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Alaskan-Type Plutons and Ultramafic Lavas in Far East Russia, Northeast China, and Japan

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Abstract

Alaskan-type zoned ultramafic complexes and ultramafic lavas, sills and dikes of Jurassic age occur in the Jurassic accretionary complex (Samarka-Nadanhada zone) of Russian Primorye and adjacent northeast China (Heilongjiang Province). The Alaskan-type complexes include ilmenite-rich pyroxenite and gabbro, and are locally associated with nepheline-bearing rocks and carbonatites. These complexes were intruded into Jurassic chert-shale-sandstone sequences, to which they gave a distinct contact metamorphism. The ultramafic volcanic rocks include massive lava, pillow lava, agglomerate, and tuff. They are dominated by picrite, but also include meimechite, a TiO_2-rich ultramafic volcanic rock. The meimechite-picrite association is also known from Japan and Sakhalin, such as in the central Hokkaido-Sakhalin belt (Jurassic), Mikabu belt (Jurassic), Mino belt (Permian), and Mineoka belt (Paleogene), although Alaskan-type complexes are not known in these belts. All these ultramafic volcanic rocks in Far East Russia, northeast China, and Japan are distinctly lower in TiO_2/Al_2O_3, Nb/Y, and Nb/Zr ratios than the meimechite series in northern Siberia, but are clearly higher in these ratios than the Japanese *in-situ* island-arc picrites, and closely resemble picritic rocks in oceanic islands, especially those with HIMU signatures. Occurrence of the Jurassic ultramafic magmatism over the 2000 km wide area of the East Asian margin, the vast development of Jurassic accretionary complexes in the same area, and the very short time interval between ultramafic magmatism and accretion suggest superplume activity in or near the subduction zone. The Permian, Jurassic, and Paleogene "oceanic meimechites" among Japanese accretionary complexes suggests repeated superplume events through the Phanerozoic.

Introduction

ALTHOUGH OPHIOLITES ARE major mafic-ultramafic complexes in orogenic belts (Coleman, 1977; Nicolas, 1989), other types of orogenic mafic-ultramafic complexes have been studied for a long time. They are Alaskan-type plutonic rocks and picritic volcanic rocks. Ophiolite studies have contributed much to the understanding of magmatism and tectonism in plate tectonics, but studies of Alaskan-type ultramafic complexes and related picritic volcanic rocks may contribute to understanding of global plume tectonics. Alaskan-type plutonic rocks have generally been regarded as products of post-accretion, island-arc (or active continental margin) magmatism, but picritic volcanic rocks have been considered to be various fragments of accreted ocean-floor edifices (seamounts, oceanic plateaus, oceanic ridges, and oceanic island arcs).

An Alaskan-type ultramafic complex is a zoned pluton of one to several kilometers in diameter, typically consisting of a dunite core and surrounded by wehrlite, clinopyroxenite, hornblendite, and gabbro zones concentrically arranged outward. The pluton is intrusive into the adjacent volcanic and sedimentary rocks, where contact metamorphism is generally evident. In this respect, they are distinct from ophiolites, which are stratified slices of more than 10 km in size, tectonically emplaced in the solid state, and in fault contact with the country rocks. Classic examples of Alaskan-type plutons are present in Alaska and along the Ural Mountains (Taylor, 1967), but new occurrences have been reported from British Columbia (Findlay, 1969; Nixon et al., 1990), the Klamath Mountains (Snoke et al., 1981; 1982), Sierra Nevada (James, 1971), Venezuela (Murray, 1972), Colombia (Tistl, 1994; Tistl et al., 1994), New Zealand (Grapes, 1975), Tasmania (Brown et al., 1988) , Kalimantan (Zientek et al., 1992), Yunnan (southern China; Zhang et al., 1992), the Qilian Mountains (northwestern China;

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Zhou et al., 1997), Heilongjiang (northeast China; Zhang et al., 1995), Kamchatka (Kepezhinskas et al., 1993; Tanaka et al., 1994; Batanova and Astrakhantsev, 1994), and Egypt (Helmy and El Mahallawi, 2003), although the three "possible" Japanese examples cited by Murray (1972) have since been shown to be an ophiolite (Miyamori and Hayachine; Ozawa, 1994) and a lherzolitic mantle diapir (Horoman; Takahashi, 1991).

In this paper, we report new occurrences of non-ophiolitic, Alaskan-type ultramafic plutons in Russian Primorye and northeastern China, and document ultramafic lavas, sills, dikes, and pipes of meimechite-picrite series rocks closely associated with the plutons. We also describe meimechite-picrite series rocks in Phanerozoic accretionary complexes and Cenozoic island-arc volcanic rocks in Japan and Sakhalin, where Alaskan-type ultramafic plutons are absent. On the basis of new insights from these examples, we discuss the origin of Alaskan-type plutons and ultramafic volcanic rocks along the margins of East Asia.

Meimechite (also spelled meymechite or maimechite) is the name given to highly olivine-phyric volcanic or hypabbysal rock found in the Maimecha River area of northern Siberia in 1943 by V. K. Kotul'skiy (Levisson-Lessing and Strouve, 1963). The recent IUGS classification defines meimechite as ultramafic volcanic rock with SiO_2 < 52%, MgO > 18% (if less, but >12%, then it is picrite), TiO_2>1% (if less, then komatiite), and $Na_2O + K_2O$ < 2% (if more, then picrite, basanite, foidite, etc.), disregarding texture (Le Bas, 2000). In Russia, picrite (Al_2O_3 = 5–10%) and meimechite (Al_2O_3 < 5%) are thought of as volcanic counterparts of clinopyroxenite and wehrlite, respectively. In this paper, a very magnesian, alkali-poor, and Ti (and other HFSE)-rich volcanic rock is called meimechite, following the IUGS classification. A unique, diverse, continental magmatism took place in the Maimecha River area, where extremely variable alkalic, tholeiitic, and ultramafic rocks, including meimechite, kimberlite, and carbonatite, occur as thick volcanic sequences, innumerable dikes and pipes, and a number of zoned plutonic complexes of Early Triassic age (~250 Ma). Recent English-language accounts concerning meimechite and related rocks include Egorov (1970), Arndt et al. (1995), and Vasiliev and Zolotukhin (1995).

