Melt Inclusions in Minerals as a Source of Principle Petrological Information

A. V. Sobolev

Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, ul. Kosygina 19, Moscow, 117975 Russia

Received December 20, 1995

Abstract—Secondary ion mass spectrometry and electron microprobe studies demonstrated that melt inclusions in magnesian olivine bear evidence of the composition and formation conditions of the primary melts and their mixing products, including the initial water contents of the mantle melts. This information is partially or completely obliterated in the compositions of rocks and glasses by later processes of mixing, contamination, degassing, and crystal fractionation. The typical oceanic basalt of the Mid-Atlantic Ridge is shown to have formed through the mixing of primary melts that were derived by the critical melting of a mantle column, more than 50 km thick. The melting began in the presence of garnet and proceeded in an open system which could retain no more than 2–3 wt % melt. The mixing of the primary melts took place both in magma chambers, simultaneously with crystallization and, probably, during melt transport through the mantle. The initial concentrations of H$_2$O in the mantle magmas of suprasubduction zones were as high as 2–3 wt %, which is significantly higher than was estimated previously. No correlation was found between the concentrations of H$_2$O in the primary MORB magmas and those of elements with a similar incompatibility degree (La, Ce, K). This fact may indicate the continuous interaction of the melts with H$_2$O-bearing CO$_2$-rich fluid.

INTRODUCTION

A unique feature of magmatic inclusions in minerals is their ability to preserve information on the instantaneous composition and evolutionary conditions of magmatic systems (e.g., Roedder, 1984), which is completely or partially obliterated from the rock or glass chemistries by later processes of mixing, contamination, degassing, and crystal fractionation. The typical oceanic basalt of the Mid-Atlantic Ridge is shown to have formed through the mixing of primary melts that were derived by the critical melting of a mantle column, more than 50 km thick. The melting began in the presence of garnet and proceeded in an open system which could retain no more than 2–3 wt % melt. The mixing of the primary melts took place both in magma chambers, simultaneously with crystallization and, probably, during melt transport through the mantle. The initial concentrations of H$_2$O in the mantle magmas of suprasubduction zones were as high as 2–3 wt %, which is significantly higher than was estimated previously. No correlation was found between the concentrations of H$_2$O in the primary MORB magmas and those of elements with a similar incompatibility degree (La, Ce, K). This fact may indicate the continuous interaction of the melts with H$_2$O-bearing CO$_2$-rich fluid.

distribution (Sobolev and Chaussidon, 1996), and contains trace amounts of most of the elements that characterize the melt composition. Glassy melt inclusions in these olivines are safely isolated from the external media and represent the composition of primary melts at the early stage of system crystallization for most elements, except for those which compose olivine: Mg, Si, and the elements of the Fe group (e.g., Green, 1994). The abundances of the latter in inclusions could be modified by olivine crystallization on the walls or exchange with the host mineral, but calculation or homogenization methods allow these effects to be easily corrected (Sobolev and Danyushevsky, 1994).

The goal of this work is to demonstrate how the application of the methods of melt inclusion investigations of minerals, more specifically, of olivine, enables us to obtain petrological and geochemical information which could not be gained by other methods. Two examples are considered: the reconstruction of primary melt compositions for the typical basalts of mid-oceanic ridges (MORB), and the determination of primary H$_2$O contents in mantle melts. The results of this investigation show that melt inclusions in olivine from a particular typical MORB sample bear information on the considerable ranges of compositions and formation conditions of primary melts, whereas the abundances of H$_2$O in melt inclusions trapped in the magnesian olivines of mantle magmas from various geodynamic set-
tions provide important information on the concentrations and behavior of H\textsubscript{2}O in mantle source regions and magmatic systems.

