Lower crustal metasomatism inferred from mafic xenoliths from Ichinomegata crater, Northeast Japan arc

Miyuki TAKEUCHI and Shoji ARAI

Department of Earth Sciences, Kanazawa University, Kanazawa 920-1192, Japan

Gabbroic xenoliths from Ichinomegata crater, Northeast Japan arc, contain a large amount of amphiboles. Some of them are obviously of secondary origin in hornblende-pyroxene gabbros; clinopyroxene in the pyroxene-spinel symplectite, which is subsolidus reaction products of olivine and plagioclase by cooling, was replaced in part with amphibole. Minerals (amphibole, clinopyroxene and spinel) in the symplectite contain appreciable TiO$_2$ (up to 1.6 wt%), although olivine and plagioclase are free from TiO$_2$. The amphibole in the symplectite is significantly enriched in Na, K, Rb and Ba relative to the other symplectite minerals that contain very low amounts of these elements. The metasomatic formation of amphibole in the symplectite was accompanied with addition of, at least, Ti, Na, K, Rb and Ba. The metasomatism is characterized by enrichment of incompatible elements, especially LILE but not HFSE (Nb, Ta, Zr and Hf). This was caused by infiltration of fluid possibly released from hydrous arc magmas. Metasomatic processes observed in the lower crustal gabbros are also recorded in peridotite and websterite xenoliths of upper mantle origin from Ichinomegata. This means widespread modification of mineral chemistry and mineral assemblage from the upper mantle to the lower crust beneath the arc.

Keywords: Gabbro, Mafic xenolith, Lower crust, Metasomatism, Northeast Japan arc

INTRODUCTION

Xenoliths from the mantle wedge (Arai et al., 2007; Arai and Ishimaru, 2008) have recorded mantle metasomatism (e.g., Arai and Kida, 2000; Abe and Arai, 2005; Ishimaru et al., 2007; Kawamoto et al., 2013). It is well known that ultramafic–mafic xenoliths from Ichinomegata, Northeast Japan arc, contain hydrous minerals (e.g., Kuno, 1967), some of which are of secondary origin (Arai and Saeki, 1980; Takahashi, 1986). The mantle metasomatism recorded by mantle-derived ultramafic xenoliths from Ichinomegata has been well documented (e.g., Arai, 1986; Abe et al., 1992); most of Ichinomegata peridotite xenoliths contain secondary hydrous minerals (pargasite and phlogopite), and olivine and chromian spinel are enriched with Fe in the hydrous peridotites. On the basis of the chemical budget, Abe et al. (1992) estimated that the formation of the hydrous minerals was accompanied with enrichment of Na,Ti and K and that the upper mantle beneath the Ichinomegata was metasomatized by arc-related hydrous magmas. In contrast, there have been few documents on metasomatism imposed on crust-derived xenoliths. Recently, Yamamoto et al. (2013) investigate isotopic characters of the Ichinomegata mafic xenoliths to conclude interaction between Ichinomegata lower crust and the host magma.

Ishikawa (2010) suggested that the heterogeneity in seismic structure beneath the Northeast Japan arc (Nakajima et al., 2001) is possibly caused by the difference in species and proportion of constituent minerals. The alteration of mineral assemblage such as the local formation of secondary amphibole may enhance the heterogeneity. We describe and discuss mineral chemical aspects of the metasomatism imposed on the Ichinomegata gabbroic xenoliths to constrain properties of the metasomatic agent (melt or fluid) responsible for the lower crustal metasomatism.

GEOLOGICAL BACKGROUND AND SAMPLE DESCRIPTIONS

Megata volcano, Northeast Japan arc, has three craters,
Ichinomegata, Ninomegata and Sannomegata, and their volcanic ejecta contain ultramafic–mafic xenoliths (e.g., Hayashi, 1955; Kuno, 1967). The Ichinomegata crater is one of the famous localities of arc-related ultramafic–mafic xenoliths, of which information gives us a petrologic model for the crust and the upper mantle beneath the Northeast Japan arc (e.g., Takahashi, 1978). Mafic xenoliths from Ichinomegata vary in lithology from amphibolites to igneous gabbros (Aoki, 1971); they contain various amounts of amphiboles.

