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Thematic Article

Paleozoic ophiolites and blueschists in Japan and Russian Primorye in the tectonic framework of East Asia: A synthesis

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Abstract Ophiolites and high-pressure (HP) metamorphic rocks are studied to test continuation of Paleozoic and early Mesozoic geological units from Japan to Primorye over the Japan Sea. The early Paleozoic ophiolites are present on both sides, and the late Paleozoic ophiolite of south-western Japan may also have its counterpart in Primorye. The Shaiginskiy HP schist and the associated Avdakimov gneiss in Primorye, both tectonically underlying the early Paleozoic ophiolitic complex, yield a 250-Ma phengite and hornblende K–Ar age, which is intermediate between those of the Renge (280–330 Ma) and Suo (170–220 Ma) blueschists in south-western Japan. This age also coincides with that of the coesite-bearing eclogites in the Sulu–Dabie suture in China and several medium-pressure metamorphic rocks in East Asia. On the basis of these results and other geological data, the authors propose the 'Yaeyama promontory' model for an eastward extension of the Sulu–Dabie suture. The collision suture warps southward into the Yellow Sea and detours around Korea, turns to the north at Ishigaki Island in the Yaeyama Archipelago of Ryukyu, where it changes into a subduction zone and further continues toward south-western Japan and Primorye. Most ophiolites from this area represent crust–mantle fragments of an island arc–back-arc basin system, and the repeated formation of ophiolite–blueschist associations may be due to the repetition of the Mariana-type non-accreting subduction and Nankai-type accreting subduction.

Key words: Japan Sea, Khanka terrane, Korea, Sikhote Alin, Sulu–Dabie suture, Yaeyama promontory.

INTRODUCTION

More than a half century ago, long before the establishment of plate tectonics, Kobayashi (1951) proposed a rifting–drifting hypothesis for the origin of the Japan Sea. From a geological point of view, the rifting–drifting theory requires the occurrence of equivalent pre-Tertiary geological units on both sides of the Japan Sea. For example, the Appalachian and Caledonian belts on both sides of the Atlantic Ocean, respectively, represent separated fragments of a single early Paleozoic orogenic belt, and include Early Ordovician ophiolites of identical age (Dunning & Pedersen 1988).

Recent paleomagnetic results indicate a fast drifting of Japan at *ca* 15 Ma in the manner of the opening of a pair of hinged doors (Otofuji & Matsuda 1984; Otofuji *et al.* 1985). Some basalt samples drilled from the Japan Sea floor have ^{40}Ar-^{39}Ar ages of 15–25 Ma (Kaneoka *et al.* 1992). These data coupled with other geophysical and geochemical data result in various models for the Miocene back-arc opening process (Nohda *et al.* 1988; Tamaki & Honza 1991). However, evidence and consideration for an original geological continuity between Japan and Russian Primorye are not conclusive.

The Japanese Islands are mainly composed of accretionary complexes of Paleozoic, Mesozoic and

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Cenozoic ages. Every accretionary complex is characterized by the ‘oceanic plate stratigraphy’, which is composed of fragments of oceanic crust and seamounts, chert and/or pelagic limestone, siliceous shale, sandstone and conglomerate (or olistostrome) in younging order (Isozaki 1996). Kojima (1989) pointed out that the Jurassic accretionary complexes showing the same age–lithology relationship are found on both sides of the Japan Sea, namely in south-western Japan (Mino-Tamba belt) and in the Sikhote Alin terrane in Primorye (Samarka zone) and the adjacent Chinese territory (Nadanhada zone). However, detailed comparison of Paleozoic ophiolites and blueschists on both sides of the Japan Sea has not previously been attempted.

The present paper reports petrologic and geochronologic similarity of the Paleozoic igneous and metamorphic rocks on both sides of the Japan Sea on the basis of our recent cooperative works with Russian geologists, and discusses configuration of the late Paleozoic–early Mesozoic collision suture and geotectonic significance of the multiple ophiolite–blueschist assemblages in East Asia. Numeric age data and detailed petrology of the dated samples will appear elsewhere.

PALEOZOIC OPHIOLITES AND BLUESCHISTS IN JAPAN

SOUTH-WESTERN JAPAN

The Japanese Islands bear ophiolitic complexes of various ages ranging from early Paleozoic to Cenozoic, forming a Phanerozoic multiple ophiolite belt (Ishiwatari 1991, 1994). Paleozoic ophiolites (Fig. 1) occupy a higher structural position in the piling nappes of the accretionary complexes. In south-western Japan (Fig. 2) the Oeyama ophiolite of Cambro-Ordovician age occupies the highest structural position, and tectonically overlies the late Paleozoic Renge blueschist, the Yakuno ophiolite, and the Permian Akiyoshi (and Ultra-Tamba) accretionary complexes. These tectonic units are bounded by thrust faults (Ishiwatari *et al.* 1999).

The Oeyama ophiolite is mainly composed of residual peridotite with podiform chromite deposits and minor gabbroic rocks; basaltic volcanic rocks are completely absent. The peridotite is lherzolitic in the eastern part (Oeyama body, spinel Cr# (Cr/(Al + Cr)) = 0.3; Kurokawa 1985), but is harzburgitic in the western part (Tari-Misaka body, spinel Cr# = 0.5; Arai 1980). The peridotite includes metagabbro and amphibolite bodies, which have

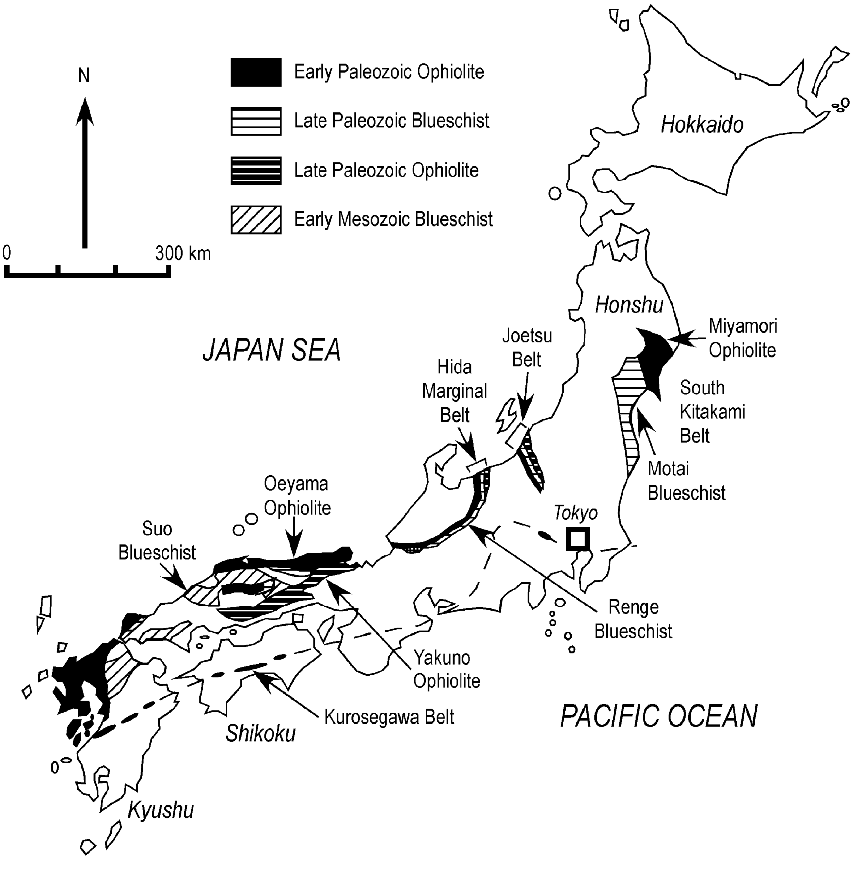


Fig. 1 Distribution of Paleozoic ophiolites and Paleozoic–early Mesozoic blueschists in Japan.