METHODS OF STUDY

This work presents the results of the investigations of natural glassy inclusions in olivine phenocrysts without their preliminary homogenization. All inclusions studied are primary (Roedder, 1984) and contain glass and shrinkage bubbles. Since most of the melt inclusions in minerals experienced the crystallization of the host mineral on the inclusion walls (Roedder, 1984; Anderson, 1974), the reconstruction of their initial composition is imperative. For the inclusions under study, this procedure included the inverse simulation of olivine fractionation until equilibrium with the host mineral was attained (Sobolev and Shimizu, 1993). The model of Ford et al. (1983) for the olivine–melt equilibrium was used for the calculations. The fractions of different valence forms of iron in melt were calculated by the model of Klinc et al. (1983) for the conditions of the quartz–fayalite–magnetite buffer. The concentrations of incompatible elements including H\textsubscript{2}O in olivine were taken to be zero. All the following considerations use the corrected compositions of trapped melts with respect to both major and trace elements.

Major Elements

The concentrations of major elements in the inclusions and their host minerals were determined under standard conditions by a Camebax Microbeam electron microprobe at the Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences. The measurements were performed at a beam current of 10–30 nA and an accelerating voltage of 15 kV. Natural glass (USNM 111240/52), olivine (USNM 111312/444), and microcline (USNM 143968) (Jarosewich et al., 1980) were used as standards.

Trace Elements

Trace elements (Zr, Y, La, Ce, Nd, Sm, Eu, Dy, Er, and Yb) and Ti in inclusions were determined by secondary ion mass spectrometry on an IMS–4f ion microprobe at the Institute of Microelectronics, Russian Academy of Sciences (Yaroslavl', Russia). The energy filtering method was used for analysis (Shimizu and Hart, 1982) with the size of a primary O\textsuperscript− beam at 20 μm, a current at 5–7 nA, and an energy offset at 50 eV. The width of the energy slit was 50 eV. Element concentrations were calculated from the ratio of respective isotopes to \textsuperscript{30}Si using calibration curves for glass and clinopyroxene standards, which were analyzed by the isotope dilution method. Figure 1a shows examples of such curves. Analyses of the standards and replicate measurements of inclusions indicated the accuracy of trace element concentrations to be better than 10% for concentrations higher than 1 ppm, better than 20% for concentrations at 0.1–1 ppm, and better than 40% for concentrations below 0.1 ppm.

H\textsubscript{2}O

The abundances of H\textsubscript{2}O in inclusions and glasses were determined by secondary ion mass spectrometry on IMS–4f and IMS–3f ion microprobes at the Institute of Microelectronics, Russian Academy of Sciences (Yaroslavl', Russia) and Centre de Recherches Petrographiques et Geochimiques (CRPG) (Nancy, France), respectively. The analytical conditions at CRPG, France, were published elsewhere (Sobolev and Chaussidon, 1996). In Yaroslavl’, H\textsubscript{2}O was determined from the mass of \textsuperscript{1}H measured in the same cycle together with trace elements under the above conditions. In order to eliminate the effect of sample charging on the real shift of energy offset, it was measured and corrected automatically in the beginning of each cycle. The low background H\textsubscript{2}O level of the equipment (0.03 wt %) was provided by keeping the sample under high vacuum conditions for 2–3 days and measured on magnesian olivine.

The calibration curve (Fig. 1b) was obtained on the basis of natural glasses with H\textsubscript{2}O contents ranging from 0.1 to 4.0 wt % as was determined by infrared spectrometry (Danyushhevsky et al., 1993). The calibration at higher water contents (6–10 wt %) was based on experimental glasses of ongonite composition (60–63 wt % SiO\textsubscript{2}, rich in fluorine (4.5 wt %), courtesy of V.I. Kovalenko. Figure 1b demonstrates that, in spite of the considerable compositional interval, the results for the whole set of the standard glasses may be satisfactorily fitted by a unique quadratic relation with an error of no more than 10% relative. The relative reproducibility of particular measurements normally equaled 2–5%. Thus, the integrated relative error in the H\textsubscript{2}O measurement in the inclusions was determined by the calibration precision, and was better than 10%.

