Ordovician Japan: geotectonic setting and palaeogeography

Yukio Isozaki
Department of Earth Science and Astronomy, The University of Tokyo, Komaba, Meguro, Tokyo 153-8902, Japan
0000-0002-3596-581X
Correspondence: isozaki@ea.c.u-tokyo.ac.jp

Abstract: Ordovician Japan formed a mature arc-trench system developed along the palaeo-Pacific (Panthalassa) margin of the Greater South China (GSC) continental block. GSC consists of South China, East China Sea, SW–NE Japan and the Khanka–Jiamusi–Bureya megablock in the Far East; Paleozoic GSC was thus, in total, twice as large as the South China components by themselves (Yangtze and Cathaysia). The Ordovician crust of Proto-Japan comprised coeval arc-related rocks, such as granitoids, supra-subduction zone ophiolites and fore-arc basin strata, although most of them were considerably fragmented. The Ordovician and middle–late Paleozoic fossils from Japan are highly limited but suggest that Proto-Japan was positioned in the low-latitude domains probably of the palaeo-Pacific Ocean in connection to Paleo-Tethys. GSC became separated from Rodinia in the Neoproterozoic, and its Proto-Japan segment evolved as a collision-free subduction margin for nearly 500 myr since the mid-Cambrian. The GSC framework provides critical constraints to the palaeogeographical reconstruction of circum-Pacific continental blocks. First, the Cambro-Ordovician GSC should have been isolated from Australia/India/East Antarctica that formed East Gondwana by a relatively wide ocean domain for keeping 'subduction potential'. Second, the Cathaysian margin of GSC should have faced to an extensive ocean without major continents since the Cambrian. The palaeo-Pacific is the only possible candidate for this.

Ordovician rocks in Japan are barely known to many geologists in the world with no informative references previously published. Indeed, their distribution, as well as that of other early Paleozoic rocks, is highly restricted within the modern arc crust exposed in Japan, which is composed mostly of Cretaceous and Cenozoic rocks. Even domestic geologists, therefore, did not know much about the Ordovician of Japan for a long time. Nevertheless, recent research has revealed the occurrence of various Ordovician rock types in Japan, which suggests the extensive development of a full-sized arc-trench system during the Ordovician. These rocks represent ancient subduction-related orogenic products including arc granitoids, supra-subduction zone ophiolites and shallow marine strata of fore-arc basin deposition (e.g. Isozaki 2011; Ozawa *et al.* 2015). The oldest fossils from Japan are rare Darriwilian–Sandbian conodonts recovered from a felsic tuff bed in central Japan (Tsukada and Koike 1997). Although extremely restricted in distribution, these rocks can provide vital pieces of information for the palaeogeographical reconstruction of Japan during the Ordovician and broader context within the Mesozoic–Cenozoic evolution of East Asia, in particular, for their plate tectonic settings with respect to relevant continents and oceans derived from the Neoproterozoic breakup of the supercontinent Rodinia.

This short article summarizes the latest knowledge on Ordovician Japan, together with fundamental information on the tectonic setting of early Paleozoic Japan, which had an intimate connection with the South China block but not with the North China block. For understanding Ordovician Japan, what is introduced first is the overall plate tectonic setting with long-term oceanic subduction from the ancient Pacific (palaeo-Pacific) Ocean. In addition, a key palaeogeographical concept, the Greater South China (GSC) continental block (Isozaki *et al.* 2014), is emphasized here. This reconstructed block extends from the Yangtze craton in SW China to the Khanka–Jiamusi–Bureya megablock in Far East Russia for up to 5000 km in length. Paleozoic Japan belonged to a segment of the active continental margin of GSC. These new perspectives may require some changes to the conventional ideas on the Ordovician palaeobiogeography.

Overall geologic setting

A brief history of the Japanese Islands is introduced first according to the time–space diagram shown in Figure 1. Proto-Japan was born *c.* 700 Ma (Isozaki 1996; Maruyama *et al.* 1997) when the Neoproterozoic supercontinent Rodinia broke up into several continental blocks, such as Australia, East Antarctica, South China, North China and Laurentia, which moved away from each other (Hoffman 1991). The nascent oceanic domain under expansion

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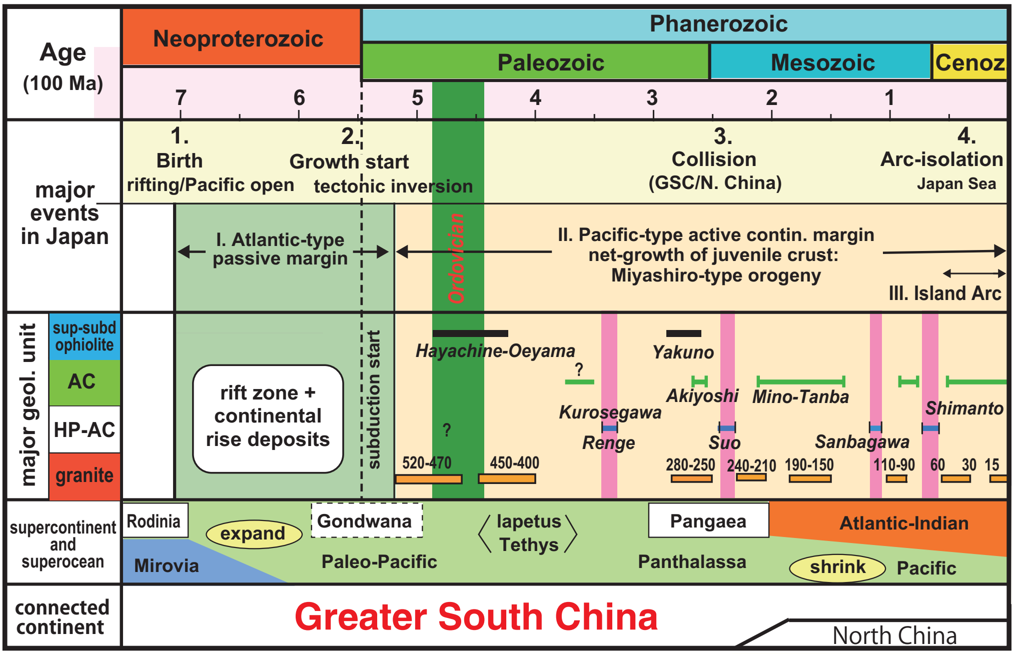

