U-Pb ages and Hf isotope composition of zircon from the Shimanto accretionary complex: Evidence for heterogeneous sources

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U-Pb zircon age spectra determined for detrital zircon from the Shimanto Accretionary Complex suggest that the sediments forming the Shimanto belt are derived from essentially the same sources as the protoliths of the Sanbagawa Belt. The prominent Early Jurassic peaks seen in the age spectra of both belts suggest that SE China is not a major source of the detrital zircons. The age spectrum of our sample from the east coast of Shikoku indicates that the outcrop of the Toichidani Unit of the Shimanto Belt extends over a larger distance than previously thought, i.e. eastwards to the coast. The age barcode of the sample from the western coast of the Kii Peninsula agrees well with that of the overlying unit, whereas the age distribution of the sample from the south coast of the Kii Peninsula is unique. Hf isotopic compositions determined for a subset of the dated zircons fall into two groups, one with $\epsilon\text{Hf}(t) = -8$ to $+12$ and the other with $\epsilon\text{Hf}(t) = -22$ to -12 . The former may be derived from sources located within the current Japanese archipelago and the latter from outside sources. These outside sources may be largely located in southern/south-eastern South Korea as indicated by the abundance of Early to Middle Jurassic zircon in the Shimanto Belt and the highly and negative $\epsilon\text{Hf}(t)$ values measured for zircon from Korean plutons.

Keywords: Shimanto Belt, U-Pb dating of zircon, Hf isotopes, sources areas, Japan, Korea, SE China

INTRODUCTION

Accretionary complexes are composed in part of the debris shed by active margins into the shelf and trench areas and thus contain significant information on the geologic constitution of the overriding plate margin. Where source areas and depocenters are possibly displaced from each other by large-scale transcurrent faults (e.g., Ikeda *et al.*, 2016; Sakashima *et al.*, 2003), the correlation between source areas and depocenters may be difficult and fraught with uncertainties. It is thus of great interest to decipher the information contained in the clastic sediments composing accretionary complexes. Tools used in such studies are sediment petrography and geochemistry (e.g., Kiminami, 2010; Kiminami *et al.*, 1999) and in the past few years, the analysis of the U-Pb age and the Hf isotopic composition of detrital zircon.

The latter methods have proven to be powerful tools to identify the sources of the sediments (or sometimes only changing source areas) and the geologic make-up and evolution of source areas (e.g., Aoki *et al.*, 2014; Bodet and Schärer, 2000; Deng *et al.*, 2017; Hara *et al.*, 2017; Lan *et al.*, 2016).

A well studied accretionary complex is the Shimanto Belt distributed along the Pacific side of south-west and central Japan along an active continental margin. This belt may have been displaced relative to the source area due to movements along the Median Tectonic Line (e.g., Ikeda *et al.*, 2016; Sakashima *et al.*, 2003). Numerous studies have dealt with various aspects of this belt. Age constraints were largely obtained by studies of the radiolarian biostratigraphy (e.g., Suzuki and Fukuda, 2012; Hara and Hara, 1919a, b). Recently, the dating of detrital zircon has been used to refine these age assignments (e.g., Hara and Hara, 2019b; Hara *et al.*, 2017; Shibata *et al.*, 2008; Tokiwa *et al.*, 2016, 2017). Hara *et al.* (2017) also used the spectra of U-Pb zircon ages to discuss the provenance of the sediments that constitute the Shimanto belt in southern Shikoku.

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Fig. 1. Tectonic map of south-eastern Shikoku and south-western Kii-Peninsula based largely on Tokiwa (2009), Hara and Hara (2019a), Bessho (2015), Suzuki and Fukuda (2012) and the seamless geological map of Japan (Geological Survey of Japan). Inset shows the general location of the study area. Units of the Shimanto Belt in Shikoku: h = Hinotani, os = Osodani, tn = Taniyama, hw = Hiwasa, mg = Mugi units. Units of the Shimanto Belt in Kii Peninsula: ry = Ryujin Complex, ot = Otonashigawa Sequence. Ta is the Miocene Tanabe Group that was deposited unconformably above the Shimanto accretionary complexes.

In this paper, age data for detrital zircon is presented for sites of the Shimanto Belt in eastern Shikoku and on the western coast of the Kii Peninsula previously not studied. In addition, Hf isotopic compositions are presented for a subset of the dated zircons. It is then shown that the combination of U-Pb ages and Hf-isotope composition leads to new insights into potential source areas and their geodynamic setting.

