Cambrian plutonism in Northeast Japan and its significance for the earliest arc-trench system of proto-Japan: New U–Pb zircon ages of the oldest granitoids in the Kitakami and Ou Mountains

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ABSTRACT

In order to clarify the early history of Japan, particularly during the Early Paleozoic, pre-Devonian granitoids in the South Kitakami Belt (SKB), NE Japan were dated by U–Pb zircon age by laser-ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS). Two samples of diorite/tonalite from the Nagasaka area (Shoboji Diorite) and two of mylonitic tonalite from the Isawa area (Isawagawa Tonalite) yielded late Cambrian ages (500–490 Ma) for the primary magmatism. These ages newly identify a ca. 500 Ma (late Cambrian) arc plutonism in central NE Japan, which has not been recognized previously and has the following geological significance. The Cambrian granitoids are the oldest felsic plutonic rocks in NE Japan, which are independent of the previously known ca. 450 Ma (latest Ordovician) Hikami Granite in SKB. The Cambrian granitoids are extremely small in size at present but likely had a much larger distribution primarily, at least 30 km wide and potentially up to 80 km wide in a cross-arc direction. Their southerly extension was recognized in the Hitachi area (ca. 200 km to the south) and in central Kyushu (ca. 1500 km to SW). They likely represent remnants of the same mature arc plutonic belt in Early Paleozoic Japan, which developed in western Panthalassan (paleo-Pacific) margin, as well as the Khanka block in Far East Russia. The extremely small size of the Cambrian granitoids at present can be best explained by intermittent, severe tectonic erosion since the Paleozoic. This Cambrian arc plutonoid belt likely developed from Primorye possibly to eastern Cathaysia (South China) via Japan.

1. Introduction

Before the end of the last century, the overall geotectonic framework of Japan and its over 500 million year-long history was documented mainly by virtue of the identification of various ancient subduction-related orogenic units in Southwest Japan, such as accretionary complex, blueschist, ophiolite, arc granite, and arc-related basin (e.g., Maruyama and Seno, 1986; Isozaki, 1996; Maruyama et al., 1997). Proto-Japan was born as a part of a passive continental margin by the breakup of the supercontinent Rodinia during the late Neoproterozoic, and it experienced a major tectonic turnover from a passive margin to an active one sometime in the earliest Paleozoic (Isozaki et al., 2010). The main lines of evidence for the oldest subduction along the proto-Japan margin include the occurrence of ca. 520 Ma (early Cambrian) metamorphic zircon in gneiss (Kunugiza and Goto, 2010), ca. 510–500 Ma (middle-late Cambrian) granitoid (Sakashima et al., 2003; Tagiri et al., 2010), ca. 480 Ma (earliest Ordovician) ophiolites (Ozawa, 1988; Nishimura and Shibata, 1989), and mid-Ordovician felsic volcanioclastics (Tsukada and Koike, 1997; Nakama et al., 2010a; Shimojo et al., 2010). Although these rocks indicate that the arc-trench system of proto-Japan had developed by the mid-Cambrian (ca. 520–500 Ma) (Isozaki et al., 2010), details of the onset of timing of subduction, in particular, that of the tectonic inversion, still remain a mystery, owing mostly to the sporadic/fragmentary occurrence of these rocks in much younger units.

The data for the Early Paleozoic evolution of Northeast Japan are more limited because of the relatively thick/extensive cover of Cenozoic volcanic rocks and sediments (Fig. 1). Nonetheless, as in SW Japan, the development of an Early Paleozoic arc-trench system in NE Japan has been suggested by the occurrence of 524–498 Ma (Cambrian) amphibolite (Kanisawa et al., 1992), Ordovician–
Fig. 1. Index map of pre-Cenozoic rocks in NE Japan (modified from Oide et al., 1989), showing the localities of interest; e.g., Kitakami Mountains, Ou Mountains, and the Hitachi area. The Nagasaka and Isawa areas are located in the west-central part of the South Kitakami Belt (SKB). Note that the current volcanic front extends in a N–S direction along the middle of the Ou Mountains.
Silurian arc-related igneous and volcanioclastic sedimentary rocks; e.g., ca. 480 Ma ophiolite (Ozawa, 1988), ca. 460–450 Ma (middle-late Ordovician) granitoids (e.g., Sasada et al., 1992; Kanisawa and Ehiro, 1997; Asakawa et al., 1999), and Silurian fossil-bearing shallow marine strata (e.g., Kitakami Paleozoic Research Group, 1982) from the South Kitakami Belt (SKB). These igneous and metamorphic rocks were only dated by conventional hornblende K–Ar and whole-rock Rb–Sr methods, and thus require more reliable modern ages by e.g. single zircon laser-ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS) or sensitive high-resolution ion microprobe (SHRIMP).

