Geological Society, London, Special Publications

Petrological diversity and origin of ophiolites in Japan and Far East Russia with emphasis on depleted harzburgite

Akira Ishiwatari, Sergei D. Sokolov and Sergei V. Vysotskiy

Geological Society, London, Special Publications 2003; v. 218; p. 597-617
doi:10.1144/GSL.SP.2003.218.01.30

Notes

Petrological diversity and origin of ophiolites in Japan and Far East Russia with emphasis on depleted harzburgite

AKIRA ISHIWATARI[1], SERGEI D. SOKOLOV[2] & SERGEI V. VYSOTSKIY[3]

[1]*Department of Earth Sciences, Faculty of Science, Kanazawa University, Kanazawa 920-1192, Japan (e-mail: geoishw@kenroku.kanazawa-u.ac.jp)*

[2]*Geological Institute, Russian Academy of Sciences, Pyzhevsky 7, Moscow 109017, Russia*

[3]*Far East Geological Institute, Russian Academy of Sciences, Prospect 100 letiya 159, Vladivostok 690022, Russia*

Abstract: Ophiolites are divided into lherzolite-type (L-type) and harzburgite-type (H-type) by the lithology of their mantle peridotites. Rare depleted harzburgite-type (DH-type) is distinguished from the normal H-type by the more refractory nature of its mantle peridotite and the occurrence of orthopyroxene-type cumulate rocks including iron-rich harzburgite and orthopyroxenite. The Shelting (Sakhalin) and Krasnaya (Koryak Mountains) ophiolites in Far East Russia, which have both depleted harzburgite and orthopyroxene-type cumulate rocks, belong to this newly defined DH-type. The ophiolites in SW Japan–Primorye, NE Japan–Sakhalin, and the Koryak Mountains in the northwestern Pacific margin have diverse ophiolite types ranging from L- to DH-types. The wide petrological diversity, the common occurrence of DH-type, and the presence of thick crustal sections in these ophiolites suggest regionally inhomogeneous, commonly very high degrees of mantle melting over subduction zones, as in the modern Mariana forearc environment. The ophiolites of Japan and Far East Russia range in age from Early Palaeozoic to Cenozoic and are tectonically underlain by younger blueschists and accretionary complexes. The spatial association of these ophiolites with blueschists is analogous to the ophiolite–blueschist assemblages recovered from the Mariana forearc. This association might have formed in a period of non-accretion at an oceanic subduction zone that was followed by voluminous accretion of sediments, facilitating subsequent uplift of the ophiolites and blueschists.

The concept of ophiolites as assemblages of mafic and ultramafic igneous rocks formed in deep ocean was first suggested by Steinmann (1927), and was further developed into the current model of obducted fossil oceanic crust–mantle by Moores (1969), Coleman (1971) and Moores & Vine (1971). This model helped to explain spreading processes at constructive plate boundaries and tectonic emplacement processes at destructive plate boundaries as the theory of plate tectonics was formulated. Ophiolites are currently used to help identify suture zones and ancient continental collision zones where they rest tectonically on older continental crust. Coleman (1986) called these ophiolites 'Tethyan-type' and distinguished them from those in Circum-Pacific belts, which were labelled 'Cordilleran-type'. In general, Cordilleran-type ophiolites are incomplete, dismembered and metamorphosed; however, they are none the less useful for unravelling global tectonic problems. The first purpose of this paper is to show that the Cordilleran-type ophiolites in the northwestern Pacific margin are emplaced over young continental crust (or an accretionary complex younger than the ophiolite), are associated with blueschists, and represent remnants of fossil oceanic subduction zones rather than continental collision zones.

Boudier & Nicolas (1985) classified ophiolites into lherzolite- and harzburgite-types (designated LOT and HOT, respectively, by Nicolas (1989)). They postulated that HOT form at mid-ocean ridges with relatively fast spreading rates. However, recent studies on contrasting structural features of the Cyprus and Oman ophiolites suggest that these two bodies, both HOT, could be correlated with slow- and fast-spreading ridges, respectively (Dilek *et al.* 1998). Petrological and geochemical studies have revealed that at least some Tethyan ophiolites were generated from suprasubduction zone (SSZ) magmas rather than mid-ocean ridge basalt (MORB) (e.g. Cyprus: Miyashiro 1973; Robinson *et al.* 1983; Hébert & Laurent 1990; Oman: Alabaster *et al.* 1982; Umino *et al.* 1990; Lachize *et al.* 1996; Ahmed & Arai 2002; Bay of Islands: Edwards 1995; Suhr &

From: DILEK, Y. & ROBINSON P. T. (eds) 2003. *Ophiolites in Earth History*. Geological Society, London, Special Publications, **218**, 597–617. 0305-8719/03/$15

Edwards 2000). Pearce *et al.* (1984) classified most HOT as SSZ-type and considered all LOT as MORB-type. Ishiwatari (1985a) divided harzburgite-type ophiolites into ordinary harzburgite (H) and depleted harzburgite (DH) categories (Fig. 1), and pointed out that DH-type ophiolites include olivine (Ol)-orthopyroxene (Opx) cumulates. In contrast, L- (lherzolite) and H-type ophiolites have olivine-plagioclase (Pl) and olivine-clinopyroxene (Cpx) cumulates, respectively. Although the crystallization order of minerals may change with pressure, all ophiolitic cumulates are believed to have crystallized at low, plagioclase-stable pressures, and compositional variations of cumulus minerals suggest that the crystallization sequence was not pressure dependent (Ishiwatari 1985a). The associated volcanic rocks also typically show similar chemical variations.

The residual peridotite of ophiolitic mantle sections is generally homogeneous over a scale of kilometres, if we exclude samples from the Moho transition zone and from dykes or veins of dunite, pyroxenite or gabbro. The mineral chemistry of such residual peridotite is the most reliable measure of the degree of melting of the mantle section. Variations in the Cr-number (Cr/(Al + Cr)) of spinel in the residual peridotite correspond closely to variations in lithology and mineral chemistry. The Cr-number is 0.3–0.5 (or less) in L-type, 0.5–0.7 in H-type, and 0.7–0.9 in DH-

Ophiolite Type	L type	H type	DH type
Volcanic Rocks	N-, T-, E-MORB, alkali basalt	N-, T-, E-MORB, Island arc basalt and andesite	Island arc basalt and andesite, boninite
Cumulate Type Cpx TiO_2 in mafic rocks	Plagioclase type 0.8 wt.%	Clinopyroxene type 0.4 wt.%	Orthopyroxene type 0.1 wt.%
Crystallization sequence of mafic and (Seismic Moho) ultramafic cumulates	Ol Pl Cpx Opx	Ol Pl Cpx Opx	Ol Pl Cpx Opx
Residual mantle peridotite Bulk Al_2O_3+CaO Spinel Cr# Opx Al_2O_3 Olivine Fo	Lherzolite and Cpx-rich harzburgite 3 - 5 wt.% 0.3 - 0.5 2 - 4 wt.% 90 or lower	Cpx-bearing harzburgite 1 - 2 wt.% 0.5 - 0.7 1 - 2 wt.% 90 - 91	Cpx-free (depleted) harzburgite 0 - 1 wt.% 0.7 - 0.9 0 - 1 wt.% 92 or higher
World classic examples	Liguria, Alps, Trinity Bay of Islands*	Semail (Oman), Troodos, Vourinos	Papua, Adamsfield, Khan Taishir
SW Japan-Primoriye	Oeyama	Yakuno Khanka	(Omi chromitite?)
NE Japan-Sakhalin	Poroshiri, Nukabira	Iwanai Miyamori	Horokanai, Takadomari, Shelting
Koryak Mts. Taigonos P.	Povorotny Elistratova South	Elistratova North	Nablyudeny
Koryak Mts. Mainits Zone	Tamvatney Yagel	Chirinai?	Krasnaya Srednaya

Fig. 1. Petrological types of ophiolites, after Ishiwatari (1991), and examples of each type in the northwestern Pacific margin. See Ishiwatari (1985a, 1991) for references. *Lewis Hills massif of the Bay of Islands ophiolite shows a more depleted nature (Edwards 1995).

type ophiolites (Fig. 1), although the associated dunite and chromitite may have more Cr-rich spinel. An increase in spinel Cr-number with degree of melting was demonstrated experimentally by Jaques & Green (1980) and was related to peridotite compositions by Dick & Bullen (1984). Although the melting process may be complicated by hydrous remelting of already depleted mantle (e.g. Bloomer & Hawkins 1987; Sobolev & Danyushevsky 1994) and later reaction with percolating melts (e.g. Cannat *et al.* 1990; Arai *et al.* 1996), the spinel Cr-number of regionally homogeneous residual peridotite probably reflects the degree of melting of the primary fertile mantle. Therefore, we consider the spinel Cr-number of the residual peridotite as a significant parameter for classifying ophiolites in this paper.

The second purpose of this paper is to report new examples of DH-type ophiolites in the northwestern Pacific region, where L- and H-types are also abundant, and to consider the geological significance of the extreme diversity of the ophiolitic mantle in this region.

The geological and petrological data on the Russian ophiolites presented in this paper are mostly based on co-operative field studies in Primorye (1993, 1998, 1999 and 2002) and the Taigonos Peninsula (1995 and 1997) as well as on a 1990 field workshop in the Mainits Zone, Koryak Mountains (Bryan 1991). Some of the important chemical data and geological maps reproduced here are from publications in Japan and Russia.

Ophiolites in the northwestern Pacific margin

The northwestern Pacific margin, which extends from Japan to Russia, contains numerous ophiolitic bodies commonly associated with blueschists (Fig. 2). These ophiolites are highly variable in age, lithology and chemical composition, even in an apparently continuous, 'single' belt. The ages of the ophiolites and associated blueschists are summarized in Table 1.

Ophiolite belts in SW Japan and Primorye

The Palaeozoic–Mesozoic accretionary complexes and associated ophiolites and blueschists of southwestern Japan may have been linked with the Sikhote–Alin Mountains of Russian Primorye before the Miocene opening of the Japan Sea (Ishiwatari & Tsujimori 2003). Jurassic accretionary complexes in Japan (Tamba, Mino and Ashio

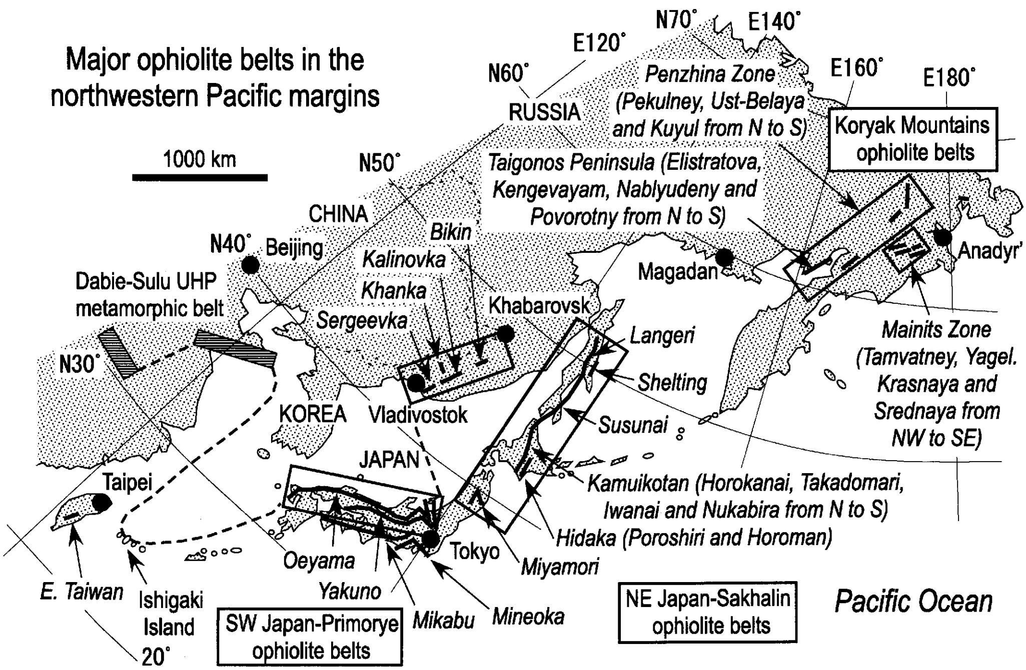

Fig. 2. Location of major ophiolite belts and ophiolite complexes in the northwestern Pacific margin. A possible western extension of the Palaeozoic ophiolite–blueschist belt of the SW Japan–Primorye area is also shown (see Ishiwatari & Tsujimori (2003) for discussion).

