2b Pre-Cretaceous accretionary complexes

SATORU KOJIMA, YASUTAKA HAYASAKA, YOSHIKUNI HIROI, ATSUSHI MATSUOKA, HIROYOSHI SANO, YOSHIAKI SUGAMORI, NORITOSHI SUZUKI, SHIZUO TAKEMURA, TATSUKI TSUJIMORI & TAKAYUKI UCHINO

Accretionary complexes (AC) form at convergent plate margins by the subduction of oceanic plate underneath the continental plate (Fig. 2b.1). The oceanic plate is created at the mid-oceanic ridge, and moves to the trench while accumulating pelagic sediments. After arriving at the trench, where the pelagic sediments are covered by continent-derived clastic materials, the plate is subducted and part of the sediments accrete to the continental plate, producing fault stacking and several types of mélanges (Fig. 2b.1). The characteristic AC succession reflects the ocean plate stratigraphy (OPS) (Matsuda & Isozaki 1991) starting with basaltic basement covered by radiolarian ribbon chert, then siliceous mudstone and finally coarse clastic rocks.

A major part of the pre-Cretaceous basement rocks of Honshu and Shikoku consists of ACs and their metamorphic equivalents (Fig. 2b.2). The fundamental process underlying the origin of these rocks has been the subduction of oceanic plates from the SE (present direction), so that the ACs become younger from NW to SE (from upper to lower structural plate), although fold structures with a NW-dipping enveloping surface partly disturb the regularity. The accretionary process has been somewhat episodic, producing mainly Permian (Akiyoshi, Maizuru and Ultra-Tamba–Tamba belts and part of the Northern Chichibu Sub-belt) and Jurassic (Mino–Tamba–Ashio, Northern and Southern Chichibu, and North Kitakami belts) ACs and their metamorphic equivalents, although fragments of Carboniferous AC, known as the Nedamo Belt, also occur.

In this chapter the lithologies, stratigraphy, geological structure and noteworthy characteristics of these older ACs are documented in order to further elucidate the geological development of the Japanese islands described in Chapter 1. Although parts of the Maizuru and Abukuma belts are not strictly composed of ACs, they are included in this chapter for convenience. The geology of the Ryoke and Sanbagawa belts, the protoliths of which are ACs, is described in Chapter 2e.

Renge high-*P*/*T* rocks (TT)

Late Palaeozoic high-pressure and low-temperature (high-*P*/*T*) metamorphic rocks known as the Renge metamorphic rocks were originally grouped within the so-called 'Sangun' Belt proposed by Kobayashi (1941) to describe high-*P*/*T* schists widely scattered across the Inner Zone of SW Japan (central-western Honshu, northern Kyushu and the Ryukyu islands). Before the late 1980s, the 'Sangun' belt was considered to define a single coherent high-*P*/*T* metamorphic belt of pre-Jurassic age, paired with the low-pressure and high-temperature (high-*T*/*P*) Hida belt (e.g. Miyashiro 1961; Fig. 2b.2). However, with the accumulation of geochronological data of mainly phengite K–Ar ages in the 1990s (e.g. Shibata & Nishimura 1989; Nishimura 1998; Tsujimori & Itaya 1999), the Sangun Belt was subdivided into two discrete geotectonic units: (1) an Early Mesozoic 'Suo' Belt and (2) an older group of Late Palaeozoic 'Renge' rocks associated with the Oeyama Belt (Fig. 2b.3). This subdivision has been generally accepted in modern geotectonic interpretations of the Japanese archipelago (e.g. Isozaki *et al.* 2010; Tsujimori 2010; Wakita 2013). The limited outcrop of the Renge rocks owes much to the overprint of voluminous Mesozoic batholith belts and an unconformable cover of Cenozoic volcaniclastic rocks in the back-arc region of Honshu. However, based on the lithological, structural, metamorphic and geochronological similarities, the Renge rocks are considered to have been constituents of a Late Palaeozoic regional high-*P*/*T* metamorphic belt.

The exposure of Renge rocks is limited to several relatively small areas in comparison with the high-*P*/*T* rocks of the Suo Belt (Fig. 2b.4). Many localities are distributed along a NE–SW-directed line from the Itoigawa–Shizuoka Tectonic Line, and occur as tectonic sheets and/or blocks in serpentinite mélange associated with the Oeyama Belt (Fig. 2b.4). In the Chugoku Mountains, the Renge rocks occur within serpentinite mélange units that lie beneath the ultra\mafic bodies of the Oeyama Belt; the serpentinite mélange units have been emplaced upon rocks of the Akiyoshi and/or Suo belts (Uemura *et al.* 1979; Kabashima *et al.* 1993; Tsujimori 1998; Tsujimori & Liou 2007). In the Hida Mountains, the Renge rocks are tectonically mixed with the ultramafic rocks of the Oeyama Belt (Nakamizu *et al.* 1989; Kunugiza *et al.* 2004).

Most of the metamorphism recorded by the Renge rocks took place in the epidote-blueschist facies and/or greenschist/blueschist transitional facies to epidote-amphibolite facies, although lawsonite-blueschist and glaucophane-bearing eclogite locally occur (cf. Tsujimori 2010). The presence of Middle–Late Palaeozoic Renge lawsonite-blueschist and glaucophane-eclogite provides evidence of a cold geotherm in the palaeosubduction zone. The protoliths of the Renge rocks were pelagic and semi-pelagic siliceous-clayey deposits, trench-fill turbidites, basaltic oceanic crusts and rare mantle wedge materials. The presence of high-*P*/*T* metamorphosed forearc ophiolitic materials (fragments of the Oeyama Belt) suggests that significant landwards subduction erosion has occurred since Early Palaeozoic time.

Renge rocks in the Hida Mountains

In the Hida Mountains, fragments of Renge rocks occur in serpentinite mélange units of the Hida-Gaien Belt exposed in areas such as Itoigawa–Omi, Renge–Shirouma, Happo-O'ne, Gamata, Naradani

From: Moreno, T., Wallis, S., Kojima, T. & Gibbons, W. (eds) 2016. *The Geology of Japan*. Geological Society, London, 61–100.

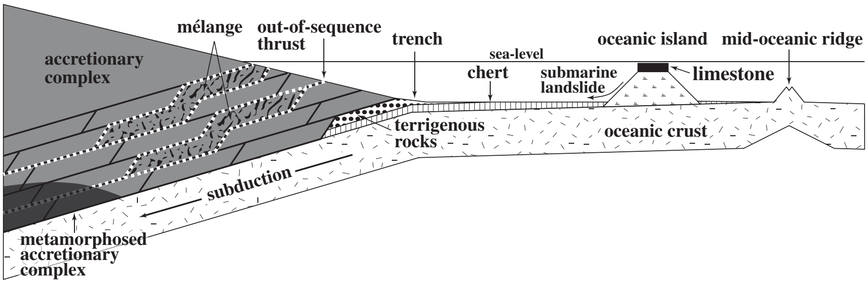

Fig. 2b.1. Formation process of accretionary complex (AC).

and Kuzuryu. These serpentinite mélanges with Renge rocks are unconformably overlain by Mesozoic sedimentary rocks of the Lower Jurassic Kuruma Group and the Middle Jurassic–Lower Cretaceous Tetori Group. The Renge rocks in the Hida Mountains record mainly greenschist/blueschist transitional facies to epidote-amphibolite facies metamorphism and locally preserve blueschist-eclogite facies metamorphism (e.g. Tsujimori 2002; Kunugiza & Maruyama 2011; Matsumoto *et al.* 2011). The mineral assemblages of these subgroups, and consequently the compositional trends of amphiboles in mafic rocks, vary from one group to another (Fig. 2b.5). The greenschist/blueschist transitional facies and epidote-amphibolite facies groups include medium- to coarse-grained garnet-amphibolites as mafic layers and lenses within garnet- and biotite-bearing pelitic schists, and are commonly characterized by the epidote-amphibolite facies mineral assemblage garnet + hornblende + plagioclase ± clinozoisite ± biotite + rutile ± ilmenite + quartz (e.g. Nakamizu *et al.* 1989; Matsumoto *et al.* 2011), with rare paragonite occurring within porphyroblastic garnet and plagioclase (Tsujimori & Matsumoto 2006). In contrast, the blueschist and eclogite facies groups are characterized by glaucophane-bearing mineral assemblages (Banno 1958; Nakamizu *et al.* 1989), with medium- to coarse-grained eclogite and garnet-blueschist occurring as mafic layers within paragonite-bearing pelitic schists, with the assemblage garnet + omphacite + glaucophane + clinozoisite + rutile + quartz ± phengite (Tsujimori 2002). Rare lawsonite and pumpellyite occur in both pelitic and mafic schists exposed in the western Hida Mountains (Miyakawa 1982; Sohma *et al.* 1983), and piemontite occurs in metachert. Phengitic white micas from these Renge rocks have yielded K–Ar and $^{40}Ar/^{39}Ar$ ages of *c.* 360–280 Ma, and zircon U–Pb geochronology constrains the timing of peak metamorphism to *c.* 360 Ma (cf. Tsujimori 2010).

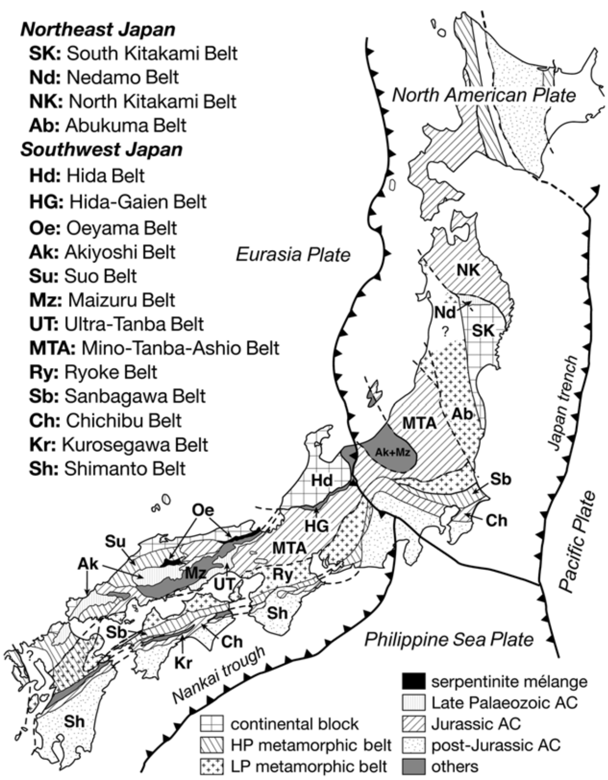

Fig. 2b.2. Tectonic map of Japan. Base map after Isozaki & Maruyama (1991).

Renge rocks in the Chugoku Mountains

In the Chugoku Mountains in western Honshu (Fig. 2b.4), two different types of high-pressure metamorphic rocks are associated with the Oeyama Belt as tectonic blocks: epidote-amphibolite facies gabbroic rocks with 470–400 Ma hornblende K–Ar ages (e.g. Nishimura & Shibata 1989; Tsujimori & Liou 2004); and blueschist facies pelitic and mafic schists with phengite K–Ar ages of *c.* 350–280 Ma (Shibata & Nishimura 1989; Nishimura 1998; Tsujimori & Itaya 1999). Of these, the younger high-P/T rocks in particular have been regarded as slices of the Late Palaeozoic Renge metamorphic belt, tectonically underlying the Oeyama Belt (e.g. Uemura *et al.* 1979; Tsujimori 1998). Renge blueschists have been described from at least five localities. A blueschist-bearing serpentinite mélange in the Osayama area (the 'Osayama serpentinite mélange'; Tsujimori 1998; Tsujimori & Itaya 1999; Fig. 2b.6) is of special interest. The matrix of the serpentinite mélange consists of schistose, friable, fine-grained serpentinite with pebble- to boulder-size fragments of serpentinized peridotite. Chrysotile and lizardite are the most dominant serpentine minerals, with rare winchitic amphibole. Blueschist blocks in this Osayama serpentinite mélange consist mainly of metasediments (pelitic, psammitic and siliceous schists), metabasites and minor marble. The blueschist

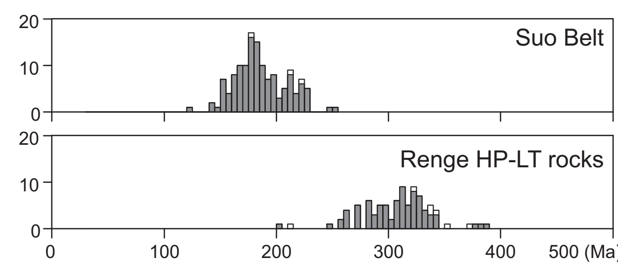

Fig. 2b.3. K–Ar and $^{40}Ar/^{39}Ar$ age histograms showing difference between the Suo and Renge high-P/T metamorphic belts; the diagram is modified after Itaya *et al.* (2011). Grey bars, phengite ages of pelitic schists; white bars, whole-rock, paragonite and amphibole ages from psammitic schists, mafic schists, amphibolites and eclogites. HP-LT: high pressure-low temperature.

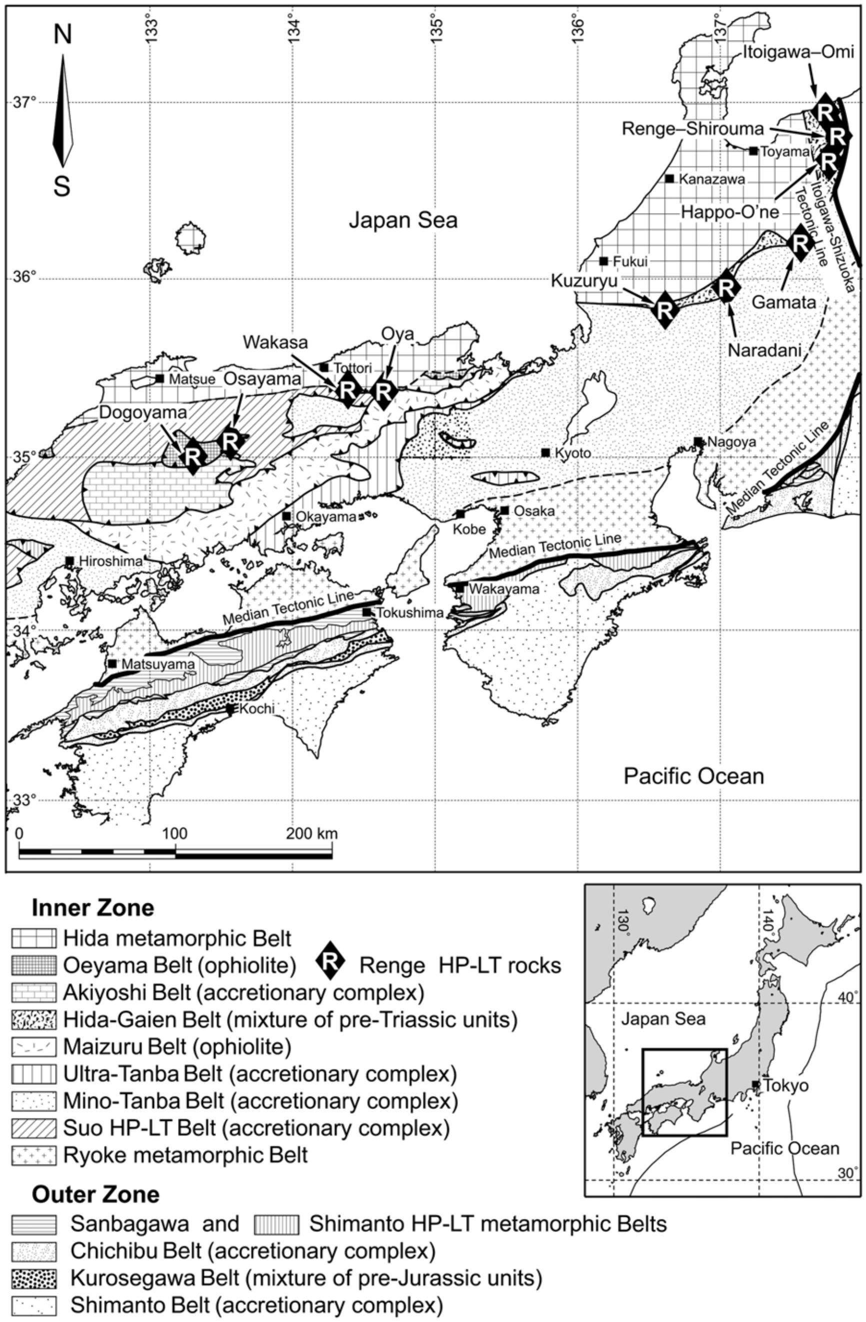

Fig. 2b.4. Tectonic framework of SW Japan, showing the localities of the Renge high-P/T schists. The map is modified after Tsujimori (2002). HP-LT: high pressure-low temperature.

facies mafic mineralogy has allowed subdivision into lawsonite-pumpellyite grade (the most abundant type) and epidote grade (sometimes accompanied by garnet in pelitic schists). Gabbro and dolerite blocks within serpentinite mélange, interpreted as fragments of the ophiolitic succession of the Oeyama Belt, also contain blueschist facies assemblages of lawsonite-pumpellyite grade. Phengite K–Ar ages of the blueschist blocks are in the range 327–273 Ma, regardless of metamorphic grade (Tsujimori & Itaya 1999). A lawsonite-blueschist-bearing small serpentinite mélange unit has also been described in the Oya area, located *c.* 150 km east of the Osayama area (Tsujimori & Liou 2007). Although there are no occurrences here of high-grade blueschists, lawsonite blueschists contains abundant metamorphic Ca–Na clinopyroxene and the rock preserves rare flattened pillow structures.

Metamorphic evolution of Renge eclogites and high-grade blueschists

The highest-grade Renge rocks of the Hida Mountains are glaucophane-bearing low-temperature eclogites of the Omi serpentinite mélange (Tsujimori *et al.* 2000; Tsujimori 2002). These eclogite facies rocks and related high-grade blueschists have mid-ocean ridge basalt (MORB)-like bulk-rock composition and contain glaucophane and epidote as both prograde and retrograde phases. Prograde-zoned porphyroblastic garnet of eclogites preserves mineral inclusions showing a transition from epidote-blueschist to eclogite facies (Fig. 2b.7). Moreover, the matrix of eclogite has been subjected to a blueschist facies overprinting after the peak eclogite facies metamorphism (at $T \approx 550$–$600°C$ and $P > 1.8$ GPa).

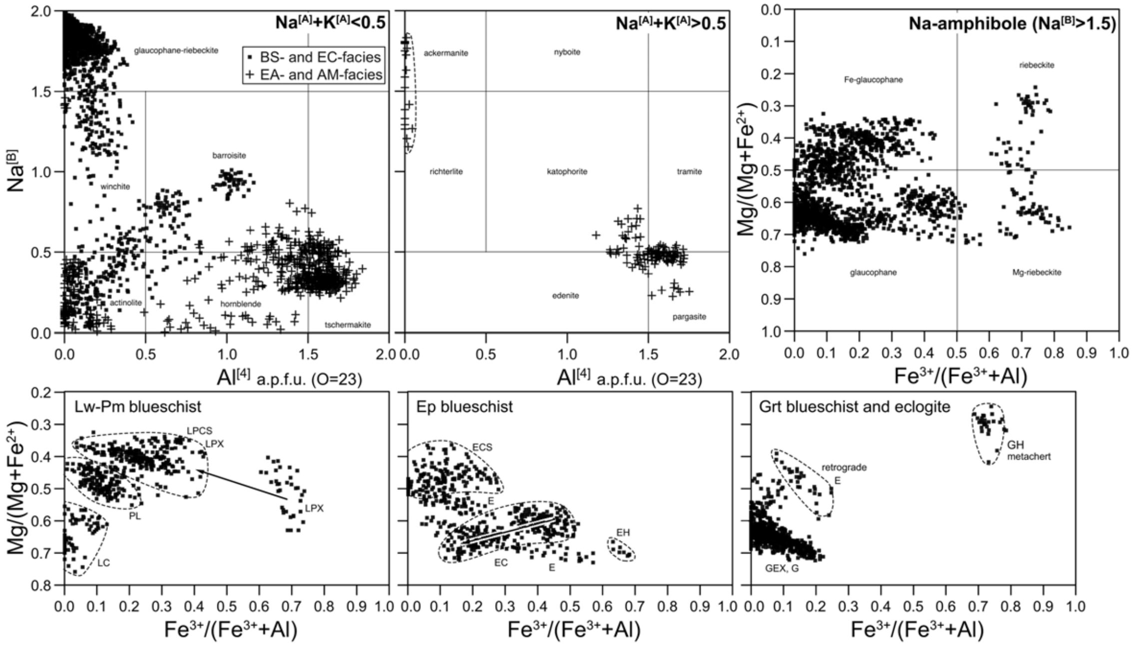

Fig. 2b.5. Compositional trend of amphiboles from Renge metamorphic rocks (Tsujimori 2010). Arrows show chemical zoning from core to rim. BS, blueschist; EC, eclogite; EA, epidote-amphibolite; AM, amphibolite; C, chlorite; S, stilpnomelane; L, lawsonite; P, pumpellyite; E, epidote; G, garnet; X, clinopyroxene; H, hematite.

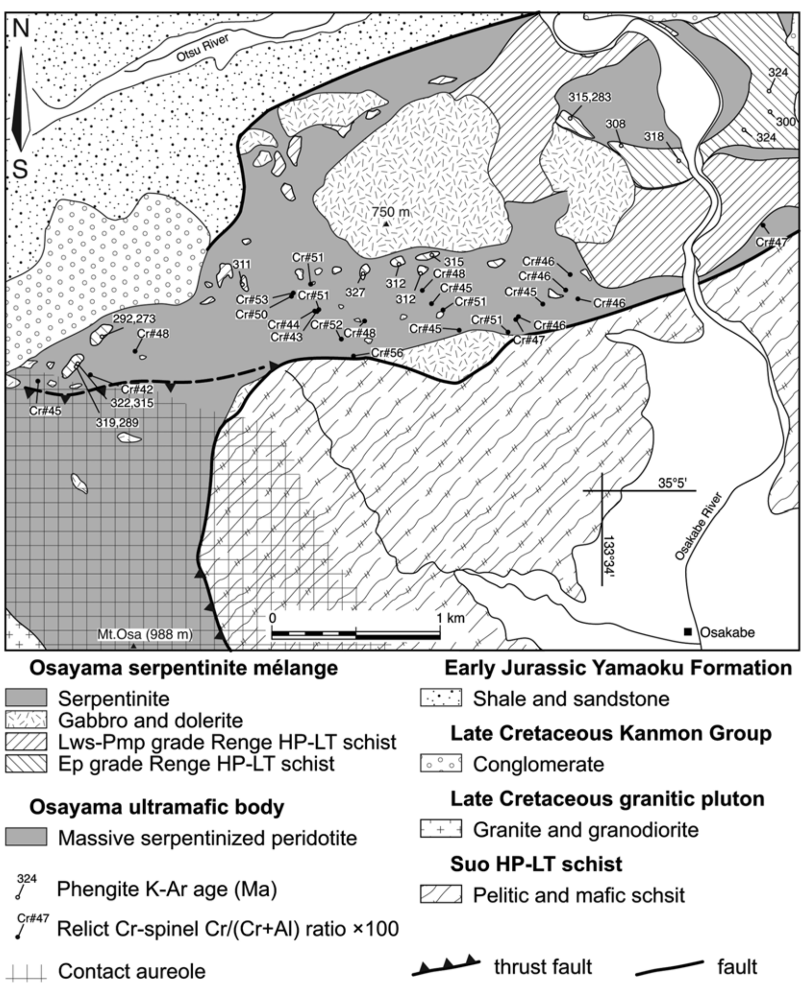

Fig. 2b.6. Geological map of the Osayama serpentinite mélange. The map is modified after Tsujimori (1998). HP-LT: high pressure-low temperature.

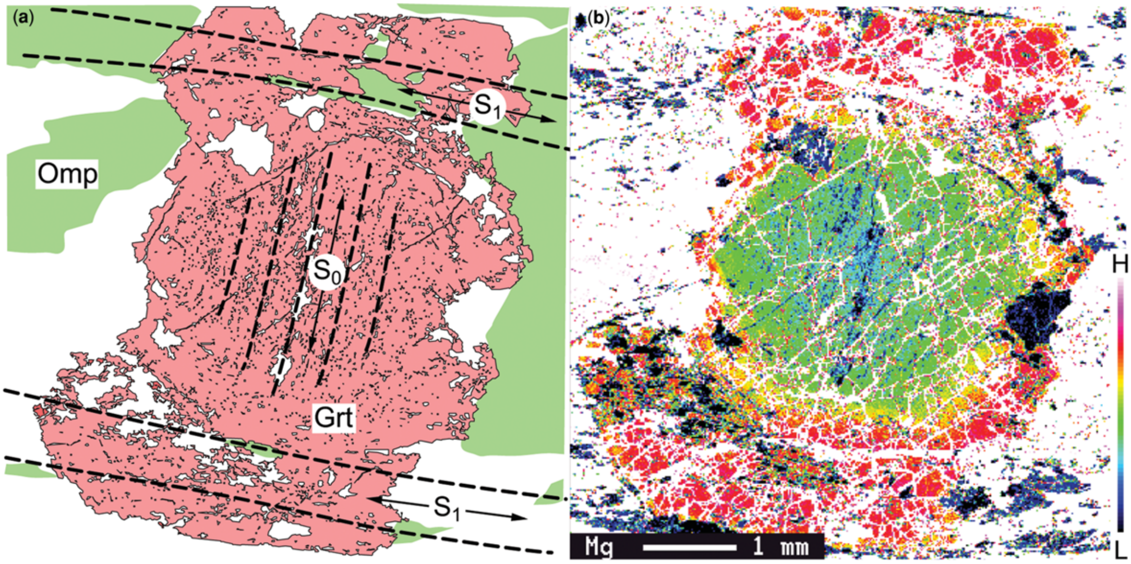

Fig. 2b.7. Representative texture of prograde-zoned garnet preserving a transition from blueschist to eclogite (Tsujimori 2002). (**a**) Textural sketch of garnet (Grt) and omphacite (Omp). Dashed lines represents schistosities S_0 (blueschist stage) and S_1 (eclogite stages). (**b**) Mg distribution of garnet of (a). A gradual colour filling bar represents concentration of Mg from low (L) to high (H).

Eclogite facies mineral assemblages also occur in a garnet-bearing blueschist block of the Osayama serpentinite mélange in the Chugoku Mountains. The blueschist block contains a retrograde lawsonite-pumpellyite grade mineral assemblage (Tsujimori 1998; Tsujimori & Liou 2005), suggesting that the rocks were 'refrigerated' during exhumation.

Detrital records of the Renge rocks

Detrital clasts derived from the Renge rocks provide important geological constraints on a 'missing' Late Palaeozoic metamorphic belt. The presence of detrital fragments of glaucophane-lawsonite and lawsonite-pumpellyite aggregates in Early Triassic sandstones of the Shidaka Group of the Maizuru Belt (Adachi 1990) indicates surface exposure of Renge rocks by earliest Mesozoic time. Furthermore, clasts of Renge rocks have been found widely in Mesozoic and Cenozoic shelf deposits and (more rarely) in back-arc and trench-fill deposits in Japan. For instance, lawsonite-bearing Late Palaeozoic schist clasts occur in the Lower Cretaceous Sasayama Group overlying the Mino–Tamba–Ashio Belt in the Eastern Chugoku Mountains (Kobayashi & Goto 2008). Similarly, Miocene Aizawa Formation conglomerate of the Joetsu Mountains (central Japan) contains abundant epidote-blueschist clasts. Furthermore, detrital phengitic micas yielding K–Ar ages of *c.* 320 Ma occur in the Eocene sandstone of the Shimanto Belt in southern Kyushu (Teraoka *et al.* 1994). We may therefore conclude that Late Palaeozoic Renge rocks were widely exposed across palaeo-Japan as a metamorphic belt, but that most of the belt has been eroded during the maturation of the Japanese Orogen.

Akiyoshi Belt (HS)

The Akiyoshi Belt is defined as a Permian (late Capitanian–early Wuchiapingian) AC that consists of an unmetamorphosed Carboniferous–Permian oceanic assemblage containing remnants of a middle Visean–Capitanian oceanic atoll(s) on basaltic seamount(s) with a Panthalassic affinity. The accreted rocks were uplifted by Late Triassic times, because they are overlain unconformably by post-orogenic Upper Triassic fluvio-lacustrine sediments. The Akiyoshi atoll stratigraphy records long-term (70–80 Ma) climatic events and sea-level changes related to the growth and retreat of the Late Palaeozoic Gondwana ice sheet. This provides an important record of Mississippian–Capitanian environmental change in the Panthalassa Ocean and tectonic events at its western margin (Fig. 2b.8). The main exposures of the Akiyoshi Belt occur in the Omi, Atetsu, Taishaku, Akiyoshi and Hirao areas in SW Japan (Fig. 2b.9). This section summarizes the lithostratigraphy and age of the Akiyoshi accreted rocks, overviews their tectonostratigraphic

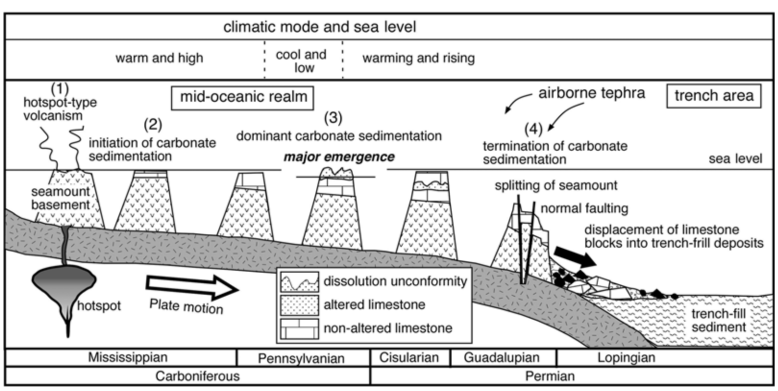

Fig. 2b.8. Birth to demise of the atoll-capped Akiyoshi seamount, modified after Sano (2006). (1) Middle Mississippian generation of an oceanic island in an equatorial zone of the Panthalassa Ocean. (2) Middle Mississippian initiation of shallow-marine carbonate sedimentation. (3) Mississippian–Guadalupian dominant accumulation of shallow-marine carbonates and Late Mississippian prominent emergence events. (4) Late Guadalupian termination of the atoll sedimentation, immediately followed by the encroachment to a trench area and the normal fault-induced tectonic collapse at an outer bulge.

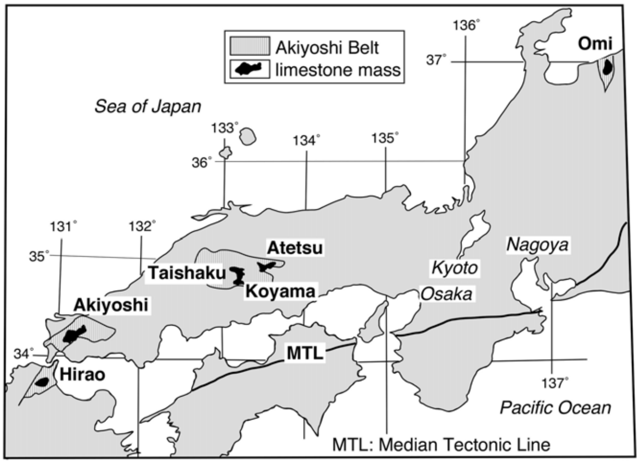

Fig. 2b.9. Approximate distribution of the Akiyoshi belt and its representative Mississippian–Permian limestone masses. Modified after Nakashima & Sano (2007).

classification and briefly introduces recent approaches to palaeoenvironmental analyses of the Akiyoshi atoll carbonates.

Stratigraphy and age

The major lithological components of the Akiyoshi belt are the Tournasian (?) to Visean basaltic rocks, middle Visean–Capitanian shallow-marine limestones and deep-water cherts, and upper Capitanian–lower Wuchiapingian siliceous tuff and terrigenous rocks (Fig. 2b.10). On the basis of the regional geology, Sano & Kanmera (1988) grouped the Carboniferous–Permian rocks into five lithologic units and reconstructed their depositional setting (A1, A2, B1, B2 and C in Fig. 2b.10).

Units A1 and A2 typically show a basaltic basement overlain by a thick pile of massive shallow-marine limestone and a succession dominated by redeposited limestone with intercalations of spicular chert (Fig. 2b.10). The basaltic rocks of both units represent relicts of seamount(s) formed by hotspot-type volcanism in the equatorial zone of the Panthalassa Ocean (S. Sano *et al.* 2000; Y. Sano *et al.* 2000). The shallow-marine limestone of unit A1 commonly forms spectacular plateaus exhibiting karst topography (Fig. 2b.11a) and consists predominantly of shallow subtidal facies rich in diverse skeletal debris, locally with metazoan reefal facies constructed by rugose corals, *Chaetetes* and algae with stromatolitic facies (Sugiyama & Nagai 1994). The occurrence of metazoan reefal facies is limited to rocks of middle Mississippian–late Pennsylvanian age (Fig. 2b.10). The redeposited limestone of unit A2 consists chiefly of limestone talus deposits, debrites and turbidites, which bear shallow-marine skeletal debris derived from the shallow-marine limestone of unit A1. Units A1 and A2 therefore represent an atoll facies upon a seamount and its upper slope facies, respectively.