We examined 9 hornblende–pyroxene gabbros, composed of anhedral grains of hornblende, clinopyroxene, plagioclase, spinel with/without subordinate olivine (Fig. 1a). The amount of amphibole varies from 30 to 80 vol%, and the modal amount of plagioclase changes from 10 to 40 vol%. Our ‘gabbros’ do not show any textures specific to metamorphic rocks or igneous rocks, although weakly foliated. They appear to be slightly modified igneous gabbros (Fig. 1a). These gabbros characteristically contain fine-grained mineral aggregates, i.e., pyroxene–spinel symplectite, between olivine and plagioclase as well as around plagioclase without associated olivine (Figs. 1b and 1c). The symplectite consists of clinopyroxene, amphibole and dark green colored vermicular spinel with polygonal orthopyroxene. The polygonal orthopyroxene always exists along olivine grains at the opposite side of plagioclase (Fig. 1b). Clinopyroxene grains in the symplectite are often replaced by amphibole. The amphibole in the symplectite can be distinguished from the discrete one by appearance; the latter is dark green–brown whereas the former, symplectite amphibole, is light green–brown in color under the microscope. The modal proportions of clinopyroxene and amphibole are various in the symplectite. The discrete spinel grain shows inhomogeneous texture, composed of two phases, light-colored magnetite and dark-colored spinel (e).

MINERAL CHEMISTRY

Major-element compositions of major mineral phases were measured by a microprobe (JEOL JXA-8800R) at Kanazawa University. We adopted an acceleration voltage of 20 kV, a beam current of 20 nA and a beam diameter of 3 µm. All Fe is assumed to be Fe$^{2+}$ in silicates. Fe$^{2+}$ and Fe$^{3+}$ in spinel were calculated assuming spinel stoichiometry. Mg# is Mg/(Mg + Fe$^{2+}$). Y$_{Fe}$ and Y$_{Cr}$ are Fe$^{3+}$/Cr + Al + Fe$^{3+}$) and Cr/(Cr + Al + Fe$^{3+}$) atomic ratios, respectively. Fo is 100Mg# for olivines.

Selected amphiboles, pyroxenes, plagioclase and olivine in 4 gabbros were analyzed for trace elements using a laser ablation system (GeoLas Q-Plus, MicroLas) coupled to an ICP-MS system (Agilent 7500s, Yokogawa Analytical Systems) (= LA-ICP-MS) at Kanazawa University (Ishida et al., 2004; Morishita et al., 2005). The laser–spot diameter was 50 µm for amphiboles and clinopyroxenes and 100–120 µm for orthopyroxene, plagioclase and olivine. The energy of laser ablation was 6 Hz and 8 J/cm$^2$. The NIST 612 standard glass was used for calibration with Si as an internal standard.