Table 1. *Ages of the ophiolites and blueschists of the northwestern Pacific margins from Japan to Russia*

Age	Area							
	Primorye	SW Japan		NE Japan	Sakhalin	Koryak Mountains		
		Inner Zone	Outer Zone			Taigonos Peninsula	Penzhina Zone	Mainits Zone
Cenozoic			Mineoka O					
				Hidaka A	Rakitinskaya A			
			Shimanto A	Poroshiri O	Susunai B			Elgevayam A
Mesozoic			Sambagawa B	Kamuikotan B	Shelting O	Taigonos A, B	Penzhina III B	Mélange blocks B
	Samarka A	Tamba A	Chichibu A	Horokanai O		Elistratova O	Kuyul O	Krasnaya O and
	Shaiginsky B	Suo B	Mikabu O	N Kitakami A		Povorotny O	Pekulney O*	other ophiolites
	Bikin O	Yakuno O						
Late Palaeozoic	Kalinovka O	Akiyoshi A	Kurosegawa O, B	Motai B			Penzhina II B	
		Renge B						
Early Palaeozoic	Khanka O	Oeyama O	Kurosegawa O, B	Miyamori O		Kengeveem O	Penzhina I B	
	Sergeevka O						Ust–Belaya O	

O, ophiolite; B, blueschist; A, accretionary complex.
*The largest mafic–ultramafic complex in the Pekulney area may be of Proterozoic age (Dobretsov 1999).

zones) are believed to correlate with the Samarka–Nadanhada terranes in Primorye and northeastern China (Kojima 1989).

Palaeozoic ophiolites in southwestern Japan include the Ordovician Oeyama ophiolite and the Permian Yakuno ophiolite. The hornblende K–Ar age of the Oeyama ophiolite is 450 Ma (Nishimura 1998), whereas that of the Yakuno ophiolite is 280 Ma (Shibata *et al.* 1977). The latter age is in agreement with zircon U–Pb dates from the same body (Herzig *et al.* 1997).

The Oeyama ophiolite is composed of lherzolitic mantle peridotite (Cr-number 0.3) in the eastern Chugoku area (Kurokawa 1985) and of clinopyroxene-bearing harzburgite (Cr-number 0.5) in the western Chugoku area. Podiform chromitites (Cr-number 0.5) encased in dunite bodies are abundant in the western area (Arai 1980; Matsumoto & Arai 1997) (Fig. 3a). In both areas the mantle peridotites commonly contain vermicular spinel–pyroxene aggregates. The mantle peridotites are thrust over the 320–280 Ma Renge blueschist (Tsujimori & Itaya 1999), the Permian Akiyoshi accretionary complex, and the Permian Yakuno ophiolite. Small mantle peridotite bodies of analogous nature are also present in the Hida marginal belt to the east, where they are associated with the Renge blueschist and eclogite in the Omi area (Tsujimori *et al.* 2000). Orbicular chromitite with high Cr-number (0.76–0.85) is present in peridotites in the Omi area (Yamane *et al.* 1988). The high Cr-number suggests formation from highly refractory melts, although the degree of melting of the mantle peridotite is generally low (Fig. 3a). This ophiolite includes minor gabbroic rocks and ultramafic cumulates (Kurokawa 1985), and granulite-facies spinel metagabbro recrystallized to kyanite-bearing epidote amphibolite has been reported from the Oeyama massif (Tsujimori & Ishiwatari 2002).

The Permian Yakuno ophiolite has a complete succession with MORB-type basalt, clinopyroxene-type cumulates, and mantle peridotite consisting of relatively depleted harzburgite with a variable composition (Cr-number 0.4-0.8) (Ishiwatari 1985a). Although regional variations in the mantle peridotite cannot be confirmed because of limited exposure, the gabbroic and basaltic rocks range from T-MORB in the eastern part to island arc tholeiite in the western part (Ishiwatari *et al.* 1990). In gabbros the Mg-number of clinopyroxene varies from 0.85 in the eastern part to 0.7 in the western part (Fig. 4a) although plagioclase has a relatively uniform composition (An_{80}) throughout. Another peculiar feature of the Yakuno ophiolite is the occurrence of granulite-facies metacumulates (e.g. spinel–two-pyroxene metagabbro) at the Moho level, which suggests unu-

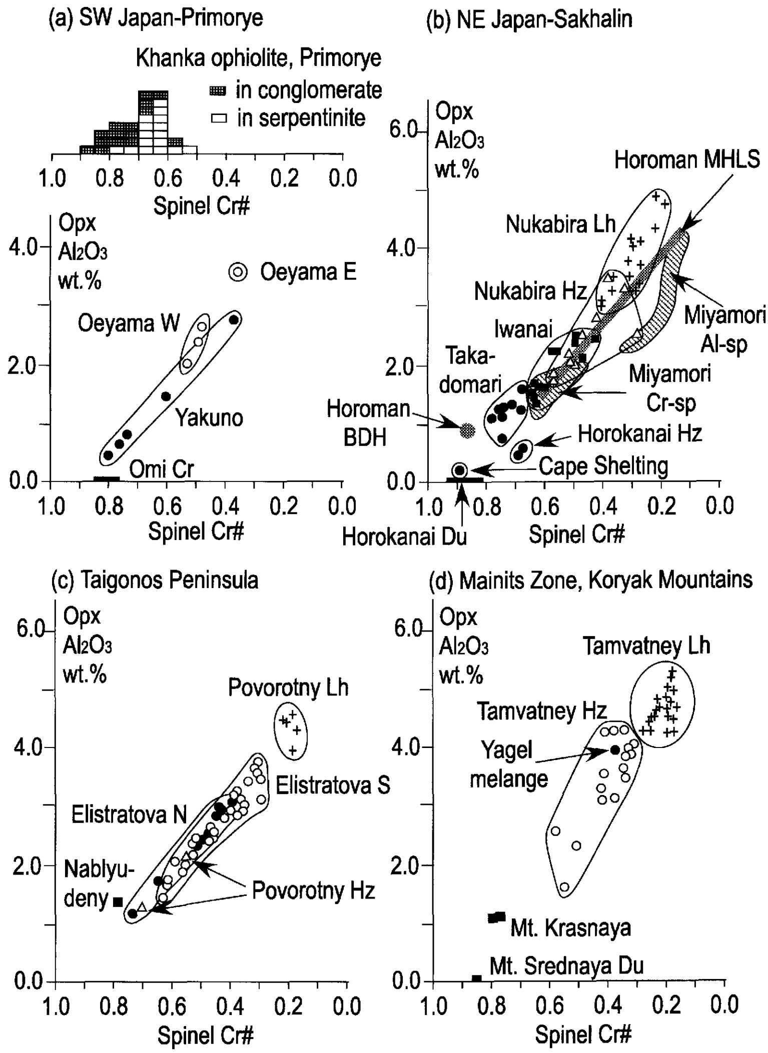

Fig. 3. Compilation of spinel Cr-number and Al_2O_3 content of coexisting orthopyroxene in residual mantle peridotite of ophiolites in (**a**) SW Japan–Primorye area, (**b**) NE Japan–Sakhalin area, (**c**) Taigonos Peninsula and (**d**) Mainits Zone, Koryak Mountains. References: (**a**) Arai (1980), Ishiwatari (1985a, 1985b), Kurokawa (1985), Yamane *et al.* (1988), Matsumoto & Arai (1997), Shcheka *et al.* (2001); (**b**) Ishizuka (1985, 1987), Ozawa (1988), Takahashi (1991), Tamura *et al.* (1999), Vysotskiy *et al.* (2000); (**c**) Saito *et al.* (1999), Bazylev *et al.* (2001); (**d**) Dmitrenko *et al.* (1990) and this study. HMLS, main harzburgite-therzolite suite; BDH, banded durite-harzburgite.

sually thick (15–30 km) oceanic crust (Ishiwatari 1985b).

In Primorye, the Sergeevka, Kalinovka and Bikin ophiolitic complexes lie along the western margin of the Mesozoic accretionary complexes near the boundary of the Khanka crystalline massif (Fig. 2). These ophiolites lack mantle peridotite and are composed solely of volcanic rocks, gabbros and mafic–ultramafic cumulates. On the other hand, the Cambrian Khanka ophiolite rests on a Cambrian limestone in a small rift zone (Spassk zone) in the Khanka massif. Middle Cambrian conglomerate covering the body contains abundant chromian spinel grains derived from the ophiolite (Shcheka *et al.* 2001). This ophiolite contains serpentinized harzburgite with relatively chromian, unusually Mn-rich spinel (Cr-number 0.6–0.7) (Shcheka *et al.* 2001); it is

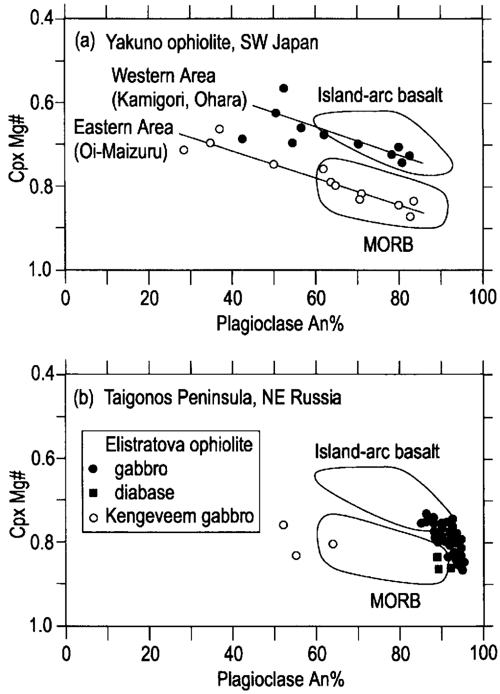

Fig. 4. Relationship between anorthite (An) content of plagioclase and Mg-number (= Mg/(Fe + Mg)) of coexisting clinopyroxene in the Yakuno ophiolite in SW Japan (**a**) and among the Elistratova ophiolite and Kengevayam gabbro body, Taigonos Peninsula, NE Russia (**b**). Fields for island arc basalts (IAB) and mid-ocean ridge basalts (MORB) are from Ishiwatari *et al.* (1990). Beard (1986) and Hébert & Laurent (1990) proposed a similar discrimination between the two suites.

considered to be an H-type ophiolite transitional to DH-type (Fig. 3a). The residual peridotite spinels of the Khanka and Oeyama ophiolites suggest that the early Palaeozoic mantle of the SW Japan–Primorye belt was inhomogeneous and was locally relatively depleted.

Dobretsov *et al.* (1994) correlated the Oeyama ophiolite with the Kalinovka ophiolite; however, age and structural data indicate that it is part of the Sergeevka terrane, a huge metagabbro body covered by Devonian and Permian sedimentary rocks. The Sergeevka terrane was later thrust onto a Jurassic accretionary complex (Samarka terrane) containing 250 Ma blueschist. The Sergeevka terrane, however, does not contain any mantle peridotite, which is abundant in the Oeyama ophiolite. The Bikin ophiolite, which consists of granulite-facies two-pyroxene metagabbro (Vysotskiy 1994) may be the Russian counterpart of the Permian Yakuno ophiolite. Recent geochronological data suggest that the Yakuno ophiolite may also correlate with the Kalinovka ophiolite, which includes spinel-bearing troctolite and garnet-bearing metagabbro (Ishiwatari & Tsujimori 2003).

Ophiolite belts in NE Japan and Sakhalin

The early Palaeozoic Miyamori (and Hayachine) ophiolite is present in the Kitakami Mountains, NE Honshu (Ozawa 1994). This ophiolite and its overlying Silurian to Jurassic sedimentary rocks were thrust over the Jurassic accretionary complex of the North Kitakami–SW Hokkaido zone (Tazawa 1988). The ophiolite consists mainly of moderately depleted harzburgite (spinel Cr-number 0.4–0.75) and clinopyroxene-type cumulates. The pervasive occurrence of hornblende (and some Ti-poor phlogopite) in the mantle peridotite indicates that it was derived from a hydrous mantle wedge above a subduction zone (Ozawa 1988). The harzburgite contains layered harzburgite–wehrlite zones, which formed by melt–mantle interaction (Ozawa 1994). The Miyamori ophiolite is associated with the Motai blueschist of Late Palaeozoic age (Maekawa 1988).

In Central Hokkaido, ophiolitic rocks occur in several zones. In the Sorachi–Yezo belt, the Jurassic Horokanai ophiolite is thrust over the Cretaceous Kamuikotan metamorphic belt, and dismembered equivalents of this ophiolite are distributed throughout the belt. The Horokanai ophiolite has a well-preserved succession, which is composed, from bottom to top, of harzburgite, orthopyroxenite–dunite cumulate rocks, metagabbros, amphibolite, MORB-type pillow lavas and an Upper Jurassic radiolarian chert. The mantle harzburgite is strongly depleted (spinel Cr-number 0.69–0.77 in harzburgite and 0.81–0.93 in dunite) (Fig. 3b) (Ishizuka 1985, 1987). In the Kamuikotan belt, the Takadomari harzburgite body near Horokanai is similarly highly depleted, but the Iwanai-dake body contains common harzburgite and the southernmost Nukabira body consists of lherzolite (Furue *et al.* 1997; Tamura *et al.* 1999) (Fig. 3b). Tamura *et al.* (1999) also reported dunite with highly chromian spinel and magnesian olivine in the Nukabira lherzolite (Table 2). The depleted harzburgite of the Horokanai and Takadomari complexes has been thrust onto the Kamuikotan metamorphic rocks, which include typical jadeite-bearing blueschists (Ishizuka 1985, 1987; Sakakibara & Ota 1994).