Geologic Outline

Jurassic accretionary complexes are widely developed in Japan (Tamba, Mino, Ashio, Chichibu, north Kitakami, and south Hokkaido zones), Russian Primorye (Samarka zone), and northeastern China (Nadanhada zone) (Fig. 1). They may have constituted a single continuous belt before the Miocene opening of the Japan Sea (Kojima, 1989). The S-shaped winding of the belt in northern Primorye may be due to Cretaceous left-lateral transcurrent movement along the central Sikhote Alin fault (Khanchuk, 2001). The distribution of Paleozoic ophiolites and blueschists also extends from Japan to Russian Primorye (Vysotskiy, 1994; Shcheka et al., 2001; Ishiwatari and Tsujimori, 2003). The Jurassic Horokanai ophiolite, Jurassic Sorachi greenstone with abundant picritic rocks, and Cretaceous Kamuikotan blueschist in Hokkaido continue to Sakhalin, where they are named, for example, the Shelting ophiolite, Aniva greenstone, and Susunai blueschist (Tatsumi et al., 1998; Ishiwatari et al., 2003). In southwestern Japan, the accretionary complexes and ophiolites range from Paleozoic to Cenozoic in age, and generally become younger southward (or toward the Pacific Ocean), as in the other circum-Pacific belts (Ishiwatari, 1994). The youngest Paleogene ophiolites are present in the Mineoka-Setogawa belt near Tokyo, and Jurassic ophiolites are distributed in the Mikabu belt about 50 km farther north (Fig. 1). These two ophiolites are different from the northern Paleozoic ophiolite nappes (Oeyama and Yakuno) in their mélange-type occurrences and abundance of picritic rocks. The Mikabu ophiolite is devoid of mantle peridotite. It is possible that the Mineoka and Mikabu ophiolite mélanges include non-ophiolitic ultramafic rocks.

Alaskan-Type Complexes in Primorye, Russia

Alaskan-type plutons and their associated ultramafic dikes and pipes (diatremes) are distributed in the area of Jurassic accretionary complexes over a length of 1,000 km in Russia (Fig. 1). Two examples are described below after Shcheka (2002).

The southwestern Ariadnoe gabbro-pyroxenite massif shows a NE-SW elongated oval shape, which is more than 10 km long and 3 km wide on the map (Fig. 2). The lithological sequence includes kaersutite dunite, wehrlite, clinopyroxenite, and ilmenite gabbro. This pluton concordantly intruded

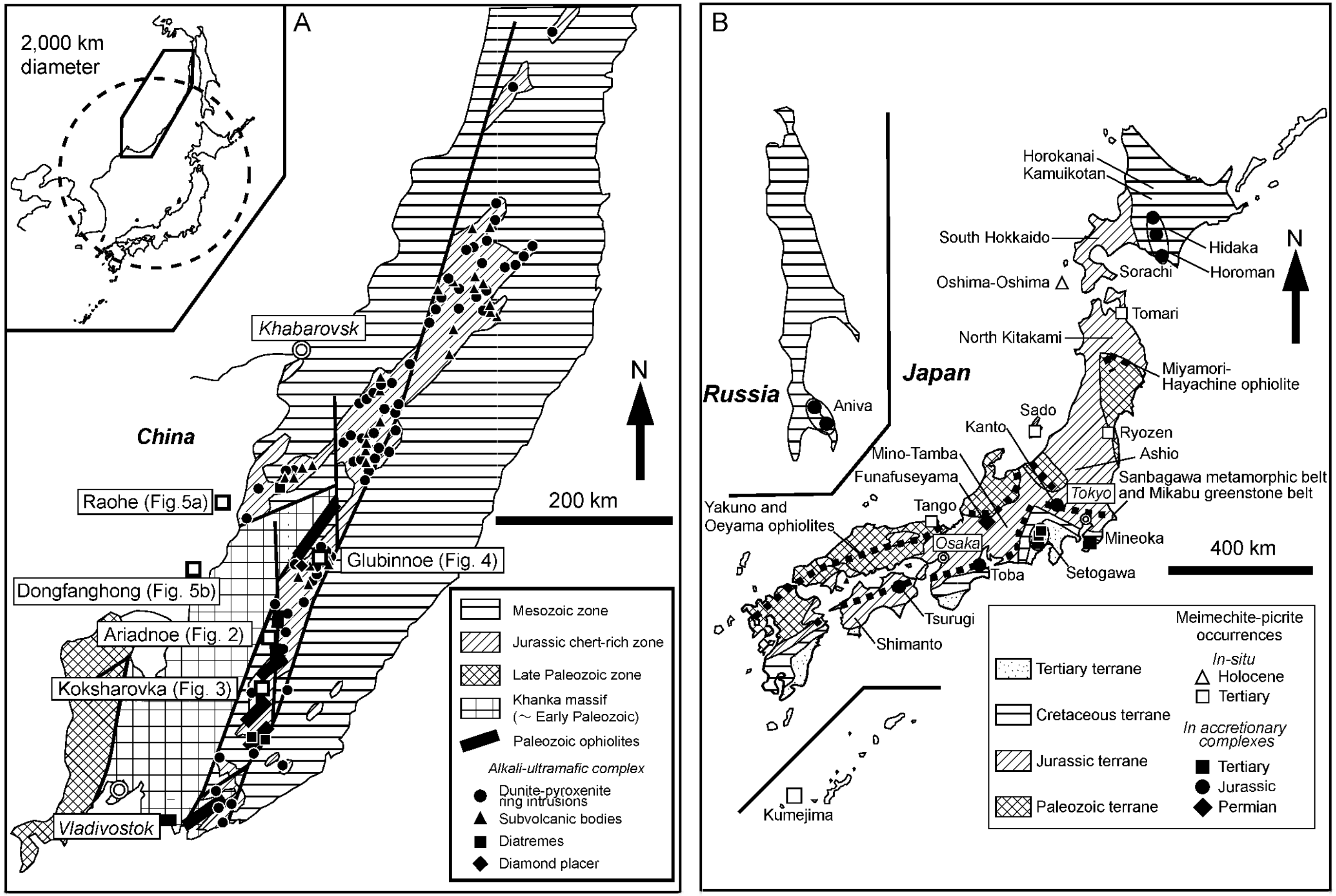

FIG. 1. Distribution of the Jurassic accretionary complexes in Russian Far East, northeast China, and Japan. Occurrence of ultramafic volcanic rocks (picrite and meimechite) and Alaskan-type zoned ultramafic plutons are shown by symbols. A. A. Vrzhosek compiled the occurrences in Primorye (Shcheka et al., 2003).

