Triassic 40Ar/39Ar ages from the Sakaigawa unit, Kii Peninsula, Japan: implications for possible merger of the Central Asian Orogenic Belt with large-scale tectonic systems of the East Asian margin

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Triassic $^{40}Ar/^{39}Ar$ ages from the Sakaigawa unit, Kii Peninsula, Japan: implications for possible merger of the Central Asian Orogenic Belt with large-scale tectonic systems of the East Asian margin

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Abstract The 218.4 ± 0.4, 228.8 ± 0.9 and 231.9 ± 0.7 Ma $^{40}Ar/^{39}Ar$ laser probe pseudo-plateau ages (2σ; 49–63% ^{39}Ar-release) of very low-grade meta-pelitic whole-rocks from the Sakaigawa unit date high-P/T metamorphism. We argue that this event occurred in a subduction–accretion complex, not along the East Asian continental margin, but on the Pacific side of the proto-Japan superterrane. Proto-Japan was a Permian magmatic arc, presently dispersed in the Japanese islands, which also contained older subduction–accretion complexes. The arc system was fringing but not yet part of the Eurasian continent. The Middle to Late Triassic high-P/T tectono-metamorphic event was partly coeval with proto-Japan's collision with proto-Eurasia along the southward extension of the Central Asian Orogenic Belt, causing the main metamorphism in the Hida-Oki terrane. It is possible that this system continued via the Cathaysia block (China) to Indochina. The Late Permian to Middle Triassic Indosinian event might stem from docking of Pacific-derived terranes with Southeast Asia's continental margin. The concept of the proto-Japan superterrane implies that the Qinling-Dabie-Sulu suture zone joined the Central Asian Orogenic Belt to the east of the North China craton and did not continue to Japan, as commonly assumed.

Keywords $^{40}Ar/^{39}Ar$ geochronology - Tectonics - Paleogeography - China - Japan

Introduction

Eurasia is a composite of many small continents separated by broad belts of Palaeozoic, Mesozoic and Early Cainozoic magmatic, deformed, and in part metamorphosed rocks (Maruyama and Seno *1986*; Zonenshain et al. *1990*; Şengör and Natal'in *1996*; Maruyama et al. *1997*; Wakita and Metcalfe *2005*; Cocks and Torsvik *2007*). Siberia, Tarim, North and South China, as well as Indochina are such continental pieces, and the Central Asian Orogenic Belt is one of the principal large-scale tectonic systems of the composite continent (Figs. 1, 2). Japan separated from mainland Asia by back-arc spreading in the Middle Miocene (see Kaneoka et al. *1996*; van der Werff *2000*, for reviews). Because they are the nearest to Asia's mainland, medium and high-grade metamorphic rocks and granitoids of central Japan and on the island of Oki-Dogo, which is part of the northern continental margin of Honshu in the Sea of Japan (Fig. 3), have been viewed as its reworked Precambrian crust (Faure and Charvet *1987*; Charvet et al. *1990*; Banno and Nakajima *1992*). These constitute the Hida-Oki terrane. Parts of the submerged continental crust of the Yamato Bank in the Sea of Japan (Fig. 2) have been compared to this terrane (Kaneoka et al. *1996*). Commonly, the metamorphic rocks of the main Hida belt of central Japan are regarded as belonging to the North China craton, and the Oki metamorphics as part of the South China craton (Sohma et al. *1990*; Banno and Nakajima *1992*; Isozaki *1997a*; Maruyama et al. *1997*; Nakajima *1997*; Ernst et al. *2007*). Consequently, the Middle–Late Triassic Qinling-Dabie-Sulu suture between both the cratons was considered to continue into the Japanese region (Maruyama and Seno *1986*; Isozaki *1997a*; Maruyama *1997*; Maruyama et al. *1997*; Ernst et al. *2007*). Accordingly, various efforts have been made to correlate rocks, structures and belts in both cratons with elements of the Japanese islands (Suzuki and Adachi *1994*; Nakajima *1997*; Ishiwatari and Tsujimori *2003*; Oh *2006*; Osanai et al. *2006*; Tsujimori et al. *2006*; Ernst et al. *2007*; Oh and Kusky *2007*). Recent studies have suggested that the Qinling-Dabie-Sulu suture could continue to the Permo-Triassic Hida-Oki terrane (Oh *2006*), or to the Higo metamorphic complex (Fig. 3), which is correlated with this terrane (Osanai et al. *2006*; Oh and Kusky *2007*). The suture belt would thus wrap around the eastern margin of the North China craton (Oh *2006*; Ernst et al. *2007*; Oh and Kusky *2007*). However, the correlation of the suture with the Higo metamorphic complex is compromised by the results of SHRIMP dating of zircons from metamorphic and associated magmatic rocks by Sakashima et al. (*2003*). The latter authors concluded that protoliths of a high-grade paragneiss in the Higo complex were in fact early Mesozoic sediments that were metamorphosed in Early Cretaceous time, as will be discussed later on in our paper

Isozaki (*1997a*) and Maruyama (*1997*) argued that erosion of the Qinling-Dabie-Sulu belt would have caused a huge sedimentary discharge into the western part of the Palaeo-Pacific ocean, nourishing the turbidite sandstones and intercalated conglomerates in trench fill deposits in the Jurassic subduction–accretion complexes with detritus of metamorphic and granitic rocks. Yet, equivalents of the sedimentary basins that record the exhumation and deep erosion of the suture zone in China, like the thick synorogenic Triassic–Jurassic foreland sedimentary series surrounding the Dabieshan (e.g. Grimmer et al. *2003*; Li et al. *2004*), seem to be lacking in Japan. This makes an extension of this suture to Japan unlikely.

The Hida-Oki terrane's range of isotopic ages is virtually identical to the 245–225 Ma age assigned to the ultrahigh-pressure metamorphism in the Qinling-Dabie-Sulu suture (see Hacker et al. *2004* and Ernst et al. *2007* for reviews). However, the east- and southward extension of this suture to Korea is still controversial and a number of highly different tectonic scenarios have been proposed (Ishiwatari and Tsujimori *2003*; Oh *2006*; Osanai et al. *2006*; Tsujimori et al. *2006*; Ernst et al. *2007*; Oh and Kusky *2007*). But the widespread occurrence of 290–240 Ma isotopic ages in the polymetamorphosed Gyeonggi granulitic gneiss terrane and the Okcheon and Imjingang metamorphic belts along its northern and southern margins, points to a major tectono-metamorphic event in the Permian–Triassic period, such as a terrane collision (see reviews by Ernst et al. *2007* and Oh and Kusky *2007*). Yet, Late Permian to Early Triassic events are not limited to the collision zone between the North and South China cratons, but also affect the East Asian margin farther to the south. A wide area of the southeastern part of South China craton is affected by magmatism, metamorphism and deformation in this period (e.g. Faure et al. *1998*; Li *1998*; Xiao and He *2005*; Li and Li *2007*). Also in Indochina magmatism, (ultra) high-temperature metamorphism and ductile deformation occurred in the 260–240 Ma time span (Lepvrier et al. *2004*).

In the current contribution, we present 218–232 Ma $^{40}Ar/^{39}Ar$ laser probe ages of very low-grade metapelite whole-rocks from the Sakaigawa subduction–accretion complex in the western Kii Peninsula, Japan (Figs. 3, 4). We explore the meaning of these late Middle to early Late Triassic dates in the context of the possible interactions of orogenic belts in Central Asia with the palaeo-Pacific subduction–accretion systems of East and Southeast Asia, as well as the role of island arcs and micro-continents along this margin, like the proto-Japan superterrane that formed a Permian arc system.

Eastward extension of the Central Asian Orogenic Belt

The Central Asian Orogenic Belt is situated between the Siberian craton to the north and Tarim and North China cratons to the south (Figs. 1, 2). The system extends from the Urals in the west to Sikhote-Alin' in the Russian Far East, where it is truncated by subduction–accretion complexes and continental margin arc systems associated with subduction of Pacific oceanic lithosphere in Mesozoic time (Fig. 1; Kojima et al. *2000*; Nokleberg et al. *2001*, *2004*; Ernst et al. *2007*). The vast Central Asian orogenic system formed in the Palaeozoic in a southwestern Pacific-like setting, by prolonged accretion of oceanic plate sediments, oceanic crust, including oceanic islands, forearc and backarc basins, and magmatic arcs, as well as by amalgamation of terranes including Gondwana- and Siberia-derived micro-continents with their passive margins (de Jong et al. *2006*; Windley et al. *2007*; and references in de Jong et al. *2008* and Xiao et al. *2008*, this issue). Plate convergence was accompanied by intense magmatic and volcanic activity in arc systems (Jahn *2004*). Final oceanic closure resulted in the formation of the Solonker suture zone. This foremost structure can be traced all along the Central Asian Orogenic Belt from Kyrgyzstan in the west, passing to the north of the Tarim (Xiao et al. *2008*, this issue) and North China (Windley et al. *2007*) cratons, to northernmost North Korea in the east (Figs. 1, 2). Some terranes in northeastern China and Far East Russia belonged to active continental margins in Permian to early Triassic time (Nokleberg et al. *2001*, *2004*; Jia et al. *2004*). At the end of the Palaeozoic, magmatic arcs accreted to the Khanka superterrane (Nokleberg et al. *2004*) that collided with the North China craton, probably in the Early Triassic (Zonenshain et al. *1990*; Wu et al. *2004*). Arc plutons of Late Permian to Early Triassic age and a subduction–accretion complex occur in the Jilin area of northeastern China (Li *2006*; Lin et al. *2008*). The Chongjin subduction–accretion complex in northernmost North Korea contains late Palaeozoic ophiolites, chert and limestone (Nokleberg et al. *2001*). These observations imply that the Solonker suture zone continued to the coastal area of the Sea of Japan (Figs. 1, 2; de Jong et al. *2006*). The South Kitakami terrane of northeast Japan (Fig. 3) is classically regarded as part of the continental margin of the South China ctaton (Yangtze shelf; Isozaki *1997a*). But South Kitakami's early Palaeozoic series have also been regarded as having been associated to the Khanka superterrane (Şengör and Natal'in *1996*; Kojima et al. *2000*; Tazawa *2002*). On the basis of such evidence, the Permian island arc system of the proto-Japan superterrane has been considered as the eastern extension of the Central Asian Orogenic Belt (de Jong et al. *2006*). A number of authors explored the possibility that the Central Asian Orogenic Belt continues southeastward from mainland Asia into the 250-235 Ma-old, mainly metasedimentary Hida-Oki terrane in Japan (Fig. 1; Arakawa et al. *2000*; Jahn et al. *2000*; de Jong et al. *2006*). Indeed, metamorphic rocks and synorogenic granites from the easternmost Central Asian Orogenic Belt in northeastern China yielded ca. 240 Ma U–Pb zircon dates (Wu et al. *2004*) and ca. 225 Ma $^{40}Ar/^{39}Ar$ mica ages (Xi et al. *2003*).

In the models that advocate that the Qinling-Dabie-Sulu continued to Japan, it is far from clear what is actually colliding with what, as two essential elements are lacking in such models. Firstly, the Permo-Triassic subduction–accretion complexes in Japan stretch all the way to the southernmost islands of the Ryukyu arc (Yaeyama promontory; Ishiwatari and Tsujimori *2003*). Secondly, the Japanese islands contain a number of terranes with fragments of a dispersed Permian magmatic arc system with a basement of Early Palaeozoic igneous and metasedimentary rocks, which have been grouped into the proto-Japan superterrane (de Jong et al. *2006*).

Regional tectonic framework of the Japanese islands

The late Palaeozoic to early Miocene tectonic evolution of the Japanese archipelago has been explained in terms of a sequence of collisions of micro-continents with the East Asian margin and the closure of intervening relatively small oceanic basins (Faure et al. *1986*; Faure and Charvet *1987*; Charvet et al. *1990*). Usually, however, with the exception of the elements of the proto-Japan superterrane, most terranes oceanward of the Hida-Oki terrane, are interpreted as subduction–accretion complexes formed due to the subduction of lithosphere of different oceanic basins below the proto-Asian continent since the early Palaeozoic (Isozaki *1997a*, *1997b*; Maruyama et al. *1997*; Nakajima *1997*; Ernst et al. *2007*). Such complexes are composed of trench fill or fore-arc sediments and oceanic components, like chert, (pillow) basalt and limestone, that is, former reef caps of seamounts (Isozaki *1997a*, *b*; Maruyama et al. *1997*; Nakajima *1997*; Wakita and Metcalfe *2005*). Especially during the Jurassic to Early Cretaceous, extensive accretion took place including the Mino-Tamba-Ishio terrane, the Northern Chichibu terrane, the North Kitakami terrane, as well as the protoliths of the Mikabu and Sambagawa belts (Isozaki *1997a*, *b*; Nakajima *1997*; Suzuki and Ogane *2004*; Wakita and Metcalfe *2005*). The Japanese Jurassic to Early Cretaceous subduction–accretion complexes form part of a huge system bordering the eastern Eurasian continental margin from Far East Russia to southwest Borneo (Hamilton *1979*; Faure and Natal'in *1992*; Zamoras and Matsuoka *2001*, *2004*; Wakita and Metcalfe *2005*). This was accompanied by the development of a vast, principally Cretaceous magmatic arc (Maruyama et al. *1997*; Nakajima *1997*; Takagi *2004*; Nakajima et al. *2005*) that continues via east China (Jahn et al. *1976*) to Indochina and southwest Borneo (Hamilton *1979*). A peculiar feature of the Japanese subduction–accretion complexes is the abundance of granitic and metamorphic detritus in sandstones and the rare occurrence of volcanic detritus (greywackes) that is so characteristic for other subduction–accretion complexes (Suzuki and Adachi *1994*; Takeuchi *1994*). Jurassic turbidite sandstones of the Mino-Tamba-Ashio terrane contain detrital metamorphic minerals (like pyrope-almandine rich garnet, chloritoid and sillimanite), rare chloritoid-bearing phyllite and sillimanite gneiss fragments and intercalated polymict conglomerate lenses with pebbles of garnet–sillimanite–biotite gneiss and granitoids (Adachi and Suzuki *1994*; Tanaka and Adachi *1999*; Sano et al. *2000*; Nutman et al. *2006*). Whole-rock Rb–Sr dating (Shibata and Adachi *1974*) and mineral dating using the Chemical Th–U–total Pb Isochron Method (CHIME) on monazite (Adachi and Suzuki *1994*) and a sensitive high-resolution ion microprobe (SHRIMP) on zircon (Sano et al. *2000*; Nutman et al. *2006*) revealed that the majority of these pebbles are derived from Palaeo- and Mesoproterozoic gneisses with minor contributions of 250 and 180 Ma-old rocks. U–Pb isotope spot analysis by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) of igneous zircons from psammitic schist of the Jurassic complex that has undergone Cretaceous high-pressure metamorphism (Sambagawa belt, see below) yielded abundant Palaeoproterozoic ages in cores of crystals (Okamoto et al. *2004*; Aoki et al. *2007*).