However, some granitoids do have U–Pb zircon ages, for example the largest (8 km N–S and 14 km E–W) Early Paleozoic granitic body (traditionally called the Hikami Granite) (Watanabe et al., 1995; Shimojo et al., 2010; Sasaki et al., 2013) in the central Kitakami Mountains of NE Japan has a U–Pb age of 470–410 Ma (Watanabe, 1950; Murata et al., 1982; Kitakami Paleozoic Research Group, 1982; Fig. 1), updated recently to ca. 450 Ma by Sasaki et al. (2013).

In the Hitachi area at the southern tip of NE Japan, more than 200 km to the south of the Kitakami Mountains (Fig. 1), a notable meta-granitoid has a U–Pb zircon age of 510–500 Ma (Sakashima et al., conformably by the Ordovician–Silurian Yakushigawa and Complex of Ehiro et al., 1988) with arc-related geochemical characteristics (Ozawa, 1988) and a U–Pb zircon age of 457 Ma (Late Ordovician), which are similar to those of the Shoboji Diorite (Kobayashi et al., 2000) in the Isawa area on the southern flank of Mt. Yakeishi-dake in the Ou Mountains, ca. 30 km to the west of the Shoboji area (Figs. 1, 2B). This tonalite is associated with amphibolites, which are correlated with the Motai metamorphic rocks (Kitamura and Kanisawa, 1971). The rock type and rock association of the tonalite and amphibolite are basically identical to those in the Shoboji area described above. Very thick Paleozoic volcanic/sedimentary rocks in the Ou Mountains conceal most of their basement, except for small windows of pre-Cenozoic rocks; nonetheless, on the eastern side of the HTL, the basement is considered to form the western extension of the Paleozoic–Mesozoic rocks of the SKB (Fig. 1). Sasada (1985) described the basic petrology of the mylonitic tonalite in the Isawa area, and Sasada et al. (1992) determined K–Ar hornblende ages of 457 Ma (Late Ordovician), which are similar to those of the Shoboji Diorite.

2. Geologic setting

NE Japan extends from northern Kanto to Hokkaido with its centre in the Tohoku region (Fig. 1). Regarding the pre-Cenozoic basement geology, the main source of information has been the SKB in the southern half of the Kitakami Mountains, which is separated on the west from the Gosaisho Belt (equivalent to the Ryoke Belt in SW Japan) by the NS-trending Hatagawa Tectonic Line (HTL). The SKB is unique in Japan in having a thick pile of the Paleozoic–Mesozoic sedimentary rocks of shelf facies (Kawamura et al., 1990); this is in remarkable contrast to the rest of Japan that is composed mostly of subduction-related accretionary complexes and their metamorphosed equivalents (Isozaki, 1996; Isozaki et al., 2010). Details of the basement geology of the SKB have not yet been fully clarified; however, the age of ca. 480 Ma (Early Ordovician) for the Hayachine ophiolite and ca. 450 Ma (latest Ordovician) for the sub-Devonian Hikami Granite were already determined by U–Pb zircon dating (Shimojo et al., 2010; Sasaki et al., 2013). The 480 Ma Hayachine ophiolite (Hayachine Complex of Ehiro et al., 1988) with arc-related geochemical characteristics (Ozawa, 1988) is mainly composed of serpentinized peridotite, gabbro, dolerite, trondhjemite and basalt, and covered conformably by the Ordovician–Silurian Yakushigawa and Nameiriizawa formations (the oldest strata in the SKB; Ehiro et al., 1988), whereas the ca. 450 Ma Hikami Granite is unconformably overlain by the Silurian Kawauchi and Okuhinotsuchi formations, i.e. the oldest fossil-bearing strata in NE Japan (Murata et al., 1974, 1982; Kitakami Paleozoic Research Group, 1982; Kawamura et al., 1990).

Besides the Hikami Granite in the central part of the SKB, there is an isolated occurrence of similar dioritic/gabbroic rocks in the Nagasaka area on the western margin of the Kitakami Mountains (Figs. 1, and 2A), which are structurally sandwiched between apparently underlying 500 Ma metamorphic rocks (Motai metamorphic rocks associated with amphibolite and serpentinite) and the overlying unmetamorphosed Upper Devonian Tobigamori Formation. This plutonic unit exposed in a small area of 4 km N–S by 3 km E–W was distinguished from the Hikami Granite (with the name of Shoboji Diorite) by K–Ar hornblende ages of 446–432 Ma (latest Ordovician to Early Silurian) at 5 localities (Kanisawa and Ehiro, 1997).

Further, there is a much smaller (500 m × 500 m) mylonitic Isawagawa Tonalite (Kobayashi et al., 2000) in the Isawa area on the southern flank of Mt. Yakeishi-dake in the Ou Mountains, ca. 30 km to the west of the Shoboji area (Figs. 1, 2B). This tonalite is associated with amphibolites, which are correlated with the Motai metamorphic rocks (Kitamura and Kanisawa, 1971). The rock type and rock association of the tonalite and amphibolite are basically identical to those in the Shoboji area described above. Very thick Paleozoic volcanic/sedimentary rocks in the Ou Mountains conceal most of their basement, except for small windows of pre-Cenozoic rocks; nonetheless, on the eastern side of the HTL, the basement is considered to form the western extension of the Paleozoic–Mesozoic rocks of the SKB (Fig. 1). Sasada (1985) described the basic petrology of the mylonitic tonalite in the Isawa area, and Sasada et al. (1992) determined K–Ar hornblende ages of 457 Ma (Late Ordovician), which are similar to those of the Shoboji Diorite.