In the Hidaka belt, to the east of the Kamuikotan belt, the Poroshiri ophiolite has a relatively complete succession (Miyashita 1983). This body contains abundant troctolite–anorthosite cumulates (Miyashita & Hashimoto 1975), whose olivine–plagioclase crystallization trend closely follows that of MORB, and which is thought to be an L-type ophiolite. Based on geological data, Miyashita & Yoshida (1988) postulated a Cretaceous age for the ophiolites in the Hidaka zone.

The Horoman complex is a well-layered peridotite–gabbro body in the southern part of the Hidaka belt. The main harzburgite–lherzolite complex has spinel with Cr-number 0.2–0.6 and contains layers of spinel-rich dunite–wehrlite, gabbro, and minor banded dunite-harzburgite (spinel Cr-number 0.8–0.9) (Takahashi 1991). The pervasive occurrence of spinel–pyroxene symplectite after garnet suggests a deep mantle origin. Rare, large corundum crystals in the metagabbro suggest that the peridotite body is a fragment of recycled oceanic crust–mantle, which has been subducted and then emplaced as a diapir (Morishita & Arai 2001). L-type residual mantle and mafic–ultramafic cumulate rocks constitute the bulk of this peridotite body, but the occurrence of highly depleted harzburgite indicates that a pre-existing DH-type ophiolite was also incorporated into the diapir.

Dobretsov *et al.* (1994) compared ophiolite–blueschist belts in central Hokkaido and Sakhalin and correlated the West and Central (Langeri–Susunai) Sakhalin Zone with the Sorachi–Yezo and Kamuikotan belts in Hokkaido. Vysotskiy *et al.* (2000) described the boninite–bearing Shelting ophiolite from central–eastern Sakhalin (Fig. 5). This ophiolite, composed of dunite–harzburgite, websterite–orthopyroxenite and gabbronorite units, occurs as a tectonic slice in fault contact with Jurassic–Cretaceous volcaniclastic rocks containing boninite (the Rakitinskaya suite). The nearby Berezov massif (Fig. 5) has the same character and lithological sequence. Spinel in the dunite and harzburgite of this ophiolite is unusually chromian (Cr-number 0.86–0.89) (Fig. 3b, Table 2). The highly depleted nature of the mantle peridotite and the presence of the adjacent orthopyroxene-type cumulate rocks help define this ophiolite as a DH-type. The associated boninite has 25–30 modal % orthopyroxene phenocrysts, which show reverse zoning with an iron-rich core (Mg-number 0.72–0.75) and a magnesian rim (Mg-number 0.84–0.89). The spinel microphenocrysts also show reverse zoning with iron-rich cores and iron-poor rims (Cr-number 0.80–0.83). Vysotskiy *et al.* (2000) suggested that crystallization of the boninitic magma under more and more reducing conditions was due to the introduction of a hydrogen-rich fluid.

Ophiolite belts in the Koryak Mountains

The Koryak Mountains extend from northern Kamchatka to the Bering Straits (Fig. 2). Fujita & Newberry (1982) described the general geology of this area and Palandzhjan (1986) studied the ultramafic rocks. Fujita & Newberry (1982) proposed that the Koryak ophiolites were emplaced in the Jurassic. Pushcharovsky *et al.* (1988) and Sokolov (1992) outlined the geological structure of the Koryak Mountains, in which Early Palaeozoic ophiolites of the Penzhina zone (also called the Talovsko–Pekulneyskaya zone or the Ust–Belskaya zone) are thrust over the Koryak nappes, which contain abundant Mesozoic and rare Palaeozoic ophiolites. Stavsky *et al.* (1990) proposed a plate-tectonic model for accretion in the Koryak Mountains, and Tilman & Bogdanov (1992) produced a comprehensive geotectonic map of the area. Dobretsov (1999) compiled chronological and petrological data from blueschists in this area.

Penzhina zone and Taigonos Peninsula

The Penzhina zone comprises the innermost part of the Koryak orogenic belt, where ophiolites and blueschists of various ages are exposed (Fig. 2). The Pekulney Range in the northern Penzhina zone has a large Proterozoic(?) metamorphosed mafic–ultramafic complex and Jurassic ophiolites (Dobretsov 1999). The Ust–Belaya ophiolite of Early Palaeozoic age (560 Ma K–Ar age on gabbro) consists of tectonic slices of pillow lava with chert, dunite–peridotite with gabbro–anorthosite layers, and gneissose metagabbro with eclogitic rocks (Dobretsov 1999). The entire complex was thrust onto the Late Jurassic–Early Cretaceous accretionary complexes of the Koryak nappe system (Sokolov 1992). The Ganychalan ('Kharitoninskii' of Dobretsov) nappe in the southern Penzhina zone also has a complete ophiolite sequence of Early Palaeozoic age (430 Ma). The Kuyul ophiolite in the southern Penzhina zone, mid-Triassic to Jurassic in age, has a complete succession, whose chemistry and mineralogy have an SSZ affinity (Khanchuk & Panchenko 1994; Luchitskaya 1996). The mineral chemistry of the harzburgite indicates that this is an H-type ophiolite. According to Dobretsov (1999), blueschists in the Koryak Mountains show chronological peaks at 330 Ma (Penzhina), 300 Ma (Penzhina), 180 Ma (Penzhina and Taigonos) and 150 Ma (Penzhina, Pekulnei and mélange blocks). Associated ophiolites have ages of 380–450 Ma, 208–290 Ma and >150 Ma, and the blueschists of each period are slightly younger than the adjacent ophiolites.

The Taigonos Peninsula constitutes the southernmost part of the Penzhina Zone (Figs 2 and 6). Several ophiolite bodies are present along the eastern coast of the peninsula, such as the Elistratova ophiolite, the Kengeveem metagabbro

Table 2. *Representative mineral analyses of residual peridotites from ophiolite complexes in Hokkaido and northeastern Russia*

Area:	Kamuikotan Belt, Hokkaido [1]								Central–Eastern Sakhalin [2]				Southern Taigonos Peninsula [3]			
Massif:	Nukabira				Takadomari				Shelting				Povorotny			Nablyudeny
Sample:	NB2811 Lh			NB2643 Du	OU09-2 Hz			OU17-2 Du	Harzburgite			Dunite	1104B Lh			1004B*
Mineral:	Opx	Cpx	Spinel	Spinel	Opx	Cpx	Spinel	Spinel	Opx	Cpx	Spinel	Spinel	Opx	Cpx	Spinel	Spinel
Wt% oxide																
SiO_2	56.03	53.08			58.14	54.24			58.07	55.11			54.43	52.42		
TiO_2	0.04	0.15	0.00	0.13	0.07	0.01	0.06	0.18	0.00	0.00	0.06	0.12	0.05	0.14	0.13	0.13
Al_2O_3	3.83	3.84	40.33	11.11	1.24	0.98	17.13	6.17	0.21	0.27	4.48	6.23	4.61	4.09	53.56	10.52
Cr_2O_3	0.92	1.06	28.88	57.52	0.27	0.55	55.23	65.23	0.31	0.30	55.83	63.05	0.59	0.88	15.04	56.54
Fe_2O_3			0.72	2.24			0.58	1.26			10.05	4.22			0.44	2.11
FeO	5.52	2.21	13.78	19.31	4.96	1.57	16.89	16.89	6.27	2.57	24.27	13.44	6.41	2.66	11.73	23.27
MnO	0.13	0.14	0.17	0.23	0.08	0.05	0.00	0.00	0.08	0.00	0.74	1.74	0.13	0.14	0.05	0.34
MgO	31.34	16.45	15.96	9.38	34.70	16.89	12.15	10.76	33.94	18.06	5.14	11.84	32.31	16.36	18.80	6.57
CaO	2.64	23.85			0.38	25.14			0.73	24.05			0.81	22.87		
Na_2O	0.00	0.00			0.00	0.00			0.00	0.08			0.00	0.00		
Total	100.45	100.78	99.84	99.92	99.84	99.43	102.04	100.49	99.61	100.44	100.57	100.64	99.34	99.56	99.75	99.48
Cation number																
O =	6	6	4	4	6	6	4	4	6	6	4	4	6	6	4	4
Si	1.930	1.913			1.991	1.980			2.008	1.992			1.896	1.912		
Ti	0.001	0.004	0.000	0.003	0.002	0.000	0.001	0.005	0.000	0.000	0.002	0.003	0.001	0.004	0.003	0.003
Al	0.155	0.163	1.341	0.433	0.050	0.042	0.627	0.242	0.009	0.011	0.185	0.243	0.189	0.176	1.670	0.421
Cr	0.025	0.030	0.644	1.505	0.007	0.016	1.356	1.718	0.008	0.009	1.547	1.647	0.016	0.025	0.315	1.518
Fe^{3+}			0.015	0.056			0.014	0.031			0.265	0.105			0.009	0.054
Fe^{2+}	0.159	0.067	0.325	0.534	0.142	0.048	0.439	0.470	0.181	0.078	0.711	0.371	0.187	0.081	0.260	0.661
Mn	0.004	0.004	0.004	0.006	0.002	0.002	0.000	0.000	0.002	0.000	0.022	0.049	0.004	0.004	0.001	0.010
Mg	1.608	0.884	0.671	0.463	1.770	0.919	0.563	0.534	1.748	0.972	0.268	0.583	1.677	0.889	0.742	0.333
Ca	0.097	0.921			0.014	0.983			0.027	0.931			0.030	0.893		
Na	0.000	0.000			0.000	0.000			0.000	0.003			0.000	0.000		
Total	3.979	3.986	3.000	3.000	3.979	3.990	3.000	3.000	3.984	3.995	3.000	3.001	4.000	3.984	3.000	3.000
Mg-no.	0.910	0.930	0.674	0.464	0.926	0.950	0.562	0.532	0.906	0.926	0.274	0.611	0.900	0.916	0.741	0.335
Cr-no.	0.139	0.156	0.324	0.777	0.127	0.273	0.684	0.877	0.497	0.427	0.893	0.871	0.079	0.126	0.159	0.783
Fe^{3+}-no.			0.008	0.028			0.007	0.016			0.133	0.053			0.005	0.027
Ol Mg-no.		0.905		0.929		0.928		0.939		0.905		–		0.905		0.932