From a tectonic point of view, southwest Japan is generally subdivided into an Inner Zone (Asian Continent side) and an Outer Zone (Pacific Ocean side) (Fig. 3; Table 1) that are separated by the Median Tectonic Line (MTL). The MTL is regarded as a major left-lateral wrench fault zone that is associated with Late Cretaceous pull-apart basins with exceptionally thick turbiditic, shallow-marine, deltaic and continental sediments with abundant volcanic rocks (Teraoka *1977*; Whitaker *1982*; Nakajima *1997*). However, deep seismic reflection data show that the fault zone is moderately dipping below the Inner zone (Ito et al. *1996*; Kawamura et al. *2003*). The Outer and Inner zones have a similar general structure: a pile of flat-lying tectonic units that become progressively younger structurally downwards. In contrast to the Outer Zone, the Inner Zone contains Cretaceous to Palaeogene subduction-related, mainly granitic volcanic–plutonic complexes (Takagi *2004*; Nakajima et al. *2005*), locally associated with high-temperature low-pressure "Ryoke" metamorphism (Nakajima *1997*; Brown *1998*).

The Outer Zone

The Outer Zone comprises (Fig. 3; Table 1) the Kurosegawa terrane and the Northern and Southern Chichibu terranes, which are grouped into the Chichibu composite terrane (Kurimoto *1995*; Matsuoka et al. *1998*) that occurs as a klippe-like structure on the Mikabu and Sambagawa belts (north) and the Shimanto terrane (south), often straddling the contact between both (Kurimoto *1995*; Matsuoka et al. *1998*; Aoki et al. *2007*). The Chichibu composite terrane truncates the imbricate structure of the Shimanto terrane (Kurimoto *1982*; Awan and Kimura *1996*). The contact between the Northern Chichibu terrane and the underlying Sambagawa belt is a low-angle normal fault (Masago et al. *2005*). Well-bedded, clastic series as old as early Late Jurassic overlie the Chichibu composite terrane and conglomerates contain pebbles of chert from the substratum, as well as granite and (sub) volcanic rocks (Umeda and Sugiyama *1998*; Kashiwagi and Yao *1999*).

The Kurosegawa terrane forms a narrow, discontinuous belt of tectonic mélange containing a great variety of lithologies; partly set in a serpentinite matrix and that were formed in various geodynamic settings. Typical lithologies of this terrane are Early and Late Palaeozoic plutonic and high-grade to low-grade metamorphic rocks of different baric type, weakly to non-metamorphic Pridolian to Eifelian tuffaceous clastic rocks, and Permo-Mesozoic continental shelf deposits (Aitchison et al. *1991*; Nakajima *1997*; Isozaki *1997a*; Hada et al. *2000*, *2001*; Kato and Saka *2003*; Takagi and Arai *2003*). Usually, a Permo-Triassic subduction–accretion complex is also regarded as part of this terrane. However, as pointed by Yamakita (*1998*) these rocks are not associated with the typical Kurosegawa lithologies and were therefore incorporated into the Northern Chichibu terrane, which we follow in this paper. The Northern Chichibu terrane is a subduction–accretion complex with virtually unmetamorphosed to pumpellyite–actinolite facies, Permian to late Jurassic pelites and basic phyllites with older tectonic blocks of sandstone, greenstone, chert and carbonate (Kurimoto *1986*; Kawato et al. *1991*; Matsuoka et al. *1998*). The Southern Chichibu terrane is an only locally metamorphosed Jurassic to Early Cretaceous subduction–accretion complex with blocks of Triassic cherts and Jurassic siliceous shales, sandstones, acidic tuffs and basaltic rocks (Kurimoto *1993*; Matsuoka *1998*).

The Mikabu belt is a greenstone-dominated subduction–accretion complex metamorphosed from pumpellyite–actinolite to clinopyroxene–lawsonite–actinolite facies (Banno and Sakai *1989*; Banno *1998*; Suzuki and Ishizuka *1998*) in the middle Cretaceous (Dallmeyer et al. *1995*; de Jong et al. *1999*, *2000*). Maruyama et al. (*1997*) considered the belt as a remnant of a palaeo-oceanic plateau. The Sambagawa belt is a very low-grade to epidote–amphibolite facies metamorphic subduction–accretion complex (Banno and Sakai *1989*; Takasu and Dallmeyer *1990*; Masago et al. *2005*; Aoki et al. *2007*), in which eclogite- or granulite-facies metamorphic gabbro or peridotite complexes also occur (Okamoto et al. *2004*; Terabayashi et al. *2005*; Miyamoto et al. *2007*). Metapelites yielded Late Cretaceous whole-rock and white mica $^{40}Ar/^{39}Ar$ plateau ages (Takasu and Dallmeyer *1990*; Dallmeyer and Takasu *1991*;

Dallmeyer et al. *1995*; de Jong et al. *2000*), whereas zircons in eclogites have metamorphic rims with SHRIMP U–Pb ages of 132 − 112 Ma (Okamoto et al. *2004*). The Shimanto terrane is an Early Cretaceous to early Miocene zeolite to prehnite-pumpellyite, prehnite–actinolite and local greenschist facies subduction–accretion complex (Toriumi and Teruya *1988*; Agar et al. *1989*; Taira et al. *1992*; Awan and Kimura *1996*; Miyazaki and Okumura *2002*). Still younger accreted material extends offshore to the Nankai trough, the present-day eastern boundary of the Eurasian plate (Fig. 3; Taira et al. *1992*).

The Inner Zone

The Inner Zone, to the south of the Hida-Oki terrane, comprises (Fig. 3; Nakajima *1997*; Nishimura *1998*; Tsujimori and Liou *2005*): a pre-Permian subduction–accretion complex [Oeyama ophiolites and underlying Carboniferous (330 − 280 Ma) high-pressure metamorphic Renge belt], a Permian subduction–accretion complex (Akiyoshi, and associated Suo belt, Maizuru, and Ultra-Tamba terranes) and a Jurassic to earliest Cretaceous complex (Mino-Tamba-Ishio terrane). The Akiyoshi terrane contains limestone blocks that originally formed the coral reef caps on a palaeo-seamount chain and the Maizuru terrane is a remnant of a palaeo-oceanic plateau (Isozaki *1997a*; Maruyama et al. *1997*). The contact between the Mino-Tamba-Ishio terrane and the Hida-Oki terrane in central Japan is a narrow, complex tectonic zone that is affected by Jurassic right-lateral and Cretaceous left-lateral strike-slip deformation (Otoh et al. *1998*; Tsukada *2003*). It consists of several long and narrow, fault-bounded blocks that partly belong to the Renge, Suo, Akiyoshi and Maizuru subduction–accretion complexes, as well as rocks referred to as the redefined Hida Gaien belt by Tsukada et al. (*2004*). The Palaeozoic subduction–accretion complexes are covered by a thick sequence of strongly deformed clastic sediments of the Early Jurassic Kuruma Group, which was deposited in a fore-arc setting (Tsukada *2003*; Tsukada et al. *2004*). The Hida Gaien terrane is only overlain by the Early Cretaceous series of the Tetori Group (Tsukada *2003*).

The pre-Permian complex of the Inner Zone is correlated with the Kurosegawa terrane of the Outer Zone (Isozaki and Itaya *1991*; Isozaki *1997a*; Nakajima *1997*). This correlation was based on the similarity of virtually all pre-Jurassic lithologies and their structural position, as well as the analogous timing of tectonic and metamorphic events with the Inner Zone (Table 1). The Jurassic–earliest Cretaceous complex is considered to have the Northern Chichibu terrane as equivalent in the Outer Zone (Isozaki and Itaya *1991*; Nakajima *1997*). The Southern Chichibu terrane seems not to have an equivalent to the North of the MTL.

Hida-Oki terrane

Amphibolite-facies and locally granulite-facies, mainly paragneisses with discontinuous, concordant layers of subordinate amphibolite and marble, occur in the main Hida belt of central Japan and on the island of Oki-Dogo (Fig. 3; Suzuki and Adachi *1994*; Isozaki *1997a*; Dallmeyer and Takasu *1998*; Arakawa et al. *2000*, *2001*; Kawano et al. *2006*). Some gneisses are migmatitic, and minor pelitic types may contain sillimanite or corundum. The Hida gneisses contain abundant granodiorite, diorite and tonalite intrusions that are not affected by the main Permo-Triassic metamorphism (Nakajima *1997*).

Arakawa et al. (*2000*) noted that the Sr–Nd isotope systematics of the Palaeozoic to Mesozoic granitic rocks, and young Sm–Nd depleted mantle model ages of paragneisses imply that the Hida belt's protoliths were not older than early Palaeozoic. Suzuki and Adachi (*1994*) pointed out that the youngest detrital zircon and monazite grains in paragneisses, with CHIME ages of ca. 350 Ma (Oki-Dogo) and ca. 300 Ma (main Hida belt), show that their protoliths were deposited after the Early to Late Carboniferous. The chemical and isotopic signatures of the mafic igneous rocks indicate that the Hida belt was formed in a continental margin affected by a subduction zone or a continental island arc (Arakawa et al. *2000*). Amphibolites with tholeiitic to alkaline chemical affinity occurring in paragneisses on Oki-Dogo Island illustrate the complex and heterogeneous nature of the Hida-Oki terrane. Their geochemistry and Sr–Nd isotope systematics show that many amphibolites were derived from basalts of inferred Carboniferous to Permian age that extruded in a within-plate setting not affected by a subduction zone (Arakawa et al. *2001*). However, some amphibolite that occur as thin concordant layers in calcareous psammitic gneisses, occasionally deformed into aggregates of lenticular blocks (chocolate tablet boudins), have island arc or mid ocean ridge basalt signatures (Arakawa et al. *2001*). The latter two basalt types would imply the presence of fragments of oceanic crust.

On the basis of sketchy Sm–Nd and Rb–Sr isotope data, with huge errors of 10–50%, it has been suggested that the Hida-Oki terrane experienced early, locally granulite-facies, metamorphism as well as mafic magmatism and volcanism before the Permian (Isozaki *1997a*; Nakajima *1997*; Arakawa et al. *2000*). The timing of the main, medium-pressure type amphibolite-facies metamorphism and associated migmatite formation is well constrained. Unzoned monazites from paragneisses on Oki-Dogo as well as metamorphic overgrowths on older cores of zoned grains yielded PbO/ThO_2 ages of 250 ± 20 Ma (Suzuki and Adachi *1994*). These dates are within error of a concordant U–Pb SHRIMP age of 236 ± 3 Ma, obtained by Tsutsumi et al. (*2006*) from the rim of a zircon grain in a paragneisses. A sillimanite-bearing paragneiss from the Hida belt in central Japan yielded a monazite with a CHIME age of 250 ± 10 Ma (Suzuki and Adachi *1994*), which is within error of the youngest concordant U–Pb SHRIMP age of 245 ± 15 Ma obtained by Sano et al. (*2000*) on zircon from a metavolcanic paragneiss. CHIME zircon ages in the 250 − 230 Ma range for a granite (Suzuki and Adachi *1991*), may indicate that metamorphism was accompanied by rare magmatism. On Oki-Dogo, the waning stages of metamorphism are constrained by earliest Jurassic 199 − 192 Ma $^{40}Ar/^{39}Ar$ hornblende plateau and isochron ages (Dallmeyer and Takasu *1998*). Muscovite on Oki-Dogo yielded considerably younger $^{40}Ar/^{39}Ar$ plateau ages of 166.5 ± 0.6 and 167.8 ± 0.6 Ma (Dallmeyer and Takasu *1998*).

The post-metamorphic Funatsu-type granitoid suite in central Japan yielded Rb–Sr whole-rock isochron ages of 188.9 ± 4.4 and 197.7 ± 15.4 Ma (Shibata and Nozawa *1984*). Dykes and veins of leucocratic granite that intruded the gneisses on Oki-Dogo are correlated with Funatsu-type granitoids (Dallmeyer and Takasu *1998*). Widespread intrusion of 230 − 180 Ma calc-alkaline plutons (late Triassic–early Jurassic) correspond to an important period of crust formation (Arakawa et al. *2000*). Kaneoka et al. (*1996*) noted that biotite (hornblende) granites that intruded the continental crust of the Yamato Bank area, have K–Ar and Rb–Sr whole-rock isochron ages in the range of 257 − 196 Ma, and might thus be comparable to the Hida-Oki terrane.

The gneissic basement and the Funatsu-type granitoids are overlain by sediments of the Tetori Group (Otoh et al. *1998*), the oldest rocks of which yielded Callovian and Oxfordian fossils (Kuzuryu subgroup, Tsukada *2003*), implying a depositional age of 165 − 156 Ma. Exhumation of the Hida-Oki terrane was thus completed in late Middle to early Late Jurassic time.

Often the Hida and Oki terranes are regarded as separate geological entities (Sohma et al. *1990*; Banno and Nakajima *1992*; Isozaki *1997a*; Maruyama et al. *1997*; Nakajima *1997*), a claim which is occasionally backed-up by geochemical and Sr–Nd isotope data (Arakawa et al. *2001*). However, because both rock suites are petrologically and geochronologically essentially similar (Suzuki and Adachi *1994*; Dallmeyer and Takasu *1998*), we do not want to focus on the possible differences between them. The small size of the outcrop (less than about 15 km^2) on the tiny island of Oki-Dogo with respect to the main occurrence in the Hida belt introduces a bias. Therefore and because of the complex tectono-metamorphic history of these rocks we prefer to focus on the similarities and group both as the Hida-Oki terrane.

Proto-Japanese superterrane

The principal elements that have been grouped into the proto-Japan superterrane are the South Kitakami terrane (northeastern Honshu) as well as parts of the Kurosegawa (western Honshu and Kyushu), Hida Gaien (or Marginal) (central Honshu) and Paleo-Ryoke (in restricted areas from Kyushu to the Kanto Mountains of central Honshu) terranes (Fig. 3). On the basis of similarities in litho- and bio-stratigraphy of Late Silurian to early Middle Devonian and Late Palaeozoic sedimentary series, as well as isotopic ages and petrochemistry of late Ordovician and Permian granitoids, parts of these terranes can be correlated (Ehiro *2000*; Hada et al. *2000*; Takagi and Arai *2003*; Kurihara *2004*; Kawajiri *2005*). Small and isolated outcrops of high-grade metamorphic rocks that yielded middle Cretaceous isotopic ages occurring in western Kyushu (Higo metamorphic complex, Fig. 3), western Shikoku (Oshima metamorphic rocks) and the Kanto Mountains (Yorii metamorphic rocks) are assigned to the Paleo-Ryoke terrane (Sakashima et al. *2003*; Takagi and Arai *2003*). Petrologically similar high-grade metamorphic complexes crop out in northern Kyushu (Sefuri metamorphic rocks), which Osanai et al. (*2006*) correlated to the Hida Gaien terrane (Fig. 3), and furthermore in the western part of the Abukuma metamorphic terrane, NE Honshu (Fig. 3; Takanuki series, Takagi and Arai *2003*; Sakashima et al. *2003*). Like the Kurosegawa terrane, metamorphic rocks of the Paleo-Ryoke terrane are covered by early Late Cretaceous clastic sedimentary series (Takagi and Arai *2003*, Fig. 2), and occur in the hanging wall of the Jurassic–Cretaceous subduction system.