RECONSTRUCTION OF INITIAL MORB MELTS

Problem Statement

According to modern concepts (McKenzie, 1994; McKenzie and O’Nions, 1995; Langmuir et al., 1992; Kinzler and Grove, 1993, etc.), the products of mantle magmatism in all main geodynamic settings are formed by multiple mixing, contamination, and crystal fractionation of continuous series of initial mantle melts formed under a finite interval of P–T conditions during decompression melting in an open mantle system. The primary mantle melts are practically absent among natural glasses and rocks (O’Hara, 1995). This fact makes the determination of the compositions of primary mantle melts an important challenge, because this information alone could be used for the direct reconstruction of melting conditions and the compositions of mantle source regions. A number of authors proposed indirect approaches to this problem based on the idealized mod-
els of primary melt modification, for instance, assuming complete mixing and reequilibration in transport systems (e.g., Langmuir et al., 1992). The present work utilizes an alternative approach based on the direct reconstruction of the compositional interval of primary melts participating in the generation of the typical oceanic basalt.

Study Object

The sample that we studied (649/c) is a olivine–plagioclase phyric basalt dredged in the rift valley of the Mid-Atlantic Ridge at 9°N (Sushchevskaya et al., 1985). The sample was described by Sobolev et al. (1988), and is of particular interest because it contains phenocrysts of unzoned magnesian olivine and is the first oceanic basalt, where the presence of ultradepleted melt inclusions in olivine was documented (Danyushevsky et al., 1987; Sobolev and Shimizu, 1992, 1993).

Major Elements

Two independent criteria were used to identify primary melts that have been in equilibrium with the mantle source: (1) equilibrium with mantle olivine (Fo 88.5–91.0) and (2) equilibrium with the olivine–orthopyrox-
plotted in Fig. 3 against the pressure of their equi-
compositions, therefore, may be accepted as the esti-
nesian olivine (equil. Fo > 88.5) claimed by Kinzler and Grove (1992). These
of olivine owing to the crystallization differentiation of
in the lowest standard deviation of pressure estimates.
the melt. Meanwhile, most of the melts trapped in mag-
magnesian olivine are either primary mantle liquids
or the products of their mixing, which migrated from
depths of 50–10 km into intermediate reservoirs at a
depth of less than 10 km, where they were trapped and
isolated by liquidus olivine.

The coexistence of chemically contrasting melt
inclusions in the liquidus olivine of a single sample is
rather common in the products of mantle magmatism of
various geodynamic settings (Sobolev and Shimizu, 1992, 1993, 1994; Sobolev, 1994; Nikogosian and
Sobolev, 1995; Gurenko and Chaussidon, 1995; Port-
ng in the quench glass (Figs. 4 and 5) indicate that the final product of mixing was in that case
the transporting melt. The compositions of melt inclusions in the magnesian olivines (Fig. 5) suggest that the mixing may have already proceeded at the earliest stages of

\[
\text{Standard deviation of } P, \text{kbar} \quad \begin{array}{c}
\text{Fo, mol % in olivine} \\
86.0 \quad 87.0 \quad 88.0 \quad 89.0 \quad 90.0 \quad 91.0 \\
0.0 \quad 2.0 \quad 4.0 \quad 6.0
\end{array}
\]

**Fig. 2.** Dependence of the standard deviation in the average equilibrium pressure of melt inclusions with olivine, ortho-
pyroxene, clinopyroxene, and an aluminous phase (spinel or plagioclase) upon the composition of host olivine. The pres-
ures were calculated by the model of Kinzler and Grove (1992).
The rectangular field shows melt compositions assumed to be potentially primary (see text).

e–clinopyroxene–aluminous phase (spinel or plagi-
clase) assemblage. The first condition is based on data
on the olivine composition in abyssal peridotites (Dick, 1989). The second one implies the convergence of pres-
calculated for the equilibrium of each of the four
mante phases with melt using the model of Kinzler and
Grove (1992). It should be pointed out that these crite-
ria do not allow primary melts to be differentiated from
the products of their mixing because of the additivity
and linearity of the considered parameters. The melts
selected on the basis of these criteria will therefore be
referred to as potentially primary (table).