Area:	Northern Taigonos Peninsula [4]					Mainits Zone, Koryak Mountains										
Massif:	Elistratova South			Elistratova North		Tamvatney [5]			Yagel Mélange [6]			Krasnaya [6]				Srednaya [6]
Sample:	1432 Hz			2113 Hz		P307/2 Lh			21F Lh			28B Hz			28C Du	17K Du
Mineral:	Opx	Cpx	Spinel	Opx	Spinel	Opx	Cpx	Spinel	Opx	Cpx	Spinel	Opx	Cpx	Spinel	Spinel	Spinel
Wt% oxide																
SiO_2	56.52	52.63		56.84		54.39	51.40		54.95	53.72		59.00	54.32			
TiO_2	0.12	0.08	0.00	0.20	0.14	0.06	0.17	0.05	0.00	0.10	0.10	0.10	0.07	0.06	0.16	0.09
Al_2O_3	3.49	4.27	41.14	1.69	20.57	5.20	5.33	51.25	4.30	3.89	40.74	0.91	1.02	10.76	9.64	6.87
Cr_2O_3	0.70	1.33	27.89	0.47	49.95	0.65	0.85	15.46	1.10	1.36	28.92	0.39	0.36	58.55	58.27	62.97
Fe_2O_3			0.85		0.84			2.57			0.54			2.32	2.65	1.07
FeO	5.96	2.17	14.06	5.40	16.48	5.98	2.50	10.25	5.27	1.87	13.57	5.69	1.56	20.08	17.76	19.97
MnO	0.16	0.13	0.00	0.23	0.17	0.10	0.14	0.18	0.03	0.07	0.00	0.22	0.09	0.00	0.00	0.00
MgO	32.28	15.87	15.99	34.34	12.39	32.55	16.30	19.21	32.12	16.52	16.40	33.77	17.19	9.16	10.13	8.57
CaO	1.00	24.14		0.95		1.32	23.12		2.23	23.10		1.06	24.54			
Na_2O	0.00	0.18		0.00		0.07	0.36		0.00	0.00		0.00	0.00			
Total	100.23	100.80	99.93	100.12	100.54	100.32	100.17	98.97	100.00	100.63	100.27	101.14	99.15	100.93	98.61	99.54
Cation number																
O =	6	6	4	6	4	6	6	4	6	6	4	6	6	4	4	4
Si	1.943	1.899		1.955		1.876	1.864		1.901	1.929		2.004	1.984			
Ti	0.003	0.002	0.000	0.005	0.003	0.002	0.005	0.001	0.000	0.003	0.002	0.003	0.002	0.001	0.004	0.002
Al	0.141	0.182	1.362	0.069	0.751	0.211	0.228	1.619	0.175	0.165	1.345	0.036	0.044	0.417	0.381	0.275
Cr	0.019	0.038	0.620	0.013	1.223	0.018	0.024	0.327	0.030	0.039	0.640	0.010	0.010	1.522	1.544	1.693
Fe^{3+}			0.018		0.020			0.052			0.011			0.057	0.067	0.027
Fe^{2+}	0.171	0.065	0.330	0.155	0.427	0.172	0.076	0.230	0.152	0.056	0.318	0.162	0.048	0.552	0.498	0.568
Mn	0.005	0.004	0.000	0.007	0.004	0.003	0.004	0.004	0.001	0.002	0.000	0.006	0.003	0.000	0.000	0.000
Mg	1.654	0.853	0.670	1.760	0.572	1.673	0.881	0.767	1.655	0.884	0.684	1.709	0.936	0.449	0.506	0.434
Ca	0.037	0.933		0.035		0.049	0.898		0.083	0.889		0.039	0.960			
Na	0.000	0.006		0.000		0.000	0.000		0.000	0.000		0.000	0.000			
Total	3.973	3.983	3.000	3.999	3.000	4.003	3.980	3.000	3.997	3.966	3.000	3.970	3.987	3.000	3.000	3.000
Mg-no.	0.906	0.929	0.670	0.919	0.573	0.907	0.921	0.769	0.916	0.940	0.683	0.914	0.952	0.448	0.504	0.433
Cr-no.	0.119	0.173	0.313	0.157	0.620	0.077	0.097	0.168	0.147	0.190	0.322	0.223	0.191	0.785	0.802	0.860
Fe^{3+}-no.			0.009		0.010			0.026			0.006			0.029	0.034	0.014
Ol Mg-no.		0.907		0.909			0.901			0.916			0.910		0.922	0.915

Data sources: [1] Tamura *et al.* (1999); [2] Vysotskiy *et al.* (2000); [3] this study (analyst: D. Saito); [4] Saito *et al.* (1999); [5] Dmitrenko *et al.* (1990); [6] this study (analyst: Y. Furuhashi). Du, dunite; Lh, lherzolite; Hz, harzburgite; Ol, olivine; Opx, orthopyroxene; Cpx, clinopyroxene.

*Sample 1004B is olivine–talc rock after harzburgite. Analyses for [1], [3], [4] and [6] were performed by the same method using the Akashi-30A SEM-EDAX 9100 system of Kanazawa University. (See López & Ishiwatari (2002) for further details of these analyses.)

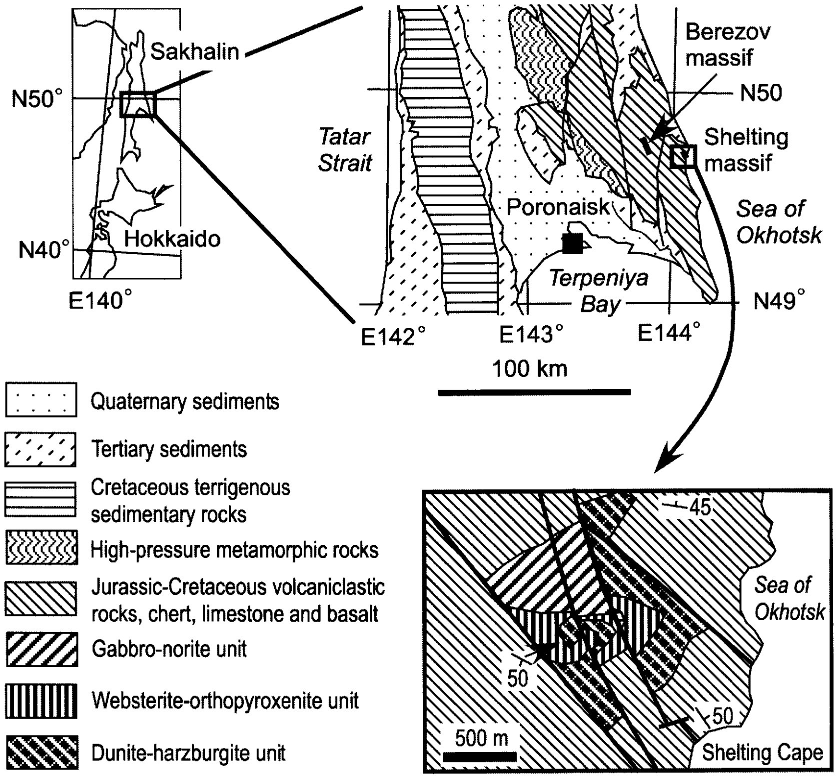

Fig. 5. Geological map of the DH-type Shelting Cape ophiolite in central eastern Sakhalin (after Vysotskiy *et al.* 2000). (See Fig. 2 for location.)

complex, the Nablyudeny complex, and the Povorotny mélange. Although the Kengeveem metagabbro complex does not have mantle peridotite, the other three complexes do (Saito *et al.* 1999; Bazylev *et al.* 2001). The Nablyudeny harzburgite has the most chromian spinel (Cr-number 0.8), whereas the harzburgites of the Elistratova ophiolite have moderately chromian varieties (Cr-number 0.3–0.7), and the Povorotny lherzolite has aluminous spinel (Cr-number 0.2) (Table 2). Some spinels in the Povorotny complex are chromian in composition with Cr-number up to 0.7 (Bazylev *et al.* 2001). Here again, an extreme diversity of residual mantle peridotite is present among these ophiolites (Fig. 3c; Table 2).

The Elistratova ophiolite consists of a central cumulate gabbro body, locally cut by sheeted dykes, whereas the northern and southern ultramafic bodies are mostly composed of residual mantle peridotite (Belyi & Akinin 1985; Saito *et al.* 1999) (Fig. 6). Disseminated spinel in peridotite of the southern body is moderately aluminous (Cr-number 0.30–0.50), whereas that in the northern body is more chromian (Cr-number 0.40–0.65) (Fig. 3c). The gabbroic body is intrusive into the southern ultramafic body with a clear-cut chilled igneous contact. Many dykes, which contain ultramafic xenoliths, also intrude into the ultramafic rocks. Saito *et al.* (1999) interpreted the northern ultramafic body and the central gabbroic body as an intact island arc ophiolite. The southern ultramafic body is less depleted than the northern one and may have served as a subvertical wall for the gabbroic magma chamber. The gabbroic rocks vary upward from olivine gabbronorite through gabbronorite to hornblende gabbronorite. The coexistence of extremely calcic plagioclase (about An_{90}) with relatively iron-rich clinopyroxene (about Mg-number 0.80) clearly indicates an island arc basalt affinity for the magma (Fig. 4b). Podiform chromitite from the northern mélange has a Cr-number of 0.70, and the chromite grains are characterized by Fe^{3+}-poor cores containing many hydrous inclusions (hornblende and phlogopite), suggesting the involvement of a hydrous, reducing fluid in podiform chromitite formation (Tsujimori *et al.* 1999).

The Kengeveem metagabbro complex is distinct from the gabbroic section of the Elistratova ophiolite. The metagabbros are almost devoid of

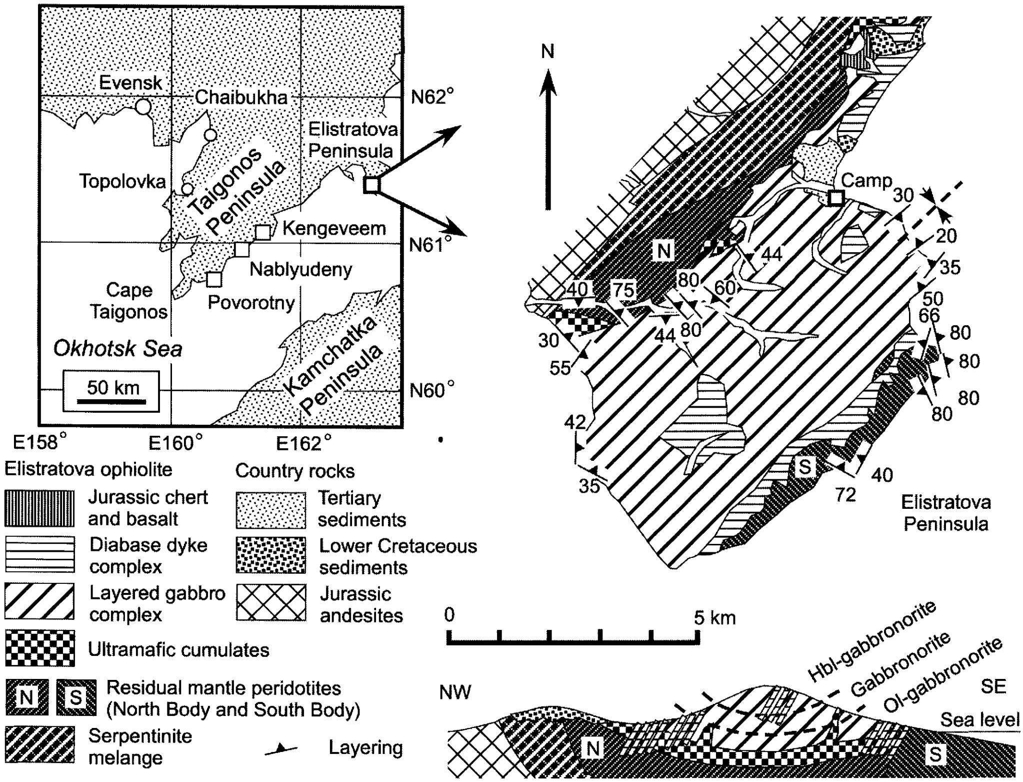

Fig. 6. Geological map and schematic cross-section of the Elistratova ophiolite in the Taigonos Peninsula (after Belyi & Akinin 1985; Saito *et al.* 1999; and our data). An intact ophiolite sequence composed of the northern ultramafic body (normal harzburgite) and central gabbro body, with ultramafic cumulates between them, and sheeted diabase dyke complexes in the gabbro, intrudes into the southern ultramafic body (less depleted harzburgite).

orthopyroxene, which is abundant in the Elistratova gabbros, but contain abundant clinopyroxene (Mg-number 0.80) and plagioclase (An_{60}) (Fig. 4b), indicating a MORB affinity. On its northern side, the Kengeveem gabbro body is associated with Ordovician sedimentary rocks, and thus they may be significantly older than the Mesozoic ophiolites of the Taigonos Peninsula. This body may possibly be the equivalent of the Early Palaeozoic Ganychalan ophiolite in the Penzhina zone.

Mainits zone

The Mainits zone in the central Koryak Mountains is characterized by the occurrence of many ophiolites associated with Jurassic–Cretaceous accretionary complexes (Stavsky *et al.* 1990). Within an area of 40 km × 100 km, there are several ophiolitic bodies such as the Tamvatney lherzolite massif, the Yagel serpentinite mélange, the Krasnaya Mountain harzburgite nappe, and the Srednaya Mountain dunite body, all of which are associated with island arc type gabbro and volcanic rocks (Fig. 7). The Tamvatney body contains mostly lherzolite (spinel Cr-number 0.20–0.30) (Table 2) with minor harzburgite (spinel Cr-number 0.35–0.50) (Dmitrenko *et al.* 1990), and contains some eclogitic inclusions. The Yagel serpentinite mélange consists of blocks of lherzolite, harzburgite (spinel Cr-number 0.4), dunite, gabbro, picritic sheeted dykes and pillow basalt. On the other hand, the Krasnaya Mountain ultramafic complex, which occurs as a subhorizontal nappe thrust onto the Jurassic–Cretaceous accretionary complexes and the Yagel mélange, contain highly chromian spinel (Cr-number 0.8) and highly magnesian olivine (Fo_{90}) (Fig. 3d, Table 2). The geological map of Dmitrenko *et al.* (1985) shows that the southern half of the complex consists mostly of depleted harzburgite, whereas the northern half is composed of ultramafic cumulates and dunite with orthopyroxenite veins (Fig. 8). The ultramafic cumulate includes iron-

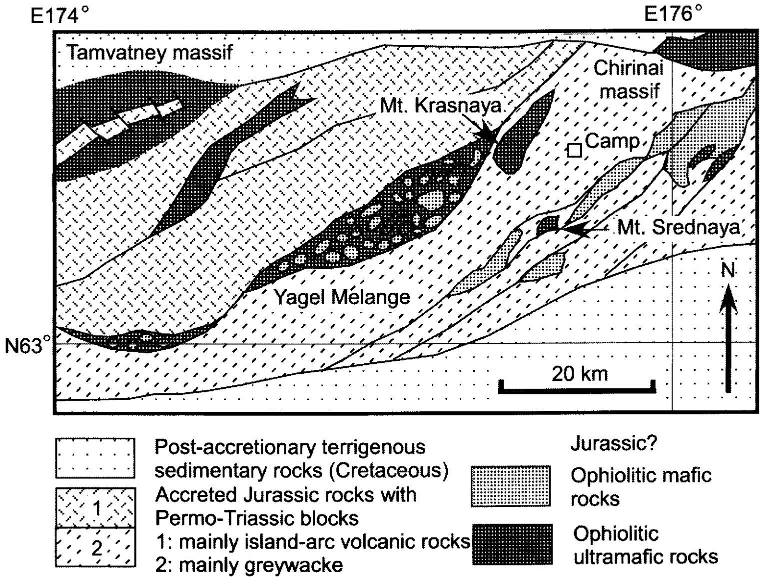

Fig. 7. Ophiolitic rock complexes of the Mainits Zone in the Koryak Mountains, NE Russia (simplified from Stavsky *et al.* 1990). (See Fig. 2 for location.)

rich harzburgite, dunite, orthopyroxenite and websterite. The Krasnaya complex has a lithological assemblage typical of the DH-type ophiolite, although gabbroic and volcanic rocks are missing. The Serdnaya Mountain dunite body includes dunite and chromitite. Disseminated spinel in the dunite is highly chromian (Cr-number 0.85) (Fig. 3d, Table 2). Although the Mainits Zone is a small area, both L-type and DH-type ophiolites are present, reflecting wide petrological diversity in the residual mantle peridotite.