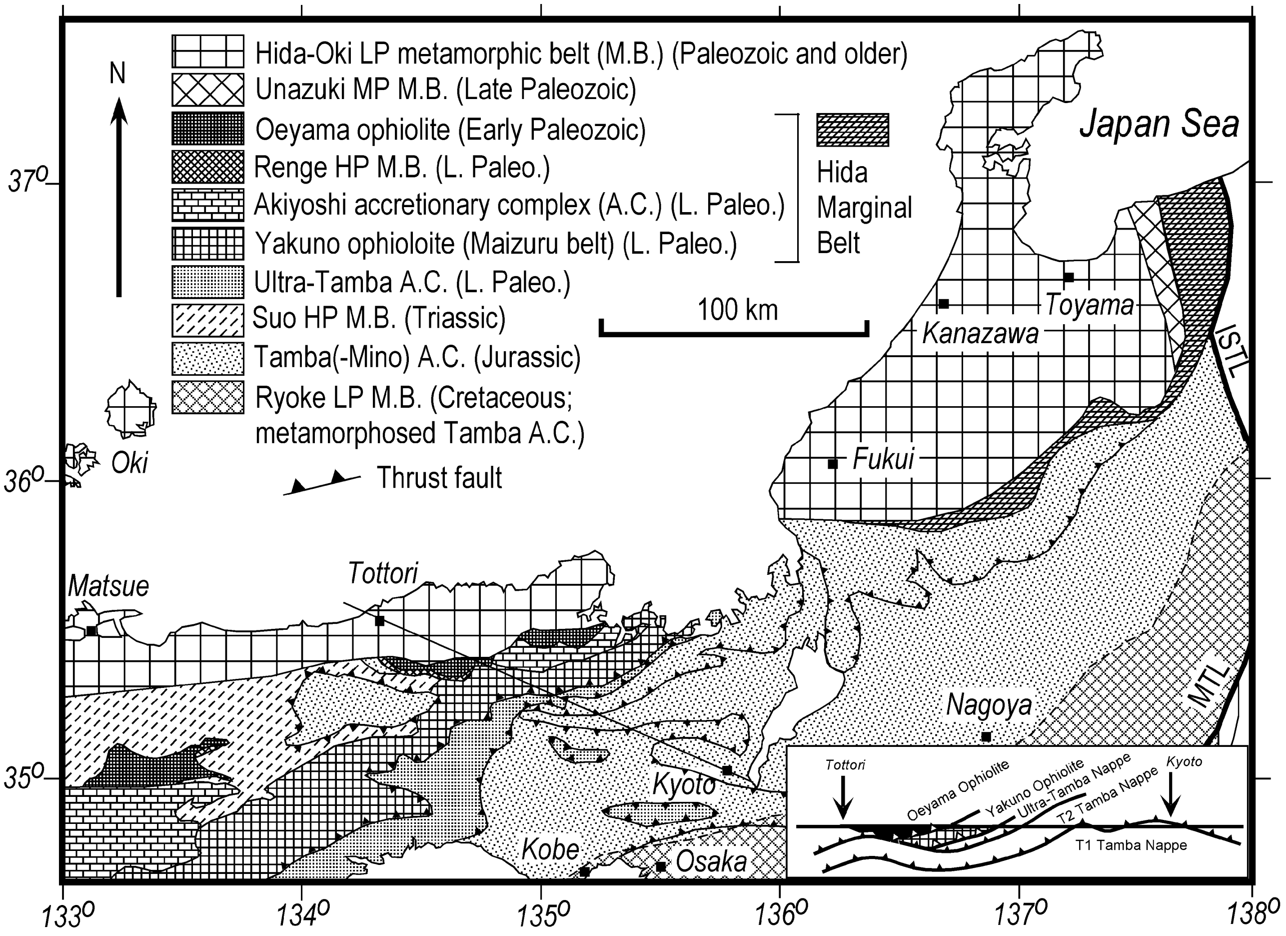


Fig. 2 Geological units in the main part of the Inner Zone of south-western Japan. Kyoto–Tottori cross-section is shown in the inset. ISTL, Itoigawa–Shizuoka Tectonic Line; MTL, Median Tectonic Line; MB, metamorphic belt; AC, accretionary complex. Unit boundaries are mainly after Ishiwatari (1994), Tsujimori (1998), and Geological Survey of Japan (1992).

hornblende K–Ar ages of 444–464 Ma (Nishimura & Shibata 1989). The kyanite- and staurolite-bearing HP metagabbro (troctolitic cumulate origin) of higher metamorphic pressure in the Oeyama peridotite body also has a similar hornblende K–Ar age of 403–443 Ma (Tsujimori 1999; Tsujimori *et al.* 2000c; Tsujimori & Ishiwatari 2002).

The Yakuno ophiolite consists of a relatively complete succession composed of harzburgite tectonite (spinel Cr# = 0.6–0.8), dunite–wehrlite–clinopyroxenite cumulate, metagabbro, amphibolite and metabasalt with abundant black shale (Ishiwatari 1985a). Middle–Late Permian radiolarian fossils were identified from the black shale intercalated with basalt lavas (Kurimoto & Makimoto 1990). Hornblende K–Ar dates of metagabbro range from 241 ± 12 to 278 ± 10 Ma (Shibata *et al.* 1977), and conventional zircon U–Pb ages of the plagiogranite are 282 ± 2 and 285 ± 2 Ma (Herzig *et al.* 1997), indicating an Early Permian igneous age and slightly later metamorphism for this ophiolite. In contrast, Sano (1992) reported a 421 ± 54-Ma Nd–Sm whole-rock isochron age (8 points) for the metagabbro and plagiogranite, and a 311 ± 65-Ma Nd–Sm rock–clinopyroxene isochron age for the metabasalt, suggesting a polygenetic nature for the Yakuno ophiolite. However, coincidence of the Nd–Sm age of the Yakuno metagabbro and the K–Ar age of the Oeyama metagabbro may not indicate their cogenetic relationship. They should be compared with the age data for the same method. Herzig *et al.* (1997) point out that the isochron from Sano (1992) might be a mixing line.

The basaltic and gabbroic rocks of the Yakuno ophiolite show transitional mid-ocean ridge basalt (T-MORB) chemistry in the eastern part and arc–tholeiite chemistry in the western part (Ishiwatari *et al.* 1990a). The metamorphic grade increases from the prehnite–pumpellyite facies in the upper basalt section to the granulite facies in the lower gabbro and ultramafic section. The granulite-facies metacumulate at the Moho is a gneissose metagabbro composed of aluminous two pyroxenes, plagioclase, and aluminous spinel (Ishiwatari 1985b). Such an aluminous-spinel metagabbro is rare among ophiolitic complexes, and has so far been reported only from Bikin, Primorye (Vysotskiy 1994) and Tonsina, Alaska (DeBari & Coleman 1989), although analogous rocks are known from meta-igneous complexes of lower continental crust (Rivalenti *et al.* 1981) and lower crustal xenoliths in island arc (Francis 1976) and oceanic plateau (Grégoire *et al.* 1998).

The Renge blueschist occurs either as thin tectonic slices or blocks in serpentinite mélanges underlying the Oeyama ophiolite (Tsujimori 1998), and has a phengite K–Ar age of 320 Ma (Tsujimori & Itaya 1999; Fig. 3). The metamorphic assemblage of the mafic schist ranges from lawsonite blueschist to epidote blueschist and further into eclogitic rocks in the Omi area (Tsujimori *et al.* 2000a,b; Tsujimori 2002). The Renge metamorphic belt also includes some relatively low-pressure, high-temperature metamorphic rocks including oligoclase–biotite schist and amphibolite. The Joetsu metamorphic belt also bears typical blueschist and relatively high-temperature pelitic schists with phengite K–Ar ages of 308 and 289 Ma (Yokoyama 1992), and is thought to be an eastern extension of the Renge belt (Fig. 1).

The Suo metamorphic belt also consists of high-pressure (HP) metamorphic rocks including pumpellyite–actinolite schist and epidote blueschist (mostly winchite schist; Nishimura 1998). Some pelitic rocks bear lawsonite (Hayasaka 1987; Watanabe *et al.* 1987, 1989) but lawsonite–glaucophane and pumpellyite–glaucophane assemblages are absent. Phengite K–Ar ages are 220 ± 7 Ma in the Nishiki area and 170–190 Ma in the eastern areas (Nishimura 1998; Fig. 3). The schists with the same K–Ar age are also known from the Kurosegawa belt of the Outer Zone of south-western Japan and Ishigaki Island of Ryukyu (Fig. 3).

