Picrites in central Hokkaido: Evidence of extremely high temperature magmatism in the Late Jurassic ocean recorded in an accreted oceanic plateau

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ABSTRACT

The Sorachi-Yezo belt, central Hokkaido, Japan, is composed of voluminous tholeiitic basaltic volcanics, and has been thought to be accreted fragments of an oceanic plateau formed in the Late Jurassic Pacific Ocean. Picrites have been reported as pillow lava and hyaloclastite from the Sorachi-Yezo belt. These picrites are characterized by very magnesian olivine phenocrysts (up to Fo [=100* Mg/(Mg+Fe)] = 94.1), which indicate that the primary magma was unusually Mg rich. The estimated MgO of the primary magma and the mantle potential temperature are as high as 29 wt% and 1700 °C, respectively, comparable to those of the Neoarchean komatiites, and higher than those of the Gorgona komatiites and picrites. The rare earth element patterns of the Sorachi-Yezo picrites are divided into two groups that are chemically akin to the Neoarchean komatiites and Gorgona komatiites and picrites, indicating different melting regimes in an extremely hot mantle plume. The Sorachi-Yezo picrites provide evidence for extremely high temperature magmatism, like that of Archean komatiite, caused by melting of the hottest mantle plume among the Phanerozoic oceanic large igneous provinces.

INTRODUCTION

Phanerozoic high-Mg volcanic rocks, such as picrite, komatiite, and meimechite, typically occur in large igneous provinces (LIPs), and have been thought of as products of the adiabatic melting of a hot mantle plume that stemmed in the deep mantle from boundary layers (e.g., Campbell and Griffiths, 1990; Campbell, 2005). These rocks have been studied to reveal the thermochemical structure of mantle plumes and origin of the LIP volcanism (e.g., Herzberg and O'Hara, 2002; Herzberg et al., 2007).

It is particularly important to understand the petrogenesis of the ultramafic volcanic rocks from oceanic LIPs, because the most volcanics from continental LIPs probably were contaminated by continental crust. The Caribbean-Colombian oceanic plateau, which likely formed at the Galapagos hotspot in the Cretaceous, is known as a representative example of the oceanic LIP that was accreted to a continental margin. On Gorgona Island (Colombia), which is thought to be part of the Caribbean-Colombian oceanic plateau, the komatiites and picrites occur as extrusive rocks associated with basalt, and many workers studied this unique occurrence of high-Mg volcanic rocks in this Cenozoic oceanic LIP (e.g., Echeverría, 1980; Kerr et al., 1996; Arndt et al., 1997; Révillon et al., 2000).

The Sorachi-Yezo belt is a large tectonic belt in central Hokkaido, Japan. Kimura et al. (1994) proposed that this belt represented the remnants of an accreted Late Jurassic oceanic plateau formed in the ancient equatorial area of the Pacific Ocean, based on a large volume of basaltic pillow lava and hyaloclastite (~9.0×10^6 km^3 in estimated volume) indicative of a major LIP, and called it the Sorachi plateau. However, it has also been proposed that the Sorachi-Yezo belt represents a normal oceanic crust (Niida and Kito, 1986) or a marginal basin crust (Takashima et al., 2002). Several workers have reported picrites from the Sorachi-Yezo belt (Maekawa, 1983; Niida and Kito, 1999; Takashima et al., 2002), but their detailed petrogenesis has not been discussed. If the Sorachi-Yezo belt is an accreted oceanic plateau like the Caribbean-Colombian oceanic plateau, these picrites probably record the information about the thermochemical structure of the Late Jurassic oceanic LIP. In this paper we examine the picrites from the Sorachi-Yezo belt and show that they provide evidence for the hottest mantle plume in Phanerozoic.

MINERAL AND WHOLE-ROCK CHEMISTRY

Fresh olivine-bearing picrites were collected from the Sorachi-Yezo unit in the Furano area and from the tectonically underlying Kamuikotan complex in the Asahikawa area, and their mineral and whole-rock chemistries were analyzed (for detailed geological background and sample description, analytical methods, and results, see Tables DR1–DR3 in the GSA Data Repository[1]). Figure 1 shows NiO content with respect to Fo [=100*Mg/(Mg+Fe)] for the olivines in the Sorachi-Yezo picrites. The olivines of the Kamuikotan picrites show a wider compositional range