3. Samples

In order to check the U–Pb zircon ages of the Shoboji Diorite and Isawagawa Tonalite, we collected and analyzed 4 samples of granitoids, two each from the Nagasaka (Fig. 2A) and Isawa areas (Fig. 2B); brief descriptions are given below.

3.1. Shoboji Diorite (Fig. 2A)

3.1.1. SB-0

Hornblende gabbroic diorite collected just beneath a road bridge near the Shoboji temple (N39°03′59″, E141°13′26″; the same outcrop as S-8 and S-9 of Kanisawa and Ehiro, 1997). Analyzed zircons were separated from a coarse-grained, plagioclase-rich diorite with semi-euhedral to anhedral hornblende. The major and trace element chemistry of the diorite from this outcrop was previously reported by Kanisawa and Ehiro (1997) as cited in Table 1.

3.1.2. SB-2

Hornblende-biotite tonalite collected along a forest road (N39°04′34″, E141°14′19″; the same outcrop as S-4 of Kanisawa and Ehiro, 1997). Zircons were separated from a quartz-rich tonalitic part of heterogeneous gabbro/tonalite, with apatite, zircon, magnetite, and ilmenite. A hornblende K–Ar age of 434 ± 20 Ma was reported from this outcrop (Kanisawa and Ehiro, 1997).
Fig. 2. Geologic sketch maps and photographs of rocks in the Nagasaka area in the Kitakami Mountains and the Isawa area in the Ou Mountains. (A) Geologic sketch map of the Nagasaka area near the Shoboji Temple with sample localities of SB-0 and SB-2 (modified from Kanisawa and Ehiro, 1997), (B) geologic sketch map of the Isawa area with sample localities YK-2 and YK-4 (modified from Sasada et al., 1992), (C) polished surface of the Shoboji Diorite (SB-2), (D–F) roadside outcrop, chipped surface, and thin section view of the Isawagawa Tonalite (YK-2, 4).

Table 1

<table>
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<th>Unit</th>
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<th>Isawagawa Tonalite (Kobayashi et al., 2000)</th>
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</table>

Major elements in wt%.
Trace elements in ppm.
3.2. Isawagawa Tonalite (Fig. 2B)

3.2.1. YK-2
Mylonitic hornblende tonalite collected along the main highway #397 (N39°6′40″; E140°51′00″; the same outcrop as Loc. 8990603 of Sasada et al., 1992), Zircons were separated from a part dominated by deformed hornblende and plagioclase, with polycrystalline quartz, biotite, chlorite, epidote, and sericite. A hornblende K–Ar age of 457 ± 10 Ma was reported from this outcrop (Sasada et al., 1992).

3.2.2. YK-4
Mylonitic hornblende tonalite collected along the main highway at the eastern entrance of a tunnel (N39°6′42″; E140°50′55″; between the outcrops of 8990603 and 8990702 of Sasada et al., 1992). Zircons were separated from a part dominated by deformed hornblende and plagioclase, with polycrystalline quartz, biotite, chlorite, epidote, and sericite.

Although the sample localities were not specifically shown, Kobayashi et al. (2000) reported major and trace element chemistry of this tonalite (cited in Table 1), which is exposed along the main highway (Fig. 2B).

4. Analytical procedures

Zircon extraction was performed with the mineral separation system at the Tokyo Institute of Technology. After crushing and sieving of a ~500 g rock sample, magnetic and heavy-liquid separations were performed. Then, separated zircons were mounted on a 5–10 mm acrylic disc and were polished. Internal structures of the zircons and the presence of inclusions were checked by transmitted and reflected optical microscopy and cathodoluminescence (CL) imaging. CL images were obtained using a JEOL JSM-5310 scanning electron microprobe combined with an Oxford CL system at the Tokyo Institute of Technology.

In situ zircon U–Pb dating was carried out using a Nu AttoM single-collector ICP-MS (Nu instruments, Wrexham, UK) coupled to a NWR-193 laser-ablation system (ESI, Portland, US), that utilizes 193 nm ArF excimer laser at the Department of Geology and Mineralogy, Kyoto University. The laser was operated with an output energy of ~9 mJ per pulse, repetition rate of 8 Hz and laser spot size of 15 μm in diameter, providing an estimated power density of the sample of ~2.5 J cm⁻². The total count of the laser pulse during the ablation was 180 shots.

