceous Northern Shimanto accretionary complexes, respectively. However, our study indicates that both units are the metamorphic equivalents of the Cretaceous Northern Shimanto accretionary complex from a U–Pb zircon perspective. Kiminami et al. (1998, 1999, 2010) and Kiminami and Ishihama (2003) revealed that the Northern Shimanto accretionary complex is divisible into two units based on lithology, geologic structure, X-ray fluorescence (XRF) and microfossil data; i.e., the KS-I unit (the structurally upper part; late Albian–early Coniacian) and KS-II unit (the structurally lower part; Coniacian–Campanian). In addition, Kiminami and co-workers suggested that the upper and lower Chl zone rocks of the Sanbagawa metamorphic belt are metamorphic equivalents of the KS-I and KS-II units, respectively. Recently, Hara et al. (2017) applied detrital zircon U–Pb analyses to sandstones from the KS-I and KS-II units in Shikoku, reporting that the youngest cluster ages (YC1: Dickinson and Gehrels, 2009) are ca. 115–100 Ma from the KS-I unit and ca. 83–64 Ma from the KS-II unit. Those ages correspond to the youngest zircon U–Pb ages obtained from the Asemi-gawa and Oboke units, respectively (Aoki et al., 2007; Nagata et al., 2016; This study). These results lead us to the conclusion that the Asemi-gawa unit does not belong to the Sanbosan accretionary complex, but rather to the structurally upper part of the Northern Shimanto accretionary complex, such as the KS-I unit. The KS-II unit is regarded as the original accretionary complex of the Oboke unit. However, regarding the position of the boundary between the Asemi-gawa and Oboke units in Shikoku, there is a difference between this study and Kiminami et al. (2010). This point calls for further investigation.

For the Besshi unit, it has been pointed out that the protoliths formed in the trench of an accretionary complex at ca. 140–130 Ma (e.g. Okamoto et al., 2004). Moreover, reconstruction of duplex structures and oceanic plate stratigraphy with thick mafic and carbonate beds were reported by Okamoto et al. (2000) and Terabayashi et al. (2005). Their lithological and geochronological characteristics are quite similar to those of the Jurassic–Early Cretaceous Sanbosan accretionary complex and the Mikabu greenstones (Takeda et al., 1977; Iwasaki et al., 1984; Isozaki and Itaya, 1990; Aoki et al.,
In addition, the structural relationship between the Mikabu and the Sanbagawa rocks suggests that the Mikabu greenstones tectonically overlie the Sanbagawa "proper" rocks (Takeda et al., 1977; Aoki et al., 2007). Hence, it is likely that the Besshi unit is a HP metamorphic equivalent of the Sanbosan accretionary complex and Mikabu greenstones.

Aoki et al. (2010b, 2011) proposed that the term 'Shimanto metamorphic rocks (belt)' applied to 80–60 Ma metamorphic rocks in the Oboke unit, because they are metamorphic equivalents of the Cretaceous Northern Shimanto accretionary complex. However, this study indicates that the Asemi-gawa unit is also the metamorphic equivalent of the Northern Shimanto accretionary complex. Hence, if we use the classification of Aoki et al. (2010b, 2011), almost all of the Sanbagawa metamorphic rocks would be referred to as the 'Shimanto metamorphic rocks (belt)'. This geological subdivision name will create confusion, and is now unsuitable.

7. Conclusions

We present new U–Pb ages using zircon grains separated from Sanbagawa metamorphic rocks in the Besshi–Asemi-gawa region of central Shikoku, Japan. We find that the youngest U–Pb age from 10 samples is Middle Cretaceous (ca. 100–90 Ma). The geological significance of this discovery combined with previous geochronological data from the Sanbagawa metamorphic rocks is summarised as follows:

1. The protoliths of the Sanbagawa psammitic schists from the upper Chl to the Oli-Bt zones were deposited in a trench after ca. 100–90 Ma. This age corresponds with the time of deposition/accretion of the Northern Shimanto accretionary complex. We con-
sider that all the Sanbagawa “proper” rocks are HP metamorphic equivalents of the Northern Shimanto accretionary complex.

2. Two types of eclogite with different deposition/accretion and prograde metamorphic ages exist in central Shikoku.

3. The Sanbagawa metamorphic belt is composed of three metamorphic units with different deposition/accretion and prograde metamorphic ages. The ages of each unit are ca. 140–130 and 120–110 Ma, ca. 100–90 and 90–88 Ma, and ca. 80 and 80–60 Ma, respectively, which we call the Besshi, Asemi-gawa and Oboke units, respectively. The unit boundaries are within the upper Minawa Formation and/or the Ojoin Formation, and the lower and middle Minawa formations in central Shikoku.

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* in Japanese with English abstract
** in Japanese
以下のAppendix（Table）は、オープンファイルとして学会ホームページ上で公開しています。<http://www.geosociety.jp/publication/content0006.html>
Aoki, K., Seo, Y., Sakata, S., Obayashi, H., Tsuchiya, Y., Imayama, T., Yamamoto, S. and Hirata, T., 2019, U–Pb zircon dating of the Sanbagawa metamorphic rocks in the Besshi–Asemi-gawa region, central Shikoku, Japan, and tectono-stratigraphic consequences. Jour. Geol. Soc. Japan, 125, 183–194. （青木一勝・瀬尾好貴・坂田周平・大林秀行・土屋裕太・今山武志・山本伸次・平田岳史．2019．四国中央部別子-汗見川地域三波川変成岩のジルコンU–Pb年代と構造層序．地質雑．125, 183–194．）

本研究では三波川変成岩類の堆積・付加年代および変成年代を制約するため、四国中央部、別子-汗見川地域に産する三波川プロパーの砂質片岩に注目し、碎屑性ジルコンを用いたレーザー照射型誘導結合プラズマ質量U–Pb年代測定を行った。その結果、各試料から得られた最も若い年代値は、変成度や原岩層序に対応関係なく、すべて約100–90 Maの年代を示した。このことは緑泥石帯上部から灰長石–黒雲母帯の変成岩が被った昇温変成作用の時期は100–90 Ma以降であり、その原岩は白亜紀四千万付加体相当であることを示す。また、本研究から三波川変成帯は堆積および変成年代ともに異なる3つの変成岩ユニットからなることが示唆された。