Fig. 1. Chronicle diagram of tectonic evolution of the Japanese Islands, with special reference to the Ordovician Period. Cenoz, Cenozoic. Proto-Japan was born when the supercontinent Rodinia broke up *c.* 700 Ma, and evolved as a passive continental margin along the Greater South China (GSC) continental block until the onset of oceanic subduction from the palaeo-Pacific Ocean *c.* 500 Ma. Note that Ordovician Japan was in the phase of active continental margin along the palaeo-Pacific side of GSC. The arc-trench system of Ordovician Japan produced representative orogenic components, such as arc granitoid, supra-subduction zone (sup-subd) ophiolite, fore-arc basin sediments and possibly blueschist (HP-AC) that sporadically occur at present in SW and NE Japan. AC, accretionary complex. Source: simplified from Isozaki *et al.* (2010).

which separated these continents was called the palaeo-Pacific Ocean that subsequently evolved into the Panthalassa Superocean (Fig. 2a, b). A large continental piece relevant to Proto-Japan was the South China block (Isozaki 1996; Maruyama *et al.* 1997), which is composed of the Yangtze and Cathaysia subblocks (e.g. Shu *et al.* 2014; Cawood *et al.* 2018). Paleozoic South China was recently revealed to have been much larger in size than previously imagined. The inferred larger continental block was named Greater South China (GSC; Isozaki *et al.* 2014), which comprised the South China block *sensu stricto* in China (Yangtze and Cathaysia), the East China Sea, pre-existing continental crusts along SW and NE Japan and the Khanka–Jiamusi–Bureya mega-block mostly in Primorye, Russia (Isozaki *et al.* 2014, 2015, 2017; Isozaki 2019; Yamamoto *et al.* 2022; Fig. 2c, d). GSC was an elongated continental block that may have attained up to 5000 km in length. Li *et al.* (1999) speculated that South China *sensu stricto* was once positioned in the middle of Rodinia, surrounded by Australia, East Antarctica and Laurentia during the early Neoproterozoic. Later, an alternative position of South China was proposed along the periphery of Rodinia with special emphasis on the connection to northern India (e.g. Zhou *et al.* 2006; Hofmann *et al.* 2011; Cawood *et al.* 2018; Fig. 2a, b).

Regardless of the original position within Rodinia, GSC became isolated from other continental blocks during the late Neoproterozoic. Its palaeo-Pacific margin developed as a passive continental margin (phase I in Fig. 1) until the onset of oceanic subduction, which converted the passive margin into an arc-trench system. After the early Cambrian, Proto-Japan grew to form a mature arc-trench system, which produced Paleozoic orogenic components, such as arc granitoids, supra-subduction zone ophiolites, accretionary complexes (ACs) and blueschists (metamorphosed ACs) (phase II). At *c.* 250–230 Ma, a major continental collision between the North China and GSC along the narrowed Paleo-Tethys occurred, and the two blocks amalgamated into one entity to form the core of Mesozoic–Cenozoic East Asia. Nonetheless, on the palaeo-Pacific side of GSC, oceanic subduction continued to keep producing new arc crusts to the present. At *c.* 20 Ma, the regional rifting along the eastern margin

