OKAYAMA University
Earth Science Reports,
Vol.25, No.1, 39-48, (2018)

U-Pb single grain zircon ages for Sanbagawa Metamorphic Rocks in central Shikoku (Japan): the Sanbagawa Belt re-united

Ulrich KNITTEL[1,2]*, Monika WALIA[2,4]
Shigeyuki SUZUKI[3], Yuan-Hsi LEE[4]

The high-P/low-T Sanbagawa Metamorphic Belt that traverses SW Japan, has been subdivided into two belts thought to have been metamorphosed at ca. 120 Ma and at ca. 65 Ma ('Sanbagawa Metamorphic Rocks' and 'Shimanto Metamorphic Rocks'). The subdivision was based on the assumption that metamorphism occurred at ca. 116 Ma, largely based on an early Rb-Sr isotope study and zircon data obtained for the eclogite unit of the Sanbagawa Belt, whereas in some parts of the belt detrital zircons of late Cretaceous age (90-80 Ma) were discovered. Analysis of detrital zircons sampled from two sites within the area considered to expose the older 'Sanbagawa Metamorphic Rocks', including the area investigated by the Rb-Sr study, reveals the presence of zircons younger than 95 Ma in all samples and some grains as young as 80 ± 4 Ma. It is therefore concluded that the Sanbagawa Belt is one single tectonic entity that formed in the Late Cretaceous though it contains older components, including fossiliferous clasts, older basic meta-volcanics and eclogite units that may record earlier metamorphic events.

Keywords: U-Pb zircon dating, Sanbagawa Metamorphic Belt, Late Cretaceous, Asemi River

Introduction

The high-pressure, low-temperature (high-P/T) Sanbagawa Metamorphic Belt in SW Japan (Fig. 1) is an intensely studied example of subduction related metamorphism. Despite decades of intense study, however, currently no consensus exists regarding the timing of the deposition and metamorphism of the belt and hence, the correlation with non-metamorphic units is contentious. Based on fossils found in clasts, it was generally assumed that the protoliths were deposited in the Late Jurassic to Early Cretaceous and based on radiometric age determinations, that peak metamorphism occurred at ca. 110-120 Ma and exhumation at 85-75 Ma (e.g., Isozaki and Itaya, 1990).

Dating of detrital zircons, however, has shown that parts of the belt have protoliths deposited in the Late Cretaceous (Manabe *et al.*, 1996; Aoki *et al.*, 2007). In order to reconcile the conflicting evidence, i.e. peak metamorphism at ca. 110-120 Ma and protoliths younger than 90 Ma, Aoki et al. (2007, 2011) concluded that the Sanbagawa Metamorphic Belt actually is composed of two belts of different age, the 'Sanbagawa Metamorphic Rocks', metamorphosed at ca. 110 - 120 Ma and the 'Shimanto Metamorphic Rocks' metamorphosed at ca. 65 Ma (Fig. 2).

In Shikoku, the Sanbagawa Belt comprises three lithologically distinct tectonostratigraphic units (nappes): the Oboke unit, the Besshi unit (Takasu and Dallmeyer, 1990), the latter was recently renamed as Shirataki unit where it was not initially subjected to eclogite facies metamorphism (Aoya and Endo, 2017), and the eclogite unit (Wallis and Aoya, 2000) from bottom to top. Evidence suggesting metamorphism at 100 – 120 Ma comes from the Besshi and eclogite units.

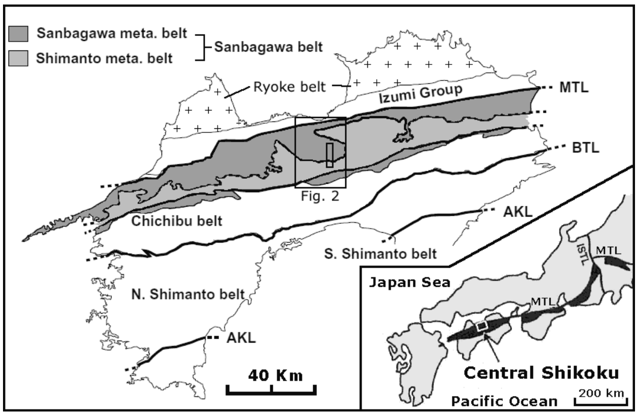

Fig. 1: Map showing the distribution of the 'Sanbagawa Metamorphic Rocks' and the 'Shimanto Metamorphic Rocks' based on Aoki et al. (2011). MTL: Median Tectonic Line, BTL: Butsuzo Tectonic Line, AKL: Aki Tectonic Line. Inset shows the distribution of the Sanbagawa belt in Japan. ISTL = Itoigawa Shizuoka Tectonic Line.

---

1) Clay and Interface Mineralogy, RWTH Aachen University, 52056 Aachen, Germany
2) Department of Geosciences, National Taiwan University, Taipei, Taiwan
3) Graduate School of Natural Science and Technology, Okayama University, Okayama, 700-8530, Japan
4) Department of Earth and Environmental Sciences, National Chung-Cheng University, Min-Hsiung, Chiayi, Taiwan

* Corresponding author, email: Knittel@rwth-aachen.de

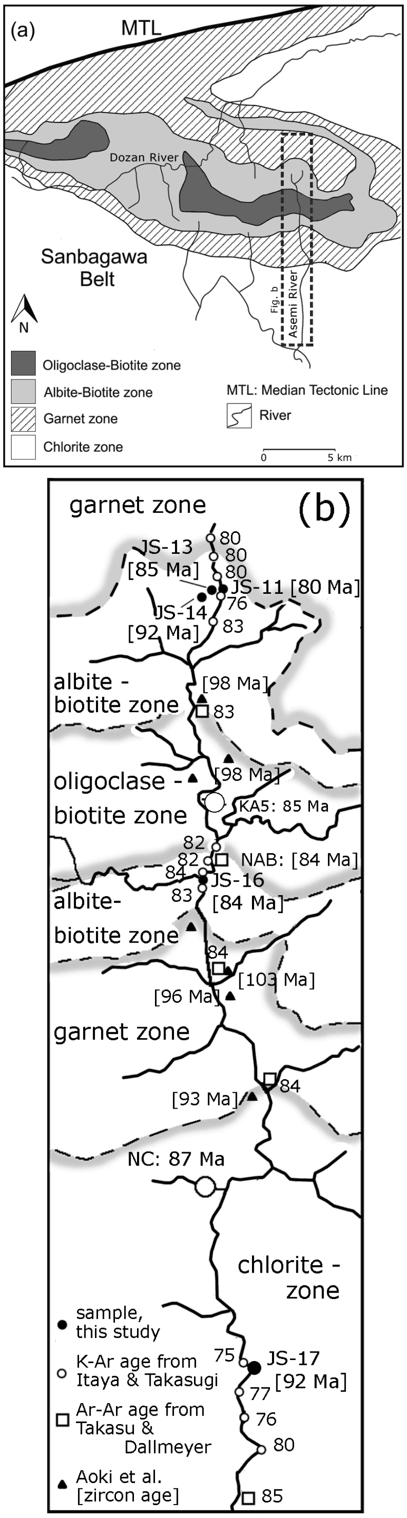

Fig. 2: Profile along the Asemi River showing our sample locations [with ages of the youngest zircons] as well as K-Ar ages for selected locations from Itaya and Takasugi (1988, open circles) and Ar-Ar ages obtained by Takasu and Dallmeyer (1990, squares); numbers are the ages obtained. NAB and NC are youngest zircons of Endo et al. (2018). KA5 is the sample dated by Aoki et al. (2009). Modified from Itaya and Takasugi (1988).