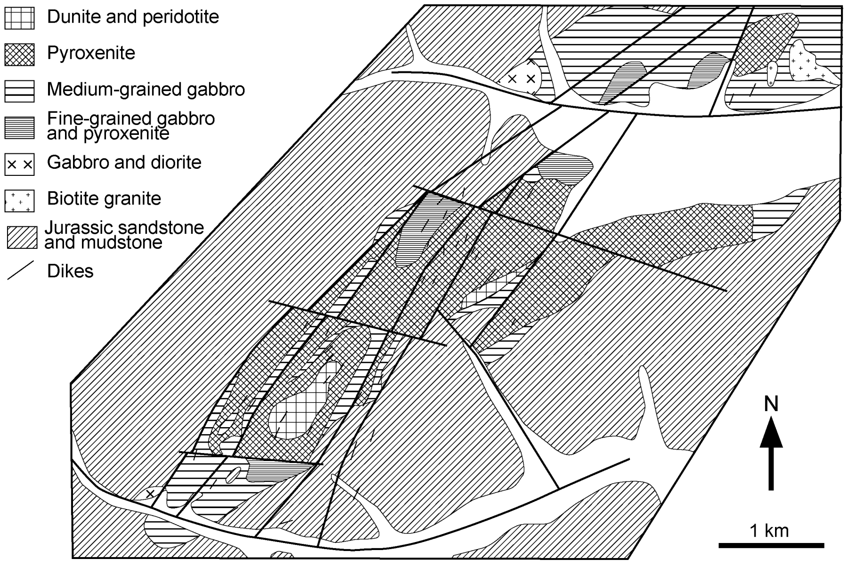

FIG. 2. Geologic map of the southwestern Ariadnoe zoned ultramafic pluton, Russian Primorye after Shcheka (2002). See Figure 1 for locality.

SE-dipping greywacke sandstone and shale, which were converted into biotite-quartz hornfels near the contact. K-Ar dating of pyroxenite indicates 155 Ma for biotite and 159 Ma for kaersutite. Ilmenite and pseudobrookite derived from the gabbro and pyroxenite form placer deposits, which are currently being exploited.

Picrite and lamprophyre dikes and pipes are abundant in the Ariadnoe area. They intruded a sandstone, shale, and chert sequence of the Jurassic accretionary complex (Samarka zone). K-Ar data of coexisting kaersutite and Ti-biotite from the picrite pipe (Table 1, no. 4) and the Alaskan-type intrusion near Ariadnoe show a short time interval between 152 and 159 Ma. Some ultramafic pipes may be the source of a diamond placer near Glubinnoe.

The northeastern Koksharovka massif is a steeply inclined, plate-shaped clinopyroxenite body of about 10 × 5 km size elongated in a NE-SW direction (Fig. 3). The complex intruded Jurassic volcanic rocks, chert, sandstone, and mudstone, metamorphosed to biotite hornfels along the contact. The biotite and kaersutite K-Ar ages of the plutonic rocks range from 145 to 160 Ma. Coarse-grained kaersutite-biotite pyroxenite occurs in the central part of the pluton, and fine-grained clinopyroxenite occupies the margin. The complex includes a 2 km-sized carbonatite body along the southern margin and many other minor bodies of Ti-augite clinopyroxenite, nepheline pyroxenite, perovskite pyroxenite, nepheline syenite, hastingsite-nepheline-syenite, orthoclase syenite, orthoclase-rich granite, and carbonatite throughout the complex. The kaersutite-biotite pyroxenite is locally very rich in Ti-magnetite and apatite. A weathering crust up to 40 m thick developed over the massif, forming a vermiculite deposit. As platinum-group minerals and chromite are found in the river sand, the massif may also contain some dunite. Numerous dikes of syenite and carbonatite intersect the pluton.

Meimechite-Picrite Volcanic Complex in Primorye, Russia

Alaskan-type plutons and subvolcanic ultramafic bodies are closely associated with mafic-ultramafic volcanic rocks such as massive lava, variolitic (pillow) lava, autobrecciated lava, volcanic breccia (agglomerate) and tuff, which form an 800- to 1300 m-thick sequence intercalated with chert, siltstone, siliceous mudstone, sandstone, and limestone along the 1,000 km-long Jurassic accretionary complex of Primorye (Fig. 1). A representative occurrence is documented below after Shcheka et al. (2003).

The Glubinnoe area (Fig. 4) is mainly underlain by Jurassic accretionary complex of the Samarka

TABLE 1. Geochemical Composition of Representative Meimechites and Picrites from the Russian Far East, Northeast China, and Japan

Country	Far East Russia					NE China	Japan (accreted oceanic picrites)				Japan (in-situ island arc picrites)			
Area	Primorye				Sakhalin	Heilong./ Raohe	Mino/ Funafuse	Mikabu/ Tsurugi	Mikabu/ Kanto	Mineoka	Ryukyu/ Kumejima	SW Jpn./ Tango	NE Jpn./ Ryozen	Oshima-Oshima
Age	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Jurassic	Permian	Jurassic	Jurassic	Paleogene	Pliocene	Miocene	Miocene	Holocene
No. (av.*)	1 (17)	2	3	4	5	6 (25)	7	8	9	10	11	12	13	14
SiO_2	43.05	46.80	42.57	40.91	41.07	48.10	42.56	42.27	45.65	44.91	50.06	51.12	49.02	47.99
TiO_2	1.26	1.38	2.06	4.39	3.06	2.18	3.48	2.27	1.37	1.18	0.67	0.72	0.54	0.79
Al_2O_3	5.45	5.63	8.73	9.19	9.62	9.48	10.06	11.74	7.25	5.58	11.68	14.22	14.30	13.33
FeO*	13.13	13.96	15.98	14.55	11.92	12.64	13.41	13.27	12.24	12.02	8.55	8.81	9.71	9.41
MnO	0.26	0.19	0.23	0.23	0.24	0.17	0.22	0.21	0.17	0.16	0.15	0.15	0.17	0.08
MgO	31.30	28.62	19.11	13.72	17.48	18.54	18.93	15.46	24.76	30.61	16.68	12.36	14.12	15.21
CaO	4.91	2.68	10.12	11.68	15.84	7.26	10.19	14.06	7.42	5.27	9.92	10.25	9.99	9.75
Na_2O	0.34	0.44	1.09	1.34	0.55	1.10	0.19	0.45	0.87	0.12	1.78	1.79	1.73	2.05
K_2O	0.20	0.16	0.11	2.55	0.22	0.23	0.13	0.09	0.17	0.03	0.42	0.44	0.35	1.08
P_2O_5	0.10	0.15		1.44		0.30	0.83	0.18	0.10	0.12	0.09	0.14	0.07	0.31
Total	100.00	100.01	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
TiO_2/Al_2O_3	0.23	0.25	0.24	0.48	0.32	0.23	0.35	0.19	0.19	0.21	0.06	0.05	0.04	0.06
FeO*/MgO	0.42	0.49	0.84	1.06	0.68	0.68	0.71	0.86	0.49	0.39	0.51	0.71	0.69	0.62
(ppm)														
Cr	2000	2314		619			532	1367	1603	2133	1340	1135		
Ni	1300	1429		318			556	633	1254	1593	396	323		
Y		16		60			28	15.9	14.9	13	16.5	13		
Zr	60	81		492			280	103	60.4	75	55.5	68		
Nb		13		144			64	12.2	2.2	8	1.5	1		

[1]Number of analyses averaged is indicated in parentheses after the sample number; one analysis if not indicated.