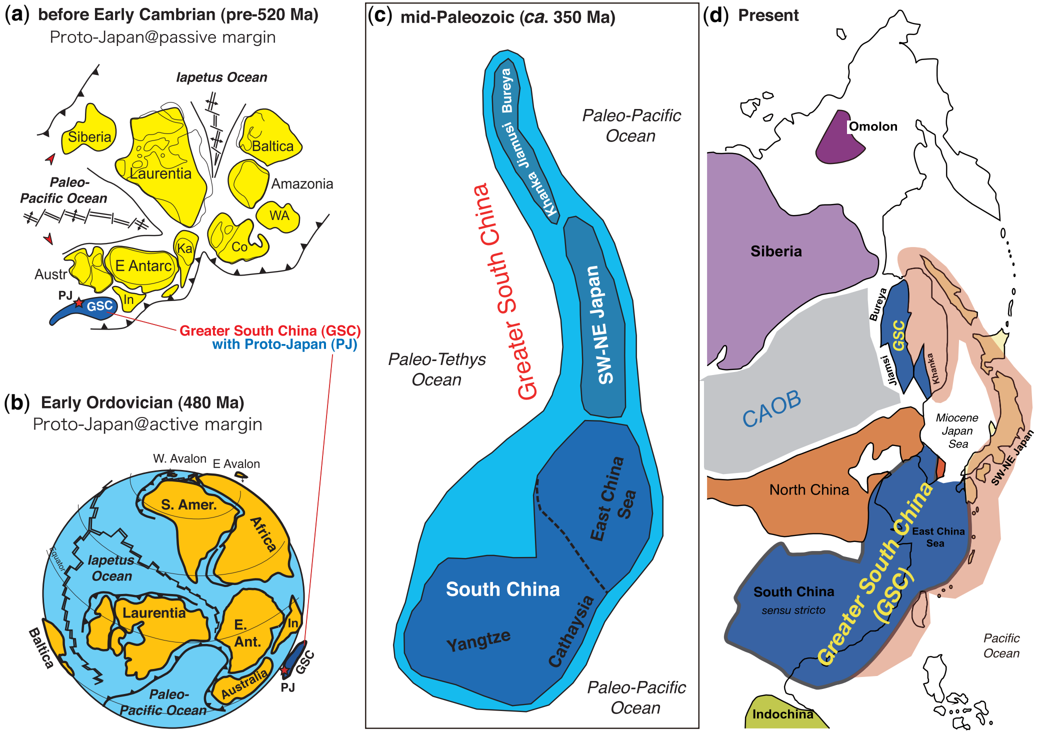

Fig. 2. Palaeogeographic position of Proto-Japan during Cambrian–Ordovician time (**a**) Cambrian, (**b**) Early Ordovician, and the configuration of Paleozoic, and present GSC (**c**) mid-Paleozoic, (**d**) present. During the Neoproterozoic to early Cambrian, Proto-Japan (red star) as a part of GSC (dark blue) was located along multiple continental blocks, i.e. Australia (Austr), East Antarctica (E Antarc), Kalahari (Ka), Congo (Co), West Africa (WA) and India (In) (e.g. Zhou *et al.* 2006; Cawood *et al.* 2018), under their initial divergence mode (a). Proto-Japan was faced to the palaeo-Pacific Ocean as a passive continental margin along GSC until the mid-Cambrian when a new oceanic subduction started (b). Proto-Japan belonged to GSC between the South China block *sensu stricto* (Yangtse + Cathaysia) and the Khanka–Jiamusi–Bureya megablock; (c) full sized GSC, up to 5000 km long, during the middle–late Paleozoic before the Triassic collision with the North China block; (d) present distribution of fragmented GSC (blue) in East Asia. The Paleozoic arc crust of Proto-Japan was almost entirely removed by tectonic erosion during the Mesozoic. GSC, Greater South China; CAOB, Central Asian orogenic belt. Source: (a–b) modified from Isozaki *et al.* (2010); (c–d) modified from Isozaki (2019).

of Eurasia created a back-arc basin (the Sea of Japan) and led to the isolation of an island arc, i.e. the present-day Japanese Islands (phase III; Fig. 2d).

The early Paleozoic rocks in Japan include arc granitoids, supra-subduction zone ophiolites and fore-arc sedimentary rocks (Fig. 3a); however, most of them are remarkably small in size (Fig. 3b), i.e. much smaller than their primary dimension that formed the arc crust of >200 km wide, for example, that of modern Japan is composed mostly of Cretaceous and Cenozoic rocks. Although extremely rare, the occurrence of Paleozoic rocks, i.e. coeval elements of a subduction-related orogen, such as granitoids, ophiolites, accretionary complexes (ACs) and meta-ACs (blueschists), proves that Paleozoic Japan has developed as a mature arc-trench system. Paleozoic Japan was located probably along the Pacific side of GSC, which was twice as large as the South China block (Fig. 2c; Isozaki 2019).

In short, Paleozoic Japan has essentially evolved as an active continental margin (Fig. 3c), along which, new crustal materials have been added from the palaeo-Pacific side. Except for minor-scale arc/oceanic plateaux, no evidence has been recognized for continental collision along the Pacific side of GSC since the onset of subduction in the early Cambrian (Fig. 1). The Hida belt in central Japan (Fig. 3) alone represents an allochthonous unit with respect to the rest of Japan, which was derived from the latest Paleozoic–Triassic suturing domain between the North China block and GSC (Isozaki *et al.* 2021, 2023), and secondarily incorporated into Japan as an exotic block during the late Mesozoic–Cenozoic.

Remnants of Ordovician Japan

The Early to Middle Ordovician rocks occur limitedly in two narrow belts in SW Japan (Fig. 3b); i.e. the Hida marginal–Nagato belt on the Japan Sea side and the Kurosegawa belt on the Pacific side of SW Japan (e.g. Ehiro 2000). The common characteristics and geological structure suggest that these units share the same origin, i.e. belong to the same subhorizontal nappe. The Kurosegawa belt occurs as a large-scale klippe, which in fact forms an extremely thin (less than 2 km) unit, as confirmed by regional field mapping (Isozaki 1996). The South Kitakami belt in NE Japan is regarded as the northeastern extension of the Kurosegawa belt. In the following discussion, the Ordovician rocks in Japan are briefly described in the tripartite subdivision of igneous, sedimentary and metamorphic rocks. Note that all numerical ages in this paper are according to Gradstein *et al.* (2020).

Granitoids

Judging from their rock types and geochemistry, all the early Paleozoic granitoids in Japan belong to arc granitoids formed in an ancient magmatic arc under oceanic subduction regimes. Most individual exposures are smaller than 2 km in diameter and are highly scattered. Their fragmentary occurrence and common association with serpentinite mélange recorded severe effects of secondary disruption after the primary magmatism/emplacement under repeated orogenesis related to oceanic subduction.

Ordovician granitoids were reported from the Hida marginal–Nagato belt and Kurosegawa belt in SW Japan, and also from the South Kitakami belt in NE Japan (Fig. 3b). Hosting the Ordovician–Silurian granitoids (e.g. Hada *et al.* 2000; Osanai *et al.* 2014; Aoki *et al.* 2015; Hasegawa *et al.* 2017; Sawada *et al.* 2020), the Kurosegawa belt comprises a discontinuous klippe composed of a serpentinite mélange zone of >1000 km long and >5 km wide, occurring in a higher structural level over the Jurassic and younger orogenic elements in SW Japan (Fig. 3). The latest U–Pb dating for igneous zircons constrains the granitoid ages to *c.* 490–440 Ma (Ordovician), and whole-rock/trace element geochemistry indicates their origin in arc crust (Yoshikura *et al.* 1990; Osanai *et al.* 2014). The coeval volcanic units in the same belt partly retain welded tuff, which certainly suggests the development of a mature volcanic arc (Yoshikura *et al.* 1990; Fig. 3c). Although very small in size, the Silurian (*c.* 400 Ma) granitoid from the Hida marginal–Nagato belt is by and large the same in rock types, geochemistry, age and mode of occurrence (Kono *et al.* 1966).