The proto-Japan superterrane is fragmented and dispersed by strike-slip faulting and other tectonic movements since the early Cretaceous (Hada and Kurimoto *1990*; Aitchison et al. *1991*; Hara et al. *1992*; Maruyama et al. *1997*; Hada et al. *2001*; Kato and Saka *2003*; Takagi and Arai *2003*). As a result of this, elements of the superterrane occur in different tectonic positions, both in the Inner and Outer Zones (Fig. 3). The Hida Gaien terrane fringes the southern boundary of the Hida-Oki terrane. As outlined above, the Kurosegawa terrane is part of the klippe of the Inner Zone on top of the Outer Zone. The Paleo-Ryoke terrane also occurs in the Outer Zone, always to the north of the Kurosegawa terrane. In the Kanto Mountains, the Paleo-Ryoke terrane occurs in a number of klippes on the Sambagawa belt (Fig. 4 of Takagi and Arai *2003*), in part along a low-angle normal fault contact (Wallis et al. *1990*). On Shikoku, the contact between the Paleo-Ryoke terrane and the Sambagawa belt, which only crops out in the easternmost part of the island (Fig. 3) due to a deeper erosion level, is not exposed because of widespread Quarternary volcanic deposits. The South Kitakami terrane is bounded by Neogene (strike-slip) faults (Fig. 3).

Southward extension of Japanese terranes

The southernmost outcrops of the Suo metamorphic belt in the Inner Zone of Japan occur on the islands of Ishigaki and Iriomote (Tomuru formation; Nishimura *1998*), located near the southern tip of the Ryukyu Arc (Fig. 2). Faure et al. (*1998*) and Zamoras and Matsuoka (*2001*, *2004*) reasoned that the Jurassic subduction–accretion complex continues southward into Taiwan, but Ishiwatari and Tsujimori (*2003*) have argued against this. The eastern part of the Tananao metamorphic complex of eastern Taiwan (Fig. 2) comprises ocean floor rocks, such as metachert and Mn-rich rocks, greenstone, serpentinite and thick marble series (Wang-Lee *1979*), which likely represent a subduction–accretion complex, and furthermore granitic gneiss and schists. Although geochronologic and microfossil data are lacking, it seems probable that the Tananao complex is the extension of the Inner Zone of Japan. Like the Inner Zone, these rocks were intruded by late Cretaceous dominantly granodiorite to quartz monzonite that yielded U–Pb zircon crystallization ages ranging from 80 to 90 Ma (Jahn et al. *1986*), which are similarly related to westward subduction of oceanic lithosphere. The meaning of the granitic gneiss and schists is unclear, in Japan such rocks are principally found in the Hida-Oki terrane.

Farther to the south, the west central Philippines, that is the northern half of Palawan, the Calamian Islands, southwest Mindoro, northwest Panay and Tablas, comprises subduction–accretion complexes (Hamilton, *1979*; Zamoras and Matsuoka *2001*, *2004*). These are regarded as having formed along the East Asian continental margin to southwest of Taiwan as continuation of Tananao complex, starting in the Middle Jurassic (Zamoras and Matsuoka *2001*, *2004* and references therein). The easternmost of these subduction-accretion complexes has been correlated to the Southern Chichibu belt of the Outer Zone in Japan (Zamoras and Matsuoka *2001*).

Sakaigawa unit

We concentrated our dating effort on the Sakaigawa unit (Kurimoto *1993*), that forms a discontinuous <300 m wide zone of metamorphic psammitic, pelitic and siliceous schists that are associated with greenschists in the western Kii peninsula (Fig. 4). This rock association also occurs in a similar narrow band in the central and eastern part of the Kii peninsula (Kato et al. *2002*; Kato and Saka *2003*). The unit overlies the Jurassic rocks of the Northern Chichibu subduction–accretion complex (Fig. 4). The Sakaigawa unit is overlain by conglomerates with coarse-grained, upward fining sandstones of the Cretaceous Futakawa formation, along a slightly undulating, primary sedimentary contact (Fig. 4). The Sakaigawa unit is an element of the Chichibu composite terrane. This complex klippe-like composite terrane is presently separated from the Shimanto terrane, in the south, by the Butsuzo tectonic line (BTL) and from the Sambagawa and Mikabu belts, in the north, by the Aridagawa tectonic line (ATL) (Fig. 4). The architecture of the eastern Kii peninsula (Kato et al. *2002*) and western Shikoku (Matsuoka et al. *1998*) is similar. These generally steeply dipping fault zones, characterised by local fault gauges and cataclasites, truncate stacks of tectonic units and the thermal structure of the adjacent terranes (Hada *1967*; Kurimoto *1995*; Awan and Kimura *1996*). Deformed, non-metamorphic, probably Cretaceous sandstones and mudstones occur discontinuously along the ATL, sandwiched between the Northern Chichibu and Sambagawa belts (Hada *1967*; Kurimoto *1986*).

The Sakaigawa unit is dominated by light grey coloured, mica- and sometimes chlorite-bearing quartzites that have a well-developed platy tectonic foliation and a grain shape fabric.

These banded quartzites contain centimetre–decimetre thick intercalations of dark grey to black coloured quartz-rich phyllites, with numerous quartz veins parallel to the main tectonic foliation. Thicker phyllite series contain sometimes rounded pluri-metre scale lenses and boudins of quartzite. Up to 10-m thick layers of foliated and well lineated chlorite schists also occur, which may contain darker and coarser grained greenstones, locally with metapelite intercalations. The rocks contain lawsonite, chlorite, K-white mica, albite and stilpnomelane (Hada *1967*) pointing to very-low-grade, high-pressure metamorphism in a subduction–accretion complex, which agrees with the encountered lithologies.

The main tectonic foliation is characterised by a strong quartz-mica differentiation and wraps around isolated quartz lenses that often are fold hinges with pinched limbs. This foliation is sub-vertical to steeply southward dipping and contains a weakly to moderately W or E plunging mineral and stretching lineation (Fig. 4). This tectonic fabric is deformed by tight centimetre-scale folds with curvilinear axes and also by mesoscopic D_3 folds that are associated with steeply dipping, anastomosing faults. These faults form conjugate systems of steeply N and S dipping sets with a normal movement sense and an important strike-slip component indicated by moderately plunging slickenside striations.

The basal contact of the Cretaceous Futakawa formation is slightly oblique to the main foliation in the substratum and also cuts later cleavages. Currently this contact and Futakawa formation are steeply dipping or northward overturned. Locally, the contact is formed by steep faults with weakly plunging linear structures. The conglomerate contains unoriented, well-rounded to sub-rounded pebbles and cobbles. Most of these are grey cherts, as well as quartzites and phyllites that are probably derived from the Sakaigawa substratum. Subordinate components are substratum-derived greenschists, and in addition, epidote veined platy greenstones, dark-bluish green and reddish-purple quartzites and red jasper/chert, as well as rare thin bedded fine-grained carbonates, described from the substratum in the central and eastern Kii peninsula (Kato et al. *2002*; Kato and Saka *2003*). Other conspicuous components are autoclasts of coarse, pebbly sandstone. The matrix-supported, unsorted rocks contain fluidization channels and may therefore be deposited by mass-flows (e.g. Postma *1986*). These observations imply that the metamorphic recrystallisation and penetrative ductile deformation in the Sakaigawa unit are of pre-Cretaceous age and that a subduction–accretion complex was being eroded in Cretaceous time. Deposition of these brackish water or shallow marine clastic sediments occurred in a forearc basin (Kato and Saka *2003*). The steep dip of the unconformity and the local fault contact with the substratum point to syn to post-Cretaceous deformation that seems in part strike-slip related. This deformation, which may be related to major left-lateral Campanian–Maastrichtian strike-slip along the MTL, has profoundly modified the earlier klippe-like juxtaposition of the different subduction–accretion terranes in the Chichibu composite terrane.

We correlate the Sakaigawa unit with the Agekura and Ino units composed of similar rocks occurring in a comparable structural position in the classical Kurosegawa terrane on central Shikoku. Adachi (*1989*) reported Triassic radiolarians from the Ino unit; whereas Matsuda and Sato (*1979*) found Early Carboniferous to Late Permian conodonts in limestone. The Agekura unit is overlain by the Shirakidani unit (Table 1), comprising weakly to unmetamorphosed greenstone, sandstone, mudstone and limestone, which Isozaki and Itaya (*1991*) considered as equivalent to the weakly metamorphic Permian Akiyoshi subduction–accretion complex of the Inner Zone. The latter complex is closely related to the high-P/T metamorphic Suo belt (Nishimura *1998*). The Shirakidani unit, at its turn, is covered by serpentinites that enclose blocks of metamorphic rocks, including garnet–clinopyroxene granulites, glaucophane–lawsonite–pumpellyite and jadeite–quartz rocks with isotopic ages that are comparable to those of the Inner Zone (Isozaki and Itaya *1991*; Table 1).

A metapelite from the Sakaigawa unit yielded a 210 ± 5 Ma K–Ar whole-rock age (Kurimoto *1993*). The Agekura rocks contain muscovite with 175 − 230 Ma K–Ar ages (Isozaki and Itaya *1991*; Hara et al. *1992*). Dallmeyer et al. (*1995*) obtained strongly disturbed $^{40}Ar/^{39}Ar$ age spectra on two phyllites with progressively decreasing apparent ages from about 255 to 235 Ma for the most mica-rich main component in these whole-rock samples.

As indicated above, classically the very-low-grade metamorphic pelites of the Sakaigawa and Agekura units are regarded as northern limit of the Kurosegawa terrane (Kurimoto *1993*; Dallmeyer et al. (*1995*). Kato et al. (*2002*) and Kato and Saka (*2003*) assign comparable rocks on the central and eastern Kii peninsula to the Kurosegawa terrane too. However, we correlate the Sakaigawa unit with the Northern Chichibu terrane. In this we follow Yamakita (*1998*), who pointed out that the Permian subduction–accretion complex on Shikoku is not associated with typical Kurosegawa lithologies but with clastic rocks of Cretaceous age, like the Sakaigawa and Agekura units.

Samples and experimental procedures

We sampled five dark grey graphite-rich, quartzitic, very low-grade metamorphic pelites from the Sakaigawa unit. These have K-white mica, chlorite and quartz as main metamorphic minerals with minor albite. The samples possess a well-defined tectonic quartz–mica differentiation foliation that is not overprinted by younger penetrative ductile deformation or late stage brecciation related to strike-slip faulting. JK49 is taken from about 10 m below the Cretaceous unconformity and contains conspicuous millimetre-thick foliation parallel quartz laminae; JK57 is taken 4 m away from a breccia zone. The grain-size of the samples is too small for a successful mineral separation, hence, we isotopically dated whole-rocks instead following a procedure outlined by Ruffet et al. (*1991*, *1995*) and that is summarised below.

We obtained thin, 0.7 − 1.2 mm diameter fragments by handpicking the sieve fraction of five crushed phyllites under a binocular zoom microscope. Handpicking enabled selection of pristine whole-rock fragments without alteration or with too many quartz veins. Each fragment was thoroughly ultrasonically rinsed in distilled water and subsequently put in a 10 × 10 × 0.5 mm Al foil envelope. Envelopes were stacked in an irradiation canister together with aliquots of flux monitor hornblende HB3gr (K–Ar age: 1071.7 ± 5.4 Ma, Turner et al. *1971*), inserted after every eight to ten samples, which allowed to determine the flux gradient with a precision of ±0.2%. The total neutron flux density during irradiation in position 5C of the McMaster University research reactor (Hamilton, Canada), which lasted 149.92 h, was 9×10^{18} n × cm^{-2}. Fragments were step-heated at Géosciences Azur (CNRS-University of Nice) with a continuous, defocused, laser beam of a Coherent Innova 70-4 argon ion laser probe; fusion during the final step is achieved by beam focusing. The homogeneity of the energy distribution over a step-heated fragment was monitored by checking its hue with a joined video-binocular microscope system. Gas cleaning was achieved with a SAES GP10 getter pump and a cold trap. Argon isotopes were measured on a VG3600 noble-gas mass spectrometer equipped with a Daly photomultiplier. System blank values were determined at the beginning of an experiment and repeated typically after each third step and were subtracted from subsequent steps. Measured mass spectrometer Ar peak intensities were corrected for mass spectrometer discrimination (1.02797; measured from analysis of air Ar), radioactive decay of ^{39}Ar and ^{37}Ar and interference of Ca- and K-derived Ar isotopes. The

$(^{36}Ar/^{37}Ar)_{Ca}$, $(^{39}Ar/^{37}Ar)_{Ca}$ and $(^{40}Ar/^{39}Ar)_K$ correction factors used were 0.000279, 0.000706 and 0.0295, respectively. Errors are quoted at the 2σ level; step errors include analytical uncertainties only; the 2.15% uncertainty in the $^{40}Ar^*/^{39}Ar_K$ ratio of the monitor is propagated into the errors on integrated and pseudo-plateau ages. Decay constant and isotopic abundance ratios used: $^{40}K_{tot} = 5.543 \times 10^{-10}$ a^{-1}; $^{40}K/K = 0.01167$ atom % (Steiger and Jäger *1977*). We use the time scale of Gradstein et al. (*2004*) to compare isotopic and time stratigraphic ages.

Results

We performed $^{40}Ar/^{39}Ar$ laser step-heating analyses of small, single whole-rock fragments to ensure a thorough degassing over an extended energy range, aiming to separate gas fractions released by different constituents of these polymineralic assemblages. The $^{40}Ar/^{39}Ar$ analytical data are presented in Table 2, and depicted as age spectra with corresponding $^{37}Ar_{Ca}/^{39}Ar_K$ ratio spectra (Fig. 5; lower and upper panels, respectively), with $^{37}Ar_{Ca}/^{39}Ar_K$ being 0.459 × (CaO/K_2O).