NORTH-EASTERN JAPAN

Early Paleozoic Miyamori ophiolite forms the basement of a nearly complete Paleozoic–Mesozoic sedimentary sequence of the South Kitakami belt ranging from Ordovician to Jurassic in age (Tazawa 1988, 2000). The Miyamori ophiolite consists mostly of wehrlitic cumulate and depleted mantle harzburgite (spinel Cr# = 0.4–0.8) with hornblende and phlogopite, which is interpreted to have been upper mantle of an island arc (Ozawa 1988). Minor lherzolite patches (spinel Cr# = 0.1–0.4) of kilometric sizes are included in the depleted harzburgite, and are interpreted to have been a relict source mantle that originated in a back-arc basin (Ozawa 1988). Hornblende K–Ar ages of four gabbroic rocks cutting peridotite of this ophiolite

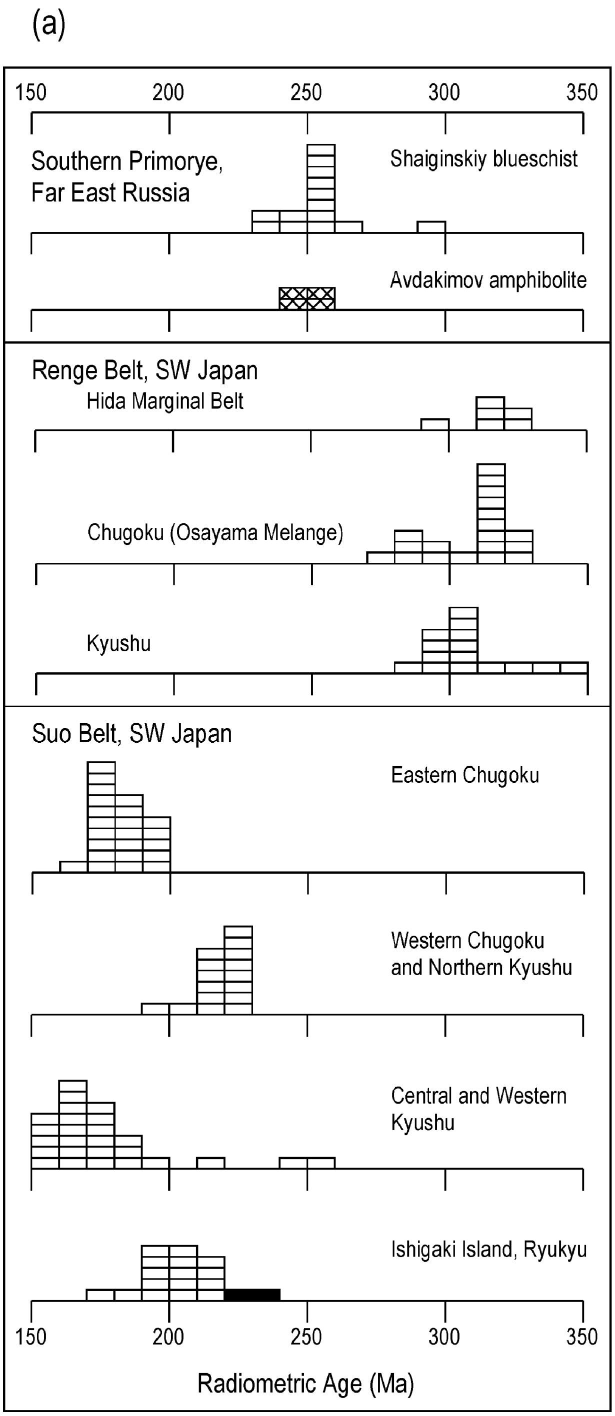


Fig. 3 Isotopic ages of ophiolitic and metamorphic rocks in south-western Japan, Russian Primorye and related areas. (a) K–Ar ages of high-pressure schists in Primorye and Japan. Data sources: Kovalenko and Khanchuk (1991); Tsujimori and Itaya (1999); Nishimura (1998) and the references therein. Data for Primorye are mostly based on our unpublished results.

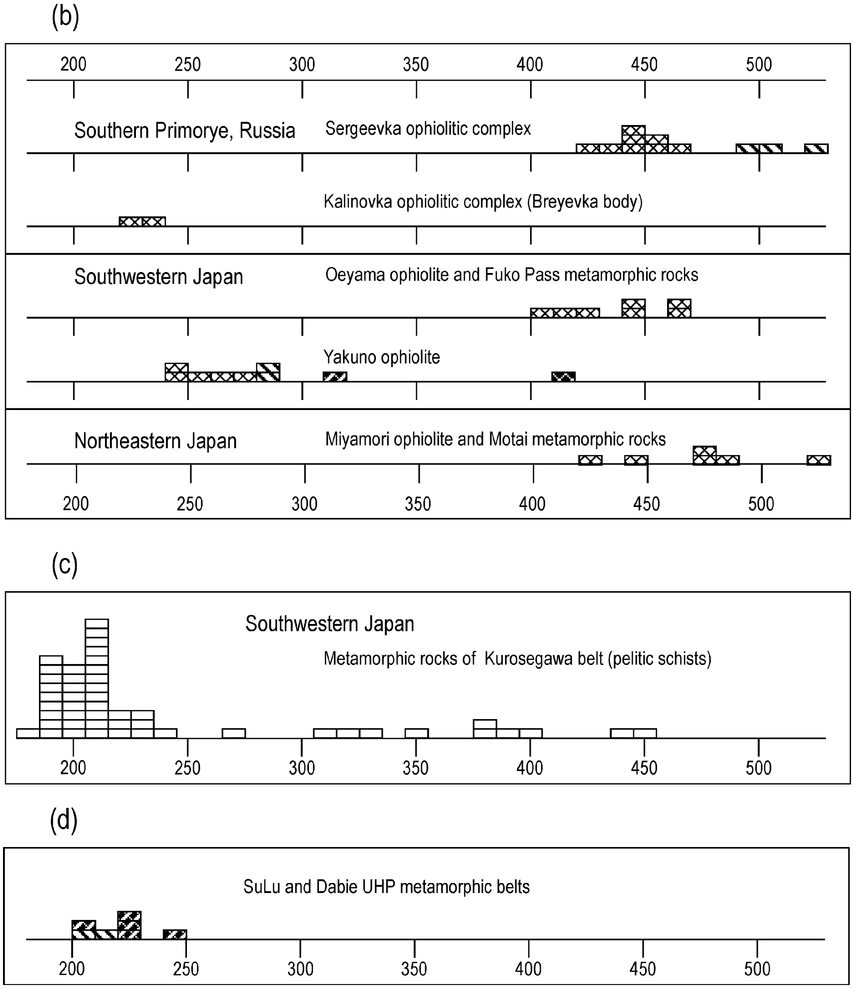


Fig. 3 (*Continued*) (b) K–Ar ages for ophiolitic complexes in Primorye and Japan. Data sources: Khanchuk *et al.* (1996); Kovalenko and Khanchuk (1991); Nishimura and Shibata (1989); Shibata *et al.* (1977); Sano (1992); Ozawa *et al.* (1988). K–Ar data for Primorye are mostly based on our unpublished results. (c) Muscovite–phengite K–Ar ages of schists in the Kurosegawa belt, Outer Zone of south-western Japan (compilation in Tsujimori *et al.* 2000c). (d) Nd–-Sm ages and zircon U–Pb ages of the ultrahigh-pressure metamorphic rocks in the Sulu and Dabie areas, China (after Ames *et al.* 1993; Li *et al.* 1993). (⊠), hornblende K–Ar age; (▭) muscovite–phengite K–Ar age; (■), muscovite–phengite Ar–Ar age; (▧), zircon U–Pb age; (▨), Nd–Sm mineral isochron; (▩), Nd–Sm rock isochron.

range from 445 to 485 Ma, although other hornblendite (421 Ma) and amphibolite (369 Ma) yield younger ages (Ozawa *et al.* 1988). These data indicate an Ordovician or earlier age for the Miyamori ophiolite, the same age as the Oeyama ophiolite in south-western Japan.

The Motai blueschist belt (Maekawa 1988) in the South Kitakami belt also bears pyroxene amphibolite blocks with hornblende K–Ar ages of 479 ± 24 and 524 ± 26 Ma (Kanisawa *et al.* 1992). The K–Ar age of a calk-alkaline tonalite dike cutting the metamorphic rocks is 457 Ma (Sasada *et al.* 1992). A monazite chemical Th-U-total Pb isochron method (CHIME, or electron microprobe method) age of 430 ± 10 Ma is also reported from the paragneiss in the 350-Ma granitic complex (Suzuki & Adachi 1991). These data indicate that ophiolites and metamorphic and granitic rocks comprised an early Paleozoic active continental margin or mature island arc. The 300-Ma muscovite K–Ar age (Kawano & Ueda 1965) and 225 ± 11- and 239 ± 12-Ma hornblende K–Ar ages (Kanisawa *et al.* 1992) of garnet–epidote amphibolites from the Yamagami area suggest that the blueschist metamorphism in the southern part of the Motai belt is contemporary with the Renge and Suo blueschists of south-western Japan. However, late Paleozoic ophiolite (Yakuno) and accretionary complexes (Akiyoshi and Ultra-Tamba) are absent in north-eastern Japan. The early Paleozoic ophiolitic–granitic basement and the sedimentary cover of Silurian–Jurassic ages in the South Kitakami belt thrust over the Jurassic accretionary complex of the North Kitakami belt (Tazawa 1988, 2000).