The ablation took place in helium gas within the sample cell of <1 ml, and then the ablated sample, aerosol and helium gas were mixed with argon gas downstream of the cell. The helium minimizes redeposition of ejecta or condensates, while argon provides sufficient sample transport to the ICP-MS (Eggins et al., 1998; Günther and Heinrich, 1999; Jackson et al., 2004). A signal-smoothing device was used (Tenhunen and Hirota, 2004). To reduce the isobaric interference, an Hg-trap device with an activated charcoal filter was applied to the Ar make-up gas before mixing with the He carrier gas (Hirata et al., 2005). Prior to each individual analysis, regions of interest were pre-ablated using a few pulses of the laser with a laser spot size diameter of 20 or 30 μm to remove potential surface contamination, dramatically reducing common Pb contamination (Iizuka and Hirata, 2004). The ICP-MS was optimized using a NWR-193 laser-ablation system (ESI, Portland, US), that utilized a 5–10 mm acrylic disc and were polished. Internal structures of the sample were measured as secondary standards for quality control. The summary of instrumental settings and the resulting ages of secondary zircons are shown in the appendix (Table A). For U–Pb dating of individual zircon by LA-ICP-MS, 18, 37, 17, and 41 data were eventually obtained from the samples SB-0, SB-2, YK-2, and YK-4, respectively.

5. Results

Measurement results are shown in Tables 2–5 and in Figs. 3 and 4. The weighted average ages of studied samples were calculated by means of isoslot/Ex 3 (Ludwig, 2003). The sample SB-0 has all analyzed zircons properly plotted on the Concordia line, whereas the sample SB-2 has 31 zircons out of 37 plotted on the Concordia line (Fig. 3). Age distributions of individual zircons indicate that two samples have almost identical weighted average ages with similar error ranges; i.e. 493.2 ± 4.8 Ma (95% confidence, MSWD = 1.3) for sample SB-0 and 493.2 ± 4.0 Ma (95% confidence, MSWD = 2.5) for SB-2. Judging from the clear oscillatory zoning in all analyzed zircons, the obtained weighted average age of the zircons is regarded as the primary crystallization age of the host Shoboji Diorite.

In contrast, the two mylonitic tonalite samples from the Isawa area (YK-2 and YK-4) contain zircons with wider age ranges, particularly with many zircons with ages that plot far from the Concordia line (Fig. 4). Seven grains out of 27 from YK-2, and 30 of 49 from YK-4 plot properly on the Concordia line, and their weighted average age is 494.7 ± 7.7 Ma (95% confidence, MSWD = 2.2) for YK-2, and 497.4 ± 4.4 Ma (95% confidence, MSWD = 2.4) for YK-4, respectively (Fig. 4). These zircon ages suggest that the tonalite magma crystallized around 490–500 Ma. These igneous ages of zircon from the Isawa area are very similar within error ranges to those from the Shoboji Diorite in the Nagasaka area.

6. Discussion

6.1. Cambrian plutons in NE Japan

The present study identified for the first time the occurrence of Cambrian plutonic bodies in the Kitakami and Ou mountains in central NE Japan. The Shoboji Diorite at two localities in the Nagasaka area (Fig. 2A) yielded ca. 493 Ma igneous zircons (Fig. 4A and B). Much younger K–Ar ages of 446–432 Ma (latest Ordovician–Silurian) were previously reported for hornblende in
the gabbro-diorite from the same unit in the same area (Kanisawa and Ehiro, 1997); however, on the basis of the robustly consistent zircon U–Pb ages that are nearly 50–60 million years older, the K–Ar ages with lower closure temperature are considered to represent cooling ages after the primary magma consolidation around 493 Ma. According to the latest geological timescale, the age of 493 Ma corresponds to the late Cambrian (Peng et al., 2012).

The current exposure of the Shoboji Diorite in the Nagasaka area is limited merely to an area of 3 km in N–S and 2 km in E–W (Kanisawa and Ehiro, 1997; Fig. 2). Nonetheless the present
identification of a 493 Ma granitoid body in the SKB is geologically significant in two aspects. First, it is clear that the Shoboji Diorite forms an independent igneous body separated distinctly from the well-described ca. 450 Ma Hikami Granite exposed about 30 km to the east (Murata et al., 1974; Kitakami Paleozoic Research Group, 1982; Watanabe et al., 1995; Sasaki et al., 2013). Second,
the Shoboji Diorite has unusual but distinctive geochemical characteristics similar to those of arc-related igneous rocks (Kanisawa and Ehiro, 1997). Thus, this granitoid body belongs to an older arc pluton, which is the oldest known so far in NE Japan.

On the other hand, zircons separated from the Isawagawa Tonalite at two localities (Fig. 2B) yielded weighted average U–Pb ages of ca. 500–490 Ma (Fig. 4), which reflect the primary crystallization of the Isawagawa Tonalite in the late Cambrian. Much younger K–Ar ages of 457, 403, and 381 Ma were previously reported for hornblende from the same body (Sasada et al., 1992); however, these ages more likely represent the time of cooling after the magma consolidation at 497–495 Ma. Indeed, Sasada et al. (1992) already considered that these K–Ar ages were partly affected by later mylonitization.