The main degassing of $^{39}Ar_K$ and $^{40}Ar^*$ is strongly correlated; additional $^{36}Ar_{AIR}$ and $^{37}Ar_{Ca}$ release occurred in the high temperature steps (Table 2). $^{37}Ar_{Ca}/^{39}Ar_K$ ratios are slightly elevated during early degassing and sharply increase for the final ^{39}Ar release (Table 2; Fig. 5 upper panels). All samples yielded $^{40}Ar/^{39}Ar$ spectra with much younger apparent ages for the first laser increments (Fig. 5 lower panels). None of the samples met the strict plateau criteria, viz. 70% or more of the $^{39}Ar_K$ released in three or more contiguous steps, the apparent ages of which agree to within 2σ of the integrated age of the plateau segment. Yet, using the above criteria, pseudo-plateau ages could be calculated for flat sections of age spectra of three samples that corresponded to 49–63% of the released ^{39}Ar. The pseudo-plateau ages (2σ) obtained were 218.4 ± 0.4 Ma (JK09) in the eastern part of the unit, and almost concordant dates of 228.8 ± 0.9 Ma (JK57) and 231.9 ± 0.7 Ma (JK61) for the westernmost part (Figs. 4, 5). Two other samples from the eastern part of the unit (JK40 and JK47; Fig. 4) lack flat sections, but their apparent ages are between ca. 205 and 225 Ma, over 80–90% of the ^{39}Ar release (Fig. 5; Table 2).

Interpretation

Obviously, isotopic ages of polymineralic whole-rocks are only meaningful if radiogenic argon ($^{40}Ar^*$) of the original detrital minerals is completely outgassed during tectono-metamorphic recrystallisation (Dodson and Rex *1971*), as the influence of a very small, substantially older detrital component can be quite significant (Reuter and Dallmeyer *1989*). Resetting of detrital mica components is regarded to have completed during low-grade (epizonal) metamorphic conditions (Reuter and Dallmeyer *1989*), that is above 300–350°C (Leitch and McDougall *1979*; Hunziker et al. *1986*). In line with interpretations by Muecke et al. (*1988*), Dallmeyer and Nance (*1994*) or de Jong et al. (*2000*), we interpret the early $^{36}Ar_{AIR}$ and $^{37}Ar_{Ca}$ release, that is unrelated to that of $^{39}Ar_K$ and $^{40}Ar^*$, (Table 2) by the degassing of slightly weathered, carbonaceous and chlorite-rich material. The important $^{37}Ar_{Ca}$ release and elevated $^{37}Ar_{Ca}/^{39}Ar_K$ ratios for the final 5–15% of the degassing (Fig. 5, upper panels) may be due to the presence of detrital plagioclase. Apparently, detrital feldspars were strongly or completely outgassed during the main tectono-metamorphic recrystallisation as this Ca-rich component is not associated with much older ages. The main and correlated release of $^{39}Ar_K$ and $^{40}Ar^*$ is probably related to degassing of K-white mica as main component of the whole-rocks.

Part of the irregularities of the age spectra is probably due to the use of fine-grained material that is made up of minerals with a strong K-contrast between K-white mica on the one hand and K-poor minerals like chlorite and plagioclase on the other (Reuter and Dallmeyer *1989*). The potential energy of fast neutrons used during irradiation of such material may cause $^{39}Ar_K$ to recoil from a K-rich mineral into an adjacent K-poor mineral at the sub-microscopic scale (e.g. $^{39}Ar_K$ recoil distance = 0.08–0.16 µm; Turner and Cadogan *1974*; Onstott et al. *1995*). As chlorite and plagioclase degas before and after K-white mica, respectively (Reuter and Dallmeyer *1989*), young apparent ages during first steps (all samples) and final gas release (JK09 and JK57), may point to $^{39}Ar_K$ recoil into these K-poor components. The hump-shape displayed by older age steps just following the young apparent ages of the first 10% of ^{39}Ar release of samples JK09, JK57 and JK61, may represent degassing of the material that has lost $^{39}Ar_K$ by recoil. Recoil of $^{37}Ar_{Ca}$ (recoil distance about four times that of $^{39}Ar_K$; Onstott et al. *1995*) from a Ca-rich mineral to the first degassing components provides an alternative interpretation for the presence of carbonate amongst the earliest degassing, weathered material that is rich in $^{36}Ar_{AIR}$.

The strongly disturbed $^{40}Ar/^{39}Ar$ age spectra obtained Dallmeyer et al. (*1995*) on whole-rock phyllites of the Agekura unit (central Shikoku) have unrealistically young apparent ages (<150 Ma) for the first 20–25% of ^{39}Ar release. $^{39}Ar_K$ recoil from the most mica-rich main component to earlier degassing, less K-rich material would explain these young ages, and would raise the apparent ages for the main degassing to the observed 255–235 Ma values. The youngest apparent ages of about 235 Ma at the end of the trajectory of progressively decreasing apparent ages would thus be least affected by $^{39}Ar_K$ recoil and thus be the best age estimate, which is comparable to our results.

Despite the complexities of our age spectra, we interpret the 218, 229 and 232 Ma pseudo-plateau ages as geologically meaningful and dating the very-low-grade, high-P/T tectono-metamorphic recrystallisation in the Sakaigawa unit. These Ladinian–Carnian (late Middle to early Late Triassic) isotopic ages are comparable to those of the Agekura unit of the Outer Zone (Dallmeyer et al. *1995*) and the Suo belt of the Inner Zone (Table 1), including a 225 ± 4.8 Ma $^{40}Ar/^{39}Ar$ plateau age on phengite from the Tomuru formation on the southern Ryukyu Islands (Faure et al. *1988*). This confirms the correlation of the Sakaigawa unit with the Agekura unit on the one hand and with the Suo belt on the other.

Regional implications: Japanese Islands

The 218–232 Ma $^{40}Ar/^{39}Ar$ pseudo-plateau ages that we obtained in the Sakaigawa unit are not only comparable to isotopic ages in the Permian subduction–accretion complex in the Outer and Inner Zones of Japan, but also to the 250–235 Ma range of isotopic ages of the Hida-Oki terrane, as well as to the 245–225 Ma age assigned to the ultrahigh-pressure metamorphism in the Qinling-Dabie-Sulu suture (Hacker et al. *2004*) between the North and South China cratons. Extension of the latter suture zone to the Japanese islands through Korea (Maruyama and Seno *1986*; Sohma et al. *1990*; Isozaki *1997a*; Maruyama *1997*; Maruyama et al. *1997*; Oh *2006*; Osanai et al. *2006*; Tsujimori et al. *2006*; Ernst et al. *2007*; Oh and Kusky *2007*), where major Permian to Triassic tectono-metamorphic events are also recorded, is virtually the only model used to explain the medium pressure metamorphism in the Hida-Oki and Hida Gaien terranes. Recent reconstructions basically follow the scheme of Sohma et al. (*1990*) with only few, relatively minor modifications (Oh *2006*; Osanai et al. *2006*; Oh and Kusky *2007*).

Below we will elaborate on a new model in which the proto-Japan superterrane is regarded as a Permian magmatic arc that collided with the East Asian margin around Permian–Triassic boundary time, giving rise to the main metamorphism in the Hida-Oki terrane. Deep erosion of the collision zone shed detritus into trench fill sediments of the Jurassic subduction–accretion complexes.

Higo complex correlative of the Hida-Oki terrane and eastward extension of the Qinling-Dabie-Sulu suture

Osanai et al. (*2006*) and Oh and Kusky (*2007*) proposed to correlate the Qinling-Dabie-Sulu suture zone, through the southwestern Gyeonggi terrane in South Korea, with the Hida belt of central Japan passing via the Higo metamorphic complex of west-central Kyushu (Fig. 3). Isozaki (*1997a*) correlated the Takanuki series (Fig. 3) of the Abukuma metamorphic terrane of NE Honshu to the Hida belt. Isotopic data imply that such correlations may be incorrect.

The Higo metamorphic complex predominantly comprises a metasedimentary sequence that increases in grade structurally downwards from amphibolite-facies to granulite-facies, including ultrahigh-temperature sapphirine- or spinel-bearing types as blocks in peridotites (Sakashima et al. *2003*; Miyazaki *2004*; Osanai et al. *2006*). Migmatites and diatexites point to abundant partial melting in the highest-grade areas, accompanied by plutonic rocks (Miyazaki *2004*). A garnet–biotite–cordierite paragneiss yielded essentially concordant $^{238}U/^{206}Pb$ SHRIMP zircon ages in the 330–184 Ma range (33 out of 36 grains), whereas zircon rims defined a mean age of 116.5 ± 18.7 Ma (Sakashima et al. *2003*). On the basis of the latter age, the authors argued that the metamorphic recrystallisation of this sample was a Late Cretaceous event. They pointed out that the depositional age of the protolith should thus be younger than the youngest detrital zircon with an age of 184.4 ± 8.5 Ma (Early Jurassic). In addition, Sakashima et al. (*2003*) obtained $^{238}U/^{206}Pb$ SHRIMP ages of 110.4 ± 4.1 and 111.4 ± 2.7 Ma on zircon from the foliated Miyanohara tonalite, which had yielded a ca. of 211 Ma Sm–Nd hornblende, whole-rock isochron age (references in Osanai et al. *2006*). The failure to obtain correct mineral—whole-rock isochron ages on the Higo metamorphic complex that generally yielded Permo-Triassic Sm–Nd and Rb–Sr dates (see Table 1 in Osanai et al. *2006*) points to isotope disequilibrium between the coexisting minerals. Also the major and trace element sector zoning of garnets (Figs. 4, 5 of Osanai et al. *2006*) indicates nonequilibrated growth during prograde metamorphism in the complex.

The upper amphibolite-facies Takanuki series (Fig. 3) mainly comprise quartz–feldspar and pelitic paragneisses intruded by 90–110 Ma granitoids (Banno and Nakajima *1992*; Nakajima *1997*; Hiroi et al. *1998*). Zircons from metapelites yielded 280–200 Ma SHRIMP U–Pb ages (Hiroi et al. *1998*) that were interpreted as detrital ages. The authors regarded that these data indicate that the Takanuki series originated from continental shelf sediments deposited from earliest Jurassic time, and were affected by low-pressure high-temperature metamorphism that resulted in andalusite–sillimanite–cordierite assemblages at about 110 Ma.

It is striking that the youngest detrital zircons are younger than the main metamorphism in the Hida-Oki terrane. A probability distribution diagram (Fig. 7b of Sakashima et al. *2003*) shows that the overwhelming majority of the $^{238}U/^{206}Pb$ ages from cores of zircon grains from the garnet–biotite–cordierite paragneiss they dated span the 250 − 175 Ma range. This age range corresponds to the timing of the main metamorphism in the Hida-Oki terrane and the intrusion of Funatsu-type granitoids. This may imply that the Higo complex and Takanuki series are metamorphic equivalents of the Early Jurassic molasse-type deposits like the Kuruma or

Tetori groups, that is the erosional products of the Hida-Oki terrane, but not the terrane itself. Consequently, the Qinling-Dabie-Sulu suture zone would not extend to the Higo metamorphic complex as proposed by Osanai et al. (*2006*) and Oh and Kusky (*2007*). Such a correlation is furthermore highly unlikely for two tectonic reasons. This loop-like belt along the eastern margin of the North China craton marks the collisional suture with the Yangtze block of the South China craton, without specifying which Japanese rocks would belong to the latter craton. It is important to underline that the Higo metamorphic rocks and correlatives occur in a thin klippe on top of the Sambagawa belt, which would be difficult for a major structure that separates two lithospheric plates. Therefore, we follow Sakashima et al. (*2003*) and Takagi and Arai (*2003*) who correlated the Takanuki series to the Higo metamorphic complex, the latter being associated with the Paleo-Ryoke terrane, an element of the proto-Japan superterrane.

Tectonic position of the Hida-Oki terrane

In Isozaki and Itaya's *1991* model, progressive accretion of younger oceanic rocks took place below crystalline rocks of the Hida-Oki terrane, regarded as reworked Precambrian crust of the East Asian continental margin, formed by the South China craton (Isozaki *1997a*; Maruyama et al. *1997*), or the North China craton (Oh *2006*). However, Sm–Nd isotope systematics and SHRIMP and CHIME zircon and monazite ages showed that the Hida-Oki terrane is not a reworked Precambrian crustal segment and the protoliths of the Hida-Oki terrane's paragneisses were deposited in Carboniferous time in a sedimentary basin that did not have an important Precambrian crystalline basement. This would suggest that the sedimentary rocks of the Hida-Oki terrane were deposited on a strongly thinned continental or oceanic crust. The multiple age, Th and U zonation of some zircon and monazite grains point to a complex history before the early Triassic metamorphism (Suzuki and Adachi *1994*). The basin received detritus from Archaean (very minor), Palaeo- to Mesoproterozoic (dominant), as well as from Early and Late Palaeozoic sources (minor) (Shibata and Adachi *1974*; Suzuki and Adachi *1994*; Yamashita and Yanagi *1994*; Sano et al. *2000*; Tsutsumi et al. *2006*). It has been argued that the presence of both Neoarchaean and Palaeo- to Mesoproterozoic detrital material in the metasedimentary gneisses of the Hida-Oki terrane points to a mixed contribution from both the North and the South China cratons (Sano et al. *2000*; Tsutsumi et al. *2006*). Whole-rock geochemistry and Sr–Nd isotope systematics of metasediments of the Hida-Oki terrane corroborate this notion as these imply that their protoliths may have been derived from several terranes of varying age and geochemical composition (Kawano et al. *2006*). Although the presence of a Mesoproterozoic basement below the Hida belt cannot be excluded, Arakawa et al. (*2000*) interpreted 1.4–2.2 Ga Sm–Nd depleted mantle model ages of some paragneisses as inherited from their source rocks, such as the Yangtze block of the South China craton. However, the 750 − 650 Ma zircon signature of Neoproterozoic rifting that is widespread in the Yangtze block and constitutes its most useful fingerprint (Hacker et al. *2004*) has so far not been recognised in Hida-Oki rocks. This would suggest that the importance of the South China craton as source was limited. Sm–Nd isotope systematics of the Hida gneisses and Precambrian rocks of the North China craton are different (Arakawa et al. *2000*). This may suggest that the clastic sediments were not principally derived from the East Asian continents. This makes it also unlikely that the Qinling-Dabie-Sulu suture zone would continue to the Hida-Oki terrane. It is a distinct possibility that the clastic sediments of the Hida-Oki terrane were deposited in a deep marine continental margin of the proto-Japan superterrane and that some of the basaltic lavas represent accreted or imbricated parts of an oceanic basin bordering it. Pre-Devonian fossil flora and fauna of one of the elements of the proto-Japan superterrane, and the Kurosegawa terrane, have affinities with Australia, suggesting that it may have been Gondwana-derived (Yoshikura et al. *1990*; Aitchison et al. *1991*; Aitchison *1993*). Consequently, the possibility that Precambrian detritus in the Hida-Oki metasediments was Gondwana-derived has to be considered. It is striking that in spectra of mainly SHRIMP U–Pb ages in zircons of bedrock and detritus in sediments in Australia, New Zealand and other parts of East Gondwana (Veevers *2004*), data in the range of 750–650 Ma are virtually lacking.