Both units B1 and B2 also have basaltic rocks at the base, but these are overlain by upper Visean–upper Capitanian cherts (Fig. 2b.10). While the chert of unit B1 is characterized by abundant siliceous sponge spicules with scarce or no radiolarians, the chert of unit B2 contains radiolarians with some sponge spicules. The spicular chert of unit B1 is also distinguished by containing redeposited limestone beds and pods from radiolarian-bearing chert of unit B2. The redeposited limestone in the spicular chert dominantly yields smaller foraminifers and fusulinids of Visean–Bashkirian and Artinskian–Wordian ages, as well as conodonts. Calcitic debris of the redeposited limestone are inferred to have been shed from the atoll margins by sediment-gravity flows (Fig. 2b.10; Nakashima & Sano 2007). Both of the B1 and B2 chert successions are overlain

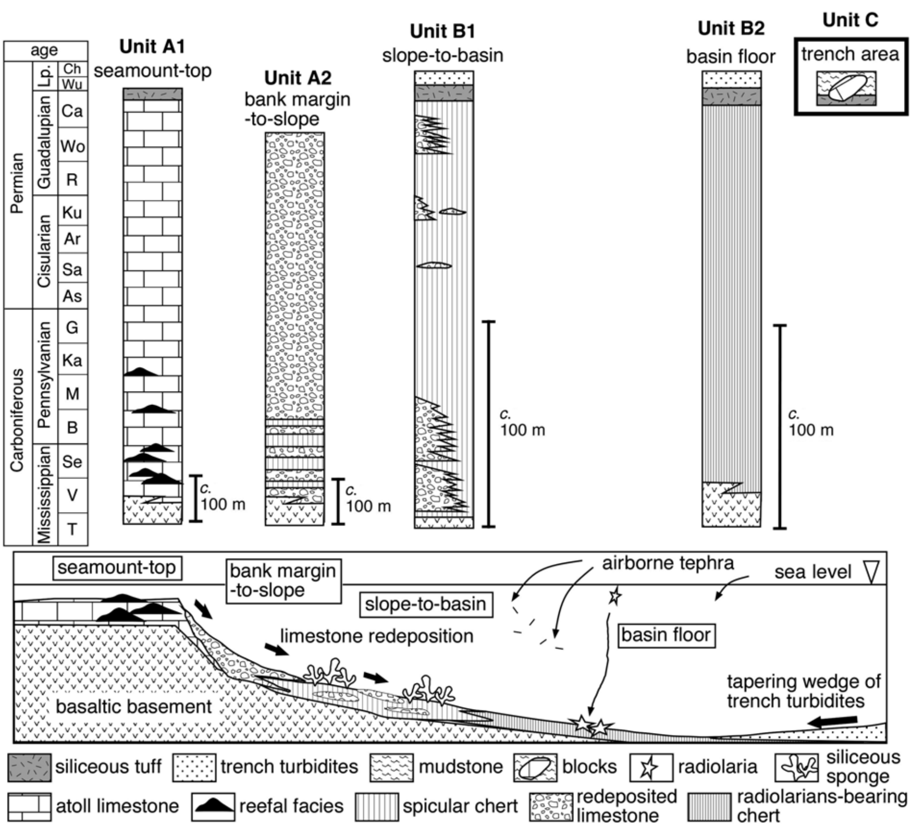

Fig. 2b.10. Sedimentary profile of the middle Lower Carboniferous–upper Middle Permian oceanic rocks on and around a mid-Panthalassic seamount, with simplified lithologic columns. The mudstone with siliceous tuff boxed at the upper right margin represents the matrix of the upper Middle–lower Upper Permian mélange unit containing exotic blocks of the oceanic rocks. Modified from Sano & Kanmera (1988) and Nakashima & Sano (2007). T, Tournaisian; V, Visean; Se, Serpukhovian; B, Bashkirian; G, Gzhelian; As, Asselian; Sa, Sakmarian; Ar, Artinskian; Ku, Kungurian; R, Roadian; Wo, Wordian; Ca, Capitanian; Wu, Wuchiapingian; Ch, Changhsingian.

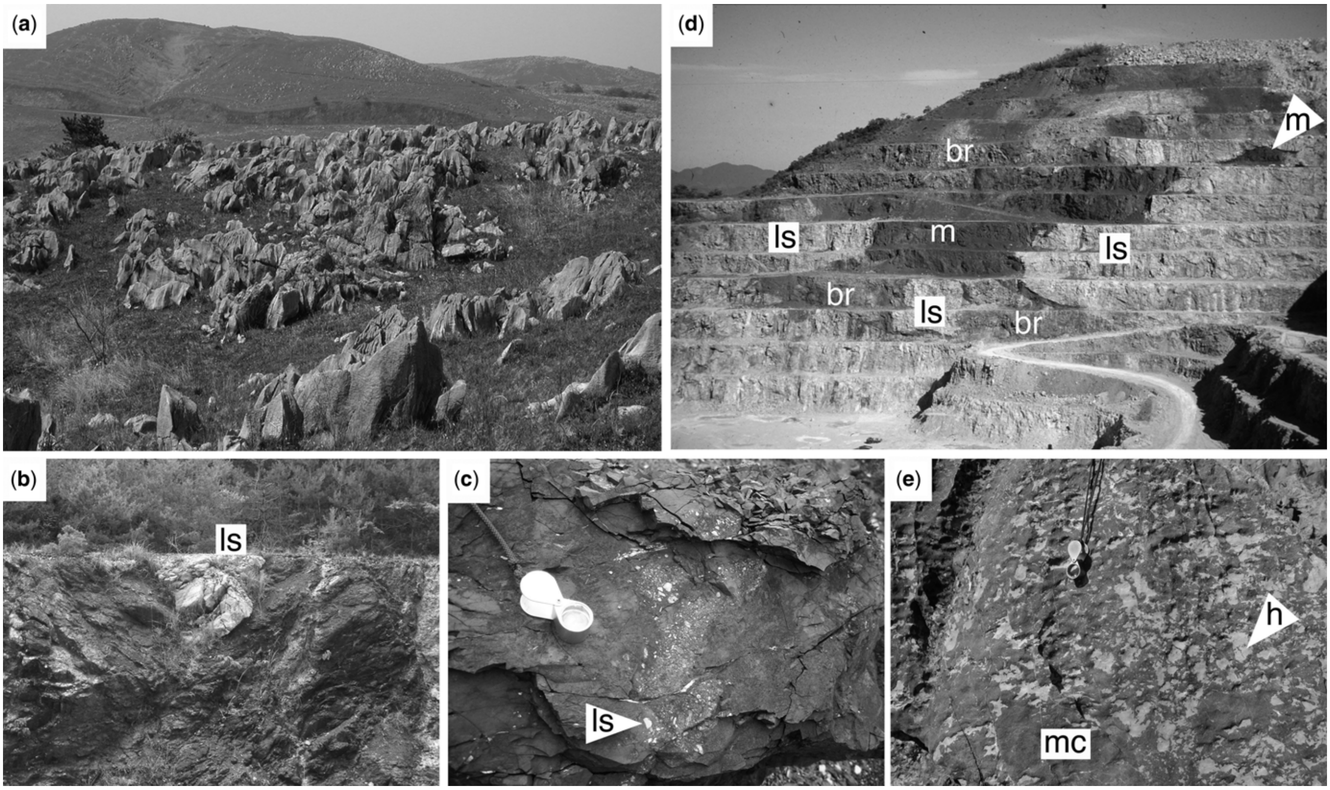

Fig. 2b.11. Exposure views of key facies of the Akiyoshi atoll carbonates and their structural relation to the upper Capitanian–lower Wuchiapingian scaly mudstone. (**a**) Numerous pinnacles of the completely massive, Cisularian–Guadalupian light-grey limestone on gently rolling hills with karstic topography. Akiyoshi-dai Plateau. (**b**) Isolated limestone block (ls) embedded in the upper Capitanian scaly mudstone. Approximate width of view is 10 m. Western margin of the Akiyoshi-dai Plateau. (**c**) Limestone fragments (ls) with clusters of crinoid debris in the upper Capitanian scaly mudstone. Western margin of the Akiyoshi-dai Plateau. (**d**) Complicated contacts between the Pennsylvanian–lower Guadalupian limestone (ls) and the upper Capitanian scaly mudstone (m) containing blocks of the limestone breccia (br). Approximately 300 m wide view in the working quarry at the northwestern margin of the Akiyoshi-dai Plateau. (e) *Microcodium* structure (mc) composed of aggregates of dark-grey to brown calcite crystals replacing the host rock (h) of the middle Kasimovian light-grey skeletal limestone. Akiyoshi-dai Plateau.

by upper Capitanian–lower Wuchiapingian siliceous tuff and alternations of turbiditic sandstone and mudstone. Sano & Kanmera (1988) considered the spicular chert and the radiolarian-bearing chert as representing deep-marine sediments on the lower slope of a seamount and the surrounding ocean floor, respectively (Fig. 2b.10). The siliceous tuff originated from airborne tephra, and the alternation of sandstone and mudstone represents the deep-marine tapering slope wedge of trench-fill turbidites. The successions of units B1 and B2 therefore both record the deep-marine OPS formed during the Mississippian–Lopingian migration of their depositional sites from a mid-oceanic setting to a trench area (Fig. 2b.10).

Unit C is characterized by the dominance of upper Capitanian–lower Wuchiapingian scaly-cleaved mudstone with subordinate siliceous tuff and sandstone (Fig. 2b.10). The scaly mudstone is strongly contorted and chaotically contains various-sized blocks of massive shallow-marine limestone and limestone breccia, thin graded beds of limestone conglomerate and sandstone and lithic fragments of limestone, with isolated individuals of fusulinids and crinoids (Fig. 2b.11b, c). These blocks and related calcareous debris occur most frequently in the scaly mudstone near its boundary with mappable-scale masses of the shallow-marine limestone of unit A (Figs 2b.11d & 2b.12; Kanmera & Nishi 1983; Sano & Kanmera 1991*a*). The scaly mudstone of unit C is interpreted as originally deposited as argillaceous sediments within a trench-fill turbidite sequence.

Tectonostratigraphically, these five units are organized into two coherent units and one mélange unit. The two coherent units correspond to units B1 and B2, and are commonly characterized by an orderly stratigraphic succession comprising basaltic rocks, spicular chert or radiolarians-bearing cherts, siliceous tuff and turbiditic terrigenous rocks, in ascending order. Each of these successions forms fault-bounded slabs, which are stacked to form a highly complicated imbricate structure (Kanmera & Nishi 1983). The mélange unit is characterized by chaotic mixing of various-sized blocks (mainly of the shallow-marine limestone dominantly derived from unit A1) and polymictic limestone breccias with an argillaceous matrix derived from the scaly mudstone of unit C (Sano & Kanmera 1991*b*, *c*). Units A1 and A2 are therefore tectonostratigraphically defined as blocks within the mélange unit. This is exemplified by the structural relation of unit A1 (Akiyoshi Limestone) to unit C (Tsunemori Formation) in the Akiyoshi-dai Plateau area, where the former structurally rests upon the latter with highly complicated contacts (Figs 2b.11d & 2b.12; Sano & Kanmera 1991*a*). The age of the scaly mudstone of unit C constrains the timing of mixing to have been Capitanian–early Wuchiapingian.

Accretion of atoll-capped Akiyoshi seamount

The structural relation of the Akiyoshi Limestone and the Tsunemori Formation, along with their ages and the lithological character of related limestone breccia rocks, led Sano & Kanmera (1991*d*)

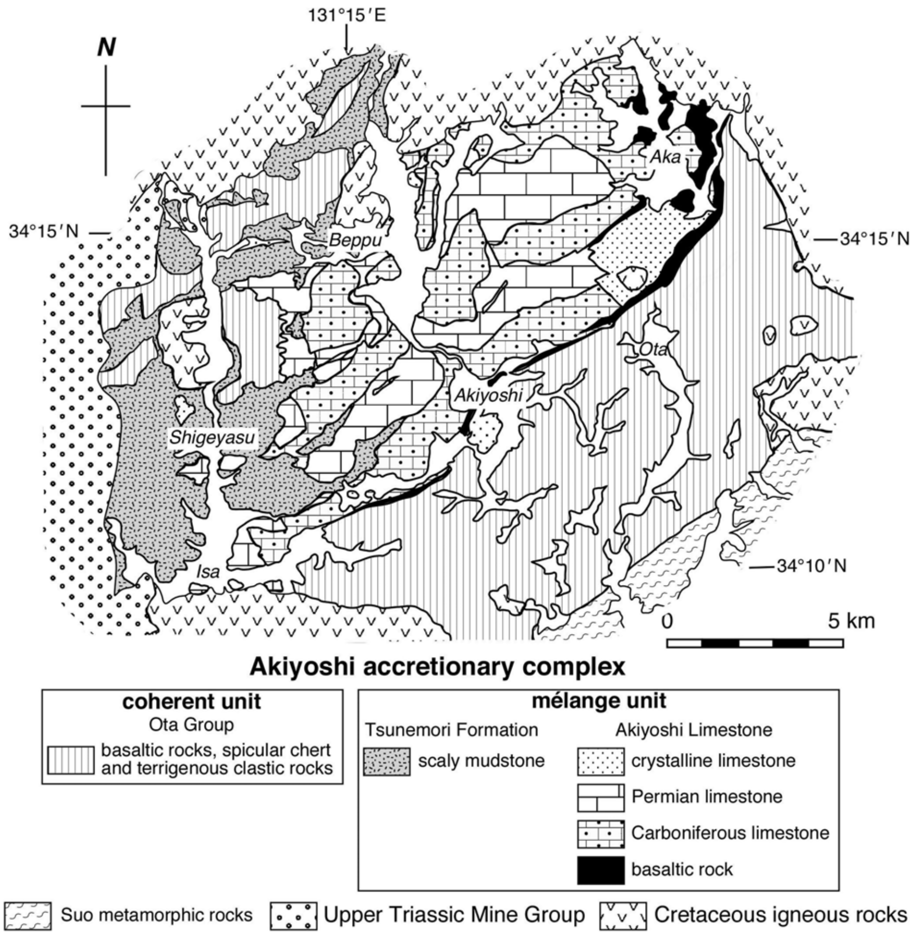

Fig. 2b.12. Simplified geological map of the Akiyoshi-dai Plateau area chiefly underlain by the Mississippian–Permian Akiyoshi accreted rocks. After Kanmera & Nishi (1983). See text for the tectonostratigraphic classification of the Akiyoshi accretionary rocks. Mapped area is shown in Figure 2b.9.

to interpret the accretionary events of the atoll-capped Akiyoshi seamount in terms of normal faulting in an outer trench area (Fig. 2b.8). Their hypothesis invokes normal fault-induced tectonic collapse of the seamount in an outer bulge, fragmenting the atoll carbonates into various-sized blocks. These blocks were gravitationally displaced down toward a trench area and mingled with argillaceous trench-fill sediments to form the chaotic rocks of unit C during late Capitanian–early Wuchiapingian times. The intermingling of smaller limestone debris with the trench-fill sediments formed the polymictic limestone breccia with its argillaceous matrix. Finally, the chaotic mixture of blocks and finer debris derived from the shallow-marine limestone of unit A1 mixed with trench-fill sediments were incorporated into the accretionary prism.

Unlocking palaeoenvironmental changes

Since the pioneering study by Ozawa (1925), a great deal of stratigraphic, sedimentological and palaeontological work has been carried out, dominantly in the shallow-marine limestone of unit A1 (e.g. fusulinoidean biostratigraphy: Toriyama 1958; Watanabe 1991; facies analysis of organic reef complex: Ota 1968; Sugiyama & Nagai 1994). In addition, plate-tectonics-based studies have revealed the tectonic and depositional settings of the Akiyoshi seamount (Kanmera & Nishi 1983; Sano & Kanmera 1988), so there has been much recent progress in our understanding of Panthalassic Mississipiian–Permian palaeoenvironments as recorded by Akiyoshi atoll stratigraphy. This section outlines these recent studies on palaeoclimatic and sea-level changes preserved in the Akiyoshi rocks.

Climatic episodes and sea-level changes recorded in the Akiyoshi atoll stratigraphy

In the course of its long journey (70–80 m.y.) across the Panthalassa Ocean, the Akiyoshi atoll recorded climate and sea-level changes that occurred during Mississippian–Permian time. Recent studies have shown that the environmental changes had pronounced impacts on carbonate sedimentation and biotic assemblages on the Akiyoshi atoll (Nakazawa & Ueno 2004; Sano *et al.* 2004; Sano 2006; Nakazawa *et al.* 2009).

Chiefly on the basis of literature review, Sano (2006) summarized the temporal changes of the dominant lithofacies and biotas of the entire Akiyoshi Limestone, the most thoroughly studied atoll unit within the Akiyoshi Belt. Its succession begins with upper Visean–Bashkirian reefal facies constructed by warm-adapted metazoan reef-builders (corals, *Chaetetes*) and oolitic-crinoidal limestone facies, which indicates deposition in a warm climate with elevated sea levels. The Visean–Bashkirian succession is followed by a Moscovian–Kasimovian muddy limestone-dominant association which records the demise of the metazoan reef builders and frequent emergence events affected by cool climatic conditions under generally lowered sea levels (Fig. 2b.12). A subsequent Gzhelian–Capitanian, muddy limestone-skeletal grainstone association is characterized by an upwards-increase in calcimicrobes, calcareous algae and calcisponges, and records less-frequent emergence events than the preceding Moscovian–Kasimovian succession. These biotic and facies characteristics are interpreted as reflecting a warming climate and sea-level rise during Gzhelian–Capitanian time.

The climate episodes and sea-level changes interpreted from Akiyoshi atoll stratigraphy generally correspond to the long-term global trend of Mississippian–Permian climatic changes and sea-level fluctuation related to Gondwana glaciation (Fig. 2b.8). These include Early–Middle Mississippian pre-glacial warm climate and elevated sea levels, Middle–Late Pennsylvanian cooling and related glacio-eustatic sea-level fluctuation at the culmination of Gondwana glaciation, and Early–Middle Permian global warming and sea-level rise due to the retreat of Gondwana ice sheets.

Following the results of detailed facies analysis using drilled core samples and sequence stratigraphic interpretation, Nakazawa & Ueno (2004) recognized the sequence boundary between the karstified skeletal grainstone of shoal facies and the overlying lime-mudstone and dolomitic micrite of transgressive peritidal facies in the upper Guadalupian section of the Akiyoshi Limestone. These authors suggested that a sea-level fall resulted in a biotic turnover, as exemplified by the coincidence of the fusulinid biostratigraphic boundary with the sequence boundary.

Also based on the drill core data, Nakazawa *et al.* (2009) recognized a long-term sea-level change comprising an late Cisularian (Kungurian) to late Guadalupain (Capitanian) gentle sea-level fall, punctuated by a short-lived middle Guadalupian (Wordian) sea-level rise event. On the basis of the correlation of the sea-level changes with sea-level curves proposed from shelf regions (e.g. Ross & Ross 1987), the Kungurian–Capitanian sea-level fluctuation is considered to have been eustatically driven. Furthermore, Nakazawa *et al.* (2009) have concluded that this long-term eustatic sea-level change controlled the development of parasequences in the Kungurian–Capitanian succession of the Akiyoshi Limestone. One such parasequence, for example, comprises shoal to lagoonal skeletal grainstone that accumulated under conditions of low accommodation during the late Wordian–Capitanian second phase of sea-level fall.

Palaeo-monsoon

Although the Akiyoshi atoll carbonates have been viewed as lacking terrigenous grains (Sano & Kanmera 1988), Soreghan *et al.* (2011) recently found atmospheric dust from the Pennsylvanian section of unit A1 in the Akiyoshi area. This finding is the first-known record of atmospheric dust from the Palaeozoic ocean. The dust is dominated by the clay fraction, but also contains medium-sand-sized grains mainly of rock fragments, quartz and plagioclase, indicating a continental source (at least in part). On the basis of the sedimentological data and climate modelling, Soreghan *et al.* (2011) have preliminarily concluded that East Pangea is the most likely provenance for the sand-sized grains, implying the operation of a palaeo-Tethyan monsoon. This conclusion implies that the Akiyoshi atoll carbonates offer us a potentially valuable record of strong and geologically frequent atmospheric convection events during Late Palaeozoic times.

Suo Belt (TT)

The Suo Belt is an Early Mesozoic unit of the so-called ‘Sangun’ Belt (see previous description of Renge rocks and Fig. 2b.3; Nishimura 1998). Although the belt overlaps the San’in and Sanyo batholith belts, the spatial distribution of the Suo schist can be traced in the Inner Zone of SW Japan for more than 500 km from the Chugoku Mountains to Kyushu. The Triassic high-P/T schists of the Tomuru Formation in the Ishigaki–Iriomote islands (Nishimura *et al.* 1983) have been considered a SW extension of the Suo Belt (Nishimura *et al.* 1983; Nuong *et al.* 2008), and other exposures of the Suo schists crop out in the Kurosegawa Sub-belt in Shikoku and central Kyushu (e.g. Isozaki & Itaya 1991). The Suo Belt is essentially a metamorphosed Permo–Triassic accretionary complex, consisting of pelagic/hemi-pelagic siliceous-clayey deposits, trench-fill turbidites, basaltic oceanic crusts and subordinate amounts of limestone, gabbro, serpentinite and serpentinized peridotite (Fig. 2b.13). The Ochiai–Hokubo ultramafic body in the central Chugoku Mountains, which is quite different in petrological features from the ultramafic bodies of the Oeyama Belt (Arai *et al.* 1988), is also considered to belong to the Suo Belt in view of the radiometric ages obtained from deformed metagabbro (245–237 Ma: Nishimura & Shibata 1989). Pumpellyite-actinolite facies metapelite contains rare Middle Permian radiolarian fossils (Takeshita *et al.* 1987). Bedded chert is more dominant as a protolith of the schist in the eastern exposures, where Triassic conodont and Jurassic radiolarian fossils have been described from the Hatto Formation (Hayasaka 1987). Because of these fossils, we cannot rule out a possibility that the eastern exposure represents a metamorphosed equivalent of the Mino–Tamba–Ashio Belt. Overall, the Suo schists exhibit multiple phases (up to five) of deformation (e.g. Oho 1990), typically with isoclinal folds associated with a penetrative schistosity overprinted more than twice by open to tight folds with crenulation cleavages.

The Suo Belt is structurally overlain by Palaeozoic geotectonic units (Oeyama and Akiyoshi). In the Nishiki area, for instance, clastic rocks of the Nishiki Group (Akiyoshi Belt) are thrust over the Suo high-P/T schists of the Tsuno Group (Fig. 2b.14; Nishimura 1971). The Suo belt is in fault contact with the Yakuno Ophiolite of the Maizuru Belt, and occupies a structurally higher part of the Mino–Tamba–Ashio Belt (Hayasaka 1987). The boundary between the Suo and Hida belts is still unclear, although cataclastic fault rocks separating a Jurassic granitic pluton from Suo schist have been described. In the Nomo Peninsula, the Suo schists are underlain by the Cretaceous high P/T schists of the Sanbagawa Belt (Nishimura *et al.* 2004).

Phengitic micas from the Suo schists have yielded K–Ar ages of *c.* 220 Ma in the east and *c.* 190 Ma in the west, whereas some Jurassic or much younger K–Ar ages were considered as a thermal effect of the Mesozoic and Cenozoic igneous activity (Shibata & Nishimura 1989; Nishimura 1998). Metagabbroic rocks have yielded hornblende K–Ar ages of 253–245 Ma (Nishimura & Shibata 1989), whereas the zircon U–Pb geochronology of psammitic schists suggests *c.* 2.0–1.9 Ga detrital ages for the metasediments and *c.* 230 Ma for the subduction-zone metamorphism (Miyamoto & Yanagi 1996; Tsutsumi *et al.* 2003).

Characteristics of metamorphism and metamorphic zonation

The metamorphic mineral assemblages in the Suo schists cover a wide range of metamorphic facies that include the pumpellyite-actinolite, epidote-blueschist, greenschist facies and epidote-amphibolite facies. Amphibolite facies rocks are also locally found in metagabbroic rocks, but these are considered to be relics from an event unrelated to the Suo metamorphism (Nishimura & Shibata 1989). Overall, metamorphic rocks of the pumpellyite-actinolite facies and blueschist/greenschist transitional facies predominate, with the presence of pumpellyite-actinolite facies being a characteristic feature of most exposures (e.g. Hashimoto 1968; Nishimura 1971; Hayasaka 1987; Watanabe *et al.* 1989; Nishimura *et al.* 2004). Barroisitic Ca–Na amphibole (with abundant porphyroblastic albite) has been described in mafic schists that have been considered to record the highest-grade reached in the Suo Belt (e.g. Hashimoto 1972). Also, it is noteworthy that the occurrence of lawsonite in the pumpellyite-actinolite facies metapelites has been described from at least four localities of the Suo Belt (Nishimura & Okamoto 1976; Watanabe *et al.* 1983; Hayasaka 1987; Karakida *et al.* 1989). A lawsonite + pumpellyite + Na-amphibole mineral assemblage only

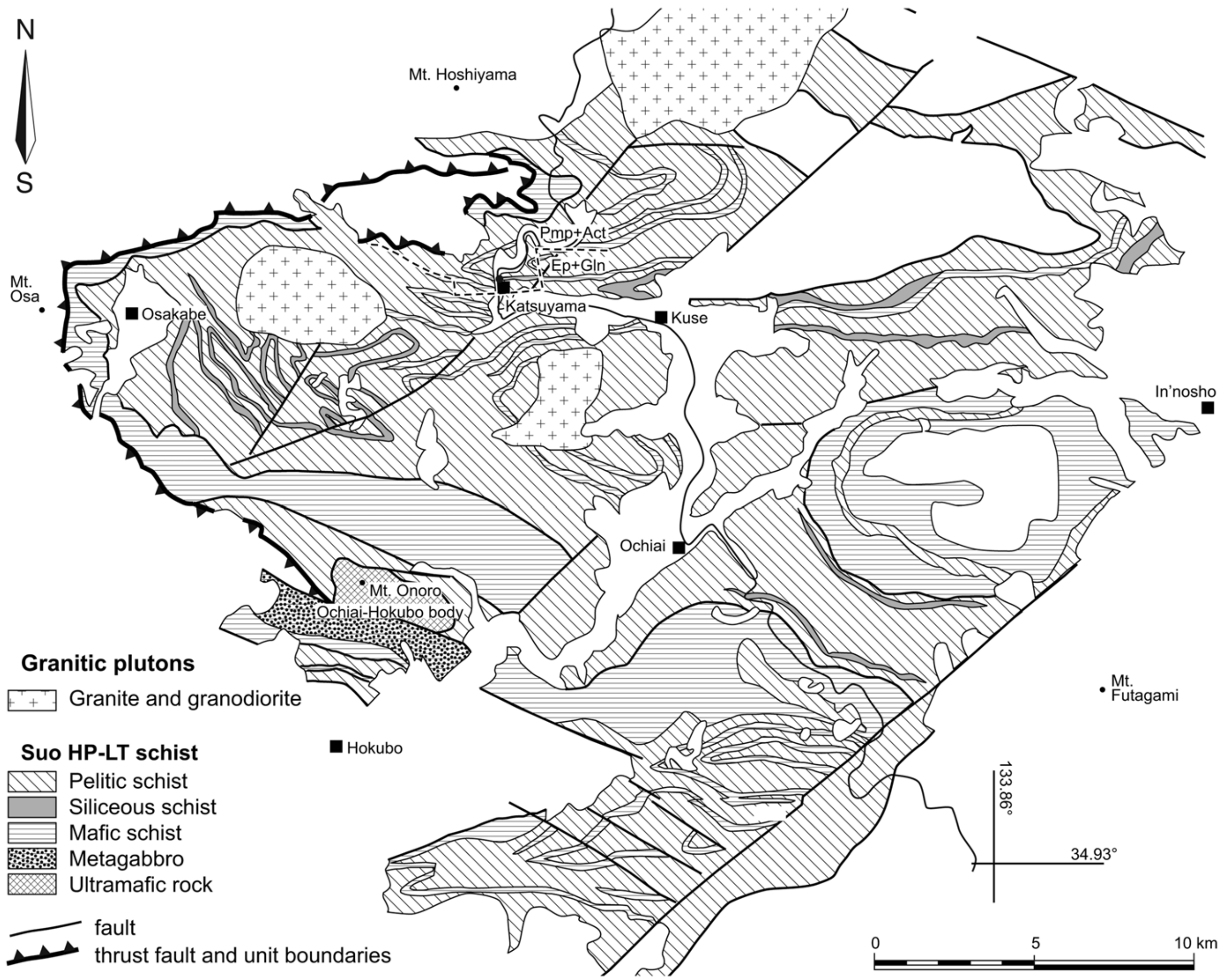

Fig. 2b.13. Simplified geological map of the Katsuyama–Asahi area, showing lithological variations and tectonic boundaries between the overlying Palaeozoic geotectonic units. The map was modified after Teraoka *et al.* (1996).

occurs in the Tomuru Formation in the Ishigaki–Iriomote islands (Nishimura *et al.* 1983), with metamorphic aragonite having been found in the lawsonite-bearing schists (Ishizuka & Imaizumi 1988). Chemical compositions of Na-amphibole of the Suo blueschists tend to have significant amounts of riebeckite and/or actinolite components, suggesting a lower pressure/temperature ratio than that of the Renge blueschists (Tsujimori 1998). High-Al glaucophane, which is common in the Renge blueschist, is relatively rare in the Suo Belt, whereas so-called 'crossite' and/or winchite are rather common.

Based on the appearance of characteristic Fe–Mg silicate minerals in mafic rocks, Nishimura (1971) identified three mineral zones in the Nishiki–Yamaguchi area: (A) pumpellyite + chlorite; (B) pumpellyite + actinolite; and (C) epidote + Na-amphibole, in ascending order of metamorphic grade. The B and C zones correspond to the Suo schists whereas the A zone belongs to the Akiyoshi Belt. Hashimoto (1972) proposed the existence of pumpellyite-actinolite and epidote-Na-amphibole zones for the Suo schists in the Katsuyama area (Hashimoto 1968). Relict igneous Ti-rich augite is commonly found in mafic schists, and metamorphosed picritic basalt contains pseudomorphs after olivine. In the Tomuru Formation of the Ishigaki Island, Nishimura *et al.* (1983) identified pumpellyite-glaucophane, epidote-glaucophane and epidote-barroisite zones.

The Suo schists exposed along the back-arc side of the Chugoku Mountains were overprinted by a thermal metamorphism from granitic plutons of the San'in batholith belt (Miyakawa 1961; Shibata & Nishimura 1989). The appearance of biotite in the pelitic schist defines the contact aureole, with hornblende and augitic clinopyroxene occurring in mafic hornfels.

K–Ar-age–temperature relationships

Two contrasting patterns of phengitic mica K–Ar ages from progressive metamorphic sequences have been described from the Nishiki area and Ishigaki Island (Shibata & Nishimura 1989; Nuong *et al.* 2008) (Fig. 2b.15). The Nishiki metamorphic sequence displays younger ages in higher-grade metamorphic rocks, and a thermal structure in which the higher-grade zone is in the lower part of the apparent stratigraphic succession. In contrast, the Ishigaki metamorphic sequence indicates that age becomes progressively older with increasing metamorphic temperature and the thermal structure is inverted, such that the highest-grade zone occurs in the uppermost parts of the apparent stratigraphic succession. Consideration of the

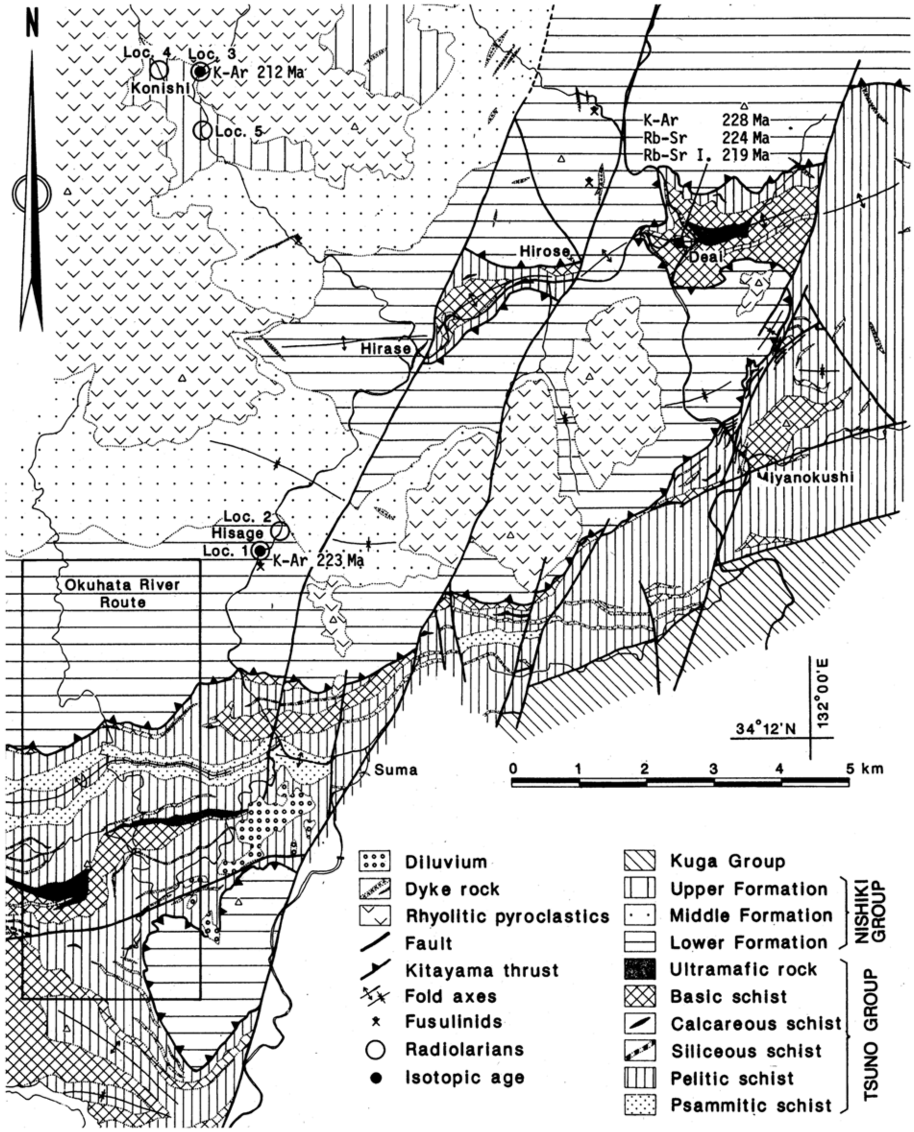

Fig. 2b.14. Geological map of the Nishiki area by Nishimura (1971) cited in Shibata & Nishimura (1989).