The radiometric ages of pre-Cretaceous ophiolitic and metamorphic rocks in south-western Japan are summarized in Fig. 3. The ophiolite ages are centered on two peaks at approximately 450 Ma (Oeyama ophiolite) and 280 Ma (Yakuno ophiolite). North-eastern Japan bears the 450-Ma ophiolites but lacks the 280-Ma ophiolites. The HP metamorphic rocks are concentrated around two other peaks at approximately 300 Ma (Renge blueschist) and 200 Ma (Suo blueschist), although minor older HP metamorphic rocks of 400–450 Ma are also present in association with the Oeyama ophiolite and the Kurosegawa mélange in Shikoku Island.

PALEOZOIC OPHIOLITES AND BLUESCHISTS IN PRIMORYE, RUSSIA

The Primorye territory of Russia is geologically divided into two parts: the Khanka terrane and the Sikhote-Alin terrane (Fig. 4). The Khanka terrane may be a part of a larger continental block including the Bureya and Jiamusi blocks to the north (Khanchuk 2001), composed of Precambrian continental basement covered by thick Cambrian calcareous sediments and post-Silurian continental sediments. The Sikhote-Alin terrane mainly consists of Mesozoic accretionary complexes of greenstone, chert, limestone, shale and sandstone, which are intruded by Cretaceous granites and covered by Cretaceous–Tertiary volcanics.

KHANKA OPHIOLITE

The Khanka terrane bears some ophiolitic bodies in the west-north-west-trending Spassk zone, which is almost perpendicular to the general trend of the Sikhote-Alin terrane. Shcheka *et al.* (2001) describe an ophiolitic sequence of serpentinite (harzburgite), pyroxenite, gabbro and basalt that are emplaced onto the Early Cambrian fossiliferous limestone–shale formation and covered by Middle Cambrian conglomerate including abundant detrital chromian spinel. The chromian spinel grains from ser-

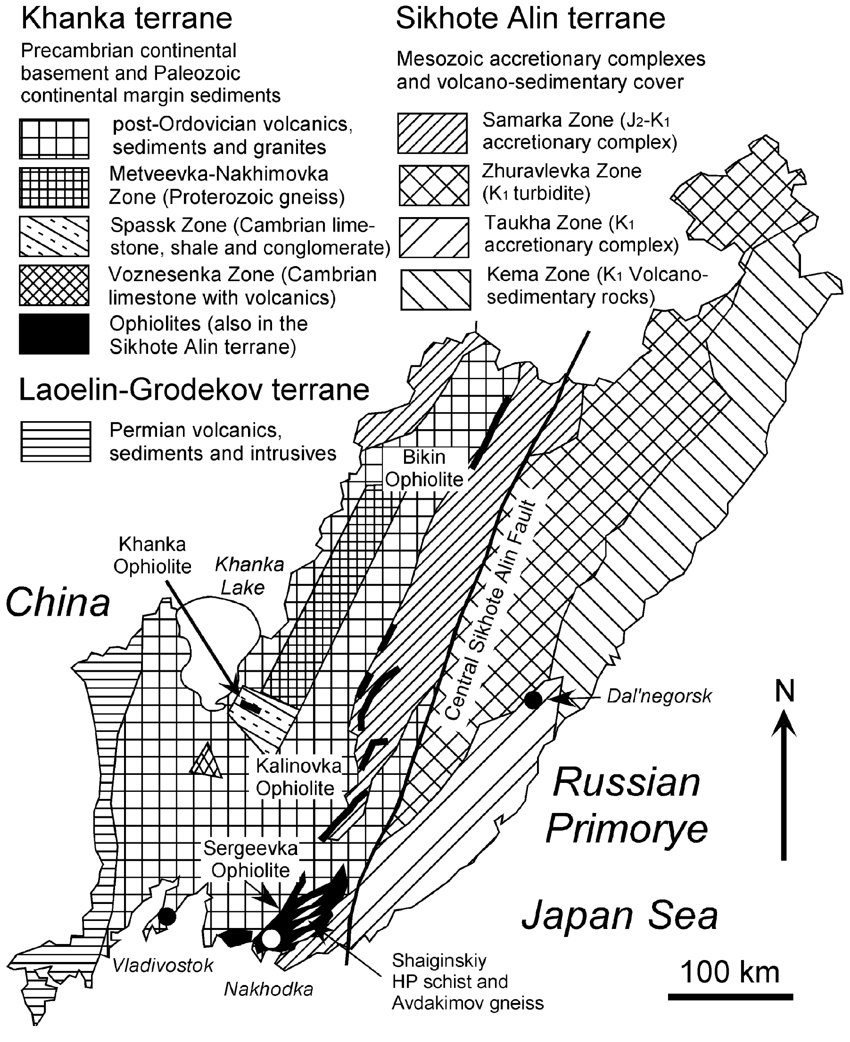


Fig. 4 Geological units of Russian Primorye (simplified after Khanchuk *et al.* 1996; with addition of Shaiginskiy blueschist).

pentinite and conglomerate are high in Cr# (0.50–0.75) and very low in TiO_2 (<0.2 wt%) as those in other ophiolites. Although the area is free from regional metamorphism, ferrichromit rims are developed in most chromian spinel grains; some are unusually rich in MnO (up to 19 wt%), suggesting ocean-floor hydrothermal alteration prior to the emplacement. Shcheka *et al.* (2001) conclude that the Khanka ophiolite may represent oceanic lithosphere formed in a small rift zone and immediately emplaced onto the adjacent passive continental margin prior to the circum-Pacific orogeny.

SIKHOTE ALIN OPHIOLITES

Major ophiolitic complexes of the Sikhote Alin terrane are aligned in a north-north-east direction parallel to the eastern margin of the Khanka terrane. The trend also parallels the Central Sikhote Alin Fault. The ophiolitic complexes are distributed in the Sergeevka, Kalinovka and Bikin areas from south to north.

The Sergeevka metagabbro body forms a north-east-trending massif of 30 × 130 km, the largest mafic body in Primorye. Gneissose hornblende metagabbro occupies more than 80% of the area in association with some granitic and troctolitic intrusions, as well as various metamorphic rocks such as gneiss, amphibolite and marble. Conventional zircon U–Pb ages of 528 ± 3 Ma are reported for gneissose metagabbro, 504 ± 3 Ma for gneissose diorite, and 493 ± 12 Ma for granite (Khanchuk *et al.* 1996). Mishkin *et al.* (1970) reported a muscovite K–Ar age of 529 Ma for another granite and a hornblende K–Ar age of 622 Ma for garnet amphibolite, but Tsujimori (unpubl. data) obtained eight hornblende K–Ar ages of metagabbros within a narrow range between 430 and 470 Ma (Fig. 3). These hornblende K–Ar ages are similar to those of the Oeyama ophiolite in south-western Japan and the Miyamori ophiolite in north-eastern Japan (Fig. 3). Khanchuk *et al.* (1996) consider that this body forms a part of the continental margin of the Khanka block, hence it is not an ophiolite. However, the dominantly mafic nature of this body, its occurrence as a nappe overlying younger blueschist and accretionary complex, and its position located on the same line as the other Sikhote-Alin ophiolites (Fig. 4) suggest that the Sergeevka massif is a dismembered ophiolite body.

The Kalinovka ophiolite group is composed of three north-east-trending ophiolitic bodies of approximately 5 × 40 km having an *en echelon* arrangement. These bodies are composed of dunite, troctolite, wehrlite, clinopyroxenite, olivine gabbro, hornblende gabbro, plagiogranite, pillow basalt and minor amphibolite and granite. The chert and limestone associated with the pillow lava bear conodont fossils of Late Devonian–Early Permian ages (Vysotskiy 1994). The K–Ar age of 410 ± 9 Ma is the only reported age determined for very K-poor hornblende (Kemkin & Khanchuk 1994). Our preliminary hornblende K–Ar dating for the metagabbro at Medvezhy Kut near Breyevka yields 230 Ma, which is younger than that of the Yakuno ophiolite (Fig. 3). Vysotskiy (1994) describes an olivine–plagioclase reaction relationship to form aluminous spinel–pyroxene symplectite in troctolite, and Khanchuk and Panchenko (1991) report garnet metagabbro. The tectonic superposition of the Kalinovka ophiolite over the Jurassic accretionary complex of the Samarka zone with an intervening older accretionary complex called the Udeka zone resembles an analogous relationship in south-western Japan, where Yakuno ophiolite thrust over the Jurassic Tamba zone with the Permian Ultra-Tamba zone in between (Kojima *et al.* 2000).