For the Besshi unit, one of the corner-stones for the assumed peak metamorphism at ca. 116 Ma is a Rb-Sr isotope study of Minamishin et al. (1979), who analysed 21 whole rock samples collected within a small area in the upper reaches of the Asemi River in central Shikoku. An isochron age of 116 ± 10 Ma was calculated and has since been considered to date peak metamorphism of the Sanbagawa Metamorphic Rocks (e.g., Isozaki and Itaya, 1990; Aoki *et al.*, 2007; Otoh *et al.*, 2010; Aoki *et al.*, 2011; Itaya *et al.*, 2011; Itaya and Tsujimori, 2015). This view was supported by single grain ages of 132–112 Ma obtained for zircon considered to be of metamorphic origin from the eclogite unit (Okamoto et al., 2004). In addition, eclogite exhibiting partial melting textures contains zircons with rim ages of 115-104 Ma (Arakawa et al., 2013).

In contrast, Wallis and co-workers (Endo et al., 2009; Wallis et al., 2009; Wallis and Endo 2010), based on Lu-Hf dating of garnet-pyroxene pairs in eclogite, suggest that Sanbagawa metamorphism actually occurred at ca. 88-89 Ma. Aoki et al. (2009) also reported an U-Pb age of 86 ± 3 Ma for metamorphic zircon from the Besshi unit but ascribed this to retrograde metamorphism. Knittel et al. (2014) and Endo et al. (2018) report ages for detrital zircon younger than 90 Ma from the purported "Sanbagawa Metamorphics" within the Besshi unit. Thus, the question of the age of the Besshi unit of the Sanbagawa Belt is contentious, in part due to the uncertain interpretation of the 116 Ma Rb-Sr age (e.g., Aoya and Endo, 2017).

In order to resolve the discussion on the significance of the Rb-Sr age obtained by Minamishin et al. (1979), we re-sampled the area studied by these authors and determined the U-Pb-ages of detrital zircon in order to determine the maximum protolith ages of these rocks. This is based on the notion that the youngest detrital zircon is older than the sediment hosting this zircon.

Geology

The Sanbagawa Metamorphic Belt extends over a distance of about 800 km across south-western Japan (Fig. 1) from Kyushu to the Kanto Mountains in Honshu. To the north it is bounded by the Median Tectonic Line. In the south, the Sanbagawa Belt is bounded by the Jurassic Chichibu composite belt. Further south, separated from the former by the Butsuzo Tectonic Line, the Shimanto accretionary belt is exposed. The latter is subdivided by the Aki Tectonic Line into the northern part, comprising strata of late Cretaceous age and the southern part, composed of Paleogene to Miocene strata.

In Shikoku three tectonostratigraphic units that differ in age, metamorphic grade and perhaps also chronology are distinguished within the Sanbagawa Belt: the Oboke unit, the Besshi unit, and the eclogite unit (Takasu and Dallmeyer, 1990; Wallis and Aoya, 2000).

The Oboke unit, composed largely of metasandstone (Koboke Formation) and minor metapelite (Kawagushi Formation) (Kenzan Research Group, 1984), records chlorite-zone metamorphism (Banno et al., 1978). Based on geochemical signatures and petrological evidence, Kiminami et al. (1999) inferred that the Oboke unit is the metamorphic equivalent of the Hiwasa Formation of the Shimanto accretionary complex that was deposited in the Campanian (84-72 Ma). Ages between 96 and 102 Ma and between 89 and 98 Ma for zircon in granite cobbles obtained by Manabe et al. (1996) and Aoki et al. (2007), respectively, are consistent with this suggestion. In addition Aoki and co-workers (Aoki et al., 2007; Aoki et al., 2012) reported ages for detrital zircon from the Oboke unit as young as 82 Ma that likewise support the suggested correlation.

The Besshi unit consists mainly of metapelite and metabasite and has been sub-divided into chlorite, garnet, albite-biotite and oligoclase-biotite zones with increasing metamorphic grade (e.g., Higashino, 1990). Kiminami (2010) used geochemical and petrographic arguments to suggest that the low-grade (chlorite-zone) of the Besshi unit are the metamorphic equivalents of late Albian to Campanian (ca. 100-80 Ma) sediments of the Shimanto accretionary complex. In contrast, Aoki et al. (2007, 2001) and others suggest that large parts of the Besshi unit are part of the older Sanbagawa metamorphic rocks. Subsequently, detrital zircon younger than 90 Ma has been found at a number of sites considered to be part of the Sanbagawa metamorphics (Knittel et al., 2014; Endo et al., 2018).

The eclogite unit (nappe) records the highest metamorphic grade (Wallis and Aoya, 2000; Miyamoto et al., 2007; Endo and Tsuboi, 2013) but eclogite facies metamorphism appears to have not been restricted to the eclogite unit as relicts of such metamorphism were also detected in parts of the Besshi unit. The units traditionally considered as eclogite unit consist largely of mafic and ultramafic rocks. Isotopic and petrologic evidence suggest that the evolution of the eclogite unit was not straightforward comprising only one phase of progressive metamophism and one phase of retrograde metamorphism (e.g., Endo et al., 2009; Endo et al., 2012; Aoya and Endo, 2017). Radiometric ages determined for the eclogite unit (Okamoto et al., 2004; Endo et al., 2009; Wallis et al., 2009; Arakawa et al., 2013) therefore may have no implications for the Besshi unit.

In the past few years, evidence has emerged that parts of the traditional Besshi unit were initially subjected to eclogite facies metamorphism prior to retrograde metamorphism in the epidote-amphibolite facies, in particular in the geographic Besshi area (Kouketsu and Enami, 2010; Kouketsu et al., 2010; Kouketsu et al., 2014) but also in the Asemi River area (Taguchi and Enami, 2014; Taguchi et al., 2018). Knittel et al. (2019), based on their own results and those of Endo et al. (2018), have shown that the schists in the Asemi River area that initially experienced eclogite facies metamorphism, have protoliths younger than 90 Ma, consistent with the views of Wallis and coworkers (Endo et al., 2009; Wallis et al., 2009).

Our study is focused on the well studied N-S traverse across the Besshi unit along the Asemi River (including the area studied by Minamishin et al., 1979) in central Shikoku (Fig. 2). One sample locality lies within the northern part of the albite-biotite zone, and the other within the southern chlorite zone. Itaya and Takasugi (1988) presented K-Ar ages of white mica for the traverse along the Asemi River ranging from ca. 65 Ma in the northern chlorite zone to ca. 82 Ma in the albite/oligoclase-biotite zone. Takasu and Dallmeyer (1990) presented additional ^{40}Ar/^{39}Ar ages that largely confirm the results of Itaya and Takasugi (1988) and also presented detailed samples descriptions that illustrate the lithologies exposed along the traverse. Mori and Wallis (2010) presented a tectonic analysis of the Asemi region and described kilometer-scale folding in the central part of the Asemi-gawa region that explains the distribution of the metamorphic zones.