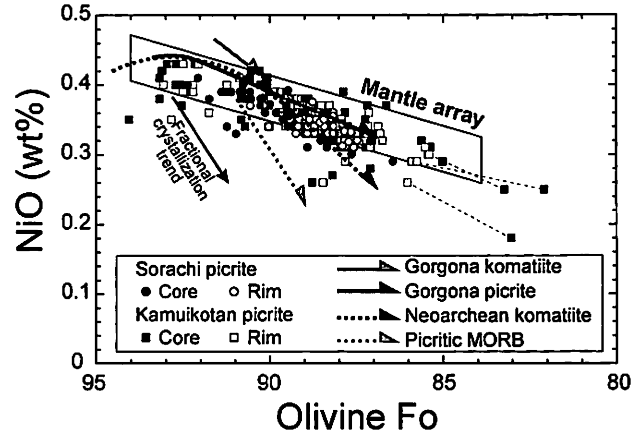

Figure 1. Fo versus NiO plots of olivine phenocrysts (core and rim) in Sorachi-Yezo picrites, with compositional trends in reported high-Mg rocks (Neoarchean komatiites (Alexo, Ontario), Gorgona komatiites and picrites, and picritic mid-oceanic ridge basalts (MORBs) (Siqueiros transform fault, East Pacific Rise). All data are from Sobolev et al. (2007). Mantle array is after Takahashi et al. (1987). Pairs of core and rim showing reverse zoning are tied by dotted lines. Solid arrow indicates inferred fractional crystallization trend.

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[1]GSA Data Repository item 2012113, supplemental information for geological background and sample description, analytical methods, calculation methods, Tables DR1–DR3 (olivine chemistry, spinel chemistry, and whole-rock chemistry and modal composition), and Figure DR1 (distribution of the Sorachi-Yezo belt and sample localities), is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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($Fo_{82.1-94.1}$) than the Sorachi picrites ($Fo_{86.5-92.4}$), although $Fo_{93.9}$ olivine was reported from the Sorachi picrite by Niida and Kito (1999). Slight normal zoning is rarely observed. Several olivines with ferrous cores (<Fo_{85}) in the Kamuikotan picrites show distinct reverse zoning, and are possibly xenocrysts (Fig. 1). The NiO content (0.18–0.43 wt%) is nearly constant regardless of the decreasing Fo content among magnesian olivines (>Fo_{90}), while it gently decreases with the Fo content among ferrous olivines. Most olivines plot in the compositional field of mantle olivines (Fig. 1; Takahashi et al. 1987). However, the CaO content (0.28–0.39 wt%) slightly increases with decreasing Fo content, and is absolutely higher than that of the mantle peridotites from the Sorachi-Yezo belt (<0.1 wt% ; Tamura et al., 1999).

The compositions of the spinels included in the olivine phenocrysts show 0.44–0.67 (average 0.56) in Cr# [= Cr/(Cr + Al)] and 0.48–0.81 (average 0.68) in Mg# [= Mg/(Mg + Fe^{2+})]. The Cr# of the Sorachi-Yezo picrites is similar to that of the Gorgona komatiites, but is lower than that of the Neoarchean Al-undepleted komatiites (compared with the compiled data of Barnes, 1998). The Fe^{3+}# [= Fe^{3+}/(Fe^{3+} + Cr + Al)] of the spinels is 0.08–0.46 (avg. 0.13), which is nearly the same as those of the Gorgona and the Neoarchean komatiites. The oxygen fugacity, Δf_{O_2}, relative to the fayalite-magnetite-quartz buffer calculated by spinel and coexisting olivine using the equation of Ballhaus et al. (1991) averages 1.8, slightly higher than that of mid-oceanic ridge basalt (MORB), and such high oxygen fugacity is estimated for the Neoarchean komatiite (Canil, 1997, 1999). The Mg-Fe equilibrium temperatures between the coexisting spinel and host olivine using the equation of Ballhaus et al. (1991) average 1156 °C.

