LETTER

Post-deformational impregnation of depleted MORB in Nain lherzolite (Central Iran)

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Plagioclase lherzolites of Nain mélange, Iran, show peculiar textures that indicate melt impregnation: (1) droplet or bleb-like grains of plagioclase distributed in the peridotite matrix, (2) plagioclase-bearing clinopyroxenite seams, and (3) trails of plagioclase crosscutting pyroxene porphyroclasts. The textural characteristics show post-deformational igneous formation of plagioclase, and possibly, associated clinopyroxene, from the impregnating melt. The melt has precipitated the clinopyroxene seams and chemically modified all the peridotite minerals. Highly refractory compositions of the precipitated minerals suggest involvement of a highly depleted MORB-like melt. The melt was an increment of partial melt produced by 8% to 10% fractional melting from the MORB source. This is in contrast to the involvement of ordinary MORB in melt impregnation in abyssal plagioclase peridotites. Integration of increments of mantle partial melts to form MORB was possibly incomplete in the very incipient mid-ocean ridge as in the short-lived Nain back-arc basin.

Keywords: Plagioclase lherzolite, Melt impregnation, Depleted MORB-related melt increment, Nain, Iran

INTRODUCTION

Plagioclase peridotites are mainly formed by two processes: (1) trapping of basaltic melts in a peridotite matrix (e.g., Dick, 1989), and (2) decompression from spinel to plagioclase peridotite field during upwelling (e.g., Hamlyn and Bonatti, 1980). Plagioclase peridotites formed by the former process, i.e., melt-impregnated plagioclase peridotites, are hybrid rocks of pre-existing host peridotite with gabbroic materials precipitated from invading melts. Their plagioclase shows varied textural characteristics depending on the origin (in-situ or exotic) of the invading melt (Nicolas, 1986). The plagioclase precipitated from the invading melt is distinct in texture from that produced by the subsolidus decompression of fertile spinel lherzolite (Rampone et al., 1993). In this paper, we describe the textural and chemical characteristics of a unique plagioclase lherzolite from Nain, Iran, formed by the impregnation of a depleted MORB-like melt.

GEOLOGICAL BACKGROUND AND PETROGRAPHY

Nain mélange is a member of the Nain–Baft ophiolite belt (inner ophiolite belt of Iran). It is located on the margin of Central–East Iranian Microcontinent, northeast of Isfahan province. The mélange is composed of a series of southwest-facing thrust sheets. These sheets are mainly composed of ultramafic, volcanic, metamorphic, and sedimentary rocks (Davoudzadeh, 1972). Recent investigations in chemistry of the volcanic rocks in the area have revealed an oceanic to island-arc affinity (Rahmani et al., 2007; Shafaii Moghadam et al., 2009), which is in accordance with the position of this mélange, i.e., in parallel with and behind the arc magmatic belt of Iran (Orumiyeh–Dokhtar magmatic belt) formed by the Neotethys subducting slab. The Nain–Baft Ocean has been widely described as a short-lived (45 Ma) back-arc basin formed related to Neotethys subduction under the Iranian continental block in Mesozoic time (Takin, 1972; McCall, 1997). Peridotites of the Nain mélange are mainly harzburgite to clinopyroxene-poor lherzolite, and plagioclase-bearing lherzolite have been exclusively found along shear zones (Fig. 1). The fault-related plagioclase lherzolites show variable degrees of deformation from proto- to ultra-mylonitization (Killick, 2003). Thin subparallel seams of clinopyroxenite, which are free from boudinage and appear magmatic, are commonly found in the plagioclase lherzolites.

The plagioclase lherzolites with a protomylonitic texture contain up to 8.7% modal plagioclase (Table 1),
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Most commonly in the form of bleb-like to amoeboid grains between the primary minerals (Fig. 2a). The plagioclase grains are observed irrespective of spinel association, although some spinel grains are enveloped by plagioclase (Fig. 2a). Porphyroclasts are distorted grains of orthopyroxene and rarely clinopyroxene (Figs. 2e–2h).

