Melt–peridotite reaction recorded in the chemistry of spinel and melt inclusions in basalt from 43°N, Mid-Atlantic Ridge

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Abstract

Compositions of spinel and glassy melt inclusions in primitive olivine (Fo 89.3–91) from basalt AII32 D11-177 at 43°N, Mid-Atlantic Ridge fall into two principal groups. The dominant (~90%) Group-I spinel and melt inclusions have typical MORB compositions. In contrast, Group-II Cr-spinels are strongly enriched in TiO$_2$ (2.6–4.1 wt%), and Group-II melt inclusions show significant enrichment in SiO$_2$ (54.6–58.4 wt%), TiO$_2$, Na$_2$O and K$_2$O, whereas their CaO contents (9.3–11.1 wt%) are unusually low. Group-II melts are also remarkable in crystallizing high-Mg orthopyroxene (Mg# 91). These mineral associations and melt compositions are unusual for MORB, and are interpreted to result from interaction between MORB-like melts and harzburgitic peridotite at low pressure. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: mid-ocean ridge basalts; melts; inclusions; spinel; peridotites; petrology

1. Introduction

Reaction between an ascending melt and wallrock peridotite beneath mid-ocean spreading centers, an idea originally developed from the study of ophiolites (e.g., [1–6]), has gained additional support from chemical ‘refertilization’ trends in abyssal peridotites [7]. The recent discovery within refractory mantle rocks of tabular to irregular bodies of dunite containing melt impregnations in the form of gabros and troctolites in a number of localities in Atlantic and Pacific oceans [8–13], allowed preliminary assessments of the nature and extent of phase modifications in peridotites. The record of melt–peridotite interaction is best shown by compositions of the mineral constituents of these rocks, which are believed to be the reaction products [9–11,14], and also by the presence of hydrous phases included in spinel in dunites and troctolites [8,15].

Despite the recent evaluation of effects of melt–harzburgite interaction during petrogenesis of Hawaiian intraplate tholeiitic magmas [16], the consequences of the reaction between percolating melt and upper mantle peridotite on MORB compositions is not as yet well constrained. Therefore, further research into diverse melt fractions that may have escaped shallow-level mixing is warranted in order to understand the compositions of MORB primary melts, their evolutionary paths during ascent and the effects of high-pressure fractionation and re-equilibration on the compositions of residual peridotites.
and erupted rocks and glasses. This will better constrain understanding of mechanisms of melt transport through the upper mantle and help to refine models for the formation of the oceanic crust.

In this paper we present the results of detailed study of mineral and melt inclusion compositions in basaltic rocks (MORB) from 43°N, Mid-Atlantic Ridge. The unusual chemistry of melts and liquidus phases is interpreted to arise from melt–peridotite interaction and reflect the evolutionary trends of common MORB melts during this interaction. These data complement our previous discovery of primitive clinopyroxene phenocrysts and high-Ca melt inclusions in basalt AII32 D12-7 from the same locality [17].

2. Phenocrysts and melt inclusions in sample AII-32 D11-177

Sample AII32 D11-177 was dredged during cruise 32 of the R/V Atlantis II from 1983–2168 m water depth in the eastern part of the median valley of the Mid-Atlantic Ridge (MAR) at 42°57’N 29°15’W [18,19]. This area is a ‘normal’ ridge segment adjacent to the 43°N fracture zone on the periphery of the Azores Platform, and is characterized by normal to enriched MORB tholeiitic magmatism [17,19] and particularly refractory abyssal peridotites [20,21].

Table 1

<table>
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<tr>
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<th>1</th>
<th>2</th>
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<td>49.30</td>
<td>50.50</td>
<td>54.97</td>
<td>58.42</td>
<td>57.29</td>
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<tr>
<td>TiO₂</td>
<td>0.93</td>
<td>0.98</td>
<td>1.09</td>
<td>2.08</td>
<td>1.95</td>
<td>0.29</td>
<td>0.42</td>
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<tr>
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<td>15.48</td>
<td>16.92</td>
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<td>14.99</td>
<td>1.22</td>
<td>20.16</td>
<td>28.67</td>
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<tr>
<td>FeO</td>
<td>7.82</td>
<td>7.65</td>
<td>7.58</td>
<td>7.45</td>
<td>5.28</td>
<td>6.01</td>
<td>15.19</td>
<td>18.52</td>
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<tr>
<td>MgO</td>
<td>9.10</td>
<td>8.32</td>
<td>5.44</td>
<td>7.32</td>
<td>5.37</td>
<td>34.24</td>
<td>15.77</td>
<td>18.04</td>
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<tr>
<td>Na₂O</td>
<td>2.00</td>
<td>1.74</td>
<td>2.00</td>
<td>2.32</td>
<td>2.90</td>
<td>0.02</td>
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<tr>
<td>K₂O</td>
<td>0.25</td>
<td>0.44</td>
<td>0.35</td>
<td>1.12</td>
<td>0.99</td>
<td>n.d.</td>
<td>n.d.</td>
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<tr>
<td>Cr₂O₃</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.40</td>
<td>47.24</td>
<td>31.42</td>
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<td>Fo host</td>
<td>90.40</td>
<td>90.53</td>
<td>89.86</td>
<td>90.10</td>
<td>90.76</td>
<td>90.79</td>
<td>89.65</td>
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</table>