On the basis of the major element composition of the
melt, equilibrium pressure was determined for each of
the four phases of the mantle association using the
algorithm of Kinzler and Grove (1992), and the average
value was then calculated. The equations for plagi-
oclase lherzolite or spinel lherzolite were used for an
average pressure of less than 9 kbar and more than
10 kbar, respectively. For intermediate pressures, between
9 and 10 kbar, the calculations were carried out for both
associations, and a model was accepted which resulted
in the lowest standard deviation of pressure estimates.
Figure 2 demonstrates the standard deviation for calcu-
ated equilibrium pressure as a function of the compo-
nent of the host olivine. The standard deviation clearly
increases with the decline of the forsterite mole fraction
of olivine owing to the crystallization differentiation of
the melt. Meanwhile, most of the melts trapped in mag-
nesian olivine (Fo > 88.5) yielded the standard devia-
tion that appeared to be lower than the method accuracy
(2.5 kbar) claimed by Kinzler and Grove (1992). These
compositions, therefore, may be accepted as the esti-
mates of potentially primary melts.

The compositions of these potentially primary melts
are plotted in Fig. 3 against the pressure of their equi-
librium with the mantle source. This diagram reveals
a considerable interval of parameters, which was not
reported previously for a single sample. The pressure
decline is accompanied by a significant increase of
SiO₂ and CaO and decrease of FeO and MgO, which
agrees with the polybaric model of mantle source melt-
ing (Kinzler and Grove, 1992, 1993).

**Rare Earth Elements**

Figure 4 shows that the melt inclusions in olivines
from the sample studied are characterized by extremely
wide variations of LREE concentrations, considerably
exceeding the range of known MORB compositions
(Sobolev and Shimizu, 1993). For instance, the mini-
imum and maximum La contents differ by a factor of 450.
The majority of the inclusions (approximately 90%) are
similar to the quench glass of the sample with respect to
REE distribution (Fig. 4) and incompatible element
ratios (Fig. 5). The remaining 10% comprise inclusions
either ultradepleted or relatively enriched in the most
incompatible elements. Most of these inclusions were
found in magnesian olivines (Fig. 5).

**Formation Conditions**

According to previous studies (Sobolev et al., 1988;
Danyushevsky et al., 1987), olivine phenocrysts from
the considered sample crystallized together with cal-
cium plagioclase at low pressures (1–4 kbar) and in the
temperature interval of 1250–1200°C. The system was
quenched in a submarine environment at a temperature
of approximately 1200°C. The magnesian olivine
(Fo 90.5–88.5) crystallized within the first 20°C of the
temperature interval. Thus, taking into account the data
presented in Figs. 2 and 3, the melts from the inclusions
in magnesian olivine are either primary mantle liquids
or the products of their mixing, which migrated from
depths of 50–10 km into intermediate reservoirs at a
depth of less than 10 km, where they were trapped and
isolated by liquidus olivine.

The coexistence of chemically contrasting melt
inclusions in the liquidus olivine of a single sample is
rather common in the products of mantle magmatism of
various geodynamic settings (Sobolev and Shimizu,
1992, 1993, 1994; Sobolev, 1994; Nikogosian and
Sobolev, 1995; Gurenko and Chaussidon, 1995; Port-
yagin et al., 1996). This phenomenon may be
explained by the crystallization of phenocrysts in dif-
f erent parts of a magmatic system (series of magma
chambers and conduits) from melts of varying compo-
sition. The chemical heterogeneity of the melt could
result from magma mixing in a dynamic system. Simi-
lar concentrations of incompatible elements in most of
the inclusions and in the quench glass (Figs. 4 and 5)
indicate that the final product of mixing was in that case
the transporting melt. The compositions of melt inclusions
in the magnesian olivines (Fig. 5) suggest that the mixing
may have already proceeded at the earliest stages of
crystallization or before it in the mantle. Direct evi-
dence on the mixing of chemically different melts
coeval with the growth of a particular phenocryst of
magnesian olivine (Fo 90) is provided by the composi-
tions of inclusions coexisting in one grain with the
ultradepleted melt inclusion [Fig. 3 and (Sobolev and
Shimizu, 1992)].