Sources: For samples 1–5 = Shcheka et al., 2003 and this study (1= Jurassic zone average, 2 and 3 = Glubinnoe, 4 = Ariadnoe, 5 = southern Sakhalin), 6 = Zhang et al., 1995; 7 = Jones et al., 1993, 8 = Ozawa et al., 1999, 9 = Ozawa et al., 1997; 10 = this study (see also Tazaki, 1975; 1976); 11 = Ito and Shiraki, 1999; 12 = Ishiwatari and Imasaka 2002, 13: Shuto et al., 1985, 14: Yamamoto (1984). Oxide weight percentages are recalculated to 100% on an anhydrous basis. FeO* = total iron as FeO. See López and Ishiwatari (2002) for the analytical method for analyses 2, 4, and 10. Analyses 1, 3, and 5 were performed at the Far East Geological Institute, Vladivostok, Russia.

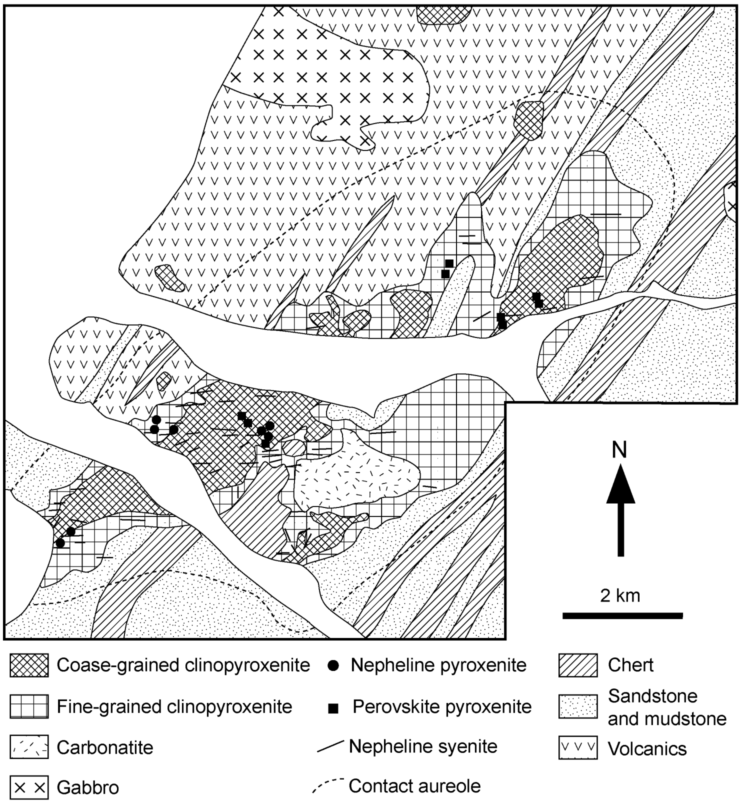

FIG. 3. Geologic map of the Koksharovka zoned ultramafic pluton, Russian Primorye after Shcheka (2002). See Figure 1 for locality.

zone consisting of chert, mudstone, sandstone and volcanic rocks. Meimechite-picrite (and kaersutite dolerite) lavas showing porphyritic texture are sandwiched between the chert-mudstone and siliceous shale sequences of Jurassic age, in association with sills of wehrlite, dunite (mostly serpentinized), and pyroxenite showing less porphyritic, more equigranular texture. The meimechite (Table 1, no. 2) and picrite (Table 1, no. 3) contain abundant, large (<10 mm) olivine and clinopyroxene phenocrysts, and the groundmass is composed of Ti-augite, kaersutite, phlogopite, and Fe-Ti ore. In some areas of northern Primorye, meimechite occurs as pillow lava.

Ultramafic Volcanic Rocks and Alaskan-Type Plutons in Northeastern China

The Raohe area described by Zhang et al. (1995) is situated at about 47°N along the Ussuri River, which marks the Chinese-Russian border, and is 50 km long in a N-S direction and 5–8 km wide (Fig. 5). The area is underlain mainly by mafic-ultramafic rocks, tectonically emplaced into shale and sandstone of a Jurassic subduction complex. The mafic-ultramafic rocks include pillow lavas of basalt and picrite associated with radiolarian-bearing chert and shale, as well as gabbros and ultramafic cumulate rocks such as dunite, wehrlite, and clinopyroxenite. Minor lherzolite, websterite, and norite also occur in some places. Forsterite content of olivine ranges from 77 to 67. The volcanic rocks are in fault contact with the plutonic rocks. The plutonic and volcanic rocks are high in TiO_2 and P_2O_5, and basaltic and gabbroic rocks show strongly LREE-enriched REE patterns. Zhang et al. (1995) concluded that these mafic-ultramafic rocks did not originate in a mid-ocean ridge or supra-subduction zone (i.e. not an ophiolite as previously postulated) but formed as a seamount.

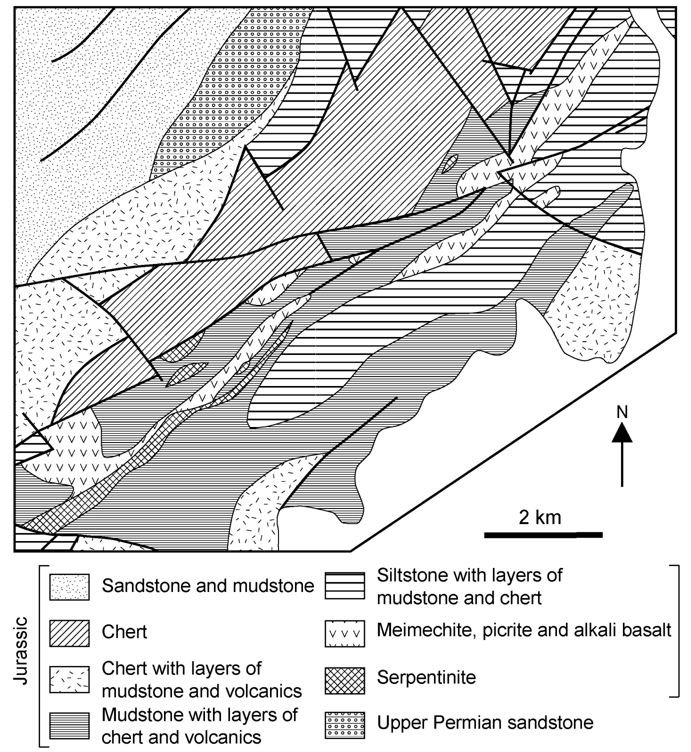

FIG. 4. Geologic map of the Glubinnoe area, Russian Primorye, after Shcheka et al. (2003). Meimechite and picrite lavas occur in the Jurassic chert-mudstone sequence. See Figure 1 for locality.