Figure 2 shows bulk-rock TiO_2 and Al_2O_3 contents with respect to MgO contents for the Sorachi-Yezo picrites. The Sorachi picrite data of Takashima et al. (2002) also plot with our data. Our new major and trace element data show narrow variation ranges, and MgO varies only from 29 to 33 wt% (TiO_2 = 0.47–0.58 wt% and Al_2O_3 = 5.7–7.2 wt%; anhydrous basis), but the Takashima et al. (2002) data are variable in MgO (16–32 wt%). The TiO_2 and Al_2O_3 values commonly follow an olivine-control line, indicating that these elements are little modified by secondary alteration. Comparing the Sorachi-Yezo picrites with the other high-Mg volcanic rocks, the TiO_2 content is equal to that of the Gorgona komatiites at a given MgO content, but is higher than those of the Gorgona picrites and the Neoarchean komatiites (Fig. 2A). A few samples from Takashima et al. (2002) show higher TiO_2 contents. These diverse TiO_2 contents are probably affected by the different degree of partial melting, melt segregation style, and/or source composition. The Al_2O_3 contents of the Sorachi-Yezo picrites are close to those of the Neoarchean komatiites, but are lower than those of the Gorgona komatiites and picrites (Fig. 2B). It is known that the Al_2O_3 content in primary melts depends on the abundance of garnet and clinopyroxene in the residue, and decreases with increasing melting pressure (Walter, 1998). Therefore, the Sorachi-Yezo picrites should have been formed by the partial melting of the source mantle at a pressure as

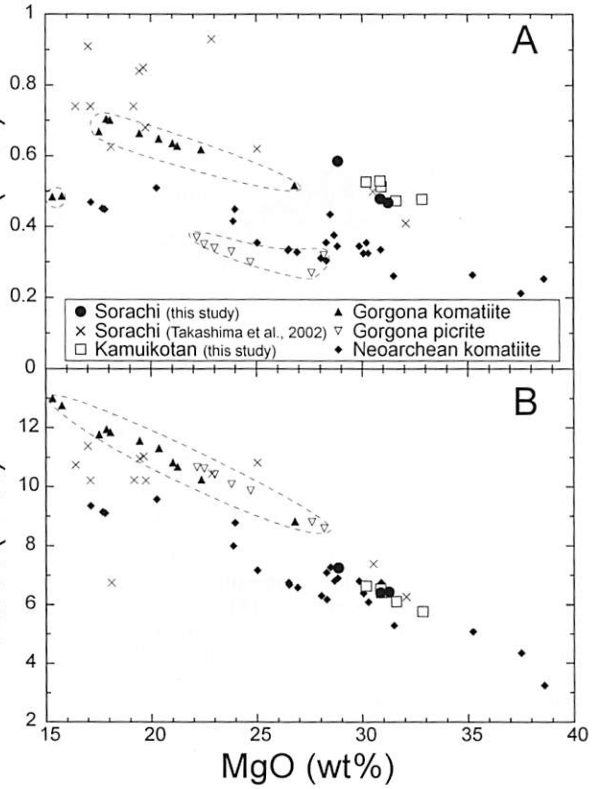

Figure 2. Whole-rock chemistry of Sorachi-Yezo picrites. A: MgO versus TiO_2. B: MgO versus Al_2O_3. Sorachi picrites of Takashima et al. (2002) are also plotted as complementary data. Neoarchean komatiites (Alexo—Lahaye and Arndt, 1996; Belingwe—Shimizu et al., 2005) and Gorgona komatiites and picrites (Révillon et al., 2000) are plotted for comparison.