The identification of a 500–490 Ma granitoid in the Isawa area in the Ou Mountains is particularly noteworthy. Its exposure is more limited than that of the Shoboji Diorite, i.e. several hundred meters along the Isawagawa River (Fig. 2B); however, their ages are almost identical. Except for the mylonitic texture recognized in the Isawagawa Tonalite, the petrological characteristics and major/trace element compositions of these two bodies are similar (Kanisawa and Ehiro, 1997; Sasada et al., 1992). The present results, therefore, confirm that these two intrusions are mutually correlative, and suggest that they once belonged to the same Cambrian granitoid belt. Independently, Tsuchiya et al. (2014c) orally reported their preliminary U–Pb zircon dates of the same bodies, which are more or less the same as ours.

The Nagasaka area is situated about 30 km to the east of the Isawa area (Fig. 1), and these two areas are currently separated from each other by the geomorphological feature called the Kitakami Lowland between the Kitakami and Ou mountains, in which no pre-Quaternary basement is exposed (Fig. 5). Nonetheless, the latest seismic profile beneath the Kitakami Lowland clearly illustrates a subsurface listric, NS-trending, normal fault system (Abe et al., 2008); these faults formed during the Miocene back-arc opening of the Japan Sea (Yamaji, 1990; Sato, 1994). After the Miocene extensional tectonics that attenuated the pre-Cenozoic crust in an E–W direction, tectonic inversion put the regime into contraction. The pre-rift relative distance between the Isawagawa and Shoboji bodies was, therefore, more or less similar to the present distance, i.e. about 30 km. This provides a minimum across-arc dimension for the ca. 500 Ma Shoboji–Isawagawa granitoids.

Lately, a ca. 500 Ma tonalite xenolith, 2 m in diameter, was reported by Tsuchiya et al. (2014a,b) (Figs. 1 and 5) within Cretaceous volcanic rocks from the Ryori area on the Pacific coast.
along the eastern margin of the SKB. This indirectly suggests that the 500 Ma granitoid in the SKB potentially had a greater subsurface extent; i.e. the primary size of the Cambrian granitoids in the SKB was probably more than 80 km in an across-arc direction. Moreover, there is also a correlative 500 Ma meta-granitoid with an arc signature in the Hitachi area at the southern tip of NE Japan, nearly 200 km to the south of the Nagasaka-Isawa area (Fig. 1; Sakashima et al., 2003; Tagiri et al., 2010, 2011). The similarity of the Paleozoic geology between the Hitachi area and the SKB has been discussed for years, despite the absence of a contemporaneous surface trace. The Hitachi area is situated in the Takanuki Belt on the southwest of the Gosaisho Belt (correlative to the Ryoke Belt in SW Japan), which is separated by the NS-trending strike-slip HTL from the SKB (Fig. 1), although the putative amount of left-lateral strike-slip dislocation is unknown. Given the ca. 500 Ma meta-granitoid in the Hitachi area correlated with the Shoboji Diorite/Isawagawa Tonalite, the primary size of the Cambrian arc granitoids in NE Japan may reach 100 km wide or more across arc, and more than 200 km along arc. Such a dimension suggests the development of a mature regional arc.

In general, it is not easy to estimate the total spatial dimension of ancient geologic entities, including the case of the putative 500 Ma arc granite belt in proto-Japan. There are another isolated occurrence of ca. 500 Ma meta-granitoid in Kyushu, SW Japan (Sakashima et al., 2003), which likely represents the western extension of the Shoboji–Isawagawa–Hitachi granitoids in NE Japan. These coeval granitoids possibly formed in the same arc of proto-Japan, although no correlative unit has been hitherto documented from the intervening area, which extends for ca. 1000 km along the arc on the main island of Honshu. Nonetheless, the occurrences of ca. 500 Ma detrital zircons in younger sedimentary rocks and high-P/T psammitic schists in various areas in Japan (Nakama et al., 2010a,b; Isozaki et al., 2010, 2014; Tsutsumi et al., 2011; Yoshimoto et al., 2013; Okawa et al., 2013) and of ca. 500 Ma xenocrysts in younger granitoids (Fujii et al., 2008; Osanai et al., 2014; Aoki et al., 2015) suggest the potential development of the coeval granitoid belt throughout early Paleozoic Japan. All of these lines of evidence, although still fragmentary, imply that the 500 Ma granitoid belt formed a major mature arc with a minimum along-arc length of up to 1500 km, at least comparable with the modern Izu-Bonin–Mariana arc (Suyehiro et al., 1996), along the western margin of Panthalassa (=paleo-Pacific).