Proto-Japan superterrane: Late Carboniferous–Permian magmatism and Triassic metamorphism

Compelling evidence has been produced that demonstrates that the South Kitakami terrane, as well as parts of the Kurosegawa, Hida Gaien and Paleo-Ryoke terranes that we have grouped as the proto-Japan superterrane were situated in an active continental margin, an immature volcanic arc and/or a back-arc basin in late Carboniferous and Permian time. Coarse-grained sandstones and conglomerates of Kurosegawa and South Kitakami occur as clastic wedges deposited by gravity flows in Permian off-shore muddy facies, overlying a Carboniferous series with a regional unconformity (Takeuchi *1994*; Hada et al. *2000*, *2001*; Yoshida and Machiyama *2004*). These clastic rocks contain abundant detritus of andesites, granites and their contact metamorphic aureoles and skarns, as well as silicic volcanic and hypabyssal rocks (Takeuchi *1994*; Hada et al. *2000*, *2001*; Yoshida and Machiyama *2004*). U–Pb zircon ages of granitic boulders derived from the magmatic arc fall within the range of stratigraphic ages for the conglomerates (Hada et al. *2000*; references in de Jong et al. *2006*). Sr–Nd isotope systematics of a garnet–biotite granodiorite pebble from Kurosegawa's middle Permian Kozaki formation (western Kyushu), which is comparable to the Usuginu conglomerate of the South Kitakami terrane, suggest a source rock in an intra-oceanic arc (Shimizu et al. *2000*). The Permian intrusive suites of the Paleo-Ryoke terrane are considered as the source of such clastic rocks in the South Kitakami and Kurosegawa terranes (Takagi and Arai *2003*). The Hida Gaien terrane experienced widespread, mainly felsic pyroclastic volcanism in the late Carboniferous and Permian, possibly in a back-arc basin (Takeuchi et al. 2004; Kawajiri *2005*).

At least, part of the terranes of the proto-Japan superterrane was affected by metamorphism in the Triassic. Metamorphic titanite from a tuff in the Siluro-Devonian volcano-sedimentary sequence of the Kurosegawa terrane in Shikoku yielded a U–Pb Concordia age of 210.5 ± 3.6 Ma (Hada et al. *2000*). Muscovite and biotite from the Unazuki schists of the Hida Gaien terrane yielded Rb–Sr ages in the 250 − 210 Ma range (references in: Banno and Nakajima *1992*; Dallmeyer and Takasu *1998*). The Unazuki schists principally comprise ferroan peraluminous metasedimentary rocks associated with well-bedded metamorphosed carbonates, which yielded Late Carboniferous bryozoa and foraminifera (Banno and Nakajima *1992*; Isozaki *1997a*, and references therein). Metamorphism has given rise to kyanite–sillimanite assemblages and some micaschists are chloritoid- and staurolite-bearing (Banno and Nakajima *1992*). Other chloritoid-bearing metamorphic assemblages have until now only been encountered in the Ryuhozan metamorphic rocks of the Paleo-Ryoke terrane on Kyushu (Sakashima et al. *2003*). The Ryuhozan series furthermore contain bedded limestone including Early to Middle Permian fusulinid fossils (Sakashima et al. *2003*, and references therein). Both the Unazuki and the Ryuhozan series did not form part of subduction–accretion complexes but are regarded as deposited in a continental shelf environment that was deformed and metamorphosed in the Triassic (Sohma et al. *1990*; Isozaki *1997a*; Nakajima *1997*; Takagi and Arai *2003*).

Triassic collision of the Proto-Japan superterrane

Since the work of Isozaki and Itaya (*1991*), subduction–accretion is envisaged to have occurred ocean ward of the Hida-Oki terrane. Most models do not take into account that the Suo belt, which yielded white mica with a 225 Ma $^{40}Ar/^{39}Ar$ plateau age, continues to the southernmost islands of the Ryukyu arc (Fig. 2; Faure et al. *1988*; Nishimura *1998*; Ishiwatari and Tsujimori *2003*). The rocks of the Suo belt must have accreted against some kind of margin, which could not have been the Hida-Oki terrane as this was undergoing deformation and metamorphism at about the same time. This is an indication that the Permian subduction–accretion complex continued far southward and formed against a margin that is independent of the North and South China cratons. We envisage that this tectonic entity was the proto-Japan superterrane (Figs. 6, 7). In pre-Cretaceous time, we position the proto-Japan superterrane between Hida-Oki terrane and the subduction–accretion complexes (Figs. 6, 7). Active subduction occurred along the southeastern margin of proto-Japan leading to formation of Permian subduction–accretion complexes (Akiyoshi, Maizuru and Ultra-Tamba terranes). Late Middle to early Late Triassic metamorphism not only affected the associated Suo belt, but also the Sakaigawa (Kii peninsula) and Agekura (Shikoku) units (Fig. 7a). Post Early Jurassic tectonic movements related to strike-slip displacements in the Hida Gaien belt, formation of the Jurassic to early Cretaceous subduction–accretion complexes and exhumation of the Cretaceous Sambagawa belt, and finally the strike-slip movement along the MTL, resulted in disruption of the palaeo-Pacific margin of proto-Japan. De Jong et al. (*2006*) argued that older subduction–accretion complexes like the Hayachine belt in the northern margin of South Kitakami terrane, and the Renge belt, which may contain fragments of the palaeo-Pacific ocean floor of Late Devonian age, and possibly as old as Cambrian (Oeyama ophiolite), had already accreted to the southeastern margin of the proto-Japan superterrane.

The late Permian to middle Triassic metamorphism in the Hida-Oki terrane may be related to the collision of the proto-Japan superterrane with East Asia's active margin along the Central Asian Orogenic Belt's extension (Fig. 6). The metamorphism that affected part of the proto-Japan superterrane in the Triassic, notably the Unazuki and the Ryuhozan series, may similarly be due to this collision. Proto-Japan was fringed by pre-Permian subduction–accretion complexes and high-pressure metamorphic belts and carried a Permian magmatic arc, all formed during subduction of palaeo-Pacific oceanic lithosphere below the micro-continent (Figs. 6, 7a). Kamada (*1989*) and Ehiro (*2002*) have shown that South Kitakami's Early Triassic series rests unconformably on Late Permian rocks with a basal conglomerate. The Triassic clastic wedges too were deposited by gravity flows with provenance from the west in a fan delta/submarine-fan sedimentary system that was developed in a margin parallel strike-slip fault zone (Kamada *1989*). Such coarse-grained clastic series may have been deposited in a foreland basin to the southeast of the collison zone. Large amounts of acidic to intermediate tuffs and volcaniclastic rocks in Late Triassic series of the South Kitakami terrane suggest continuing volcanism and/or exhumation of such rocks in the hinterland (Takeuchi *1994*). Also zircons from granitic pebbles in series of early Middle Jurassic age of the Kurosegawa terrane that yielded U–Pb ages of 204 ± 15 Ma (Hada et al. *2000*), suggest that magmatic activity related to subduction continued into the Late Triassic. Interestingly, also the Late Triassic Mine group, which overlies the Permian Akiyoshi subduction–accretion complex of the Inner Zone, records a change in detritus from sedimentary rocks derived from the immediate substratum to granulite- to amphibolite-facies metamorphic rocks, granitoid and skarn (Kametaka *1999*). This may point to erosion of a magmatic arc (Kametaka *1999*) and/or of exhumed regional metamorphic rocks of a collision zone situated to the north of the Palaeozoic subduction–accretion complex of the Inner Zone.

The position of the proto-Japan superterrane in the late Permian to middle Triassic, close to the South China craton at a palaeo-equatorial latitude in the palaeo-Pacific (Fig. 6a) is in agreement with reconstructions based on Middle Permian fusulinacean fossils (Kurosegawa terrane, Colania-Lepidolina territory; Hada et al. *2001*), Early to Middle Permian ammonoids (South Kitakami terrane; Ehiro et al. *2005*) and Early to Middle Permian rugose coral faunas that are comparable to those in South China but absent in North China (South Kitakami terrane; Wang et al. *2006*).

A geodynamic reconstruction introducing the proto-Japan superterrane relieves the somewhat forced efforts to correlate terranes in Korea and Japan. It specifically implies that the Qinling-Dabie-Sulu suture zone, the position of which is not resolved even in Korea, cf. Ernst et al. (*2007*) and Oh and Kusky (*2007*), does not continue to Japan, but joins the southern extension of the Central Asian Orogenic Belt (Fig. 6). The currently available time constraints do not permit to distinguish between the age of the collision of the Yangtze block with the North China craton, the main metamorphism in the Hida-Oki terrane, and the age of metamorphic recrystallisation in the Permian subduction–accretion complexes in Japan. Consequently, this reconstruction envisages that these events were essentially coeval, and in a way independent. The Hida-Oki terrane is thus not a backstop to the Japanese subduction–accretion complexes, but is a part of a complex collision zone between proto-Japan and East Asian margin. The complex and heterogeneous nature of the Hida-Oki terrane is particularly well illustrated by the geochemistry of amphibolite layers in paragneisses that points to formation in a within-plate setting not affected by a subduction zone, a continental margin affected by a subduction zone or a continental island arc, an island arc or a mid ocean ridge (Arakawa et al. *2000*, *2001*). Stacking of thrust slices with different provenance or even subduction–accretion could easily account for the diversity of these basaltic rocks of inferred Carboniferous to Permian age.

Jurassic exhumation and erosion of the collision zone

Takeuchi (*1994*) documented a fundamental change in the sources of sedimentary rocks around Triassic–Jurassic boundary time, not only in the South Kitakami terrane, but also in most other Japanese terranes. He interpreted the abundance of detrital chromian spinels and pyrope–almandine-rich garnets in Early Jurassic sandstones, in contrast to the pre-Jurassic deposits, as derived from eroding upper mantle peridotite and cumulate rocks of an island arc ophiolitic complex and a medium- to high-grade metamorphic belt. The Hida-Oki terrane is the only possible source of such rocks in Japan. In this respect, the occurrence of chloritoid in South Kitakami's Early Jurassic deposits is paramount, as this mineral was not formed during metamorphism of the pelites of the subduction–accretion complexes because they were too poor in Al. As already mentioned, chloritoid has only been encountered in ferroan peraluminous rocks of the proto-Japan superterrane, namely the Unazuki schists (Hida Gaien terrane) and the Ryuhozan schists (Paleo-Ryoke terrane). Middle to Late Jurassic clastic series of the South Kitakami terrane contain many pebbles of acidic volcanic and granitic rocks that are petrographically different from those found in Permo-Triassic conglomerates (Takeuchi *1994*), suggesting erosion of a Jurassic magmatic arc, of which Funatsu-type intrusions were part (Fig. 7b).

As indicated earlier, sandstones and conglomerate in trench fill deposits of the Japanese Jurassic subduction–accretion complexes demonstrate a substantial influx of granitic and metamorphic sources (Adachi and Suzuki *1994*; Tanaka and Adachi *1999*; Sano et al. *2000*; Okamoto et al. *2004*; Nutman et al. *2006*; Aoki et al. *2007*). Sano et al. (*2000*) favoured a mixed contribution from both the North and the South China cratons to explain the presence of both Neoarchaean and Palaeo- to Mesoproterozoic detrital material. On the basis of euhedral zircons without obvious inheritance that yielded a SHRIMP U–Pb date of 743 ± 17 Ma, Nutman et al. (*2006*) underlined the importance the South China craton as source area. However, the 250 and 220 Ma-old zircons (Sano et al. *2000*) and the youngest ca. 180 Ma-old monazite (Adachi and Suzuki *1994*) and 179.3 ± 12.1 Ma-old igneous zircons (Nutman et al. *2006*) could equally well point to erosion of the metamorphic rocks of the proto-Japan superterrane, and/or of the Hida-Oki terrane with Funatsu-type granitoids. Dallmeyer and Takasu (*1998*) suggested that pebbles of (sillimanite) gneisses, chloritoid-bearing phyllite and bedded limestone that occur in Jurassic trench fill sandstones of the Mino-Tamba-Ashio subduction–accretion terrane, may have been derived from the Hida-Oki terrane and the Unazuki schists.

We interpret this evolution as indicative of deep erosion of the collision zone between East Asia and the docked proto-Japan superterrane, of which the Hida-Oki terrane was an element (Figs. 6b, 7b). The occurrence of late Early Jurassic igneous material shows that this event took place during continued westward subduction of palaeo-Pacific oceanic lithosphere (Figs. 6b, 7b). During this process, the huge Jurassic subduction–accretion complex and the Funatsu-type granitoids, which show calc-alkaline chemical affinity indicating emplacement in a continental margin or continental arc environment (Arakawa et al. *2000*), were formed (Fig. 7b).

Permian to Triassic active margin in East Asia

To the south of the Ryukyu Arc of Japan, Jurassic subduction–accretion complexes occur as isolated belts, probably in Taiwan, the Philippines and Indonesia (e.g. Hamilton, *1979*; Zamoras and Matsuoka *2001*, *2004*; Wakita and Metcalfe *2005*, and references therein). The part of Taiwan located to the west of the subduction–accretion complexes (Tananao complex), belongs to the eastern margin of the South China craton (Figs. 1, 2). A peculiar feature of the craton is the ca. 1300 km-wide South China Indosinian Orogen that occupies its southeastern half (Xiao and He *2005*; Li and Li *2007*, and references therein). The southeastern part of the craton, the Cathaysia block, contains an extensive belt of granitoids that has been interpreted as a continental margin magmatic arc within which a granitic belt of Mesozoic and possibly Palaeozoic age was generated due to northwestward subduction of oceanic lithosphere (Jahn et al. *1976*; Li et al. *2006*). Syntectonic calc-alkaline I-type granites that yielded SHRIMP U–Pb zircon ages of 267 ± 3 and 262 ± 3 Ma (Li et al. *2006*) indicate that this arc was present at least as far south as Hainan Island (Figs. 2, 6a) in late Early Permian time. Also Vietnam experienced important Indosinian magmatism, high-temperature metamorphism and ductile deformation in the Late Permian to Early Triassic period (Lepvrier et al. *2004* and references therein).

South China

The South China craton is divided by the 2,000-km long northeast–southwest trending Jiangshan-Shaoxing fault zone into the northwestern Yangtze block and the southeastern Cathaysia block. The fault zone contains an ophiolitic mélange with blocks of ultramafic and mafic rocks, including basalt and blueschist (Zhao and Cawood *1999*; Xiao and He *2005*). On the basis of ca. 870–820 Ma isotopic ages for such rocks, the fault zone has been interpreted as a suture zone along which both blocks collided in the Neoproterozoic, forming the South China craton that remained a single entity thereafter (Zhao and Cawood *1999*).