The orthopyroxene porphyroclasts (up to 3.5 mm across) contain thin exsolution lamellae of clinopyroxene and are commonly cut by trails of plagioclase (Fig. 2g). The clinopyroxene porphyroclasts are strongly impregnated, corroded, and split to smaller grains surrounded by plagioclase (Fig. 2h) by the melt. Neoblasts of clinopyroxene are usually replaced along the margins by plagioclase (Figs. 2c and 2d). The thin clinopyroxenitic seams and clusters are composed of clinopyroxene and subordinate orthopyroxene with substantial amounts of interstitial plagioclase (Fig. 2b). The seam pyroxenes are slightly finer in size than neoblasts and are free of deformation (Fig. 2b). It is noteworthy that olivine and spinel are not associated with plagioclase in pyroxenite seams (Fig. 2b). Most of the plagioclase grains are altered to saussurite (Fig. 2).

MINERAL CHEMISTRY AND THERMOBAROMETRY OF PLAGIOCLASE LHERZOLITE

Major-element mineral chemical data were acquired using an electron microprobe, JXA8800 (JEOL), at Kanazawa University. Analysis was conducted under the following conditions: an accelerating voltage of 20 kV, a probe current of 20 nA, and a focused beam diameter of 3 μm. Mg# represents the atomic ratio Mg/(Mg + Fe2+); Cr#, Cr/(Cr + Al). For the silicates, all iron is assumed to be Fe2+. Fe2+ and Fe3+ in chromian spinel were calculated assuming spinel stoichiometry. Olivines show Fo and NiO contents ranging from 89.5 to 90.4 and 0.34 wt% to 0.40 wt%, respectively. The Cr# of spinels is relatively high, i.e., around 0.5, at around Fo90 of olivine (Arai, 1994) (Fig. 3a). Spinels have a slightly high TiO2 content (0.28–0.41 wt%) and low Mg# (0.47–0.59) relative to those in abyssal spinel peridotites with Cr# of 0.43–0.53 (Dick and Bullen, 1984). Orthopyroxenes are chemically zoned; Mg# varies from 0.89 to 0.91 on average, with a decrease of Al2O3 (from 6 wt% to 2 wt%) and Cr2O3 (from 0.9 wt% to 0.3 wt%) contents from the porphyroclast core to the rim. The orthopyroxene porphyroclast cores display relatively low Al2O3 (~ 2 wt%) and Cr2O3 (~ 0.6 wt%) contents only when they are adjacent to plagioclase trails. Clinopyroxenes exhibit broad ranges of Al2O3 (from 2.7 wt% to 6.8 wt%) and Cr2O3 (from 0.86 wt% to 1.45 wt%) contents (Figs. 3b and 3c). The highest Al2O3 content is recorded by the core of the clinopyroxene porphyroclast and slightly coarse neoblasts (Fig. 3b). In contrast, the lowest Al2O3 content is measured in the seam clinopyroxenes and the rim of neoblasts (Fig. 3b). Clinopyroxenes show Mg# ranging from 0.89 to 0.94, and they are char-

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Table 1. Modal compositions of the Nain plagioclase lherzolites

<table>
<thead>
<tr>
<th>Sample</th>
<th>Oi %</th>
<th>Opx %</th>
<th>Cpx %</th>
<th>Spl %</th>
<th>Plg %</th>
<th>Cpx/(Cpx + Opx)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-116</td>
<td>62.1</td>
<td>24.4</td>
<td>4.7</td>
<td>1.1</td>
<td>7.7</td>
<td>0.16</td>
</tr>
<tr>
<td>N-114</td>
<td>65.4</td>
<td>23.4</td>
<td>4.4</td>
<td>0.9</td>
<td>6.9</td>
<td>0.16</td>
</tr>
<tr>
<td>N-234</td>
<td>64.5</td>
<td>22.5</td>
<td>5.0</td>
<td>0.5</td>
<td>7.5</td>
<td>0.18</td>
</tr>
<tr>
<td>N-115</td>
<td>68.7</td>
<td>17.6</td>
<td>3.8</td>
<td>1.2</td>
<td>8.7</td>
<td>0.18</td>
</tr>
<tr>
<td>Clinopyroxenite seam</td>
<td>0.9</td>
<td>13.0</td>
<td>58.1</td>
<td>-</td>
<td>28.0</td>
<td>-</td>
</tr>
</tbody>
</table>