Analytical procedures

The samples were thoroughly cleaned before crushing. Zircons were separated by conventional methods and were then hand-picked and mounted using epoxy resins. Prior to analysis, Cathodoluminescence images (CL) were taken at the Institute of Earth Sciences, Academia Sinica, Taipei. The U-Pb analyses were carried out using an Agilent 7500s quadruple inductively coupled plasma mass spectrometer (ICP-MS) equipped with a Photon Machines Analyte G2 laser ablation system with a beam diameter of ~30 μm at the Department of Geosciences, National Taiwan University, Taipei. The analytical procedures are the same as described in Chiu et al. (2009) and Knittel et al. (2010). Zircon GJ (Jackson et al., 2004) was used for calibration. Data quality was controlled by analyzing zircon standards 91500 (^{207}Pb/^{206}Pb age: 1065 Ma; Wiedenbeck et al., 1995) and Plešovice (^{206}Pb/^{238}U age: 337.1±0.4 Ma; Sláma et al., 2008) at the beginning of each run. Values obtained during the period of our study were 336.1 ± 1.6 Ma (n=20) for the Plešovice zircon and 1070.1 ± 4.6 Ma (n=22) for 91500. U-Th-Pb isotope ratios were calculated using the GLITTER 4.0 (GEMOC) software and common lead was corrected following Andersen (2002). Concordia plots and probability density plots were produced using Isoplot v. 3.0 (Ludwig, 2003). Analyses of broad rims in sample SJ-13 were calculated on the basis of the first 15 seconds of data acquisition in order to avoid including the core in the analysis.

Samples and Results

Samples JS-11, JS-13 and JS-14 (Fig. 2) were collected in the area studied by Minamishin et al. (1979). 244 spots were dated and 61, 97 and 50 concordant ages were obtained for samples JS-11, JS-13, and JS 14, respectively (Fig. 3; Table 1). Most grains exhibit oscillatory zoning in CL images (Fig. 4) and all but one has Th/U = 0.21-1.25. Both features are typical for magmatic zircon (Corfu et al., 2003; Hoskin and Schaltegger, 2003). The youngest ages are 80 ± 4 Ma (2σ error; Fig. 3) for sample JS-11, 85 ± 4

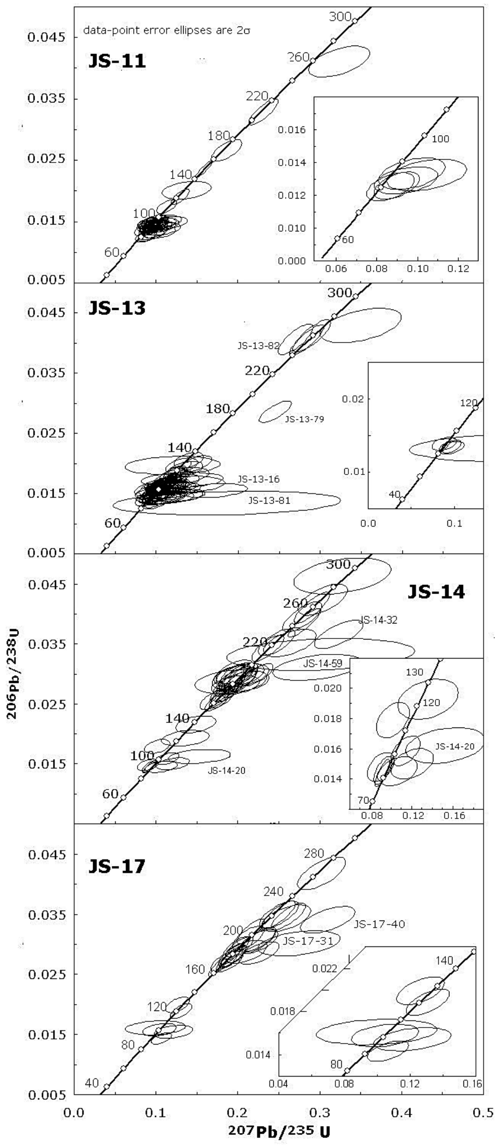

Fig. 3: Concordia diagrams for Mesozoic zircons (insets show the youngest zircons).

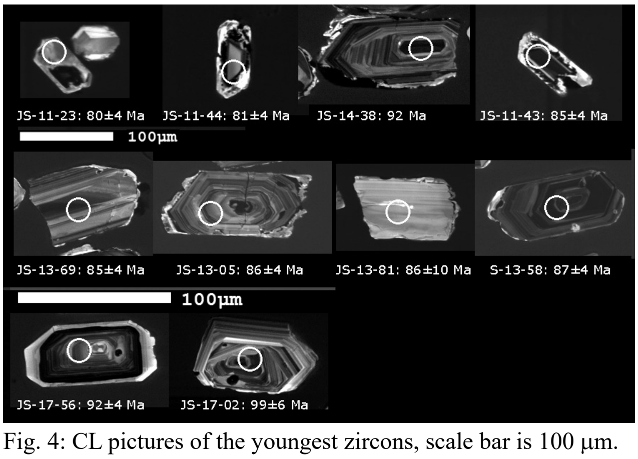

Fig. 4: CL pictures of the youngest zircons, scale bar is 100 µm.

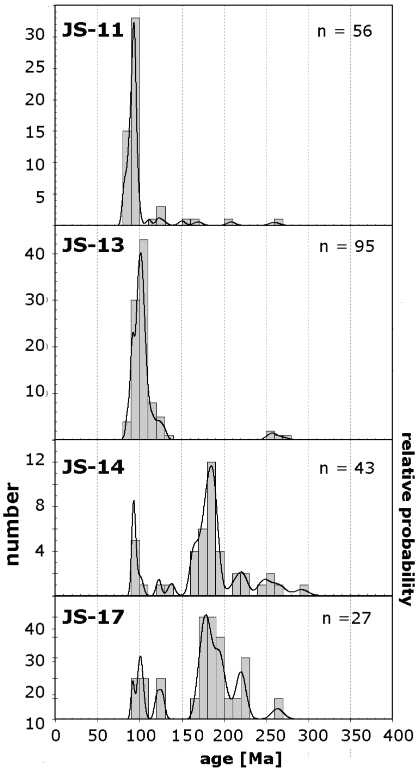

Fig. 5: Probability density plots for Mesozoic zircons based on concordant grains (number refers to the number of concordant Mesozoic grains).