The equivalents in NE Japan occur in the South Kitakami belt, which were dated *c.* 445–400 Ma (zircon U–Pb ages) by sensitive high-resolution ion microprobe (SHRIMP) and laser ablation-inductively coupled plasma mass spectrometer (LA–ICPMS) (Watanabe *et al.* 1995; Shimojo *et al.* 2010). Previous petrochemical studies confirmed their calc-alkaline nature, implying a volcanic-arc origin (Shibata 1974; Asakawa *et al.* 1999; Kobayashi *et al.* 2000). Their common association with Cambrian granitoids (Sakashima *et al.* 2003; Tagiri *et al.* 2011; Isozaki *et al.* 2015) indicates their origin in the Cambrian and Ordovician–Silurian arc crusts in Japan, which were all formed by ancient oceanic subduction from the palaeo-Pacific side.

Despite the current restricted occurrences, extensive development of the Ordovician granitoid batholith is inferred from the abundant detrital zircons of igneous origin preserved in upper Paleozoic sandstones in Japan (Fig. 3b; Isozaki *et al.* 2010, 2014; Nakama *et al.* 2010; Okawa *et al.* 2013; Hasegawa *et al.* 2017).

Ophiolites

Four examples of ophiolitic units of Ordovician age occur in Japan, i.e. the Hida marginal–Nagato,

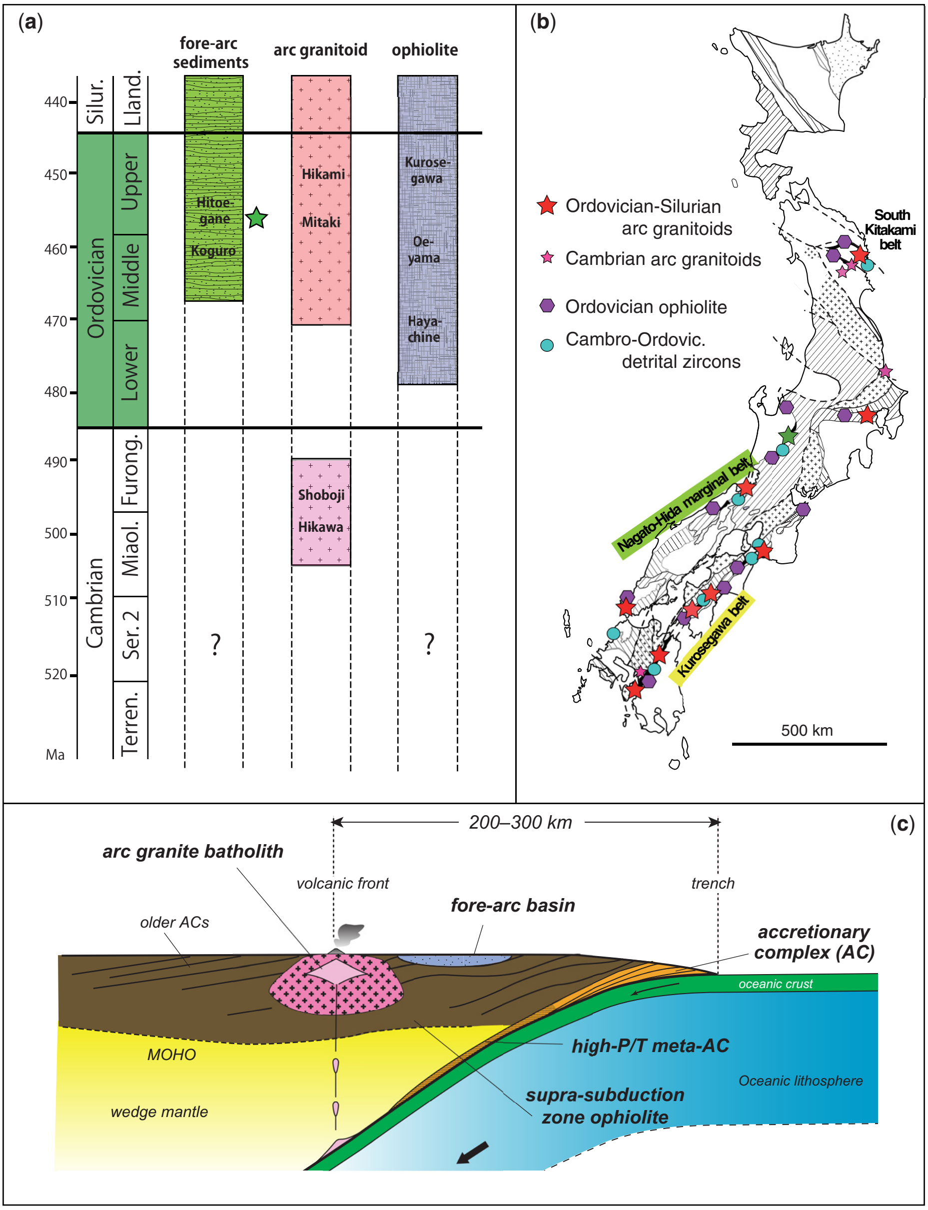

Fig. 3. (**a**) Age coverage and (**b**) distribution of the Ordovician and other early Paleozoic rocks in Japan, (**c**) with schematic profile of a mature arc-trench system featuring essential components, i.e. arc granitoid, supra-subduction zone ophiolite, fore-arc basin strata, accretionary complex and blueschist (high-P/T meta-AC). Note that the Ordovician rocks as dismembered forms occur in restricted narrow belts characterized by serpentinite mélange; i.e. the Nagato–Hida marginal belt and Kurosegawa belt in SW Japan, and the South Kitamaki belt in NE Japan. Red stars, green star and purple hexagons in (a,b) show the occurrences of Ordovician arc granitoids, fossil-bearing fore-arc strata and supra-subduction zone ophiolite, respectively. These three separated belts with Ordovician rocks share the same origin, as they form parts of the same nappe unit. Although their occurrence is limited in size and amount at present, i.e. mostly as tectonic blocks within serpentinite mélange, their overall distribution both in SW and NE Japan proves the primary extent of a mature arc-trench system on the order of 2000 km long and 200–300 km wide. Detrital zircon ages (*c.* 500–400 Ma) from Paleozoic–Mesozoic sandstones in SW and NE Japan (blue circles in b) support the extensive exposure of the Cambro-Ordovician felsic igneous rocks of arc signature in their provenance during the Ordovician. Source: (a–b) modified from Isozaki (2019).