The investigation of abyssal peridotites (Johnson
et al., 1992), cumulates of dike complex in the oceanic
crust (Ross and Elthon, 1993), and melt inclusions in
the olivines of oceanic basalts (Sobolev and Shimizu,
1993) demonstrated that the melting of the oceanic
mantle proceeded through a mechanism similar to frac-
tional melting. Primary melts formed in this process
must display the extensive fractionation of the most
incompatible elements and differ significantly from
typical MORBs by both depletion and enrichment in
these elements (Sobolev, 1994). These are precisely the
patterns typical of approximately 10% of the inclusions
in the most magnesian olivines of the sample studied
(Figs. 4 and 5).

The variations of incompatible element contents in
the melt inclusions may be explained in the context of
the critical melting of the mantle source (Sobolev and
Shimizu, 1992). The calculations demonstrated (Fig. 6a)
that the abundances of REE in the ultradepleted melt
inclusions are satisfactorily modeled by the melting of
oceanic spinel lherzolite at a degree of melting ranging
from 13 to 18%, and a fraction of melt retained in the
residua, from 2 to 3%. The presence of garnet in a
source material is required to explain the high Nd and
Sm contents relative to heavy REE (Er, Yb) in the
enriched melts. In this case, the composition of the
most enriched melt may be approximated by a mixture
of 60% of the melt formed by the low-degree melting
of the garnet-bearing oceanic mantle and 40% of the
ultradepleted melt. The fraction of melt retained by the
mantle material was estimated in all models as no more
than 2–3%, which indicates the high permeability of
the oceanic mantle for low melt fractions and agrees
with the results of previous studies (Johnson et al.,
1990; Sobolev and Shimizu, 1993; Sobolev, 1994). The
compositions of most inclusions are satisfactorily mod-
el by the mixing of all primary melts formed over the
entire melting interval.

Figure 6 compares the P–T parameters of the forma-
tion of potentially primary melts estimated on the basis
of major element compositions and the results of
geochemical modeling. The obtained data are consis-
tent with each other and with the decompression melt-
ing model of the oceanic mantle. The latter may be
inferred from the following observations:

1. All the P–T estimates of melt formation condi-
tions lie within the interval of the partial melting of the
mantle lherzolite and show a temperature decline with
decreasing pressure.

2. The minimum degrees of melting and the pres-
ence of garnet in the mantle source region were
detected for the deepest melt (Fig. 6, composition 4).

3. Geochemical criteria of mixing between the
deepest melt with the most shallow ultradepleted one
are consistent with the fact that the estimated formation
pressure of the former is not high enough to equilibrate
with a garnet-bearing source (14 kbar at a required
value of 22–24 kbar). The total pressure for such a mix-
ture should be approximately 16 kbar, which agrees
Representative compositions of potentially primary melts from inclusions in the olivine of sample 649/c