K–Ar-age-temperature relationships trajectory of the rocks from these two areas suggests that a shorter period of deformation could explain the Nishiki pattern, whereas a more prolonged duration of deformation could produce the Ishigaki pattern (Itaya *et al.* 2011; Fig. 2b.16).

Maizuru Belt (YHa)

The Maizuru Belt is a narrow (10–30 km wide) but long (380 km) zone extending from the Oshima Peninsula (on the Sea of Japan side at the western end of Fukui Prefecture) through Kyoto, Hyogo, Okayama and Hiroshima prefectures to the SW end of Shimane Prefecture (Fig. 2b.17). Exposures of this belt are rather sporadic in the western areas because of intrusions of Late Cretaceous granites and extensive cover by coeval ignimbrite. Nevertheless, its coherence as one terrane is justified by a close association of Permian clastic formations with metabasites and sheared granites. A similar association is known as the Katashina Belt exposed in central Japan, where it is considered to be the eastern extension of the Maizuru Belt although details are yet unknown. The Maizuru Belt has been subdivided into Southern, Central and Northern zones (Kano *et al.* 1959; Fig. 2b.18) as described in the following sections. Overall, the belt can be summarized as a collided arc–back-arc system formed during Late Palaeozoic (mainly Permian) time (Hayasaka *et al.* 1996), with the three zones representing (from south to north): a collided intra-oceanic island arc; back-arc basin deposits; and continental crust.

Southern Zone

The Southern Zone consists mainly of the Yakuno Ophiolite which represents the juvenile crust of an intra-oceanic island arc originating on Late Palaeozoic oceanic crust (Ishiwatari 1985; Hayasaka 1990; Ishiwatari *et al.* 1990; Suda 2004). This igneous complex records at least two stages of activity, with the older showing T-type MORB or oceanic plateau affinity and the younger of island-arc origin. Sano (1992) reported Sm–Nd whole-rock/mineral internal isochron ages of 410–430 Ma, disregarding the above classification. However, zircon U–Pb ages show *c.* 340–320 Ma for the oceanic crust and *c.* 290–280 Ma for the island-arc crust (Herzig *et al.* 1997). The geology of the Yakuno Ophiolite is described in more detail in Chapter 3.

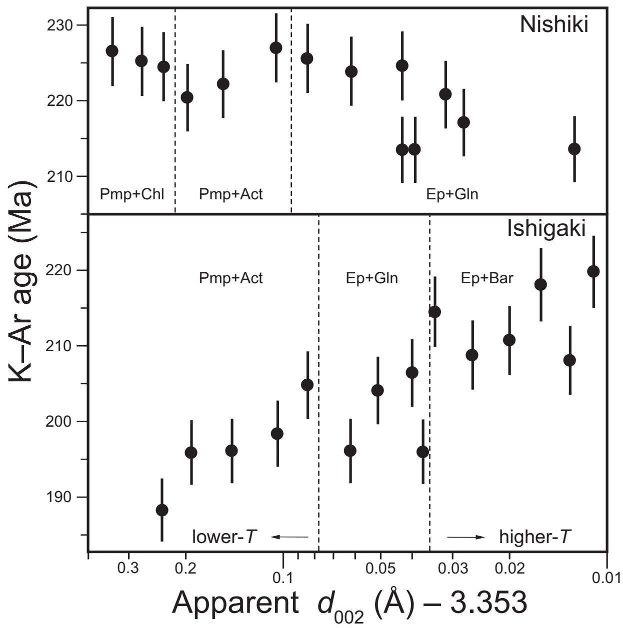

Fig. 2b.15. Age–temperature relations of the Ishigaki and Nishiki metamorphic sequences of the Suo high-pressure schist belt (Nuong *et al.* 2008).

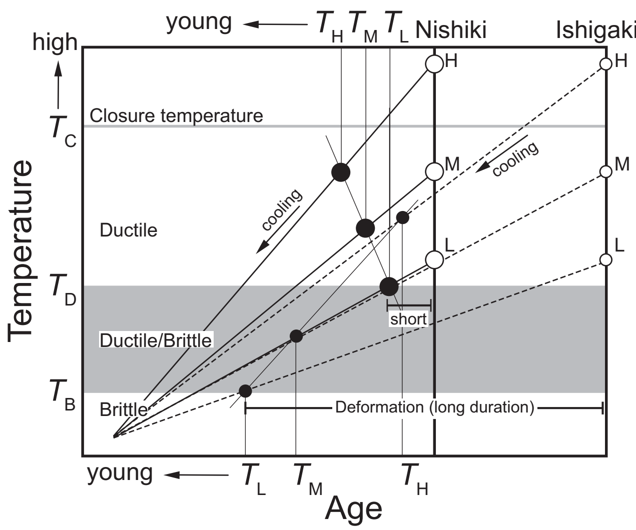

Fig. 2b.16. Generalized temperature–age diagram showing a possible mechanism to form negative and positive K–Ar-age–temperature (T) relationships in the Suo belt (Itaya *et al.* 2011). T_L, K–Ar age of low-T portion; T_M, K–Ar age of moderate-T portion; T_H, K–Ar age of high-T portion; T_C, closure T of phengite; T_D, maximum T of ductile/brittle boundary; T_B, minimum T of ductile/brittle boundary.

Central Zone

The Central Zone consists mainly of the Permian Maizuru Group and unconformably overlying Triassic formations (Nakazawa 1958; Shimizu 1962; Suzuki 1987).

Permian Maizuru Group

The Maizuru Group comprises three formations (Lower, Middle and Upper), with the Lower Formation comprising metabasalt and basaltic tuff with subordinate amounts of metagabbro, metadolerite and siliceous reddish brown claystone. Based on their chemistry these metabasites can be considered as a dismembered basement complex

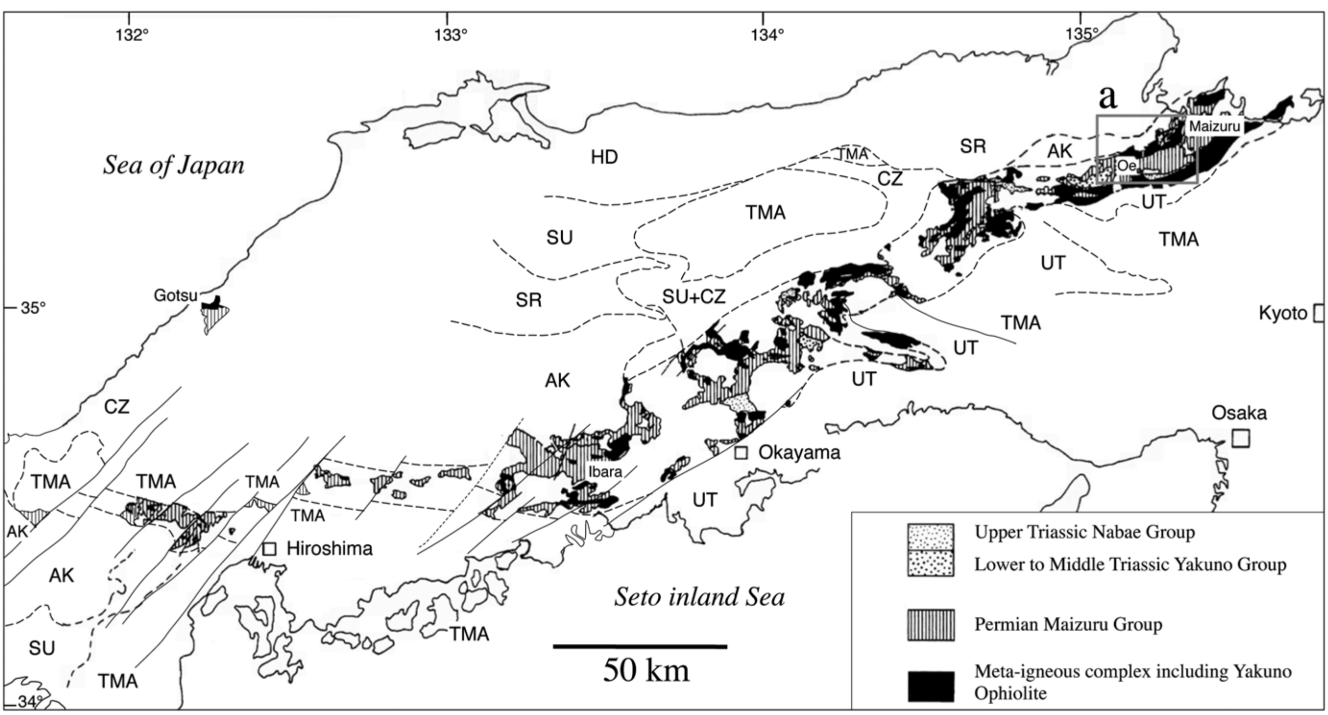

Fig. 2b.17. Geological map of the Maizuru Belt modified after Hayasaka (1990). HD, Hida–Oki Belt; SR, Sangun–Renge Belt; AK, Akiyoshi Belt; UT, Ultra-Tamba Belt; SU, Suo metamorphic belt; CZ, Chizu Belt; TMA, Tamba–Mino–Ashio Belt. Classification and name of each belt are adopted from those of *Pre-Cretaceous Terranes of Japan* compiled by Ichikawa (1990). The box 'a' shows the area of Figure 2b.18.

of a back-arc basin (Koide 1986), and have yielded Rb–Sr whole-rock isochron ages of 290 ± 26 Ma and 281 ± 8 Ma (Koide *et al.* 1987). These ages coincide with the formation of younger-stage rocks of the Yakuno Ophiolite, indicating coeval igneous activity of Early Permian 'Yakuno island arc' and the opening of the 'Maizuru back-arc basin'. The preservation of hemipelagic claystone indicates a rather wide spreading of the back-arc basin, analogous to the modern Shikoku Basin on the Philippine Sea Plate.

The Middle Formation is dominated by massive mudstone with subordinate amounts of sandstone and thin alternating beds of sandstone and mudstone representing a distal turbiditic sequence, mixed with occasional intercalations of siliceous tuffs. The upper half of the Middle Formation yields late Middle Permian fusulinids (Working Group on the Permian–Triassic Systems 1975) and late Middle–early Late Permian radiolarians (Ishiga 1984; Ishiga *et al.* 1988).

The Upper Formation is further subdivided into two members. The Lower Member consists mostly of sandstone with subordinate amounts of conglomerate and alternating beds of sandstone and mudstone representing proximal turbidite facies. The Upper Member is dominated by mudstone, and is characterized by intercalations of displaced limestone lenses. The Upper Member of the Upper Formation contains Late Permian fusulinids and smaller foraminifers (Ishii *et al.* 1975). An uppermost unit known as the Gujyo Formation consists mainly of greywacke-type sandstone with subordinate conglomerate, mudstone and siltstone, is exposed only in the Oe district (Fig. 2b.18), and has yielded latest Permian molluscs and brachiopods (Suzuki 1987). Osozawa *et al.* (2004) considered the lithologies comprising the Gujyo Formation to be forearc basin deposits.

The upwards coarsening observed from the Middle to Upper formations, combined with their complex south-vergent fold–thrust structure, indicate that the sedimentary basin approached the convergent margin to form a collision-accretion complex together with the Yakuno Ophiolite (Hayasaka *et al.* 1996; Osozawa *et al.* 2004). The Maizuru back-arc basin was closed and disappeared due to the collision of a Yakuno island arc by the end of Permian time.

Triassic rocks

Triassic formations are distributed sporadically in the Maizuru Belt, unconformably overlying the Maizuru Group. They are formally classified into the Lower–lower Middle Triassic Yakuno Group and Upper Triassic Nabae Group (Nakazawa 1958). Obvious Ladinian strata are not known in the Maizuru Belt and the basin tectonics of the above two groups are thought to have been quite different. The Yakuno Group (up to 700 m thick) is exposed in the Oe region and other areas further southwest (Figs 2b.17 & 2b.18). Marked sedimentary and biofacies changes indicate the change from deltaic through nearshore to offshore environments from north to south (Nakazawa 1958). This strongly suggests the presence of an uplifting landmass just to the north of the Central Zone of the Maizuru Belt in Early Triassic time. The Yakuno Group can therefore be defined in terms of foreland basin deposits, recording one broad cycle of transgression and regression. The Yakuno Group yields abundant molluscan fossils, indicating an earliest Triassic–early Middle Triassic age.

The Upper Triassic Nabae Group is exposed as a narrow tectonic basin bounded by high-angle faults and lying between the Central and Southern zones of the Maizuru Belt (Fig. 2b.18). This group

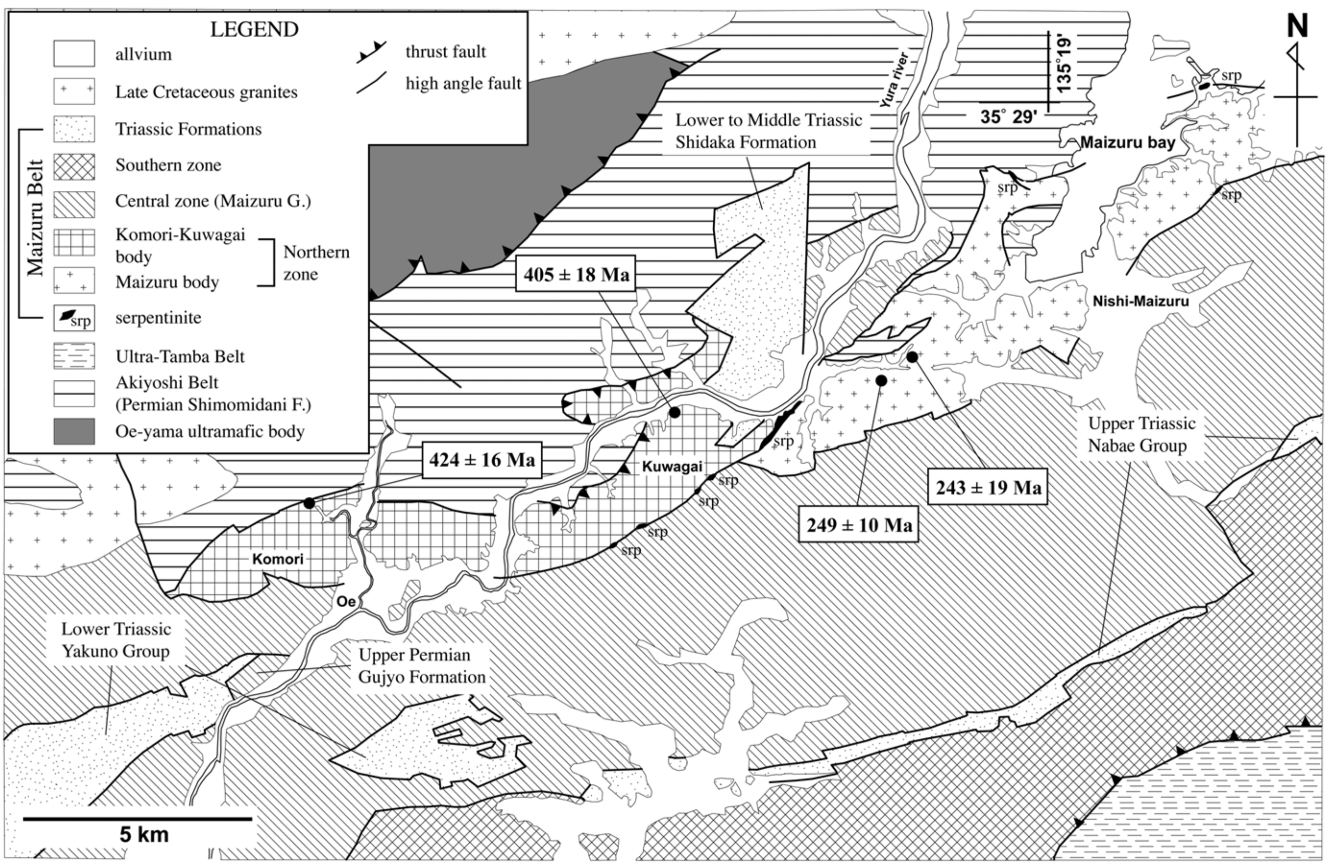

Fig. 2b.18. Geological map of the Maizuru-Oe district partly modified after Fujii *et al.* (2008). Original data are from Igi *et al.* (1961), Igi & Kuroda (1965), Suzuki (1987) and Ikeda & Hayasaka (1994). Location of the mapped area is shown in Figure 2b.17.

(up to 940 m thick) consists mainly of sandstone, mudstone, alternating beds of sandstone and mudstone, and conglomerate in order of abundance, and is characterized by intercalations of thin coal seams (Nakazawa 1958). Lithofacies and biofacies indicate that the Nabae Group was deposited in a neritic- to brackish-water environment, and it records one cycle of transgression and regression. Adachi & Suzuki (1992) reported EPMA (electron probe microanalyser) U–Th–total-Pb ages of detrital zircon and monazite from sandstones in the Nabae Group consisting of age clusters around 260 and 380–520 Ma. These ages demonstrate a provenance from the Northern Zone of the Maizuru Belt, as described in the following section.

Northern Zone

The Northern Zone is exposed only in the Maizuru–Oe district, northwestern Kyoto Prefecture, and is subdivided into the Komori–Kuwagai Complex in the west and the Maizuru Complex in the east (Fig. 2b.18). These two bodies are bounded by a high-angle fault associated with serpentinite lenses. Moreover, they differ from each other in their rock associations and ages, as well as in the degree of deformation. The Komori–Kuwagai Complex consists mainly of moderately to highly deformed granites with subordinate amounts of metagabbros, metadolerite, amphibolite and garnet-biotite gneiss. On the other hand, the Maizuru Complex consists exclusively of weakly deformed or undeformed granites (referred to informally as the 'Maizuru Granite'). SHRIMP zircon U–Pb ages of 424 $\pm$ 16 Ma and 405 $\pm$ 18 Ma for the granites from the Komori–Kuwagai Complex and 249 $\pm$ 10 Ma and 243 $\pm$ 19 Ma for the Maizuru Granite have been reported (Fujii *et al.* 2008; Fig. 2b.19). The granites of the Komori–Kuwagai body contain much older component of zircon (*c.* 580 and 765 Ma), which are likely inherited from host rock. They also contain monazite grains dated at *c.* 470 and 450 Ma, and their $^{87}Sr/^{86}Sr$ initial ratio is 0.70645 (Ikeda & Hayasaka 1994).

The Komori–Kuwagai Complex is thrust over the Permian Shimomidani Formation of the Akiyoshi belt to the north, whereas to the south it is brought into contact with the Permian Maizuru Group of the Central Zone by high-angle faults. The Lower–Middle Triassic Shidaka Formation unconformably overlies the Komori–Kuwagai body, which is composed mainly of fluvial fan sandstone and conglomerate with intercalated mudstone. From lithofacies, ages and geological structure, the Komori–Kuwagai body is postulated to be derived from the Khanka Massif of Prymorie in far eastern Russia, having been displaced by dextral fault movement during Late Triassic–Early Cretaceous time (Fujii *et al.* 2008). The Maizuru body can be age-correlated with granites in the Hida–Oki Belt.

Development of the Maizuru tectonic belt as a large-scale dextral shear zone

The above-mentioned history of the Maizuru Belt is summarized in Figure 2b.19 in the postulated context of a collided arc–back-arc system. The distribution of the Maizuru Belt shows a marked zonal arrangement cutting across the subhorizontal piled nappe structure of other belts present in the Inner Zone of SW Japan (Fig. 2b.17). This zonal arrangement becomes clear by removing the effect of Late Cretaceous NE–SW and NW–SE transverse fault movements. The northern boundary of the Maizuru Belt represents a high-angle dextral fault, whereas its southern boundary is a low-angle fault thrusting over the Ultra-Tamba belt (Hayasaka 1987). High-angle dextral faults are also ubiquitous within the Central Zone, forming a tectonic mélange zone that differs from those of more typical accretionary complexes. Many lenticular blocks of metagabbro, metadolerite as well as some granite lie in a longitudinally subparallel alignment. Moreover, kilometre-long exotic duplexes displaced from the Suo and Akiyoshi belts have been brought into the Central Zone. Because of this structural complexity imposed by major dextral shearing deformation, the Maizuru Belt has often been referred

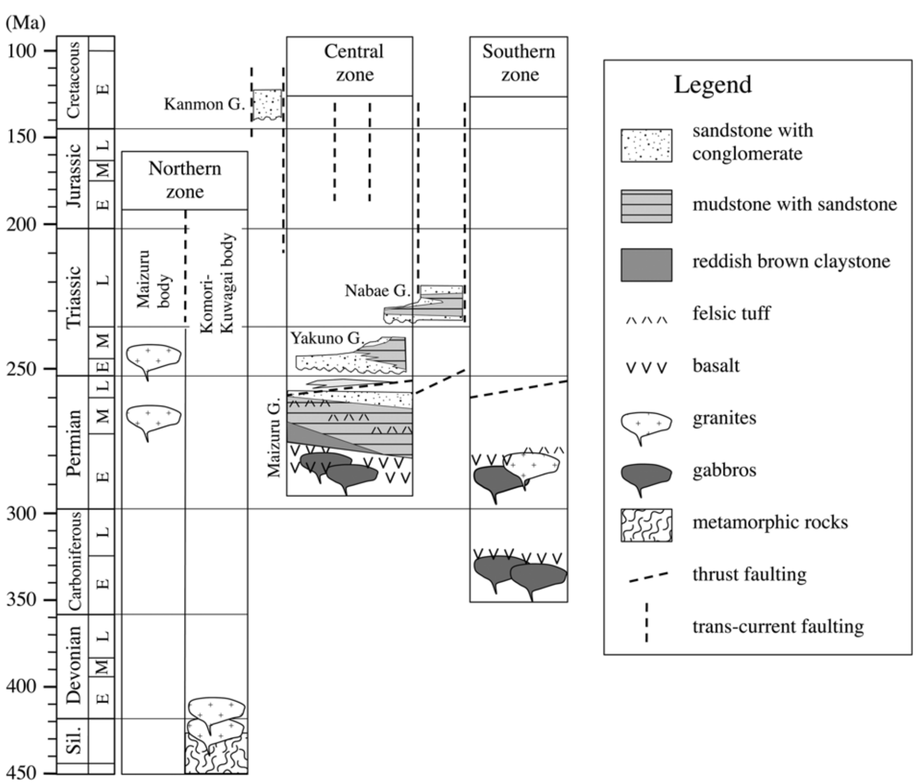

Fig. 2b.19. Generalized geo-historical column for the Maizuru Belt arranged from Hayasaka (1990), Hayasaka *et al.* (1996) and Fujii *et al.* (2008) with new data. Time scale is relatively expanded to 167% between 300 and 200 Ma.

to as the 'Maizuru tectonic belt'. An isolated and remote exposure of probable Maizuru Belt is known in the Gotsu area, northwestern Chugoku Province (Fig. 2b.17), and may have been separated from its main body by large-scale transcurrent displacement related to the dextral shearing.

Ultra-Tamba Belt (ST & YS)

The Ultra-Tamba Belt was first defined by Caridroit *et al.* (1985) and Ishiga (1986), although this definition was subsequently modified by Ishiga (1990). The belt extends from western Fukui Prefecture to western Okayama Prefecture, trending ENE–WSW except for where it has been subjected to intense post-Jurassic deformation (Fig. 2b.2). Correlatives of the belt include those found in the Tohoku region (Nakae & Kurihara 2011) and in the Sikhote–Alin Mountains of the Russian Far East (Kojima *et al.* 2000). The Ultra-Tamba belt is situated between the Maizuru and Tamba belts, and is tectonically divided into three sub-belts (UT-3, UT-2 and UT-1), each separated by a thrust fault (Fig. 2b.20).

Lithology and ages of sub-belts

The UT-3 sub-belt, which occupies the structurally uppermost part of the Ultra-Tamba belt, includes the Kozuki Formation (SW Hyogo Prefecture), the Kunisaki Complex (SE Hyogo Prefecture; Fig. 2b.20) and the Hiehara Formation (western Okayama Prefecture). These units consist mainly of mudstone, sandstone, felsic tuff and greenstones, along with minor chert and limestone which display coherent, broken and mixed facies. Mudstone, felsic tuff and chert yield early Middle–early Late Permian, Carboniferous and early Early Permian radiolarians, respectively (e.g. Pillai & Ishiga 1987; Takemura *et al.* 1993). Limestone associated with greenstones contains Carboniferous corals and Carboniferous and Permian fusulinids (e.g. Igi 1969).

The UT-2 sub-belt, which is structurally located between UT-3 and UT-1, contains strata named the Oi Formation, correlated with the Tokura Formation in northern Kyoto Prefecture, the Takatsuki Formation in northern Osaka Prefecture and the Inagawa Complex in southeastern Hyogo Prefecture (Fig. 2b.20). The sub-belt mainly consists of sandstone, laminated mudstone, chert, siliceous mudstone and felsic tuff, with minor amounts of 'greenstone' metabasalt. The chert yields late Middle–early Late Permian radiolarians, and the mudstone, siliceous mudstone and felsic tuff contain early–middle Late Permian radiolarians (e.g. Sugamori 2009*a*).

UT-1 occupies the structurally lowermost part of the Ultra-Tamba belt. Strata of this sub-belt are generally called the Hikami Formation, which is correlative with the Kuchikanbayashi Formation in northern Kyoto Prefecture and part of the Yamasaki Formation in southwestern Hyogo Prefecture. These formations consist of sandstone and mudstone with minor chert and greenstones. Mudstone contains poorly preserved radiolarians that appear to indicate a Middle–Late Permian age (Kurimoto 1986). The age of the formation of the UT-1 sub-belt remains unknown. Although some formations of the Ultra-Tamba belt were previously believed to contain Mesozoic forearc sediments, they have since yielded Late Permian radiolarians (e.g. Sugamori 2011) and are now considered to be part of the UT-2 sub-belt.

Tectonics of the Ultra-Tamba Belt

The following points are important in the context of the tectonics of the Ultra-Tamba belt: (1) some formations display broken or mixed facies; (2) the terrigenous clastic rocks are the same age as, or younger than, cherts that occur in the same unit; (3) typical chert–clastic sequences are exposed locally; and (4) shallow-water limestone containing corals and fusulinids is associated with metabasaltic 'greenstones'. These lines of evidence indicate that the Ultra-Tamba belt is an AC that formed in a subduction zone during Middle–Late Permian times.

The Maizuru, Ultra-Tamba and Tamba belts occur as a pile of nappes (Fig. 2b.21) although the nature of the rock assemblages, combined with their ages, indicate that these belts formed at different times and in different tectonic settings. The present distribution of three belts was probably formed after Late Jurassic times as the Tamba Belt contains Late Jurassic rocks. Deformation structures (e.g. slaty cleavage and folding) indicating southwards vergence are penetratively developed in the Ultra-Tamba Belt, and the deformation and metamorphism increase in grade towards structurally underlying units (Kimura 1988; Takemura & Suzuki 1996). These deformation structures probably formed when the Ultra-Tamba Belt was thrust over the Tamba Belt. The Ultra-Tamba and Tamba belts consist mainly of AC materials that formed at Permian and late Triassic–Jurassic times, respectively. Triassic tectonics in the region are poorly understood, however. Middle Triassic radiolarians have been reported from the Kamitaki Formation (mid-eastern Hyogo Prefecture) in the UT-1 sub-belt (Sugamori 2009*b*). Further study is required to understand the original relationship between the Ultra-Tamba and Tamba belts, and to accurately reconstruct Triassic tectonics.

Mino–Tamba–Ashio Belt (SK)

The Mino–Tamba–Ashio Belt is located geographically south of, and structurally beneath, the Palaeozoic belts, always with fault boundaries, and gradually changes into the Ryoke metamorphic belt to the south. Rocks of this belt comprise Jurassic ACs, and they can be traced from the northeastern Ashio area to the southwestern Iwakuni area in Honshu (Figs 2b.2 & 2b.22). The Jurassic ACs extend north to the Sikhote–Alin Range in far-eastern Russia and Nadanhada Mountains in NE China (Kojima 1989; Kojima *et al.* 2000). The lithologies common to these areas are Permian basalt and limestone, Permian–Jurassic radiolarian ribbon chert, and Jurassic clastic rocks and, as such, the succession represents a typical OPS (Matsuda & Isozaki 1991). In this section the ACs in the Mino area of central Japan, one of the best-studied areas, are described in detail and the more important findings emphasized.

Subdivision

The ACs in the Mino area have been subdivided into six tectonostratigraphic units (Sakamoto-toge, Samondake, Funafuseyama, Nabi, Kamiaso and Kanayama) on the basis of their lithology, geological structure and age of accretion (Wakita 1988). Accretion ages of these Mino units become younger from north to south with the structurally lower units occurring in the southern area, although the surface distribution is disturbed by a fold structure with a gently north-dipping enveloping surface (Fig. 2b.23). The Sakamoto-toge unit is the oldest AC in the Mino area, accreted during Early Jurassic times, and mostly composed of mélanges with blocks of sandstone, chert, basalt and limestone within a weakly sheared shale matrix. The Samondake unit is characterized by Middle Jurassic massive sandstone and alternating sandstone and mudstone, whereas the Funafuseyama unit consists of mélanges including large slabs and blocks of Permian limestone and chert. The accretionary age of both the Samondake and Funafuseyama units is Middle Jurassic. Much of the Nabi unit is also stratigraphically chaotic, varying from highly deformed mélanges with Triassic chert slabs to weakly broken Jurassic turbidite, but the timing of

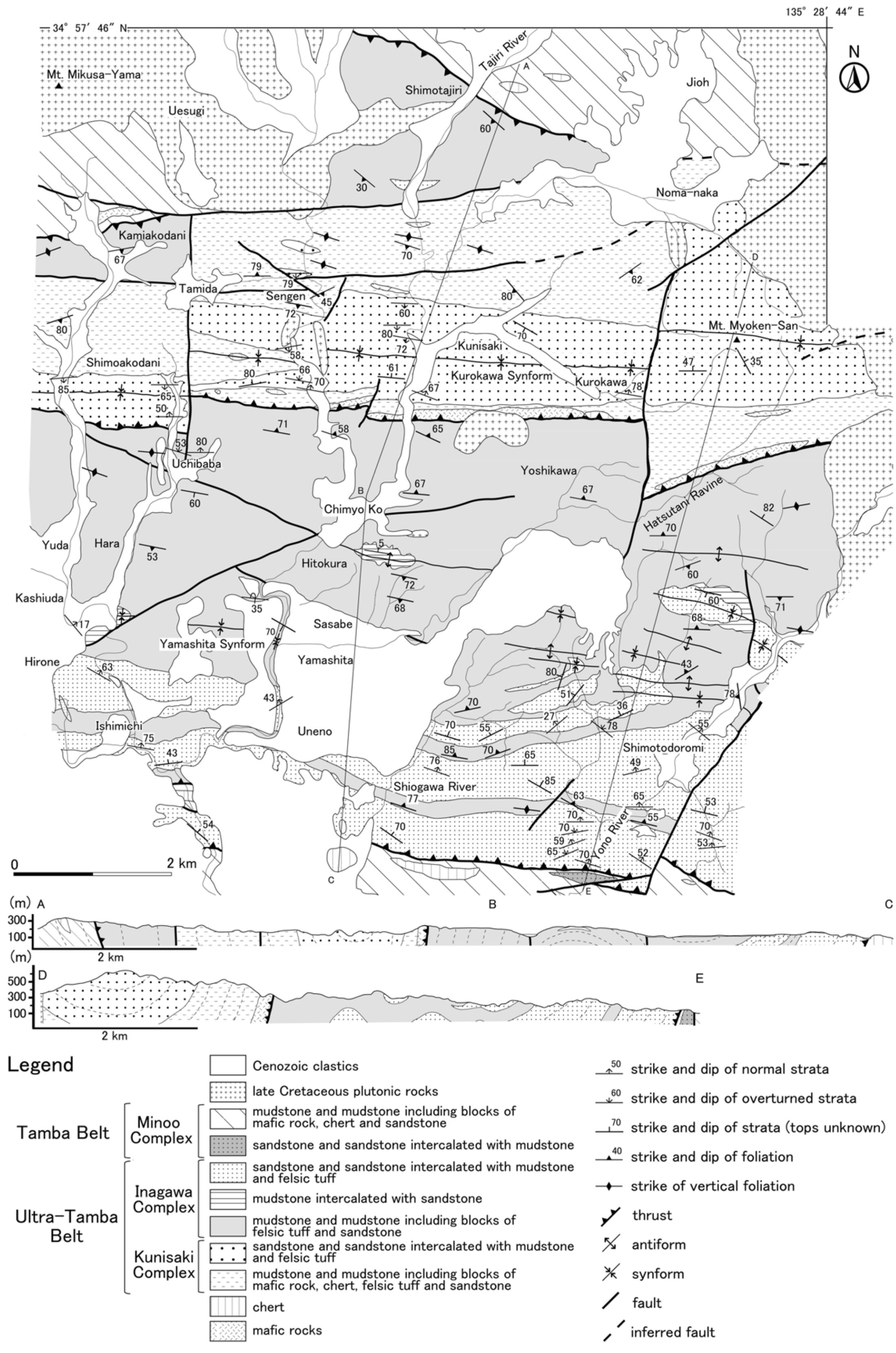

Fig. 2b.20. Geological map and geological cross-section of the Kawanishi–Inagawa area, southeastern part of Hyogo Prefecture and northwestern part of Osaka Prefecture (modified after Sugamori 2009*a*). The Ultra-Tamba Belt in the area is thrust over the Tamba Belt (Jurassic AC) and divided into the Kunisaki and Inagawa complexes (in structurally descending order). These complexes form a pile of nappes that in the Inagawa Complex includes clastic rocks younger than those in the Kunisaki Complex, and are interpreted as being formed by successive accretionary growth. The age of east–west-trending upright folds developing into the Ultra-Tamba and Tamba belts is probably early Cretaceous, because of late Cretaceous plutonic rocks intruded.