GEOLOGY

The Shimanto Belt is exposed over a distance of 2,000 km from the Nansei Islands to the Kanto Mountains. It is the southernmost exposed geotectonic unit of the Japanese Islands. To the north, the Shimanto Belt is separated from the Jurassic accretionary complexes of the Chichibu Belt by the Bustuzo Tectonic Line. The belt is subdivided into the upper Cretaceous northern belt and the Paleogene to early Miocene southern belt by a major longitudinal fault (the Aki Tectonic Line in Shikoku and the Gobo-Totsugawa Line in the Kii Peninsula). The Shimanto Belt is mainly composed of flysch and mélangé. Most of the

flysch sediments consist of trench-filling turbidites, whereas the mélangé usually consists of blocks and slivers of basalt and radiolarian-bearing chert embedded in an argillaceous matrix. Sandstone petrography and geochemistry, as well as detrital zircon ages indicate that the Late Cretaceous Shimanto accretionary complex was largely sourced from acid volcanic rocks and acid igneous or metamorphic rocks (e.g., Hara *et al.*, 2017; Kiminami, 2010).

In Shikoku, the Upper Cretaceous Shimanto accretionary complex is divided into seven tectono-stratigraphic units. These are, from north to south, the Tochidani, Izuhara, Hinotani, Osodani, Taniyama, Hiwasa, and the Mugi Units (Fig. 1). These units become progressively younger towards the south. The youngest detrital zircon ages obtained for these units vary systematically from 111 to 62 Ma, i.e., the southernmost unit, the Mugi Unit is actually of Paleocene age (Hara *et al.*, 2017). The Paleogene Shimanto belt consists solely of the Naharigawa Unit, a coherent turbidite unit of Eocene age.

In the Kii Peninsula, the Shimanto accretionary complex is divided into the Cretaceous Kouyasan and

Hidakagawa Sub-belts and the Paleogene Hikigawa Sub-belt. The Hidakagawa Sub-belt is subdivided into the Yukawa Complex (Albian-Cenomanian), the Miyama Complex (Turonian-Campanian) and the Ryujin Complex (Campanian-Maastrichtian) (Fig. 1), which are in thrust contact with each other (Suzuki and Nakaya, 2012). The Hikigawa Sub-belt, a Paleogene accretionary prism, consists of the Otonashigawa (Paleocene to Early Eocene) and the Muro sequences (Middle Eocene to Early Miocene). They are composed mostly of clastic rocks with subordinate greenstones that are only weakly deformed and maintain their primary stratigraphy.

SAMPLES

All samples are medium-grained impure sandstones. Sample J160401-1 (henceforth J-01) was collected just south of the Butsuzo Tectonic Line on the eastern coast of Shikoku (Fig. 1). The sample was taken from a continuous sandstone band within a sandstone-mudstone sequence exposed in a cliff. Based on the map in Hara and Hara (2019b), the sampling site is part of the Hinotani Unit, based on the seamless Geological Map of Japan it is part of the Izuhara Unit and based on Ishida (1998) it is part of the Tanimaya Unit. The results of this study suggest, however, that it might be an eastward extension of the Tochidani Unit.

Sample J160402-1 (henceforth J-02) comes from the west coast of the Kii Peninsula where the Miyama Complex of the Hidakagawa Sub-belt (Fig. 1) is exposed. The sampling site is underlain by the Ubuyukawa Unit that is the lowermost unit of the Miyama Complex. Recently, Takesue and Suzuki (2016) described the sampling area in detail. To our knowledge, sample J-02 is the first sample of the Ubuyukawa Unit, for which age data for detrital zircon is reported.

Sample J160403-1 (henceforth J-03) was collected from an outcrop of the Muro Sequence of the Hikigawa Sub-belt along the southern coast of the Kii Peninsula (Fig. 1). In detail, the sample comes from the Susami Unit of the Muro Sequence (Suzuki and Nakaya, 2012). Based on radiolarian fossil evidence, this subunit is considered to be of late Middle Eocene to Late Eocene age (*ca.* 34–42 Ma; Suzuki and Fukuda, 2012). To our knowledge, no U-Pb zircon data has so far been reported for the Muro Sequence (confirmed by T. Tokiwa, written communication), whereas Tokiwa *et al.* (2016) presented data for a sample of the Otonashigawa Sequence to the north (Fig. 1).