Oeyama and Kurosegawa belts in SW Japan and the South Kitakami belt in NE Japan (Fig. 3b). Judging from their rock types, geochemistry and mode of occurrence, the Ordovician ophiolites in Japan are all classified as supra-subduction zone ophiolite that developed in ancient arc-trench systems, similar to the Troodos complex in Cyprus (Miyashiro 1973; Pearce *et al.* 1984).

The Oeyama ophiolite in SW Japan is composed of peridotites, mostly of lherzolite–harzburgite, whose geochemistry and texture indicate their origin in a young arc or back-arc domain (Arai and Yurimoto 1995; Machi and Ishiwatari 2010). Their age is constrained to *c.* 450 Ma by various dating methods (Ishiwatari and Tsujimori 2003). The ophiolite in the Kurosegawa belt in SW Japan was primarily composed of peridotite, in particular, harzburgite, or lherzolite with associated dunite and wehrlite, whose geochemistry suggests their back-arc origin (Yokoyama 1987). Those in the Hida marginal–Nagato belt are similar. These mantle-derived rocks were almost totally altered into serpentinite to form matrix of the mélange of the belt (Maruyama *et al.* 1984).

The Ordovician ophiolite in the South Kitakami belt is called the Hayachine–Miyamori ophiolite, which represents the most complete set of ophiolitic rock varieties in Japan, consisting of various peridotites with small amounts of mafic-felsic plutonic rocks (Ozawa *et al.* 2015). Their petrochemical aspects consistently indicate an ancient arc origin but in two contrasting modes, i.e. the Miyamori complex from fore-arc v. the Hayachine complex from back-arc. The igneous age was indicated as 484–420 Ma by K–Ar dating, also confirmed by a U–Pb zircon age of 462 Ma from gabbro and tonalite (Ozawa 1988; Shibata and Ozawa 1992; Shimojo *et al.* 2010).

The along-arc extent of these Ordovician ophiolites in Japan, at least over 1000 km (Fig. 3b) with no evidence for large-scale strike-slip displacement along the arc, proves the development of significant arc crust of the same spatial dimension. Therefore, oceanic subduction continued throughout the entire Ordovician period along a continental block, which corresponds to the Pacific margin of GSC.

Tuffaceous clastic rocks

The Ordovician sedimentary rocks in Japan occur solely in two areas; i.e. the Hida marginal–Nagato belt in SW Japan and the South Kitakami belt in NE Japan (Fig. 4). In both belts, the sedimentary units are composed of terrigenous clastics of non-marine to shallow marine facies associated intimately with felsic volcaniclastics. These strata likely represent sedimentary units deposited in a

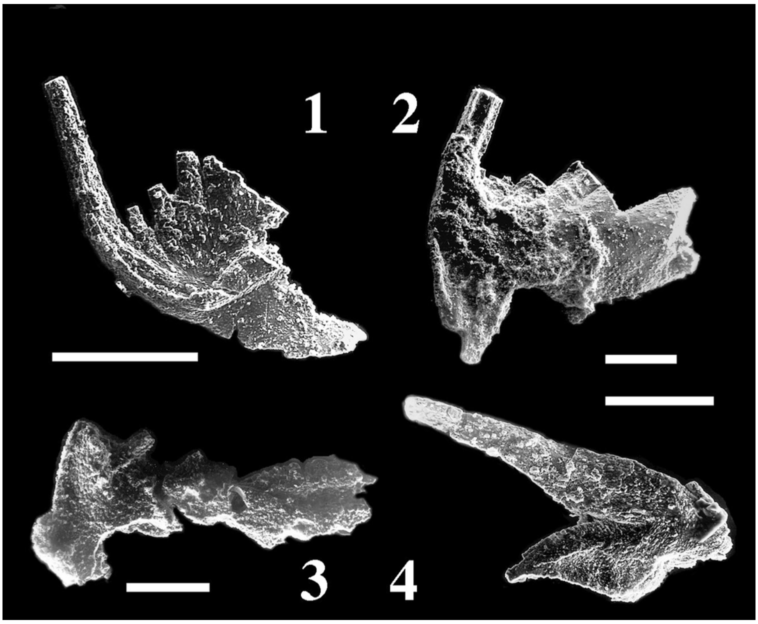

Fig. 4. Late Ordovician conodonts *Periodon aculeatus* Haggins from shallow marine fore-arc strata (Hitoegane Fm. in the Nagato–Hida marginal belt; green star in Fig. 3a, b). Note that these conodonts represent 'the oldest fossil from Japan'. Source: courtesy of Dr Kazuhiro Tsukada.

volcanically active, orogenic domain, such as an intra- or fore-arc basin (Fig. 3c).