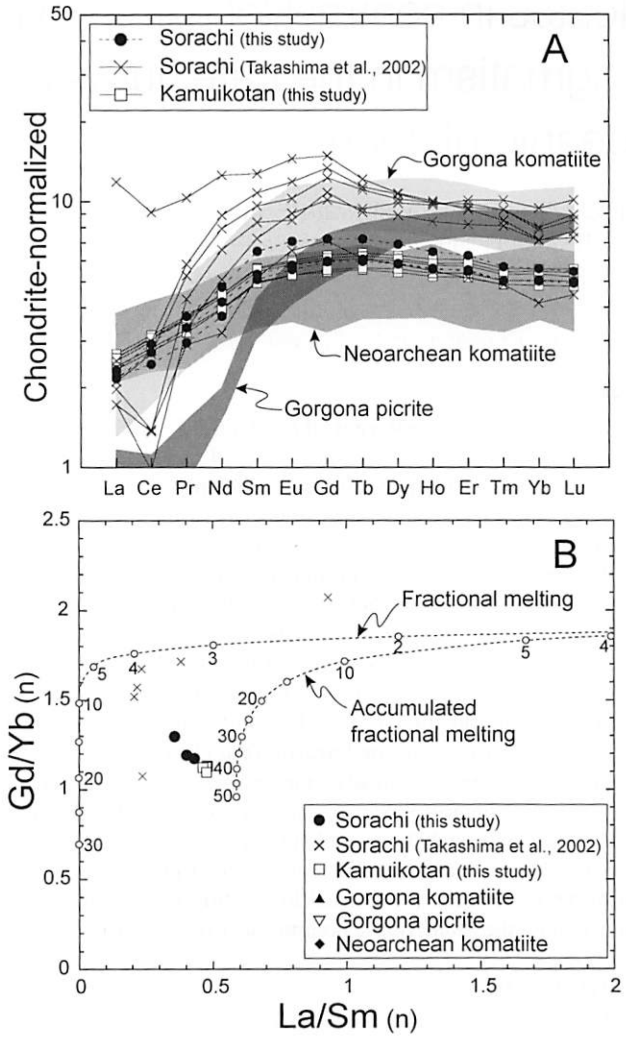

Figure 3. Chondrite-normalized rare earth element (REE) characteristics of Sorachi-Yezo picrites. A: REE patterns. B: La/Sm versus Gd/Yb. Normalized value is after McDonough and Sun (1995). Complementary data are same as in Figure 2. Two dashed lines indicate compositional trends of melt calculated by nonmodal melting of depleted garnet lherzolite. All calculation parameters were compiled by Arndt et al. (2008). Equations of Shaw (1970) were used for calculations.

TABLE 1. ESTIMATED PRIMARY MELTS AND TEMPERATURES CALCULATED BY OUR METHOD AND BY PRIMELT2

	Results from this study				Results from PRIMELT2			
	n	Maximum olivine Fo	Primary magma MgO (wt%)	T_p (°C)	n	Primary melt MgO (wt%)	T_p (°C)	Melt fraction
Sorachi-Yezo picrite	4	91.38–94.05 (92.73)	20.99–29.12 (24.73)	1591–1734 (1658)	4	25.2–26.8 (26.0)	1669–1695 (1682)	0.20–0.27 (0.23)
Gorgona komatiite	1	91.62	18.62	1543	9	21.5–23.4 (22.3)	1600–1637 (1614)	0.11–0.35 (0.23)
Gorgona picrite	2	93.05–93.42 (93.24)	21.18–21.95 (21.57)	1594–1609 (1602)	5	21.8–23.6 (22.4)	1606–1640 (1618)	0.28–0.38 (0.32)
Neoarchean komatiite	3	93.45–94.57 (94.05)	24.45–28.81 (27.16)	1655–1728 (1701)	2	27.0–27.2 (27.1)	1699–1702 (1701)	0.45–0.51 (0.48)
Picritic MORB	6	90.95	11.83–13.21 (12.26)	1367–1410 (1380)	5	13.1–13.9 (13.5)	1407–1430 (1420)	0.05–0.11 (0.09)

Note: MORB—mid-oceanic ridge basalt; Fo—100*Mg/(Mg+Fe); *Tp*—mantle potential temperature; n—number; averages in parentheses. For detailed calculation methods, see the GSA Data Repository (see text footnote 1).

high as that of the Neoarchean komatiites, for which 5–6 GPa has been estimated (Arndt et al., 2008).

The chondrite-normalized rare earth element (REE) patterns are characterized by light REE depletion (Fig. 3A), akin to the patterns of the Neoarchean komatiites. However, the REE patterns in Takashima et al. (2002) show strong depletion in light REE, suggesting kinship to the Gorgona komatiites and picrites.

DISCUSSION

Estimation of Mantle Potential Temperature

The very magnesian olivine phenocrysts (up to Fo$_{94.1}$) in the Sorachi-Yezo picrites have important petrological significance. Such magnesian olivines are also found in the Phanerozoic picrites in some LIPs (Larsen and Pedersen, 2000; Révillon et al., 2000; Thompson and Gibson, 2000) and in the Archean komatiites in greenstone belts (e.g., Arndt, 1986). The olivine compositional trends in the reported high-Mg volcanic rocks are shown in Figure 1. In particular, the Fo contents and Fo-NiO trends of the Gorgona picrites and Neoarchean komatiites are similar to those of the Sorachi-Yezo picrites. The magnesian olivines in the Sorachi-Yezo picrites do not show distinct chemical zoning, and show the Fo-NiO trend along mantle olivine array (Fig. 1). These chemical characteristics may result from the Fe-Mg diffusion in the olivine crystals after their crystallization caused the compositional homogenization (Nakamura, 1995). This is also supported by the Fe-Mg equilibrium temperature between olivine and spinel, as low as that observed in basalts. Therefore, it is probable that the magnesian olivines in the Sorachi-Yezo picrites were more Mg rich before cooling reequilibration.