Discussion

Multiple nappe pile of ophiolites of various ages

Irwin (1981) first described multiple nappe piles of ophiolites from the Klamath Mountains of the western USA, where the Jurassic Josephine ophiolite is tectonically overlain by an Upper Palaeozoic–Triassic ophiolite, which is in turn structurally overridden by the Lower Palaeozoic Trinity ophiolite, with intervening blueschists and accretionary complexes. Emplacement of older ophiolites over younger accretionary complexes and ophiolites is a regular rule not only for the Klamath Mountains but also for SW Japan (the Upper Palaeozoic Yakuno ophiolite is tectonically overlain by the Lower Palaeozoic Oeyama ophiolite), NE Japan (the Lower Palaeozoic Miyamori ophiolite is thrust over the Jurassic accretionary complex and Jurassic–Cretaceous ophiolites in central Hokkaido), and northeastern Russia (Lower Palaeozoic ophiolites of the Penzhina zone are thrust over the Koryak nappe system containing abundant Mesozoic ophiolites). The Jurassic(?) Mikabu ophiolite and the Tertiary Mineoka (–Setogawa) ophiolite are both present on the Pacific side of SW Japan, and one of the youngest ophiolites on Earth is present in East Taiwan (further review and references have been given by Ishiwatari (1991, 1994)). This is consistent with the long-lasting (Phanerozoic) subduction and accretion of the circum-Pacific orogenic belts.

Petrological diversity of the northwestern Pacific margin ophiolites

Nicolas & Jackson (1972) demonstrated that lherzolite is the dominant mantle peridotite in the western Mediterranean ophiolites, whereas harzburgite dominates in the eastern Mediterranean. This implies that the mantle composition is relatively homogeneous for more than 1000 km along the ophiolite belt, although small-scale heterogeneities may occur in the boundary area (e.g. in the Balkan Peninsula). Harzburgite represents residual mantle left after higher degrees of melting of lherzolite, and the degree of melting is represented by various mineralogical parameters such as increasing Cr-number of spinel, increasing Fo content of olivine, and decreasing Al_2O_3 content of

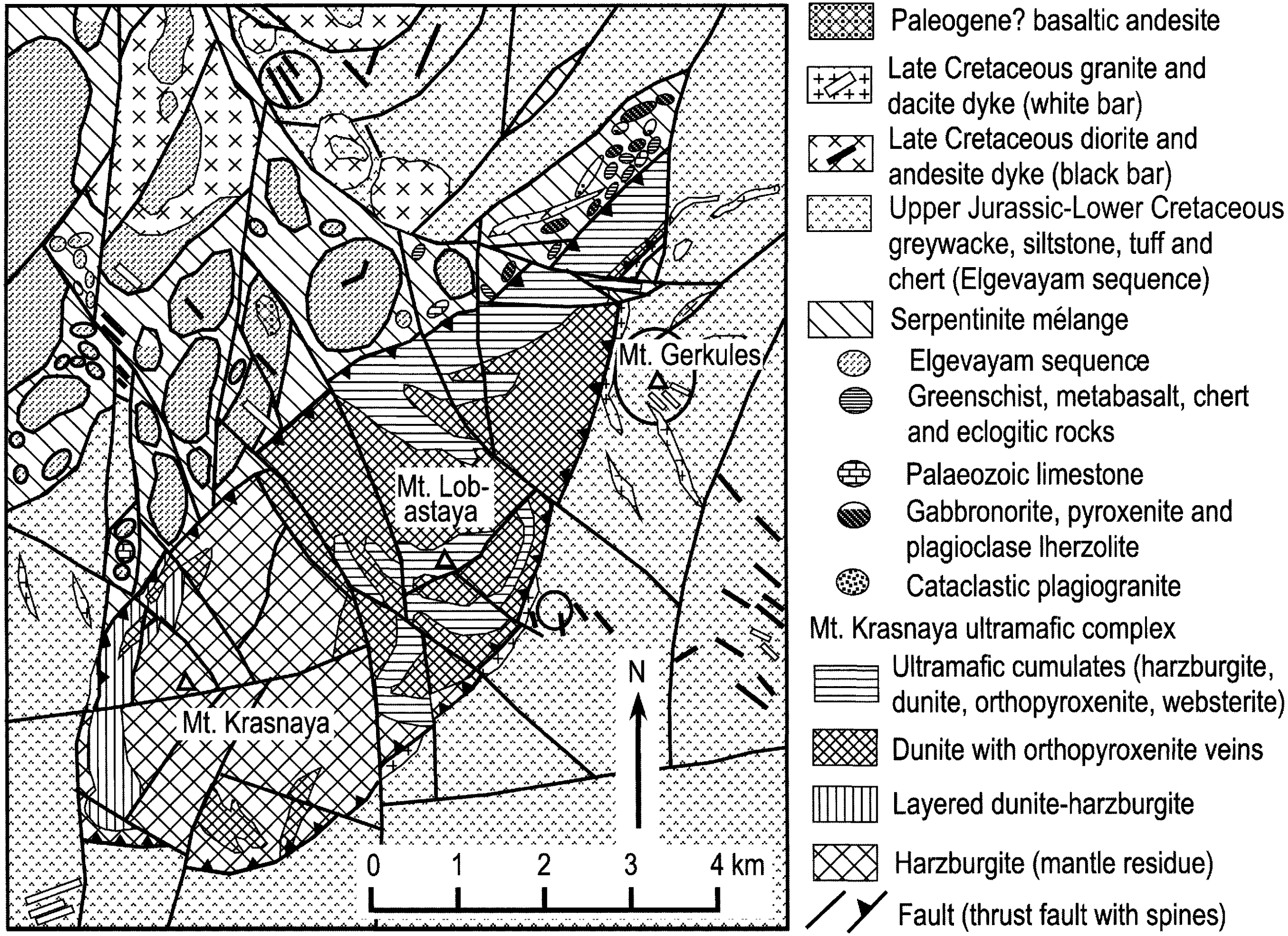

Fig. 8. Geological map of the DH-type Mt. Krasnaya ultramafic complex (possibly the lower part of an ophiolite) after Dmitrenko *et al.* (1985). (See Fig. 7 for location.)

orthopyroxene (Ishiwatari 1985a). DH-type ophiolites have not been found in the eastern Mediterranean area.

However, the degree of depletion may vary significantly within a single 'Tethyan-type' ophiolite as in the Bay of Islands (Edwards 1995), and high-Cr spinel forms chromitite ore in many ophiolites far from the Pacific Rim, such as in Albania (Bulqiza massif: Çina *et al.* 1987) and the southern Urals (e.g. Kempirsai massif: Melcher *et al.* 1997), where boninitic volcanic rocks with high-Cr spinel microphenocrysts are also present (Spadea & Scarrow 2000). In these massifs, the high-Cr spinel is generally restricted to chromitite ores, and associated dunites and disseminated spinel in the surrounding harzburgite are more aluminous (e.g. Cr-number 0.41 in Kempirsai). Mantle sections composed totally of highly depleted harzburgite (spinel Cr-number >0.7) are characteristic of the western Pacific ophiolite belts. Such harzburgite is associated with orthopyroxene-type cumulates, which may have crystallized from boninitic or island arc tholeiitic melts, suggesting an SSZ origin of these ophiolites. The Shelting ophiolite in Sakhalin and the Mt. Krasnaya ultramafic complex in the Koryak Mountains are new examples of the DH-type ophiolites. Previously known DH-type ophiolites include Horokanai–Takadomari (Hokkaido; Ishizuka 1985, 1987; Tamura *et al.* 1999), Papua (England & Davies 1973; Jaques & Chappell 1980) and Adamsfield (Tasmania; Varne & Brown 1978).

Highly depleted harzburgite (spinel Cr-number 0.77) and dunite (spinel Cr-number 0.81) were drilled from a conical serpentinite seamount in the Mariana forearc. Relatively fertile harzburgite (Cr-number 0.36) and intermediate varieties were also recovered from this site (Ishii *et al.* 1992), and the spinel Cr-number of all mantle peridotites from this seamount averages 0.61 (Fig. 9a). Harzburgite samples from the nearby landward walls of the Mariana Trench also have Cr-rich spinel (Cr-number 0.55–0.69) (Bloomer & Hawkins 1983), and a forearc seamount in the Izu islands has similar rocks. However, lherzolite samples with spinel Cr-number of 0.27 were recovered from the Mariana Trough, an active back-arc rift zone (Ohara *et al.* 2002). Mantle peridotites from the extinct Parece Vela rift zone and southern Mariana Trench walls near Yap Island contain spinels of intermediate composition (Cr-number 0.43–0.52) (Bloomer & Hawkins 1983; Ohara *et al.* 1996) (Fig. 9a).

On the other hand, peridotites from fracture zones of the slow-spreading South Atlantic–Southwest Indian ridges such as Islas Orcadas, Vulcan and Bullard have aluminous spinels (Cr-number 0.15–0.30) (Dick 1989). The Bouvet fracture zone has peridotites with spinel Cr-number of 0.34–0.55, similar to peridotites of fracture zones along the fast-spreading East Pacific Rise (such as the Garrett fracture zone) and the Hess Deep (Cr-number 0.35–0.45) (Cannat *et al.* 1990; Arai *et al.* 1996; Edwards & Malpas 1996). Spinels from forearc peridotites are clearly more Cr rich and more depleted when compared with those from mid-oceanic ridge peridotites. Boninites from the Mariana and Tonga forearcs have highly chromian spinel (Cr-number 0.70–0.90) and are believed to have formed by hydrous melting of a depleted mantle (Bloomer & Hawkins 1987; Sobolev & Danyushevsky 1994). Primitive magnesian andesite, containing chromian spinel (Cr-number >0.74) and magnesian orthopyroxene (Mg-number 0.88), has also been reported from Oligo-Miocene island arc volcanic rocks of Japan in association with tholeiitic basalt and calc-alkaline andesite (López & Ishiwatari 2002). The occurrence of diverse mantle peridotites including highly depleted harzburgite (spinel Cr-number >0.70) in the Mariana forearc suggests that the ophiolite belts of the northwestern Pacific margins also originated in intra-oceanic SSZ environments extending from landward trench walls to back-arc basins.

It should be noted, however, that the variation in Os isotopic composition among ophiolitic chromites, including those from the northwestern Pacific margins, is significantly less than has been reported for oceanic peridotites and MORB. Thus, there is little evidence to suggest modification of the mantle's original Os isotopic composition via radiogenic melts or fluids derived from subducting slabs (Walker *et al.* 2002). This may partly reflect the extremely low concentration of platinum-group elements in such fluids but essentially suggests that simple, high-temperature melting of homogeneous, depleted MORB mantle (DMM) is the major ophiolite-forming process.