The Hitoegane Formation in the Hida marginal–Nagato belt is composed of tuffaceous sandstone/mudstone beds (Tsukada and Koike 1997; green star in Fig. 3a, b). This unit occurs within a highly tectonized zone as a block, and its stratigraphical information, such as total thickness and lateral extent, is unknown. Nonetheless, this unit yielded conodonts that represent the sole Ordovician fossil occurrence as well as the oldest known fossil from Japan. The conodont *Periodon aculeatus* Hadding (Fig. 4) occurs, which is indicative of the early Darriwilian to late Sandbian of the Ordovician (Zhen *et al.* 2020). Nakama *et al.* (2010) added a zircon U–Pb age of 472 Ma (Floian, Early Ordovician) from a felsic tuff bed from a lower horizon. As to conodonts, there is another report on 'Ordovician forms' of genera *Belodina* and *Belodella* from a Silurian limestone of the Kurosegawa belt (Kuwano 1983), which were described originally as 'reworked Ordovician elements in the Silurian assemblage'. However, these conodonts were lately amended to genus *Ansella*, which ranges from the Early Ordovician up into the early Silurian (Männik *et al.* 2018), thus merely representing an equivocal Ordovician age.

The Upper Ordovician Koguro Formation in the South Kitakami belt is composed of unfossiliferous felsic tuff with a 457 Ma U–Pb zircon-derived age (Sandbian), which overlies the uppermost part of the above-described 466 Ma (Darriwilian, Middle Ordovician) ophiolite (Shimojo *et al.* 2010).

These Ordovician terrigenous clastic rocks of non-marine to shallow marine facies likely represent cover sediments that accumulated in the Ordovician intra-arc and/or fore-arc basin of Paleozoic Japan (Fig. 3c) as a part of GSC, over the contemporary arc crust including granitoids/gneisses and ophiolite. These Ordovician beds represent the oldest sedimentary units in Japan, except for highly metamorphosed units with possible Cambrian protoliths in the South Kitakami belt in the Hitachi area (Tagiri *et al.* 2011).

Metamorphic rocks

The occurrence of Ordovician blueschists was previously reported from the Kurosegawa belt (Maruyama and Ueda 1975), as well as Permo-Triassic examples for the Paleozoic subduction system along the Japan margin. However, latest re-examination confirmed that the previously claimed Ordovician example is much younger (Matsunaga *et al.* 2021). At present, there are no blueschists older than 360 Ma in Japan; nonetheless, the sporadic occurrences of Ordovician jadeite-bearing pyroxenite, within ophiolitic mélanges in the Oeyama and Hida marginal–Nagato belts, suggest their origin in hydrothermal systems in a nascent subduction zone with secondary incorporation into Proto-Japan (Tsujimori 2017). This is not yet direct evidence for a high-pressure/low-temperature (high-P/T) setting for the typical 'paired metamorphic belts' (Miyashiro 1961), but still suggests the development of a subduction system along Ordovician Japan.

Ordovician arc-trench system: its growth and annihilation

Despite the fragmentary nature of the above-mentioned orogenic elements, the occurrences of Ordovician granitoids, ophiolites, fore-arc clastic strata and jadeite-bearing rocks altogether indicate that a mature arc-trench system existed (Fig. 3c) during the Ordovician along the Japan segment of GSC. The granitoids and ophiolites formed much of the arc crust on which the conodont-bearing felsic tuffs/mudstones were deposited, likely in the fore-arc basin adjacent to the active volcanic front characterized by felsic magmatism.

The age spectra of detrital zircons in the middle–upper Paleozoic sandstones in Japan, in particular the dominance of 480–440 Ma grains of igneous origin (Isozaki *et al.* 2010, 2014; Nakama *et al.* 2010; Okawa *et al.* 2013; Hasegawa *et al.* 2017), further indicate that the main provenance of the mid–late Paleozoic fore-arc basin was predominately in early Paleozoic arc crustal rocks, mostly by felsic igneous rocks, particularly granitoids. The co-occurrence of Neoproterozoic (1000–600 Ma) grains also recorded the proximity to the Yangtze craton (Fig. 2c), with basement rocks of corresponding ages. The spatial dimension of the claimed Ordovician arc-trench system of Proto-Japan was much larger than the present length of Japan (Fig. 3c), because its lateral equivalents were identified not only in Primorye, Far East Russia (Isozaki *et al.* 2017; Isozaki 2019), but also in the Cathaysia margin of South China in the traditional sense (Shu *et al.* 2014; Hu *et al.* 2015; Cocks and Torsvik 2021; Wang *et al.* 2021).

Although nearly a full set of orogenic elements of an arc-trench system was recognized for Ordovician Japan, the total amount at present appears too small with respect to the crust size of modern Japan (Fig. 3b), which is composed mostly of Cretaceous and Cenozoic rocks of the same geologic assemblage, i.e. ACs, blueschists, ophiolites, granitoids and fore-arc basin deposits. The primary dimension of the Ordovician arc crust was probably the same as that of the modern Japan arc, i.e. over 2000 km and *c.* 200–300 km wide; however, most of the Ordovician arc-trench elements were likely removed secondarily after the Paleozoic. It is noteworthy that Cambrian, Ordovician and Silurian zircon grains predominate in the Paleozoic sandstones in Japan, guaranteeing extensive exposures of pre-existing early Paleozoic crustal rocks. In contrast, their almost complete absence in post-Permian sandstones indicates the drastic renewal of the arc crust from a Paleozoic one to a post-Paleozoic one (Isozaki *et al.* 2010; Nakama *et al.* 2010). The scarce preservation/occurrence of these Ordovician crustal rocks can be inferred on tectonic erosion relevant to subduction processes (e.g. von Huene and Scholl 1990; Clift and Vannucchi 2004; Yamamoto *et al.* 2009) during the late Paleozoic to Triassic (Fig. 1; Isozaki *et al.* 2010; Suzuki *et al.* 2010).

Palaeobiogeography

Following the above-discussed tectonic setting reconstructed on the basis of the diverse Ordovician rocks in Japan, this section explores the palaeogeographic position of Ordovician Japan. It was in the Miocene when SW Japan and NE Japan became tectonically separated not only from each other but also from mainland Asia by the back-arc opening of the Sea of Japan (Fig. 1). Before that, the Paleozoic to Paleogene crusts of SW and NE Japan formed side-by-side segments of the pre-Miocene Pacific margin of GSC (Isozaki 2019; Fig. 2c).