The Bikin ophiolite group is composed of three, north–south-trending ophiolitic bodies of 1 × 2–3 km in size; namely the Oronsky, Zalominsky and Soldinsky bodies (Vysotskiy 1994; Vysotskiy *et al.* 1995). Dunite, harzburgite, wehrlite, orthopyroxenite, and aluminous spinel-bearing noritic gabbro are associated with Late Permian basaltic pillow lava and siliceous volcanic rocks as well as a serpentinite mélange. The aluminous spinel-bearing, olivine-free gabbro with very aluminous pyroxenes (Al_2O_3 > 8 wt%) at the Moho is evidence for unusually thick oceanic crust (Ishiwatari 1985a), and its occurrences on both sides of the Japan Sea (in the Yakuno and Bikin ophiolites) suggest original contiguity of the Paleozoic ophiolite belt.

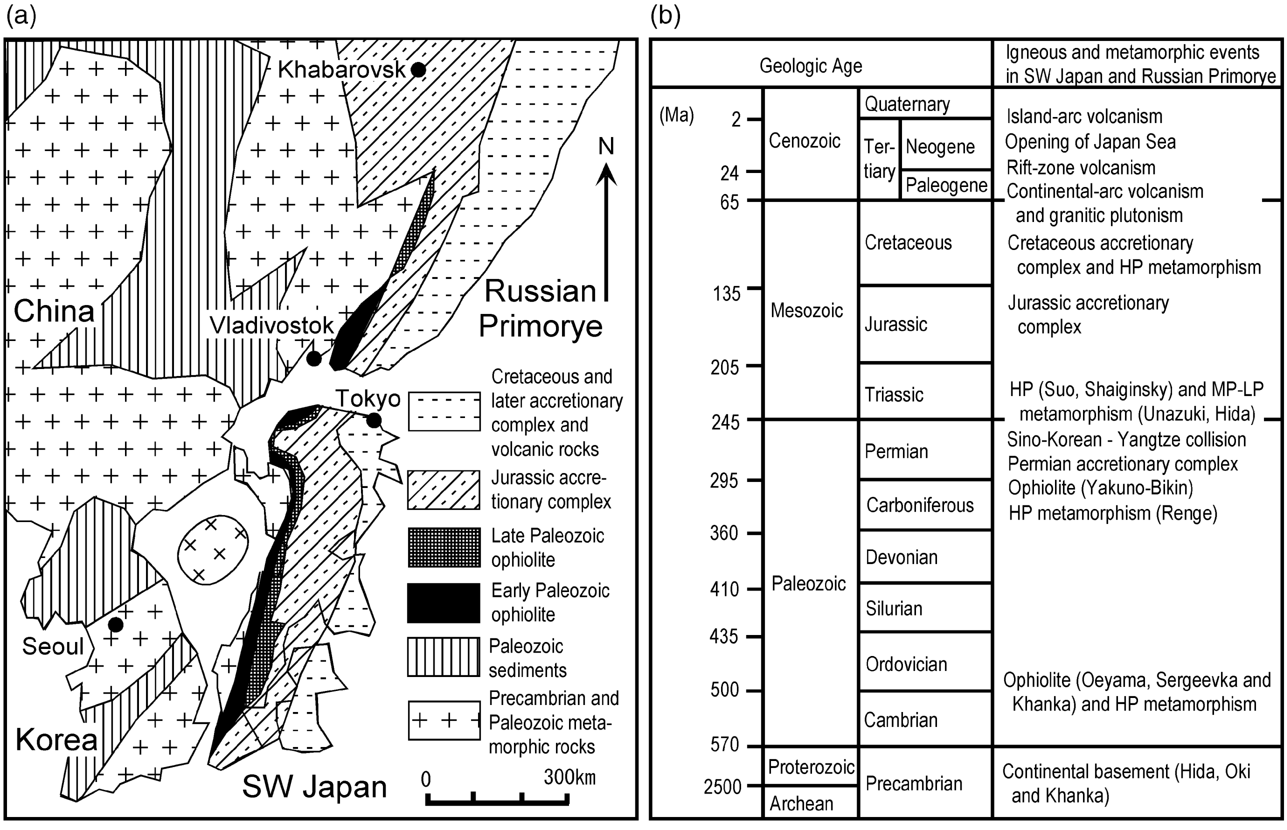
SIKHOTE ALIN BLUESCHIST

The Shaiginsky blueschist occurs as windows and thin thrust sheets beneath the Sergeevka ophiolitic body. The epidote blueschist bears crossite and barroisite. Pelitic rocks are of a higher grade than the garnet zone, and some samples bear oligoclase (An_{18}), although biotite is completely absent. Garnet preserves progressive normal zoning with decreasing Mn toward the rim; some shows reverse zoning at the rim. Piemontite-bearing siliceous schist is also present near Partisansk. The Shaiginsky schists yield phengite K–Ar ages of 230–250 Ma (Fig. 3). These age data lie between those of the two HP metamorphic belts in south-western Japan (i.e. the Renge (280–330 Ma) and Suo belts (170–220 Ma)). The Shaiginsky blueschist is associated with the 'Avdakimov gneiss' composed mainly of hornblende gneiss with marble and coarse-grained garnet amphibolite. Although a Precambrian Rb–Sr mineral whole-rock isochron age was reported from this gneiss complex, our hornblende K–Ar ages are centered at 250 Ma (Fig. 3), the same age as the Shaiginsky blueschist complex. Kovalenko and Khanchuk (1991) reported a 255-Ma and 290-Ma phengite K–Ar age for pelitic schists of the Shaiginsky complex; our K–Ar data are centered at 250 Ma (Fig. 3). These ages are intermediate between those of the Renge (280–330 Ma) and Suo (170–220 Ma) blueschists of south-western Japan. Nevertheless, the K–Ar age of the Suo metamorphic rocks varies significantly from area to area (Fig. 3); some metamorphic rocks in western Kyushu and in the Kurosegawa Belt have the same age as the Shaiginskiy blueschist.

GEOLOGICAL CONTINUATION FROM JAPAN TO PRIMORYE

Even if we accept the rifting–drifting hypothesis, the Pre-Japan Sea configuration of the Japanese Islands is not easy to restore. Some authors assume that south-western Japan was located directly to the south of Primorye and on the east of the Korean Peninsula (with Yamato Bank in between) as shown in Fig. 5 (Kojima 1989; Khanchuk 2001). In contrast, the South Kitakami Belt and associated accretionary complexes of north-eastern Japan should already have been placed alongside Primorye or between Primorye and south-western Japan in the Early Tertiary prior to the opening of the Japan Sea. However, paleontologic data of Paleozoic and Mesozoic formations in Japan indicate that the South Kitakami Belt and the Kurosegawa Belt (the Outer Zone of south-western Japan) were placed in the Chinese continental margin to the south of south-western Japan in Cretaceous and earlier time (Otoh & Sasaki 1998; Tazawa 2000), and displaced northward through fast and extensive left-lateral strike–slip movement.

Arakawa *et al.* (2000) mention the possibility that the Hida belt does not belong to the Sino-Korean block, but has evolved as a part of the East-Central Asian Orogenic Belt, which is a wide accretionary belt extending from Primorye to Central Asia via north-eastern China and Mongolia along



(Ma)	Geologic Age			Igneous and metamorphic events in SW Japan and Russian Primorye
2	Cenozoic	Quaternary		Island-arc volcanism
		Tertiary	Neogene	Opening of Japan Sea Rift-zone volcanism
24			Paleogene	Continental-arc volcanism and granitic plutonism
65	Mesozoic	Cretaceous		Cretaceous accretionary complex and HP metamorphism
135		Jurassic		Jurassic accretionary complex
205		Triassic		HP (Suo, Shaiginsky) and MP-LP metamorphism (Unazuki, Hida)
245	Paleozoic	Permian		Sino-Korean - Yangtze collision Permian accretionary complex
295		Carboniferous		Ophiolite (Yakuno-Bikin) HP metamorphism (Renge)
360		Devonian		
410		Silurian		
435		Ordovician		Ophiolite (Oeyama, Sergeevka and Khanka) and HP metamorphism
500		Cambrian		
570	Proterozoic	Precambrian		Continental basement (Hida, Oki and Khanka)
2500	Archean			

Fig. 5 (a) Continuation of geological units from south-western Japan to Russian Primorye before opening of the Japan Sea. Position of south-western Japan follows that of Kojima (1989). (b) Major geological events in Japan and Primorye.

the northern margin of the Sino-Korean block. Khanchuk (2001) suggests that the Laoelin–Grodekovo belt and Cheongjin belt in the Russia–China–North Korea border area are possible extension of the ophiolite belts in south-western Japan.