Occurrence of the ophiolites with thick oceanic crust

Granulite-facies, two-pyroxene spinel metagabbro (sometimes with garnet) occurs at the Moho level of some circum-Pacific ophiolites in Japan, eastern Russia and Alaska (Ishiwatari 1985b; DeBari & Coleman 1989; Vysotskiy 1994; Tsujimori & Ishiwatari 2002). This observation suggests a relatively thick oceanic crust for these ophiolites, which are believed to have formed in island arc (DeBari & Coleman 1989), marginal basin (Ishiwatari 1985b), and/or oceanic plateau (Isozaki 1997) environments. Granulite-facies metagabbros (mostly spinel and garnet free) have also been

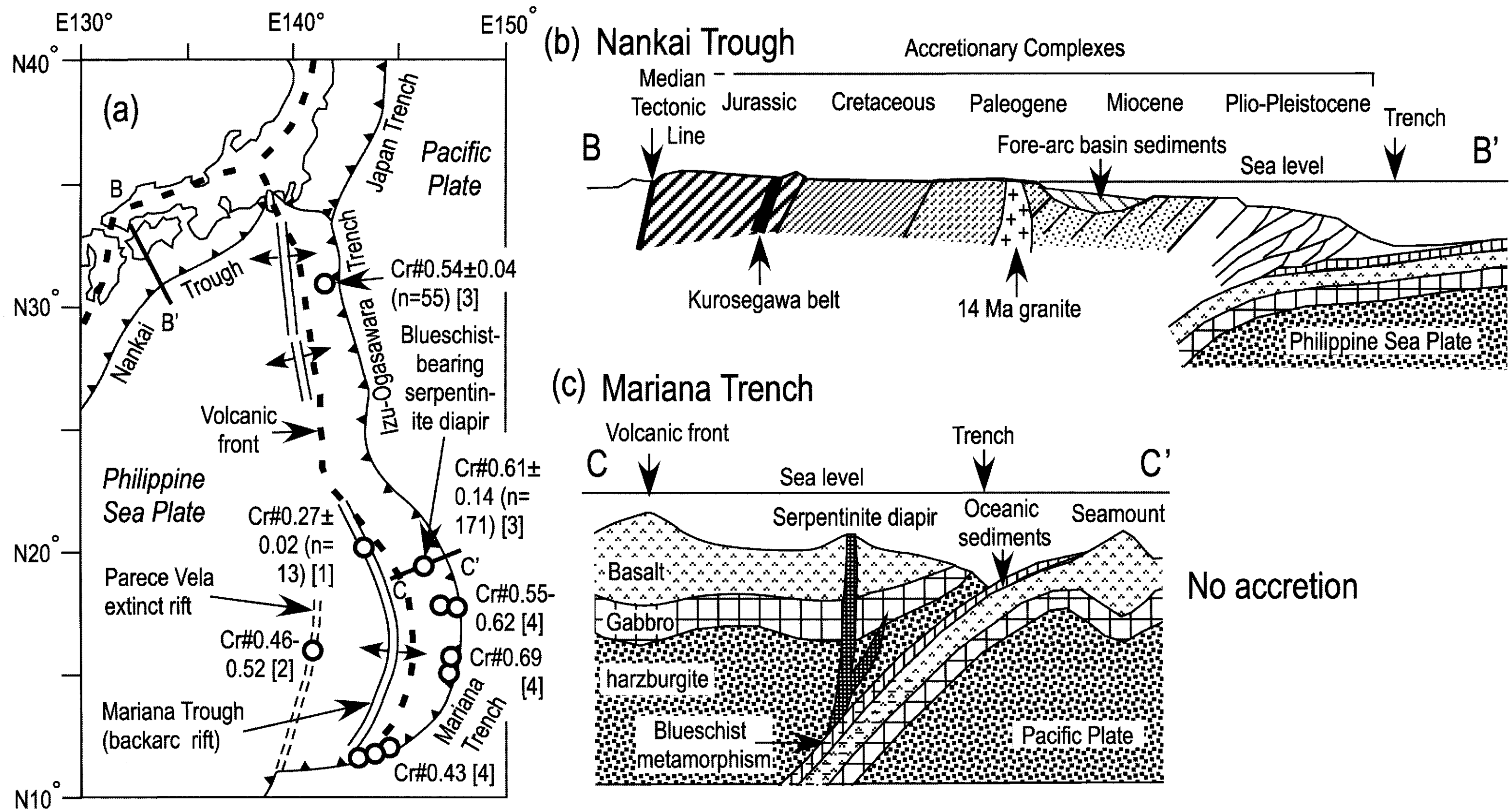

Fig. 9. (**a**) Tectonic framework of the Western Pacific area (with cross-section profiles marked). Spinel Cr-number data of mantle peridotites dredged and drilled from the Izu–Mariana island arc system are also shown. Average and standard deviations are indicated (av. ± s.d.) if many analyses are available (number in parentheses), but only a value or range is shown if three or fewer analyses are available. Data sources: [1] Ohara *et al.* (2002); [2] Ohara *et al.* (1996); [3] Ishii *et al.* (1992); [4] Bloomer & Hawkins (1983). (**b**) Schematic cross-section of the Nankai Trough, a typical accreting subduction zone with well-developed accretionary complexes (based on Taira 1985). (**c**) Schematic cross-section of the Mariana Trench (based on Bloomer & Hawkins 1983; Bloomer & Fisher 1987; Maekawa *et al.* 1993, 1995), a typical non-accreting subduction zone with outcrops of ophiolitic rocks on the landward trench slope and blueschist occurrences in a forearc serpentinite seamount.

recovered from mid-oceanic ridges, but Gaggero & Cortesogno (1997) estimated that the pressure of formation for these rocks was 0.3 GPa (*c.* 10 km depth). This is much lower than the pressure (0.5–1.1 GPa) estimated for ophiolitic granulite-facies metagabbros (Ishiwatari 1985*b*; DeBari & Coleman 1989; Vysotskiy 1994; Tsujimori & Ishiwatari 2002).

Coffin & Eldholm (2001) pointed out that sections of oceanic crust in large igneous provinces (LIPs) are two or five times thicker than those of 'normal' oceanic crust and postulated that some ophiolites are of LIP origin. Xenoliths of granulite-facies, two-pyroxene spinel metagabbro have been reported in alkali basalt from the Kerguelen Archipelago, a typical LIP (Grégoire *et al.* 1998). However, analogous spinel metagabbro xenoliths are also known from continental margins (e.g. Francis 1976), although higher-pressure garnet granulites may comprise typical lower continental crust (e.g. Loock *et al.* 1990). Based on their petrology, mineralogy and geochemistry, circum-Pacific ophiolites with relatively thick mafic crust represent SSZ lithosphere (DeBari & Coleman 1989; Ishiwatari *et al.* 1990). Many are tectonically underlain by blueschist and younger accretionary complexes, suggesting that they represent the hanging wall of the subduction zone (i.e. mantle wedge and overlying crust). The Os isotope character of chromitite in the Yakuno ophiolite does not support an origin in a superplume-related LIP, which would be characterized by an isotopically distinct HIMU or enriched mantle (Walker *et al.* 2002).

Origin of the ophiolite–blueschist assemblage

Japanese ophiolites commonly have metamorphic soles composed of blueschist and are tectonically underlain by younger, sediment-rich accretionary complexes, which contain greenstones of OIB and MORB origin (Table 1). For example, in southwestern Japan, the Ordovician Oeyama ophiolite (>450 Ma) is underlain by the 320 Ma Renge blueschist and the Upper Permian (250 Ma) Akiyoshi accretionary complex. This spatial relationship suggests tectonic erosion or non-accretion during the intervening Siluro-Devonian time. A similar gap exists between the Lower Permian (280 Ma) Yakuno ophiolite and the underlying Jurassic Tamba accretionary complex (150 Ma). The accretionary complex is characterized by 'oceanic plate stratigraphy' composed of greenstone, chert, limestone, mudstone and sandstone in a younging order (Isozaki 1997). The basal greenstone commonly includes tholeiitic and alkaline seamount basalt (OIB) with high Ti and Nb concentrations, but the ophiolite itself is almost free of OIB.

In the present-day western Pacific, the Izu–Mariana and Tonga subduction zone environments are characterized by the presence of ophiolite outcrops on the trench slopes (Bloomer & Hawkins 1983; Bloomer & Fisher 1987) and blueschists (Maekawa *et al.* 1993, 1995), by the absence or scarcity of accretionary complexes, and by the currently active back-arc spreading. In contrast, areas off northeastern Honshu and Hokkaido are characterized by the development of vast accretionary complexes (Taira 1985) without submarine ophiolite or blueschist outcrops and without active back-arc spreading (Fig. 9). These different environments may have been repeated in any segment of the Japanese orogenic belt throughout Phanerozoic time. Periods of oceanic island arc and marginal basin development (ophiolite formation) and tectonic erosion (blueschist metamorphism) might have alternated with periods of normal subduction, during which accretionary complexes were developed.

The ophiolite–blueschist association is well documented in the Japan–Primorye area, e.g. the Oeyama ophiolite–Renge blueschist (Tsujimori & Itaya 1999) and Sergeevka ophiolite–Shaiginskiy blueschist (Kovalenko & Khanchuk 1991; Zakharov *et al.* 1992). In the NE Japan–Sakhalin belt, the Palaeozoic Miyamori ophiolite–Motai blueschist pair (Maekawa 1988; Ozawa 1988, 1994) and the Mesozoic Horokanai ophiolite–Kamuikotan blueschist pair (Ishizuka 1985, 1987; Sakakibara & Ota 1994) are well documented. Although a major blueschist belt is absent in the Koryak Mountains, many blueschist blocks occur in the Palaeozoic and Mesozoic accretionary complexes (Stavsky *et al.* 1990; Dobretsov 1999).

It is likely that periods of accretion and non-accretion, as represented by the present-day Nankai Trough and Mariana Trench, respectively, have been repeated many times in different segments of the Japan–NE Russia accretionary orogenic belts in the past. Periods of ophiolite–blueschist formation and tectonic erosion at subduction zones might have been followed by periods of massive accretion. Tectonic underplating of accreted sediments beneath the mantle wedge might have facilitated the uplift of overlying ophiolite–blueschist assemblages. This idea is compatible with the geochemical signatures of ophiolitic rocks showing SSZ affinities.

Conclusions

The northwestern Pacific margin extending from Japan to Russia has many ophiolites of widely varying ages, different petrological characteristics and distinctive tectonic histories. The following geological features suggest that these ophiolites probably formed in island arc environments in intra-oceanic settings: extremely diverse degree of melting in the residual mantle peridotite up to clinopyroxene disappearance and spinel Cr-number >0.70; the common occurrence of hydrous minerals and various metasomatic features in the mantle section; the common association with blueschist rocks; the presence of unusually thick oceanic crust. The modern Mariana and Tonga trenches, where ophiolitic rocks including highly depleted harzburgite and typical blueschist have been dredged from the sea floor, may be the modern analogues. The orogenic belts from Japan to NE Russia may have evolved through repeated stages of non-accretion, in which SSZ ophiolites and blueschists formed, and accretion, in which accretionary complexes mainly composed of clastic and volcaniclastic rocks developed.

The association of highly depleted mantle harzburgite and orthopyroxene-type cumulate rocks is reinforced by reported occurrences of DH-type ophiolites from NE Russia (Shelting and Krasnaya). These ophiolites have only been reported so far from the western Pacific margins such as Hokkaido (Horokanai), Papua, and Tasmania (Adamsfield). The association of some DH-type ophiolites with boninitic volcanic rocks (Shelting, Papua, and possibly Mariana and Tonga) suggests that the depleted harzburgite is a residuum after boninitic melt production, although boninite is also reported from some ophiolites with less depleted peridotite (e.g. Robinson *et al.* 1983; Spadea & Scarrow 2000). Some primitive island arc tholeiite and magnesian andesite magmas could also coexist with the depleted harzburgite. The depleted harzburgite may form by either high-temperature dry melting of primary mantle or hydrous melting of previously depleted mantle. However, Os isotope studies of ophiolitic chromitites do not support much involvement of slab-derived fluids in mantle melting. The Os isotope data are also inconsistent with an oceanic plateau (or LIP) origin postulated for some ophiolites with thick crustal sections. These instead may represent robust magmatic activity in SSZ environments, where they would be associated with highly depleted harzburgite massifs.

We are grateful for T. Tsujimori, D. Saito, S. Miyashita, A. P. Stavsky, O. Morozov, S.A. Shcheka, A. I. Khanchuk, S. G. Byalobzhesky, W. B. Bryan and J. Hourigan for their help with fieldwork in Far East Russia. A.I. thanks S. A. Palandzhjan for valuable information on the ophiolites of the Koryak Mountains, and Y. Dilek for his encouragement in writing this paper. S. Maruyama is acknowledged for his help in arranging financial support for our fieldwork. A.I. also acknowledges Grant-in-Aid for Scientific Research (C)-(2)-10640462 and -14540447 by the Ministry of Education, Japan. S. Arai is thanked for several discussions. Y. Furuhashi and D. Saito contributed the mineral analyses.