In the Dongfanghong area about 100 km south of Raohe, several Alaskan-type plutons intrude greenschist-facies metamorphic rocks. Dunite, wehrlite, olivine clinopyroxenite, clinopyroxenite, and gabbro are arranged sequentially from the center to the margin of each ultramafic body, forming zoned plutons. Hornblende gabbro, olivine gabbro, anorthosite, and diorite are associated with the gabbro. Mg/(Fe+Mg) of the dunite and wehrlite averages 0.83, and anorthite content of plagioclase in the gabbroic rocks ranges from 56 to 90.

Ultramafic Volcanic Rocks in Accretionary Complexes in Japan and Sakhalin

Japanese accretionary complexes developed in subduction zones from Paleozoic time to the present, and voluminous mafic-ultramafic rocks that originated in various oceanic environments have been accreted among these complexes. The majority of them are ophiolites as reviewed by Ishiwatari (1991), but some non-ophiolitic rocks are present as follows.

A voluminous Late Jurassic greenstone complex named the Sorachi Group in the Kamuikotan zone, central Hokkaido, bears picritic rocks in the Biei area (Maekawa, 1986), the Mt. Ashibetsudake area (Niida and Kito, 1999), and Shizunai area (Sakakibara et al., 1999). The Ashibetsudake picrite contains more than 60% olivine phenocrysts up to 6.5 mm in size, and the groundmass consists of olivine, augite, and glass. The Fo content of olivine ranges from 90 to 94, and spinel is Cr#57–64 (100Cr/(Al+Cr)) with 0.3–0.4% TiO_2 (Niida and Kito, 1999). Tatsumi et al. (1998) demonstrated that the greenstones of the Aniva zone in southern Sakhalin, a northern continuation of the Sorachi Group, show unusual chemistry, with Nb/Y and Nb/Zr ratios as high as those of the superplume-related, Polynesian lavas (see Table 1, no. 4 for major-element data). Sakakibara et al. (1999) demonstrated that some Ti-rich greenstones (alkali basalts) of the Sorachi

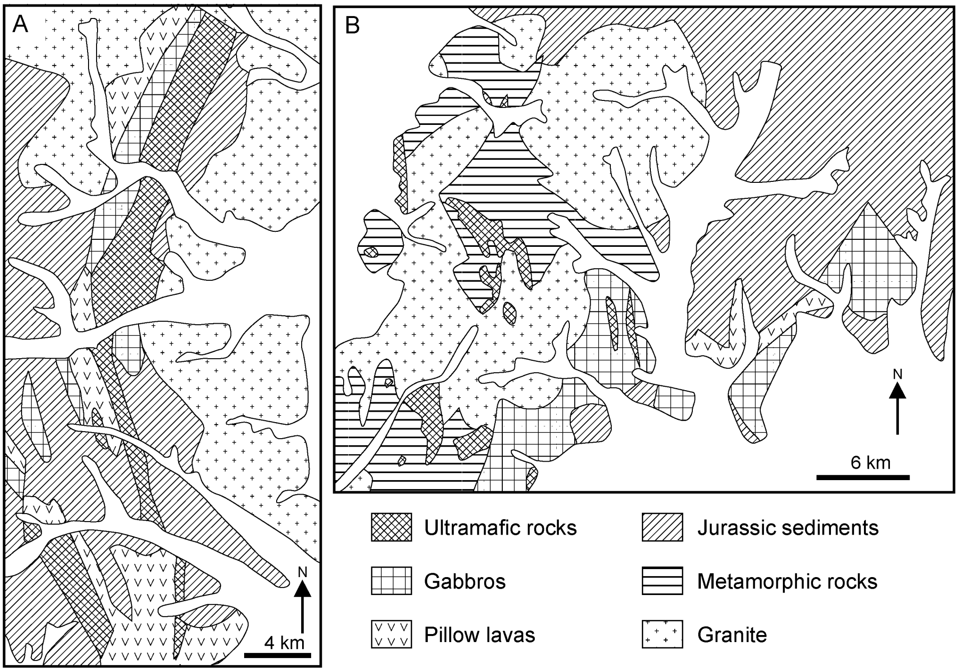

FIG. 5. Geologic maps of the Raohe (A) and Dongfanghong (B) areas, Heilongjiang Province, northeast China, after Zhang et al. (1995). Ultramafic-mafic rocks form Alaskan-type complexes, and pillow lava includes picrite and meimechite. See Figure 1 for locality.

Group in the Biei and Pippu areas also have high Nb/Y and Nb/Zr ratios characteristic of the Polynesian HIMU basalt.[2]

The Funafuseyama complex of the Mino zone, central Japan, consists of a large greenstone body overlain by limestone, dolomite, and chert beds of Permian age (Jones et al., 1993). The greenstones include Lower Permian tholeiites of E-MORB affinity and Middle Permian alkali basalts of OIB affinity, and may have originated in a spreading-axis-centered plateau with off-axis, plume-type volcanism (Jones et al., 1993). Ichiyama and Ishiwatari (2002, 2003) have found some meimechite sills and hyaloclastites intercalated in the red chert of the Funafuseyama complex. The meimechite chemistry presented by Jones et al. (1993) as "picrite?" (FU10) without petrography, is characterized by low SiO_2 (39%), high MgO (18%), and high TiO_2 (3.2%) and P_2O_5 (0.77%), and low alkalis (Na_2O = 0.18%, K_2O = 0.12%) (Table 1, no. 7). This chemistry completely satisfies the meimechite definition of Le Bas (2000). Ichiyama and Ishiwatari (2002) confirmed this chemistry (MgO reaches 20%), and described the petrography. It contains phenocrysts of olivine (35%, av. <1 mm and max. 3.5 mm size), Ti-augite (<20%), kaersutite (<10%) and minor Fe-Ti ores, and the groundmass consists of kaersutite, phlogopite, apatite, Fe-Ti oxides, titanite, and secondary chlorite with or without minor plagioclase. The trace-element pattern of this rock resembles that of HIMU picrite of St. Helena (Chaffey et al., 1989) and Siberian meimechites (Arndt et al., 1995), but is different from Kilauean picrite (Norman and Garcia, 1999) in its higher concentration of HFSE and the presence of a negative K anomaly.