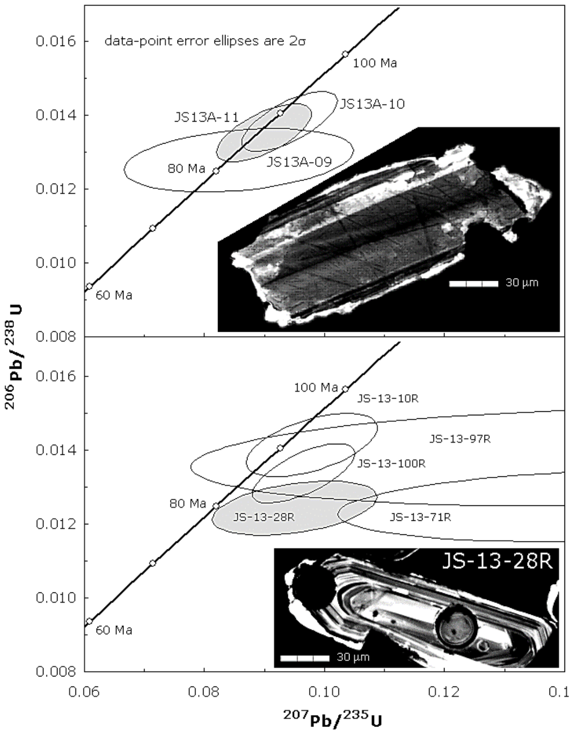

Fig. 6: Concordia diagram for depth profiles and rim analyses of zircons in sample JS-13. Insets show CL-pictures of analyzed grains.

Ma for sample JS-13 and 92 ± 4 for sample JS-14. In sample JS-11, most concordant grains fall into the range 80 – 96Ma (n=39), whereas in sample JS-13 most grains fall into the range 91 – 110 Ma (n = 77) and in JS-14 into the range 161 – 197 Ma (n = 27) (Fig. 5). All three samples contain a number of grains of Precambrian age, but no grains were found in the range 300 Ma to 1.8 Ga.

Some zircons of sample JS-13 in CL exhibit very bright rims that may be of metamorphic origin. We have attempted to date these, where they are relatively broad (Fig. 6). In order to restrict the analysis as much as possible to the rim, we used in general only the first 20 seconds of measuring time for the age calculation and obtained ages ranging from 80 ± 4 Ma to 91 ± 4 Ma. In all cases, the rim ages are younger than the core ages, but only the youngest rim has Th/U = 0.01, typical for metamorphic zircon, whereas the others have Th/U = 0.11-0.23. Nevertheless, all rims have lower Th/U than the cores. Thus most rim "ages" may represent mixtures of core and rim.

In addition we attempted depth profiling, i.e. we mounted zircons on a sticky tape without embedding them and analyzed them. As we did not have CL pictures before analysis, we could not be sure, whether or not the analyzed zircons had broad bright rims. Since the laser in all cases penetrated through the rim, we again calculated the ages on the basis of the first 20 seconds of measuring time. The youngest ages obtained this way are 82 ± 4 and 87 ± 4 Ma, respectively.

58 grains separated from sample JS-17 (Figs. 2, 3, 4) were analyzed and 43 grains yielded concordant ages. The two youngest grains have ages of 92 ± 4 Ma and 99 ± 6 Ma. In the probability density plot, a broad peak is formed by zircon dated at 173 – 197 Ma (Fig. 5, similar to JS-14). A number of grains have Precambrian ages.

Discussion

There are, at present, three models to explain the currently available age data for the Sanbagawa Metamorphic Belt. The belt may consist of two units of different age, the 'Sanbagawa Metamorphic Rocks' and the 'Shimanto Metamorphic Rocks' that experienced peak metamorphism at ca. 110 – 120 Ma and at ca. 65 Ma, respectively (e.g., Isozaki and Itaya, 1990; Aoki et al., 2007, 2011; ; Isozaki et al., 2010; Otoh et al., 2010; Itaya and Tsujimori, 2015). For the 'Sanbagawa Metamorphic Rocks', this implies a significant time gap between peak metamorphism and exhumation at ca. 85 Ma. In contrast, Wallis and co-workers (Endo et al., 2009; Wallis et al., 2009; Wallis and Endo, 2010) suggested that peak metamorphism of the Sanbagawa Belt in Shikoku occurred at ca. 88 – 89 Ma followed by rapid exhumation. Tsutsumi et al. (2012) suggested that while some units of the Sanbagawa Belt were already being subjected to metamorphism, others were still at the depositional stage, implying that there is no dateable short period of peak metamorphism applying to the whole belt. These models will be addressed in the following sections.

Protolith age of the schists of the Besshi unit

Large parts of the Besshi unit were considered to be part of the Sanbagawa Metamorphic Rocks, metamorphosed at ca. 110 – 120 Ma. This was based on the Rb-Sr "age" of 116 ± 10 Ma obtained by Minamishin et al. (1979) and the lack of zircon younger than 150 Ma in two samples from the Besshi unit (Aoki et al., 2007, 2012). Subsequent work has shown, however, that zircon younger than 90 Ma exists in the chlorite zone in the northwest of Shikoku (Knittel et al., 2014).

The samples studied here come from the Asemi River area previously considered to be underlain by 'Sanbagawa Metamorphic Rocks'. Samples JS-11, -13, and -14 were collected in the area studied by Minamishin (1979) and contain numerous detrital zircon grains in the range 80 – 90 Ma. This shows that the results of the Rb-Sr study of Minamishin et al. (1979) do not date the metamorphism as obviously, metamorphism cannot have occurred prior to deposition. The age of the youngest zircon of sample JS-11 (80 ± 4 Ma; 2σ error) would suggest that the maximum age of the protoliths is 84 Ma. This is also compatible with the average age of the five youngest zircon grains of this sample of 82 ± 2 Ma. Zircon in samples JS-13 and -14 are slightly older, but it must be kept in mind, that the ages of detrital zircon are maximum ages, that the zircon spectrum apparently may be quite variable even for samples taken in close proximity and that younger zircons might have escaped detection in some samples.

Recently, age data for detrital zircon has been presented for a number of samples taken along the Asemi River between our sample locations JS-11, -13, 14 and location JS-17, including samples JS-16 (Knittel et al., 2019), NAB and NC (Endo et al., 2018) and samples studied by Aoki et al. (2019) as shown on the map Fig. 2b. These samples cover the complete range of chlorite, garnet, albite-biotite, and oligoclase-biotite zones. Since in all samples the youngest detrital zircon falls into the range 80 – 100 Ma, it appears that the schist-unit exposed in central Shikoku is of roughly uniform age. This includes also those schists that were subjected to eclogite facies metamorphism prior to retrograde metamorphism in the epidote-amphibolite facies exposed in the albite-biotite zone south of the oligoclase-biotite zone (Taguchi et al., 2018; Knittel et al., 2019; youngest zircon 84 ± 4 Ma). It appears possible that the schists of the chlorite zone have slightly older protoliths as the youngest zircon of sample JS-17 has an age of 92 ± 4 Ma and the youngest zircon from the chlorite zone reported by Aoki et al. (2019) has an age of 93 ± 2. However, the similarity of the age spectra of samples JS-17 and JS-14 from the northern and southern ends of the profile (Fig. 5) would argue against different protolith ages (and sources). Since the protolith ages of the Oboke unit, which largely coincides with the proposed Shimanto Metamorphic Rocks, likewise fall into the range 80 – 90 Ma, it is proposed to abandon the subdivision of the Sanbagawa belt into

'Sanbagawa Metamorphic Rocks' and the 'Shimanto Metamorphic Rocks'. Both, Besshi and Oboke units may be correlated with the northern (Cretaceous) part of the Shimanto accretionary complex as already suggested by Kiminami (2010) for low-grade rocks. The correlation of the Sanbagawa belt with the Jurassic – Early Cretaceous Chichibu accretionary complex (e.g., Aoki et al., 2007, 2011), on the other hand, is not supported.