Li and Li (*2007*) regarded the South China Indosinian Orogen, which was accompanied by granitoid intrusions of mainly Triassic age, as intracontinental. They presented a flat-slab model to explain the very broad nature of the belt, and the northwest migration of magmatism in time and space, from the coastal region (mid-Permian) to the interior (Late Triassic or Early Jurassic). They suggested that the transformation of a passive continental margin of the South China craton into an active one was triggered by the onset of its collision with the North China craton in the late Early Permian, that is around ca. 270 Ma (Fig. 6a). Faure et al. (*1998*) and Li (*1998*) explained Triassic deformation developed in the northern part of the South China craton up to 400 km to the south of the Dabieshan, by a far-field stress regime related to the collision with the North China craton.

The late Palaeozoic to early Mesozoic tectonic evolution of South China has also been discussed within the framework of accretion and collision of terranes in an archipelago palaeogeography similar to the present-day Southwest Pacific (Hsü *1994*; Xiao and He *2005*). The latter authors pointed out that a number of isotopical, micropalaeontological, sedimentological and structural data imply that the Cathaysian block on the one hand and the Yangtze block and the Lower Yangtze sub block on the other, were independent microplates in the late Palaeozoic to Early Triassic. In the first place, Neoproterozoic and younger sedimentary series of the Cathaysia block are disrupted along the Jiangshan–Shaoxing fault (Zhao and Cawood *1999*), and isotopic ages as young as Triassic have been reported (references in: Xiao and He *2005*). The latter authors underscored that Carboniferous to Late Permian fossils, including radiolaria in chert blocks in ophiolite mélange, occur in rocks of inferred Neoproterozoic age along this fault zone and associated faults. A gneissic granodiorite with island arc geochemical signature that occurs as fragment in a mélange, yielded zircons with a 242 ± 2 Ma U–Pb age (Kong et al. 1995, in: Xiao and He *2005*). The southeastern continental margin of the Yangtze block and Lower Yangtze sub block (Fig. 6a) formed a SE-facing continental margin that evolved from shallow marine condition, during most of the Permian, to a deep water environment through the Early Triassic (Xiao and He *2005*). Subsequently, a foreland fold-and-thrust belt developed in these continental margin series that is unconformably overlain by weakly deformed, Late Triassic continental, molasse-type deposits. Xiao and He (*2005*) emphasised that these observation can only be explained by regarding the Cathaysian block as a magmatic arc related to northwestward subduction of the Pacific plate in late Palaeozoic and Early Triassic times. The ophiolite mélange zones along the Jiangshan–Shaoxing fault and associated faults represent, in their view, the remnants of a back-arc basin, which was closed in mid-Triassic time. As a result of this, the Cathaysian arc collided with the Yangtze block and the Lower Yangtze sub block, leading to deformation of the sedimentary prisms of the continental margins of these blocks, before the Late Triassic. Xiao and He's tectonic model of the Cathaysian arc colliding with the Yangtze block is similar to our proposed model for the proto-Japan superterrane.

Indochina and Southeast Asia

The Jurassic subduction–accretion complexes of the west central parts of the Philippines (Zamoras and Matsuoka *2001*, *2004*) were grouped into the North Palawan block by Hamilton (*1979*). The nature of the Southeast Asian margin off Indochina between Palawan and the small oceanic basin of the South China Sea (Fig. 2) in the area of the Spratly Islands and Dangerous Grounds is not well known. This 400 km wide and 900 km long terrane ("Nansha block"), mostly shallower than 2 km, consist of thinned continental crust with a tilted fault block and horst block topography covered by thin Neogene sediments (Hamilton, *1979*; Morley *2002*; Yan and Liu *2004*). Locally occurring Mesozoic marine sediments, including

Late Triassic/Early Jurassic siltstone, shale and volcanic rocks, overlie an acoustic basement (Yan and Liu *2004*).

U–Pb zircon and $^{40}Ar/^{39}Ar$ mineral ages in Indochina span the ca. 260 − 240 Ma range (see Lepvrier et al. *2004* for a review). Relics of ca. 260 Ma-old ultrahigh-temperature metamorphism occur in the Kontum massif of central Vietnam (Owada et al. *2006*). The main Indosinian magmatism, high-temperature metamorphism and ductile deformation of Late Permian to Early Triassic age is usually explained as resulting from collision between Indochinan terranes and South China (Lepvrier et al. *2004* and references therein). In the light of the occurrence of late Palaeozoic to early Mesozoic magmatic arcs on microcontinental fragments that collided with the East Asian margin farther north, as discussed above, the docking of such an arc, like the Nansha continental block, with Southeast Asia's active margin during westward subduction of Pacific oceanic lithosphere below the amalgamated Indochinan terranes (Fig. 6), might have contributed equally well.

Miocene rifting concentrated in Permo-Triassic collision zones

The late Oligocene–Middle Miocene and younger back-arc basins of the Sea of Japan and the Okinawa trough (Kaneoka et al. *1996*; Maruyama et al. *1997*; van der Werff *2000*; Hall *2002*) coincide with the trace of the Hida-Oki terrane (Fig. 2). The continental crust of the Yamato Bank in the centre of the Sea of Japan rift may be a part of the Hida-Oki terrane (Kaneoka et al. *1996*). The South China Sea rift basin may similarly have formed in lithosphere affected by thickening during the Triassic "Indosinian" event. The most important extension in the area between the small oceanic basin of the South China Sea and Palawan including the Spratly Islands and Dangerous Grounds (Fig. 2) occurred during the Eocene–Oligocene (Morley *2002*). Due to rifting and subsequent seafloor spreading during the mid-Oligocene to early Miocene, which created the South China Sea (Hall *2002*; Morley *2002*, and references therein), the North Palawan block broke away from the East Asian continent, migrated southward and collided with the Philippine island arc system in the middle Miocene (Zamoras and Matsuoka *2004*, and references therein).

In a review, Cloetingh et al. (*2005*) pointed out that during rifting the weakest parts of the lithosphere will yield first once stress levels equate their strength. These authors underlined that lithological discontinuities that enhance the mechanical anisotropy of the lithosphere can weaken the strong upper part of the mantle-lithosphere of former orogenic belts. Compared to the crust of old stable cratonic areas, younger orogenic belts have a higher crustal thickness and an elevated heat flow; their strong upper parts of the crust are thus thinned and weakened. Moreover, former orogens contain deep-reaching crustal discontinuities, such as thrust- and strike-slip faults, which can further weaken the upper parts of the crust and can be tensionally reactivated. Former orogens, thus, constitute rheologically weak zones that can be preferentially reactivated during rifting. Hence, the stress exerted on the East Asian continental margin since middle Eocene time by slab pull forces generated by the subducting Pacific oceanic lithosphere (Hall *2002*) seems to have preferentially reactivated Permo-Triassic collision zones of the margin. This very mechanism is thus an argument in favour of the presence of collision zones along the East Asian continental margin formed around Permo-Triassic boundary times, and may have been the extension of the Central Asian Orogenic Belt into the circum-Pacific region.

Conclusions

The 218, 229 and 232 Ma $^{40}Ar/^{39}Ar$ pseudo-plateau ages date the very-low-grade high-pressure metamorphism in the Sakaigawa unit, which is part of the Permian subduction–accretion complex that continues to the southernmost part of the Ryukyu arc. This late Middle to early Late Triassic tectono-metamorphic event is virtually coeval with the main metamorphism in the Hida-Oki terrane and the docking of the North China and Yangtze cratons. The Hida-Oki terrane is not a backstop to the Japanese subduction–accretion complexes, but is part of a complex collision zone along the East Asian margin, which is considered as the southward extension of the Central Asian Orogenic Belt. The Japanese islands contain dispersed terranes that include fragments of a Permian island arc system with a basement of Early Palaeozoic igneous and metasedimentary rocks. These terrane fragments have been grouped into the proto-Japan superterrane, also situated in the extension of the Central Asian Orogenic Belt. The main metamorphism in the Hida-Oki terrane occurred during the collision of the proto-Japan superterrane with the East Asian active margin. Subduction–accretion and metamorphism of the Sakaigawa unit took place on the Pacific side of the proto-Japan superterrane, during and following this collision.

The concept of the proto-Japan superterrane implies that the Qinling-Dabie-Sulu suture zone did not continue to Japan, but joined the Central Asian Orogenic Belt to the east of the North China craton. It is possible that this orogenic system continued farther to the south via Taiwan and the Cathaysia block in China to Indochina. The Late Permian to Middle Triassic Indosinian thermo-tectonic event might, consequently, also be due to docking of Pacific-derived terranes with Southeast Asia's continental margin.

Major implications of this model are that (1) early Palaeozoic subduction–accretion complexes formed alongside the proto-Japan superterrane, before it collided with East Asia, and (2) only Jurassic and younger rocks derived from subducted Pacific plates directly accreted to the East Eurasian margin and received detritus from the earlier docked proto-Japan superterrane, the exhumed and deeply eroding Hida-Oki collision belt and Eurasia's eastern margin.

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Figures

Fig. 1 Tectonic sketch map of Central and East Asia (modified after de Jong et al. *2006*). The Central Asian Orogenic Belt has a *dark shading*; cratons have a *light hatching*; Kazakhstan, a composite continent or a terrane assemblage formed by amalgamated microcontinental fragments with Proterozoic basement and volcanic arcs, separated by Palaeozoic subduction–accretion complexes (Windley et al. *2007*; Cocks and Torsvik *2007*), is not distinguished from the Central Asian Orogenic Belt. HO, Hida-Oki terrane that may be the prolongation of the Central Asian Orogenic Belt into the Pacific region. *Thick lines*, main subduction zones fringing the eastern margin of the Eurasian continent. Strings of dots, Solonker zone

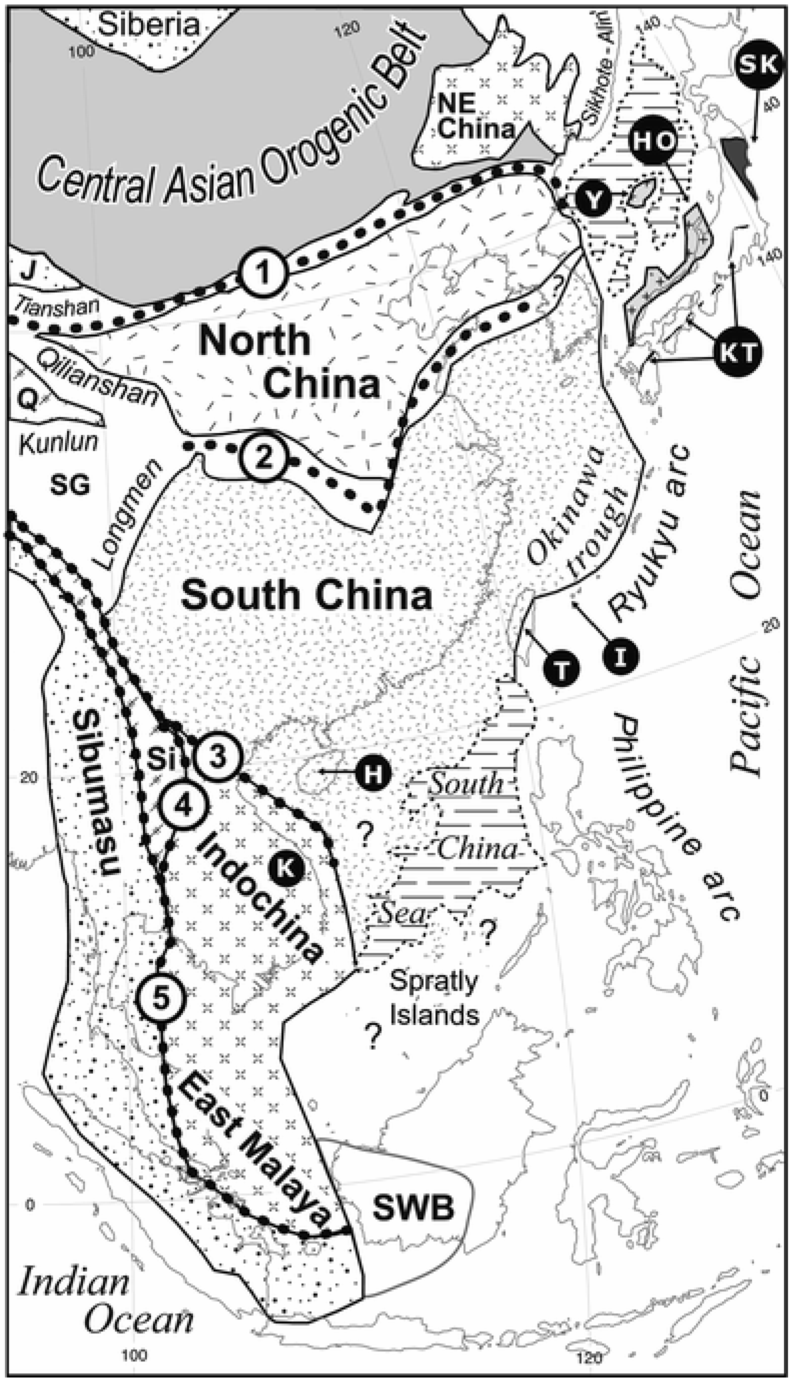

Fig. 2 Tectonic map of East and Southeast Asia. Main terranes, the Central Asian Orogenic Belt, modified after de Jong et al. (*2006*); Gondwana-derived continental terranes, subduction-accretion complexes and suture zone in Southeast Asia, modified after Wakita and Metcalfe (*2005*); extension of the Qinling-Dabie-Sulu suture zone into the Korean Peninsula after Oh (*2006*). *H* Hainan, *HO* Hida-Oki terrane, *I* Ishigaki and Iriomote islands, *J* Jungar terrane, *K* Kontum massif, *KT* Kurosegawa terrane (simplified), *Q* Qaidam terrane, *SG* Songpan Ganzi subduction–accretion complex, *SK* South Kitakami terrane and correlatives of the Abukuma metamorphic terrane, *SWB* Southwest Borneo terrane, *T* Taiwan, *Y* Yamato Bank. Main sutures (*strings of dots*): *1* Solonker zone, *2* Qinling-Dabie-Sulu belt and possible correlatives on the Korean peninsula, *3* Ailaoshan–Song Ma zone, *4* Nan-Uttaradit zone, *5* Lancangjiang–Changning-Menglian–Chiang Mai–Sra Kaeo–Bentong Raub zone (Palaeo-Tethys Main Suture zone). Azimuthal equal-area projection