Modal was calculated according to the following assumptions:
(a) serpentine with mesh texture was added to olivine,
(b) bastite was added to orthopyroxene, and
(c) late tensional veins filled with serpentine fibers, carbonate, or secondary minerals were not considered.
The total count of each modal analysis was 2000 points.
The average modal composition of plagioclase-rich clinopyroxenite seams in samples N-116 and N-115 is also shown.
All the peridotites are lherzolite with clinopyroxene/pyroxenes volume ratio more than 0.1 (Arai, 1984).
acterized by low TiO$_2$ (0.14–0.29 wt%) and Na$_2$O (0.27–0.43 wt%) contents (Figs. 3b and 3c). Plagioclases range in composition from bytownite to anorthite (An$_{88-100}$).

The equilibration temperatures were estimated based on two pyroxene compositional relationships (Wells, 1977; Brey and Köhler, 1990). The yielded temperatures in the peridotite (855 °C to 1002 °C) are slightly lower than that in the seams (965 °C to 1078 °C). Nominal temperatures obtained for the peridotite pyroxenes from core–core and rim–rim pairs are 933 °C and 848 °C on average, respectively. Coexistence of calcic plagioclase with magnesian olivine indicates low pressure conditions (<1 GPa) (e.g., Kushiro and Yoder, 1966).

The trace element abundances in the clinopyroxenes and orthopyroxenes were determined using a laser ablation system (Geolas Q–Plus, MicroLas) coupled to an Agilent 7500s ICP–MS system at Kanazawa University following the method proposed by Morishita et al. (2005). The laser-spot diameter was 60 μm for clinopyroxenes and 100 μm for orthopyroxenes. The repetition rate and fluence of the laser ablation system were 6 Hz and 8 J/cm$^2$, respectively. Orthopyroxenes are characterized by extremely low REE contents ($\leq$3 times of chondritic values) and strongly fractionated patterns (Nd$_N$/Yb$_N$ $\leq$ 0.02) (subscript N: normalization to chondritic values) (Fig. 4a). Only Sr shows a positive anomaly that is intensified in parts adjacent to plagioclase (Fig. 4a).

All the clinopyroxenes (porphyroclast, neoblast, and seam) exhibit a similar LREE-depleted (Ce$_N$/Sm$_N$ = 0.004–0.01) REE pattern with flat MREE$_N$ to HREE$_N$ (2 to 11) and a weak negative Eu anomaly (Fig. 4b). We found neither significant core–rim variations nor vari-
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ation between peridotite and seams in trace element abundances of clinopyroxenes (Fig. 4a). Clinopyroxenes are closely similar in chemistry to those in abyssal peridotites (Johnson et al., 1990). The Sr anomaly in clinopyroxenes is highly scattered from negative, mostly in clinopyroxene cores, to positive in the rims (Fig. 4a).

DISCUSSION AND CONCLUSION

A high modal abundance of plagioclase and pyroxene coupled to a low modal value of olivine (Table 1) is a characteristic feature of melt-impregnated plagioclase peridotites (e.g., Dick, 1989; Tartarotti et al., 2002). In addition, textural characteristics of the Nain lherzolite also strongly indicate that the plagioclase and associated minerals (mainly clinopyroxene) were precipitated from impregnating melt (Fig. 2). The stress-free appearance of minerals (cpx + plg ± opx) free from associated olivine and spinel is distinct in the clinopyroxenite seams of Nain, suggesting their post-deformational igneous origin. The post-deformational nature of melt impregnation is revealed by the presence of plagioclase-rich veinlets cross-cutting pyroxene porphyroclasts (Figs. 2g and 2h) in addition to the stress-free appearance of related minerals (Fig. 2b). This is further supported by a slight corrosion of peridotite pyroxenes (Figs. 2c, 2d, 2e, and 2h). Distribution of large amount of plagioclase (Table 1) possibly indicates pervasion of the melt during impregnation. The plagioclase veinlets randomly cut pyroxenes, and the vein network is not elongate, indicating melt impregnation after strong deformation (mylonitization).