[2]HIMU basalt is a variety of oceanic-island basalt (OIB) characterized by a high μ ratio ($^{238}U/^{204}Pb$), very high lead-isotope ratios (typically $^{206}Pb/^{204}Pb > 20.5$), and mid-ocean ridge basalt (MORB)–like strontium and neodymium isotope ratios. They are also higher in Ti/Al, Nb/Y, and Nb/Zr ratios than the normal OIB. The present HIMU basalt erupts only in the southern Atlantic (e.g., St. Helena) and southern Pacific (e.g., Polynesia) areas, where large-scale mantle plumes are inferred by seismic tomography, and a deep mantle origin is implied for the HIMU mantle source. See Kogiso et al. (1997) for references.

The Mikabu greenstone belt in southwestern Japan has been regarded as tectonic fragments of oceanic crust (ophiolite) since Iwasaki (1971) and Ernst (1972), but the lithology and geochemistry of the greenstones do not coincide with those of typical ophiolites. Ozawa et al. (1999) reported TiO_2- and Nb-rich, HIMU-type basalt and non-spinifex komatiite lavas from the Mikabu zone in Shikoku (Tsurugi area, see Table 1, no. 8), and picritic lavas are also reported from the Mikabu zone in the Kii Peninsula (Nakamura, 1971). Uesugi and Arai (1999) concluded that the Shiokawa dunite-troctolite-gabbro complex in central Honshu originated as within-plate tholeiitic magma on the basis of TiO_2-rich spinel chemistry. The Kurouchi-yama wehrlitic complex in the Kanto Mountains, central Honshu, bears TiO_2-rich phlogopite and pargasite (Tazaki and Inomata, 1974), and is cut by a picrite dike (Table 1, no. 9), which gives an amphibole K-Ar age of 199 Ma (Early Jurassic) (Ozawa et al., 1997).

Meimechite and picrite lavas also occur in the Paleogene accretionary complexes of the Mineoka and Setogawa zones (Sameshima, 1960; Tazaki, 1975, 1976; Takasawa, 1976; Tazaki and Inomata, 1980; Ishida et al. 1988, 1990). Meimechite occurs as pillow lava and massive lava blocks in the Paleogene Mineoka Group and Miocene Sakuma Group in the Boso Peninsula southeast of Tokyo. Abundant olivine phenocrysts (50–60%, 2–8 mm size) occur in a groundmass of olivine, Ti-augite, phlogopite, plagioclase, and glass. The bulk-rock composition includes 38% SiO_2, 28% MgO, 1.1% TiO_2, 0.7% Na_2O, and 0.4% K_2O (Tazaki, 1975) (see Table 1, no. 10 for our analysis), and completely fulfills the IUGS meimechite definition. Olivine Fo ranges from 86 to 90, and spinel Cr# ranges from 55 to 70.

Cenozoic, *in-situ* Ultramafic Lavas in the Japanese Island Arcs

Cenozoic high-Mg (picritic) basalts occur as *in-situ*, non-accretionary volcanic rocks in the Japanese Islands. Kumejima Island near the backarc basin (Okinawa trough) of the Ryukyu arc also contains the Uegusukudake picrite (Ito and Shiraki, 1999). This picrite is only 2.8 Ma old (Late Pliocene), and it erupted prior to the opening of the Okinawa trough (Sibuet et al., 1987). It contains up to 25% olivine (1–5 mm size), minor clinopyroxene and plagioclase, and includes 50% SiO_2, 17% MgO, 1.8% Na_2O, 0.4% K_2O, and 0.7% TiO_2 (Table 1, no. 11). Olivine Fo ranges from 75 to 92, and spinel Cr# varies from 60 to 80. The Miocene backarc areas also bear picrites such as on Sado Island (a vesicle-rich layered sill showing gravitational olivine accumulation; Toramaru et al., 1996) and on Tango Peninsula (Ishiwatari and Imasaka, 2002). The Tango picrite (18–21 Ma) contains fine-grained, euhedral phenocrysts (0.5–1.0 mm size) of olivine (22%), clinopyroxene (14%), and plagioclase (3%), and includes 50% SiO_2, 12% MgO, 1.8% Na_2O, 0.5% K_2O, and 0.7% TiO_2 (Table 1, no. 12). Olivine Fo ranges from 81 to 90, and spinel Cr# does from 64 to 79. This picrite erupted prior to the opening of the Japan Sea (about 15 Ma; Tatsumi et al., 1989).

The high-Mg 13–15 Ma basaltic lavas in the Tomari (Takimoto, 1986; Takimoto and Shuto, 1994) and Ryozen (Shuto et al., 1985) areas in northeastern Japan erupted along the Miocene volcanic front. The Tomari high-Mg basalt contains 10% olivine, 7% clinopyroxene, and 2% plagioclase phenocrysts, and includes 51% SiO_2, 12% MgO, 1.8% Na_2O, 0.4% K_2O, and 0.5% TiO_2. Olivine Fo is 85–89, and spinel Cr# is 68–76. Ryozen high-Mg basalt contains 13% olivine phenocrysts, and includes 49% SiO_2, 14% MgO, 1.7% Na_2O, 0.4% K_2O, and 0.5% TiO_2 (Table 1, no. 13). Olivine Fo varies widely (70–89), and spinel Cr# ranges from 59 to 69. Picrite lava of the Oshima-Oshima volcano in the backarc area off southwestern Hokkaido erupted in Holocene time (Yamamoto, 1984; Ninomiya and Arai, 1993) (Table 1, no. 14 for analysis). These data indicate that *in-situ* ultramafic magmatism took place in the Japanese Islands, both along the volcanic front and in backarc areas.

Geochemical Characteristics of the Accreted Picrites

Major-element chemistry of picrite is affected by the accumulation and fractionation of dominant phenocryst minerals such as olivine and, to a lesser degree, clinopyroxene. Inasmuch as Ti and Al atoms do not enter olivine, the TiO_2/Al_2O_3 ratio is free from olivine control, and is a good parameter to characterize a group of genetically related picritic rocks, as shown by the constancy of this ratio over a wide range of FeO*/MgO variation among Polynesian and Hawaiian picrites (Fig. 6A). The TiO_2/Al_2O_3 ratio is very high (0.6–1.1) in the continental meimechite-picrite suite in central Siberia, somewhat high in the Polynesian and Atlantic (including