PALEOZOIC-EARLY MESOZOIC BLUESCHISTS IN JAPAN AND PRIMORYE: RELATION TO THE COLLISION BELT IN CHINA

As noted in the previous section, some late Paleozoic–early Mesozoic blueschist facies rocks of *ca* 250 (± 100) Ma occur in southern Primorye (Shaiginsky blueschist: Kovalenko & Khanchuk 1991 and the present study), northern Honshu (Motai belt: Maekawa 1988; Kanisawa *et al.* 1992), western Honshu and Kyushu (Renge and Suo belts: Nishimura 1998; Tsujimori & Itaya 1999), and Ishigaki Island of Ryukyu (Tomuru Formation: Nishimura *et al.* 1983; Faure *et al.* 1988). They are mostly epidote blueschist in Primorye, Motai, Suo and Ishigaki, but typical lawsonite blueschist and eclogitic rocks occur in the Renge belt (Tsujimori 1998; Tsujimori *et al.* 2000a,b). It should be noted that HP metamorphism in Japan took place not only in late Paleozoic–Early Mesozoic time but also in early Paleozoic time (Kurosegawa: Maruyama & Ueda 1974; Oeyama: Tsujimori 1999; Tsujimori *et al.* 2000c) and in Cretaceous time (Sambagawa, Nagasaki, and Kamuikotan). Thus, subduction-zone metamorphism repeatedly took place in Japan; a subduction zone also existed in Japan at *ca* 250 Ma, when collision of the Sino-Korean and Yangtze cratons took place (Fig. 3).

DOES THE CHINESE COLLISION SUTURE GO TO KOREA?

The Chinese Dabie-Sulu ultrahigh-pressure (UHP) metamorphic belt is believed to be a collisional suture between the Sino-Korean and Yangtze blocks, which amalgamated during the 200–250-Ma period, on the basis of the Nd–Sm and U–Pb ages of the UHP metamorphic rocks (Ames *et al.* 1993; Li *et al.* 1993; Hacker *et al.* 1998; Jahn 1998). The presence of Triassic flysch and Jurassic molasse along the suture also supports early Mesozoic collision of the continental blocks (Li 1996). However, K–Ar ages of phengite and hornblende in the UHP metamorphic rocks are scattered widely, from the Proterozoic to the Mesozoic (Ishiwatari *et al.* 1990b; Li *et al.* 1994), possibly due to excess argon inherited from their Precambrian protoliths (Giorgis *et al.* 2000). The Chinese suture is postulated to extend into the Korean Peninsula, namely into the Imjingang or Ogcheon belt (Ernst & Liou 1995; Ree *et al.* 1996), and further continuing into the Hida (marginal) belt in Japan (Isozaki 1996, 1997). The latter idea is based on Hiroi's works of 1981 and 1983 (Hiroi 1981, Hiroi 1983), which first correlated the Unazuki metamorphic rocks in the Hida belt to the Ogcheon and Imjingang (Yonchon or Yeoncheon) metamorphic belts. In their model, the northern part of the Korean Peninsula belongs to the Sino-Korean block, whereas its southern part belongs to the Yangtze block. Kim *et al.* (2000) reported a Rb–Sr mineral isochron age of 226 ± 1.2 Ma for the mylonite in the Gyeonggi (Kyonggi) massif on the south of the Imjingang belt, and interpreted it to represent post-collisional, extensional ductile shear. Lee *et al.* (2000) correlated the early Proterozoic granulites of the Gyeonggi massif to that of the Yangtze craton on the basis of zircon–monazite sensitive high mass-resolution ion microprobe (SHRIMP) U–Pb age and an Nd–Sm isotope model age (T_{DM}), although they admit 'it is probably not warranted to attempt any tectonic correlation solely based on the resemblance in T_{DM} ages or SHRIMP zircon ages'.

The Imjingang metamorphic belt is a typical Barrovian kyanite–sillimanite-type metamorphic belt (Yamaguchi 1951). Ree *et al.* (1996) reported a Nd–Sm mineral isochron age of 249 ± 31 Ma, and 0.8–1.3 GPa and 630–790°C metamorphic conditions for the adjacent garnet amphibolite unit on the south, and correlated it to the Permo-Triassic suture in China, regarding the garnet amphibolite as retrograded from UHP eclogite. However, 'critical evidence of UHP metamorphism such as eclogite, diamond and coesite remains to be found' (Ree *et al.* 1996). Min and Cho (1998) identified a three-stage metamorphic evolution of the Ogcheon belt: (1) Siluro-Devonian medium-pressure (0.5–0.8 GPa and 520–590°C) metamorphism; (2) Triassic regional retrograde metamorphism (0.1–0.3 GPa and 350–500°C); and (3) Jurassic–Cretaceous thermal metamorphism around granitoids. This metamorphic history coincides with the structural development of the Ogcheon belt as an early Paleozoic intracontinental rift zone evolved into an intracontinental fold–thrust belt without ophiolite (Cluzel *et al.* 1990), but is not consistent with the Permo-Triassic intercontinental collision process that involves HP metamorphism (Ernst & Liou 1995). Moreover, another medium-pressure metamorphic belt with a muscovite ^{40}Ar–^{39}Ar age of 200–230 Ma is reported from the Fangshan area in the

Western Hills of Beijing (Fig. 6), that is, in the middle of the Sino-Korean craton (Wang & Chen 1996). As aforementioned, there is no direct evidence of UHP–HP metamorphism in the Korean metamorphic belts; it is likely that the 200–250-Ma medium-pressure metamorphic belts such as Imjingang, Ogcheon and Fangshan took place in the intracontinental fold–thrust belts of the Sino-Korean craton during the Yangtze–Sino-Korean collision.

The most convincing criteria with which to define tectonic affiliation of an area may be stratigraphy of the sediments covering continental basement. The Paleozoic system of the Ogcheon zone shows typical 'Sino-Korean' stratigraphy characterized by thick Cambro-Ordovician limestone, late Paleozoic coal-bearing sediments, and 'the great hiatus' in between (Fig. 7). This is different from the Yangtze stratigraphy with thick Siluro-Devonian shale (Fig. 7). This suggests that no major suture exists between the northern and southern parts of Korea. Lee *et al.* (1998) also state that the Korean Peninsula as a whole belongs to the Sino-Korean craton at least from the late Proterozoic in view of the overall similarity in age, geology, petrography and geochemistry.

YAEYAMA PROMONTORY HYPOTHESIS

In view of the eastward-convex, winding geological structure over the Korean Peninsula, Teraoka *et al.* (1998) proposed that the Sulu suture does not extend to Korea, but turns southward beneath the Yellow Sea. They did not specify, however, where the destination of the redirected suture is. Their intensive studies on the chemistry of clastic garnets in the Japanese Cretaceous–Tertiary sediments indicate that these eclogitic, pyrope (Mg)-rich and spessartine (Mn)-poor garnets occur in sandstones of the Shimanto accretionary complex in the outer zone of the South-west Japan and Ryukyu arcs (Takeuchi 1992; Teraoka *et al.* 1999), whereas such garnets are not found from the Cretaceous–Paleogene fore-arc and intra-arc basins of south-western Japan. This finding suggests that the Sulu UHP belt does not extend to Korea and north-eastern China, but turns to the south into the provenance area of the Shimanto sediments. We propose that the Sulu suture reappears at Ishigaki Island, Yaeyama Archipelago, southern Ryukyu, and continues into Japan and Primorye, detouring around Korea (Fig. 6). Along this highly sinuous