Selective corrosion of peridotite pyroxenes (Figs. 2c, 2d, 2e, and 2h) indicates chemical disequilibrium between the impregnating melt and the host peridotites, i.e., an exotic origin of the melt. Infiltration by the exotic melt in the Nain lherzolites has been made by focused flow, represented by the clinopyroxene-plagioclase rich seam (Fig. 2b), with subsequent diffusive porous flow to the surroundings (Fig. 2a). The seams followed olivine-rich bands, simply because the melt could permeate more easily through the olivine grains than through the pyroxenes (Toramaru and Fujii, 1986). The parallelism of the seams with the foliation plane is not related to the deformation in shear zones.

The possibly depleted composition of the melt is supported by the highly depleted composition of magmatic seam minerals, clinopyroxenes (low in TiO₂, Na₂O, and LREE), and associated plagioclases (An₉₃ to An₁₀₀) (Panjasawatwong et al., 1995). It is noteworthy that the clinopyroxene and plagioclase formed from the impregnating melt are quite different in chemistry from their equivalents in abyssal plagioclase peridotites. The ordinary MORB are involved in melt impregnation for the latter (Fig. 4b). In contrast, depleted to ultra-depleted composition for impregnating melt is suggested for the Nain lherzolite (Fig. 4b).

The equilibrium melt was calculated for the seam and peridotite clinopyroxenes (using Cpx/Liquid of Hart and Dunn (1993)), which share similar trace-element compositions. The calculated melt shows fractionated LREE with a flat M to HREE pattern, similar to but higher in abundances than UDM (ultra-depleted melt) from the Mid-Atlantic ridge and East Pacific Rise (Sobolev and Shimizu, 1993; Arai and Takemoto, 2007) (Fig. 4b). TheREE pattern of the melt well matches with an increment of melt produced by 8% to 10% fractional melting of a depleted mantle source in spinel peridotite facies (Johnson et al., 1990) (Fig. 4b). The strong depletion in other in-
compatible elements of clinopyroxenes is consistent with the depleted nature of the melt (Fig. 4a). The impregnating melt has chemically modified pre-existing peridotite minerals, giving rise to chemical equilibration for all the minerals as described for other melt-impregnated lherzolites (e.g., Rampone et al., 1997, 2008; Dijkstra et al., 2001, 2003). Subsequent cooling during and after deformation partly modified all the minerals in major- to minor element chemistry, although REE in pyroxenes have been kept immobile. Sr enrichment in orthopyroxenes around the plagioclase veinlets may be related to the low-temperature alteration of the plagioclase (saussurite formation) (Fig. 4a). Involvement of an ultra-depleted melt in the formation of plagioclase peridotites has been reported only from a few ophiolites (e.g., Rampone et al., 1997, 2008; Dijkstra et al., 2001, 2003). The Nain lherzolite possibly provides the best example for the depleted nature of impregnating melts. The Nain melt is more depleted than the melts estimated for other ophiolitic peridotites (e.g., Rampone et al., 1997, 2008; Dijkstra et al., 2001, 2003).

The Nain plagioclase lherzolite protomylonites possibly recorded rifting around the margins of the Central-East Iranian Microcontinent (CEIM) to form the Nain basin as initiation of ocean floor spreading in Mesozoic time. The narrow oceanic basin existed around the CEIM until early Tertiary. In such very initial stages of mid-ocean ridge activity, increments of partial melts were failed to produce aggregates as the ordinary MORB within the uppermost mantle.

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