Scarce fossil evidence is not enough to constrain the palaeobiogeographic position of Ordovician Japan; however, the overlying Silurian and upper Paleozoic shallow/non-marine strata and their fossils provide indirect but reliable clues. The rugose corals of Siluro-Devonian and Carboniferous–Permian ages from SW and NE Japan consistently indicate a strong similarity to those reported from Australia and the Yangtze platform of South China (Kato 1990; Wang and Sugiyama 2000; Kido and Sugiyama 2011), and so do the Silurian conodonts and trilobites from SW Japan (Männik *et al.* 2018; Stocker *et al.* 2018). The Carboniferous–Permian fusulines (Ishii 1990; Kasuya *et al.* 2012) and Permian ammonoids (Ehiro 1997) likewise share the similar warm-water Tethyan affinity, echoing a link to Yangtze fauna.

From the palaeobotanical aspect, the sporadically reported Devonian flora from SW and NE Japan is non-diagnostic because floral provincialism became distinct first in the Carboniferous. The Permian plant fossils from NE Japan are different from those of the Angara (high latitude, Northern Hemisphere), Euramerica (mid-low latitude, Western Hemisphere) and Gondwana (middle–high latitude, Southern Hemisphere) floras; instead, they are similar to the Cathaysian flora commonly unearthed from East Asia, which indicates warm climates in low to middle latitudes during the Permian (Kimura 1987).

By pointing out the palaeobiogeographical aspects of the Siluro-Devonian corals and trilobites from Japan, however, Williams *et al.* (2014) cautioned against too much emphasis on the proximity between Paleozoic Japan and South China/Australia in regard to possible endemism and facies control. Some Silurian conodonts, together with rare chitinozoans, scolecodonts and ostracods from Japan may indicate similarity to those from Baltica–Laurentia (Männik *et al.* 2018; Siveter *et al.* 2018; Vandenbroucke *et al.* 2018), which implies their cosmopolitan or at least pan-tropical nature. Furthermore, some Permian brachiopod faunas in Japan with Boreal elements among dominant Tethyan representatives were used to support proximity to the North China block rather than to South China (Tazawa 2018). Nonetheless, immediately before the mid-Triassic collision/amalgamation of the South and North China blocks (Fig. 1), these two blocks were located already close from each other by and large in the same latitude (Isozaki 2019). Thus, the distinction of Permian fauna/floras between them and Japan was unlikely to be clear. It is also noteworthy that the north–south elongated aspect of GSC (Fig. 2c) may have allowed a wide latitude variation for hosting two or more bioprovinces.

In short, most of the middle to late Paleozoic fossil evidence from Japan generally suggests Tethyan affinity. Although more fossil evidence directly from Japan is inevitable, it is reasonable to place Ordovician Japan in the low latitude domain in the western palaeo-Pacific (Panthalassa) Ocean. Previous palaeogeographic maps commonly placed Ordovician South China around the equatorial domain (e.g. Isozaki 1996; Maruyama *et al.* 1997; Domeier 2018; Cocks and Torsvik 2021; Scotese 2021; Fig. 5) on the basis not only of faunal characteristics but also of palaeomagnetism. The latest palaeomagnetic data from the northwestern Yangtze platform indeed suggest the palaeolatitude of 19.5° S during the Ordovician (Han *et al.* 2015).

Spacious ocean for ‘subduction potential’

The GSC continental block became isolated during the late Neoproterozoic breakout of Rodinia (Hoffman 1991) and drifted away from the Gondwanan blocks, such as Australia, India, East Antarctica, etc. (Fig. 2a). Detrital zircon analyses for provenance (e.g. Wang *et al.* 2010, 2021; Hofmann *et al.* 2011) indicate that Ordovician South China was likely located along East Gondwana, in particular, immediately west of Australia/India (Lesser Himalaya)/East Antarctica that have the palaeomagnetism data for the low latitudes (Li *et al.* 1999; Grunow and