ANALYTICAL PROCEDURES

The zircons were dated at the Department of Geosciences of the National Taiwan University using an

Agilent 7500s quadrupole ICP-MS instrument equipped with a Photon Machines 193 nm Analyte G2 excimer laser ablation system. The laser beam had a diameter of about 30 μm . The system was calibrated using the GJ-1 zircon standard (Jackson *et al.*, 2004), whereas the 91500 zircon and the Plešcovice zircon were used for data quality control. The $^{206}\text{Pb}/^{238}\text{U}$ -ages obtained in the period of study were for 91500: 1062 ± 20 Ma (2σ) and for Plešcovice: 333.9 ± 6.8 Ma (2σ) compared to accepted values of 1062.4 ± 0.4 Ma and 337.1 ± 0.4 Ma, respectively (Sláma *et al.*, 2008; Wiedenbeck *et al.*, 1995). Additional details of the analytical procedures are provided by Chiu *et al.* (2009) and Shao *et al.* (2014). All U-Th-Pb isotope ratios were calculated using the GLITTER 4.0 (GEMOC) software, and common lead was corrected using the common lead correction function proposed by Andersen (2002). The weighted mean U-Pb ages were calculated using Isoplot v. 3.0 (Ludwig, 2003). The concordia plots were likewise drawn using the Isoplot programme. Cathodoluminescence (CL) images were obtained using a Quanta 200F scanning electron microscope equipped with a MiniCL in low vacuum mode in the Department of Geosciences at the National Taiwan University. Discordance was calculated as $\text{disc} = (1 - ^{206}\text{Pb}/^{238}\text{U}_{\text{age}}/^{207}\text{Pb}/^{235}\text{U}_{\text{age}}) \times 100$ for zircon younger than 1 Ga and as $\text{disc} = (1 - ^{207}\text{Pb}/^{206}\text{Pb}_{\text{age}}/^{206}\text{Pb}/^{238}\text{U}_{\text{age}}) \times 100$ for zircon older than 1 Ga.

In-situ Hf isotopic analysis of zircons was conducted using the Nu Plasma HR Multi-Collector Inductively-Coupled plasma Mass Spectrometer (MC-ICP-MS) connected to a Photon Machines 193 nm Analyte G2 laser system at the Institute of Earth Sciences, Academia Sinica, Taipei. Lu-Hf isotopic analyses were carried out on zircon grains that were previously analyzed for U-Pb isotopes and where possible on the same spot. Each measurement, with a beam diameter of *ca.* 50 μm , a 5–8 Hz repetition rate, and energy of $\sim 8\text{--}9$ J/cm², took ~ 2 minutes including the blank time of 30 s and the ablation time of ~ 85 s. Some dated grains were too small for Hf isotope analysis. The laser ablation was performed with a He carrier gas of ~ 0.9 L/min (MFC1 = ~ 0.7 L/min and MFC2 = ~ 0.2 L/min) that could substantially reduce the deposition of ablated material onto the sample surface and greatly improve transport efficiency. Then it would mix with Ar gas of ~ 0.7 L/min to attain the best high intensity. Mud Tank (MT) zircon standard was analyzed to evaluate the accuracy of the data in the beginning and end of each run comprising 10 spot analyses. The average $^{176}\text{Hf}/^{177}\text{Hf}$ ratio obtained during the analyses was 0.282501 ± 0.000028 ($n = 17$). This value is in good agreement with the average $^{176}\text{Hf}/^{177}\text{Hf}$ value reported in literature which is 0.282504 ± 44 (Woodhead and Hergt, 2005).

During the Hf analyses, isobaric interference correc-

Fig. 2. Cathodoluminescence (CL) pictures of zircons studied. The circles indicate the spot analyzed and have a diameter of 30 μm .

tions of ^{176}Lu and ^{176}Yb on ^{176}Hf were made. Due to the extremely low $^{176}\text{Lu}/^{177}\text{Hf}$ in zircon (normally < 0.002), the isobaric interference of ^{176}Lu on ^{176}Hf was negligible (Iizuka and Hirata, 2005). $\epsilon\text{Hf}(t)$ values were calculated with reference to the chondritic reservoir (CHUR) at the time of zircon crystallization. The decay constant for ^{176}Lu of $1.865 \times 10^{-11} \text{ year}^{-1}$ (Scherer *et al.*, 2001), the present-day chondritic ratios of $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{176}\text{Lu}/^{177}\text{Hf}$, respectively, of 0.282772 and 0.0332 (Blichert-Toft and Albarède, 1997) were adopted to calculate $\epsilon\text{Hf}(t)$ values.

For Phanerozoic zircons we use $^{206}\text{Pb}/^{238}\text{U}$ ages in the plots and discussion whereas for Precambrian grains we use $^{207}\text{Pb}/^{206}\text{Pb}$ ages that are considered to be more reliably and have smaller errors. To allow a proper comparison with our data we therefore calculated $^{207}\text{Pb}/^{206}\text{Pb}$ ages for zircon older than 1 Ga for the data in Lee *et al.* (2015), Hara *et al.* (2017) and Tokiwa *et al.* (2017). This procedure considerably improves the similarity between the samples analyzed in this study and those analyzed by the above mentioned authors as all zircons (with one exception) with $^{206}\text{Pb}/^{238}\text{U}$ ages in the range 1.50 to 1.80 Ga have $^{207}\text{Pb}/^{206}\text{Pb}$ ages > 1.80 Ga (Fig. 4).