References

AHMED, A.H. & ARAI, S. 2002. Unexpectedly high-PGE chromitite from the deeper mantle section of the northern Oman ophiolite and its tectonic implications. *Contributions to Mineralogy and Petrology*, **143**, 263–278.

ALABASTER, T., PEARCE, J.A. & MALPAS, J. 1982. The volcanic stratigraphy and petrogenesis of the Oman ophiolite complex. *Contributions to Mineralogy and Petrology*, **81**, 168–183.

ARAI, S. 1980. Dunite–harzburgite–chromitite complexes as refractory residue in the Sangun–Yamaguchi zone, western Japan. *Journal of Petrology*, **21**, 141–165.

ARAI, S. *ET AL.* 1996. Petrology of the gabbro–troctolite–peridotite complex from Hess Deep, Equatorial Pacific: implications for mantle–melt interaction within the oceanic lithosphere. *In:* MÉVEL, C. (ed.) *Proceedings of the Ocean Drilling Program, Scientific Results, 147*. Ocean Drilling Program, College Station, TX, 135–155.

BAZYLEV, B.A., PALANDZHJAN, S.A., GANELIN, A.V., SILANTYEV, S.A., ISHIWATARI, A. & DMITRENKO, G.G. 2001. Petrology of peridotites from the ophiolite mélange in Cape Povorotny, Taigonos Peninsula, NE Russia: mantle processes beneath a subduction zone. *Petrology*, **9**(2), 142–160.

BEARD, J.S. 1986. Characteristic mineralogy of arc-related cumulate gabbros: implications for the tectonic setting of gabbroic plutons and for andesite genesis. *Geology*, **14**, 848–851.

BELYI, V.F. & AKININ, V.V. 1985. *Geologic Structure and Ophiolites in the Elistratova Peninsula, Volumes 1 and 2*. Academy of Sciences of the USSR, Far East Science Centre, Magadan (in Russian).

BLOOMER, S.H. & FISHER, R.L. 1987. Petrology and geochemistry of igneous rocks from the Tonga Trench—a non-accreting plate boundary. *Journal of Geology*, **95**, 469–495.

BLOOMER, S.H. & HAWKINS, J.W. 1983. Gabbroic and ultramafic rocks from the Mariana Trench: an island arc ophiolite. *In:* HAYES, D.E. (ed.) *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Part 2*. Geophysical Monograph, American Geophysical Union, **27**, 294–317.

BLOOMER, S.H. & HAWKINS, J.W. 1987. Petrology and geochemistry of boninite series volcanic rocks from the Mariana trench. *Contributions to Mineralogy and Petrology*, **97**, 361–377.

BOUDIER, F. & NICOLAS, A. 1985. Harzburgite and lherzolite subtypes in ophiolitic and oceanic environments. *Earth and Planetary Science Letters*, **76**, 84–92.

BRYAN, W.B. 1991. Exploring Pacific seafloor ashore: Magadan Province, USSR. *Oceanus (Woods Hole Oceanographic Institution), Summer 1991*, 48–61.

CANNAT, M., BIDEAU, D. & HÉBERT, R. 1990. Plastic deformation and magmatic impregnation in serpentinized ultramafic rocks from the Garrett transform fault (East Pacific Rise). *Earth and Planetary Science Letters*, **101**, 216–232.

ÇINA, A., TASHKO, A. & TËRSHANA, A. 1987. The Bulqiza and Gomsiqe ultrabasic massifs, ophiolites of Albanides: a geochemical comparison. *Ofioliti*, **12**, 219–236.

COFFIN, M.F. & ELDHOLM, O. 2001. Large igneous provinces: progenitors of some ophiolites? *In:* ERNST, R.E. & BUCHAN, K.L. (eds) *Mantle Plumes: Their Identification through Time*. Geological Society of America, Special Papers, **352**, 59–70.

COLEMAN, R.G. 1971. Plate tectonic emplacement of upper mantle peridotites along continental edges. *Journal of Geophysical Research*, **76**, 1212–1222.

COLEMAN, R.G. 1986. Ophiolites and accretion of the North American Cordillera. *Bulletin de la Société Géologique de France*, **1986**, 961–968.

DEBARI, S.M. & COLEMAN, R.G. 1989. Examination of the deep levels of an island arc: evidence from the Tonsina ultramafic–mafic assemblage, Tonsina, Alaska. *Journal of Geophysical Research*, **94**(B4), 4373–4391.

DICK, H.J.B. 1989. Abyssal peridotites, very slow spreading ridges and ocean ridge magmatism. *In:* SAUNDERS, A.D. & NORRY, M.J. (eds) *Magmatism in the Ocean Basins*. Geological Society, London, Special Publications, **42**, 71–105.

DICK, H.J.B. & BULLEN, T.B. 1984 Chromian spinel as a petrogenetic indicator in abyssal and alpine-type peridotites and spatially associated lavas. *Contributions to Mineralogy and Petrology*, **86**, 54–76.

DILEK, Y., MOORES, E.M. & FURNES, H. 1998. Structure of modern oceanic crust and ophiolites and implications for faulting and magmatism at oceanic spreading centers. *In:* BUCK, W.R., DELANEY, P.T., KARSON, J.A. & LAGABRIELLE, Y. (eds) *Faulting and Magmatism at Mid-Ocean Ridges*. Geophysical Monograph, American Geophysical Union, **106**, 219–265.

DMITRENKO, G.G., MOCHALOV, A.G., PALANDZHJAN, S.A. & GORYACHEVA, E.M. 1985. *Chemical Composition of the Rock-forming and Accessory Minerals of the Koryak Highland Alpine-type Ultramafics. Part 1. Rock-forming Minerals*. Academy of Sciences of the USSR, Far East Science Centre, Interdisciplinary Research Institute, Magadan (in Russian).

DMITRENKO, G.G., MOCHALOV, A.G. & PALANDZHJAN, S.A. 1990. *Petrology and Platinum Occurrence in Lherzolite Massifs of the Koryak Mountains*. Academy of Sciences of the USSR, Far East Science Centre, Interdisciplinary Research Institute, Magadan (in Russian).

DOBRETSOV, N.L. 1999. Systematic periodicity of glaucophane metamorphism: an illusion or an important geologic regularity. *Petrology*, **7**, 410–439.

DOBRETSOV, N.L., WATANABE, T., NATAL'IN, B. & MIYASHITA, S. 1994. Comparison of ophiolites and blueschists of Sakhalin and Hokkaido. *Ofioliti*, **19**, 157–176.

EDWARDS, S.J. 1995. Boninitic and tholeiitic dykes in the Lewis Hills mantle section of the Bay of Islands ophiolite: implications for magmatism adjacent to a fracture zone in a back-arc spreading environment. *Canadian Journal of Earth Science*, **32**, 2128–2146.

EDWARDS, S.J. & MALPAS, J. 1996. Melt–peridotite interactions in shallow mantle at the East Pacific Rise: evidence from ODP Site 895 (Hess Deep). *Mineralogical Magazine*, **60**, 191–206.

ENGLAND, R.N. & DAVIES, H.L. 1973. Mineralogy of ultramafic cumulates and tectonites in eastern Papua. *Earth and Planetary Science Letters*, **17**, 416–425.

FRANCIS, D. 1976. Corona-bearing pyroxene granulite xenoliths and the lower crust beneath Nunivak Island, Alaska. *Canadian Mineralogist*, **14**, 291–298.

FUJITA, K. & NEWBERRY, J.T. 1982. Tectonic evolution of northeastern Siberia and adjacent regions. *Tectonophysics*, **89**, 337–357.

FURUE, R., NIIDA, K. & KATOH, T. 1997. Origin of ophiolitic chromitites in the Kamuikotan Belt, Hokkaido. *Bulletin of Hobetsu Museum*, **13**, 9–26 (in Japanese with English abstract).

GAGGERO, L. & CORTESOGNO, L. 1997. Metamorphic evolution of oceanic gabbros: recrystallization from subsolidus to hydrothermal conditions in the MARK area (ODP Leg 153). *Lithos*, **40**, 105–131.

GRÉGOIRE, M., COTTIN, J.Y., GIRET, A., MATTIELLI, N. & WEIS, D. 1998. The meta-igneous granulite xenoliths from Kerguelen Archipelago: evidence of a continent nucleation in an oceanic setting. *Contributions to Mineralogy and Petrology*, **133**, 259–283.

HÉBERT, R. & LAURENT, R. 1990. Mineral chemistry of the plutonic section of the Troodos ophiolite: new constraints for genesis of arc-related ophiolites. *In:* MALPAS, J., MOORES, E.M., PANAYIOTOU, A. & XENOPHONTOS, C. (eds) *Ophiolites: Oceanic Crust Analogues. Proceedings of the Troodos '87 Symposium*. Geological Survey Department, Nicosia, 149–163.

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.

IRWIN, W.P. 1981. Tectonic accretion of the Klamath Mountains. *In:* ERNST, W.G. (ed.) *The Geotectonic Development of California (Rubey Volume 1)*. Prentice Hall, Englewood Cliffs, NJ, 29–49.

ISHII, T., ROBINSON, P.T., MAEKAWA, H. & FISKE, R. ET AL. 1992. Petrological studies of peridotites from diapiric serpentinite seamounts in the Izu–Ogasawara–Mariana forearc. *In:* FRYER, P., PEARCE, J. & STOKKING, L.B. (eds) *Proceedings of the Ocean Drilling Program, Scientific Results, 125*. Ocean Drilling Program, College Station, TX, 445–485.

ISHIWATARI, A. 1985a. Igneous petrogenesis of the Yakuno ophiolite (Japan) in the context of the diversity of ophiolites. *Contributions to Mineralogy and Petrology*, **89**, 155–167.

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

ISHIWATARI, A. 1991. Time–space distribution and petrologic diversity of Japanese ophiolites. *In:* PETERS, TJ., NICOLAS, A. & COLEMAN, R.G. (eds) *Ophiolite Genesis and Evolution of the Oceanic Lithosphere*. Kluwer, Dordrecht, 723–743.

ISHIWATARI, A. 1994. Circum-Pacific Phanerozoic multiple ophiolite belts. *In:* ISHIWATARI, A., MALPAS, J. & ISHIZUKA, H. (eds) *Circum-Pacific Ophiolites (Proceedings of the 29th IGC, Kyoto, Part D)*. VSP, Utrecht, 7–28.

ISHIWATARI, A. & TSUJIMORI, T. 2003. Paleozoic ophiolites and blueschists in Japan and Russian Primorye in the tectonic framework of East Asia: a synthesis. *Island Arc*, **12**, 190–206.

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., MOORES, E.M., PANAYIOTOU, A. & XENOPHONTOS, C. (eds) *Ophiolites: Oceanic Crust Analogues. Proceedings of the Troodos '87 Symposium*. Geological Survey Department, Nicosia, 497–506.

ISHIZUKA, H. 1985. Prograde metamorphism of the Horokanai ophiolite in the Kamuikotan Zone, Hokkaido, Japan. *Journal of Petrology*, **26**, 391–417.

ISHIZUKA, H. 1987. Igneous and metamorphic petrology of the Horokanai ophiolite in the Kamuikotan zone, Hokkaido, Japan: a synthetic thesis. *Memoirs of Faculty of Science, Kochi University, Series E*, **8**, 1–70.

ISOZAKI, Y. 1997. Contrasting two types of orogen in Permo-Triassic Japan: accretionary versus collisional. *Island Arc*, **6**, 2–24.

JAQUES, A.L. & CHAPPELL, B.W. 1980. Petrology and trace element geochemistry of the Papuan ultramafic belt. *Contributions to Mineralogy and Petrology*, **75**, 55–70.

JAQUES, A.L. & GREEN, D.H. 1980. Anhydrous melting of peridotite at 0–15 kb pressure and the genesis of tholeiitic basalts. *Contributions to Mineralogy and Petrology*, **73**, 287–310.

KHANCHUK, A.I. & PANCHENKO, I.V. 1994. Mineral assemblages of the Gankuvayam ophiolitic section in the Kuyul ophiolitic terrane of the Russia Far East. *Ofioliti*, **19**, 257–268.

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

KOVALENKO, S.V. & KHANCHUK, A.I. 1991. First find of glaucophane schist in Sikhote Alin. *Doklady Akademii Nauk SSSR*, **318**, 692–694 (in Russian).

KUROKAWA, K. 1985. Petrology of the Oeyama ophiolitic complex in the Inner Zone of Southwest Japan. *Science Reports, Niigata University, Series E, Geology and Mineralogy*, **6**, 37–113.

LACHIZE, M., LORAND, J.P. & JUTEAU, T. 1996. Calc-alkaline differentiation trend in the plutonic sequence of the Wadi Haymiliyah section, Haylayn massif, Semail ophiolite, Oman. *Lithos*, **38**, 207–232.