6.2. Lost arc: where have all the granitoids gone?

The potentially huge extent of the late Cambrian arc batholith in both NE and SW Japan provides significant evidence for the first oceanic subduction in proto-Japan, i.e. the initial development of a mature arc-trench system with a granitoid batholithic belt (Fig. 6). Along active continental margins in general, a subduction-related arc-granite belt develops on a scale of >2000 km along-arc and >100 km across-arc (e.g., Takahashi, 1983; Suyehiro et al., 1996; Ito et al., 2008). In contrast, the overall volume of the exposed 500 Ma granitoids in present-day Japan is small. This size difference naturally suggests that the 500 Ma arc granite belt in
proto-Japan was originally much larger (not necessarily of huge batholithic proportions), and that a considerable proportion has completely disappeared secondarily after residing on the surface long enough for its erosion to feed terrigenous clastics to arc-related basins.

During the 1980s and 1990s, so-called strike-slip tectonics became popular in Japan (e.g., Taira et al., 1983; Yamakita and Otoh, 2000), and under the contemporary influence of such an idea, Sakashima et al. (2003) explained the isolated occurrence of the 500 Ma granite in Hitachi and Kyushu as the consequence of >1000 km large-scale strike-slip dislocation along the Median Tectonic Line (MTL) without mentioning its primary size. There are two difficult issues, however, in their interpretation. First, strike-slip dislocation itself cannot completely remove/erase a large batholith belt from the surface, and dissect/translate it to somewhere else, as in the case of the Salinian block dislocated by the San Andreas Fault in western North America (e.g., Wallace, 1990). In fact, in Japan and in conterminous Far East Asia, we cannot identify any large Cambrian granitoid body that was putatively dislocated along the MTL. Similar problems arise in interpreting the many, extremely small, occurrences of Paleozoic orogenic components in SW Japan, such as accretionary complexes and blueschists that likely had similar dimensions to their coeval granitoids, as pointed out by Isozaki et al. (2010). Surface erosion can be an efficient process to remove a granitic belt; however, in order to totally remove an entire batholith, large-scale sedimentary basins are required to accommodate the equivalent amounts of terrigenous clastics derived from the relevant batholith belt. Without identifying such a “graveyard” of older granitoids, therefore, the claimed strike-slip interpretations cannot reasonably explain the almost total disappearance of the Early Paleozoic orogenic components, which include the Cambrian arc granite belt.

Second, none of the strike-slip faults in Japan records clear evidence of >1000 km strike-slip dislocation with well documented reference points. For example, the MTL in SW Japan was re-evaluated as a strike-slip fault activated not during the Cretaceous as previously believed, but merely in the Quaternary (Isozaki, 1996; Sato et al., 2015). A recent seismic profile clearly illustrated the north-dipping sub-horizontal structure of the MTL that transected and dissected the entire arc crust of SW Japan (Ito et al., 2009), and this post-late Cretaceous structure is inconsistent with the claimed Cretaceous oblique subduction and resultant large-scale dislocation. The MTL is better explicable as a low-angle thrust that was activated during the Miocene back-arc (Japan Sea) opening associated with across-arc contraction in the fore-arc (Isozaki, 1996; Isozaki et al., 2010; Aoki et al., 2011; Sato et al., 2015). Under the circumstances, we need another feasible and more viable explanation for the disappearance of the old arc granitic belt.

6.3. Unavoidable fate: tectonic erosion

The latest studies of detrital zircon chronology of Paleozoic–Mesozoic sandstones in Japan have demonstrated a remarkable difference between the occurrence of abundant Paleozoic zircons in pre-Cretaceous sandstones and the total amount of extant Paleozoic granitic bodies exposed in SW Japan (Nakama et al., 2010b; Isozaki et al., 2010). In general, the main source of detrital zircons is felsic plutonic rocks, i.e., granitoids, rather than finer-grained volcanic rocks. The age spectra of detrital zircons from Silurian to Jurassic sandstones demonstrate that Early–Middle Paleozoic granitoids were exposed extensively in proto-Japan, and they provided the main source of terrigenous clastics to feed Middle Paleozoic to Triassic basins, whereas the Paleozoic granitic plutons disappeared almost totally from the surface after the end-Triassic. In Japan and nearby areas in Far East Asia, there are no Paleozoic–Triassic sedimentary basins that could have accommodated such abundant granitic clastics of corresponding volume. In other words, Paleozoic arc granitoid bodies indeed existed prominently in proto-Japan (Fig. 6); however, they were totally removed from the surface afterwards. Can large granitic bodies disappear from the planet’s surface and subduct into the mantle, despite their relatively lower density with respect to mantle rocks? For the present data from SKB, we need to check the background plate tectonic regime and physical conditions for this granitoid-disappearance episode in NE Japan.

To explain the disappearance of such a large Paleozoic arc pluton, the process of tectonic erosion is the most promising (Isozaki et al., 2010; Suzuki et al., 2010). Tectonic erosion or subduction erosion is a process occurring in many modern active continental margins, which can remove a significant amount of crustal material from the bottom of a fore-arc (e.g., Scholl et al., 1980; von Huene and Scholl, 1991, 1993; Scholl and von Huene, 2010). This mechanism has been operating much more frequently than previously realized (e.g., Vannucchi et al., 2008; Yamamoto et al., 2009; Clift et al., 2009; Aoki et al., 2012).