<table>
<thead>
<tr>
<th>Components</th>
<th>18/4</th>
<th>14/4</th>
<th>UDM*</th>
<th>36a/4</th>
<th>4/4</th>
<th>1a/4</th>
<th>16/4*</th>
<th>21/4</th>
<th>19/4</th>
<th>29/4</th>
<th>34/4*</th>
<th>27/4*</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂, wt %</td>
<td>48.8</td>
<td>49.67</td>
<td>52.9</td>
<td>50.15</td>
<td>50.16</td>
<td>49.63</td>
<td>48.52</td>
<td>49.85</td>
<td>49.65</td>
<td>49.84</td>
<td>50.1</td>
<td>49.64</td>
<td>49.7</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.78</td>
<td>0.79</td>
<td>0.29</td>
<td>1</td>
<td>0.74</td>
<td>0.75</td>
<td>1.24</td>
<td>0.88</td>
<td>0.86</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>1.25</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>17.45</td>
<td>16.73</td>
<td>15.5</td>
<td>17.07</td>
<td>16.64</td>
<td>16.62</td>
<td>16.8</td>
<td>16.31</td>
<td>17.34</td>
<td>16.88</td>
<td>17.24</td>
<td>16.48</td>
<td>15.9</td>
</tr>
<tr>
<td>FeO</td>
<td>7.76</td>
<td>7.63</td>
<td>7.03</td>
<td>7.46</td>
<td>7.84</td>
<td>8.08</td>
<td>8.65</td>
<td>8.04</td>
<td>7.93</td>
<td>7.96</td>
<td>7.91</td>
<td>8.48</td>
<td>9.20</td>
</tr>
<tr>
<td>MnO</td>
<td>0.12</td>
<td>0.13</td>
<td>0.08</td>
<td>0.13</td>
<td>0.14</td>
<td>0.16</td>
<td>0.13</td>
<td>0.18</td>
<td>0.14</td>
<td>0.12</td>
<td>0.15</td>
<td>0.12</td>
<td>0.2</td>
</tr>
<tr>
<td>MgO</td>
<td>10.64</td>
<td>10.51</td>
<td>10.5</td>
<td>9.93</td>
<td>10.15</td>
<td>10.39</td>
<td>11.02</td>
<td>10.36</td>
<td>10.09</td>
<td>10.22</td>
<td>10.13</td>
<td>10.78</td>
<td>8.1</td>
</tr>
<tr>
<td>CaO</td>
<td>12.3</td>
<td>12.51</td>
<td>12.5</td>
<td>12.09</td>
<td>12.22</td>
<td>12.29</td>
<td>11.54</td>
<td>12.4</td>
<td>11.74</td>
<td>12.18</td>
<td>11.51</td>
<td>11.7</td>
<td>11.8</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.01</td>
<td>1.89</td>
<td>1.12</td>
<td>1.99</td>
<td>1.96</td>
<td>1.89</td>
<td>1.93</td>
<td>1.81</td>
<td>2.06</td>
<td>1.84</td>
<td>2.04</td>
<td>1.87</td>
<td>2.58</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.03</td>
<td>0.04</td>
<td>0</td>
<td>0.08</td>
<td>0.05</td>
<td>0.06</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
<td>0.1</td>
<td>0.05</td>
<td>0.02</td>
<td>0.1</td>
</tr>
<tr>
<td>Fo (olivine)</td>
<td>90</td>
<td>89.92</td>
<td>89.9</td>
<td>89.52</td>
<td>89.23</td>
<td>89.22</td>
<td>89.2</td>
<td>89.13</td>
<td>89.13</td>
<td>89.08</td>
<td>89.02</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>P avg, kbar</td>
<td>9.4</td>
<td>7.7</td>
<td>4.5</td>
<td>8.0</td>
<td>7.4</td>
<td>7.8</td>
<td>13.3</td>
<td>7.1</td>
<td>9.2</td>
<td>8.0</td>
<td>9.2</td>
<td>8.6</td>
<td>–</td>
</tr>
<tr>
<td>P std. dev.</td>
<td>1.5</td>
<td>1.8</td>
<td>1.0</td>
<td>0.7</td>
<td>1.3</td>
<td>1.6</td>
<td>1.3</td>