1 = pillow-rim glass; 2, 3 and 7 = Group-I (‘common’ MORB) melt and spinel inclusions, respectively; 4, 5 and 8 = Group-II melt and spinel inclusions, respectively; 6 = orthopyroxene inclusions, associated with Group-II glass (Fig. 6). 4 and 8 = melt and spinel inclusions coexisting in the same olivine grain #23 (see text and Fig. 5).

All oxides in wt%, Fo in mol%. n.d. — not determined.

The sample is a glassy olivine-phyric basalt (olivine ~10–15 vol%) with quenched pillow-rim glass. The glass has a primitive major element composition with Mg# = 69.7 and CaO/Al₂O₃ = 0.86 (Table 1), and is enriched in K₂O, H₂O (0.49 wt%) and other highly incompatible elements (e.g., La/Yb = 3.7), thus having affinities with E-MORB. Olivine phenocrysts (up to 4 mm in size) range from Fo₉₀.₃ to Fo₉₁, and they contain abundant inclusions of spinel and glass. Their CaO contents are more variable (0.18–0.4 wt%) than expected for a single fractionation-related population of magnesian olivine (Fig. 1).
Fig. 2. Compositions (Cr$_2$O$_3$ and TiO$_2$, in wt%) of spinel inclusions (squares, Group-I; triangles, Group-II) in olivine. Spinels in mid-oceanic basalts (field A, our unpublished data and [22–24]) and in melt impregnated mantle rocks from Hess Deep and Garrett Transform fault (field B, [8–10,13–15,25]) are shown for comparison.

Compositions of spinel inclusions (Table 1) fall into two principal groups based on their TiO$_2$ (0.32–0.57 wt% in Group-I (85%), 2.6–4.1 wt% in Group-II (15%)) and Cr$_2$O$_3$ (42.2–47.2 and 26.6–41.8, respectively) contents (Fig. 2), with one intermediate composition (TiO$_2$ 0.92 wt%). Group-II spinels also have higher Al$_2$O$_3$ (21–29.3) and Fe$_2$O$_3$ (5.1–8.8) than Group-I spinels (19.8–23.2 and 4–6.2 wt%, respectively), and are hosted by statistically less magnesian olivine (average Fo: 90.1 vs. 90.7). Note that extremely high TiO$_2$ compositions of Group-II spinel are atypical of MORB, and suggest unusual parental melt compositions.

Compositions of glassy melt inclusions can also be subdivided into two groups (Fig. 3, Table 1). Group-I glasses are more evolved than pillow-rim glass in terms of their MgO contents (3–8.5 wt%), and their compositional trends are broadly consistent with crystallization of olivine (Fo < 90) on the inclusion walls. When corrected for olivine fractionation, they have typical MORB compositions and are similar to the pillow-rim glass, though the latter has notably higher SiO$_2$ and Na$_2$O. In contrast, Group-II melt inclusion compositions (10% in total) are unusual in having abnormally high SiO$_2$ (54.6–58.4 wt%) and low CaO (9.3–11.1 wt%) contents, and in comparison with Group-I inclusions their TiO$_2$, Na$_2$O and K$_2$O contents are higher, but Al$_2$O$_3$ is lower (Fig. 3). The spread in Group-II compositional arrays is not related to processes of post-entrapment modification caused by olivine fractionation (Fig. 2, e.g., MgO vs. CaO). Furthermore, these inclusions are hosted by olivine whose Fo (<90.2) and CaO (<0.24 wt%) values are at the lowest end of the compositional arrays, whereas Group-I high CaO/Al$_2$O$_3$ melt inclusions associate exclusively with high-Ca (>0.27 wt%) olivine (Fig. 4).