The gabbros examined here are within the compositional range of Ichinomegata gabbros reported by Aoki (1971), and all of the minerals are almost free from Cr. All discrete minerals show intra-grain homogeneity ex-
cept for spinel. Plagioclase is anorthite (An_{93-98}; Fig. 2), and contains no K_{2}O (below the detection limit). Olivine is Fo_{77-79} in composition (Fig. 2), and almost free from NiO and Al_{2}O_{3}. Discrete amphibole is pargasitic with Mg# 0.69-0.75. Na_{2}O and K_{2}O contents are 1.9-2.5 wt% and 0.10-0.42 wt%, respectively, and TiO_{2} content varies from 1.0 to 2.5 wt% in the discrete amphibole (Fig. 3a). Discrete clinopyroxene shows higher Mg# (0.76-0.81) than amphibole, and is poor in Na_{2}O (0.15-0.30 wt%). It shows wide ranges of Al_{2}O_{3} (5.5-7.3 wt%) and TiO_{2} (0.5-1.0 wt%) (Figs. 3b and 3c). Al_{2}O_{3} and TiO_{2} contents of clinopyroxene increase with a decrease of SiO_{2} content. The discrete spinel grain is composed of spinel and magnetite; the spinel part is Al-rich spinel, showing very low Y_{Cr} (almost nil) and Y_{Fe}, 0.11-0.15, as well as intermediate Mg#, 0.49 to 0.56. TiO_{2} content of spinel part is 0.09-0.32 wt%. The magnetite part in the discrete spinel grain is also free from Cr, and higher in Y_{Fe} and TiO_{2} than spinel (0.74-0.76, 1.8-6.8 wt%, respectively). It is lower in Mg# (0.16-0.21) than the spinel part.

The minerals in the symplectite show different chemical characteristics (especially in TiO_{2} and trace element contents) from the discrete minerals. The symplectite amphibole is pargasitic, and is almost identical to the discrete one in Mg# (0.70-0.76), Na_{2}O (1.8-2.5 wt%) and K_{2}O contents (0.02-0.45 wt%), whereas TiO_{2} content is lower (0.3-1.6 wt%) in the symplectite amphibole than in the discrete one (Fig. 3a). The symplectite clinopyroxene is the same in Mg# (0.76-0.81) and Na_{2}O content (0.15-0.30 wt%) as the discrete one, although higher in Al_{2}O_{3} (5.5-7.3 wt%) and TiO_{2} contents (0.5-1.0 wt%) than the latter (Figs. 3b and 3c). The symplectite spinel is Al-rich spinel, and shows lower Y_{Fe} (0.09-0.14) and TiO_{2} content (0.03-0.23 wt%) and higher Mg# (0.52-0.62) than the spinel part of discrete spinel grain. The symplectite orthopyroxene changes the Mg# from 0.74 to 0.81 with an increase of Al_{2}O_{3} content (26.5-29.6 wt%), and shows lower TiO_{2} content (less than 0.11 wt%).

The studied gabbros are relatively homogeneous with respect to the REE and trace-element patterns of discrete amphibole and clinopyroxene, but symplectite minerals show variable contents of REEs and other trace-elements (Figs. 4 and 5). The discrete amphibole...
and clinopyroxene display LREE-depleted smooth convex-upward condite-normalized patterns, whereas the pattern show positive spikes at Eu in symplectite clinopyroxene and amphibole (Fig. 4). MREE to HREE contents are remarkably higher in discrete clinopyroxene and amphibole than in symplectite ones (Fig. 4). Symplectite minerals show almost similar in abundances in LILE (= LIL elements) to discrete ones, except for Ba and Sr contents, which are higher in symplectite clinopyroxene (0.06–2.0 ppm and 22–33 ppm) than in discrete clinopyroxene (<0.12 ppm, 13–20 ppm) (Fig. 5). Some HFSE (= HFS elements) (Zr, Hf and Ti) contents are markedly higher in discrete minerals than in symplectite ones (Fig. 5b). Plagioclase shows a HREE-depleted chondrite-normalized pattern and a strong positive anomaly at Eu. It is almost free from HREE, and enriched in Ba (3.6–8.9 ppm) and Sr (360–820 ppm; Fig. 6a). Olivine shows very low contents of trace elements (REEs, Rb, Ba and Sr; Fig. 6b).