It is noteworthy that the Cambrian arc granitoids newly recognized in the Kitakami and Ou mountains are located on the trench side of the present volcanic front of the active NE Japan arc (Figs. 1 and 5). A brand-new granitoid is under construction beneath the current volcanic front, about 300 km to the west of the modern Japan trench. In other words, the fore-arc of NE Japan has not gained any extra across-arc breadth during the last 500 million years, regardless of the long-continued subduction processes coupled with intermittent granitoid production in large amounts ever since the Early Paleozoic; e.g., in the Cambrian, Ordovician–Silurian, Devonian–Carboniferous, Cretaceous, and Paleogene. This positively indicates that large amounts of pre-Cenozoic fore-arc crust, mostly composed of granitoids, have been
transported from the surface into the deep mantle via a subduction zone. Along the modern active Japan Trench, tectonic erosion is indeed currently in operation, as confirmed by seismic profiles (von Huene and Scholl, 1991, 1993; Scholl and von Huene, 2010). Marine geological research and direct GPS observations in the Japanese trench have documented the absence of any modern accretionary complex, but the presence of a Cretaceous accretionary complex obliquely truncated by the trench axis, and of a regional unconformity that records a major subsidence in the fore-arc (Nasu et al., 1980; Heki, 2004).

The Paleozoic granitoids in NE Japan (and probably also in SW Japan) have been totally eroded from the bottom of a fore-arc crust, in other words they have been subducted into the mantle by tectonic erosion since the Paleozoic. As preliminarily speculated by Isozaki et al. (2010) and Suzuki et al. (2010), the Paleozoic granitoids in SW Japan (e.g., Fujii et al., 2008; Osanai et al., 2014; Aoki et al., 2015) likely shared a similar fate, i.e. the mature arc plutons were totally removed and disappeared by tectonic erosion.

6.4. Regional connections in Far East Asia

At the end of this article, we discuss possible correlations of the early Paleozoic granitoids in Far East Asia. There are sporadic occurrences of Early Paleozoic granitoids in Primorye (Russia) and in South China, with more or less the same ages as the Shoboji–Saawagawa granitoids; e.g., ca. 500 Ma plutons in the Khanka and Jiamsi blocks and so-called Caledonian granitoids in the Cathaysia block (Fig. 7).

All the circum-Japan Sea 500 Ma granitoids, i.e. those in the SKB (present study), the Kuroseagwa belt in SW Japan (Sakashima et al.,

![Fig. 7. The distribution of Early Paleozoic granitoids in Far East Asia (A: compiled from Li et al., 2012; Shu et al., 2014; Khanchuk et al., 1996, and Bi et al., 2014), and of the Japanese ca. 500 Ma zircons (detrital and xenocryst) and >400 Ma granitoids (B: compiled from Sakashima et al., 2003; Fujii et al., 2008; Nakama et al., 2010a,b; Isozaki et al., 2010, 2014; Tsutsumi et al., 2011; Okawa et al., 2013; Yoshimoto et al., 2013; Osanai et al., 2014; Aoki et al., 2015; this study). Although their current distribution is patchy, the Early Paleozoic arc-related granitoids in Japan (B) likely belonged to a much larger arc crust that extended to the northeast to the Khanka block in Primorye, Far East Russia, and possibly further to the eastern Cathaysian margin of South China (A). The ca. 500 Ma granitoids in the Jiamsi block and in Cathaysia (blank star) are of non-arc affinity. Nonetheless, an “early Paleozoic granitoid belt” probably developed along an active western Panthalassan (=paleo-Pacific) margin before the Pangean time, as suggested by detrital zircons in younger sedimentary rocks and high-P/T psammitic schists in South China, Taiwan, and Japan (Isozaki et al., 2010, 2014; Tsutsumi et al., 2011; Yui et al., 2012; Okaa et al., 2013; Hu et al., 2015) and by zircon xenocrysts in younger granitoids (Fujii et al., 2008; Osanai et al., 2014; Aoki et al., 2015). Note that the general trend of ca. 500 Ma arc granitoid extends in a N–S direction, almost perpendicular to the E–W oriented Central Asian Orogenic Belt (CAOB).]
Sea. In other words, the northeastern extension of Cathaysia in the coastal mountains and/or the basement of the East China by the severe overprint of Mesozoic magmatism, and from the information of the Paleozoic geology of eastern Cathaysia caused Cathaysia have distinctive geochemistry of atypical arc affinity (Li et al., 2012; Shu et al., 2014), and thus they cannot be directly correlated with those in Japan.