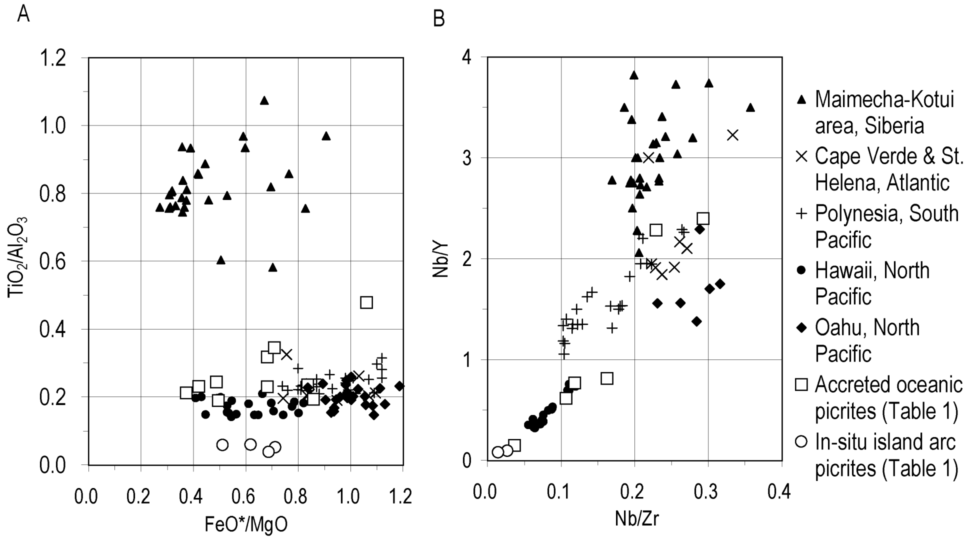

FIG. 6. Geochemical characteristics of the accreted oceanic picrites in the Russian Far East, northeast China, and Japan in comparison with continental, oceanic, and island-arc picrites. A. TiO_2/Al_2O_3 – FeO*/MgO diagram. B. Nb/Y – Nb/Zr diagram. See Table 1 for data of accreted oceanic picrites and island-arc picrites. Other data sources are: (Siberia) Arndt et al. (1995), (Cape Verde) Davies et al. (1989), (St. Helena), Chaffey et al. (1989), (Polynesia) Kogiso et al. (1997), (Hawaii) Norman and Garcia (1999), and (Oahu) Clague and Frey (1982).

HIMU) picrites (0.2–0.3), moderate in Hawaiian picrites (0.1–0.2), and very low (<0.1) in island-arc picrites. Meimechites and picrites in the accretionary complexes of the Russian Far East region, northeast China, and Japan commonly exhibit somewhat high TiO_2/Al_2O_3 ratios (0.2–0.5), which correspond to that of Polynesian-type ocean-island picrites, and are distinctly different from Siberian meimechites. Tatsumi et al. (1998) showed that Polynesian-type ocean-island basalts have higher Nb/Y ratios than Hawaiian-type analogues, and Polynesian HIMU basalts are higher both in Nb/Y and Nb/Zr. This relationship is clearly reproduced among picritic rocks (Fig. 6B), where Siberian meimechites are the highest, oceanic-island picrites are intermediate, and Japanese *in-situ* island-arc picrites are the lowest both in Nb/Y and Nb/Zr ratios (Fig. 6B). The Permian, Jurassic, and Tertiary picrites and meimechites in the accretionary complexes of the Russian Far East, North China, and Japan are correlative with oceanic-island picrites in terms of the TiO_2/Al_2O_3, Nb/Y, and Nb/Zr ratios. Moreover, some of them resemble HIMU picrites in the South Pacific (Polynesia) and in the Atlantic (St. Helena, Cape Verde, etc.).

Discussion

Early studies on Alaskan-type plutons postulated their origin by successive intrusion of ultramafic magmas (Taylor, 1967), whereas later studies proposed formation by accumulation and flow differentiation of early crystallized minerals from calc-alkaline basaltic-andesitic magmas in the conduit of island-arc volcanoes (Murray, 1972). The latter idea may explain the origin of orthopyroxene-bearing Alaskan-type ultramafic complexes associated with a large amount of dioritic (or granitic) rocks of calc-alkaline nature (e.g., James, 1971; Snoke et al. 1981). Orthopyroxene-rich Alaskan-type complexes in Tasmania (Brown et al., 1988) and Egypt (Helmy and El Mahallawi, 2003) may also be related to island-arc magmas. However, typical Alaskan-type ultramafic complexes are extremely rich in TiO_2 and are silica-undersaturated (Taylor, 1967; Grapes, 1975), suggesting an affinity with TiO_2-rich, plume-related, within-plate magmas. Grapes (1975) correlated the Blue Mountain Complex to plutonic complexes exposed on some oceanic islands such as the Canaries, Reunion, and Tahiti, although this body intruded greywacke. The Blue Mountain complex and the nearby Tapuaenuku Complex are in fact associated with lamprophyre-alkali dolerite dike swarms. In this respect, the TiO_2-rich, orthopyroxene-free, ultramafic zoned plutons in Russian Primorye and northeast China belong to the classic Alaskan type.

On the other hand, recent studies of volcanic rocks in the circum-Pacific accretionary complexes report ultramafic volcanic rocks such as picrite and meimechite, as well as the rare Mesozoic komatiite in Gorgona Island, Colombia (Gansser et al., 1979; Echeverria, 1980), which is interpreted to be an accreted fragment of an ocean plateau (Révillon et al., 2000). Moreover, Tistl et al. (1994) stressed a comagmatic relationship between the Miocene Alaskan-type Condoto pluton and adjacent magnesian basaltic lavas (MgO = 11.4 wt% on average and 17 wt% maximum) in Colombia. It is possible that some Alaskan-type plutons may have formed from a more magnesian magma than ordinary island-arc basalt or andesite.

The ultramafic volcanic rocks associated with radiolarian chert, reef limestone, and voluminous TiO_2-rich tholeiitic greenstones may result from plume magmatism at oceanic seamounts, which later accreted to subduction zones. However, Alaskan-type complexes are intrusive into surrounding sedimentary rocks (Taylor, 1967) or into ophiolite (Snoke et al., 1981), forming distinct contact metamorphic effects, hence their intrusion should be post-accretion. Thus, accreted seamount ultramafic lavas and Alaskan-type complexes originated in completely different tectonic settings that are within-plate seamounts and supra-subduction zones, respectively, and no genetic linkage might be expected between them. However, close spatial association of the Alaskan-type plutons and ultramafic lavas (as well as dikes and sills) is apparent in Primorye, and common geochemical features including high TiO_2 suggest a genetic kinship.

How can this controversy be reconciled? Recent geological studies in Japan revealed the presence of near-trench, MORB-type magmatism in subduction zones, possibly related to the subduction of an oceanic ridge. Cretaceous greenstones in the Shimanto and Hidaka belts include N-MORB, which erupted on or intruded into newly accreted, soft sediments (and hence are called in-situ greenstones). They may represent MORB magmatism in the accretionary wedge (Miyake, 1985) caused by subduction of an oceanic ridge, which swept beneath Japan in Cretaceous time from southwest to northeast (Kiminami et al., 1992; Miyashita et al., 1997). This means that oceanic magmatism (either mid-ocean ridge type or oceanic-island type) can take place in subduction zones.