The age of metamorphism

Based on protolith ages of at most ca. 90 Ma, locally perhaps less than 84 Ma, metamorphism must have occurred later. For the rim of a zircon that probably is of metamorphic origin an age of 80 ± 4 Ma was obtained suggesting that metamorphism occurred not later than at 76 Ma. Metamorphism at ca. 80 Ma is also suggested by U-Pb ages obtained by Aoki et al. (2009) for zircon rims ranging from 81.3 ± 4.9 Ma to 96.4 ± 7.6 Ma (average 86 ± 3 Ma) in a sample taken from a location between our northern and central sites, though these authors interpret their ages as dating retrograde metamorphism. In view of the errors involved and the evidence for deposition after ca. 90 Ma, it appears to be currently impossible to distinguish peak and retrograde metamorphism. K-Ar and Ar-Ar ages reported for the traverse along the Asemi River from samples JS-11 to south of sample JS-16 range from 79 to 83 Ma and in the chlorite zone around sample JS-17 from 75 to 77 Ma (Itaya and Takasugi, 1988; Takasu and Dallmeyer, 1990). Regardless of whether these ages are considered to date the formation of phengite or to be cooling ages, these ages suggest that metamorphism was accomplished by 79 Ma for most of the area and by 75 Ma in the southern chlorite zone. Metamorphism in the Oboke unit may have occurred about 10 m.y. later at around 65 Ma (Itaya and Takasugi, 1988; Aoki et al., 2008).

Systematic variations in K-Ar and Ar-Ar ages in areas to the east support the model that Sanbagawa metamorphism occurred over a certain period of time (Tsutsumi et al., 2012). Somewhat earlier metamorphism compared to central Shikoku is for example suggested by ages obtained for metamorphic monazite of 90 – 92 Ma obtained by Suzuki et al. (2018) for Sanbagawa metamorphics from Nushima island, located east of Shikoku.

Rapid vs. slow exhumation

Furthermore, our data support the rapid subduction/rapid exhumation model of Wallis et al. (2009), in particular if we look at the results for the northernmost site (JS-11 and JS-13), where the youngest zircon has ages of 80 - 85 Ma, i.e. falls into the same range as K-Ar ages of 79.6 ± 1.8 and 75.8 ± 1.7 Ma for white mica (Itaya and Takasugi, 1988) and a muscovite plateau age of 83.0 ± 0.5 Ma (Takasu and Dallmeyer, 1990) for samples taken at almost the same location and about 2 km south of our sampling site, respectively (Fig. 2b). Hence the period between sedimentation and metamorphism is in the same magnitude as the error of the age determinations (ca. 4 m.y.).

In sample JS-17 the youngest zircon was dated at 92 ± 4 Ma and is distinctly older than phengite K-Ar ages of 75 – 77 Ma (Itaya and Takasugi, 1988) and a whole rock Ar-Ar plateau age of 84.6 ± 0.7 Ma (Takasu and Dallmeyer, 1990) obtained for samples collected nearby. However, it must be kept in mind that the ages of detrital zircon only provide a maximum deposition age and the variability observed for the three samples taken at about the same locality (JS-11, JS-12, JS-14) shows that age assignments based on detrital zircon easily may overestimate the age of a sediment.

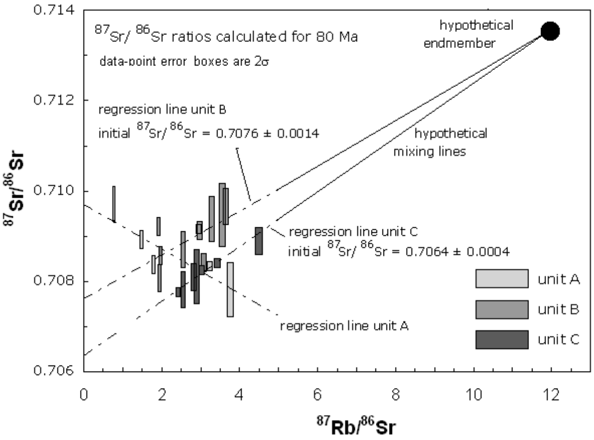

Fig. 7: Interpretation of the Rb-Sr data of Minamishin et al. (1979) as rotated mixing lines: $^{87}Sr/^{86}Sr$ ratios were re-calculated for an age of 80 Ma. White boxes: unit A, dark grey boxes: unit B, medium grey boxes: unit C. The dashed lines are regression-lines for the units A, B, C. The line obtained for unit A probably has no significance whereas those obtained for units B and C could be interpreted as mixing-lines.

The significance of the 116 ± 10 Ma Rb-Sr errorchron

The "isochron" age of 116 ± 10 Ma obtained by Minamishin et al. (1979) has been considered to date peak metamorphism of the schists of the Besshi unit in Shikoku for a long time (e.g., Aoki et al., 2007; Isozaki et al., 2010; Otoh et al., 2010; Aoki et al., 2011; Itaya et al., 2011). This "age" was based on the analysis of 21 whole rock samples collected within a small area in the upper reaches of the Asemi River in central Shikoku which, based on lithology, were grouped into 3 units (A, B, C). For units A and C combined, an age of 116 ± 10 Ma was calculated. Itaya et al. (2011) recalculated the data for the individual units using the currently accepted decay constant (Steiger and Jäger, 1977) and obtained ages of 115 ± 26 Ma for unit B and 122 ± 12 Ma for unit C. Assuming that the errors for $^{87}Sr/^{86}Sr$ in Minamishin et al. (1979) are 2σ errors and that the 2σ error for $^{87}Rb/^{86}Sr$ is 2%, the MSWD for unit C is 0.58 suggesting that it could be a valid isochron, whereas MSWD for unit B is 11.1.

However, dating a metamorphic event by analyzing whole rock samples requires that complete homogenization within each unit was achieved, whereas no significant exchange took place between the units as indicated by the variable initial Sr isotopic compositions derived from the two ‘isochrons’ for units B and C ($^{87}Sr/^{86}Sri$ = 0.7076 and 0.7064, respectively, see calculations in Wallis and Endo (2010) and Itaya et al. (2011)). Furthermore, interpretation of the ‘isochrons’ as ages of peak metamorphism assumes that no re-setting occurred during later retrograde metamorphism and hydration (Aoki et al., 2011), though it is known that the presence of water facilitates isotopic equilibration. Finally, the idea that isochrones based on (large) whole rock samples can date metamorphism has been largely abandoned, rather it is thought that whole rock isochrones may “see through” the metamorphic events and under favorable conditions may give clues to the original age of the protolith (e.g., Jäger, 1979). Thus, in principle, the 116 ± 10 Ma age of Minamishin et al (1979) might correspond to the approximate date of deposition. Alternatively, the linear arrays of data points could be mixing lines rather than isochrones as Wallis and Endo (2010) point out.

In order to test these possibilities, we recalculated the Sr isotope data for an age of 80 Ma (the age of the youngest zircon) and plotted these data in Fig. 7. As can be seen from the figure, the linear arrays for units B and C might be explained as mixing lines as a result of three component mixing.