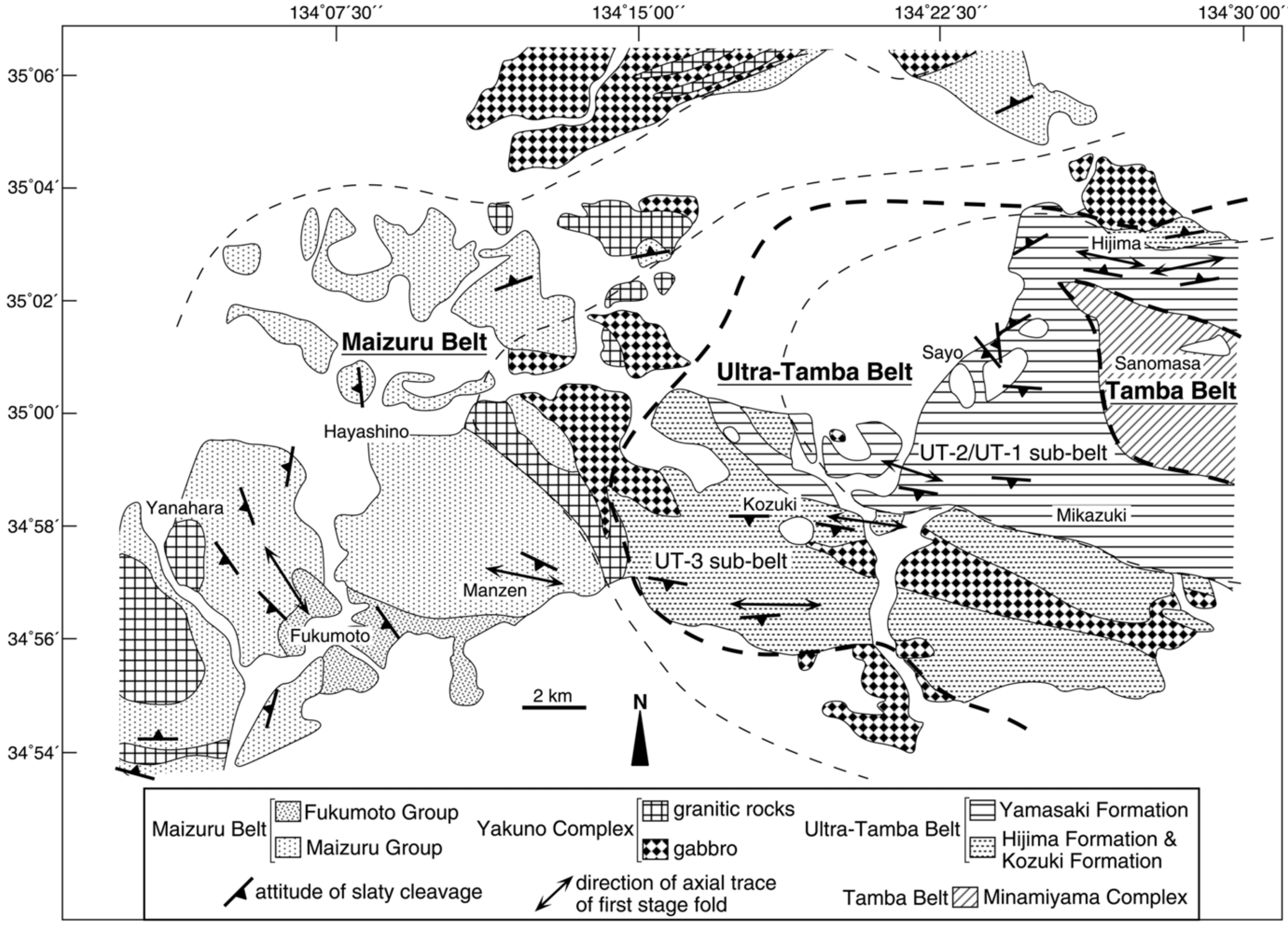

Fig. 2b.21. Regional structure in western Hyogo and eastern Okayama prefectures (modified after Takemura & Suzuki 1996). The Maizuru, Ultra-Tamba and Tamba belts occur as a pile of nappes and form an antiform in this area.

accretion was early Late Jurassic. The Kamiaso unit shows a stratigraphically coherent upper oceanic plate succession, comprising Lower Triassic siliceous claystone, Middle Triassic–Early Jurassic radiolarian ribbon chert and Middle Jurassic siliceous mudstone conformably covered by turbidite with rare conglomerate interbeds. Finally, the Kanayama unit consists of mélanges and is the youngest of the Mino ACs, yielding earliest Cretaceous radiolarians from mudstones.

Lithology

Although varying from unit to unit, the main lithologies of the ACs in the Mino area are summarized in Figure 2b.24.

Basalt

The basaltic rocks are massive, pillowed, brecciated (hyaloclastite), heavily altered and weakly metamorphosed to prehnite-pumpellyite

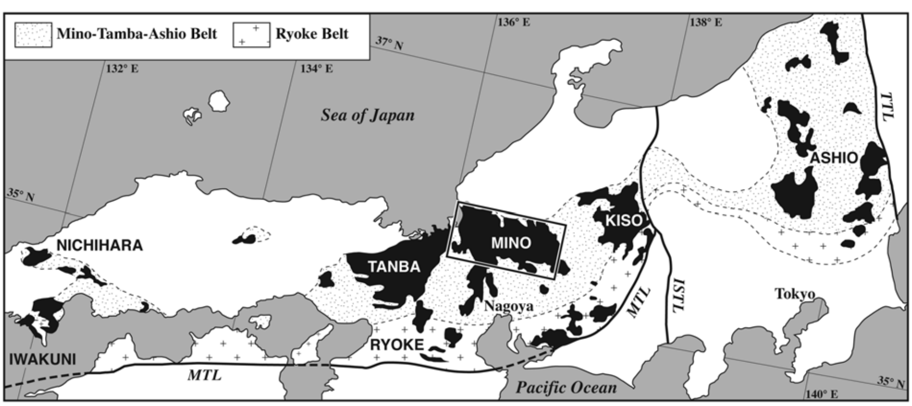

Fig. 2b.22. Map showing the location of the Mino–Tamba–Ashio Belt and the Ryoke Belt (metamorphic equivalent of the former). Black areas indicate the actual distribution of the rocks of these belts (modified from Nakae 2000). Open box indicates the map area of Figure 2b.23. MTL, Median Tectonic Line; ISTL, Itoigawa–Shizuoka Tectonic Line; TTL, Tanakura Tectonic Line.

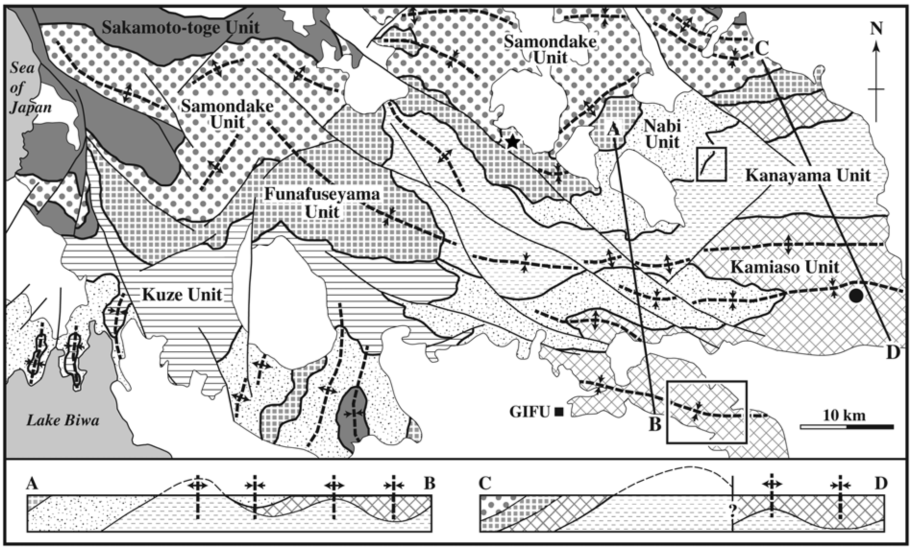

Fig. 2b.23. Map showing the tectonostratigraphic subdivision of the ACs in the Mino area and geological cross-sections along the lines A–B and C–D (modified from Nakae 2000). Map area is indicated in Figure 2b.22. Larger and smaller open boxes indicate the map areas of Figures 2b.25 and 2b.27, respectively. Black star is the locality of Permo-Triassic boundary section reported by Sano *et al.* (2010), and black circle is the locality of Kamiaso conglomerate including *c.* 2000 Ma gneiss clast (Adachi 1971).

facies. The radiometric ages are difficult to measure because of the alteration, but conformable relationships with overlying limestone and chert formations suggest that the basalts are Early Permian or older. Triassic basalts have also been reported from a few localities on the basis of their intimate occurrence with Triassic radiolarian chert (e.g. Wakita 1984). Chemical compositions indicate that the basalts formed in a hot-spot oceanic island setting near mid-ocean ridges (Jones *et al.* 1993).

Limestone
The majority of the limestones in the Mino area are Early–Middle Permian cap carbonates resting on the basaltic oceanic island basement, although Carboniferous limestone blocks in mélanges and Upper Triassic deep-marine micritic limestones are known at several localities (Sano & Kojima 2000). The Permian limestone yields fossils such as fusulinaceans, bivalves, brachiopods, corals and gastropods. No Triassic shallow-marine limestone has been reported from the Mino Belt, but Triassic conodonts have been recovered from cave-filling clastic carbonates in the Permian limestone (Sano & Kojima 2000). Further, Middle Triassic submarine landslide deposits occur embedded within deep-marine chert (Kojima & Sano 2011), implying that shallow carbonate accumulation continued into Triassic time (Fig. 2b.24). The Upper Triassic deep-marine limestones (5–10 cm in thickness) are interbedded with chert, and characteristically include thin shells of planktonic bivalves and radiolarian tests.

Chert
This lithology is mostly radiolarian ribbon chert composed of alternating beds of several-centimetres-thick chert and several-millimetres-thick siliceous shale. The chert consists of micro- to crypto-crystalline quartz and radiolarian remains, and is lacking in coarse clastic materials. The chert and overlying siliceous mudstone have been biostratigraphically studied by using radiolarian and conodont fossils. The cherts rest conformably on the basalt with interbeds of hydrothermal chert and resedimented dolomite at the boundary horizon (Sano 1988). The Upper Permian chert is covered by Permo-Triassic boundary carbonaceous black shale, followed by Early Triassic siliceous lithologies comprising alternating light grey siliceous shale and carbonaceous black shale. This Early Triassic siliceous unit, referred to as siliceous claystone in this chapter, grades upwards into radiolarian chert. These Middle Triassic cherts contain rare coarse clastic horizons containing chert, siliceous shale, basic volcanic rock, apatite, dolomite, glauconite, polycrystalline quartz and Permian and Triassic radiolarian and conodont remains (Kojima *et al.* 1999). The clastic materials are considered to have been transported by submarine landslides from nearby oceanic islands (Kojima & Sano 2011). The chert sequence gradually changes to overlying Early–Late Jurassic siliceous mudstone, deposited as the oceanic plate approached the trench (Fig. 2b.24). Manganese-carbonate nodules often found near the chert-mudstone boundary contain extraordinarily well-preserved radiolarians and provide important age controls.

Clastic sediments
The siliceous mudstones mentioned above are locally interbedded with acidic tuff derived from volcanic arc on the continental margin, and are overlain by trench-fill turbidites. Although the palaeocurrent directions analysed by using sole markings of the turbidites are not consistent throughout the Mino area, north–south-aligned across-trench and west–east-aligned trench-parallel transportation of clastic materials are dominant (Adachi & Mizutani 1971). Mineralogical studies of sandstones and conglomerates in this clastic succession indicate a metamorphic provenance (e.g. Mizutani 1959) because of the occurrence of pyrope-rich garnet indicating a granulite facies protolith (Adachi & Kojima 1983; Takeuchi 2000). Rb–Sr whole-rock isochron data from gneiss clasts in the Kamiaso conglomerate (see Fig. 2b.23 for the locality) yielded an age of *c.* 2000 Ma (Adachi 1971; Shibata & Adachi 1974; Fig. 2b.23), and CHIME and SHRIMP ages of zircons and monazites in sandstone and clasts of conglomerate range from 3420 to 161 Ma (Suzuki *et al.* 1991; Y. Sano *et al.* 2000; Hidaka *et al.* 2002; Nutman *et al.* 2006). Taken together, these lines of evidence described above demonstrate that the clastic materials of the Mino ACs were derived from a Precambrian continent exposing high-grade metamorphic rocks.

Geological structure

The ACs in the Mino–Tamba–Ashio Belt have two types of characteristic geological structures: fault-bounded stack of chert-clastic sequence; and mélange.

Fault-bounded stack of chert-clastic sequence
Rocks of the Kamiaso unit are characterized by the repeated occurrence of chert and clastic rocks, with one of the best examples being observed in the Unuma area (Fig. 2b.25). Early Triassic siliceous

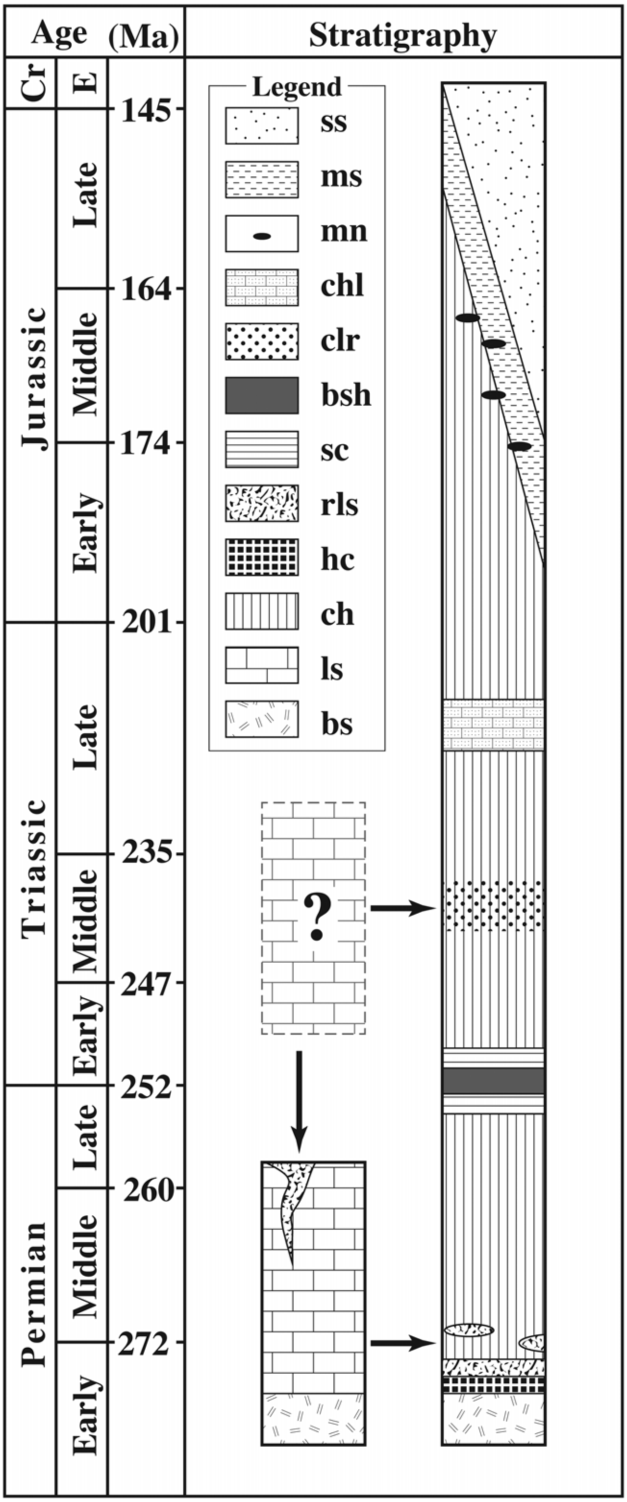

Fig. 2b.24. Schematic diagram illustrating stratigraphy of the Permian–earliest Cretaceous shallow-marine (left) and deep-marine (right) oceanic rock assemblages of the Mino–Tamba–Ashio Belt (after Sano & Kojima 2000). Presence of the Triassic shallow-marine carbonate is estimated on the basis of the Triassic fossils found in the cave deposits in Permian limestone and of the submarine landslide deposits in the Triassic deep-marine chert derived from shallow-marine oceanic rocks. ss, sandstone; ms, mudstone; mn, manganese carbonate nodule; chl, alternating chert and limestone; clr, submarine landslide deposit; bsh, black carbonaceous shale; sc, siliceous claystone; rls, resedimented limestone and dolomite; hc, hydrothermal chert; ch, chert; ls, limestone; bs, basalt.

claystone, Middle Triassic–Early Jurassic radiolarian ribbon chert and Middle Jurassic siliceous mudstone covered by coarse clastic rocks together define a synformal structure with a westwards-plunging fold axis (Kondo & Adachi 1975; Kimura & Hori 1993; Yoshida & Wakita 1999). Detailed radiolarian and conodont biostratigraphic studies of the rocks exposed along the Kiso River reveal that the geological package, apparently composed of many layers of chert and clastic rocks, actually comprises thin sheets of one chert-clastic formation repeated by thrust faults (Fig. 2b.26; Yao *et al.* 1980; Matsuoka *et al.* 1994). The stacking structure is considered to have formed during the off-scraping process of subduction-accretion (Fig. 2b.2), with the Permo/Trias boundary black shale deforming more easily than the underlying and overlying cherts and so acting as a décollement surface during accretion (Matsuda & Isozaki 1991; Kimura & Hori 1993).

Mélange

Although the occurrence of mélange is common throughout the Mino–Tamba–Ashio Belt, only one example (Kanayama unit) is described here. The Kariyasu area near the boundary between the Kanayama and Nabi units is underlain by mélanges composed of blocks and sheets of variable size, shape and lithology within a sheared shale matrix (Wakita 1984, 1995). As well as the larger blocks (depicted in Fig. 2b.27a), the mélange also includes many smaller blocks such as metre- to centimetre-scale blocks of chert, siliceous mudstone and sandstone as seen in exposures along the Nagara River near Kariyasu (Fig. 2b.27b). The larger sheets preserve, in part, the original OPS, with Early Triassic siliceous claystone, Middle Triassic–Early Jurassic chert and Middle–Late Jurassic siliceous mudstone forming a coherent mass in the mélange (Fig. 2b.27a). The original OPS can be reconstructed even in the more chaotic mélanges as shown in Figure 2b.27b, indicating that the southeastern part of the mélange formed during the Early–Late Triassic part of the OPS and the northwestern part comprises the Middle Triassic–Jurassic part. Most of the mélanges in the Mino–Tamba–Ashio Belt are thought to have formed along out-of-sequence thrusts during structural thickening within the AC (Fig. 2b.1), although some might have formed by sedimentary and diapiric processes (Wakita 2000).

Recent discoveries

Low-latitude and Southern Hemisphere origin of the Middle Triassic chert

The exact origins of the Mino ACs are difficult to pinpoint because plate configurations during Palaeozoic–Jurassic time are still unclear. However, Ando *et al.* (2001) performed palaeomagnetic and micropalaeontological analyses on the Middle Triassic–earliest Jurassic chert in the Unuma area (Fig. 2b.25). By comparing the magnetic reversal patterns with those of the coeval European sections, they concluded that the chert was deposited in an equatorial region with a palaeolatitude between 10° N and 10° S and that the lower–middle Anisian (Middle Triassic) chert depositional basin was situated in the Southern Hemisphere.

Continuous Permo-Triassic boundary section

The lithological contrast between the Permo-Triassic boundary black shale and the underlying and overlying cherts is too great to have allowed accretion of the succession as a whole without some degree of thrust décollement. While Permian and Triassic chert formations occur ubiquitously not only in the Mino–Tamba–Ashio Belt but also in the Northern and Southern Chichibu belts, completely continuous sections across the system boundary are very rare. However, Sano *et al.* (2010) discovered one such continuous section in the Funafuseyama unit of the Mino area (see Fig. 2b.23 for the

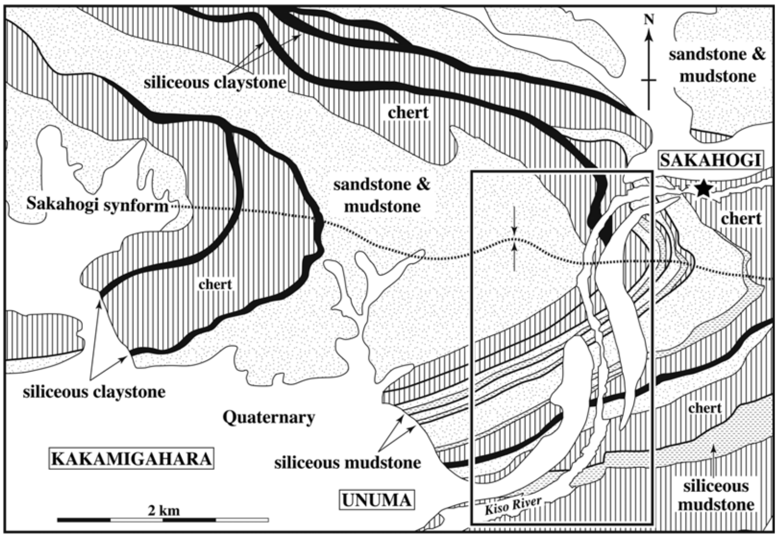

Fig. 2b.25. Geological map of the Unuma area (modified from Yoshida & Wakita 1999). Map area is shown in Figure 2b.23. Star indicates the locality of the Middle Norian (Upper Triassic) impact ejecta reported by Onoue *et al.* (2012). Open box indicates the map areas of Figure 2b.26.

locality). The section comprises uppermost Permian black chert including radiolarians of *Neoalbaillella optima* Zone and lowermost Triassic black claystone with thin black chert beds yielding conodonts of the *Hindeodus parvus* Zone. Sano *et al.* (2012) discussed palaeoenvironmental changes in the Panthalassic Ocean on the basis of the geochemical data obtained from this section.

Upper Triassic impact ejecta preserved in chert

The slow accumulation of sediments such as the radiolarian chert of the Mino–Tamba–Ashio Belt, with apparent average sedimentation rate of several metres per million years (Matsuda & Isozaki 1991), provides the potential opportunity to identify very rare events such as giant meteorite impacts. Onoue *et al.* (2012) reported evidence for such an impact event (based on a platinum group elements anomaly along with nickel-rich magnetite and microspherules) from the middle Norian (Upper Triassic) chert at Sakahogi (see Fig. 2b.25 for the locality). They were able to precisely determine the age by using the microfossils, and suggested the probable correlation of the event with the 215.5 Ma Manicouagan impact crater in Canada.

Chichibu Belt (AM)

The Chichibu Belt is one of several elements in the Outer Zone of SW Japan characterized by a zonal arrangement of basement rocks outcropping broadly parallel to the Japanese islands. The geological units of the belt are composed mainly of Late Palaeozoic–middle Mesozoic ACs and are in fault contact with the Sanbagawa metamorphic rocks to the north and with Cretaceous ACs of the Shimanto Belt to the south. The belt is distributed over a distance of 1500 km from the Kanto Mountains in the NE through Shikoku and Kyushu to the Ryukyu islands in the SW. The Chichibu Belt is divided into three sub-belts based on characteristic features of their components and geological structures. From north to south these are the Northern Chichibu, Kurosegawa (Middle Chichibu) and Southern Chichibu sub-belts, the three being juxtaposed with each other in most areas from the Kanto Mountains to Kyushu.

This section begins with a brief overview of research history of the Chichibu Belt followed by descriptions of the stratigraphy and age. The OPS reconstructed from components of the Chichibu Belt is summarized in Figure 2b.28. Finally, formative processes are discussed on the basis of comparisons of OPS between the Northern and Southern Chichibu sub-belts.

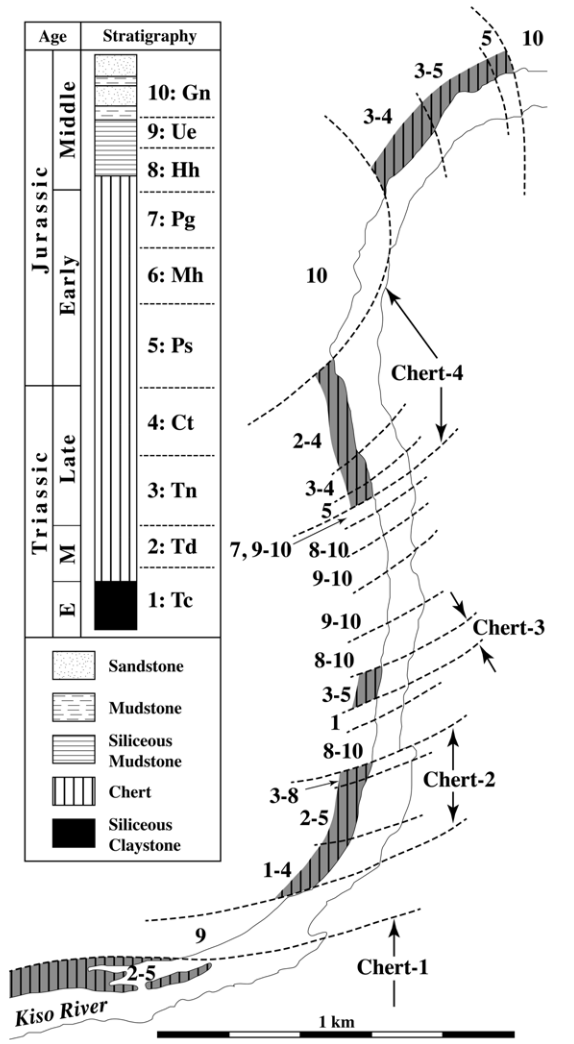

Fig. 2b.26. Radiolarian ages of the rocks along the Kiso River. Map area is shown in Figure 2b.25. Gn, *Guexella nudata*; Ue, *Unuma echinatus*; Hh, *Hsuum hisuikyoense*; Pg, *Parahsuum* (?) *grande*; Mh, *Mesosaturnalis hexagonus*; Ps, *Parahsuum simplum*; Ct, *Canoptum triassicum*; Tn, *Triassocampe nova*; Td, *Triassocampe deweveri*; Tc, *Triassocampe coronata* (after Matsuoka *et al.* 1994).

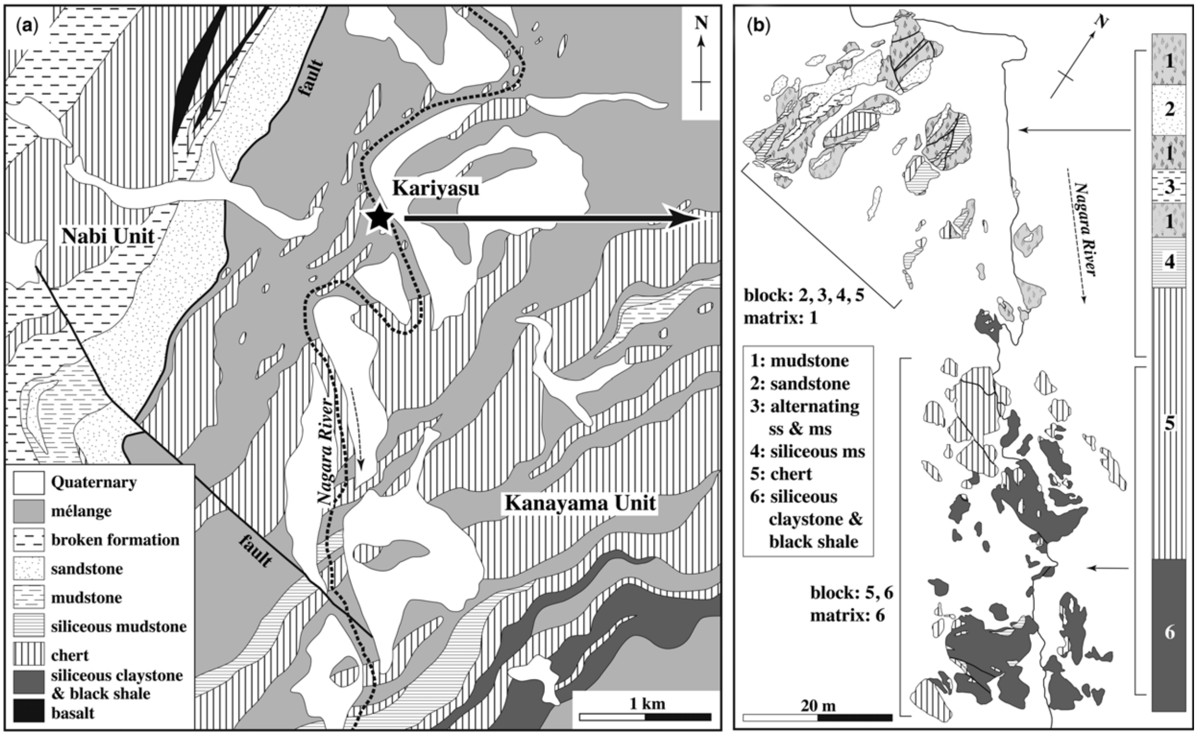

Fig. 2b.27. (**a**) Geological map of the Kariyasu area (modified from Wakita 1984, 1995). Map area is shown in Figure 2b.23. (**b**) Geological map along the right bank of the Nagara River (modified from Wakita 2000). Map area is indicated as black star in (a).

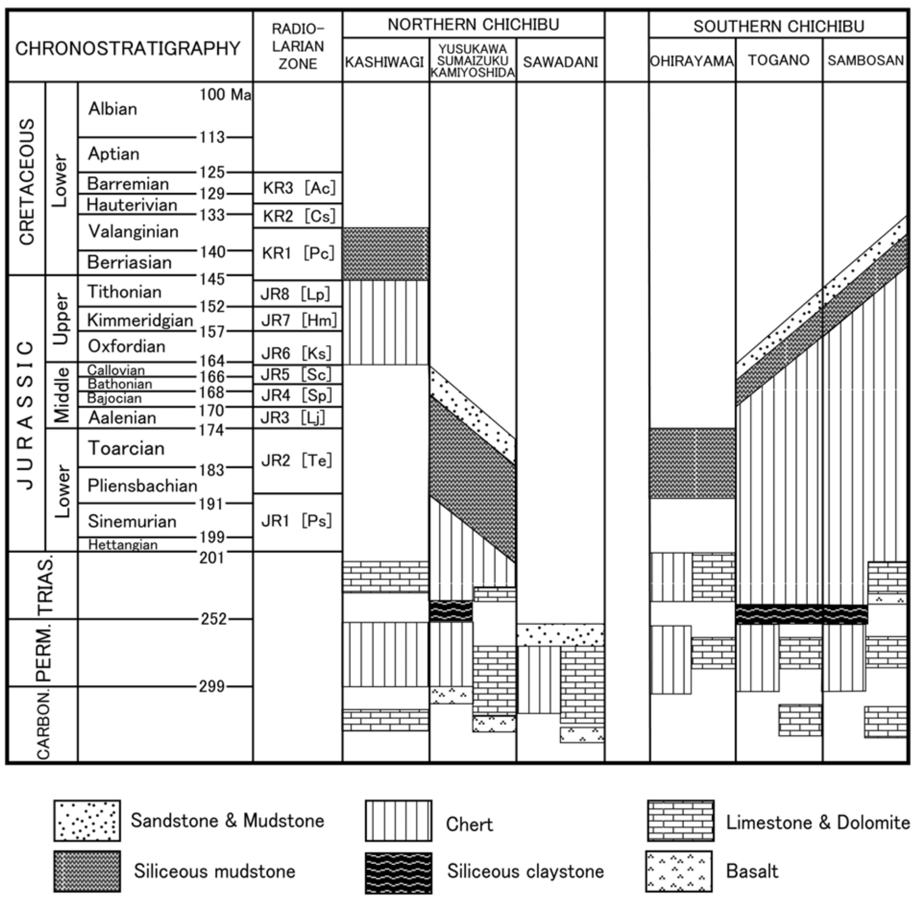

Fig. 2b.28. Stratigraphy and age of units in the Chichibu Belt. Adopted from Matsuoka *et al.* (1998). Radiolarian zonation for the Jurassic and Lower Cretaceous is updated from Matsuoka (1995).