DISCUSSION

The studied gabbros contain two types of amphibole, clinopyroxene and spinel. The differences in mode of occurrence and chemical composition indicate that the symplectite minerals were not of igneous origin but formed by subsolidus reaction between plagioclase and olivine (Pl + Ol → Cpx + Amp + Spl + Opx) by decompression and/or cooling (e.g., Kushiro and Yoder, 1966). The reaction is the same as for the formation of pyroxene–spinel symplectite in Ichinomegata peridotite (Takahashi, 1986). In the Ichinomegata gabbro, the mineral assemblage of symplectite is different; the symplectite consists of clinopyroxene, spinel, orthopyroxene and amphibole. The hydrous symplectite is formed in the presence of water by the reaction, Pl + Ol + H2O → Cpx + Amp + Spl + Opx, which has been documented from metagabbros (e.g., Lang et al., 2004). The positive Eu anomaly in the symplectite amphibole and clinopyroxene is possibly inherited from precursor plagioclase, strongly suggesting that these minerals are of subsolidus reaction origin.

We examine the chemical budget during this transformation to constrain the nature of the agent concerned (Fig. 7). Symplectite minerals must be almost free from the elements (e.g., TiO2) that are not included in precursor plagioclase and olivine, if they are their reaction products. In the simply hydrated metagabbros (Lang et al., 2004; Cruciani et al., 2008), the symplectite amphibole shows very low TiO2 content (less than 0.4 wt%). In the Ichinomegata gabbros, the symplectite amphibole contains appreciable amounts of TiO2 (up to 1.6 wt%; Fig. 7b), even though they were formed from precursor plagioclase and olivine were also almost free from these elements. In addition, clinopyroxene, orthopyroxene and spinel in the symplectite also contain TiO2 (Fig. 7b). It is likely that the metasomatic formation of symplectite amphibole was accompanied with addition of, at least, Ti, Na, K, Rb and Ba with H2O (Figs. 7b–7f).

We estimated lower crustal evolution beneath Ichinomegata as follows; the precursor gabbros, either igne-
ous or metamorphic, were composed of plagioclase, olivine, clinopyroxene, amphibole (±) and spinel. Then, the symplectite consisting of clinopyroxene, amphibole, spinel and orthopyroxene were formed possibly by cooling from plagioclase and olivine (Kushiro and Yoder, 1966), synchronous with invasion of aqueous fluid. Discrete clinopyroxene grains are also replaced by pargasite along cracks or grain boundaries through the spread of the fluid. The cooling process is also recorded in the discrete spinel grain with inhomogeneous texture. Unmixed spinels due to immiscibility gap between Al–rich spinel and Fe3+–rich magnetite (Sack and Ghiorso, 1991) have been frequently described from some ultramafic rocks (e.g., Loferski and Lipin, 1983; Tamura and Arai, 2005). In the Ichinomegata case, the discrete spinel grain had been enriched with Ti and Fe (especially Fe3+), and then separated into two phases, Ti, Fe3+–rich magnetite and Al–rich spinel, due to immiscibility on cooling (Fig. 8).

This lower crustal metasomatization is characterized by enrichment of H2O and LILE but not of HFSE (Figs. 5 and 7), and has the same features as the mantle metasomatism recorded by the Ichinomega peridotites (Abe et al., 1992). This metasomatism was caused by infiltration of fluids related to hydrous arc magmas. Websterite xenoliths from Ichinomega have also experienced the similar metasomatism; secondary amphiboles replace clinopyroxene along cracks and grain boundaries. The upper mantle–lower crust system has been metasomatized beneath Ichinomega. On the other hand, mafic–ultramafic xenoliths from Sannomegata, which is 2.5 km away from Ichinomega, are very poor from amphiboles (Arai and Saeki, 1980; Abe et al., 1992). The metasomatism was not pervasive but selective possibly through cracks (Arai et al., 2005). We expect widespread but heterogeneous modification of mineral chemistry and mineral assemblage by fluid metasomatism in the sub-arc lower crust–mantle system. The formation of amphibole at the expense of plagioclase and olivine in the lowermost crust possibly blurs the contrast between mafic and peridotitic rocks, promoting to form fuzzy Mohos, because amphiboles have intermediate Vp between anhydrous mafic minerals and plagioclase (e.g., Christensen and Salisbury, 1975).

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