Although Tatsumi et al. (1998) correlated the magmatic event of the Aniva-Sorachi "plateau" to the mid-Cretaceous superchron (the long period without geomagnetic reversals), the age of the magmatism in this zone is uniformly Late Jurassic (Sakakibara et al., 1999). Late Jurassic (around 150 Ma) HIMU magmatism in Hokkaido and Sakhalin is coeval with Alaskan-type plutons and meimechitic volcanism in Primorye and Northeast China. Wide distribution of the Late Jurassic ultramafic volcano-plutonic rocks over 2,000 km suggests that large-scale plume magmatism, similar to that produced in the Early Triassic (around 250 Ma) by mafic-ultramafic volcano-plutonic rocks of the Maimecha-Kotui area of central Siberia, took place in the Jurassic active convergent margins of East Asia and the adjacent ocean floor.

Occurrence of HIMU picrites (meimechites) of Permian and Jurassic ages in Russian-Chinese-Japanese accretionary complexes, as well as the present HIMU magmatism in the Southern Hemisphere, indicates that HIMU (superplume) magmatism has not been restricted to the mid-Cretaceous superchron period, but has happened many times in earth history. Jurassic Alaskan-type complexes and the associated meimechite-picrite association in Primorye and northeast China also indicate that HIMU magmatism occurred not only in the within-plate (mid-oceanic or continental) environment but also in the supra-subduction zone environment. It is interesting that some Alaskan-type complexes were intruded into ophiolites possibly of supra-subduction zone origin (Snoke et al., 1981; Fershtater et al., 1997). Although most Alaskan-type complexes in Alaska are of Cretaceous age, an Early Paleozoic complex with silica-undersaturated chemistry is also known (Loney and Himmelberg, 1992). The Alaskan-type complexes of Paleozoic, Mesozoic, and Tertiary ages in circum-Pacific orogenic belts suggest that supra-subduction zone plume magmatism has been pervasive along Mesozoic–Cenozoic active continental margins.

The Japanese Cenozoic *in-situ* picrites clearly show island-arc geochemical signatures, such as depletion in Ti, Nb, and other HFSE (e.g., Ito and Shiraki, 1999; Ishiwatari and Imasaka, 2002) (Fig. 6, Table 1). These ultramafic lavas are not directly related to HFSE-rich mantle plumes. However,

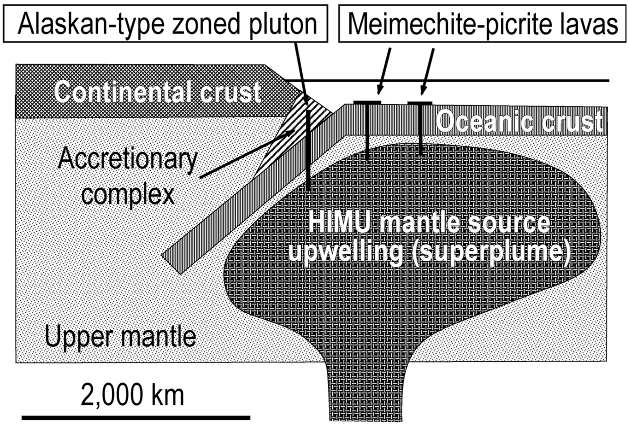

FIG. 7. A tectonic model for the Jurassic ultramafic magmatism in the East Asian continental margin. A superplume hit the subduction zone and the adjacent ocean floor to produce Alaskan-type zoned plutons and meimechite-picrite lavas. Japan was a part of the continental margin before the Miocene opening of the Japan Sea.

inasmuch as some ultramafic lavas erupted coeval with or slightly earlier than the opening of the adjacent backarc basin, it is possible they are related to the asthenospheric injection (i.e., large-scale plume) that caused back-arc opening (Tatsumi et al., 1989). Moreover, plume-type alkali basalt magmatism with mantle xenoliths has taken place widely over western Japan since Miocene time coeval with island-arc magmatism (Iwamori, 1991). This indicates that plume-type ultramafic magmatism to form the meimechite-picrite association and TiO_2-rich, silica-undersaturated Alaskan-type ultramafic plutons can take place in supra-subduction zone areas, if any large-scale mantle plume with HIMU composition ascends into the region (Fig. 7).

Conclusion

Late Jurassic ultramafic volcanic rocks are widely distributed in southwestern Japan (Mikabu), Hokkaido (Sorachi), Sakhalin (Aniva), Primorye (Samarka), and Heilongjiang (Nadanhada), typically in association with Alaskan-type plutonic complexes and picritic dikes of the same age. Chert-mudstone-sandstone sequences hosting these mafic-ultramafic rocks are also of Late Jurassic age. The 2,000 km wide occurrence of coeval ultramafic volcano-plutonic rocks in the studied area is analogous to that of the Early Triassic ultramafic volcano-plutonic rocks in northern Siberia, although the typical continental environment in northern Siberia is in strong contrast to the subduction-zone environment of the studied area. Jurassic magmatism in Far East Russia, northeast China, and Japan is characterized by the occurrence of TiO_2-rich ultramafic volcanic rock, meimechite. Meimechites and picrites in the accretionary complexes are characterized by TiO_2/Al_2O_3, Nb/Zr, and Nb/Y ratios as high as those of the HIMU-source picrites in the present Polynesian Islands, South Pacific, and are clearly different from both TiO_2-poor island-arc picrites and continental meimechites with extremely high TiO_2/Al_2O_3. In Japan, meimechite is known among accreted oceanic edifices not only of Jurassic age but also of Permian and Tertiary ages. A HIMU source may represent large-scale upwelling of deep mantle material contaminated with once-subducted, recycled oceanic crust (Kogiso et al., 1997). The repeated occurrence of HIMU-source magmatic products in Japan indicates multiple, frequent upwelling of a HIMU source (superplumes) throughout Phanerozoic time, especially in the Late Jurassic, when the superplume impinged on a wide area of active continental margins across Far East Russia, northeast China, and Japan. The studies of meimechite-picrite suites and the Alaskan type complexes in these areas are not yet sufficient, and further studies are needed to depict the Phanerozoic superplume history of the earth, hopefully with some understanding of economic byproducts such as Ti-, Pt-, and diamond-related ores.

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APPENDIX

A recent study showed that the plume-type magmatism in the subduction zone, as modeled in Figure 7, actually occurred near the northern Japan Trench in the Late Miocene. Hirano et al. (2001) reported the discovery of magnesian alkali basalt lava (48.2% SiO_2, 11.7% MgO, 2.6% TiO_2, and 6.1% alkalis) of 6 Ma age from the toe of the oceanward trench slope.

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