Conclusions

The present study shows that the schists of the Sanbagawa Metamorphic Belt exposed along the Asemi River have Late Cretaceous protolith ages. There is no evidence for metamorphism at 116 Ma in the Besshi unit. It is thus proposed to abandon the separation of the Sanbagawa Belt into ‘Sanbagawa Metamorphic Rocks’ and the ‘Shimanto Metamorphic Rocks’. This implies that the Sanbagawa Metamorphic Rocks in all likelihood can be correlated with the Shimanto accretionary complex.

Acknowledgements

As usual, it is a pleasure to thank Sun-Lin Chung for generous access to his ICP lab. Norito Taksue is thanked for his help during sample collection. We also thank Tetsu Itaya for providing a map showing the location of the Minamishin study. Comments by Simon Wallis and anonymous reviewers on earlier versions led to improvements.

References

Andersen, T. 2002, Correction of common lead in U-Pb analyses that do not report 204Pb. Chemical Geology. 192, 59-79.

Aoki, K., Iizuka, T., Hidaka, T., Maruyama, S. and Terabayashi, M. 2007, Tectonic boundary between the Sanbagawa belt and the Shimanto belt in central Shikoku, Japan. Journal of the Geological Society of Japan. 113, 171-183.

Aoki, K., Isozaki, Y., Yamamoto, S., Maki, K., Yokoyama, T. and Hirata, T. 2012, Tectonic erosion in a Pacific-type orogen: Detrital zircon response to Cretaceous tectonics in Japan. Geology. 40, 1087-1090.

Aoki, K., Itaya, T., Shibuya, T., Masago, H., Kon, Y., Terabayashi, M., Kaneko, Y., Kawai, T. and Maruyama, S. 2008, The youngest blueschist belt in SW Japan: implication for the exhumation of the Cretaceous Sanbagawa high-P/T metamorphic belt. Journal of Metamorphic Geology. 26, 583-602.

Aoki, K., Kitajima, K., Masago, H., Nishizawa, M., Terabayashi, M., Omori, S., Yokoyama, T., Takahata, N., Sano, Y. and Maruyama, S. 2009, Metamorphic P–T–time history of the Sanbagawa belt in central Shikoku, Japan and implications for retrograde metamorphism during exhumation. Lithos. 113, 393-407.

Aoki, K., Maruyama, S., Isozaki, Y., Otoh, S. and Yanai, S. 2011, Recognition of the Shimanto HP metamorphic belt within the traditional Sanbagawa HP metamorphic belt: New perspectives of the Cretaceous–Paleogene tectonics in Japan. Journal of Asian Earth Sciences. 42, 355-369.

Aoki, K., Seo, Y., Sakata, S., Obayashi, H., Tsuchiya, Y., Imayama , T., Yamamoto, S. and Hirata, T. 2019, U–Pb zircon dating of Sanbagawa metamorphic rocks in the Besshi–Asemi-gawa region, central Shikoku, Japan, and tectonostratigraphic consequences. Journal of the Geological Society of Japan. 125, 000-000.

Aoya, M. and Endo, S. 2017, Recognition of the 'early' Sambagawa metamorphism and a schematic cross-section of the Late-Cretaceous Sambagawa subduction zone. Journal of the Geological Society of Japan. 123, 677-689.

Arakawa, M., Okamoto, K., Yi, K., Terabayashi, M. and Tsutsumi, Y. 2013, SHRIMP U–Pb dating of zircons related to the partial melting in a deep subduction zone: Case study from the Sanbagawa quartz-bearing eclogite. Island Arc. 22, 74-88.

Banno, S., Higashino, T., Otsuki, M., Itaya, T. and Nakajima, T. 1978, Thermal structure of the Sanbagawa metamorphic belt in central Shikoku. Journal of Physics of the Earth. 26, S345-S356.

Chiu, H., Chung, S., Wu, F., Liu, D., Liang, Y., Lin, I., Iizuka, Y., Xie, L., Wang, Y. and Chu, M. 2009, Zircon U–Pb and Hf isotopic constraints from eastern Transhimalayan batholiths on the precollisional magmatic and tectonic evolution in southern Tibet. Tectonophysics. 477, 3-19.

Corfu, F., Hanchar, J. M., Hoskin, P. W. and Kinny, P. 2003, Atlas of zircon textures. Reviews in mineralogy and geochemistry. 53, 469-500.

Endo, S., Miyazaki, K., Danhara, T., Iwano, H. and Hirata, T. 2018, Progressive changes in lithological association of the Sanbagawa metamorphic complex, Southwest Japan: Relict clinopyroxene and detrital zircon perspectives. Island Arc. e12261.

Endo, S. and Tsuboi, M. 2013, Petrogenesis and implications of jadeite-bearing kyanite eclogite from the Sanbagawa belt (SW Japan). Journal of Metamorphic Geology. 31, 647-661.

Endo, S., Wallis, S., Hirata, T., Anczkiewicz, R., Platt, J., Thirlwall, M. and Asahara, Y. 2009, Age and early metamorphic history of the Sanbagawa belt: Lu–Hf and P–T constraints from the Western Iratsu eclogite. Journal of Metamorphic Geology. 27, 371-384.

Endo, S., Wallis, S. R., Tsuboi, M., Aoya, M. and Uehara, S.-i. 2012, Slow subduction and buoyant exhumation of the Sanbagawa eclogite. Lithos. 146, 183-201.

Group, K. R. 1984, Stratigraphy and geologic structure of the Sambagawa metamorphic belt in the Oboke area, central Shikoku. Japan Earth Science (Chikyu Kagaku). 38, 53-63.

Higashino, T. 1990, Metamorphic zones of the Sambagawa metamorphic belt in central Shikoku, Japan. Journal of the Geological Society of Japan. 96, 703-718.

Hoskin, P. W. and Schaltegger, U. 2003, The composition of zircon and igneous and metamorphic petrogenesis. Reviews in mineralogy and geochemistry. 53, 27-62.

Isozaki, Y., Aoki, K., Nakama, T. and Yanai, S. 2010, New insight into a subduction-related orogen: a reappraisal of the geotectonic framework and evolution of the Japanese Islands. Gondwana Research. 18, 82-105.

Isozaki, Y. and Itaya, T. 1990, Chronology of Sanbagawa metamorphism. Journal of Metamorphic Geology. 8, 401-411.

Itaya, T. and Takasugi, H. 1988, Muscovite K-Ar ages of the Sanbagawa schists, Japan and argon depletion during cooling and deformation. Contributions to Mineralogy and Petrology. 100, 281-290.

Itaya, T. and Tsujimori, T. 2015, White mica K–Ar geochronology of Sanbagawa eclogites from Southwest Japan: implications for deformation-controlled K–Ar closure temperature. International Geology Review. 57, 1014-1022.

Itaya, T., Tsujimori, T. and Liou, J. G. 2011, Evolution of the Sanbagawa and Shimanto high-pressure belts in SW Japan: Insights from K–Ar (Ar–Ar) geochronology. Journal of Asian Earth Sciences. 42, 1075-1090.

Jackson, S. E., Pearson, N. J., Griffin, W. L. and Belousova, E. A. 2004, The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. Chemical Geology. 211, 47-69.

Jäger, E. (1979) The Rb—Sr Method. Lectures in Isotope Geology, 13-26, Springer.