Historical review

Geological investigations of the Chichibu Belt were initiated at the end of the 19th century, and included early reconnaissance work by Naumann (1885). A comprehensive study was completed by Kobayashi (1941) who wrote an article entitled 'Sakawa Orogenic Cycle and its bearing on the origin of the Japanese Islands'. The Sakawa area is located in the central part of Shikoku and has become regarded as a key area for clarifying the stratigraphy and age of the geological units in the Chichibu Belt (e.g. Yehara 1927; Kobayashi 1941). In the 1950s extensive field research was carried out mainly in Shikoku, detailed geological maps were produced and the threefold subdivision was introduced (Northern, Middle and Southern sub-belts). The Middle Chichibu Sub-belt, which is characterized by serpentinites, granitic rocks of *c.* 400 Ma, metamorphic rocks, and marine fossil-bearing beds ranging from middle Palaeozoic to Cretaceous in age, has come to be called the Kurosegawa Sub-belt (Ichikawa *et al.* 1956). Since the 1970s Triassic conodonts and Triassic–Early Cretaceous radiolarians have been reported from the Chichibu Belt and, with the introduction of plate tectonic theory, the sedimentary rocks of the Chichibu Belt have been interpreted as representing slices of ACs. Previous publications are summarized in Hada & Kurimoto (1990) for the Northern Chichibu Sub-belt and Matsuoka & Yao (1990) for the Southern Chichibu Sub-belt. Matsuoka *et al.* (1998) proposed a division of the ACs into units applicable for the entire Chichibu Belt and well as the Kanto Mountains and Shikoku, where sufficient geological and micropalaeontological data were available.

Stratigraphy and age

The stratigraphy and age of each of the Chichibu units defined by Matsuoka *et al.* (1998) are illustrated on Figure 2b.28. These ACs essentially consist of pelagic sequences and terrigenous sediments, with the former being further divided into deep-water chert successions and a shallow-water limestone-basalt association. The terrigenous sediments consist chiefly of sandstone-dominated alternating sandstone/mudstone beds of trench-fill origin. Characteristic facies of the ACs include coherent chert-clastic sequences and mélange, with the former preserving a stratigraphic succession from pelagic chert through hemi-pelagic siliceous mudstone to terrigenous coarse clastic rocks and typically represented by the Togano Group (Matsuoka 1984, 1992) in the Sakawa area, central Shikoku (Fig. 2b.29). On the other hand, the mélanges comprise mixtures of pelagic rocks (including chert) and limestone-basalt lithologies in a mudstone matrix, as represented by the Sambosan Group in central Shikoku. Rock successions in Figure 2b.28 are based either on the real stratigraphy of chert-clastic sequence or reconstructed sequences based on the relationship between rock types and their microfossil (radiolarian, conodont, foraminifer) ages.

Northern Chichibu Sub-belt

The rocks of the Northern Chichibu Sub-belt are composed mainly of Mesozoic ACs subdivided into the Early–Middle Jurassic Kamiyoshida, Sumaizuku and Yusukawa units and earliest Cretaceous Kashiwagi unit. In addition there are subordinate amounts of Late Palaeozoic AC rocks, known as the Sawadani unit. The spatial distributions of these ACs are well documented in the Kanto Mountains and Shikoku, and the boundary between the Northern Chichibu Sub-belt and the Kurosegawa Sub-belt has been discussed by Yamakita (1998). A younger age limit for the Chichibu rocks is provided by an unconformable cover of Lower Cretaceous shallow-marine and brackish sediments, collectively known as the Ryoseki–Monobegawa groups.

The Kashiwagi unit rests directly on the Mikabu metabasalts, which are sandwiched between the Chichibu ACs and the Sanbagawa metamorphic rocks. The type area of the Kashiwagi unit is located in the Kanto Mountains, and consists mainly of weakly metamorphosed oceanic sequences such as chert, limestone and metabasalt. It is not well dated by microfossils, although the youngest bed is siliceous mudstone and known to be of earliest Cretaceous in age.

The Kamiyoshida, Sumaizuku and Yusukawa units are Lower–Middle Jurassic ACs. The Kamiyoshida and Sumaizuku units have their type areas in the Kanto Mountains, and mainly comprise disrupted chert-clastic sequences associated with basalt. In contrast, the Yusukawa unit, which crops out only in the southern part of the Northern Chichibu Sub-belt, has a type section in western Shikoku and is characterized by terrigenous clastics-dominated mélange facies. A reconstructed stratigraphy for these three units is shown together in Figure 2b.28 as age-diagnostic microfossil data are too sporadic to allow more specific detail. However, it is known that clastic rocks of the Kamiyoshida unit are younger (and tectonostratigraphically lower) than those of the Sumaizuku unit. Finally, the oldest rocks of the sub-belt, represented by the Sawadani unit, crop out mainly in Shikoku and consist of Carboniferous–Permian limestone-basalt associations and Late Permian clastic rocks. This unit occupies the uppermost part of the ACs exposed in the Northern Chichibu Sub-belt.

The geological units in the Northern Chichibu Sub-belt exhibit a classic thrust-stacked geometry. The structurally lowest but geochronologically youngest Kashiwagi unit (lowest Cretaceous) is overlain by the Lower–Middle Jurassic Kamiyoshida–Sumaizuku–Yusukawa units which themselves lie beneath the oldest (Upper Permian) and highest Sawadani unit. This tectonic stacking was formed by successive accretion from Late Permian to earliest Cretaceous times. The notable apparent absence of Triassic and Upper Jurassic AC rocks in the Northern Chichibu Sub-belt may be related to the effects of tectonic erosion or strike-slip movement along the plate boundary.

Southern Chichibu Sub-belt

The rocks of the Southern Chichibu Sub-belt mainly comprise Jurassic and earliest Cretaceous ACs, and have been subdivided into the Ohirayama, Togano and Sambosan units from north to south. No Palaeozoic ACs have been reported so far. The accreted units are associated with Jurassic–Lower Cretaceous shallow-marine deposits distributed from the Kanto Mountains to Kyushu and collectively known as the Torinosu Group. These shallow marine deposits (which characteristically include 'Torinosu-type' reef limestone) are now intercalated with the ACs, but probably unconformably rested upon them originally.

All of the type localities of the Ohirayama, Togano and Sambosan units are in central Shikoku (Fig. 2b.29), but equivalent geological entities are traceable from the Kanto Mountains to the Ryukyu islands. The Ohirayama unit has been studied in detail only in its type locality, the Sakawa area, central Shikoku, where it consists mainly of mélange facies containing Permian limestone and Triassic chert (Triassic limestone blocks are also reported from western Shikoku).

The Togano unit is composed predominantly of Triassic–Jurassic chert-clastic sequences associated with subordinate mélange. The chert-clastic sequences show an upwards-coarsening succession which reflects landwards drift of the seafloor from a pelagic realm towards a trench (Fig. 2b.1). The unit is characterized by a south-vergent imbricate structure and south-younging polarity of the chert-clastic sequences.

The Sambosan unit consists mainly of Upper Jurassic–Lower Cretaceous mélange sequences which include abundant

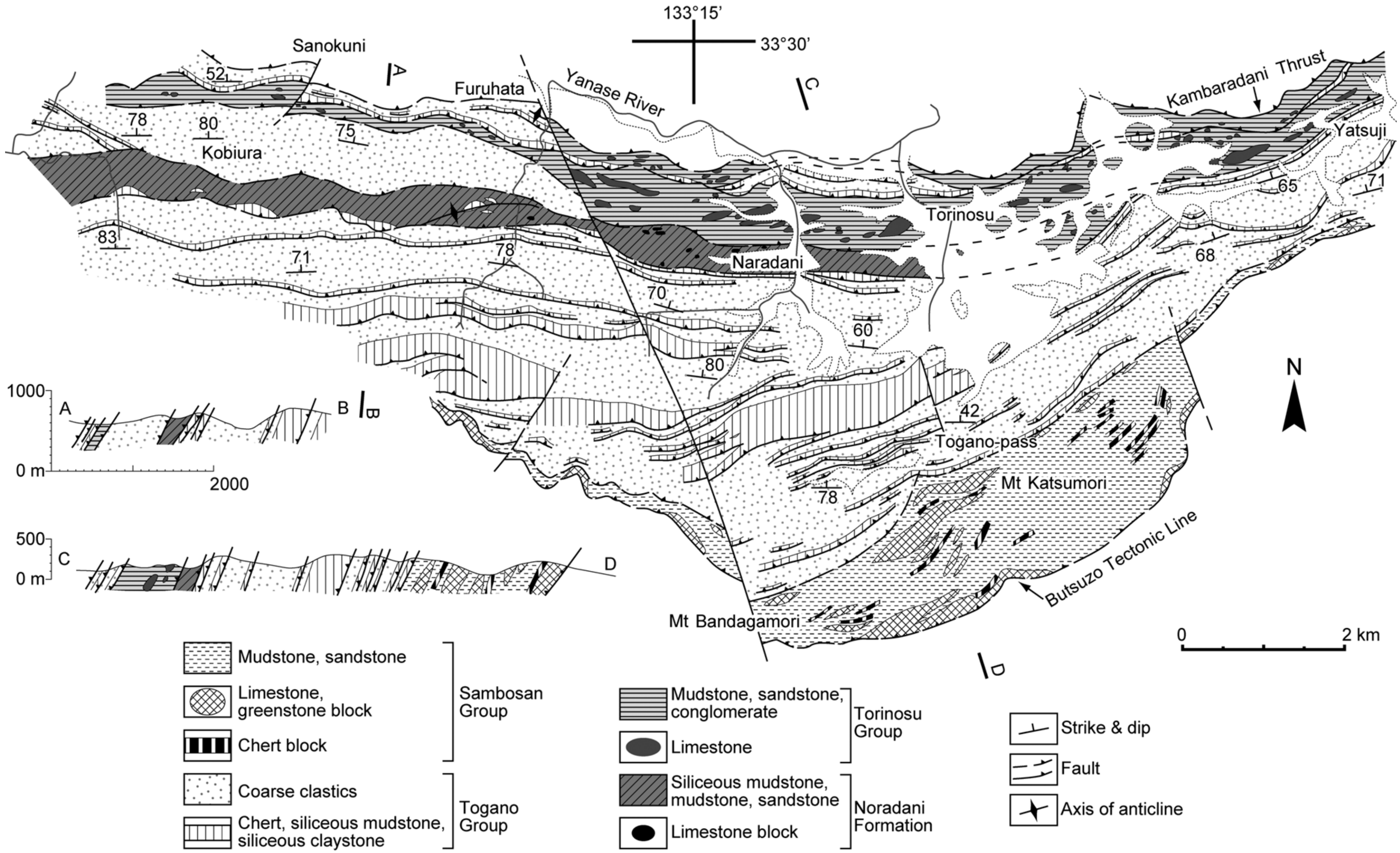

Fig. 2b.29. Geological map of the Southern Chichibu Belt in the Sakawa area, central Shikoku. The Togano and Sambosan groups are representative of the Togano and the Sambosan units, respectively. The Togano Group is characterized by alternating occurrence of chert and coarse clastic rocks. This is due to tectonic repetition of chert-clastic sequences. The Sambosan Group is distributed south of the Togano Group and is characterized by chert and limestone-greenstone blocks in a matrix composed mainly of mudstone. The Naradani Formation and the Torinosu Group are shallow-marine sequences which originally covered the Togano Group with an unconformity. Adopted from Matsuoka (1992).

Triassic–Jurassic chert blocks and Triassic limestone blocks accompanied by basalts of seamount origin. Late Triassic megalodont (bivalve) -bearing limestones have been found from many localities in the Sambosan unit, indicating that the limestones were formed in the Tethyan Province (Tamura 1987). Terrigenous rocks in the Sambosan unit are always younger than those in the Togano unit juxtaposed to the north.

Finally, two major stages of tectonic development have been detected in the Southern Chichibu Sub-belt (Fig. 2b.30). The Togano unit was formed by successive offscrape-accretion mainly during Middle–Late Jurassic times, whereas the Sambosan unit was constructed by Late Jurassic–Early Cretaceous collision-accretion of seamounts. This difference in tectonic setting is considered to be related to the topography of the subducting oceanic plate: an oceanic plate with an abyssal plain for the Togano unit and an oceanic plate with seamounts for the Sambosan unit.

Formative processes of the Chichibu Belt

Diverse scenarios have been proposed for the origins of the Chichibu belt, with Yao (2000) categorizing these into five major models used to explain the tectonic evolution of SW Japan. When limited to the Chichibu Belt, such models can be divided into two types – nappe model and translation model – with the differences between these depending largely on how the Kurosegawa Sub-belt is interpreted. The nappe model requires that the Kurosegawa rocks rest on the Jurassic ACs as a nappe, with the Northern and Southern Chichibu sub-belts being directly connected to each other beneath the nappe (Isozaki & Itaya 1991; Hara *et al.* 1992; Isozaki 1996; Yao 2000). The translation model assumes that the Kurosegawa rocks are sandwiched between the ACs of the Northern and Southern Chichibu sub-belts (Taira & Tashiro 1987). These models can be tested by comparing the ACs in the Northern and Southern sub-belts (Fig. 2b.28). In this context, it is clear that there is an overall similarity between the two sub-belts, both being dominated by Jurassic–earliest Cretaceous ACs with Lower Triassic siliceous claystone, Middle Triassic–Jurassic chert and younger terrigenous sequences. Furthermore, limestone blocks within mélange facies have similar Carboniferous–Triassic ages. On the other hand, considerable differences are recognizable in the stratigraphy of the two sub-belts, the most critical being the duration of hemi-pelagic siliceous mudstone sedimentation. The deposition of siliceous mudstone in the Northern Chichibu Sub-belt lasted two to three times longer than that in the Southern Chichibu Sub-belt. In addition, whereas Upper Jurassic ACs are common in the Southern Chichibu Sub-belt, they are missing from the Northern Chichibu Sub-belt. To satisfy both these similarities and differences at the same time, we view the translation of the model as being more suitable as an explanation for the structural evolution of the Chichibu Belt (Fig. 2b.31). Such a model allows for the ACs of both sub-belts to have been formed along a single convergent plate margin but apart from each other, with lateral variations in oceanic plate stratigraphy. Following their accretion, rocks from the two areas were subsequently juxtaposed with each other during northwards translation of the Southern Chichibu Sub-belt. Such movements, probably linked to left-lateral faulting during Early Cretaceous time along the eastern margin of Asia, have resulted in the Kurosegawa Sub-belt representing the suture zone between the Northern Chichibu and Southern Chichibu sub-belts.

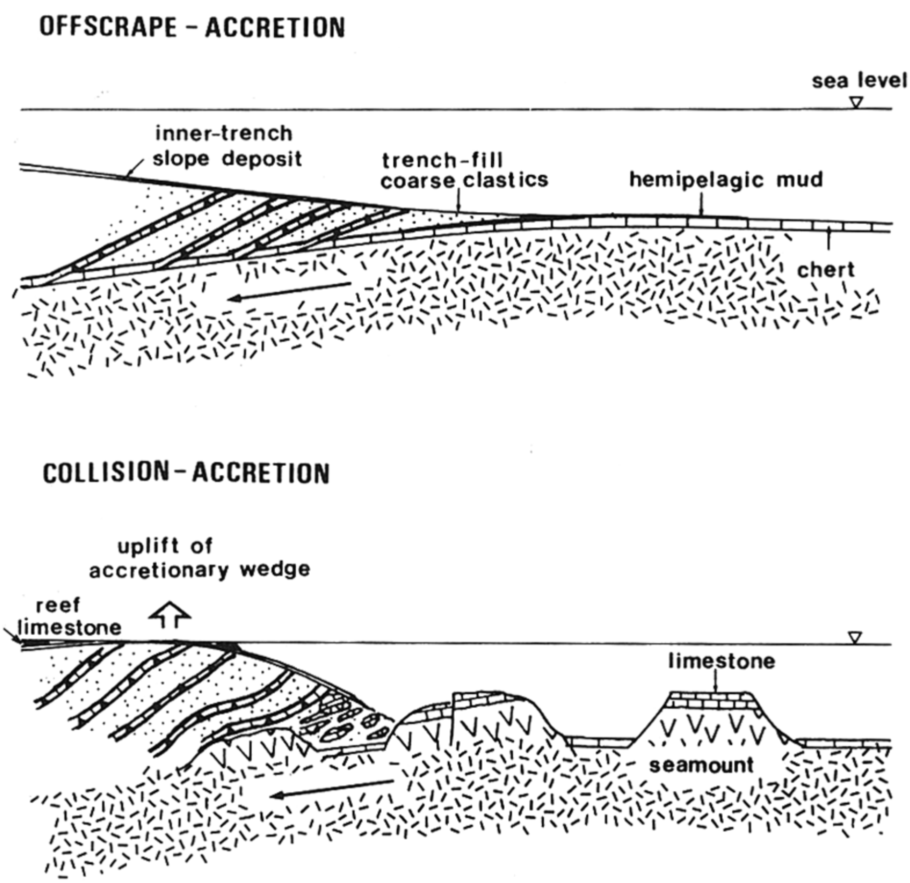

Fig. 2b.30. Schematic diagram showing two major tectonic stages of the Southern Chichibu Belt. Adopted from Matsuoka (1992).

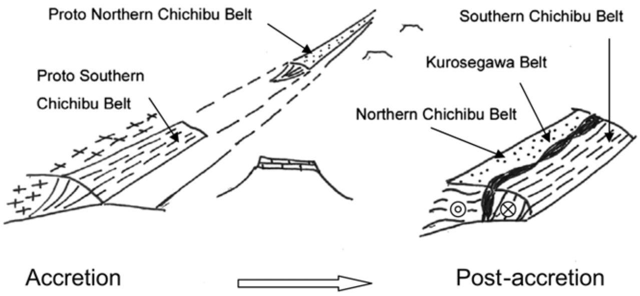

Fig. 2b.31. Formative processes of the Chichibu Belt, characterized by an accretion event along a single subduction zone and a post-accretion translation event.

Nedamo Belt (TU)

The Nedamo Belt (previously referred to as part of the 'Hayachine Tectonic Belt') represents an Early Carboniferous AC named the Nedamo Complex, and crops out across an area 40 km long and 10 km wide. It is a fault-bounded belt sandwiched between the South Kitakami Belt (mainly Palaeozoic shallow-marine deposits; see Chapter 2a) and the North Kitakami Belt (Jurassic AC; see 'North Kitakami Belt' section below) in the Kitakami Massif, Tohoku district, NE Japan (Figs 2b.2 & 2b.32) The boundary faults are generally high-angle and associated with serpentinite, and the tectonic relationships between the Nedamo Belt and the North/South Kitakami belts remain unclear. Generally, both bedding and cleavage strike NW–SE and are steeply SW-dipping, with closed folds (wavelengths of several metres to several hundred metres) being commonplace.

Lithostratigraphic and fossil age constraints

The Nedamo Complex comprises mafic rock, chert, alternations of mudstone and felsic tuff, sandstone and conglomerate, most of them affected by low-grade regional metamorphism and shearing deformation. On the map scale of 1:50 000, the Nedamo Complex indicates large-scale mélange facies disruption with a matrix of alternating mudstone and felsic tuff containing more competent blocks such as basalt and chert. On the outcrop scale, however, exposures display smaller-scale disruption, producing the so-called broken or dismembered facies of Raymond (1984).

Mafic rocks are common in the belt, and consist primarily of basalt (volcaniclastic rock and lava, locally pillowed) with minor amounts of dolerite. Chemical signatures of the mafic rocks show affinities with oceanic island basalt (alkali basalt and within-plate tholeiite) and MORB (Hamano *et al.* 2002; Uchino & Kawamura 2009). The mafic rocks have been affected by metamorphism at prehnite-pumpellyite facies (Moriya 1972), pumpellyite-actinolite facies (Onuki *et al.* 1988), greenschist facies (Uchino & Kawamura 2010*a*) and blueschist facies (epidote-blueschist subfacies; Uchino & Kawamura 2010*a*).

Chert provides a minor component of the belt, occurring as both red hydrothermal massive types with basalt as well as grey varieties. The former often contains iron-manganese layers several centimetres in thickness and microfossils of radiolarians, conodonts and sponge spicules.

Alternations of mudstone and felsic tuff (Fig. 2b.33a, b) are common in the belt, and characterize the Nedamo Complex because they

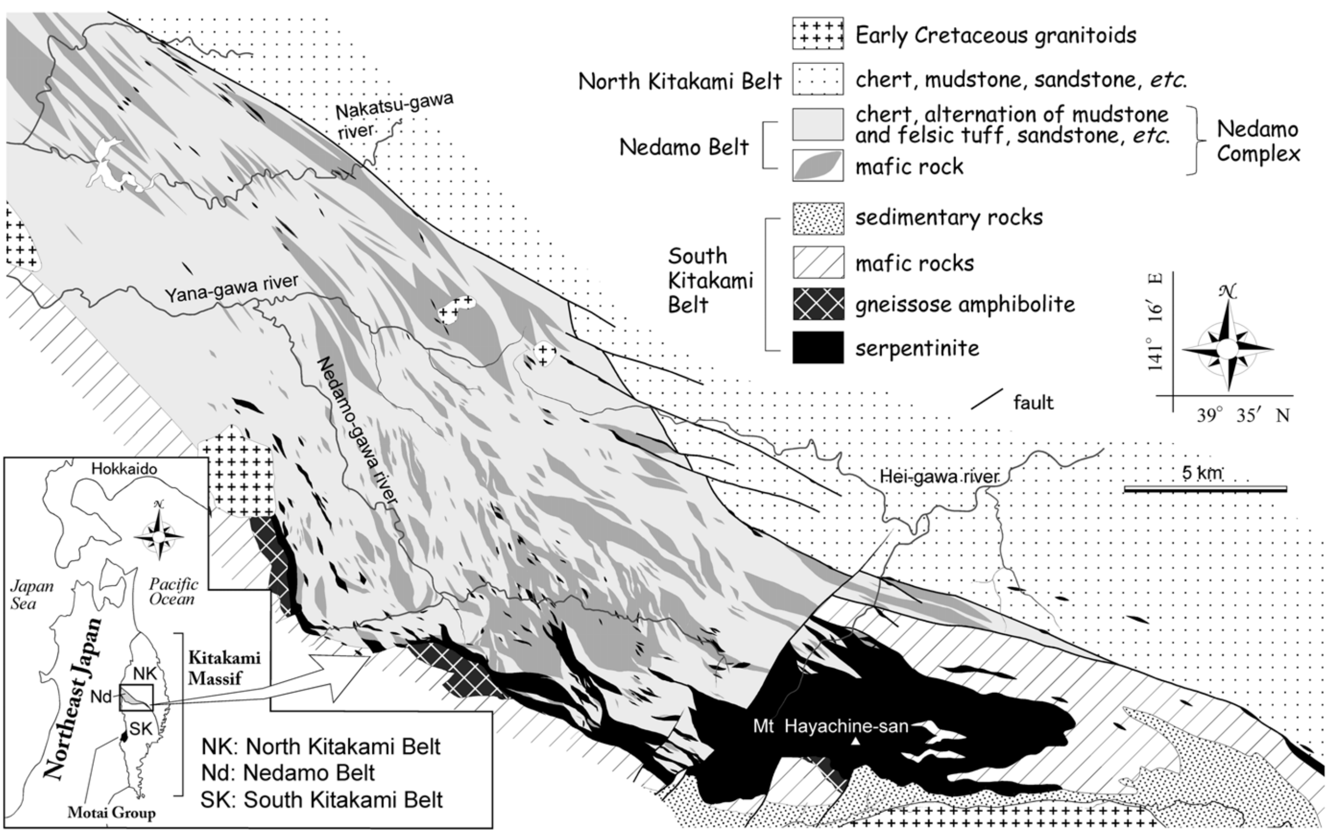

Fig. 2b.32. Geological map of the Nedamo Belt.

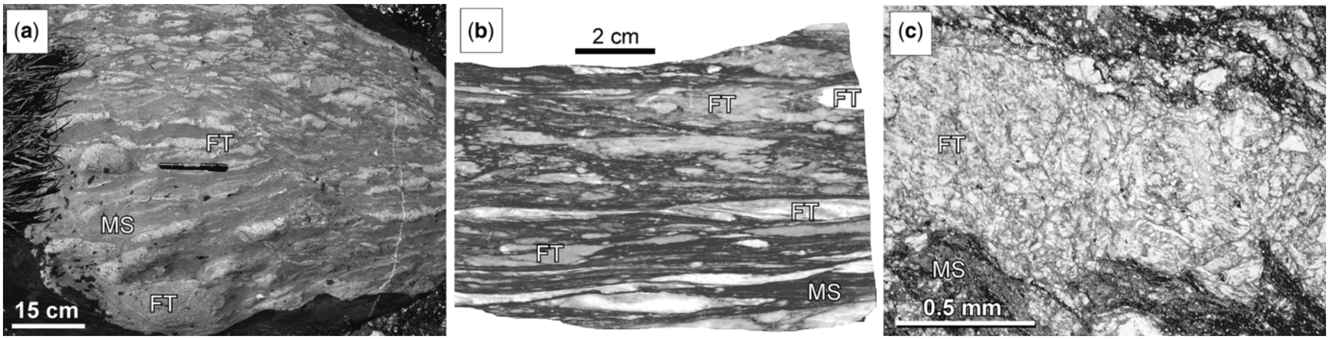

Fig. 2b.33. Outcrop (**a**) and specimen (**b**) of alternation of mudstone and felsic tuff, and photomicrograph (**c**) of the felsic tuff which shows the vitroclastic texture in the alternation (after Kawamura *et al.* 2013). FT, felsic tuff; MS, mudstone.

are few in ACs of other belts in the Japanese islands. Although the pale green felsic tuff looks like chert on outcrop, the vitroclastic texture is recognizable under the microscope (Fig. 2b.33c). The mudstone and felsic tuff beds range in thickness from several millimetres to centimetres, but some felsic tuffs occur as a layer of several metres in thickness within the couplet.

Sandstone occurs sporadically in the belt and is classified as lithic wacke, with the ratio of rock fragments occasionally reaching >75%. Conglomerate, rare in this belt, contains a wide variety of clasts that include dacite-rhyodacite, felsic tuff, basalt, sandstone, chert, limestone and schist.

Limestone clasts in the conglomerate have yielded Chaetetids of uncertain age (Kawamura *et al.* 2013). However, the hydrothermal massive chert associated with MORB includes Late Devonian conodonts *(Palmatolepis glabra prima* and *Palmatolepis* cf. *minuta minuta*) (Hamano *et al.* 2002) and Middle–Late Devonian radiolarians (*Trilonche* sp.) (Kawamura *et al.* 2013), and mudstones have yielded Early Devonian–Early Carboniferous radiolarians (*Palaeoscenidium cladophorum*). The age of trench-fill sediments (i.e. accretion age) is therefore considered to be Early Carboniferous (Uchino *et al.* 2005).

Despite the intense shearing deformation that disturbs the original stratigraphy of the Nedamo Complex, the OPS can be reconstructed (in ascending order) as MORB, hydrothermal massive chert, thin-bedded chert, alternations of mudstone and felsic tuff, and sandstone. Such an oceanic stratigraphy is in marked contrast to that of other Jurassic ACs, which are characterized by limestone, thick-bedded chert and rare felsic tuff. The duration of the OPS of the Nedamo Complex appears to have occupied a relatively short range lasting from Late Devonian (massive chert with MORB) to Early Carboniferous (mudstone) times.

Tectonostratigraphic constraints, regional correlations and geotectonic model

In some places within the Nedamo Belt, there are small (less than several metres in size) exotic masses of ultramafic rock (serpentinite, hornblendite and pyroxenite), hornblende gabbro, granitoids (tonalite and quartz diorite), gneissose amphibolite and schist (garnet-bearing pelitic schist and glaucophane-bearing mafic schist; Figure 2b.34). They are considered to be tectonic blocks displaced along faults during post-accretionary tectonic movements (e.g. Kawamura *et al.* 2007). Phengite in the pelitic and mafic schists has yielded *c.* 380 Ma ^{40}Ar/^{39}Ar radiometric ages (Kawamura *et al.* 2007), which is older than the accretion age of the Nedamo Belt. The amphibolite and igneous rocks are considered to be fragments of Ordovician island-arc basement rocks of the South Kitakami Belt (Kawamura *et al.* 2013), and the schist is considered to be part of the high-P/T schist fragmentary distributed in the Abukuma Massif.

No geological body in the Japanese islands can be fully correlated with the Early Carboniferous AC of the Nedamo Belt. However, the Motai Group (Onuki *et al.* 1962) (Fig. 2b.32) located in the western part of the Kitakami Massif could be lined up as a possible candidate, judging from its geographical location before Early Cretaceous sinistral strike-slip faulting (e.g. Hizume-Kesennuma fault; Ehiro 1977) and its lithologic similarity to the Nedamo Complex (Kawamura & Kitakami Paleozoic Research Group 1988; Uchino & Kawamura 2010*a*). Protoliths of the Renge schists (Carboniferous high-P/T metamorphic complex; see ‘Renge high-P/T rocks’ section) in SW Japan could be another correlative unit, given the metamorphic ages of the Renge schists.

Uchino & Kawamura (2010*b*) provide a geotectonic model (Fig. 2b.35) depicting the Early Carboniferous forearc of the eastern palaeo-Asian arc–trench system, based on sedimentological and petrological studies from the conglomerate containing clasts of ultramafic rock and on 347–317 Ma high-P/T schist (Uchino *et al.* 2008). Given that the Lower Carboniferous successions in the South Kitakami and Nedamo belts are rich in igneous rock and felsic tuff, respectively, volcanism in the island-arc system would have been very active, with a correspondingly large amount of volcanic ash brought down into the trench. The high-P/T schist and the ultramafic rocks would have been rapidly uplifted to crop out in the forearc, given the constraints provided by the schist clast ages and the Early Carboniferous accretion age of the Nedamo Belt.

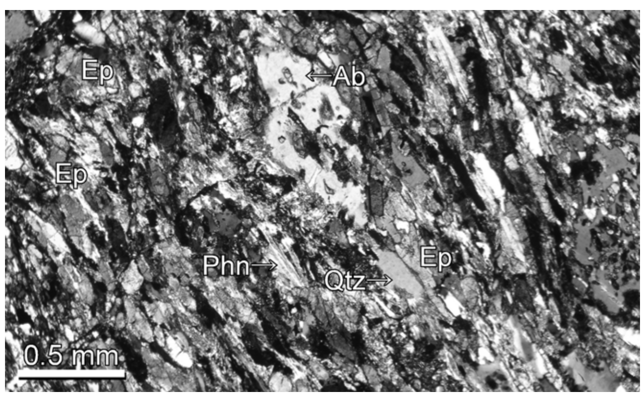

Fig. 2b.34. 380 Ma glaucophane-bearing mafic schist (tectonic block). Ab, albite; Ep, epidote; Phn, phengite; Qtz, quartz.

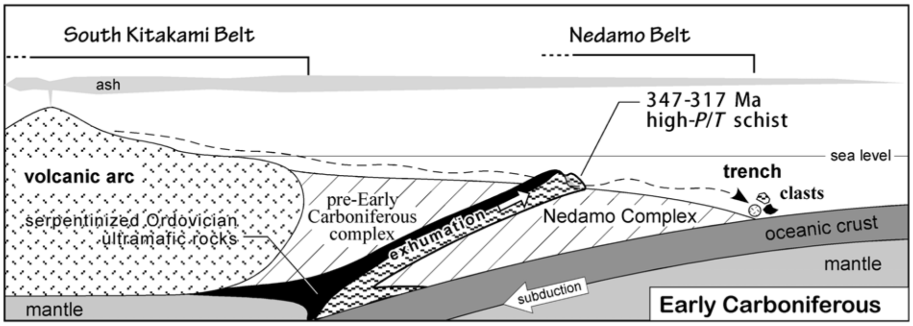

Fig. 2b.35. Geotectonic model of the eastern palaeo-Asian arc-trench system during the Early Carboniferous. The high-P/T schist with ultramafic rock uplifted and cropped out in the forearc within 30 m.y. (after Uchino & Kawamura 2010*b*).

Abukuma Belt (YHi)

The Abukuma Plateau is located in the southernmost part of the pre-Palaeogene outcrop in NE Japan, and is underlain mostly by Early–middle Cretaceous plutonic rocks. Metamorphic rocks occur rather sporadically in this region, and have been divided into four groups based on spatial distribution, metamorphic ages and lithological characteristics (Fig. 2b.36).