RESULTS

The analytical data is provided as Supplementary Material Tables S1 and S2. 61 U-Pb analyses were carried out for sample J-01 from Shikoku; of these 6 are dis-

Fig. 3. Concordia diagrams for samples J-01, J-02, and J-03 for zircons younger than 450 Ma.

tinctly discordant and are therefore not considered furthermore. In cathodoluminescence (CL) pictures most grains show oscillatory zoning (Fig. 2). Th/U ranges from 0.25 to 1.92, i.e., in all likelihood all zircons are of magmatic origin. The youngest grain has an age of 106 ± 6 Ma (2σ error) (Fig. 3). In the probability density curve three peaks are evident that occur at *ca.* 111 ± 3 Ma, 186 ± 3 Ma, and at 252 ± 5 Ma (Fig. 4). Five concordant or almost concordant grains have Precambrian ages (1.86–2.43 Ga). No grains have ages between 267 Ma and 1.86 Ga.

The Hf isotopic composition was determined for 21 grains of sample J-01. The younger grains have Hf isotopic compositions that scatter around chondritic values ($\epsilon\text{Hf}(t) = -3.3$ to $+3.7$). Most grains in the range 161 to 267 Ma have distinctly positive $\epsilon\text{Hf}(t)$ ranging from 4.4 to 11.1 (Fig. 5). The grain dated at 1.86 Ga has a slightly negative $\epsilon\text{Hf}(t)$, whereas the 2.43 Ga grain has $\epsilon\text{Hf}(t) = 10.9$.

71 grains of sample J-02 were dated. Four discordant ages are excluded from further discussion though they

Fig. 4. Probability density curves and histograms for the samples investigated. Corresponding data is shown for detrital zircons of the Sanbagawa belt (Aoki et al., 2019; Endo et al., 2018; Knittel et al., 2014, 2018, 2019) for samples KS1-Tc (Tochidani Unit; Hara and Hara, 2019b) and sample 160705-01 (Hattomaki Unit of the Miyama Complex; Tokiwa et al., 2017), and for detrital zircon from south-eastern Korea (Lee et al., 2015). Note that the ages of the peaks were calculated from the data and do not exactly coincide with the location of the peaks. The dark bar in the graph of the detrital zircons from SE China indicates the location of the early Jurassic peak of the Shimanto and Sanbagawa spectra.

Fig. 5. $\epsilon\text{Hf}(t)$ plotted vs. age for the samples studied. Data for the igneous rocks from the Shionomisaki and Nariwa areas are unpublished data of the authors. The field for zircon from the Permian Akiyoshi Belt is based on Zhang et al. (2019). Data for detrital zircons from Korea is taken from Lee et al. (2015, Myogok Formation) and for Triassic and Jurassic plutons in South Korea from Cheong et al. (2013, average values, light gray squares), Cheong et al. (2015, open squares), and Jo et al. (2018, average values, dark gray squares). Data for detrital zircons from SE China comes from X. Xu et al. (2007; Ou River (Oujiang), North River) and Y. Xu et al. (2014, 2016; Min River (Minjiang), Jiulong River). The dark bar in the graphs indicates the location of the early Jurassic peak of the Shimanto and Sanbagawa spectra. Abbreviations: DM - depleted mantle, B. - batholith, R. - rhyolite, G. - granite.

may define a discordia. The youngest grain has an age of 81 ± 6 Ma. As this grain plots almost off the Concordia (Fig. 3), we do not place too much significance on that age. In the probability density plot peaks occur at *ca.* 88 ± 2 Ma, 104 ± 3 Ma, 184 ± 3 Ma and 219 ± 4 Ma (Fig. 4). Almost a third of the grains (21 out of 67 concordant grains) have Precambrian ages in the range 1.81–2.97 Ga. Most of these grains are dark in CL pictures and show well rounded outlines suggesting abrasion during long transport (Fig. 2, grains 28 and 11). The grain dated at 2.97 Ga (Fig. 2, grain 11) plots slightly off the Concordia but discordance calculated as $\text{disc} = (1 - {}^{206}\text{Pb}/{}^{238}\text{U}_{\text{age}}/{}^{207}\text{Pb}/{}^{206}\text{Pb}_{\text{age}}) \cdot 100[\%]$ is only 5 %. It is the oldest grain found in this study and probably the oldest zircon from the Shimanto belt found so far.