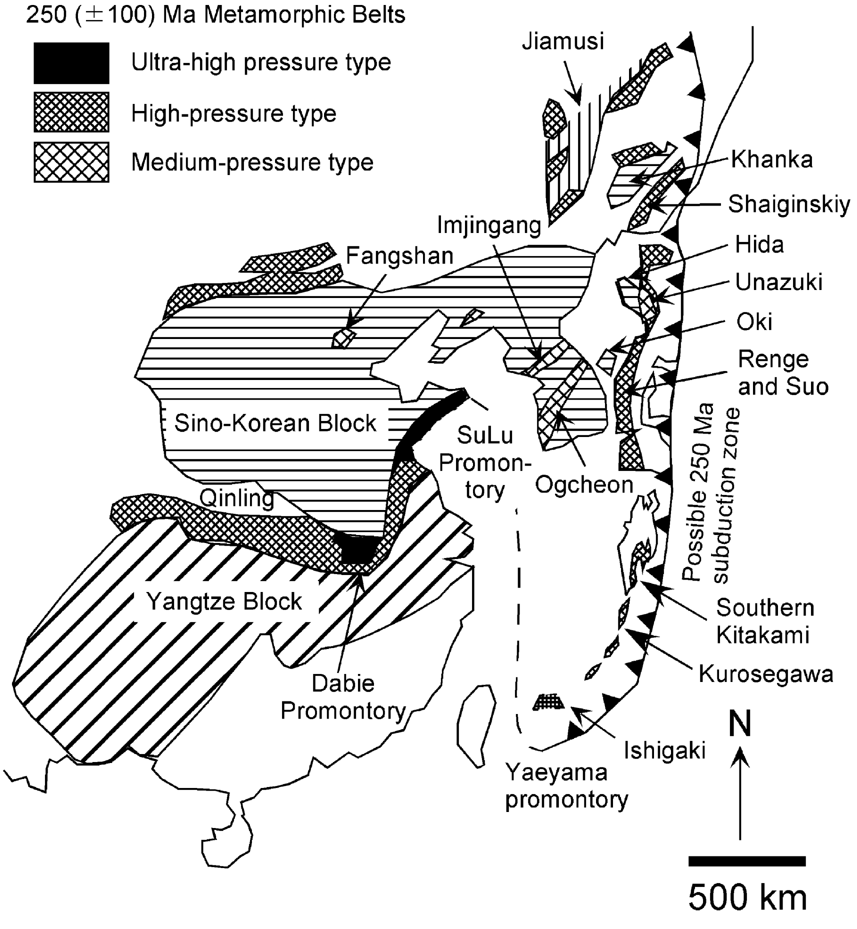


Fig. 6 Proposed sinuous configuration of the eastern elongation of the Sulu–Dabie suture (*ca* 250 Ma) of China passing subduction zones of Ryukyu, south-western Japan and Russian Primorye but detouring around Korea. A preliminary version of this diagram appeared in Ishiwatari and Tsujimori (2001).

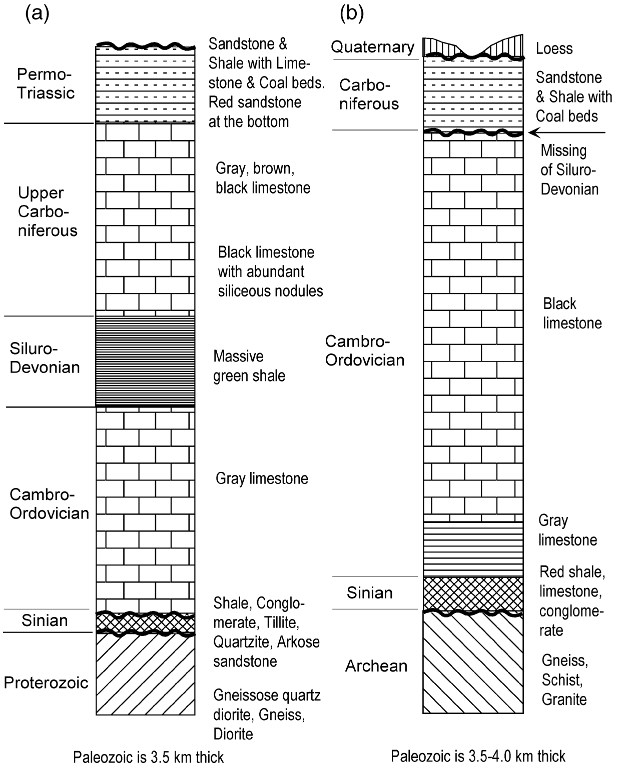


Fig. 7 Schematic stratigraphic columns for the contrasting Paleozoic sequences on the (a) Yangtze block (eastern Sichuan, lower Yangtze Valley) and (b) Sino-Korean block (Hebei, Shanxi; after Willis & Blackwelder 1907). The paleozoic sequence in southern Korea is also of the Sino-Korean type.

suture line, continental collision took place in the Chinese segment, whereas subduction of oceanic lithosphere took place in the Japanese–Russian segment. This agrees with the argument of Ernst and Liou (1995) that UHP metamorphism takes place in the continental collision segment, while normal HP metamorphism takes place in the oceanic subduction segment, along a single suture line.

Such a sinuous configuration of the collisional suture is also observed in the Alpine chain in the Mediterranean area. It is noteworthy that the coesite-bearing UHP metamorphic rocks of the Dora Maira massif (Chopin 1984) occur at the northwestern tip of the acute Adriatic (Apulian) promontory, whose profile is clearly visible on the present-day seismic map (Mueller 1989). Our model suggests that the Chinese UHP rocks occur at the southern tip of the Dabieshan promontory of the Sino-Korean Craton and at the northern tip of the Sulu promontory of the Yangtze craton. In this context, the early Mesozoic HP schists of the Ishigaki Island possibly represent the southern tip of another promontory of the Sino-Korean Craton, which we call Yaeyama promontory after the regional name for the southernmost Ryukyu Islands. The late Paleozoic–early Mesozoic (200–250-Ma) HP metamorphic belts in Ryukyu, Japan and Russian Primorye are suitable as an eastern extension of the Chinese collisional suture of the same age. The late Paleozoic–early Mesozoic (Indosinian) dextral ductile shearing reported from the Ogcheon belt (Cluzel *et al.* 1991; Otoh *et al.* 1999) is compatible with the reciprocal movement between the Sulu and Yaeyama promontories.

The Tananao schist complex of eastern Taiwan has long been regarded as a late Paleozoic orogenic belt (Fig. 4 of Cluzel 1991), but hornblende K–Ar ages of the schist are younger than 90 Ma, and the associated gneiss and granite also give 90 Ma or younger Rb–Sr and U–Pb ages (Yuli blueschist is as young as 10 Ma; Jahn *et al.* 1986). This indicates that the late Paleozoic–early Mesozoic metamorphic belt around the Yaeyama promontory does not extend to Taiwan.

The Yaeyama promontory hypothesis provides some insights for pre-Cretaceous paleogeography of Japan. Paleozoic and Mesozoic fossil faunas indicate that the South Kitakami and Kurosegawa Belts were situated further to the south of the Hida marginal belt before the Late Cretaceous large-scale strike–slip movement (Otoh & Sasaki 1998; Tazawa 2000). These three belts show overall stratigraphic similarity with the Khanka massif; these terranes may have together developed along the active continental margin of the Sino-Korean craton, although the South Kitakami and Kurosegawa Belts were later displaced toward the north by a Cretaceous left-lateral strike–slip movement (Tazawa 2000). Isozaki (1997) proposed that Japanese accretionary complexes, including the South Kitakami block and 'Yakuno oceanic plateau', developed along the Yangtze continental margin, assuming that the Sino-Korean–Yangtze suture zone passes through central Korea and extends to the Hida Mountains in south-western Japan. As mentioned earlier, however, the fossil fauna and lithology of the Permo-Triassic cover of the Yakuno ophiolite closely resemble those of Primorye (Nakazawa 1958). Permian strata of the Hida marginal belt and South Kitakami belt also show a faunal kinship with those of north-eastern China and Primorye (Tazawa 1993, 2000; Otoh & Yanai 1996; Otoh & Sasaki 1998). Our model infers that all Japanese Paleozoic terranes, except for accreted seamounts, have developed along the Sino-Korean margin. The South Kitakami and Kurosegawa Belts may have been placed somewhere between Kyushu and Ishigaki Island along the eastern margin of the Yaeyama promontory (Fig. 6).