The first of these groups is limited to sparse exposures along the northeastern margin of the Abukuma Plateau and collectively named the Matsugadaira–Motai metamorphic rocks. They are characterized by middle Palaeozoic high-P/T metamorphism and belong to the South Kitakami Belt. The second group occurs as isolated roof remnants on plutonic rocks in the northern Abukuma Plateau and consists of thermally metamorphosed limestones, pelites, cherts and basic-ultrabasic rocks (Ehiro *et al.* 1989), similar in lithology to those constituting oceanic islands. Neither fossil nor radiometric age data have been obtained from these rocks. The third group is found in the south-central part of the plateau (the Gosaisyo–Takanuki district) and has been referred to as the Gosaisyo–Takanuki metamorphic rocks. More specifically, however, they are divided into the Gosaisyo Complex of oceanic-crust-type which is thrust over

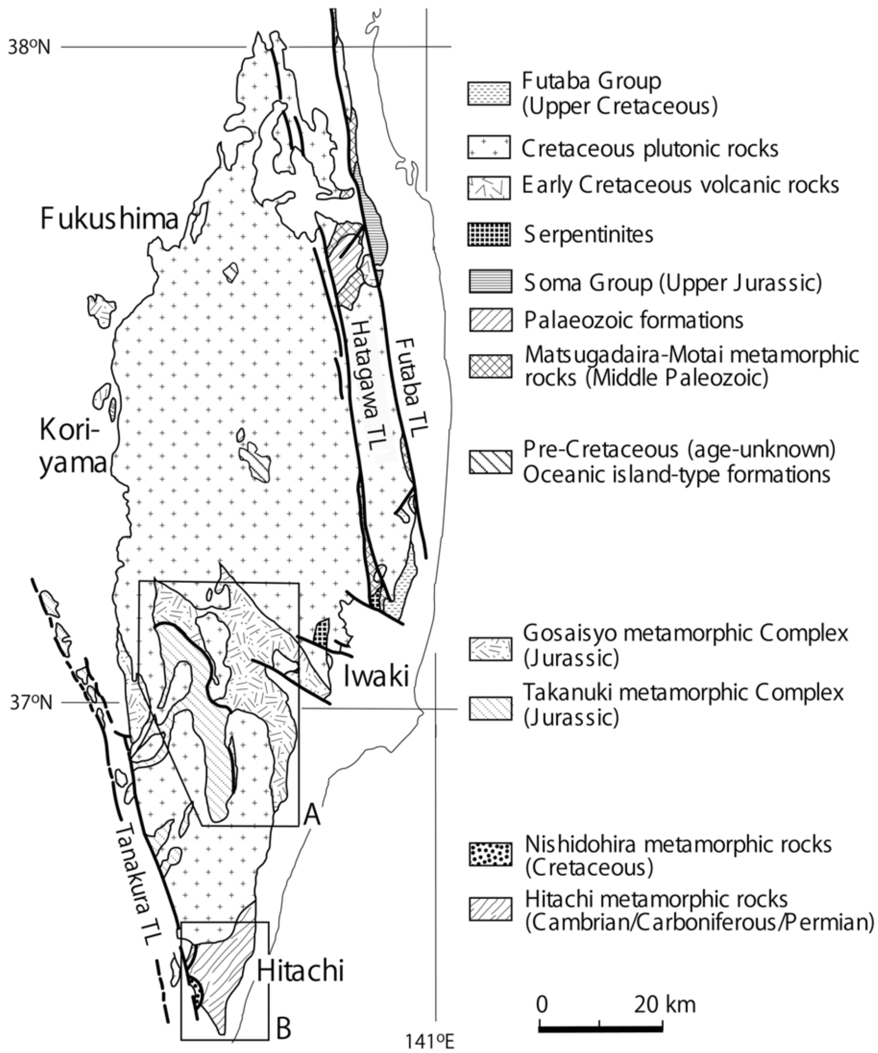

Fig. 2b.36. Geological map of Abukuma Plateau, modified after Tagiri *et al.* (2011). A, Gosaisho–Takanuki district; B, Hitachi district; TL, tectonic line. Note that in the text the Gosaisho and Takanuki metamorphic rocks are referred to as ‘complexes’.

the Takanuki Complex of terrigenous origin. Finally, the fourth metamorphic group crops out in the Hitachi district of the southernmost part of the Abukuma Plateau, comprising the Hitachi and Nishidohira metamorphic rocks. The protoliths of the Hitachi metamorphic rocks are Early and Late Palaeozoic sedimentary, volcanic and related intrusive rocks, including Late Cambrian sediments which are the oldest rocks in Japan. The Nishidohira metamorphic rocks originate from Cretaceous sedimentary rocks, and are in fault contact with the Hitachi lithologies.

The exact relationships between these four metamorphic groups are not yet established. The metamorphic rocks in the Gosaisyo–Takanuki and Hitachi districts will be described below as those constituting the Abukuma Belt, mainly after Hiroi *et al.* (1987, 1998) and Tagiri *et al.* (2010, 2011). The northwestern extension of the belt is obscured by an extensive cover formed by Cenozoic volcanic activity.

Gosaisyo–Takanuki district

The metamorphic rocks of the Gosaisyo and Takanuki complexes are extensively intruded and thermally metamorphosed by Cretaceous plutonic complexes. Several of these plutons were emplaced along or close to the boundary between the two complexes, along with sheets and lenses of ultrabasic rocks enclosed within metamorphic rocks (Fig. 2b.37).

The Gosaisyo Complex is composed mainly of basic and siliceous rocks with subordinate pelitic and calcareous rocks. Chemical compositions of homogeneous and massive basic rocks (probably derived from lava) are similar to those of T-type MORB. Some siliceous rocks preserve Early Jurassic radiolarian fossils and are intercalated with iron ore (magnetite and hematite) layers similar to banded iron formations (Hiroi *et al.* 1987). Zircon grains from a pelitic-siliceous rock yield a broad age clustering at *c.* 450 Ma (Fig. 2b.38b). However, the SHRIMP zircon ages range to *c.* 520 Ma and form a continuum on the Tera–Wasserburg concordia plot. These analyses do not reflect the age of sedimentation, but rather the provenance. It is noteworthy that a fairly uniform provenance age is recorded, in marked contrast with the case of the Takanuki pelitic rocks (Fig. 2b.38e, f). It is significant that a small number of andesitic to rhyolitic dykes belonging to the calc-alkalic rock series occur and have experienced deformation and metamorphic events that are nearly identical to those

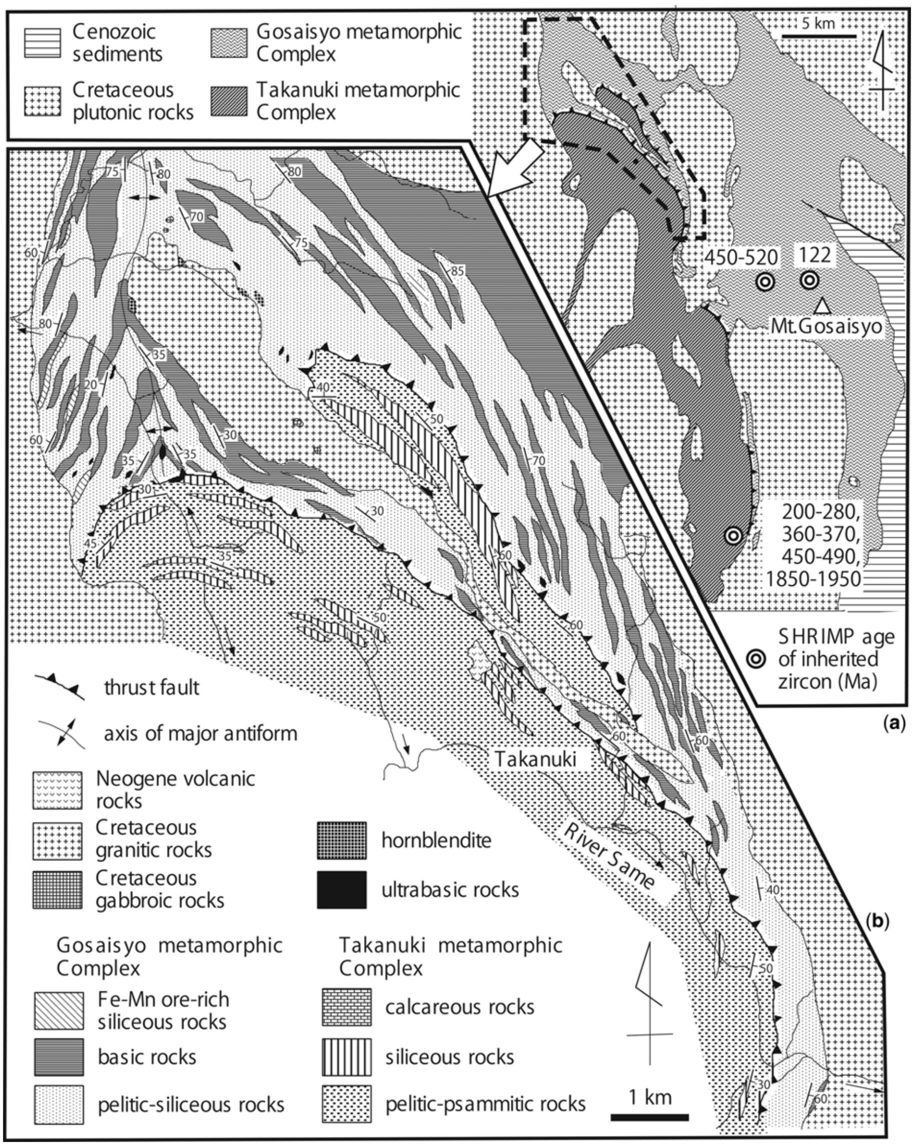

Fig. 2b.37. Geological map of Gosaisyo–Takanuki district, modified after Goto (1991) and figure 2 of Ishikawa *et al.* (1996). Note that in the text the Gosaisho and Takanuki metamorphic rocks are referred to as 'complexes'.

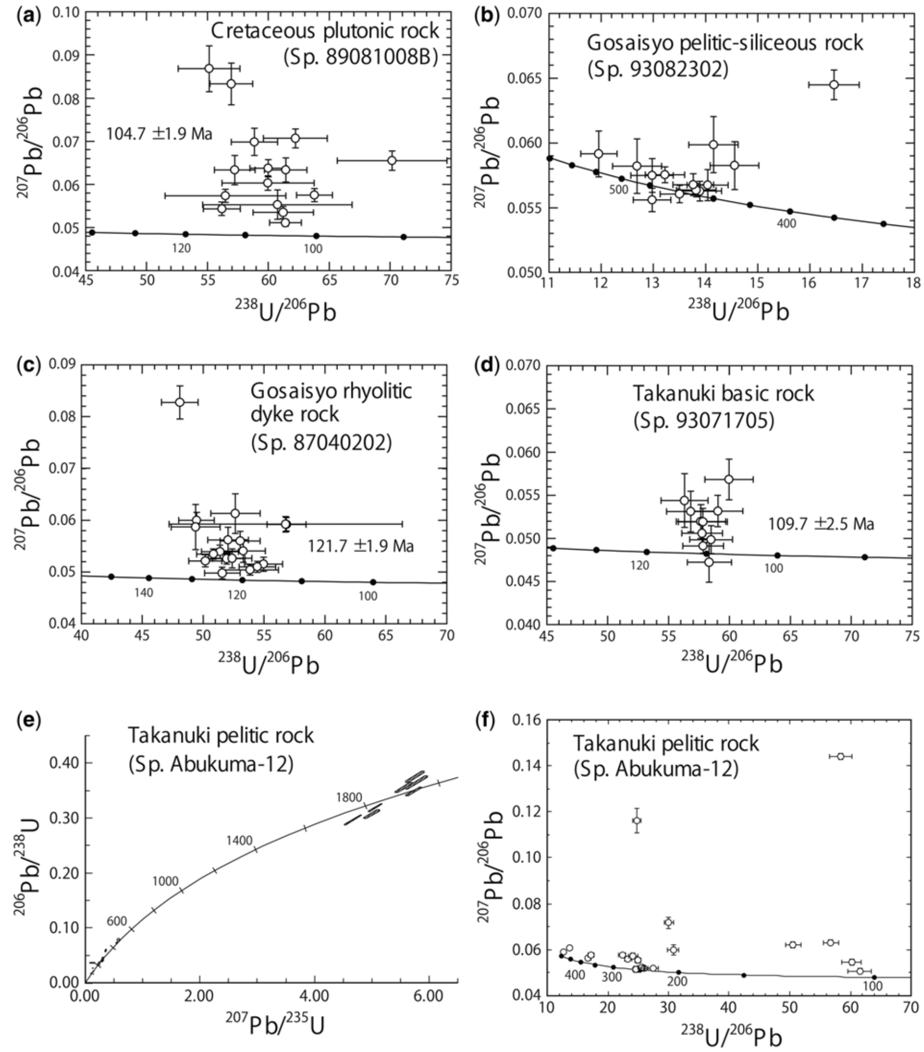

Fig. 2b.38. Tera–Wasserburg and U–Pb concordia plots for zircons from plutonic and metamorphic rocks in the Gosaisyo–Takanuki district.

of the host rocks. Zircons in one of these rhyolitic dykes yielded an age population of igneous zircon grains. A weighted mean of U–Pb ages for most analyses gives an age of 121.7 ± 1.9 Ma (Fig. 2b.38c), which is interpreted to reflect the time of igneous crystallization. Some analyses suggest a loss of radiogenic Pb during the 110 Ma metamorphic overprint. Three to four deformation events have been distinguished in the Gosaisyo Complex on the basis of four different types of fold: F1, isoclinal flow folds; F2, predominant buckle folds with a subvertical axial plane and subhorizontal fold axis nearly parallel to mineral lineation; F3, drag folds associated with axial plane cleavage; and F4, kink folds (Ishikawa & Otsuki 1990). These authors also showed that the regional thermal structure is discordant with the geological structure, and suggested a close link between the left-lateral ductile shearing (F3) within the Gosaisyo Complex and the activities of the Tanakura, Hatakawa and Futaba tectonic lines (shear zones) shown in Figure 2b.36.

The Takanuki Complex consists dominantly of pelitic-psammitic rocks with small amounts of calcareous, lateritic, siliceous and basic rocks. Pelitic-psammitic rocks are commonly migmatitic, indicating that partial melting has taken place during high-grade metamorphism. Although the Takanuki siliceous rocks are far more coarse-grained than those in the Gosaisyo Complex, they may have originated from cherts. Silica-poor lateritic rocks are found as lenses completely enclosed by coarse-grained marbles. A weighted mean of U–Pb ages of zircons from a minor basic rock gives an age of 109.7 ± 2.5 Ma (Fig. 2b.38d), and zircon morphology and age determinations indicate that this rock went through a single high-grade metamorphic event at *c.* 110 Ma. Cores of zoned zircon grains in a pelitic rock give concordant to nearly concordant ages of 200–280 Ma while rims yield a concordant age of 110 Ma (Fig. 2b.38e, f). Scattered Proterozoic (1850–1950 Ma) and Ordovician–Devonian ages (360–370 and 450–490 Ma) were also obtained mainly in the inherited cores of zircons which may be of detrital origin. The depositional age of the Takanuki sedimentary protoliths may therefore have been between 110 and 200 Ma, with new zircon growth and overgrowth taking place at about 110 Ma during the regional and almost contemporaneous contact metamorphic events. The Takanuki Complex as a whole shows gentle dome structures around cores of Cretaceous plutonic masses (Fig. 2b.37).

Although the dominant mineralogy indicates a classic andalusite-sillimanite type progressive metamorphism as defined by Miyashiro (1961), there are several lines of evidence suggesting that the Takanuki and Gosaisyo complexes underwent rapid high-temperature (>700°C) loading (up to more than 10 kbar in the kyanite stability field), followed by subsequent unloading during a single Cretaceous metamorphic event (Hiroi & Kishi 1989; Hiroi *et al.* 1998). Such an event may have resulted from ridge–trench interactions (Brown 1998), such as the obduction of oceanic crust. Similar high-temperature loading has been inferred from several Cretaceous regional metamorphic terrains around the Pacific Ocean (e.g. the Fiordland granulites in New Zealand; Bradshaw 1989).

Hitachi district

The Hitachi metamorphic rocks predominantly dip moderately–steeply SE, metamorphic grade increases westwards, and they are intruded and locally thermally metamorphosed by the Cretaceous Irishiken granodiorite mass in the north. SHRIMP U–Pb zircon ages have revealed these rocks to have originated from Early and Late Palaeozoic formations with a 'great hiatus' between Late Cambrian and Early Carboniferous times (Sakashima *et al.* 2003; Tagiri *et al.* 2010, 2011; Fig. 2b.39). The Early Palaeozoic rocks are divided into the Akazawa and Tamadare units, which are bounded by serpentinite shear zones and are almost contemporary in age. The Akazawa Unit consists mainly of volcanic rocks with subordinate amounts of clastic sediments. The unit is subdivided into upper and lower subunits based on the stratigraphic position and metamorphic grade, with the upper subunit being intruded by metagranitoids which have been grouped into northern and southern bodies by Tagiri *et al.* (2011). Sakashima *et al.* (2003) first reported the age of 491 Ma for zircons from a metagranitoid of the northern body. Granitic porphyry also occurs sporadically as dykes in the Akazawa Unit and the metagranitoids. The Tamadare Unit is composed mainly of biotite-hornblende gneiss originating from diorite, along with minor amounts of mica schist. Tagiri *et al.* (2011) reported the Late Cambrian ages for zircons from various rocks as follows: andesitic lava of the Lower Akazawa Subunit, diorite of the Tamadare Unit and shallow-level quartz porphyry dyke intruding into the Upper Akazawa Subunit.

The Upper Palaeozoic deposits are subdivided into the Daioin, Ayukawa and Omika units. The Daioin Unit has a basal conglomerate containing granitic boulders within a fine-grained quartzo-feldspathic to micaceous matrix, and is overlain by the Ayukawa Unit that consists mainly of slate and sandstone. Fossiliferous

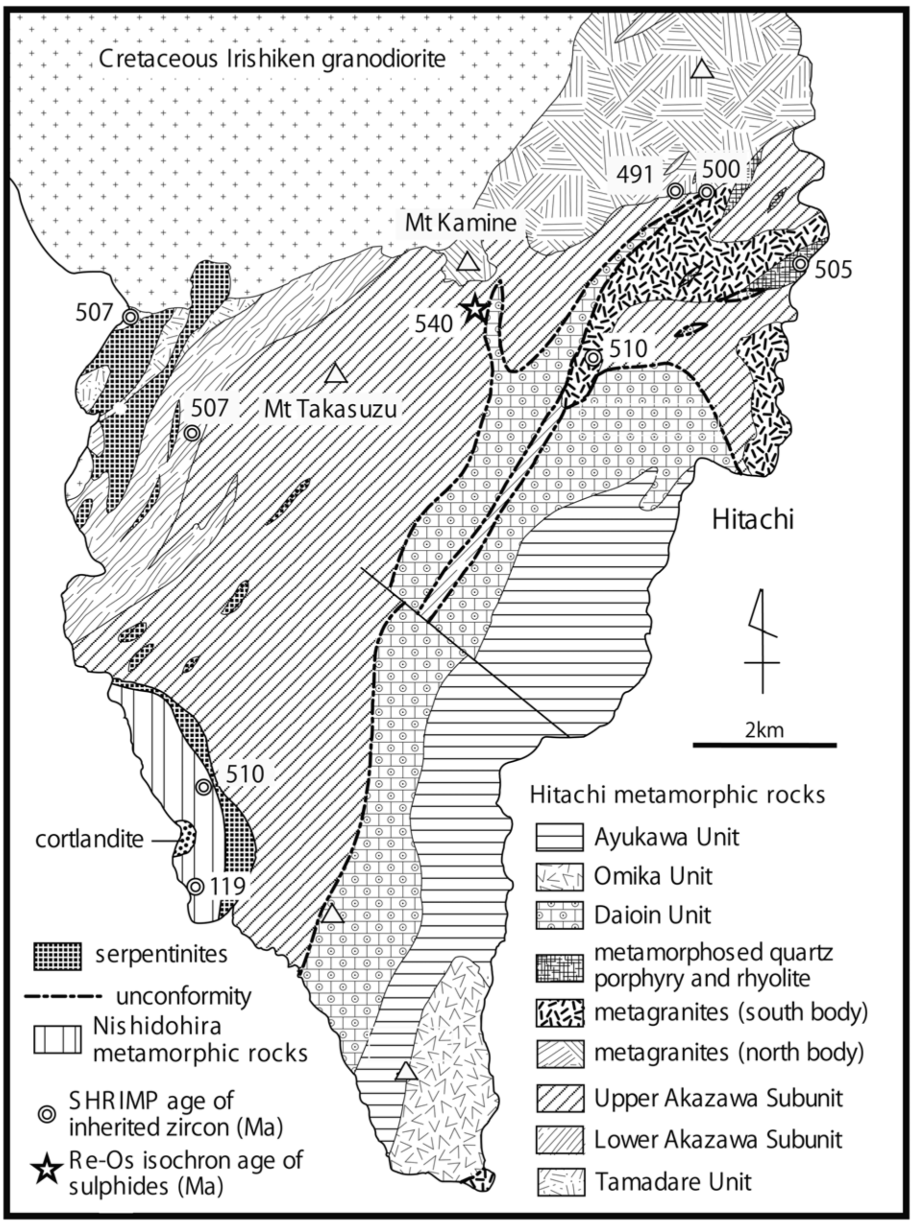

Fig. 2b.39. Geological map of Hitachi district, modified after Tagiri *et al.* (2011). Re-Os isochron age of sulfides is after Nozaki *et al.* (2012).

limestones occur in both the Daioin and Ayukawa units, yielding Early Carboniferous and Early Permian ages, respectively. The Omika Unit crops out further to the SE and is composed mainly of greenstones with a small amount of fossiliferous limestone. This unit also contains blocks of metagranitoids similar to the possibly correlative Daioin Unit, although its depositional age remains unknown.

Finally, the previously mentioned Cretaceous Nishidohira metamorphic rocks in the Hitachi district are composed mainly of arkosic sandstone and mudstone with subordinate volcaniclastic sediments and granitic conglomerate, metamorphosed into micaceous and felsic schists, fine-grained gneisses and amphibolites. They dip gently (*c.* 30°) to ENE, and the total thickness is estimated to be *c.* 300 m. Sedimentary structures preserved in coarser-grained mica schist beds and alternating layers of micaceous and felsic schists demonstrate that some beds are overturned. Metamorphic grade increases up-sequence from lower to upper amphibolite facies, and cortlandite and gneissose granite are intruded into the upper levels, inducing thermal effects on surrounding rocks. The Nishidohira metamorphic rocks were once considered to be a member of the Early Palaeozoic units because of the occurrence of *c.* 510 Ma detrital zircons (Tagiri *et al.* 2011), but they have been revealed by additional dating to be Cretaceous in age (Kanamitsu *et al.* 2011; M. Tagiri pers. comm. 2012) (Fig. 2b.39).

North Kitakami Belt (NS)

The North Kitakami Belt occupies a wide area in the northern part of the Kitakami Massif, Iwate Prefecture, and occurs as small remnants in Aomori Prefecture. The rocks in this belt consist of: Upper Carboniferous–Upper Jurassic chert; Middle–Upper Jurassic hemipelagic siliceous mudstone and terrigenous mudstone; Middle Jurassic–lowest Cretaceous sandstone; Upper Carboniferous–Lower Permian or Middle–Upper Triassic sequences of basaltic rocks, limestone and ribbon chert; and small lenses of Lower–Middle Permian limestone. Upper Jurassic limestone with corals is also patchily found, and can be correlated with the Torinosu-type limestone of the Chichibu Belt. These rocks are, in part, thermally metamorphosed by Early Cretaceous plutonic activities (Suzuki *et al.* 2007*a*).

The North Kitakami Belt is tectonically a southern extension of the Oshima Belt in SW Hokkaido as well as a northern extension of the Chichibu Belt (Ehiro *et al.* 2008). The lithologic and tectonic units of the North Kitakami belt show NW–SE-trending distributions. The western and southwestern boundary with the Nedamo Belt (Carboniferous AC) and the South Kitakami Belt (Ordovician–Jurassic isolated continental fragment) is defined by the SE–NW-trending Hayachine Eastern Marginal Fault (Fig. 2b.40), whereas the eastern boundary of this belt is submerged beneath the Pacific Ocean (Ehiro & Suzuki 2003). The North Kitakami Belt is divided by the Seki–Odaira Fault (or Iwaizumi Tectonic Line) into two sub-belts: Kuzumaki–Kamaishi Sub-belt in the SW and the Akka–Tanohata Sub-belt in the NE (Fig. 2b.40).

The Kuzumaki–Kamaishi Sub-belt is different from the Akka–Tanohata Sub-belt in the presence of Palaeozoic sequences and plagioclase-rich sandstone in the former as opposed to K-feldspathic sandstones in the latter (Okami *et al.* 1992), although the change is gradual (Takahashi *et al.* 2006). Another distinctive feature of the Kuzumaki–Kamaishi Sub-belt is the presence along its western

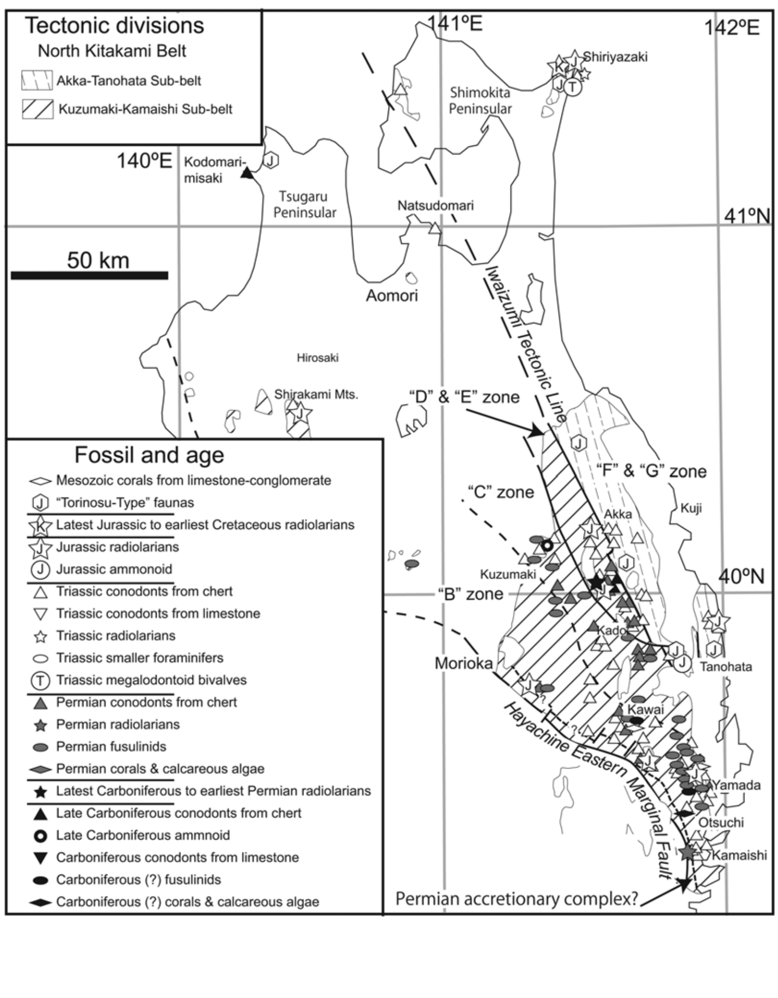

Fig. 2b.40. Schematic tectonic division for the North Kitakami Belt in Tohoku, NE Japan, with all fossil localities. Map based on Suzuki *et al.* (2007*a*); tectonic divisions in the North Kitakami Belt are mainly referred to Otoh & Sasaki (2003), Kanisawa *et al.* (2006) and Nakae & Kurihara (2011). Note that Carboniferous and Permian fossils are limited in the Kuzumaki–Kamaishi Sub-belt. This figure was the first to distinguish the Permian accretionary complex in the sense of Nakae & Kurihara (2011) from the North Kitakami Belt. The precise distribution of the Permian accretionary complex is still unknown.

margin of a unit known as the Kirinai Formation. This unit consists of black phyllitic mudstone (yielding Late Permian radiolarians) and greenish-grey massive sandstone in association with a minor amount of basic tuff. These rocks have been interpreted to be a Permian AC correlative to the Ultra-Tamba Belt (Nakae & Kurihara 2011), despite the occurrences of Triassic conodonts in chert and Jurassic-type radiolarians in chert and siliceous mudstone known from the western part of the Kirinai outcrop (Ehiro & Suzuki 2003).

The typical lithologies and tectonic structures of the North Kitakami Belt are best documented in the Kawai area for the Kuzumaki–Kamaishi Sub-belt (Suzuki *et al.* 2007*a*), in the Akka area for the Akka–Tanohata Sub-belt (Sugimoto 1974), and in the southern part of the Kuzumaki–Kamaishi Sub-belt for the Permian AC (Nakae & Kurihara 2011) (Fig. 2b.40). The geological structure of the Kuzumaki–Kamaishi Sub-belt is different between outcrop and map scales because bedding planes in exposed outcrops dip subvertically–vertically, but commonly dip shallowly to the SSW on the map. This difference is caused by the development of high-angle intrafolial folding with a shallow-dipping enveloping surface. In contrast, the Akka–Tanohata Sub-belt on the map scale is characterized by NNW–SSE-trending anticlines and synclines with wavelengths of a few kilometres in the northern North Kitakami Massif (Sugimoto 1974).

The Kuzumaki–Kamaishi and Akka–Tanohata Sub-belts have been further subdivided into three ‘zones’ comprising ten units and a single ‘zone’ with five units, respectively, based on detailed field mapping (Fig. 2b.41) (e.g. Otoh & Sasaki 2003; Takahashi *et al.* 2006; Suzuki *et al.* 2007*a*; Ehiro *et al.* 2008; Kawamura 2010). Although the tectonostratigraphic correlation between the North Kitakami and Chichibu belts is still in dispute (e.g. Otoh & Sasaki 2003; Suzuki *et al.* 2007*a*), the ‘C’ zone, ‘D’ and ‘E’ zones, and ‘F’ and ‘G’ zones of the North Kitakami Belt are correlated with the Ohirayama, Togano and Sambosan units of the Southern Chichibu Belt, respectively. No unit correlating with the ‘B’ zone of the North Kitakami Belt has been detected in the Chichibu Belt.

Differences and similarities between the Chichibu and the Mino–Tamba–Ashio belts

The North Kitakami Belt is considered to have been originally connected with the Chichibu Belt, but there are several differences between these two belts. The width of the former reaches up to

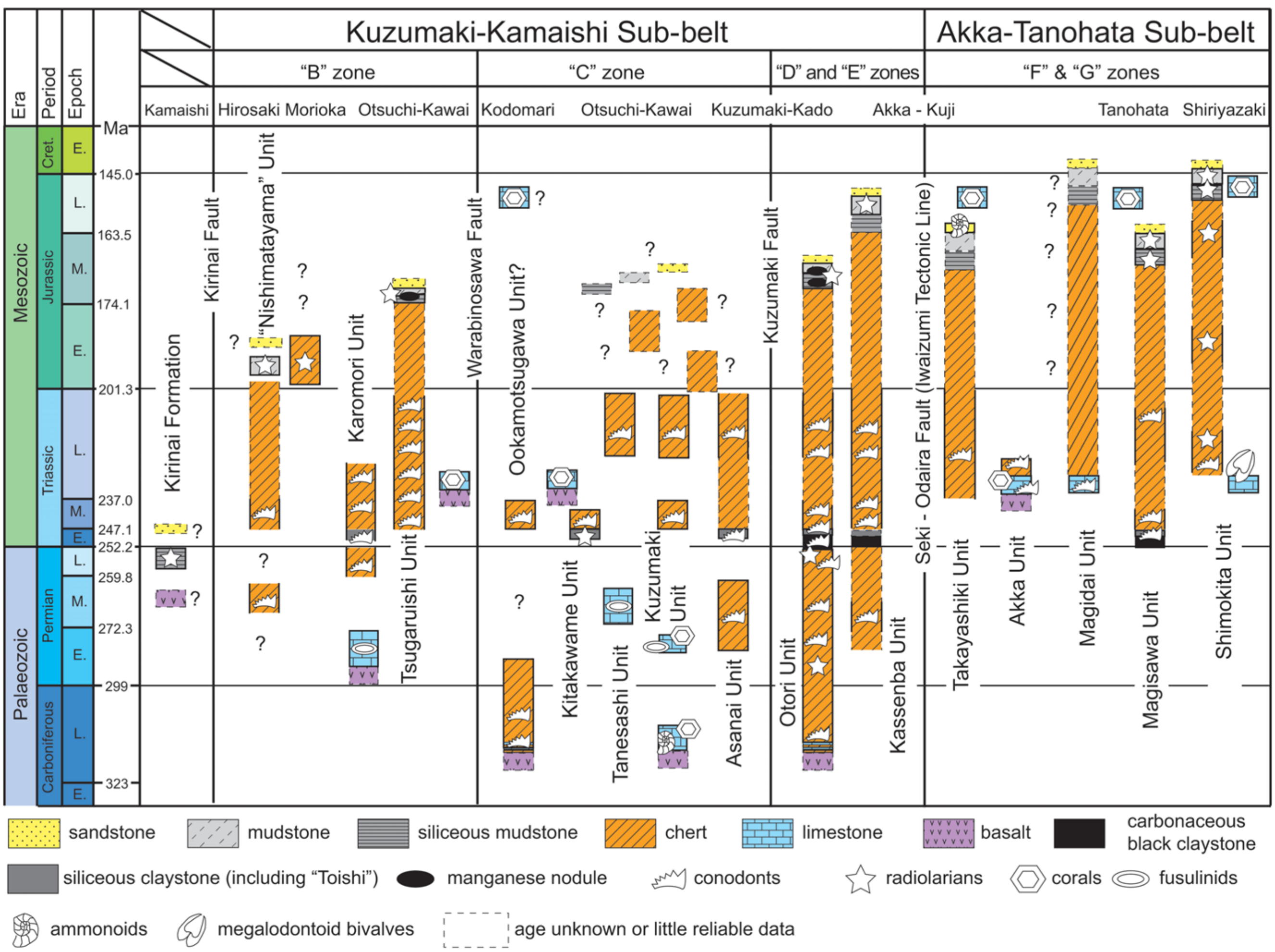

Fig. 2b.41. Schematic compilation of age and lithostratigraphic diagram of the North Kitakami Belt and the newly recognized Permian accretionary complex. As the data source exceeds more than 45 references, the original source should be referred to Suzuki *et al.* (2007*a*) and Ehiro *et al.* (2008). The tectonostratigraphic divisions, formation names and assigned numerical ages are partly updated from both Suzuki *et al.* (2007*a*) and Ehiro *et al.* (2008). The age of the siliceous mudstone and mudstone tends to become younger from the ‘Nishimatayama’ Unit of ‘B’ Zone in the Kuzumaki–Kamaishi Sub-belt to the Shimokita Unit in the Akka–Tanohata Sub-belt.