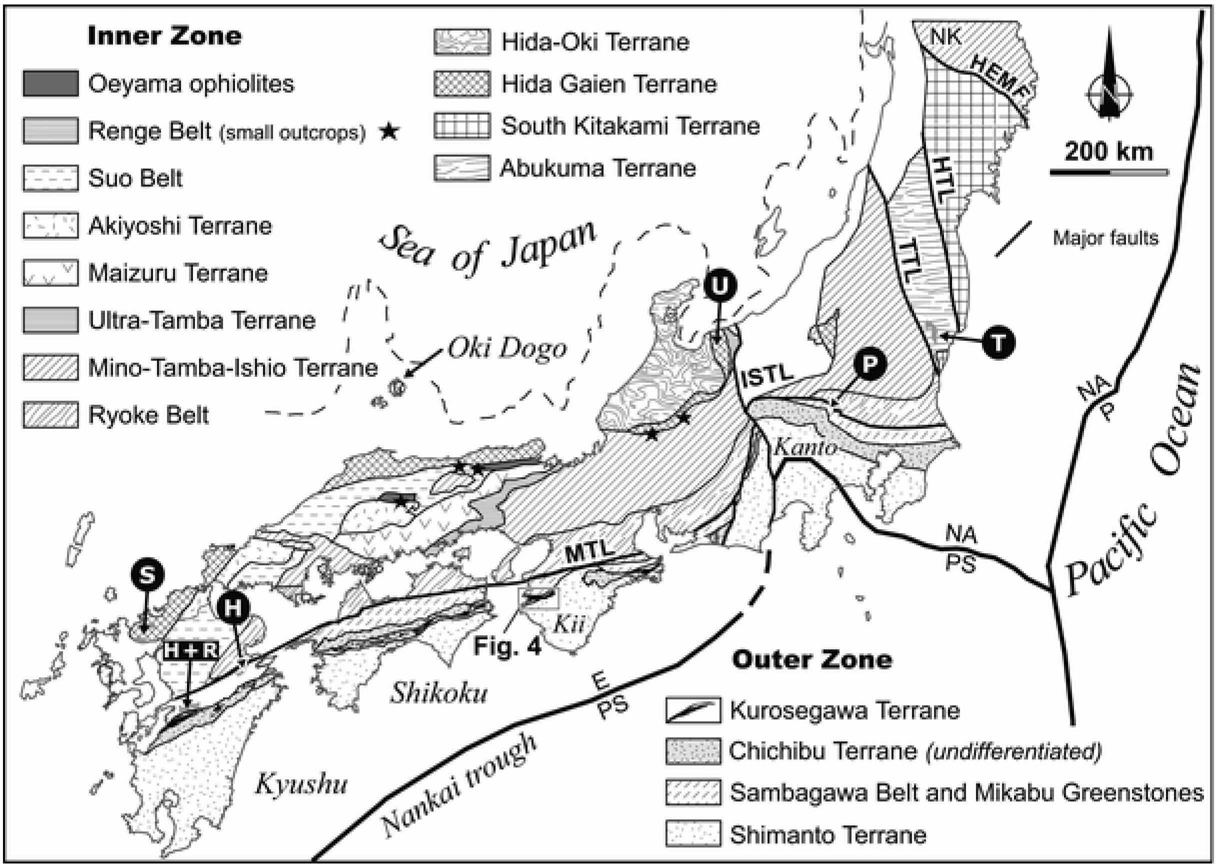

Fig. 3 Tectonic sketch map of Japan, compiled using the 1:1,000,000 map sheets of the 1995 on-line version of the geological atlas of the Geological Survey of Japan (http://www.aist.go.jp/GSJ/PSV/Map/mapIndex.html), with modifications after Nishimura (*1998*), Kato and Saka (*2003*), Takagi and Arai (*2003*), Ishiwatari and Tsujimori (*2003*), Tsukada et al. (*2004*), Tsujimori and Liou (*2005*). The high-grade to ultrahigh-grade metamorphic Sefuri (*S*) and Higo (*H*) rocks and the peraluminous Unazuki (*U*) and Ryuhozan (*R*) meta-sediments occur associated with the Hida Gaien and Paleo-Ryoke terranes, respectively; (*T*) Takanuki paragneisses. The Paleo-Ryoke terrane occurs as scatted outcrops (P and R), generally in a zone running just north of the Kurosegawa terrane. *HEMF* Hayachine Eastern Marginal Fault, *HTL* Hatagawa Tectonic Line, *ISTL* Itoigawa-Shizuoka Tectonic Line, *MTL* Median Tectonic Line, *TTL* Tankura Tectonic Line, *NK* North Kitakami, *O* Oki-Dogo Island. Ryukyu Islands (see Fig. 2) with local outcrops of Palaeozoic rocks, northernmost Honshu and Hokkaido are omitted for simplicity. *Dashed line* northern margin of the continental shelf of Japan (500 m depth). *E–PS* boundary of the Eurasian and Philippine Sea plates, *NA–P* boundary of the North American and Pacific plates, *NA–PS* boundary of the North American and Philippine Sea plates. The location of Fig. 4, the geological map of the western Kii peninsula where the samples were taken, is outlined

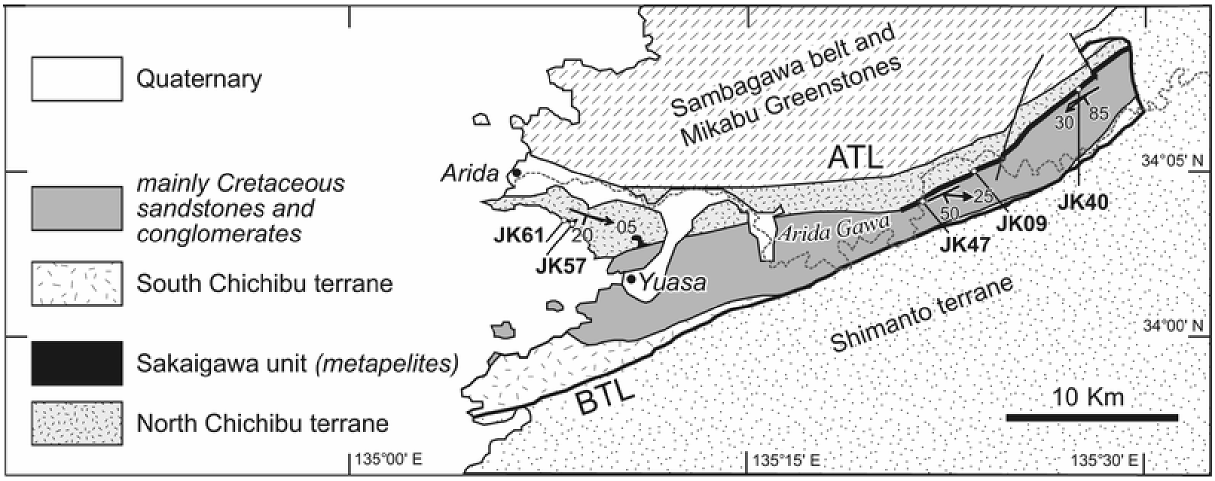

Fig. 4 Geological map of the northern Wakayama Prefecture, western Kii peninsula (modified after de Jong et al. *2000*) with the location of the dated samples and representative main phase foliation and lineations. The principal tectonic units are separated by major fault zones: Aridagawa Tectonic Line (*ATL*) and Butsuzo Tectonic Line (*BTL*), indicated by *thick lines*

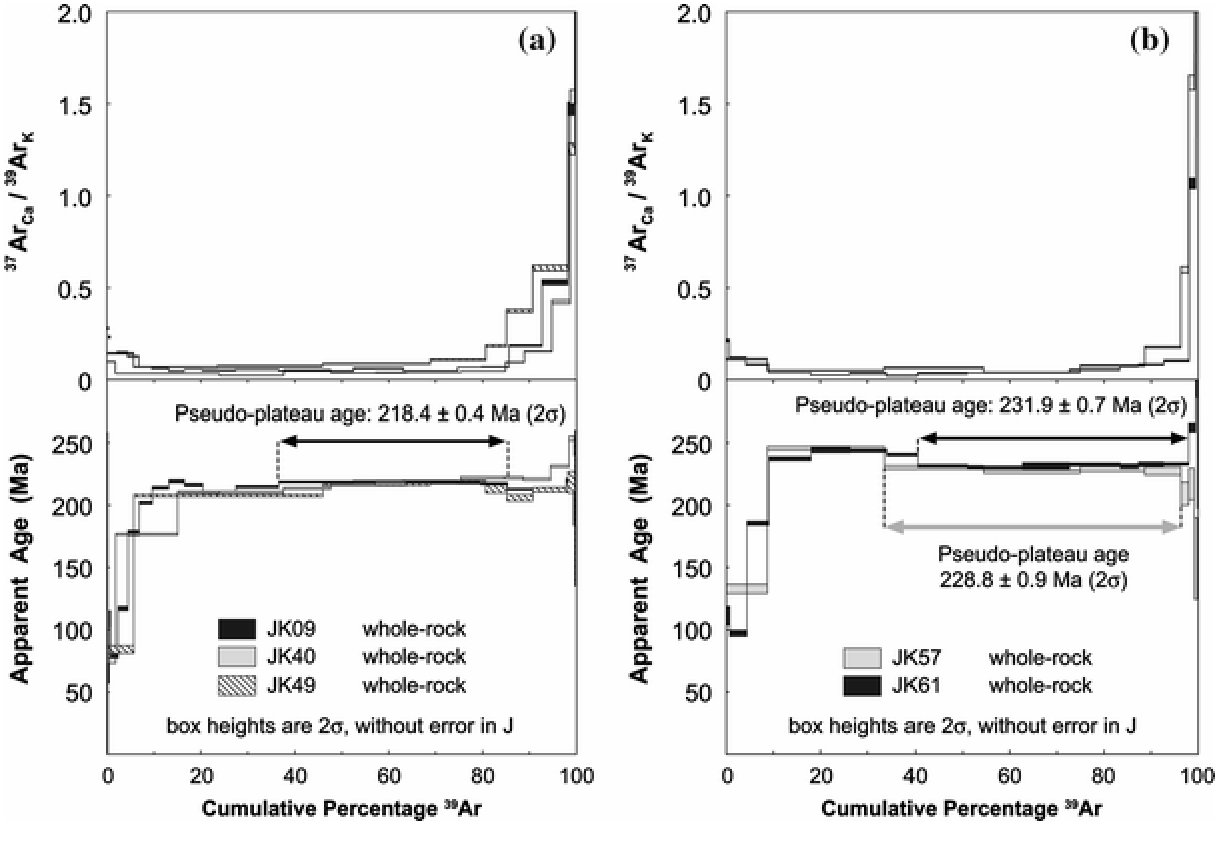

Fig. 5 $^{40}Ar/^{39}Ar$ age spectra (lower panels) and $^{37}Ar_{Ca}/^{39}Ar_K$ ratio spectra (upper panels) of whole-rock metapelites from: **a** the main outcrop of the Sakaigawa unit; **b** the westernmost isolated outcrop. The pseudo-plateau ages have errors quoted at 2σ and correspond to 49.0% of ^{39}Ar release in five steps for JK09; 62.7% in four steps for JK57; 57.6% in seven steps for JK61

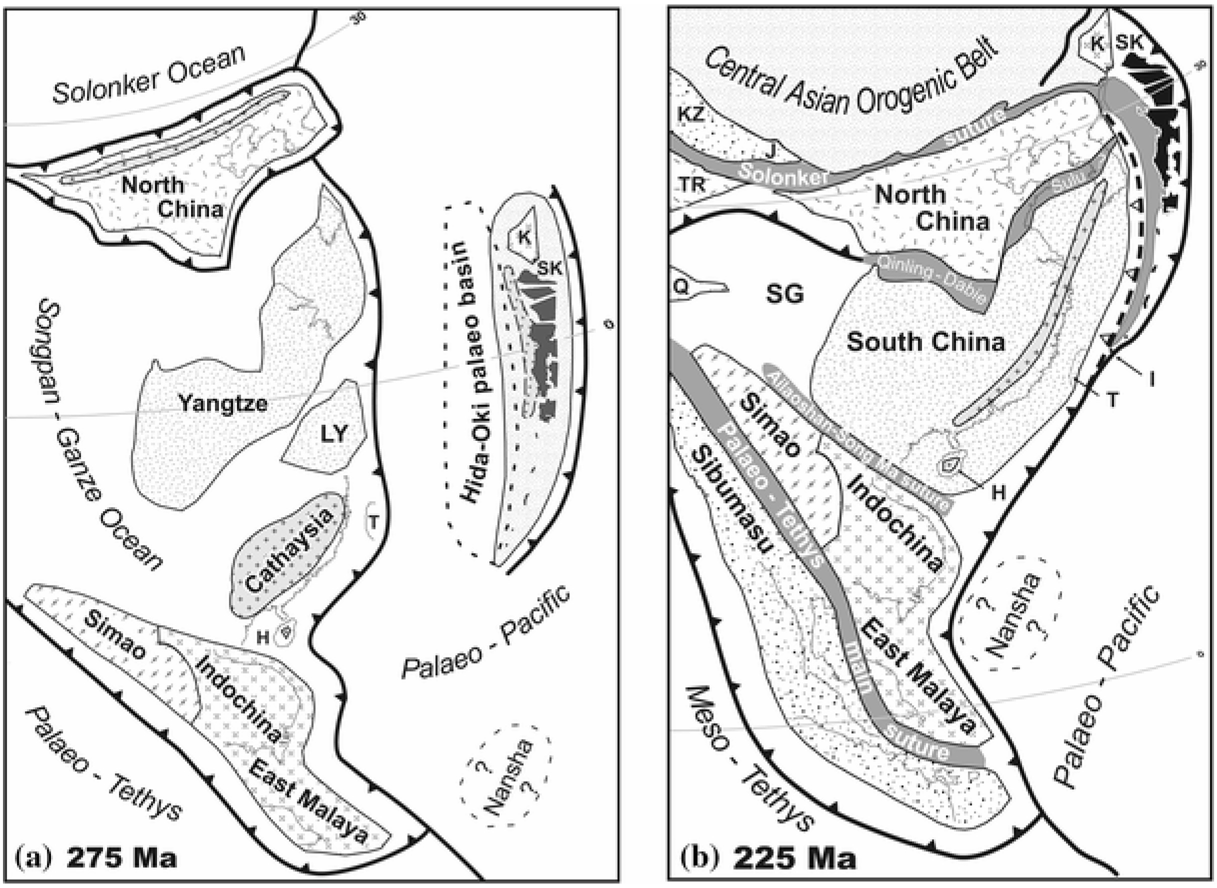

Fig. 6 Cartoons showing the late Palaeozoic plate tectonic evolution of East and Southeast Asia. **a** Highly schematic representation of proto-Japan as micro-continent with a magmatic arc along its western margin in the late Early Permian (around 275 Ma; Artinskian-Kungurian). The Hida-Oki terrane is envisaged as a sedimentary basin bordering proto-Japan and separated from the Yangtze block, Lower Yangtze sub block and Cathaysia arc (after Xiao and He *2005*) by a subduction zone; Permian granitoids in Hainan and South China, after Li et al. (*2006*). **b** Position of major lithosperic plates in the Late Triassic (around 225 Ma; Carnian). Most terranes and cratons had been sutured by this time (Hacker et al. *2004*; Lepvrier et al. *2004*; Wakita and Metcalfe *2005*; Oh *2006*). *Open triangles* indicate cessation of subduction and suturing of the proto-Japan superterrane at that time. Triassic granitoid belt in the South China craton, after Maruyama et al. (*1997*) and Li et al. (*2006*), which may continue into Vietnam, is the result of westward subduction of Palaeo-Pacific oceanic lithosphere below the amalgamated terranes of Southeast Asia. The proto-Japan terrane occurs to the east of the Hida belt; the northern part of proto-Japan is subdivided along post-Miocene strike-slip faults; the Khanka terrane (*K*) of the Russian Far East may have been associated with proto-Japan. The southernmost outcrops of the mainly Triassic Suo metamorphic belt are on Ishigaki and Iriomote Islands (*I*). Collision of the hypothetical Nansha block may have provoked part of the Indosinian events in Indochina. *H* Hainan, *J* Jungar terrane, *KZ* Kazakhstan terrane, *LY* Lower Yangtze block, *Q* Qaidam terrane, *SG* Songpan Ganzi subduction–accretion complex, *SK* South Kitakami terrane and correlatives of the Abukuma metamorphic terrane, *T* Taiwan, *TR* Tarim craton. Palaeo-lattitudes for reference only