PALEOZOIC OPHIOLITES IN JAPAN AND PRIMORYE: GEOTECTONIC IMPLICATIONS

Cluzel (1991) proposed that the Yakuno ophiolite formed in a rift zone in the Sino-Korean continental margin in Middle–Late Carboniferous time, and was emplaced onto the 'Honshu block' in the middle Permian by the closure of the small sea basin between the rifted continental blocks. Such a 'Tethyan ophiolite' model including continental rifting, sea-floor spreading, and obduction may be applicable to the Cambrian Khanka ophiolite in Primorye, which may have formed before the beginning of the circum-Pacific-type orogeny, but may not apply for the other circum-Pacific ophiolites (Ishiwatari 1994). The Yakuno ophiolite is tectonically underlain by the Permian Ultra-Tamba accretionary complex, which is in turn underlain by the Jurassic Tamba accretionary complex. Each of the two complexes consists of 'oceanic plate stratigraphy' (Isozaki 1996); successive underplating of oceanic and trench-fill sediments beneath the Yakuno ophiolite may have developed these accretionary complexes. The Miyamori ophiolite also thrust over the Jurassic accretionary complex (Tazawa 1988). These ophiolites did not thrust onto old continental blocks as imagined in the Tehyan model. Instead, younger accretionary complexes formed beneath the old ophiolites.

In contrast, Isozaki (1996, 1997) proposed that the Yakuno ophiolite with thick crust represents oceanic plateau, which has formed in the midst of the ocean by a superplume activity and later accreted to Japan. However, the sedimentary cover of the Yakuno ophiolite is thick black shale with a restricted age of radiolarian fossils (middle Permian), which is incompatible with a long plate-tectonic travel in the ocean.

Ishiwatari *et al.* (1990a) divided the gabbroic rocks of the Yakuno ophiolite into two types: a MORB type in the eastern area and an island-arc basalt (IAB) type in the western area, according to the chemistry of coexisting clinopyroxene and plagioclase. They postulated the Yakuno ophiolite as being a cross-cut section of oceanic island arc and an adjacent back-arc basin, which was affected by a mantle plume. The granulite-facies metacumulate represents the basal part of thickly developed mafic crust of the island arc and back-arc basin. The mantle section of the Miyamori ophiolite is also interpreted as hydrous mantle beneath island arc (Ozawa 1988). Mantle peridotite of the Oeyama ophiolite resembles that from the ocean floor, and bears some podiform chromitite with hydrous mineral inclusions such as Na-phlogopite and pargasite (Matsumoto *et al.* 1995), suggesting either a supra-subduction zone (SSZ) or a fast spreading ridge setting (Arai 1997). However, the SSZ setting is more preferable in view of the orbicular chromitite with a very high Cr# (0.76–0.85) reported by Yamane *et al.* (1988).

It should be noted that the ophiolite sequence is actually exposed in the submarine trench walls aside the Mariana arc (Bloomer & Hawkins 1983) and Tonga arc (Bloomer & Fisher 1987; Fig. 8). It is important that back-arc spreading is active behind these island arcs, and the accretionary complex is currently absent in the subduction zone. Moreover, lawsonite-bearing blueschist blocks were drilled from serpentinite seamounts (diapirs) in the Mariana fore-arc area (Maekawa *et al.* 1993, 1995; Fig. 8). The ophiolite–blueschist association is well demonstrated in the Japan–Primorye area such as the Oeyama ophiolite–Renge blueschist, Yakuno ophiolite–Suo blueschist, Miyamori ophiolite–Motai blueschist and Sergeevka ophiolite-Shaiginskiy blueschist. In contrast, subduction zones such as the Japan Trench and Nankai Trough have formed huge accretionary complexes from the Cretaceous to the present (Taira 1985; Fig. 8).

It is likely that the accretion period and non-accretion period as represented by the present Nankai Trough and Mariana Trench, respectively, have repeated one after another and from segment to segment in the history of the Japan–Primorye accretionary orogenic belt. The ophiolite–blueschist period with tectonic erosion at the subduction zone may have been followed by a period of massive accretion. This idea is quite compatible with the geochemical island-arc and marginal-basin signatures of the ophiolitic rocks.

CONCLUSIONS

Age, lithology, and structural position of the Paleozoic ophiolites and blueschist in south-western Japan and Primorye strongly support original continuation of the geological units over the two sides before the Miocene opening of the Japan Sea. The newly obtained K–Ar ages of the blueschists and associated gneiss complex of Primorye (250 Ma) coincide with the widespread metamorphic events in East Asia such as the UHP metamorphism of the Sulu–Dabie suture and medium- and low-pressure metamorphism in Japan (Unazuki and Hida), Korea (Imjingang and Ogcheon), and northern China

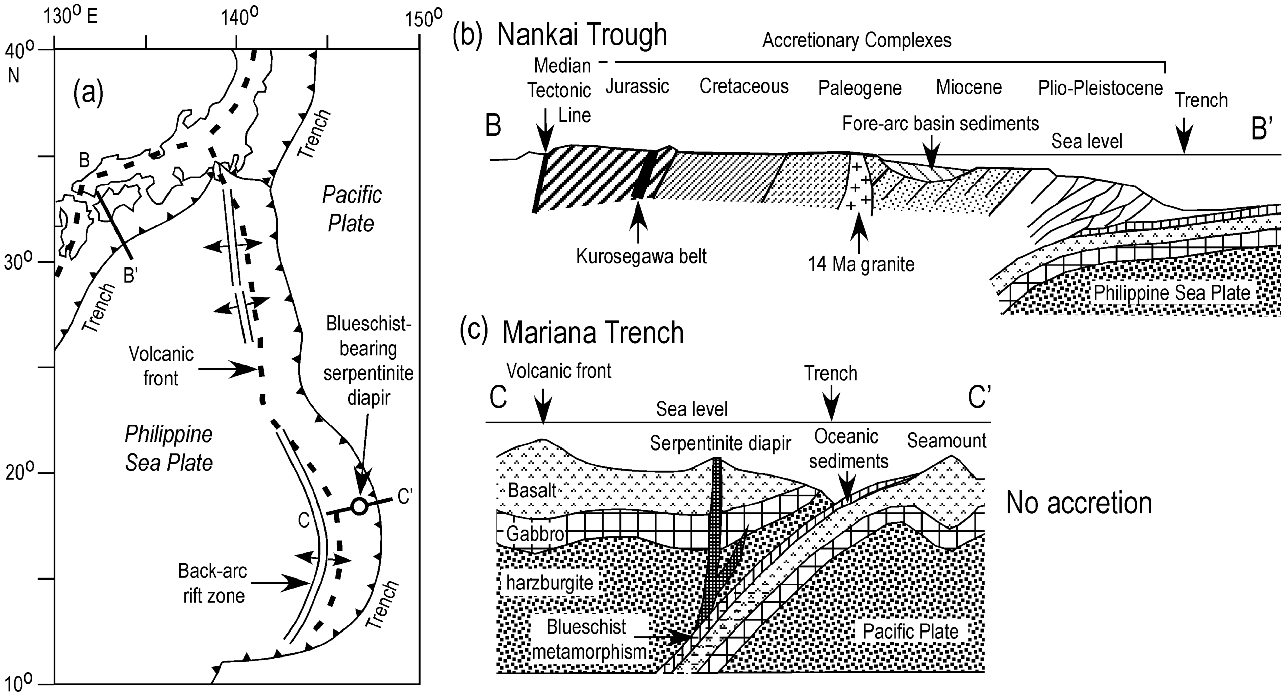


Fig. 8 Schematic cross-sections showing the accreting and non-accreting subduction zones. (a) Tectonic framework of the Western Pacific area with positions of the cross-sections. (b) Schematic cross-section of the Nankai Trough (based on Taira 1985), where accretionary complexes are developed. (c) Schematic cross-section of the Mariana Trench (based on Bloomer & Hawkins 1983; Bloomer & Fisher 1987; Maekawa *et al.* 1993, 1995), where ophiolitic rocks are exposed on the trench slope, blueschist are discovered from the serpentinite seamount, and the accretionary complexes are almost absent.

(Fangshan). The wide-scale convergence resulted in the UHP metamorphism along the continental collision zone, but ordinary HP metamorphism took place along the sinuous oceanic extension of the same suture passing Ryukyu, Japan and Primorye beyond the Yaeyama promontory, detouring around Korea. Although 250-Ma HP schists are rare in Japan, slightly older (Renge) and younger (Suo) blueschists are preserved in many places, suggesting persistent subduction. The repeated formation of the ophiolite–blueschist assemblages and the tectonically underlying, younger accretionary complexes suggests repetition of the non-accreting subduction as in the present Mariana Trench and the accreting subduction as in the Nankai Trough through development of the orogenic belts in Japan and the Russian Far East.

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