LOOCK, G., STOSCH, H.-G. & SECK, H.A. 1990. Granulite facies lower crustal xenoliths from the Eifel, West Germany: petrological and geochemical aspects. *Contributions to Mineralogy and Petrology*, **105**, 25–41.

LÓPEZ, J.C. & ISHIWATARI, A. 2002. Petrogenesis of the tholeiitic basalt, calc-alkaline basaltic andesite and high magnesian andesite lava succession of the Oligo-Miocene Anamizu Formation in northeastern Noto Peninsula, central Japan. *Journal of Mineralogical and Petrological Sciences*, **97**, 85–113.

LUCHITSKAYA, M.V. 1996. Plagiogranites of the Kuyul ophiolite massif (northeastern Kamchatka, Koryak Upland). *Ofioliti*, **21**, 131–138.

MAEKAWA, H. 1988. High *P/T* metamorphic rocks in Northeast Japan: Motai–Matsugadaira zone. *Earth Science (Chikyu Kagaku)*, **42**, 212–219 (in Japanese with English abstract).

MAEKAWA, H., SHOZUI, M., ISHII, T., FRYER, P. & PEARCE, J.A. 1993. Blueschist metamorphism in an active subduction zone. *Nature*, **364**, 520–523.

MAEKAWA, H., FRYER, P. & OZAKI, A. 1995. Incipient blueschist-facies metamorphism in the active subduction zone beneath the Mariana forearc. *In:* TAYLOR, B. & NATLAND, J. (eds) *Active Margins and Marginal Basins of the Western Pacific*. Geophysical Monograph, American Geophysical Union, **88**, 281–289.

MATSUMOTO, I. & ARAI, S. 1997. Characterization of chromian spinel as a tool of petrological exploration for podiform chromitite. *Resource Geology*, **47**, 189–199.

MELCHER, F., GRUM, W., SIMON, G., THALHAMMER, T.V. & STUMPEL, E.F. 1997. Petrogenesis of the ophiolitic giant chromite deposits of Kempirsai, Kazakhstan: a study of solid and fluid inclusions in chromite. *Journal of Petrology*, **38**, 1419–1458.

MIYASHIRO, A. 1973. The Troodos ophiolitic complex was probably formed in an island arc. *Earth and Planetary Science Letters*, **19**, 218–224.

MIYASHITA, S. 1983. Reconstruction of the ophiolite succession in the western zone of the Hidaka Metamorphic Belt, Hokkaido. *Journal of the Geological Society of Japan*, **89**, 69–86.

MIYASHITA, S. & HASHIMOTO, S. 1975. The layered basic complex of Mt. Poroshiri, Hokkaido, Japan. *Journal of Faculty of Science, Hokkaido University, Series IV*, **16**, 421–452.

MIYASHITA, S. & YOSHIDA, A. 1988. Pre-Cretaceous and Cretaceous ophiolites in Hokkaido, Japan. *Bulletin de la Société Géologique de France*, **1988**, 251–260.

MOORES, E.M. 1969. *Petrology and Structure of the Vourinos Ophiolitic Complex of Northern Greece*. Geological Society of America, Special Papers, **118**. 74 p.

MOORES, E.M. & VINE, F.J. 1971. The Troodos massif, Cyprus and other ophiolites as oceanic crust: evaluation and implications. *Philosophical Transactions of the Royal Society of London, Series A*, **268**, 443–466.

MORISHITA, T. & ARAI, S. 2001. Petrogenesis of corundum-bearing mafic rock in the Horoman Peridotite complex, Japan. *Journal of Petrology*, **42**, 1279–1299.

NICOLAS, A. 1989. *Structures of Ophiolites and Dynamics of Oceanic Lithosphere*. Kluwer, Dordrecht.

NICOLAS, A. & JACKSON, E.D. 1972. Répartition en deux provinces des péridotites des chaînes alpines longeant la Méditerranée: implications gétectoniques. *Schweizerische Mineralogische und Petrographische Mitteilungen*, **52**, 479–495.

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

OHARA, Y., KASUGA, S. & ISHII, T. 1996. Peridotites from the Parece Vela rift in the Philippine Sea: upper mantle material exposed in an extinct back-arc basin. *Proceedings of Japan Academy, Series B*, **72**, 118–123.

OHARA, Y., STERN, J.R., ISHII, T., YURIMOTO, H. & YAMAZAKI, T. 2002. Peridotites from the Mariana Trough: first look at the mantle beneath an active back-arc basin. *Contributions to Mineralogy and Petrology*, **143**, 1–18.

OZAWA, K. 1988. Ultramafic tectonite of the Miyamori ophiolite complex in the Kitakami Mountains, Northeast Japan: hydrous upper mantle in an island arc. *Contributions to Mineralogy and Petrology*, **90**, 159–175.

OZAWA, K. 1994. Melting and melt segregation in the mantle wedge above a subduction zone: evidence from the chromite-bearing peridotites of the Miyamori ophiolite complex, northeastern Japan. *Journal of Petrology*, **35**, 647–678.

PALANDZHJAN, S.A. 1986. Ophiolite belts in the Koryak upland, northeast Asia. *Tectonophysics*, **127**, 341–360.

PEARCE, J.A., LIPPARD, S.J. & ROBERTS, S. 1984. Characteristics and tectonic significance of supra-subduction zone ophiolites. *In:* KOKELAAR, B.P. & HOWELLS, M.F. (eds) *Marginal Basin Geology*. Geological Society, London, Special Publications, **16**, 79–95.

PUSHCHAROVSKY, YU.M., RUZHENTSEV, S.V. & SOKOLOV, S.D. 1988. Tectonic thrust sheets and geologic mapping. *Geotectonics*, **22**, 1–8 (original Russian paper published in 1969).

ROBINSON, P.T., MELSON, W.G., O'HEARN, T. & SCHMINCKE, H.-U. 1983. Volcanic glass compositions of the Troodos ophiolite, Cyprus. *Geology*, **11**, 400–404.

SAITO, D., ISHIWATARI, A., TSUJIMORI, T., MIYASHITA, S. & SOKOLOV, S.D. 1999. Elistratova ophiolite in Taigonos peninsula, Far East Russia: an island arc ophiolite intruding into oceanic mantle. *Memoirs of the Geological Society of Japan*, **52**, 303–316 (in Japanese with English abstract).

SAKAKIBARA, M. & OTA, T. 1994. Metamorphic evolution of the Kamuikotan high-pressure and low-temperature metamorphic rocks in central Hokkaido, Japan. *Journal of Geophysical Research*, **99**, 22221–22235.

SHCHEKA, S.A., ISHIWATARI, A. & VRZHOSEK, A.A. 2001. Geology and petrology of Cambrian Khanka ophiolite in Primorye (Far East Russia) with notes on its manganese-rich chromian spinel. *Earth Science (Chikyu Kagaku)*, **55**, 265–274.

SHIBATA, K., IGI, S. & UCHIUMI, S. 1977. K–Ar ages of hornblendes from gabbroic rocks in Southwest Japan. *Geochemical Journal*, **11**, 57–64.

SOBOLEV, A.V. & DANYUSHEVSKY, L.V. 1994. Petrology and geochemistry of boninites from the north termination of the Tonga Trench: constraints on the generation conditions of primary high Ca-boninite magmas. *Journal of Petrology*, **35**, 1183–1211.

SOKOLOV, S.D. 1992. *Accretion Tectonics in the Koryak–Chukotka Segment of the Pacific Belt*. Nauka, Moscow (in Russian).

SPADEA, P. & SCARROW, J.H. 2000. Early Devonian boninites from the Magnitogorsk arc, southern Urals (Russia): implications for early development of a collisional orogen. *In:* DILEK, Y., MOORES, E.M., ELTHON, D. & NICOLAS, A. (eds) *Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program*. Geological Society of America, Special Papers, **349**, 461–472.

STAVSKY, A.P., CHEKHOVICH, V.D., KONONOV, M.V. & ZONENSHAIN, L.P. 1990. Plate tectonic and palinspastic reconstructions of the Anadyr–Koryak region, Northeast Russia. *Tectonics*, **9**, 81–101.

STEINMANN, G. 1927. Die ophiolitischen Zonen in den Mediterranen Kettengebirgen. *In:* JACOB, C.H. (ed.) *Géologie de la Méditerranée. Proceedings of the 14th International Geological Congress, Madrid*. Graficas Reunidas, Madrid, **2**, 638–667.

SUHR, G. & EDWARDS, S.J. 2000. Contrasting mantle sequences exposed in the Lewis Hills massif: evidence for the early, arc-related history of the Bay of Islands ophiolite. *In:* DILEK, Y. ET AL. (eds) *Ophiolites and Oceanic Crust: New Insights From Field Studies and the Ocean Drilling Program*. Geological Society of America, Special Papers, **349**, 433–442.

TAIRA, A. 1985. Sedimentary evolution of Shikoku subduction zone: the Shimanto belt and Nankai trough. *In:* NASU, N. ET AL. (eds) *Formation of Active Ocean Margins*. Terra, Tokyo, 835–851.

TAKAHASHI, N. 1991. Evolutional history of the uppermost mantle of an arc system: petrology of the Horoman peridotite massif, Japan. *In:* PETERS, TJ, NICOLAS, A. & COLEMAN, R.G. (eds) *Ophiolite Genesis and Evolution of the Oceanic Lithosphere*. Kluwer, Dordrecht, 195–205.

TAMURA, A., MAKITA, M. & ARAI, S. 1999. Petrogenesis of ultramafic rocks in the Kamuikotan belt, Hokkaido, northern Japan. *Memoirs of the Geological Society of Japan*, **52**, 53–68 (in Japanese with English abstract).

TAZAWA, J. 1988. Paleozoic–Mesozoic stratigraphy and tectonics of the Kitakami Mountains, northeast Japan. *Earth Science (Chikyu Kagaku)*, **42**, 165–178 (in Japanese with English abstract).

TILMAN, S.M. & BOGDANOV, N.A. 1992. *Tectonic Map of Northeast Asia, 1:5,000,000, with Explanatory Notes*. Institute of the Lithosphere, Moscow, **000**.

TSUJIMORI, T. & ISHIWATARI, A. 2002. Granulite facies relics in the Early Paleozoic kyanite-bearing ultrabasic metacumulate in the Oeyama belt, the Inner Zone of southwestern Japan. *Gondwana Research*, **5**, 823–835.

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 mélange beneath early Paleozoic Oeyama ophiolite. *Island Arc*, **8**, 190–205.

TSUJIMORI, T., SAITO, D., ISHIWATARI, A., MIYASHITA, S. & SOKOLOV, S.D. 1999. Electron microprobe element image of zoned chromian spinel with hydrous mineral inclusions in a chromitite from Elistratova ophiolite, Far East Russia. *Science Reports of Kanazawa University*, **43**, 1–11.

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 the Geological Society of Japan*, **106**, 353–362.

UMINO, S., YANAI, S., JAMAN, A.R., NAKAMURA, Y. & IIYAMA, J.T. 1990. The transition from spreading to subduction: evidence from the Semail ophiolite, Northern Oman Mountains. *In:* MALPAS, J., MOORES, E.M., PANAYIOTOU, A. & XENOPHONTOS, C. (eds) *Ophiolites: Oceanic Crustal Analogues. Proceedings of Troodos '87 Symposium*. Geological Survey Department, Nicosia, 375–384.

VARNE, R. & BROWN, A.V. 1978. The geology and petrology of the Adamsfield ultramafic complex, Tasmania. *Contributions to Mineralogy and Petrology*, **67**, 195–207.

VYSOTSKIY, S.V. 1994. High and low pressure cumulates of Paleozoic ophiolites in Primorye, eastern Russia. *In:* ISHIWATARI, A., MALPAS, J. & ISHIZUKA, H. (eds) *Circum-Pacific Ophiolites. Proceedings of the 29th IGC, Kyoto, Vol. D.* VSP, Utrecht, 145–162.

VYSOTSKIY, S.V., GOVOROV, G.I., KEMKIN, I.V. & SAPIN, V.I. 2000. Boninitic ophiolite assemblage on eastern Sakhalin Island: geology and petrogenesis. *Geology of Pacific Ocean*, **15**, 1067–1090.

WALKER, R.J., PRICHARD, H.M., ISHIWATARI, A. & PIMENTEL, M. 2002. The osmium isotopic composition of convecting upper mantle deduced from ophiolite chromites. *Geochimica et Cosmochimica Acta*, **66**, 329–345.

YAMANE, M., BAMBA, M. & BAMBA, T. 1988. The first finding of orbicular chromite ore in Japan. *Mining Geology*, **38**, 501–508.

ZAKHAROV, YU.D., PANCHENKO, I.V. & KHANCHUK, A.I. 1992. *A Field Guide to the Late Paleozoic and Early Mesozoic Circum-Pacific Bio- and Geologic Events*. Russian Academy of Sciences, Far East Geological Institute, Vladivostok.