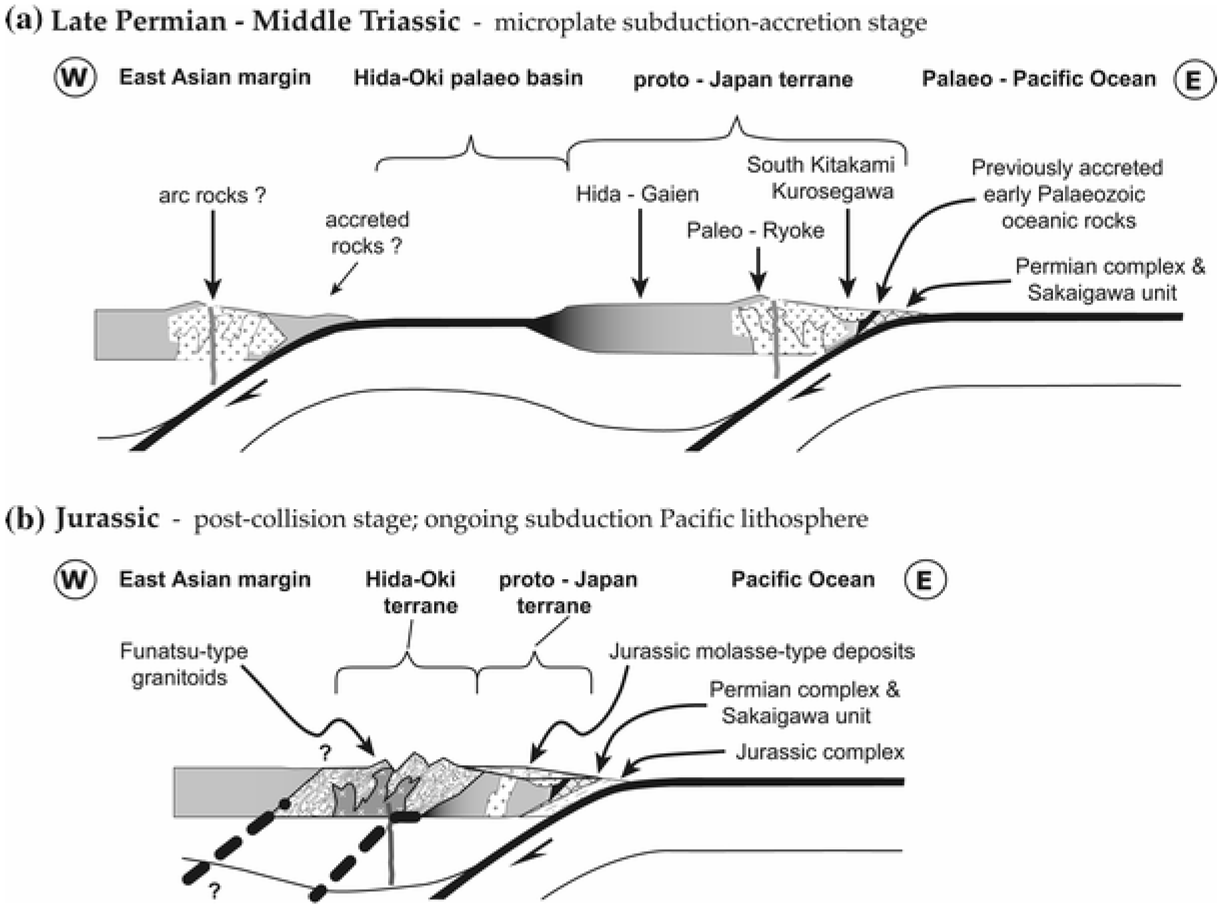

Fig. 7 Cartoon-like profiles in the present-day geographic reference frame illustrating the tectonic evolution of the proto-Japan superterrane situated in the extension of the Central Asian Orogenic Belt along of the eastern margin of East Asia in late Palaeozoic and early Mesozoic times. **a** In the late Permian to middle Triassic the proto-Japan superterrane was situated between the Hida-Oki terrane on its northwestern margin and the Permian Akiyoshi, Maizuru and Ultra-Tamba subduction–accretion complexes and associated late Middle to early Late Triassic Suo, Sakaigawa and Agekura metamorphic belts along its southeastern margin. The subduction–accretion complexes, metamorphic belts and the Permian magmatic arc of Proto-Japan were formed during subduction of palaeo-Pacific oceanic lithosphere below the micro-continent. The late Permian to middle Triassic metamorphism in the Hida-Oki terrane may be related to proto-Japan's collision with East Asia's active margin. The pre-Permian subduction–accretion complexes and high-pressure metamorphic belts had already accreted to the southeastern margin of the proto-Japan superterrane during earlier events. **b** Deep erosion of the collisional zone (Hida-Oki terrane) between the proto-Japan superterrane and the East Eurasian margin in the Jurassic. Clastic sediments (Early Jurassic Kuruma Group, Hida-Oki terrane) were deposited in a fore-arc and comparable rocks as trench fill deposits in the Jurassic complex. Westward subduction of palaeo-Pacific oceanic lithosphere continued, forming the Jurassic subduction–accretion complex and a continental margin arc (Funatsu-type suite)

Tables

Table 1 Correlation of tectonic units in the Outer and Inner Zones of Japan on central Shikoku, which are separated by the Median Tectonic Line

Inner Zone

Belt / Terrane	Characteristics	isotopic age (Ma)
Hida Gaien	Gneisses; high-grade to ultra-high-grade metamorphic rocks (Sefuri rocks); Al-rich metasediments (Unazuki schists)	mainly 220-250; K-Ar mica
Oeyama ophiolite	High-P/T metamorphic ophiolite belt	Ca. 560 Sm-Nd isochron gabbro dyke; Ca. 470 SHRIMP U-Pb zircon glaucophane schist block in serpentinite mélange
Renge	High-P/T metamorphic belt	280-330; K-Ar mica
Akiyoshi	Permian subduction-accretion complex	
Suo	Middle-Late Permian subduction-accretion complex High-P/T metamorphic	200-240; K-Ar mica
Maizuru	Late Permian subduction-accretion complex	Yakuno gabbro 280-285 Ma; U-Pb zircon
Ultra Tamba	Late Permian subduction-accretion complex	
Mino-Tamba-Ashio	Jurassic subduction-accretion complex; southern part affected by Cretaceous magmatism and low-P/T metamorphism (Ryoke belt)	

MEDIAN TECTONIC LINE

Outer Zone

Belt / Terrane		Characteristics	isotopic age (Ma)
KUROSEGAWA TERRANE	**Serpentinite unit**	Serpentinite mélange with various blocks Siluro-Devonian sediments	
		Late Ordovician to Silurian granitoids and metamorphic rocks	400-445; K-Ar, Ar/Ar mica
		High-P/T metamorphic rocks	315-380; 210-240; K-Ar mica
	Shirakidani unit	Unmetamorphosed to very-low-grade metamorphic pelites and greenstones	
	Agekura unit	Very-low-grade to low-grade metamorphic pelites and greenstones	175-230; K-Ar, Ar/Ar mica
North Chichibu		Jurassic subduction-accretion complex Unmetamorphosed to very-low-grade metamorphic	

Modified after Isozaki (*1997a*, *b*), Nakajima (*1997*), Nishimura (*1998*), Takagi and Arai (*2003*), and de Jong et al. (*2006*)

Table 2 $^{40}Ar/^{39}Ar$ analytical data of quartz-rich whole-rock metapelites from the Sakaigawa unit, northern Wakayama prefecture, western Kii Peninsula

JK 09	**J factor: 0.03694458**				
Step #	**Atm. contam. (%)**	**$^{39}Ar_K$ (%)**	**$^{37}Ar_{Ca}/^{39}Ar_K$**	**$^{40}Ar^*/^{39}Ar_K$**	**Apparent age (Ma)**
1	50.927	0.02	0.000	1.318	85.6 ± 172.0
2	47.609	0.26	0.276	1.046	68.3 ± 8.9
3	18.074	0.35	0.229	1.706	110.1 ± 6.6
4	11.081	1.54	0.144	1.239	80.7 ± 1.4
5	5.875	2.14	0.148	1.840	118.5 ± 1.8
6	3.155	2.46	0.123	2.812	178.1 ± 2.2
7	1.447	2.79	0.068	3.211	201.9 ± 1.0
6	1.095	3.55	0.060	3.415	214.1 ± 1.1
9	1.214	3.28	0.044	3.499	219.0 ± 1.3
10	1.354	3.90	0.054	3.452	216.3 ± 1.2
11	0.866	7.09	0.048	3.343	209.8 ± 1.0
12	0.567	9.21	0.053	3.427	214.8 ± 0.9
13	0.579	15.94	0.045	3.488	218.4 ± 0.7
14	0.688	10.56	0.061	3.496	218.8 ± 0.8
15	0.507	11.70	0.047	3.498	218.9 ± 0.8
16	0.908	5.06	0.066	3.480	217.9 ± 1.0
17	0.737	5.77	0.069	3.468	217.2 ± 0.9
18	0.729	7.07	0.182	3.391	212.7 ± 0.7
19	1.084	5.49	0.526	3.403	213.4 ± 0.9
20	1.750	1.57	1.466	3.505	219.4 ± 2.0
21	8.277	0.25	6.461	3.214	202.1 ± 17.9
				Integrated age	210.2 ± 0.3

JK 40	**J factor: 0.03689923**				
1	30.615	1.71	0.097	1.184	77.1 ± 2.2
2	5.834	13.27	0.031	2.794	177.0 ± 0.8
3	1.238	8.92	0.031	3.352	210.3 ± 0.8
4	1.342	13.67	0.021	3.349	210.2 ± 0.8
5	1.791	10.01	0.049	3.406	213.5 ± 0.9
6	1.339	9.53	0.034	3.459	216.6 ± 0.8
7	1.480	6.55	0.037	3.472	217.4 ± 1.0
6	1.415	11.69	0.038	3.484	218.1 ± 0.8
9	1.176	9.40	0.042	3.549	221.9 ± 1.0
10	0.851	4.06	0.092	3.549	221.9 ± 1.0
11	1.778	5.87	0.153	3.527	220.6 ± 1.0

JK 40	**J factor: 0.03689923**				
12	1.281	3.82	0.422	3.701	230.9 ± 1.0
13	3.268	1.19	1.532	4.080	252.9 ± 1.9
14	11.488	0.31	3.488	3.980	247.2 ± 7.9
				Integrated age	209.6 ± 0.3

JK 49	**J factor: 0.03701197**				
Step #	**Atm. contam. (%)**	**$^{39}Ar_K$ (%)**	**$^{37}Ar_{Ca}/^{39}Ar_K$**	**$^{40}Ar^*/^{39}Ar_K$**	**Apparent age (Ma)**
1	26.183	5.65	0.141	1.323	85. 9 ± 3.0
2	2.135	17.95	0.070	3.307	207.7 ± 1.0
3	1.120	22.33	0.075	3.308	207.7 ± 1.1
4	0.590	23.04	0.085	3.457	216.5 ± 0.9
5	0.350	11.86	0.106	3.488	218.3 ± 1.5
6	2.836	4.39	0.180	3.393	212.8 ± 3.1
7	3.649	5.57	0.371	3.276	205.8 ± 2.6
6	2.784	7.58	0.603	3.384	212.2 ± 1.8
9	2.119	1.38	1.250	3.483	218.1 ± 8.5
10	19.188	0.24	6.283	3.141	197.8 ± 61.7
				Integrated age	204.9 ± 0.5

JK 57	**J factor: 0.03692105**				
1	34.058	8.74	0.106	2.094	134.2 ± 3.6
2	3.125	24.86	0.045	3.955	245.7 ± 1.4
3	1.307	20.84	0.060	3.697	230.6 ± 1.5
4	1.711	20.54	0.033	3.637	227.1 ± 1.3
5	1.517	13.70	0.074	3.674	229.3 ± 1.9
6	1.990	7.65	0.170	3.643	227.5 ± 3.2
7	11.952	1.70	0.590	3.337	209.5 ± 9.1
6	10.322	1.27	1.606	3.473	217.5 ± 12.4
9	37.879	0.49	3.672	2.489	158.5 ± 32.2
10	8.875	0.19	8.227	3.945	245.1 ± 46.9
11	58.080	0.04	10.746	3.709	231.4 ± 599.2
				Integrated age	224.2 ± 0.8

JK 61	**J factor: 0.03687240**				
1	47.196	0.75	0.21	1.754	113.1 ± 7.5
2	13.574	3.53	0.12	1.534	99.3 ± 2.4
3	3.737	4.77	0.08	2.949	186.3 ± 1.5
4	1.675	8.97	0.03	3.814	237.5 ± 1.5
5	0.663	8.25	0.02	3.934	244.5 ± 2.3

JK 61	**J factor: 0.03687240**				
6	0.307	7.77	0.03	3.922	243.8 ± 1.3
7	0.100	6.40	0.02	3.863	240.3 ± 1.2
6	0.190	10.54	0.03	3.717	231.8 ± 1.0
9	0.320	11.72	0.03	3.695	230.5 ± 0.9
10	0.000	10.00	0.03	3.714	231.6 ± 2.6
11	0.503	10.72	0.05	3.733	232.8 ± 1.2
12	1.758	3.97	0.07	3.712	231.5 ± 2.0
13	1.394	5.29	0.08	3.737	233.0 ± 1.7
14	1.307	5.40	0.10	3.742	233.3 ± 1.1
15	0.000	1.43	1.06	4.235	261.9 ± 3.7
16	3.612	0.50	3.60	4.938	301.9 ± 16.7
				Integrated age	228.2 ± 0.5

^{40}Ar* is radiogenic argon from natural K-decay; ^{37}Ar and ^{39}Ar are Ca- and K-derived argon during irradiation. $^{37}Ar_{Ca}/^{39}Ar_{K}$ = 0.459 × (CaO/K_2O)