To estimate the primary magma composition of the Sorachi-Yezo picrites, the compositions in equilibrium with the most magnesian olivine included in the samples were calculated. The results are shown in Table 1 (for detailed calculation methods, see the Data Repository). For comparison, the primary magma compositions for the high-Mg volcanic rocks were also calculated by using the same procedure. The calculated primary MgO content of the Sorachi-Yezo picrites is 29.1 wt%. Furthermore, the mantle potential temperature, T_p, for the source of the Sorachi-Yezo picrites calculated on the basis of the estimated MgO content yields an average of 1658 °C (maximum 1734 °C), which is comparable to that of the Neoarchean komatiite, and is significantly higher than those of the Gorgona komatiites and picrites. Considering the relatively high Δf_{O_2} estimated from the Sorachi-Yezo picrites, a higher Fe^{3+}/ΣFe should be assumed. However, even if Fe^{3+}/ΣFe = 0.2 is used in the calculation, the T_p may be lowered by only 40 °C. Such high Δf_{O_2} implies a possible hydrous mantle source for the Sorachi-Yezo picrites, as sometimes discussed for the origin of komatiites (Arndt et al., 1998; Kamenetsky et al., 2010). However, for the melts produced by high degree of partial melting such as the Sorachi-Yezo picrites, there is no distinct difference in melting conditions between dry and hydrous mantle source (Katz et al., 2003). Similar results can also be obtained by the calculation using PRIMELT2 software (Herzberg and Asimow, 2008), which gives higher T_p values than those of Gorgona (Table 1). The very high T_p estimated from the Sorachi-Yezo picrites clearly means that they were most likely derived from an extremely hot mantle plume, and excludes the possibility of normal oceanic crust or backarc basin origins, as proposed by previous workers.

Various Melting Modes of the Sorachi-Yezo Picrites

As shown in Figure 3A, the two different degrees of light REE depletion are recognized in the REE patterns of the Sorachi-Yezo picrites, which are analogous to those of the Neoarchean and Phanerozoic komatiites. The high-Mg and high-Ni and light REE–depleted characteristics of the Sorachi-Yezo picrites imply that depleted peridotitic mantle is suitable for their source mantle. Figure 3B shows the chondrite-normalized La/Sm and Gd/Yb plots with the two melting paths calculated by the two different melting modes of a depleted peridotitic composition; fractional melting and accumulated fractional melting. The Sorachi-Yezo picrites and the Neoarchean komatiites plot around the accumulative fractional melting path. The calculated degrees of partial melting are <40% for the Sorachi-Yezo picrites and ~50% for the Neoarchean komatiites. However, the data in Takashima et al. (2002) and the Gorgona komatiites and picrites plot away from the accumulative fractional melting path, probably indicating that they were generated by a melt segregation style closer to fractional melting and/or more depleted source composition. In any case, the Sorachi-Yezo picrites of Takashima et al. (2002) should have been produced by a lower degree of partial melting than those of this study, and various REE patterns of the Sorachi-Yezo picrites can be mainly explained by various degrees of partial melting, which may have been caused by the local differences in temperature in the source mantle. The ascending mantle may be hotter in the axial area and cooler in the peripheral areas.

Evidence for Extremely High Temperature Magmatism in the Sorachi Plateau

Kimura et al. (1994) suggested that the voluminous basaltic rocks in the Sorachi-Yezo belt are an accreted oceanic plateau formed on the Izanagi plate in the equatorial area of the Late Jurassic Pacific Ocean. In addition, they proposed that this Sorachi plateau was the twin of the extant Shatsky Rise, which formed at the triple junction of the Izanagi, Pacific, and Farallon plates. Several petrological studies also seem to support this hypothesis (Tatsumi et al., 1998; Sakakibara et al., 1999; Nagahashi and Miyashita, 2002). The Sorachi-Yezo picrites not only provide further evidence for the existence of the Sorachi plateau, but also prove the presence of extremely high temperature magmatism derived from a source region with a T_p as high as 1700 °C in the Late

Jurassic ocean. This magmatism was produced by the melting of a hotter mantle plume than that for the Caribbean-Colombian oceanic plateau, and it represents the hottest Phanerozoic plume magmatism in the oceanic regions. A spinifex texture may have not been formed in the cooling magma in the Sorachi plateau, because the cooling conditions to grow spinifex olivines, such as supercooling following superheating and crystallization in an appropriate thermal gradient, were not satisfied (Faure et al., 2006). The similarities of the melting conditions between the Sorachi-Yezo picrites and the typical Neoarchean komatiites give evidence for the formation of an extremely high temperature plume in the Phanerozoic oceanic area, implying that parts of the modern mantle are still as hot as that of the Archean.

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