Kiminami, K. 2010, Parentage of low-grade metasediments in the Sanbagawa belt, eastern Shikoku, Southwest Japan, and its geotectonic implications. Island Arc. 19, 530-545.

Kiminami, K., Hamasaki, A. and Matsuura, T. 1999, Geochemical contrast between the Sanbagawa psammitic schists (Oboke unit) and the Cretaceous Shimanto sandstones in Shikoku, Southwest Japan and its geologic significance. Island Arc. 8, 373-382.

Knittel, U., Hung, C.-H., Yang, T. F. and Iizuka, Y. 2010, Permian arc magmatism in Mindoro, the Philippines: An early Indosinian event in the Palawan Continental Terrane. Tectonophysics. 493, 113-117.

Knittel, U., Suzuki, S., Nishizaka, N., Kimura, K., Tsai, W.-L., Lu, H.-Y., Ishikawa, Y., Ohno, Y., Yanagida, M. and Lee, Y.-H. 2014, U–Pb ages of detrital zircons from the Sanbagawa Belt in western Shikoku: Additional evidence for the prevalence of Late Cretaceous protoliths of the Sanbagawa Metamorphics. Journal of Asian Earth Sciences. 96, 148-161.

Knittel, U., Walia, M., Suzuki, S. and Lee, Y.-H. 2019, Late Cretaceous age of eclogite facies metamorphism of the Sanbagawa Belt in the Asemi River area, Shikoku (SW Japan): evidence from detrital zircon. Journal of Asian Earth Sciences, https://doi.org/10.1016/j.jseaes.2019.03.003.

Kouketsu, Y. and Enami, M. 2010, Aragonite and omphacite-bearing metapelite from Besshi region, Sambagawa belt in central Shikoku, Japan and its implication. Island Arc. 19, 165-176.

Kouketsu, Y., Enami, M. and Mizukami, T. 2010, Omphacite-bearing metapelite from the Besshi region, Sambagawa metamorphic belt, Japan: Prograde eclogite facies metamorphism recorded in metasediment. Journal of Mineralogical and Petrological Sciences. 105, 9-19.

Kouketsu, Y., Enami, M., Mouri, T., Okamura, M. and Sakurai, T. 2014, Composite metamorphic history recorded in garnet porphyroblasts of S ambagawa metasediments in the B esshi region, central S hikoku, Southwest J apan. Island Arc. 23, 263-280.

Ludwig, K. R. (2003) Isoplot v. 3.0: a geochronological toolkit for Microsoft Excel. Berkeley Geochronology Center

Manabe, Y., Yoshikura, S. and Gabites, J. (1996) U-Pb zircon ages for the felsic igneous cobbles in the Oboke conglomeratic schist. Abstract of Annual Meeting of the Geological Society of Japan.

Minamishin, M., Yanagi, T. and Yamaguchi, M. 1979, Rb-Sr whole rock age of the Sanbagawa metamorphic rocks in central Shikoku, Japan. Isotope Geosciences of Japanese Islands. 68-71.

Miyamoto, A., Enami, M., Tsuboi, M. and Yokoyama, K. 2007, Peak conditions of kyanite-bearing quartz eclogites in the Sanbagawa metamorphic belt, central Shikoku, Japan. Journal of Mineralogical and Petrological Sciences. 102, 352-367.

Mori, H. and Wallis, S. 2010, Large-scale folding in the Asemi-gawa region of the Sanbagawa Belt, southwest Japan. Island Arc. 19, 357-370.

Okamoto, K., Shinjoe, H., Katayama, I., Terada, K., Sano, Y. and Johnson, S. 2004, SHRIMP U–Pb zircon dating of quartz-bearing eclogite from the Sanbagawa Belt, south-west Japan: implications for metamorphic evolution of subducted protolith. Terra Nova. 16, 81-89.

Otoh, S., Shimojo, M., Aoki, K., Nakama, T., Maruyama, S. and Yanai, S. 2010, Age distribution of detrital zircons in the psammitic schist of the Sanbagawa Belt, southwest Japan. Journal of Geography. 119, 333-346.

Sláma, J., Kosler, J., Condon, D. J., Crowley, J. L., Gerdes, A., Hanchar, J. M., Horstwood, M. S. A., Morris, G. A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M. N. and Whitehouse, M. J. 2008, Plesovice zircon -- A new natural reference material for U-Pb and Hf isotopic microanalysis. Chemical Geology. 249, 1-35.

Steiger, R. H. and Jäger, E. 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology. Earth and Planetary Science Letters. 36, 359-362.

Suzuki, K., Enami, M., Maekawa, H., Kato, T. and Ueno, T. 2018, Late Cretaceous CHIME monazite ages of Sanbagawa metamorphic rocks from Nushima, Southwest Japan. Journal of Mineralogical and Petrological Sciences. 113, 1-9.

Taguchi, T. and Enami, M. 2014, Coexistence of jadeite and quartz in garnet of the Sanbagawa metapelite from the Asemi–gawa region, central Shikoku, Japan. Journal of Mineralogical and Petrological Sciences. 109, 169-176.

Taguchi, T., Masaki, E. and Kouketsu, Y. 2018, Metamorphic record of the Asemi-gawa eclogite unit in the Sanbagawa belt, southwest Japan: Constraints from inclusions study in garnet porphyroblasts. Journal of Metamorphic Geology.

Takasu, A. and Dallmeyer, R. 1990, 40Ar/39 Ar mineral age constraints for the tectonothermal evolution of the Sambagawa metamorphic belt, central Shikoku, Japan: a Cretaceous accretionary prism. Tectonophysics. 185, 111-139.

Tsutsumi, Y., Miyashita, A., Horie, K. and Shiraishi, K. 2012, Existence of multiple units with different accretionary and metamorphic ages in the Sanbagawa Belt, Sakuma–Tenryu area, central Japan. Island Arc. 21, 317-326.

Wallis, S. and Aoya, M. 2000, A re-evaluation of eclogite facies metamorphism in SW Japan: proposal for an eclogite nappe. Journal of Metamorphic Geology. 18, 653-664.

Wallis, S. and Endo, S. 2010, Comment on 'Metamorphic P–T–time history of the Sanbagawa belt in central Shikoku, Japan and implications for retrograde metamorphism during exhumation'by K. Aoki, K. Kitajima, H. Masago, M.

Nishizawa, M. Terabayashi, S. Omori, T. Yokoyama, N. Takahata, Y. Sano, S. Maruyama [Lithos 113 (2009) 393–407]. Lithos. 116, 195-196.

Wallis, S. R., Anczkiewicz, R., Endo, S., Aoya, M., Platt, J. P., Thirlwall, M. and Hirata, T. 2009, Plate movements, ductile deformation and geochronology of the Sanbagawa belt, SW Japan: tectonic significance of 89–88 Ma Lu–Hf eclogite ages. Journal of Metamorphic Geology. 27, 93-105.

Wiedenbeck, M., Alle, P., Corfu, F., Griffin, W., Meier, M., Oberli, F., Quadt, A. v., Roddick, J. and Spiegel, W. 1995, Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. Geostandards newsletter. 19, 1-23.

Table 1: Analytical data for the ten youngest analyzed zircons of each sample with $^{206}Pb/^{238}U$ ages younger than 110 Ma (older zircons are only reported where their rims were analyzed separately)

The complete dataset is available upon request to the corresponding author.