For 23 grains of sample J-02, the Hf isotopic composition could be determined. Grains in the age range 87–108 Ma have either distinctly negative $\epsilon\text{Hf}(t)$ in the range

–8.3 to –18.2 or positive $\epsilon\text{Hf}(t)$ of 6.3 and 9.4. In the range 157–254 Ma zircons have, in contrast to sample J-01, highly negative $\epsilon\text{Hf}(t)$ of –12.8 to –22.5 (Fig. 5). Like in sample J-01, the *ca.* 1.86 Ga old grains have slightly negative $\epsilon\text{Hf}(t)$ (–0.7 to –3.9) and the 2.47–2.97 Ga grains have positive $\epsilon\text{Hf}(t)$ of 0.2–5.9.

For sample J-03, we could analyze only 42 grains and three of them yielded discordant ages. Th/U ranges of 0.24 to 1.49 as well as oscillatory zoning seen in CL pictures (Fig. 2) suggest a magmatic origin for these zircons. The youngest grain found has an age of 68 ± 4 Ma and is significantly younger than the next youngest grains (81 and 83 Ma). However, it plots well on the Concordia and given the small number of grains analyzed, there is no reason to distrust this age. No significant clustering of ages is seen in the probability density curve except for a peak at 185 ± 4 Ma (based on 13 grains; Fig. 4), but the overall lack of clustering could be due to the small number of

grains analyzed. Seven grains are of Precambrian age (1.84–2.35 Ga or 2.52 Ga if a discordant grain is taken into consideration).

For 21 zircons, the Hf isotope was determined but four results had to be rejected due to large errors. Zircons in the age range 81–164 Ma have $\epsilon\text{Hf}(t)$ scattering around chondritic values (-3.6 to $+0.2$) whereas those in the range 182–192 Ma have distinctly positive $\epsilon\text{Hf}(t)$ of 5.8–10.1. Zircon in the range 242 to 415 has variable $\epsilon\text{Hf}(t)$ ranging from -20.8 to $+7.8$. The Precambrian grains have slightly negative $\epsilon\text{Hf}(t)$ (-2.5 to -3.6).

DISCUSSION

Zircon data can be used to clarify the age of non-fossiliferous strata as detrital zircons provide an estimate of maximum depositional age for the strata that contain the zircons. Tokiwa *et al.* (2017) as well as Hara *et al.* (2017) used this approach for the Shimanto Belt and confirmed that age assignments based on detrital zircons are generally in good agreement with those based on radiolarians. They also suggested that in some cases, the age estimate based on detrital zircon, is more precise than that based on radiolarians. This indicates that there was a continuous supply of juvenile zircon to the depocenters in the late Cretaceous and Paleocene.

In addition, detrital zircons provide insights into the geological constitution of the source areas, i.e., zircons of a specific age require the presence of rocks of that age in the provenance. Alternatively, such zircons could be recycled.

a) Stratigraphic position of the samples

Sample J-01 exhibits significant peaks at 111 ± 3 , 186 ± 3 , and 252 ± 5 Ma and is thus similar to the Tohidani Unit sample of Hara *et al.* (2017), which has peaks 114 ± 2 , 186 ± 2 , 219 ± 2 , and 259 ± 4 Ma. Given the errors attached to the averages, they are indistinguishable. The 219 Ma group of Hara's sample is lacking in our sample, but there are two grains dated at 228 and 231 Ma. In both samples the highest peak occurs at 186 Ma. Given the variability of the zircon age spectra of samples taken from a single unit and in short distance from each other (e.g., Knittel *et al.*, 2017, 2018) the agreement of the age patterns is remarkably good. The age of the youngest grain of 106 ± 6 Ma appears to be younger than the youngest grain reported by Hara *et al.* (2017; 111 ± 5 Ma) but given the errors, they are also indistinguishable and besides, even if the younger age is accepted at face value, it still lies within the age estimate based on radiolarians.

Since the sample was collected from a locality just south of the Butsuzo Line, the coincidence with the Tohidani Unit sample of Hara *et al.* (2017) is not unexpected. However, various maps (including those in Hara

and Hara, 2019a; Ishida, 1998) suggest that this unit may not be exposed on the eastern coast of Shikoku (H. Hara, personal communication 2019). Both, the youngest grain in sample J-01 as well as the age of the youngest cluster age would also be compatible with the sample of the Hinotani Unit analyzed by Hara *et al.* (2017), but the overall age pattern of the latter differs in detail from that of J-01. The Tanimaya Unit, suggested to underlie the sampling site by Ishida (1998), is distinctly younger than suggested by the data for J-01. Therefore, based on the results of this study, the Tohidani Unit is tentatively extended to the coast in Fig. 1.