<td>1.6</td>
<td>0.3</td>
<td>0.7</td>
<td>0.8</td>
<td>1.2</td>
<td>–</td>
</tr>
<tr>
<td>T, °C</td>
<td>1287</td>
<td>1271</td>
<td>1247</td>
<td>1272</td>
<td>1268</td>
<td>1270</td>
<td>1332</td>
<td>1264</td>
<td>1282</td>
<td>1272</td>
<td>1282</td>
<td>1278</td>
<td>–</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.26</td>
<td>0.13</td>
<td>–</td>
<td>0.17</td>
<td>0.17</td>
<td>0.26</td>
<td>0.17</td>
<td>0.20</td>
<td>0.18</td>
<td>0.20</td>
<td>0.25</td>
<td>0.19</td>
<td>0.15</td>
</tr>
<tr>
<td>Ti</td>
<td>5064</td>
<td>5045</td>
<td>1722</td>
<td>5645</td>
<td>4623</td>
<td>4802</td>
<td>8231</td>
<td>5467</td>
<td>5439</td>
<td>4675</td>
<td>4872</td>
<td>4812</td>
<td>6743</td>
</tr>
<tr>
<td>Y</td>
<td>14.7</td>
<td>17.0</td>
<td>10.2</td>
<td>15.1</td>
<td>15.0</td>
<td>16.3</td>
<td>14.6</td>
<td>17.5</td>
<td>15.0</td>
<td>14.3</td>
<td>14.4</td>
<td>22.3</td>
<td>–</td>
</tr>
<tr>
<td>Zr</td>
<td>47.9</td>
<td>47.9</td>
<td>2.9</td>
<td>53.7</td>
<td>46.1</td>
<td>47.1</td>
<td>98.6</td>
<td>54.3</td>
<td>55.6</td>
<td>49.7</td>
<td>22.6</td>
<td>6.4</td>
<td>67.5</td>
</tr>
<tr>
<td>La</td>
<td>1.65</td>
<td>1.78</td>
<td>0.015</td>
<td>2.08</td>
<td>1.97</td>
<td>2.30</td>
<td>4.03</td>
<td>2.53</td>
<td>2.57</td>
<td>1.96</td>
<td>0.50</td>
<td>0.16</td>
<td>2.56</td>
</tr>
<tr>
<td>Ce</td>
<td>5.94</td>
<td>6.06</td>
<td>0.09</td>
<td>6.69</td>
<td>6.27</td>
<td>7.50</td>
<td>13.45</td>
<td>7.49</td>
<td>7.85</td>
<td>6.47</td>
<td>2.10</td>
<td>0.53</td>
<td>8.12</td>
</tr>
<tr>
<td>Nd</td>
<td>5.29</td>
<td>5.33</td>
<td>0.30</td>
<td>6.32</td>
<td>5.29</td>
<td>5.28</td>
<td>9.91</td>
<td>5.32</td>
<td>5.96</td>
<td>5.46</td>
<td>2.87</td>
<td>0.91</td>
<td>7.28</td>
</tr>
<tr>
<td>Sm</td>
<td>1.99</td>
<td>2.02</td>
<td>0.21</td>
<td>2.04</td>
<td>2.04</td>
<td>2.04</td>
<td>2.17</td>
<td>2.10</td>
<td>2.00</td>
<td>1.81</td>
<td>1.73</td>
<td>0.84</td>
<td>2.71</td>
</tr>
<tr>
<td>Eu</td>
<td>0.63</td>
<td>0.67</td>
<td>0.12</td>
<td>0.65</td>
<td>0.58</td>
<td>0.63</td>
<td>0.77</td>
<td>0.65</td>
<td>0.68</td>
<td>0.60</td>
<td>0.61</td>
<td>0.41</td>
<td>0.82</td>
</tr>
<tr>
<td>Dy</td>
<td>2.48</td>
<td>2.94</td>
<td>0.93</td>
<td>2.51</td>
<td>2.52</td>
<td>3.20</td>
<td>2.28</td>
<td>2.65</td>
<td>2.65</td>
<td>2.49</td>
<td>2.58</td>
<td>2.28</td>
<td>3.78</td>
</tr>
<tr>
<td>Er</td>
<td>1.41</td>
<td>1.62</td>
<td>0.62</td>
<td>1.43</td>
<td>1.36</td>
<td>1.70</td>
<td>1.67</td>
<td>1.68</td>
<td>1.50</td>
<td>1.43</td>
<td>1.37</td>
<td>1.18</td>
<td>2.20</td>
</tr>
<tr>
<td>Yb</td>
<td>1.53</td>
<td>1.77</td>
<td>0.57</td>
<td>1.65</td>
<td>1.48</td>
<td>1.83</td>
<td>1.56</td>
<td>1.69</td>
<td>1.45</td>
<td>1.63</td>
<td>1.63</td>
<td>1.50</td>
<td>2.41</td>
</tr>
</tbody>
</table>