The relation between melt and spinel inclusion compositional groups is examined in Fig. 5. Individual compositions of melt and spinel inclusions, which are trapped in different olivine phenocrysts, define wide ranges of TiO$_2$/Al$_2$O$_3$ (Group-I and Group-II compositions). Two glass inclusions and one spinel inclusion (Group-II), coexisting in the same olivine grain #23 (Table 1, NN 4 and 8) are plotted inside coordinates. The compositions of homogenized melt inclusions trapped in spinel from samples D11-92 and D12-2 (same locality) are also plotted as a guide to the equilibrium chemistry of coexisting melt and spinel in this system. They are best approximated by a second degree polynomial function ($R = 0.84$) which trends towards the high TiO$_2$/Al$_2$O$_3$ end of D11-177 array, passing through the composition of associated melt and spinel inclusions in olivine (grain #23). This implies that melt and spinel compositional groups described above are mutually correlated, and that the unusually high-Ti spinel compositions are a reflection of melt compositions enriched in Ti and depleted in Al.

Silica-enriched Group-II melt compositions are clearly saturated in orthopyroxene component, and might be expected to have orthopyroxene on the liquidus. A careful search located euhedral crystals of high-Mg (Mg# 91) orthopyroxene (Table 1, Fig. 6) in low-CaO (0.21 wt%) olivine in association with high-Si melt inclusions. To the best of our knowledge this is the second finding of orthopyroxene in MORB (see [27,28]).

3. Discussion

Common MORB minerals and melt inclusions in basalt D11-177 coexist with an atypical liquidus assemblage (~10–15%), comprising primitive low-Ca olivine, high-Ti chromian spinel, orthopyroxene and melt enriched in Si, Ti, Na and K, and depleted
in Al and Ca. The record of diverse mineral and melt inclusion compositions within a single MORB sample is not uncommon (e.g., [17,24,28]), but in this case the compositional groups cannot be directly linked by mantle melting or magma chamber fractionation processes. Previously, the rare presence of primitive orthopyroxene in DSDP Site 334 cumulates [29] and in a Vema fracture zone basalt in association with high-Si ultra-depleted (UDM) melt [27,28] was interpreted to result from crystallization of highly depleted magmas, formed by shallow level (<5 kbar) critical (continuous) melting of already depleted mantle peridotite. As these latest-stage, low-pressure fractional melts are very depleted in Ti and Na and have elevated Al contents [27,28] this could not be a viable explanation for our Group-II melt compositions. Note, that the composition of primitive orthopyroxene (Mg# 90.8) in association with the UDM [27,28] is quite different from the composition of orthopyroxene on
Fig. 4. Correlation between CaO/Al₂O₃ in melt inclusions and CaO of host olivines. Symbols as in Fig. 3. Compositions of high-Ca melt inclusions in olivine from basalt AII2 D12-7 [17], plotted as a field, can be considered complimentary to low-Ca Group-II melts.

Fig. 5. Plot of TiO₂/Al₂O₃ in spinel inclusions vs. TiO₂/Al₂O₃ in melt inclusions hosted in primitive olivine (Fo 89.3–91) in basalt AII-32 D11-177. During sample preparation and analysis, only a single olivine grain (23) showed simultaneous exposure at the grain surface of both one spinel and two melt inclusions; these are plotted as triangles. In other olivines, melt inclusions (open diamonds) or only spinels (closed diamond) but never both, were exposed in any individual grain, precluding plotting any more compositional pairs in this diagram. To provide further data, we have analysed homogenized melt inclusions in spinel phenocrysts in two other MORB from the same locality AII-32 D11-92 and AII-32 D12-2 (circles). Note the trend through the latter data (solid line) extrapolates (dotted line) to the Group-II spinel/melt compositions in grain #23 (Table 1, NN 4 and 8), and that compositions of other spinels and melt inclusions in our sample (plotted outside the diagram, as they occur in different olivine grains) can be projected (shaded areas) to define the same trend.

Fig. 6. Complex inclusion in forsteritic olivine (Fo 90.8) comprising orthopyroxene crystal (Table 1, N6), Group-II high-Si, low-Ca glass and fluid bubble. This orthopyroxene is compositionally different from orthopyroxene found in the ultra-depleted melt inclusion in Vema fracture zone basalt [27,28].

liquidus of Group-II melts (Table 1, N6) in having lower SiO₂ (55.3) and TiO₂ (0.04) and higher Al₂O₃ (2.1) and CaO (2.2). These diverse orthopyroxene compositions are in agreement with the contrasting compositional features of the UDM and D11-177 Group-II magmas and suggest different genesis.