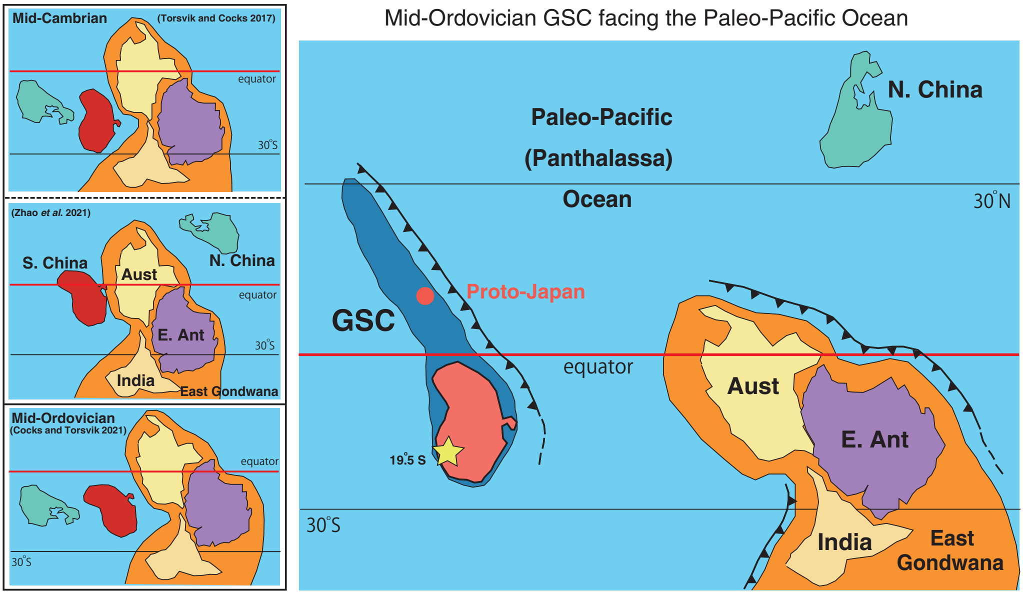

Fig. 5. Palaeogeographic position of Ordovician Japan within GSC and other continental blocks, such as North China and East Gondwana composed of Australia (Aust), East Antarctica (E. Ant) and India. Top and middle images on the left for the mid-Cambrian, and bottom one for the mid-Ordovician (previous works). Main image for the Mid-Ordovician (this study). Yellow star on GSC indicates the locality of the Ordovician palaeomagnetic data for 19.5° S from northern Sichuan, China (Han *et al.* 2015). By the Middle Ordovician, Proto-Japan became a mature arc-trench system with a thick arc crust along the palaeo-Pacific side of GSC. To allow the onset of a new oceanic subduction in the mid-Cambrian (Fig. 1), Proto-Japan within GSC needed to avoid facing any continental margin but instead faced an extensive oceanic domain, most likely the southern part of the palaeo-Pacific (main image). Wang *et al.* (2021) speculated on the early Paleozoic subduction system also on the northern margin of India. In regard to the 'subduction potential' around GSC, therefore, many previous palaeogeographic maps depicting 'continental congestion' around the South China block, particularly around much larger GSC, appear problematic. Note also that the 500 myr-long collision-free history of the Pacific margin of Japan indicates the long-term contact solely with oceanic plates. GSC, Greater South China. Source: top and middle left, modified from Torsvik and Cocks (2017), Zhao *et al.* (2021); bottom left, modified from Cocks and Torsvik (2021).

Encarnacion 2000). According to this speculation, GSC likewise was positioned closely to the East Gondwana blocks.

In contrast, two new critical constraints were lately added for the Ordovician position of GSC from the geology of Paleozoic Japan; i.e. the accommodation space for GSC within Rodinia and the inevitable spacious oceanic domain for initiating a new Cambrian subduction. First, the South China block needs to be re-perceived as the southwestern major component within GSC (Fig. 2c), which had a size twice as that of the South China block (i.e. Yangtze and Cathaysia). This new view requires all palaeogeographical schemes for the Neoproterozoic to early Paleozoic to prepare a much larger accommodation space for GSC than that for South China alone.

Second, the Paleozoic orogenic framework of Japan indicates that the orientation of GSC is critical, particularly for early Paleozoic palaeogeography. The mid-Cambrian palaeo-Pacific margin of GSC, including the Cathaysian side of South China, should have been already in contact with an oceanic plate with ample width for initiating a new oceanic subduction. In this regard, Cambrian GSC, at least the palaeo-Pacific margin, was significantly isolated from other major continents for more than several hundreds of kilometres.

Most of the published Cambro-Ordovician palaeogeographic maps (e.g. Popov and Cocks 2017; Cawood *et al.* 2018; Domeier 2018; Cocks and Torsvik 2021; Scotese 2021; Wang *et al.* 2021), nonetheless, placed South China on the immediate west of early Paleozoic Australia/India (Fig. 5, 3 images on the left) without assuming any wide in-between ocean. To avoid such an imaginary continental congestion and instead to prepare a spacious ocean domain for 'subduction potential', it is more reasonable to place GSC away from the East Gondwana margin, i.e. Australia/India (Fig. 5, main image).

One more point to note is that the Cathaysian margin needs to have always faced an extensive ocean, simply because the active margin of GSC has never experienced major continental collision for nearly 500 myr during the Phanerozoic (Fig. 1), regardless of those by minor-scale island arcs or oceanic plateaux/seamounts (Isozaki *et al.* 2010). This long-term collision-free history of the active margin requires a large-scale open ocean, again, for 'subduction potential' on the Cathaysian side of GSC throughout the Phanerozoic, and the only candidate for such a vast open ocean is the palaeo-Pacific (Panthalassa) Ocean. From the above-mentioned new perspectives, the early Paleozoic palaeogeography of the western palaeo-Pacific around GSC is tentatively summarized in Figure 5 (main image). An intimate connection was emphasized for Neoproterozoic South China–India (Zhou *et al.* 2006; Cawood *et al.* 2018), however, along the same context, the hysteresis of the claimed connection into the early Paleozoic (Wang *et al.* 2021) needs reconsideration.

For detailed palaeogeographical reconstruction, simple geometrical/geological fitting of continental blocks, like a jigsaw puzzle, is not enough; instead, we need to pay more attention to orogenic histories of involved active continental margins in the past, in particular about the dimension of lost ocean domains for 'subduction potential'. This case study in Japan, a segment of a long-time active continental margin of GSC, may encourage further studies on other early Paleozoic *terra incognito* in the rest of the world. Many significant areas of interest may have been possibly overlooked in previous studies; in other words, there are great opportunities to reveal hidden secrets of palaeogeography.

Summary

Ordovician Japan formed an active continental margin with a mature arc-trench system that developed along the palaeo-Pacific-facing GSC margin. The Ordovician crust was composed of arc granitoids, ultramafic–mafic igneous complex of supra-subduction zone ophiolite affinity, fore-arc basin sediments and possibly high-P/T blueschists derived from accretionary complexes. However, most of these geological entities were considerably fragmented by secondary tectonics, particularly by severe tectonic erosion. Ordovician Japan was located somewhere in low-latitude domains in the western palaeo-Pacific (Panthalassa) as a part of GSC, particularly on the Cathaysian side of South China *sensu stricto* (i.e. Yangtze and Cathaysia). For palaeogeographical reconstruction of the Ordovician continental blocks around GSC, the significance of a spacious ocean domain to provide 'subduction potential' is emphasized for explaining the initiation of a new subduction system, and also for the long-lived active margin of Japan, sustained over several hundred million years.

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