	CORRECTED AGES (Ma)					CORRECTED RATIOS						
	$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		disc.	$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		U	Th	Th/U
		1σ		1σ	%		1σ		1σ	(ppm)	(ppm)	
JS-11												
JS11-23	84	4	80	2	4.8	0.08670	0.00480	0.01253	0.00035	2419	279	0.12
JS11-44	87	4	81	2	6.9	0.08977	0.00458	0.01260	0.00034	1238	351	0.28
JS11-77	92	6	83	2	9.8	0.09437	0.00642	0.01292	0.00034	476	76	0.16
JS11-43	94	6	85	2	9.6	0.09716	0.00671	0.01333	0.00039	1284	538	0.42
JS11-74	101	7	85	2	15.8	0.10447	0.00806	0.01324	0.00039	206	163	0.79
JS11-46	89	3	87	2	2.2	0.09116	0.00307	0.01357	0.00036	900	555	0.62
JS11-67	85	5	87	2	-2.4	0.08730	0.00551	0.01358	0.00038	320	156	0.49
JS11-73	86	4	87	2	-1.2	0.08826	0.00377	0.01360	0.00033	643	137	0.21
JS11-40	92	4	88	2	4.3	0.09458	0.00447	0.01381	0.00039	1116	154	0.14
JS11-14	90	5	89	2	1.1	0.09305	0.00492	0.01394	0.00036	970	535	0.55
JS-13												
JS-13-81	174	48	86	5	50.6	0.18637	0.05661	0.01341	0.00081	34	16	0.47
JS-13-69	94	6	85	2	9.6	0.09710	0.00606	0.01335	0.00035	328	215	0.66
JS-13-05	94	4	86	2	8.5	0.09677	0.00467	0.01350	0.00036	485	378	0.78
JS-13-58	87	2	87	2	0.0	0.08975	0.00238	0.01357	0.00032	3404	2049	0.60
JS-13-01	86	5	89	2	-3.5	0.08870	0.00582	0.01385	0.00037	337	313	0.93
JS-13-31	90	2	91	2	-1.1	0.09226	0.00267	0.01419	0.00037	4098	1086	0.27
JS-13-41	99	9	91	3	8.1	0.10198	0.00948	0.01419	0.00040	351	205	0.58
JS-13-46	101	10	91	3	9.9	0.10434	0.01042	0.01421	0.00044	407	278	0.68
JS-13-52	91	3	91	2	0.0	0.09390	0.00270	0.01418	0.00037	3221	1805	0.56
JS-13-72	94	5	91	2	3.2	0.09721	0.00576	0.01426	0.00037	309	222	0.72
JS-13: core/ rim analyses												
JS-13-28 (core)	108	8	92	3	14.8	0.11263	0.00909	0.01431	0.00041	230	92	0.40
JS-13-28 (rim)	92	5	80	2	13.0	0.09502	0.00561	0.01243	0.00030	954	190	0.20
JS-13-97 (core)	96	7	95	3	1.0	0.09921	0.00736	0.01478	0.00042	317	282	0.89
JS-13-97 (rim)	140	25	89	3	36.4	0.14789	0.02864	0.01382	0.00054	161	18	0.11
JS-13-71 (core)	100	5	99	3	1.0	0.10333	0.00550	0.01549	0.00040	339	175	0.52
JS-13-71 (rim)	140	17	80	3	42.9	0.14808	0.01874	0.01251	0.00040	249	3	0.01
JS-13-100 (core)	108	6	104	3	3.7	0.11277	0.00644	0.01621	0.00044	347	201	0.58
JS-13-100 (rim)	94	3	86	2	8.5	0.09653	0.00349	0.01337	0.00033	1420	333	0.23
JS-13-10 (core)	120	5	114	3	5.0	0.12541	0.00512	0.01785	0.00047	622	257	0.41
JS-13-10 (rim)	95	4	91	2	4.2	0.09788	0.00445	0.01414	0.00035	730	124	0.17

	CORRECTED AGES (Ma)					CORRECTED RATIOS						
	$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		disc.	$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		U	Th	Th/U
		1σ		1σ	%		1σ		1σ	(ppm)	(ppm)	
JS-13: depth profiling												
JS13A-09	83	7	82	2	1.2	0.08570	0.00781	0.01278	0.00035	361	85	0.24
JS13A-11	87	3	87	2	0.0	0.08992	0.00322	0.01352	0.00032	4085	268	0.07
JS13A-10	91	3	89	2	2.2	0.09418	0.00325	0.01383	0.00033	909	384	0.42
JS13A-05	116	7	98	2	15.5	0.12060	0.00825	0.01534	0.00038	760	366	0.48
JS13A-06	104	7	99	2	4.8	0.10775	0.00749	0.01544	0.00038	658	336	0.51
JS13A-21	107	4	100	2	6.5	0.11163	0.00419	0.01563	0.00039	654	222	0.34
JS13A-15	108	4	101	2	6.5	0.11205	0.00411	0.01572	0.00039	543	192	0.35
JS13A-16	105	3	102	2	2.9	0.10863	0.00337	0.01587	0.00039	922	327	0.35
JS13A-20	98	7	103	3	-5.1	0.10097	0.00710	0.01618	0.00044	267	74	0.28
JS13A-07	116	3	104	2	10.3	0.12059	0.00317	0.01634	0.00038	3704	1300	0.35
JS13A-08	111	7	104	3	6.3	0.11595	0.00754	0.01633	0.00045	488	337	0.69
JS13A-14	107	3	104	3	2.8	0.11133	0.00359	0.01624	0.00040	775	243	0.31
JS13A-12	117	5	108	3	7.7	0.12208	0.00501	0.01695	0.00041	400	210	0.53
JS13A-13	123	5	108	3	12.2	0.12846	0.00546	0.01690	0.00042	334	145	0.43
JS-14												
JS-14-38	89	3	92	2	-3.4	0.09157	0.00295	0.01440	0.00037	1236	496	0.40
JS-14-10	103	7	93	2	9.7	0.10624	0.00787	0.01452	0.00039	257	448	1.74
JS-14-52	89	3	93	2	-4.5	0.09212	0.00360	0.01457	0.00038	1258	551	0.44
JS-14-31	87	5	95	2	-9.2	0.08999	0.00527	0.01480	0.00039	414	780	1.88
JS-14-21	115	8	96	3	16.5	0.12039	0.00835	0.01501	0.00041	244	265	1.09
JS-14-04	110	5	102	3	7.3	0.11402	0.00574	0.01587	0.00040	383	1011	2.64
JS-17												
JS-17-56	103	5	92	2	10.7	0.10655	0.00511	0.01434	0.00039	408	264	0.65
JS-17-02	116	9	99	3	14.7	0.12136	0.00963	0.01543	0.00044	190	96	0.50
JS-17-36	101	8	101	3	0.0	0.10467	0.00837	0.01579	0.00043	205	175	0.85
JS-17-19	96	14	103	3	-7.3	0.09964	0.01503	0.01611	0.00048	107	1ß3	0.96

disc = (1 - [^{206}Pb/^{238}U-age] / [^{206}Pb/^{238}U-age]) * 100