We also note that our Group-II melt inclusions have some chemical affinities with Si-rich, Ca-poor alkaline glasses found in mantle xenoliths worldwide (see reviews in [30,31]), and Group-II spinels are much closer to Ti- and Fe³⁺-rich chromites in some mantle rocks from Hess Deep and Garrett transform fault on the East Pacific Rise (EPR), than to MORB spinel (Fig. 2). What do these glass-hosting xenoliths and titaniferous spinel-bearing abyssal rocks have in common? They all demonstrate textural and chemical evidence of melt–peridotite reaction followed by extensive replacement of primary orthopyroxene by olivine + clinopyroxene + spinel ± plagioclase assemblages [11,12,31]. What features do the melt-impregnated peridotites from the EPR and 43°N MAR peridotites have in common? They all are Cpx-poor harzburgites with similar, most refractory compositions of residual phases [9–
Moreover, 43°N MAR peridotites, in contrast to the majority of porphyroclastic abyssal peridotites, have protogranular textures expressed by clinopyroxene and spinel occurring “at the peripheries of, interstitially between, or as irregular blebs in, the large orthopyroxene grains” [20]. Such a texture is commonly attributed to recrystallization processes in the mantle (e.g., [33,34]).

The notion of dissolution of pyroxene in olivine-saturated magmas [3] has been elaborated by Kelenben and coworkers (e.g., [26,35]), who discussed dissolution of orthopyroxene and concomitant precipitation of olivine and clinopyroxene during melt–peridotite interaction at constant or decreasing temperatures in the shallow mantle. Thus, the origin of clinopyroxene dunite or olivine-rich wehrlite mantle lithologies was explained by the reaction between basaltic magma saturated in olivine and calcic pyroxene and peridotite wall rocks. Similarly, orthopyroxene dissolution and concomitant crystallization of olivine and diopside has been demonstrated to result from reaction of ephemerall carbonatite magmas with lherzolitic lithospheric mantle [36]. Also, the presence of melt–peridotite interaction has usually been inferred from the compositions of abyssal and alpine peridotites. Our study links composition of melts and liquidus assemblage in erupted lavas with unusual ‘recrystallization’ features of upper mantle peridotites.

To explain the peculiar features (high Si, Ti, Na, K and low Ca and Al) of D11-177 Group-II melt inclusions we propose the following:

1. ‘Typical’ MORB liquids (e.g., with the composition of magmas parental to the Group-I melt inclusions) produced within lherzolitic mantle at high pressure segregate and commence ascent;
2. These melts are saturated in olivine and undersaturated in orthopyroxene component at low pressure (e.g., [37,38]), and particularly at elevated H2O abundances;
3. Some melt fractions react with the shallow wallrock harzburgitic mantle residual after MORB extraction, whereas others pass through unmodified;
4. The reactive melts crystallize olivine, clinopyroxene, and an aluminous phase (spinel or possibly plagioclase if pressures <10 kbar) within harzburgite and dissolve orthopyroxene [11,12,15], and resultant melts are thus buffered at high ‘mantle’ Mg# values [26,35], whereas the abundances of Si increase and Ca and Al decrease. The observed enrichment of the Group-II melts in moderately incompatible Ti and Na argues for a decrease in the magma mass, i.e. amount of crystallizing phases exceeds the amount of orthopyroxene dissolving into melt;
5. Mixing of common MORB melts and the products of their interaction with harzburgite en route to the surface or in shallow magma chambers beneath the ridge may produce hybrid magmas with elevated Si and Na and reduced Ca abundance, similar to AII32 D11-177 pillow rim glass (Fig. 3);
6. Clinopyroxene-rich, orthopyroxene-poor mantle lithologies within shallow mantle peridotite are likely to be left behind as a result of melt–peridotite interaction outlined above.

Significant evidence for the formation of clinopyroxene-enriched peridotite during migration of ‘typical’ MORB melts comes from the study of mineralogy and melt inclusions in basalt AII32 D12-7 [17]. This rock was dredged from the same locality at the Mid-Atlantic Ridge as our sample AII32 D11-177, but at a shallower depth (1440–1820 m water depth), so it may be slightly younger. D12-7 is unusual in that it carries extremely primitive Cr-diopside (Mg# 90–92), high-Ca olivine (Fo up to 92, Fig. 1), and Cr-spinel (Cr# up to 70, cf. <60 in MORB) phenocrysts. The unusual mineral assemblage in this basalt is in excellent agreement with similarly atypical compositions of homogenized high-Mg (MgO 10–12 wt%) melt inclusions in olivine phenocrysts, which have high CaO (up to 15.2) and low Al2O3 (12.8–15.5), so their CaO/Al2O3 value (Fig. 4) trends to very high values (up to 1.2 — cf., <0.9 in MORB). Because these melt compositions deviate strongly from 4-phase peridotite saturation and are saturated with olivine + clinopyroxene only, they have been earlier interpreted as the products either of melt–wallrock reaction between a MORB melt and clinopyroxene-rich lithology (e.g., wehrlite), or of mixing between melts derived separately from distinct mantle lithologies [17]. Therefore, our detailed mineralogical and melt inclusion data from basalts from 43°N MAR provide additional insight into the mechanism of melt–peridotite interaction and subsequent effects on the composition of erupted MORB magmas.
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