Sample J-02 has peaks at 88 ± 2 , 104 ± 3 , 184 ± 3 , and 219 ± 4 Ma resembles most closely sample 160705-01 of Tokiwa *et al.* (2017) which comes from the lower (younger) part of the Miyama Complex (Hattomaki Unit, exposed north of the Ubuyukawa Unit) and exhibits peaks at 78 ± 3 , 98 ± 7 , 184 ± 4 , and 224 ± 7 Ma. The youngest grain in sample J-02 has an age of 81 ± 6 Ma, whereas the youngest grain in sample 160705-01 was dated at 77 ± 4 Ma. Again it is noteworthy that in both samples the 184 Ma peak is based on the largest number of zircons. The observed coincidences agree well with the sample location, which is generally mapped as part of the Ubuyukawa Unit of the Miyama Complex that underlies the Hattomaki Unit and indicates that both units are characterized by similar zircon age spectra (in contrast to the overlying Chikai and Gomadanzen Units that appear to be characterized by essentially Late Cretaceous peaks only).

To our knowledge, sample J-03 is the first sample of the Muro Sequence for which detrital zircons were analyzed. The sample comes from the Susami Unit, the age of which is considered to be *ca.* 34–42 Ma based on radiolarian fossils (Suzuki and Fukuda, 2012). The age of the youngest grain in sample J-03 is 68 ± 4 Ma, i.e., significantly older than the age estimate based on radiolarians. It is also older than the age of 51 ± 1 Ma obtained by Tokiwa *et al.* (2016) for detrital zircons of the Otonashigawa Sequence overlying the Muro Sequence. This discrepancy could be due to the small number of zircons analyzed or the lack of zircons that are roughly contemporaneous with the sediments deposition. In particular, it should be remembered that the youngest zircons provides only an estimate for the maximum age of the sediment. Alternatively, the possibility that the sampling site is an “out-of-sequence” unit, might require further study.

b) Potential sources of the zircons

The age pattern of detrital zircon observed for the Shimanto samples exhibits peaks at *ca.* 100 Ma, *ca.* 185 Ma, *ca.* 221 Ma, and *ca.* 255 Ma (Fig. 4) and hence is relatively similar to that found for the Sanbagawa

Metamorphics with peaks at 94 ± 1 , 183 ± 1 , 220 ± 3 , and 257 ± 2 Ma (based on 814 concordant zircon ages compiled from Aoki *et al.*, 2019; Endo *et al.*, 2018; Knittel *et al.*, 2014, 2018, 2019). The youngest peaks of the Shimanto samples vary in the range 70–110 Ma depending on the actual age and stratigraphic position of the sample. The Late Cretaceous peak is much more prominent in the Sanbagawa pattern than in the Shimanto patterns. This is largely due to the fact that some samples from the Sanbagawa Belt contain almost exclusively zircon of late Cretaceous age, e.g., samples S-5 and S-8 in Knittel *et al.* (2014) and JS-11 and JS-13 in Knittel *et al.* (2018). Samples that exhibit essentially only one age peak were also found by Hara *et al.* (2017, samples for the Mugi Unit) and Tokiwa *et al.* (2017, some samples of the Miyama and Ryujin complexes). Therefore it is suggested that despite differences in the intensities of the peaks both units received their sedimentary inventory from roughly the same source areas. Kiminami and co-workers reached the same conclusion for low grade Sanbagawa metamorphics on the basis of geochemical studies (Kiminami, 2010 and references therein).

Hara *et al.* (2017) provided a very detailed discussion of the potential source rocks for the detrital zircons of the Shimanto Belt in Shikoku trying to relate the zircons to known exposures of igneous rocks of the corresponding age within the Japanese archipelago. As for the zircons of Permian age, they considered the few Permian intrusive complexes known within Japan as potential sources. Examples are the older Funatsu Granites occurring in the Hida Belt that yield U-Pb zircon ages in the range 240–250 Ma (Takahashi *et al.*, 2010; Zhao *et al.*, 2013) and the Kinshozan Quartz Diorite in the Kanto Mountains, which is, however older (dated at 282 ± 2 Ma Ogasawara *et al.*, 2016). The Usukigawa Granodiorite (Sakashima *et al.*, 2003) dated at 292 ± 12 Ma is another example and we actually prefer an age of 276 ± 6 Ma age for this pluton based on the younger group of analyses. This age agrees well with the Rb-Sr whole-rock age of 275 ± 56 Ma reported by Takagi *et al.* (1997). Kawagoe *et al.* (2013) determined U-Pb zircon ages in the range 240–270 Ma for volcanoclastic rocks in the Hida-Gaien belt.

For the Jurassic zircons, the only known sources within Japan appear to be the younger granites of the Hida-Belt. U-Pb zircon ages reported for a pluton are 193–197 Ma (Takahashi *et al.*, 2010; Zhao *et al.*, 2013), but Rb-Sr ages suggest a longer period of activity from 180–190 Ma (e.g., Arakawa, 1988; Shibata, 1988). For both periods it appears possible that the sources for Permian and Jurassic zircon in Japan have now been largely eroded as suggested by Nakama *et al.* (2010) and Isozaki *et al.* (2010).