150 km, whereas that of the latter is 10 km at maximum. The Upper Triassic limestones with megalodontoid bivalves typically found in the Chichibu and North Kitakami belts have not been reported from the Mino–Tamba–Ashio Belt (Sano *et al.* 2009), and they are much larger in the North Kitakami Belt exemplified by the Akka Limestone body than those in the Chichibu Belt. Furthermore, large Permian limestone bodies common in the Chichibu and Mino–Tamba–Ashio belts have never been found in the North Kitakami Belt. On the other hand, the Upper Carboniferous sequence from basalt through alternating beds of dolomite and red ribbon chert, to red ribbon chert in the Otori Unit of the 'D' and 'E' zones of the Akka–Tanohata Sub-belt, is equivalent to the red ribbon chert sequence of the Kamiyoshida Unit of the Northern Chichibu Belt.

The broad width of the North Kitakami Belt is similar to that of the Mino–Tamba–Ashio Belt. Radiolarian-bearing manganese carbonate nodules of Middle Jurassic age are stratigraphically embedded in siliceous mudstone and mudstone of the Tsugaruishigawa Unit of the 'B' zone and the Otori Unit of 'D' and 'E' zones in the North Kitakami Belt. Similar Middle Jurassic manganese nodules in siliceous mudstone or mudstone are only found in the Mino–Tamba–Ashio Belt based on the compiled occurrence data of radiolarian-bearing carbonate nodules by Yamakita & Hori (2009) and Suzuki *et al.* (2007*b*). The distribution and tectonic relationship between the Ultra-Tamba Belt (Permian AC) and Mino–Tamba–Ashio Belt (Jurassic AC) is similar to those of the Kirinai Formation (Permian AC) and the North Kitakami Belt (Jurassic AC).

Tectonic events recorded in the North Kitakami Belt

The juxtaposition of the North and South Kitakami belts was completed after the deposition of the Jurassic Torinosu-type limestone, the youngest sediments of the North Kitakami Belt, but before the Oshima Orogeny which has affected both belts. The deformation and thermal metamorphism induced by the Oshima Orogeny occurred between Barremian and probably Aptian times, and no later than the deposition of the undeformed Miyako Group of Aptian–Albian age (Kobayashi 1941; Onuki 1981; Kanisawa & Ehiro 1989). More extensive information, including the main references for the North Kitakami Belt, are summarized in Suzuki *et al.* (2007*a*) and Nakae & Kurihara (2011), including a historical overview of changing ideas on how these rocks have been interpreted.

Relationship between the older AC and mainland Asia (SK)

The older ACs described in this chapter had been developed in relation to mainland Asia as the Sea of Japan opened around 15 Ma. Kojima (1989) and Kojima *et al.* (2000, 2008) reconstructed and illustrated the northern extension of the Maizuru, Ultra-Tamba, Mino–Tamba–Ashio, Southern Chichibu and North Kitakami belts into NE Asia before the opening of the Sea of Japan (Fig. 2b.42). Different views of the reconstruction are provided by Niitsuma *et al.* (1985) and Matsuda *et al.* (1998). The complicated arrangement of the older ACs, high- and low-P/T metamorphic complexes and fragments of continent and island arc (Figs 2b.2 & 2b.42) formed through the processes of subduction-accretion, nappe formation, ophiolite emplacement and large-scale strike-slip faulting before 15 Ma is described in Chapter 1.

The kinematics of each geological entity have been analysed by several different methods including palaeomagnetic and palaeobiogeographic methods, and provenance and structural analyses. One of the results of the palaeomagnetic analyses, namely the low-latitude and Southern Hemisphere origin of the Middle Triassic chert in the Mino–Tamba–Ashio Belt, is explained in this chapter.

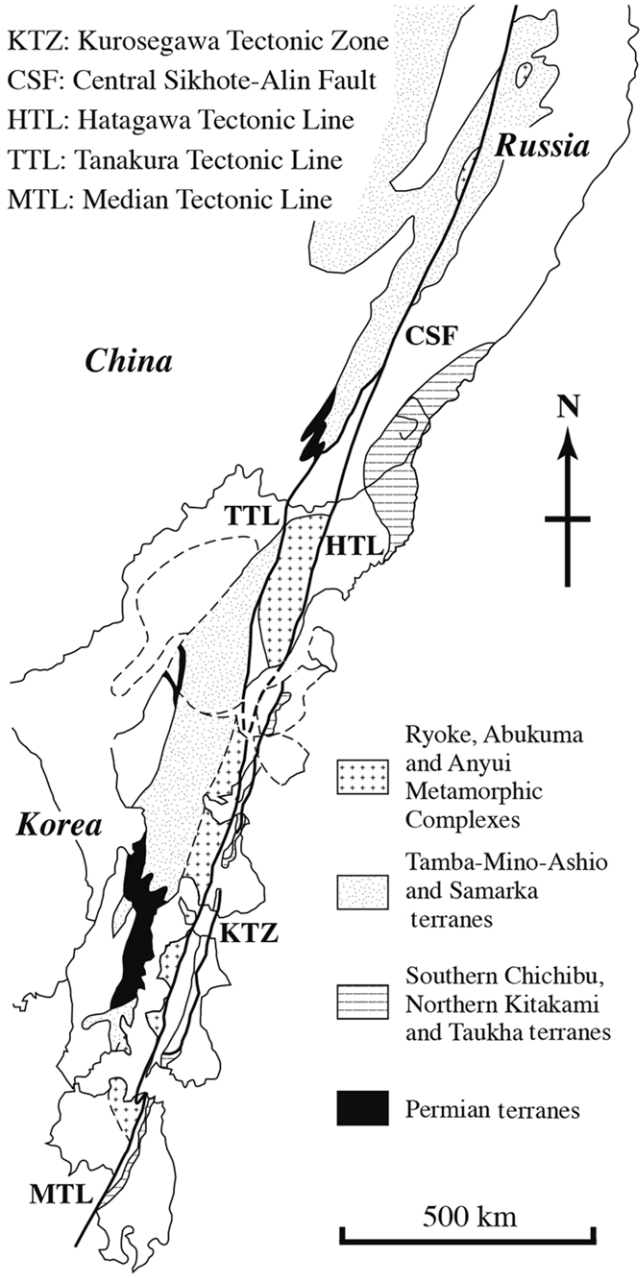

Fig. 2b.42. Map showing northern extension of the Japanese older AC belts into NE Asia before the opening of the Sea of Japan (after Kojima *et al.* 2008). The Permian terranes in this figure include Maizuru and Ultra-Tamba belts of this book.

Palaeobiogeographic analyses using endemic faunas and floras are also useful to estimate the palaeo-position of sedimentary basins; for example, Tazawa (1993) reconstructed the original arrangement of the Palaeozoic–Mesozoic belts on the basis of Permian brachiopod fauna, and Ehiro (1997) indicated close relationships between Permian ammonoid faunas among the South Kitakami, South China and Khanka massifs. The relationships between ACs and the continental margins where they accreted have been analysed by using clastic materials in trench-fill turbidites, as demonstrated in this chapter (e.g. Mino–Tamba–Ashio Belt). Recent progress in detrital zircon chronology by using laser ablation inductively coupled plasma mass spectrometry has accumulated a vast amount of age data (e.g. Otoh *et al.* 2013) which should reveal the nature of the continental provenance.

Y. Hiroi is most grateful to M. Tagiri for the detailed and new information about the Hitachi and Nishidohira metamorphic rocks and M. Fanning for the zircon SHRIMP dating. H. S. gives special thanks to Gerilyn S. Soreghan (University of Oklahoma) for her review on the early version of the manuscript.

Appendix

English to Kanji and Hiragana translations for geological and place names

Abukuma	阿武隈	あぶくま
Aizawa	会沢	あいざわ
Akazawa	赤沢	あかざわ
Akiyoshi	秋吉	あきよし
Akiyoshi-dai	秋吉台	あきよしだい
Akka	安家	あっか
Aomori	青森	あおもり
Asahi	旭	あさひ
Ashio	足尾	あしお
Atetsu	阿哲	あてつ
Ayukawa	鮎川	あゆかわ
Butsuzo	仏像	ぶつぞう
Chihibu	秩父	ちちぶ
Chizu	智頭	ちず
Chugoku	中国	ちゅうごく
Daioin	大雄院	だいおういん
Dogoyama	道後山	どうごやま
Fukui	福井	ふくい
Fukumoto	福本	ふくもと
Funafuseyama	舟伏山	ふなふせやま
Futaba	双葉	ふたば
Gamata	蒲田	がまた
Gosaisho	御斎所	ごさいしょ
Gotsu	江津	ごうつ
Gujyo	公庄	ぐじょう
Happo-one	八方尾根	はっぽうおね
Hatakawa (Hatagawa)	畑川	はたかわ
Hatto	八東	はっとう
Hayachine	早池峰	はやちね
Hida	飛騨	ひだ
Hida-Gaien	飛騨外縁	ひだがいえん
Hiehara	稗原	ひえはら
Hikami	氷上	ひかみ
Hirao	平尾	ひらお
Hiroshima	広島	ひろしま
Hitachi	日立	ひたち
Hizume	日詰	ひづめ
Hokubo	北房	ほくぼう
Honshu	本州	ほんしゅう
Hyogo	兵庫	ひょうご
Inagawa	猪名川	いながわ
Iriomote	西表	いりおもて
Irishiken	入四間	おりしけん
Ishigaki	石垣	いしがき
Itoigawa	糸魚川	いといがわ
Iwaizumi	岩泉	いわいずみ
Iwakuni	岩国	いわくに
Joetsu	上越	じょうえつ
Kamaishi	釜石	かまいし
Kamiaso	上麻生	かみあそう

(*Continued*)

English to Kanji and Hiragana translations for geological and place names (*Continued*)

Kamitaki	上滝	かみたき
Kamiyoshida	上吉田	かみよしだ
Kanayama	金山	かなやま
Kanto	関東	かんとう
Kariyasu	刈安	かりやす
Kashiwagi	柏木	かしわぎ
Katashina	片品	かたしな
Katsuyama	勝山	かつやま
Kawai	川井	かわい
Kawanishi	川西	かわにし
Kesennuma	気仙沼	けせんぬま
Kirinai	桐内	きりない
Kiso	木曽	きそ
Kitakami	北上	きたかみ
Komori	河守	こうもり
Kozuki	上月	こうづき
Kuchikanbayashi	口上林	くちかんばやし
Kuga	玖珂	くが
Kunisaki	国崎	くにさき
Kurosegawa	黒瀬川	くろせがわ
Kuruma	来馬	くるま
Kuwagai	桑飼	くわがい
Kuzumaki	葛巻	くずまき
Kuzuryu	九頭竜	くずりゅう
Kyoto	京都	きょうと
Kyushu	九州	きゅうしゅう
Maizuru	舞鶴	まいづる
Matsugadaira	松ヶ平	まつがだいら
Miharaiyama	御祓山	みはらいやま
Mikabu	御荷鉾	みかぶ
Mikata	三方	みかた
Mino	美濃	みの
Miyako	宮古	みやこ
Monobegawa	物部川	ものべがわ
Motai	母体	もたい
Nabae	難波江	なばえ
Nabi	那比	なび
Nagara	長良	ながら
Naradani	楢谷	ならだに
Nedamo	根田茂	ねだも
Nishidohira	西堂平	にしどうひら
Nishiki	錦	にしき
Nishimatayama	西股山	にしまたやま
Nomo	野母	のも
Ochiai	落合	おちあい
Odaira	大平	おおだいら
Oe	大江	おおえ
Oeyama	大江山	おおえやま
Ohirayama	大平山	おおひらやま
Oi	大飯	おおい
Okayama	岡山	おかやま
Oki	隠岐	おき
Omi	青海	おうみ
Omika	大甕	おおみか
Osayama	大佐山	おおさやま
Oshima*	渡島	おしま
Oshima†	大島	おおしま
Otori	大鳥	おおとり
Otsuchi	大槌	おおつち
Oya	大屋	おおや
Renge	蓮華	れんげ
Ryoke	領家	りょうけ

(*Continued*)

English to Kanji and Hiragana translations for geological and place names (Continued)

Ryoseki	領石	りょうせき
Ryukyu	琉球	りゅうきゅう
Sakahogi	坂祝	さかほぎ
Sakamoto-toge	坂本峠	さかもととうげ
Sakawa	佐川	さかわ
Samondake	左門岳	さもんだけ
San'in	山陰	さんいん
Sanbagawa (Sambagawa)	三波川	さんばがわ
Sanbosan (Sambosan)	三宝山	さんぼうさん
Sangun	三郡	さんぐん
Sanyo	山陽	さんよう
Sasayama	篠山	ささやま
Sawadani	沢谷	さわだに
Seki	関	せき
Shidaka	志高	しだか
Shikoku	四国	しこく
Shimane	島根	しまね
Shimanto	四万十	しまんと
Shimokita	下北	しもきた
Shimomidani	下見谷	しもみだに
Shirouma	白馬	しろうま
Shizuoka	静岡	しずおか
Sumaizuku	住居附	すまいづく
Suo	周防	すおう
Taishaku	帝釈	たいしゃく
Takanuki	竹貫	たかぬき
Takatsuki	高槻	たかつき
Tamadare	玉簾	たまだれ
Tanakura	棚倉	たなくら
Tanba (Tamba)	丹波	たんば
Tanesashi	種差	たねさし
Tanohata	田野畑	たのはた
Tanzawa	丹沢	たんざわ
Tetori (Tedori)	手取	てとり
Togano	斗賀野	とがの
Tohoku	東北	とうほく
Tokura	十倉	とくら
Tomuru	トムル	とむる
Torinosu	鳥の巣	とりのす
Toyogadake	豊ヶ岳	とよがだけ
Tsugaruishigawa	津軽石川	つがるいしがわ
Tsunemori	常森	つねもり
Tsuno	都濃	つの
Unuma	鵜沼	うぬま
Wakasa	若桜	わかさ
Yakuno	夜久野	やくの
Yamada	山田	やまだ
Yamaguchi	山口	やまぐち
Yamasaki	山崎	やまさき
Yusukawa	遊子川	ゆすかわ

*For 'Oshima belt'.
†For 'Oshima Peninsula' and 'Oshima Orogeny'.

References

ADACHI, M. 1971. Permian intraformational conglomerate at Kamiaso, Gifu Prefecture, central Japan. *Journal of Geological Sociey of Japan*, **77**, 471–482.

ADACHI, M. 1990. Heavy mineral assemblage of the Triassic Shidaka Group in the Maizuru terrane. Abstract of the Annual Meeting of the Geological Society of Japan, Tokyo, Japan, 278 [in Japanese].

ADACHI, M. & KOJIMA, S. 1983. Geology of the Mt. Hikagedaira area, east of Takayama, Gifu Prefecture, central Japan. *Journal of Earth Sciences, Nagoya University*, **31**, 37–67.

ADACHI, M. & MIZUTANI, S. 1971. Sole markings and paleocurrent system in the Paleozoic group of the Mino terrain, central Japan. *Memoir of Geological Society of Japan*, **6**, 39–48.

ADACHI, M. & SUZUKI, K. 1992. A preliminary note on the age of detrital monazites and zircons from sandstones in the Upper Triassic Nabae Group, Maizuru terrane. *Memoirs of Geological Society of Japan*, **38**, 111–120 [in Japanese with English abstract].

ANDO, A., KODAMA, K. & KOJIMA, S. 2001. Low-latitude and Southern Hemisphere origin of Anisian (Triassic) bedded chert in the Inuyama area, Mino terrane, central Japan. *Journal of Geophysical Research*, **106**, 1973–1986.

ARAI, S., INOUE, T. & OYAMA, T. 1988. Igneous petrology of the Ochiai-Hokubou ultramafic complex, the Sangun zone, western Japan: a preliminary report. *Journal of Geological Society of Japan*, **94**, 91–102 [in Japanese with English abstract].

BANNO, S. 1958. Glaucophane schists and associated rocks in the Omi district, Niigata Prefecture, Japan. *Japanese Journal of Geology and Geography*, **29**, 29–44.

BRADSHAW, J. Y. 1989. Origin and metamorphic history of an Early Cretaceous polybaric granulite terrain, Fiordland, southwest New Zealand. *Contributions to Mineralogy and Petrology*, **103**, 346–360.

BROWN, M. 1998. Ridge-trench interactions and high-T-low-P metamorphism, with particular reference to the Cretaceous evolution of the Japanese Islands. *In*: TRELOAR, P. J. & O'BRIEN, P. L. (eds) *What Drives Metamorphism and Metamorphic Reactions?* Geological Society, London, Special Publications, **138**, 137–169.

CARIDROIT, M., ICHIKAWA, K. & CHARVET, J. 1985. The Ultra-Tamba Zone, a new unit in the Inner Zone of Southwest Japan: its importance in the nappe structure after the example of the Maizuru area. *Earth Science (Chikyu-kagaku)*, **39**, 210–219.

EHIRO, M. 1977. The Hizume-Kesennuma Fault –with special reference to its character and significance on the geologic development. *Contributions from the Institute of Geology and Paleontology, Tohoku University*, **77**, 1–37 [in Japanese with English abstract].

EHIRO, M. 1997. Ammonoid palaeobiogeography of the South Kitakami Palaeoland and palaeogeography of eastern Asia during Permian to Triassic time. *In*: JIN, Y. G. & DINELEY, D. (eds) *Proceedings of 30th International Geological Congress*. VSP, Utrecht, **12**, 18–28.

EHIRO, M. & SUZUKI, N. 2003. Re-definition of the Hayachine Tectonic Belt of Northeast Japan and a proposal of a new tectonic unit, the Nedamo Belt. *Japanese Journal of Structural Geology*, **47**, 13–21 [in Japanese with English abstract].

EHIRO, M., KANISAWA, S. & TAKETANI, Y. 1989. Pre-tertiary Takine Group in the central Abukuma massif. *Bulletin of Fukushima Museum*, **3**, 21–37 [in Japanese with English abstract].

EHIRO, M., YAMAKITA, S., TAKAHASHI, S. & SUZUKI, N. 2008. Jurassic accretionary complexes of the North Kitakami Belt in the Akka-Kuji area, Northeast Japan. *Journal of Geological Society of Japan*, **114** (supplement), 121–139 [in Japanese with English abstract].

FUJII, M., HAYASAKA, Y. & TERADA, K. 2008. SHRIMP zircon and EPMA monazite dating of granitic rocks from the Maizuru terrane, southwest Japan: correlation with East Asian Paleozoic terranes and geological implications. *Island Arc*, **17**, 322–341.

GOTO, J. 1991. *Geological and Petrological Study of the Boundary Area Between the Gosaisyo and Takanuki Metamorphic Rocks in the Abukuma Metamorphic Terrane*. MSc thesis, Chiba University, Japan.

HADA, S. & KURIMOTO, C. 1990. Northern Chichibu Terrane. *In*: ICHIKAWA, K., MIZUTANI, S., HARA, I., HADA, S. & YAO, A. (eds) *Pre-Cretaceous Terranes of Japan*. Department of Geosciences, Osaka City University, Osaka, 165–183.

HAMANO, K., IWATA, K., KAWAMURA, M. & KITAKAMI PALEOZOIC RESEARCH GROUP 2002. Late Devonian conodont age of red chert intercalated in greenstones of the Hayachine Belt, Northeast Japan. *Journal of Geological Society of Japan*, **108**, 114–122 [in Japanese with English abstract].

HARA, I., SHIOTA, T. *ET AL*. 1992. Tectonic evolution of the Sambagawa schists and its implications in convergent margin processes. *Journal of Science of Hiroshima University, Series C*, **9**, 495–595.

HASHIMOTO, M. 1968. Glaucophanitic metamorphism of the Katsuyama district, Okayama Prefecture, Japan. *Journal of the Faculty of Sciences, University of Tokyo, Section II*, **17**, 99–162.

Hashimoto, M. 1972. Mineral facies of the Sangun metamorphic rocks of the Chugoku Provinces. *Bulletin of Japan National Science Museum*, **15**, 767–775.

Hayasaka, Y. 1987. Study on the late Paleozoic-early Mesozoic tectonic development of western half of the Inner zone of Southwest Japan. *Geological Report of Hiroshima University*, **27**, 119–204 [in Japanese with English abstract].

Hayasaka, Y. 1990. Maizuru Terrane. *In*: Ichikawa, K., Mizutani, S., Hara, I., Hada, S. & Yao, A. (eds) *Pre-Cretaceous Terranes of Japan*. Department of Geosciences, Osaka City University, Osaka, 81–95.

Hayasaka, Y., Ikeda, K., Shishido, T. & Ishizuka, M. 1996. Geological reconstruction of the Maizuru Terrane as an arc-back arc system. *In*: Shimamoto, T., Hayasaka, Y., Shiota, T., Oda, M., Takeshita, T., Yokoyama, S. & Ohtomo, Y. (eds) *Tectonics and Metamorphism (The Hara Volume)*. SOUBUN, Tokyo, 134–144 [in Japanese with English abstract].

Herzig, C. T., Kimbrough, D. L. & Hayasaka, Y. 1997. Early Permian zircon uranium–lead ages for plagiogranites in the Yakuno ophiolite, Asago district, Southwest Japan. *Island Arc*, **6**, 396–403.

Hidaka, H., Shimizu, H. & Adachi, M. 2002. U-Pb geochronology and REE geochemistry of zircons from Palaeoproterozoic paragneiss clasts in the Mesozoic Kamiaso conglomerate, central Japan: evidence for an Archean provenance. *Chemical Geology*, **187**, 279–293.

Hiroi, Y. & Kishi, S. 1989. P-T evolution of Abukuma metamorphic rocks in north-east Japan: metamorphic evidence for oceanic crust obduction. *In*: Daly, J. S., Cliff, R. A. & Yardley, B. D. D. (eds) *Evolution of Metamorphic Belts*. Geological Society, London, Special Publications, **43**, 481–486.

Hiroi, Y., Yokose, M., Oba, T., Kishi, S., Nohara, T. & Yao, A. 1987. Discovery of Jurassic radiolaria from acmite-rhodonite-nearing metachert of the Gosaisyo metamorphic rocks in the Abukuma terrane, northeast Japan. *Journal of Geological Society of Japan*, **93**, 445–448.

Hiroi, Y., Kishi, S., Nohara, T., Sato, K. & Goto, J. 1998. Cretaceous high-temperature rapid loading and unloading in the Abukuma metamorphic terrane, Japan. *Journal of Metamorphic Geology*, **16**, 67–81.

Ichikawa, K. 1990. Pre-Cretaceous Terranes of Japan. *In*: Ichikawa, K., Mizutani, S., Hara, I., Hada, S. & Yao, A. (eds) *Pre-Cretaceous Terranes of Japan*. Department of Geosciences, Osaka City University, Osaka, 1–12.

Ichikawa, K., Ishii, K., Nakagawa, C., Suyari, K. & Yamashita, N. 1956. Die Kurosegawa Zone. *Journal of Geological Society of Japan*, **62**, 82–103.

Igi, S. 1969. Findings of the Carboniferous corals from the so-called Kamigori Structural Belt, Japan. *Bulletin of Geological Survey of Japan*, **20**, 77–78.

Igi, S. & Kuroda, K. 1965. *Explanatory Text of the Geological Map of Japan, Scale 1:50000, Oeyama*. Geological Survey of Japan, Kawasaki [in Japanese with English abstract].

Igi, S., Kuroda, K. & Hattori, H. 1961. *Explanatory Text of the Geological Map of Japan, Scale 1:50000, Maizuru*. Geological Survey of Japan, Kawasaki [in Japanese with English abstract].

Ikeda, K. & Hayasaka, Y. 1994. Rb–Sr ages of the Yakuno rocks from the Northen subzone of the Maizuru Terrane, Kyoto Prefecture, Southwest Japan. *Journal of Mineralogy, Petrology and Economic Geology*, **89**, 443–54.

Ishiga, H. 1984. Follicucullus (Permian Radiolaria) from the Maizuru Group in the Maizuru Belt, Southwest Japan. *Earth Science (Chikyu Kagaku)*, **38**, 427–434.

Ishiga, H. 1986. Ultra-Tamba Zone of Southwest Japan. *Journal of Geosciences, Osaka City University*, **29**, 89–100.

Ishiga, H. 1990. Ultra-Tamba Terrane. *In*: Ichikawa, K., Mizutani, S., Hara, I., Hada, S. & Yao, A. (eds) *Pre-Cretaceous Terranes of Japan*. Department of Geosciences, Osaka City University, Osaka, 97–107.

Ishiga, H., Takamatsu, M., Takigawa, T., Nishimura, K. & Tokuoka, T. 1988. Radiolarian biostratigraphy of Maizuru Group in the northwest of Ibara and Kanagawa areas, Okayama Prefecture. *Geological Report of Shimane University*, **7**, 39–48 [in Japanese with English abstract].

Ishii, K., Okimura, K. & Nakazawa, K. 1975. On the genus *Colaniella* and its biostratigraphic significance. *Journal of Geosciences, Osaka City University*, **19**, 107–138.

Ishikawa, M. & Otsuki, K. 1990. Fold structures and left-lateral ductile shear in the Gosaisho metamorphic belt, Northeast Japan. *Journal of Geological Society of Japan*, **96**, 719–730 [in Japanese with English abstract].

Ishikawa, M., Hiroi, Y. & Tagiri, M. 1996. Metamorphic rocks and geologic structures of the Takanuki-Gosaisho metamorphic belt. *In*: Mori, K. & Nagahama, H. (eds) *Excursion Guidbook, 103rd Annual Meeting of Geological Society of Japan*. Tokyo, Japan, 155–176.

Ishiwatari, A. 1985. Granulite-facies metacumulates of the Yakuno ophiolite, Japan: evidence for unusually thick oceanic crust. *Journal of Petrology*, **26**, 1–30.

Ishiwatari, A., Ikeda, Y. & Koide, Y. 1990. The Yakuno ophiolite, Japan: fragments of Permian island arc and marginal basin crust with a hotspot. *In*: Malpas, J. G., Moores, E. M., Panayiotou, A. & Xenophontos, C. (eds) *Ophiolites: Oceanic Crustal Analogues (Proceedings of the Troodos '87 Symposium)*. Geological Survey Department, Ministry of Agriculture and Natural Resources, Strovolos, Cyprus, 479–506.

Ishizuka, H. & Imaizumi, M. 1988. Metamorphic aragonite from the Yaeyama metamorphic rocks on Ishigaki-jima, southwest Ryukyu Islands. *Journal of Geological Society of Japan*, **94**, 719–722.

Isozaki, Y. 1996. Anatomy and genesis of a subduction-related orogen: a new view of geotectonic subdivision and evolution of the Japanese Islands. *Island Arc*, **5**, 289–320.

Isozaki, Y. & Itaya, T. 1991. Pre-Jurassic Klippe in northern Chichibu Belt in west-central Shikoku, Southwest Japan. Kurosegawa Terrane as a tectonic outlier of the pre-Jurassic rocks of the Inner Zone. *Journal of Geological Society of Japan*, **97**, 431–450 [in Japanese with English abstract].

Isozaki, Y. & Maruyama, S. 1991. Studies on orogeny based on plate tectonics in Japan and new geotectonic subdivision of the Japanese Islads. *Journal of Geography (Tokyo)*, **100**, 697–761 [in Japanese with English abstract].

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

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

Jones, G., Valsami-Jones, E. & Sano, H. 1993. Nature and tectonic setting of accreted basalts from the Mino terrane, central Japan. *Journal of the Geological Society of London*, **150**, 1167–1181.

Kabashima, T., Isozaki, Y. & Nishimura, Y. 1993. Find of boundary thrust between 300 Ma high-P/T type schists and weakly metamorphosed Permian accretionary complex in the Nagato tectonic zone, Southwest Japan. *Journal of the Geological Society of Japan*, **101**, 397–400 [in Japanese].

Kanamitsu, G., Otoh, S., Shimojo, M., Hirata, T. & Yokoyama, T. 2011. New detrital-zircon ages and geological setting of the Hitachi area, Ibaraki Prefecture. *Abstracts of 2011 Joint Annual Meeting of Japan Association of Mineralogical Sciences and the Geological Society of Japan*, 10 September, 2011, Mito, Japan, T10-O-6 [in Japanese].

Kanisawa, S. & Ehiro, M. 1989. The Oshima Orogeny and the tectonic development from the Cretaceous to the Paleogene. *In*: Editorial Committee of Tohoku, Part 2 of Regional Geology of Japan (ed.) *Regional Geology of Japan, Part 2, Tohoku*, Kyoritsu Shuppan, Tokyo, 244–246 [in Japanese].

Kanisawa, S., Ehiro, M. & Otsuki, K. 2006. Chapter 3. The Geology of Paleozoic, Mesozoic and Paleogene in Tohoku. *In*: Tohoku Construction Association (ed.) *Geology of Tohoku Region for Construction Engineers*, Tohoku Construction Association, Sendai, 151–193 [in Japanese].

Kanmera, K. & Nishi, H. 1983. Accreted oceanic reef complex in southwest Japan. *In*: Hashimoto, M. & Ueda, S. (eds) *Accretion Tectonics in the Circum-Pacific Regions*. Terra Scientific Publishing Company, Tokyo, 195–206.

Kano, H., Nakazawa, K., Igi, S. & Shiki, T. 1959. On the high-grade metamorphic rocks associated with the Yakuno intrusive rocks of the Maizuru zone. *Journal of Geological Society of Japan*, **65**, 267–271.

Karakida, Y., Yamamoto, H. & Hayama, Y. 1989. The Manotani metamorphic rocks, Kumamoto Prefecture and its reversion. *Memoir of Geological Society of Japan*, **33**, 199–215 [in Japanese with English abstract].

Kawamura, M. & Kitakami Paleozoic Research Group 1988. On the geology of Hayachine Tectonic Belt. *Earth Science (Chikyu-Kagaku)*, **42**, 371–384 [in Japanese with English abstract].

Kawamura, M., Uchino, T., Gouzu, C. & Hyodo, H. 2007. 380 Ma $^{40}Ar/^{39}Ar$ ages of the high-P/T schists obtained from the Nedamo

Terrane, Northeast Japan. *Journal of Geological Society of Japan*, **113**, 492–499 [in Japanese with English abstract].

Kawamura, N. 2010. The Oshima Belt, a Jurassic accretionary complex. *In*: Geological Society of Japan (eds) *Geology of Hokkaido*. Asakura, Tokyo, 19–25 [in Japanese].

Kawamura, T., Uchino, T., Kawamura, M., Yoshida, K., Nakagawa, M. & Nagata, H. 2013. *Geology of the Hayachine San district, Quadrangle series, 1:50,000*. Geological Survey of Japan, AIST, Tsukuba [in Japanese with English abstract].

Kimura, K. 1988. Geology and tectonic setting of the Ultra-Tamba Belt in the western part of Ayabe City, Kyoto Prefecture, Southwest Japan. *Journal of Geological Society of Japan*, **94**, 361–379.

Kimura, K. & Hori, R. 1993. Offscraping accretion of Jurassic chert-clastic complexes in the Mino-Tamba Belt, central Japan. *Journal of Structural Geology*, **15**, 145–161.

Kobayashi, F. & Goto, A. 2008. Stratigraphy of the Lower Formation of the Sasayama Group (Lower Cretaceous) in the Kamitaki-Shimotaki area, Tamba City, Hyogo Prefecture, Japan and the K-Ar age of a schist cobble contained in the conglomerate of the formation. *Journal of Geological Society of Japan*, **114**, 577–586 [in Japanese with English abstract].

Kobayashi, T. 1941. The Sakawa orogenic cycle and its bearing on the origin of the Japanese Islands. *Journal of Faculty of Science, Imperial University of Tokyo, Section II*, **5**, 219–578.

Koide, Y. 1986. Origin of the Ibara metabasalt from the Maizuru Tectonic Belt, Southwest Japan. *Journal of Geological Society of Japan*, **92**, 329–348.

Koide, Y., Tazaki, K. & Kagami, H. 1987. Sr isotopic study of Ibara dismembered ophiolite from Maizuru Tectonic Belt, Southwest Japan. *Journal of Mineralogy, Petrology and Economic Geology*, **82**, 1–15.

Kojima, S. 1989. Mesozoic terrane accretion in Northeast China, Sikhote-Alin and Japan regions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **69**, 213–232.

Kojima, S. & Sano, H. 2011. Permian and Triassic submarine landslide deposits in a Jurassic accretionary complex in central Japan. *In*: Yamada, Y., Kawamura, K., Ikehara, K., Ogawa, Y., Urgeles, R., Mosher, D., Chaytor, J. & Strasser, M. (eds) *Submarine Mass Movements and Their Consequences*. Springer, Dordrecht, Advances in Natural and Technological Hazards Research **31**, 639–648.