Nevertheless, the intimate consanguinity between Paleozoic Japan and South China is suggested by the following various criteria. (1) Zircon xenocrysts in mid-Paleozoic granitoids in Japan range in age-range of 3200–500 Ma (Fujii et al., 2008; Osanai et al., 2014; Aoki et al., 2015) that overlap the ages of the Yangtze basement; thus suggest the significant geological connection between the South China crust and the site of granitoid-dominant arc of Paleozoic Japan. (2) Paleozoic sandstones and Paleozoic-Triassic high-P/T metamorphic rocks in Japan often contain abundant Proterozoic detrital zircons (e.g., Nakama et al., 2010a,b; Shimojo et al., 2010; Isozaki et al., 2010, 2014; Tsutsumi et al., 2011; Yoshimoto et al. 2013; Okawa et al., 2013), in particular, Neoproterozoic (1200–600 Ma) zircons have the same ages as the basement of South China (Fig. 7B). (3) The occurrence of Paleozoic shallow marine fossils in Japan, such as Silurian to Carboniferous rugose corals and Permian mollusks (e.g., Kato, 1990; Nakazawa, 1991; Ehiro, 1997; Isozaki and Kase, 2014) suggests a significant faunal similarity with South China and accordingly an intimate geotectonic connection during the Paleozoic.

In addition, some indirect data support the development of a ca. 500 Ma granitoid belt along the western active margin of early Paleozoic Panthalassa, which includes the eastern margin of Cathaysia. For example, (4) the occurrence of ca. 500 Ma zircons from a Permo-Triassic basin in southwestern Cathaysia, the main clastic source of which was located to the southeast (Fig. 7A; Hu et al., 2015), (5) The occurrence of ca. 500 Ma detrital zircons from a Cretaceous accretionary complex in Taiwan off Cathaysia (Yui et al., 2012) also suggests the clastic delivery from an adjacent provenance with a relic granitoid belt of similar age. The occurrences require the exposure of ca. 500 Ma granitic crust in the late Paleozoic to Mesozoic in the corresponding domain of the modern South China Sea, i.e. eastern Cathaysia.

By summarizing all these, we speculate the development of an Early Paleozoic arc-trench system featuring a trench-parallel granitoid belt along the western margin of Panthalassa. Owing to the Mesozoic-Cenozoic tectonic modifications, this largely linear granitoid belt was probably dissected into smaller fragments that currently occur in Japan and Primorye (Fig. 7A). The current uncertainty in the geotectonic connection between Japan and South China derives mostly from obscured information of the Paleozoic geology of eastern Cathaysia caused by the severe overprint of Mesozoic magmatism, and from the absence of information of pre-Cenozoic basement under the East China Sea. Nonetheless we predict the future finding of small remnants of ca. 500 Ma arc granitoids from the eastern Cathaysia, e.g., in the coastal mountains and/or the basement of the East China Sea. In other words, the northeastern extension of Cathaysia probably continued into Paleozoic Japan and further to Paleozoic Khanka in Far East Russia, thus the Paleozoic South China was much larger than the currently exposed mainland South China (to form the Greater South China by Isozaki et al., 2014).

On the other hand, the Central Asian Orogenic Belt (CAOB; Fig. 7A) contains many Paleozoic granitoids (e.g., Xiao et al., 2004), although their occurrence is rather restricted to the western part of the CAOB, and the general structural E–W trend of the CAOB is highly oblique or almost perpendicular to the general trend of the putative paleo-Pacific margin “granitoid belt”, which extends mostly in a N–S direction. Thus it seems reasonable to consider that the apparently coeval arc granitoids in the CAOB were not genetically related to those in Far East Asia. At any rate, in order to reconstruct the paleogeography of Paleozoic Japan and its surroundings, we need further detailed geological, geochemical and isotopic studies of the tectonic setting of individual pre-Pangean continental blocks.

7. Conclusions

The present study presents four new U–Pb ages of zircons separated from pre-Devonian granitoids in the Nagasaka and Isawa areas in the SKB, NE Japan. All the 4 analyzed samples have late Cambrian ages (ca. 500–490 Ma), which document the time of crystallization of the granitic magmatism. These new ages identify a late Cambrian arc-related regional plutonic belt in NE Japan, the geological significance of which is summarized as follows:

1. The newly recognized Cambrian granitoids correspond to the oldest felsic plutonic rocks in NE Japan, which are independent of, and younger by ca. 50 million years than, the previously known ca. 450 Ma Hikami Granite.
2. The Cambrian granitoid pluton has an across-arc spatial width of 40 km, and potentially of 80 km in the SKB. Together with coeval granitoids in the Hitachi area in southernmost NE Japan and in central Kyushu, SW Japan, the Cambrian granitoids in central NE Japan likely represent the remnants of the oldest Japanese arc crust, which probably formed a highly matured arc granitic belt, possibly with batholithic aspect.
3. The small size of these granitoids today is due to intermittent, severe tectonic erosion along subduction zones since the Paleozoic.
4. The early Paleozoic granitoid belt likely developed along an active margin of the western Panthalassa (paleo-Pacific) Ocean, and was dissected by the Mesozoic-Cenozoic tectonics into several pieces currently exposed in Japan, Primorye, and possibly in eastern Cathaysia.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jseaes.2015.04.024.