Cretaceous igneous activity in Japan was ubiquitous but generally appears to be younger than about 100 Ma.

Iida *et al.* (2015), for example, in a traverse across SW Japan determined U-Pb zircon ages in the range 95–30 Ma for granitoids. Igneous rocks from the Kinki District dated at 109–99 Ma are considered to be very early expressions of Cretaceous magmatism (Imaoka *et al.*, 2014, and references therein). Hence the origin of Cretaceous zircon older than *ca.* 95 Ma is not really clear.

The ultimate source of Precambrian zircons must be sought outside of the Japanese archipelago but it is well possible that they were recycled from older sediments or younger intrusives. With regard to their age patterns it is noteworthy that zircon of Early Paleozoic, Neoproterozoic, and Mesoproterozoic age are virtually absent. This is also true for sediments of the Middle Jurassic to Upper Jurassic Mino-Tanba belt that contain more detrital zircons of Precambrian age than of Phanerozoic age (Fujisaki *et al.*, 2014). Hence, these sediments could be a source of the Precambrian zircons in the Shimanto Belt protoliths. Horie *et al.* (2010) found xenocrystic zircon of Eoarchean to Paleoproterozoic age in granites of Permo-Triassic age in the Unazuki area that is a part of the Hida Metamorphic Complex, and thus, younger magmatic rocks could be the source of older zircon.

Both the South China Block, in particular the Cathaysia Block, and the North China Block have been considered as potential sources of zircon found in the Japanese archipelago (e.g., Fujisaki *et al.*, 2014; Isozaki *et al.*, 2014; Nutman *et al.*, 2006). In Fig. 4, the age spectrum of zircon from the Shimanto Belt is compared to that of detrital zircons from recent river sediments from SE China. The latter should reflect the zircon inventory of the area as indicated by a comparison between detrital zircons from recent river sediments and those from sediments of various ages (Xu *et al.*, 2016). One obvious result of the comparison is that Early Jurassic (180–190 Ma) zircons that are abundant in all Shimanto (and Sanbagawa) samples, are relatively rare SE China. In contrast, 130–160 Ma old zircon that comprise the majority of Phanerozoic zircon in SE China, are rare in both, the Shimanto and the Sanbagawa Belts. An early Jurassic belt of granitic intrusives does occur in the provinces Fujian and Zhejiang (Jiang *et al.*, 2015), but this belt may be located too far from the coast and/or is volumetrically too small to have an impact on the overall age spectra of detrital zircon derived from SE China. It is therefore concluded that SE China is not a significant source of sediment comprising the Shimanto and the Sanbagawa Belts.

In contrast, early Jurassic magmatism is well developed in southern Korea. The age spectrum of detrital zircon from recent river sediments of three rivers draining southern Korea contains a large number of zircons in the age range 177–202 Ma and peaks are recognized at 185 ± 2 and 197 ± 1 Ma (Choi *et al.*, 2012; group 2). The age

spectrum of detrital zircons from the Early Cretaceous Myogok Formation that is exposed in SE Korea in the north of the Gyeongsang Basin (Lee *et al.*, 2015) is very similar to that of the recent river sediments. The presence of early Jurassic zircon in southern Korea and the paucity of such zircon in SE China points to Korea as the source of at least part of the zircon inventory of the Shimanto (and the Sanbagawa) Belt. The absence of Early Paleozoic, Neoproterozoic, and Mesoproterozoic zircons likewise supports this suggestion as these are scarce in Korea (Lee *et al.*, 2015) that shows more affinity to the North China Block than to the South China Block. This tentative conclusion is supported by the Hf isotope data.

The Hf isotopic compositions of the zircons investigated in this study fall into two groups. The majority of the grains have $\epsilon\text{Hf}(t)$ around chondritic values, i.e., $\epsilon\text{Hf}(t)$ ranges from -8 to $+12$. In addition, there are zircons with distinctly negative $\epsilon\text{Hf}(t)$ in the range -22 to -12 (Fig. 5). Positive $\epsilon\text{Hf}(t)$ values are generally considered to indicate significant mantle input into the magmas from which the zircons crystallized, whereas distinctly negative values indicate zircon that crystallized from magmas that were generated by re-melting of the continental crust.