Kojima, S., Ando, H., Kida, M., Mizutani, S., Sakata, Y., Sugiyama, K. & Tsukada, H. 1999. Clastic rocks in Triassic bedded chert in the Mino terrane, central Japan: their petrographic properties and radiolarian ages. *Journal of Geological Sociey of Japan*, **105**, 421–434 [in Japanese with English abstract].

Kojima, S., Kemkin, I. V., Kametaka, M. & Ando, A. 2000. A correlation of accretionary complexes between southern Sikhote-Alin of Russia and Inner Zone of Southwest Japan. *Geosciences Journal*, **4**, 175–185.

Kojima, S., Tsukada, K. *et al.* 2008. Geological relationship between Anyui Metamorphic Complex and Samarka terrane, Far East Russia. *Island Arc*, **17**, 502–516.

Kondo, N. & Adachi, M. 1975. Mesozoic strata of the area north of Inuyama, with special reference to the Sakahogi conglomerate. *Journal of Geological Sociey of Japan*, **81**, 373–386 [in Japanese with English abstract].

Kunugiza, K. & Maruyama, S. 2011. Geotectonic evolution of the Hida marginal belt, central Japan: reconstruction of the oldest Pacific-type orogeny of Japan. *Journal of Geography (Tolyo)*, **120**, 960–980 [in Japanese with English abstract].

Kunugiza, K., Goto, A., Itaya, T. & Yokoyama, K. 2004. Geological development of the Hida Gaien belt: constraints from K-Ar ages of high P/T metamorphic rocks and U-Th-Pb EMP ages of granitic rocks affecting contact metamorphism of serpentinite. *Journal of Geological Society of Japan*, **110**, 580–590.

Kurimoto, C. 1986. Ultra-Tamba Zore in the Fukuchiyama area, Kyoto Prefecture: its constituent rocks and distribution. *Earth Science (Chikyukagaku)*, **40**, 64–67.

Matsuda, T. & Isozaki, Y. 1991. Well-documented travel history of Mesozoic pelagic chert in Japan: from remote ocean to subduction zone. *Tectonics*, **10**, 475–499.

Matsuda, T., Sakiyama, T. *et al.* 1998. Fission-track ages and magnetic susceptibility of Cretaceous to Paleogene volcanic rocks in southeastern Sikhote Alin, Far East Russia. *Resource Geology*, **48**, 285–290.

Matsumoto, K., Sugimura, K., Tokita, I., Kunugiza, K. & Maruyama, S. 2011. Geology and metamorphism of the Itoigawa-Omi area of the Hida Gaien belt, central Japan: reconstruction of the oldest Pacific-type high P/T type metamorphism and hydration metamorphism during exhumation. *Journal of Geography (Tokyo)*, **120**, 4–29 [in Japanese with English abstract].

Matsuoka, A. 1984. Togano Group of the Southern Chichibu Terrane in the western part of Kochi Prefecture, southwest Japan. *Journal of Geological Society of Japan*, **90**, 455–477 [in Japanese with English abstract].

Matsuoka, A. 1992. Jurassic-Early Cretaceous tectonic evolution of the Southern Chichibu Terrane, Southwest Japan. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **96**, 71–88.

Matsuoka, A. 1995. Jurassic and Lower Cretaceous radiolarian zonation in Japan and in the western Pacific. *Island Arc*, **4**, 140–153.

Matsuoka, A. & Yao, A. 1990. Southern Chichibu terrane. *In*: Ichikawa, K., Mizutani, S., Hara, I., Hada, S. & Yao, A. (eds) *Pre-Cretaceous Terranes of Japan*. Department of Geosciences, Osaka City University, Osaka, 203–216.

Matsuoka, A., Hori, R., Kuwahara, K., Hiraishi, M., Yao, A. & Ezaki, Y. 1994. Triassic-Jurassic radiolarian-bearing sequences in the Mino terrane, central Japan. *In*: Organizing Committee of Interrad VII (eds) *Guide Book for INTERRAD VII Field Excursion*. Department of Geosciences, Osaka City University, Osaka, 19–61.

Matsuoka, A., Yamakita, S., Sakakibara, M. & Hisada, K. 1998. Unit division for the Chichibu Composite Belt from a view point of accretionary tectonics and geology of western Shikoku, Japan. *Journal of Geological Society of Japan*, **104**, 634–653 [in Japanese with English abstract].

Miyakawa, K. 1961. General considerations on the Sangun metamorphic rocks on the basis of their petrographical features observed in the San-in provinces, Japan. *Journal of Earth Sciences, Nagoya University*, **9**, 345–393.

Miyakawa, K. 1982. Low-grade metamorphic rocks of the Hida marginal belt in the upper Kuzuryu river area, central Japan. *Journal of Japanese Association of Mineralogist, Petrologist and Economic Geologist*, **77**, 256–265 [in Japanese with English abstract].

Miyamoto, T. & Yanagi, T. 1996. U-Pb dating of detrital zircons from the Sangun metamorphic rocks, Kyushu, Southwest Japan: an evidence for 1.9–2.0 Ga granite emplacement in the provenance. *Geochemical Journal*, **30**, 261–271.

Miyashiro, A. 1961. Evolution of metamorphic belts. *Journal of Petrology*, **2**, 277–311.

Mizutani, S. 1959. Clastic plagioclase in Permian greywacke from the Mugi area, Gifu Prefecture, central Japan. *Journal of Earth Sciences, Nagoya University*, **7**, 108–136.

Moriya, S. 1972. Low-grade metamorphic rocks of the northern Kitakami Mountainland. *Science Reports of Tohoku University, Series 3*, **11**, 239–282.

Nakae, S. 2000. Regional correlation of the Jurassic accretionary complex in the Inner Zone of Southwest Japan. *Memoir of Geological Society of Japan*, **55**, 73–98 [in Japanese with English abstract].

Nakae, S. & Kurihara, T. 2011. Direct age for Upper Permian accretionary complex (Kirinai Formation), Kitakami Mountains, Northeast Japan. *Palaeoworld*, **20**, 146–157.

Nakamizu, M., Okada, M., Yamazaki, T. & Komatsu, M. 1989. Metamorphic rocks in the Omi-Renge serpentinite melange, Hida Marginal Tectonic Belt, Central Japan. *Memoirs of Geological Society of Japan*, **33**, 21–35 [in Japanese with English abstract].

Nakashima, K. & Sano, H. 2007. Palaeoenvironmental implication of resedimented limestones shed from Mississippian–Permian mid-oceanic atoll-type buildup into slope-to-basin facies, Akiyoshi, Japan. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **247**, 329–356.

Nakazawa, K. 1958. The Triassic system in the Maizuru zone, Southwest Japan. *Memoirs of College of Science, University of Kyoto, Series B*, **24**, 285–313.

Nakazawa, T. & Ueno, K. 2004. Sequence boundary and related sedimentary and diagenetic facies formed on Middle Permian mid-oceanic carbonate platform: core observation of Akiyoshi Limestone, Southwest Japan. *Facies*, **50**, 301–311.

Nakazawa, T., Ueno, K., Kawahata, H., Fujikawa, M. & Kashiwagi, K. 2009. Facies stacking patterns in high-frequency sequences influenced by long-term sea-level change on a Permian Panthalassan oceanic atoll: an example from the Akiyoshi Limestone, SW Japan. *Sedimentary Geology*, **214**, 35–48.

Naumann, E. 1885. *Uber den Bau und die Entstehung der japanischen Inseln*. R. Friedlaender und Sohn, Berlin.

NIITSUMA, N., TAIRA, A. & SAITO, Y. 1985. Japanese Islands before the opening of the Sea of Japan. *Science (Kagaku)*, **55**, 744–747 [in Japanese].

NISHIMURA, Y. 1971. Regional metamorphism of the Nishiki-cho district Southwest japan. *Journal of Science, Hiroshima University, Series C*, **6**, 203–268.

NISHIMURA, Y. 1998. Geotectonic subdivision and areal extent of the Sangun belt, Inner Zone of Southwest Japan. *Journal of Metamorphic Geology*, **16**, 129–140.

NISHIMURA, Y. & OKAMOTO, T. 1976. Lawsonite-albite schist from the Masuda district, southwest Japan. *Jubilee Publication in the Commemoration of Professor G. Kojima, Sixtieth Birthday*. Hiroshima University Press, Hiroshima, Japan, 144–152 [in Japanese].

NISHIMURA, Y. & SHIBATA, K. 1989. Modes of occurrence and K-Ar ages of metagabbroic rocks in the Sangun metamorphic belt, Southwest Japan. *Memoir of Geological Society of Japan*, **33**, 343–357 [in Japanese with English abstract].

NISHIMURA, Y., MATSUBARA, Y. & NAKAMURA, E. 1983. Zonation and K-Ar ages of the Yaeyama metamorphic rocks, Ryukyu Islands. *Memoir of Geological Society of Japan*, **22**, 27–37 [in Japanese with English abstract].

NISHIMURA, Y., HIROTA, Y., SHIOZAKI, D., NAKAHARA, N. & ITAYA, T. 2004. The Nagasaki metamorphic rocks and their geotectonics in Mogi area, Nagasaki Prefecture, Southwest Japan: juxtaposition of the Suo belt with the Sanbagawa belt. *Journal of Geological Society of Japan*, **110**, 372–383 [in Japanese with English abstract].

NOZAKI, T., KATO, Y., SUZUKI, K. & KASE, K. 2012. Re-Os geochronology of the Hitachi VMS deposit, Ibaraki Prefecture: the oldest sulfide deposit in the Japanese Islands. *Abstracts of Japan Geoscience Union 2012*, 23 May, 2012, Makuhari, Japan, SGL43-05.

NUONG, N. D., ITAYA, T. & NISHIMURA, Y. 2008. Age (K–Ar phengite)–temperature–structure relations: a case study from the Ishigaki high-pressure schist belt, southern Ryukyu Arc, Japan. *Geological Magazine*, **145**, 677–684.

NUTMAN, A. P., SANO, Y., TERADA, K. & HIDAKA, H. 2006. 743 ± 17 Ma granite clast from Jurassic conglomerate, Kamiaso, Mino Terrane, Japan: the case for South China Craton provenance (Korean Gyeonggi Block?). *Journal of Asian Earth Sciences*, **26**, 99–104.

OHO, Y. 1990. Superimposed folds of the Sangun metamorphic rocks in the Ochiai-Asahi area, Okayama Prefecture, Southwest Japan. *Journal of Geological Society of Japan*, **95**, 541–551 [in Japanese with English abstract].

OKAMI, K., KOSHIYA, S. & EHIRO, M. 1992. Compositions of the Paleozoic and Mesozoic sandstones distributed in the Kitakami and Abukuma Mountains, Northeast Japan. *Memoir of Geological Society of Japan*, **38**, 43–57 [in Japanese with English abstract].

ONOUE, T., SATO, H. *ET AL*. 2012. Deep-sea record of impact apparently unrelated to mass extinction in the Late Triassic. *Proceedings of National Academy of Sciences, USA*, **109**(47), 19134–19139, http://www.pnas.org/cgi/doi/10.1073/pnas.1209486109

ONUKI, H., SHIBA, M., KAGAWA, H. & HORI, H. 1988. Low-temperature regional metamorphic rocks in the northern Kitakami Mountains. I. Kuzakai-Morioka area. *Journal of Mineralogy, Petrology and Economic Geology*, **83**, 495–506 [in Japanese with English abstract].

ONUKI, Y. 1981. Part 1. The Kitakami Mountains. *In*: HASE CHICHITSU CHOSA JIMUSHO (ed.) *Explanation of the Geological Map of the Kitakami River Area, Kitakami Mountains, at a Scale of 1:200,000*. Hase Chichitsu Chosa Jimusho, Sendai, 3–223 [in Japanese].

ONUKI, Y., TAKAHASHI, K. & ABE, T. 1962. On the Motai Group of the Kitakami Massif, Japan. *Journal of Geological Society of Japan*, **68**, 629–639 [in Japanese with English abstract].

OSOZAWA, S., TAKEUCHI, H. & KOITABASHI, T. 2004. Formation of the Yakuno ophiolite; accretionary subduction under medium-pressure-type metamorphic conditions. *Tectonophysics*, **393**, 197–219.

OTA, M. 1968. The Akiyoshi Limestone Group: a geosynclinal organic reef complex. *Akiyoshi-dai Science Museum Bulletin*, **5**, 1–44.

OTOH, S. & SASAKI, M. 2003. Tectonostratigraphic divisions and regional correlation of the sedimentary complex of the North Kitakami Belt. *Journal of Geography (Tokyo)*, **112**, 406–410 [in Japanese with English abstract].

OTOH, S., OBARA, H. *ET AL*. 2013. Provenance of pre-Aptian sandstones of Japan viewed from detrital zircon geochronology. *Japan Geoscience Union Meeting 2013*, 19–24 May, 2013, Makuhari, Japan, Abstract.

OZAWA, Y. 1925. Paleontological and stratigraphical studies on the Permo-Carboniferous limestone of Nagato, Pt. II. Paleontology. *Journal of College of Science, Imperial University of Tokyo*, **45**, 1–90.

PILLAI, D. & ISHIGA, H. 1987. Discovery of Late Permian radiolarians from Kozuki Formation, Kozuki-Tatsuno Belt, Southwest Japan. *Journal of Geological Society of Japan*, **93**, 847–850.

RAYMOND, L. A. 1984. Classification of mélanges. *Geological Society of America Specical Papers*, **198**, 7–20.

ROSS, C. A. & ROSS, J. R. P. 1987. Late Paleozoic sea levels and depositional sequences. *In*: ROSS, C. A. & HAMAN, D. (eds) *Timing and Depositional History of Eustatic Sequences: Constraints on Seismic Stratigraphy*. Cushman Foundation for Foraminiferal Research, Special Publication, **24**, 137–149.

SAKASHIMA, T., TERADA, K., TAKESHITA, T. & SANO, Y. 2003. Large-scale displacement along the Median Tectonic Line, Japan: evidence from SHRIMP zircon U-Pb dating of granites and gneisses from the South Kitakami and paleo-Ryoke belts. *Journal of Asian Earth Sciences*, **21**, 1019–1039.

SANO, H. 1988. Permian oceanic-rocks of Mino terrane, central Japan. Part I Chert facies. *Journal of Geological Society of Japan*, **94**, 697–709.

SANO, H. 2006. Impact of long-term climate change and sea-level fluctuation on Mississippian to Permian mid-oceanic atoll sedimentation (Akiyoshi Limestone Group, Japan). *Palaeogeography, Plaeoclimatology, Paleoecology*, **236**, 169–189.

SANO, H. & KANMERA, K. 1988. Paleogeographic reconstruction of accreted oceanic rocks, Akiyoshi, southwest Japan. *Geology*, **16**, 600–603.

SANO, H. & KANMERA, K. 1991*a*. Collapse of ancient reef complex. What happened during collision of Akiyoshi reef complex? Geologic setting and age of Akiyoshi terrane rocks on western Akiyoshi-dai plateau. *Journal of Geological Society of Japan*, **97**, 113–133.

SANO, H. & KANMERA, K. 1991*b*. Collapse of ancient reef complex. What happened during collision of Akiyoshi reef complex? Broken limestone as collapse products. *Journal of Geological Society of Japan*, **97**, 217–229.

SANO, H. & KANMERA, K. 1991*c*. Collapse of ancient reef complex. What happened during collision of Akiyoshi reef complex? Limestone breccias, redeposited limestone debris and mudstone injection. *Journal of Geological Society of Japan*, **97**, 297–309.

SANO, H. & KANMERA, K. 1991*d*. Collapse of ancient oceanic reef complex. What happened during collision of Akiyoshi reef complex? Sequence of Collisional collapse and generation of collapse products. *Journal of Geological Society of Japan*, **97**, 631–644.

SANO, H. & KOJIMA, S. 2000. Carboniferous to Jurassic oceanic rocks of Mino-Tamba-Ashio terrane, southwest Japan. *Memoir of Geological Society of Japan*, **55**, 123–144 [in Japanese with English abstract].

SANO, H., FUJII, S. & MATSUURA, F. 2004. Response of Carboniferous–Permian mid-oceanic seamount-capping buildup to global cooling and sea-level change: Akiyoshi, Japan. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **213**, 187–206.

SANO, H., KUWAHARA, K., YAO, A. & AGEMATSU, S. 2010. Panthalassan seamount associated Permian-Triassic boundary siliceous rocks, Mino terrane, central Japan. *Paleontological Research*, **14**, 293–314.

SANO, H., WADA, T. & NARAOKA, H. 2012. Late Permian to Early Triassic environmental changes in the Panthalassic Ocean: record from the seamount-associated deep-marine siliceous rocks, central Japan. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **363–364**, 1–10.

SANO, S. 1992. Neodymium isotopic compositions of Silurian Yakuno metagabbros. *Journal of Mineralogy, Petrology and Economic Geology*, **87**, 272–282 [in Japanese with English abstract].

SANO, S., HAYASAKA, Y. & TAZAKI, K. 2000. Geochemical characteristics of Carboniferous greenstones in the inner zone of Southwest Japan. *Island Arc*, **9**, 81–96.

SANO, S., SUGISAKA, N. & SHIMAGUCHI, T. 2009. Discovery of megalodontid bivalves in the Shiriya area, northern Honshu, Northeast Japan, and its geological implications. *Memoir of Fukui Prefectural Dinosaur Museum*, **8**, 51–57 [in Japanese with English abstract].

SANO, Y., HIDAKA, H., TERADA, K., SHIMIZU, H. & SUZUKI, M. 2000. Ion microprobe U-Pb zircon geochronology of the Hida gneiss: finding of the oldest minerals in Japan. *Geochemical Journal*, **34**, 135–153.

SHIBATA, K. & ADACHI, M. 1974. Rb-Sr whole-rock ages of Precambrian metamorphic rocks in the Kamiaso conglomerate from central Japan. *Earth and Planetary Science Letters*, **21**, 277–287.

SHIBATA, K. & NISHIMURA, Y. 1989. Isotopic ages of the Sangun crystalline schists, Southwest Japan. *Memoir of Geological Society of Japan*, **33**, 317–341.

SHIMIZU, D. 1962. The Permian Maizuru Group, its stratigraphy and syntectonic faunal succession through the latest Paleozoic Orogeny. *Memoirs of College of Science, University of Kyoto, Series B*, **28**, 571–609.

SOHMA, T., MARUYAMA, S., MATSUSHITA, S., YAMAMOTO, M. & MATSUMOTO, K. 1983. Olistoststrome in western area of the Hida-Gaien belt and its geotectonic bearings. *Journal of Faculty of Education, Toyama University*, **31**, 13–23 [in Japanese].

SOREGHAN, G. S., HEAVENS, N., PATTERSON, E. P., SANO, H., MAHOWALD, N., DAVYDOV, V. & SOREGHAN, M. J. 2011. Giant grains from Pennsylvanian Dust of the Panthalassic Ocean: evidence for Extreme Winds and a Paleo-Tethyan Monsoon. *AGU Annual Meeting Abstract*, 5–9 December, 2011, San Francisco, USA, PP22D-07.

SUDA, Y. 2004. Crustal anatexis and evolution of granitoid magma in Permian intra-oceanic island arc, the Asago body of the Yakuno ophiolite, Southwest Japan. *Journal of Mineralogical and Petrological Sciences*, **99**, 339–356.

SUGAMORI, Y. 2009*a*. Ultra-Tamba Terrane in the Kawanishi-Inagawa area, southwestern part of Hyogo Prefecture, Southwest Japan. *Journal of Geological Society of Japan*, **115**, 80–95 [in Japanese with English abstract].

SUGAMORI, Y. 2009*b*. Middle Triassic Kamitaki Formation between the Ultra-Tamba and Tamba terranes, Southwest Japan and its geological implication for tectonic evolution of the eastern margin of East Asia. *In*: LUO, H., AITCHISON, J. C. *ET AL.* (eds) *Abstracts of InterRad 12*, 14–17 September, 2009. Nanjing, China, 162–163.

SUGAMORI, Y. 2011. Late Permian radiolarians from the Ajima Formation of the Ultra-Tamba Terrane in the Sasayama area, southwest Japan. *Palaeoworld*, **20**, 158–165.

SUGIMOTO, M. 1974. Stratigraphical study in the Outer Belt of the Kitakami Massif, Northeast Japan. *Contributions from Institute of Geology and Paleontology, Tohoku University*, **74**, 1–48 [in Japanese with English abstract].

SUGIYAMA, T. & NAGAI, K. 1994. Reef facies and paleoecology of reef-building corals in the lower part of the Akiyoshi Limestone Group (Carboniferous), Southwest Japan. *Courier Forschungsinstitus Senckenberg*, **172**, 140–231.

SUZUKI, K., ADACHI, M. & TANAKA, T. 1991. Middle Precambrian provenance of Jurassic sandstone in the Mino Terrane, central Japan: Th-U-total Pb evidence from an electron microprobe monazite study. *Sedimentary Geology*, **75**, 141–147.

SUZUKI, N., EHIRO, M., YOSHIHARA, K., KIMURA, Y., KAWASHIMA, G., YOSHIMOTO, H. & NOGI, T. 2007*a*. Geology of the Kuzumaki-Kamaishi Subbelt of the North Kitakami Belt (a Jurassic accretionary complex), Northeast Japan: case study of the Kawai-Yamada area, eastern Iwate Prefecture. *Bulletin of Tohoku University Museum*, **6**, 103–174.

SUZUKI, N., YAMAKITA, S., TAKAHASHI, S. & EHIRO, M. 2007*b*. Middle Jurassic radiolarians from carbonate manganese nodules in the Otori Formation in the eastern part of the Kuzumaki-Kamaishi Subbelt, the North Kitakami Belt, Northeast Japan. *Journal of Geological Society of Japan*, **113**, 274–277 [in Japanese with English abstract].

SUZUKI, S. 1987. Sedimentary and tectonic history of the eastern part of Maizuru zone, Southwest Japan. *Geological Peport of Hiroshima University*, **27**, 1–54 [in Japanese with English abstract].

TAGIRI, M., MORIMOTO, M., MOCHIZUKI, R., YOKOSUKA, A., DUNKLEY, D. J. & ADACHI, T. 2010. Hitachi metamorphic rocks: Occurrence and geology of metagranitic rocks with Cambrian SHRIMP zircon age. *Journal of Geography (Tokyo)*, **119**, 245–56 [in Japanese with English abstract].

TAGIRI, M., HORIE, K., ADACHI, T. & HIROI, Y. 2011. SHRIMP dating of magmatism in the Hitachi metamorphic terrane, Abukuma Belt, Japan: evidence for a Cambrian volcanic arc. *Island Arc*, **20**, 259–279.

TAIRA, A. & TASHIRO, M. 1987. Late Paleozoic and Mesozoic accretion tectonics in Japan and Eastern Asia. *In*: TAIRA, A. & TASHIRO, M. (eds) *Historical Biogeography and Plate Tectonic Evolution of Japan and Eastern Asia*. Terra Scientific Publishing Company, Tokyo, 1–43.

TAKAHASHI, S., EHIRO, M. & SUZUKI, N. 2006. Preliminary report on the geology of the North Kitakami Belt, a Jurassic accretionary complex in the west Akka area, Iwaizumi-Town, Iwate Prefecture, northeast Japan. *Geology of Iwate*, **35/36**, 66–71 [in Japanese].

TAKEMURA, S. & SUZUKI, S. 1996. The geology and tectonics of the Ultra-Tamba Zone, western Hyogo Prefecture, Southwest Japan. *Journal of Geological Society of Japan*, **102**, 1–12 [in Japanese with English abstract].

TAKEMURA, S., SUZUKI, S. & ISHIGA, H. 1993. Stratigraphy of the Kozuki Formation, Kamigori Zone, Southwest Hyogo Prefecture, Japan, reconsideration with the discvery of *Albaillella asymmtrica* (radiorarian fossil) and the structural analysis. *Journal of Geological Society of Japan*, **99**, 675–678 [in Japanese with English abstract].

TAKESHITA, H., WATANABE, T. & ISHIGA, H. 1987. Discovery of Permian radiolarians from the Tanoharagawa Formation (the Sangun metamrophic rocks), Gotsu, Shimane Prefecture, Japan. *Journal of Geological Society of Japan*, **93**, 435–438 [in Japanese].

TAKEUCHI, M. 2000. Origin of Jurassic coarse clastic sediments in the Mino-Tamba Belt. *Memoir of Geological Society of Japan*, **55**, 107–121 [in Japanese with English abstract].

TAMURA, M. 1987. Distribution of Japanese Triassic bivalve faunas and sedimentary environment of megalodont limestone in Japan. *In*: TAIRA, A. & TASHIRO, M. (eds) *Historical Biogeography and Plate Tectonic Evolution of Japan and Eastern Asia*. Terra Scientific Publishing Company, Tokyo, 97–110.

TAZAWA, J. 1993. Pre-Neogene tectonics of the Japanese Islands from the viewpoint of paleobiogeography. *Journal of Geological Society of Japan*, **99**, 525–543 [in Japanese with English abstract].

TERAOKA, Y., SHIBATA, K., OKUMURA, K. & UCHIUMI, S. 1994. K-Ar ages of detrial K-feldspars and muscovites from the Shimanto Supergroup in east Kyushu and west Shikoku, Southwest Japan. *Journal of Geological Society of Japan*, **100**, 477–485 [in Japanese with English abstract].

TERAOKA, Y., MATSUURA, H. *ET AL.* 1996. Geological Map of Japan 1:200000 NI-53-26 Takahashi. *Geological Survey of Japan*, Tsukuba.

TORIYAMA, R. 1958. Geology of Akiyoshi: part III. Fusulinids of Akiyoshi. *Memoir of Faculty of Science, Kyushu University, D*, **VII**, 1–48.

TSUJIMORI, T. 1998. Geology of the Osayama serpentinite melange in the central Chugoku Mountains, southwestern Japan: 320 Ma blueschist-bearing serpentinite melange beneath the Oeyama ophiolite. *Journal of Geological Society of Japan*, **104**, 213–231 [in Japanese with English abstract].

TSUJIMORI, T. 2002. Prograde and retrograde P-T paths of the late Paleozoic glaucophane eclogite from the Renge metamorphic belt, Hida Mountains, Southwest Japan. *International Geology Review*, **44**, 797–818.

TSUJIMORI, T. 2010. Paleozoic subduction-related metamorphism in Japan: new insights and perspectives. *Journal of Geography (Tokyo)*, **119**, 294–312 [in Japanese with English abstract].

TSUJIMORI, T. & ITAYA, T. 1999. Blueschist-facies metamorphism during Paleozoic orogeny in southwestern Japan: phengite K-Ar ages of blueschist-facies tectonic blocks in a serpentinite melange beneath early Paleozoic Oeyama ophiolite. *Island Arc*, **8**, 190–205.

TSUJIMORI, T. & LIOU, J. G. 2004. Metamorphic evolution of kyanite-staurolite-bearing epidote-amphibolite from the Early Paleozoic Oeyama belt, SW Japan. *Journal of Metamorphic Geology*, **22**, 301–313.

TSUJIMORI, T. & LIOU, J. G. 2005. Eclogite-facies mineral inclusions in clinozoisite from Paleozoic blueschist, central Chugoku Mountains, Southwest Japan: evidence of regional eclogite-facies metamorphism. *International Geology Review*, **47**, 215–232.

TSUJIMORI, T. & LIOU, J. G. 2007. Significance of the Ca-Na pyroxene-lawsonite-chlorite assemblage in blueschist-facies metabasalts: an example from the Renge metamorphic rocks, SW Japan. *International Geology Review*, **49**, 415–430.

TSUJIMORI, T. & MATSUMOTO, K. 2006. P-T pseudosection of a glaucophane-epidote eclogite from Omi serpentinite melange, SW Japan: a preliminary report. *Journal of Geological Society of Japan*, **112**, 407–414 [in Japanese with English abstract].

TSUJIMORI, T., ISHIWATARI, A. & BANNO, S. 2000. Eclogitic glaucophane schist from the Yunotani valley in Omi Town, the Renge metamorphic belt, the Inner Zone of southwestern Japan. *Journal of Geological Society of Japan*, **106**, 353–362 [in Japanese with English abstract].

TSUTSUMI, Y., YOKOYAMA, K., TERADA, K. & SANO, Y. 2003. SHRIMP U-Pb dating of zircons in metamorphic rocks from northern Kyushu, western Japan. *Journal of Mineralogical and Petrological Sciences*, **98**, 181–193.

UCHINO, T. & KAWAMURA, M. 2009. Chemical composition of the green rocks in the Nedamo Terrane, Northeast Japan. *Journal of Geological Society of Japan*, **115**, 242–247 [in Japanese with English abstract].

UCHINO, T. & KAWAMURA, M. 2010*a*. Glaucophane found from meta-basalt in the Nedamo Terrane, Northeast Japan, and its geologic significance. *Bulletin of Geological Survey of Japan*, **61**, 445–452 [in Japanese with English abstract].

UCHINO, T. & KAWAMURA, M. 2010*b*. Tectonics of an Early Carboniferous forearc inferred from a high-P/T schist-bearing conglomerate in the Nedamo Terrane, Northeast Japan. *Island Arc*, **19**, 177–199.

UCHINO, T., KAWAMURA, M. & KURIHARA, T. 2005. Early Carboniferous radiolarians discovered from the Hayachine Terrane, Northeast Japan: the oldest fossil age for clastic rocks of accretionary complex in Japan. *Journal of Geological Society of Japan*, **111**, 249–252 [in Japanese with English abstract].

UCHINO, T., KAWAMURA, M., GOUZU, C. & HYODO, H. 2008. Phengite $^{40}Ar/^{39}Ar$ age of garnet-bearing pelitic schist pebble obtained from conglomerate in the Nedamo Terrane, Northeast Japan. *Journal of Geological Society of Japan*, **114**, 314–317 [in Japanese with English abstract].

UEMURA, F., SAKAMOTO, T. & YAMADA, N. 1979. *Geology of the Wakasa District, with Geological Sheet Map at 1:50,000*. Geological Survey of Japan, Tsukuba [in Japanese with English abstract].

WAKITA, K. 1984. *Geology of the Hachiman District, with Geological Sheet Map at 1:50,000*. Geological Survey of Japan, Tsukuba [in Japanese with English abstract].

WAKITA, K. 1988. Origin of chaotically mixed rock bodies in the Early Jurassic to Early Cretaceous sedimentary complex of the Mino terrane, central Japan. *Bulletin of Geological Survey of Japan*, **39**, 675–757.

WAKITA, K. 1995. *Geology of the Mino District, with Geological Sheet Map at 1:50,000*. Geological Survey of Japan, Tsukuba [in Japanese with English abstract].

WAKITA, K. 2000. Melanges of the Mino terrane. *Memoir of Geological Society of Japan*, **55**, 145–163 [in Japanese with English abstract].

WAKITA, K. 2013. Geology and tectonics of Japanese islands: a review. The key to understanding the geology of Asia. *Journal of Asian Earth Sciences*, **72**, 75–87.

WATANABE, K. 1991. Fusuline biostratigraphy of the Upper Carboniferous and Lower Permian of Japan, with special reference to the Carboniferous-Permian boundary. *Paleontological Society of Japan, Special Paper*, **32**, 1–150.

WATANABE, T., KOBAYASHI, H. & SENGAN, H. 1983. Lawsonite from quartzfeldspathic schist in the Sangun metamorphic belt, Shikuma, Shimane Prefecture. *Memoirs of Faculty of Science, Shimane University*, **17**, 81–86.

WATANABE, T., SENGAN, H. & KOBAYASHI, H. 1989. The Hazumi-minami tectonic melange in the eastern Goutsu City, Shimane Prefecture: geology, petrology and structure. *Memoir of Geological Society of Japan*, **33**, 107–124 [in Japanese with English abstract].

WORKING GROUP ON THE PERMIAN-TRIASSIC SYSTEMS 1975. Stratigraphy near the Permian-Triassic boundary in Japan and its correlation. *Journal of Geological Society of Japan*, **81**, 165–184 [in Japanese with English abstract].

YAMAKITA, S. 1998. What belongs to the Northern Chichibu Belt? Tectonic division between the Northern Chichibu Belt and the Kurosegawa Belt. *Journal of Geological Society of Japan*, **104**, 623–633.

YAMAKITA, S. & HORI, R. S. 2009. Early Jurassic radiolarians from a carbonate nodule in the Northern Chichibu Belt in western central Shikoku, Southwest Japan. *News of Osaka Micropaleontologists, Special Volume*, **14**, 497–505 [in Japanese with English abstract].

YAO, A. 2000. Tectonic arrangement of Southwest Japan in view of the Paleozoic-Mesozoic tectonics of East Asia. *In*: ISHIGA, H., TAKAZU, A. & HAYASAKA, Y. (eds) *Tectonic Division and Correlation of Terranes of Southwest Japan*. Association for Geological Collaboration in Japan, Monograph, Tokyo, Japan, **49**, 145–155.

YAO, A., MATSUDA, T. & ISOZAKI, Y. 1980. Triassic and Jurassic radiolarians from the Inuyama area, central Japan. *Journal of Geosciences, Osaka City University*, **23**, 135–154.

YEHARA, S. 1927. Faunal and stratigraphical study of the Sakawa Basin, Shikoku. *Japanese Journal of Geology and Geography*, **5**, 1–40.

YOSHIDA, S. & WAKITA, K. 1999. *Geology of the Gifu District, with geological sheet map at 1:50,000*. Geological Survey of Japan, Tsukuba [in Japanese with English abstract].