To our knowledge, there are no Hf isotope data for igneous rocks from SW Japan with which to compare our data. Zhang *et al.* (2019) studied the Hf isotope composition of detrital zircon from the Akiyoshi Belt, an accretionary complex of Permian age and found that Permian zircon has $\epsilon\text{Hf}(t)$ in a very restricted range ($+8$ to $+15$). In two forthcoming papers (manuscripts in preparation; data available upon request), we will present Hf isotope data for two igneous rocks from the Nariwa area, one of which is a dike, probably related to the Okayama batholith (Iida *et al.*, 2015; Kagami *et al.*, 1988) and the other a rhyolitic tuff of Jurassic age and for two intrusive rocks from the Shionomisaki area (Miyake, 1985, 1988; Shinjoe *et al.*, 2011), located south of our sample location J-03. Data obtained for these samples suggest that igneous rocks from central Honshu have $\epsilon\text{Hf}(t)$ in the range -8 to $+15$ (Fig. 5). This agrees well with the results obtained by Zhang *et al.* (2019) for zircon from the Permian Akiyoshi Belt. It is therefore tentatively suggested that the zircons from the Shimanto Belt with $\epsilon\text{Hf}(t)$ ranging from -8 to $+12$ are derived from “local” sources, i.e., from igneous rocks that were largely emplaced within the area of the current SW Japanese archipelago.

The zircons with distinctly negative $\epsilon\text{Hf}(t)$ [-22 to -12], on the other hand, as well as the zircons of Precambrian age may be ultimately derived from the Asian craton in China or Korea, perhaps by recycling of older sediments or as xenocrysts in younger igneous rocks. Zircons from river sediments in SE China (Xu *et al.*, 2007; Xu *et al.*, 2014, 2016) mostly have distinctively negative $\epsilon\text{Hf}(t)$ as shown in Fig 5, but as noted above, Early

Fig. 6. Possible configuration of the inner and outer parts of the Japanese Archipelago in the Late Cretaceous (modified after Ikeda *et al.*, 2016). Jurassic plutons exposed in Korea are indicated by dark shading (based on Yi *et al.*, 2012).

Jurassic zircon is very sparse in SE China. Therefore, as suggested above, the southern part of the Korean Peninsula, where early Jurassic magmatism is well developed (e.g., Jo *et al.*, 2018; Park *et al.*, 2009; Sagong *et al.*, 2005; Yi *et al.*, 2012), is a more likely source area. In the compilation of Kiminami and Imaoka (2013, Fig. 2) a significant peak in magmatic activity is indicated for the Yeongnam Massif for exactly the same time as observed in the zircon age distributions (170–200 Ma). Hf isotopic data for detrital zircons of Jurassic age from South Korea has been published so far only by Lee *et al.* (2015), who studied the detrital zircons from the Early Cretaceous Myogok Formation that is exposed in SE Korea in the north of the Gyeongsang Basin. These data show that the zircons in the age range between 178 and 195 Ma have $\epsilon\text{Hf}(t)$ ranging from -22 to -8 (with one grain having $\epsilon\text{Hf}(t)$ of -0.4 ; Fig. 5). Data from North Korea (Wu *et al.*, 2007) and for Triassic (Cheong *et al.*, 2015) and Jurassic granites (Cheong *et al.*, 2013; Jo *et al.*, 2018) likewise indicate that $\epsilon\text{Hf}(t)$ values of <-12 should be expected for the Jurassic zircons from Korea. These zircons are probably derived from granites intruding the Yeongnam Massif and the Gyeongsang Basin.

It thus appears that south-eastern Korea is a potential source for some of the zircons found in the Shimanto sediments and this would further support the northward transport of the outer parts of the Japanese islands since the Late Cretaceous as suggested earlier by, among oth-

ers, Sakashima *et al.* (2003) and Ikeda *et al.* (2016). This is illustrated in Fig. 6, which is based on figure 30 of Ikeda *et al.* (2016), but the amount of displacement is reduced to about one third.

CONCLUSIONS

Dating of detrital zircon from three samples from the Shimanto Belt confirm the age estimates based on radiolarian fossils in two cases. The observed age spectra suggest that the Toichidani Unit extends south of the Butsuzo Tectonic line to the east coast of Shikoku.

The age spectra of detrital zircon from the Shimanto and the Sanbagwa Belts are very similar and thus confirm earlier suggestions that both are derived from essentially the same source areas. These source areas may comprise igneous complexes located within current Japan but also appear to comprise south-eastern Korea as indicated by an abundance of Early Jurassic zircon. Early Jurassic plutons are exposed in central South Korea and detrital zircon of Early to Middle Jurassic age is abundant in Cretaceous sediments (Lee *et al.*, 2015) and in recent river sediments (Choi *et al.*, 2012) from SE Korea and mostly have distinctly negative $\epsilon\text{Hf}(t)$ values like some of the detrital zircons from the Shimanto Belt.

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SUPPLEMENTARY MATERIALS

URL (<http://www.terrapub.co.jp/journals/GJ/archives/data/54/MS596.zip>)
Tables S1 and S2