Note: Trace elements (ppm) and H₂O (wt %) were determined by secondary ion mass spectrometry. Fo (olivine)—composition of host olivine; Pavg and T are the pressure (average of four values for olivine, orthopyroxene, clinopyroxene, and an aluminous phase) and temperature of equilibrium with mantle lherzolite calculated by the model of Kinzler and Grove (1992). P std. dev. is the standard deviation of pressure estimates. UDM is the inclusion described by Sobolev and Shimizu (1993). Glass is the quench glass of the sample. Asterisks mark the compositions that approach real primary melts modeled in Fig. 6a. Dashes—not determined.
with the pressure estimate within the claimed precision of the method (Kinzler and Grove, 1992).

4. The highest degrees of melting were determined for the most shallow melt (Fig. 6, composition 1).

5. The majority of the melts may be interpreted as products of the mixing of primary melts on the basis of both geochemical and petrological modeling (Fig. 6, composition 6).

Thus, the obtained result indicates that melt inclusions in olivine phenocrysts from a single MORB sample bear information on melting conditions in a mantle column, approximately 60 km thick, and demonstrates the efficient mixing of the primary melts during the stage of shallow-level crystallization and, probably, under mantle conditions as well.

INITIAL H₂O CONTENTS OF MANTLE MAGMAS

Problem Statement

The determination of volatiles, and especially water, in mantle magmas and their source regions is an important petrological task (e.g., Sobolev, 1973; Thompson, 1992). Currently, the main approach to this problem is the investigation of natural glasses in the products of submarine eruptions (see the reviews of Michael (1995) and Jambon (1994)). However, the processes of degassing and contamination could significantly change the chemistry of mantle melts by increasing or decreasing H₂O abundances (Kyser et al., 1986; Sobolev and Chaussidon, 1996). In this case, inclusions of melt in the early crystalline phases may provide more reliable information on the initial H₂O contents of the magmas (Sisson and Layne, 1993; Sobolev and Chaussidon, 1996) owing to the isolation effect, as was discussed in the introduction.
Study Objects

In addition to the above-described sample, primitive MORBs were studied from the Mid-Atlantic Ridge, at 12°–14° and 36°N, and the Siqueiros Fracture Zone of the East Pacific Rise. The primitive magmas of subduction-related zones were studied on the example of island-arc tholeiites of the Troodos ophiolites (Cyprus), Hunter Fracture Zone (Pacific Ocean), calc-alkaline magmas of the Klyuchevskoi Volcano (Kamchatka), boninites of the Tonga Trench, Hunter Fracture zone, Bonin Island, Papua New Guinea (Pacific Ocean), and Troodos and Mamonia ophiolite complexes (Cyprus). These objects are described in more detail by Sobolev and Chaussidon (1996).

Fig. 6. Results of geochemical and petrological modeling.
(a) Normalized REE concentrations in the anomalous melt inclusions and the results of their modeling. The symbols show real compositions, the dashed lines are the models of critical melting after Sobolev and Shimizu (1992) and Gurenko and Chaussidon (1995). 1—17.5% melting, 2.3% melt in the residua; 2—15% melting, 2.5% melt in the residua; 3—13% melting, 3% melt in the residua; 4—mixture of 60% melt, formed in equilibrium with garnet (4%) at 4% melting, and 2.3% melt in the residua (composition 5) and 40% melt of composition 1; 6—product of mixing of all melt portions formed in the interval of critical melting up to 17.5% with 2.3% melt retained in the residua. The shaded area shows the field of typical melt compositions (Fig. 4).
(b) Formation conditions of the primary melts. Phase boundaries for the mantle source of MORB are shown according to the experimental results of Falloon and Green (1988), Thompson (1992), and calculations by the model of Sobolev and Babeyko (1994) for composition MPY-87 (Falloon and Green, 1988). The P–T conditions of potentially primary melts equilibration with the lherzolite association were calculated by the model of Kinzler and Grove (1992). The solid circle shows the assumed conditions of lherzolite melting with 4 wt % garnet [calculated by the model of Sobolev and Babeyko (1994)]. Ol—olivine, Opx—orthopyroxene, Cpx—clinopyroxene, Pl—plagioclase, Sp—spinel, Gar—garnet.
Effect of Degassing on the H$_2$O Content of Melt

The relative abundances of H$_2$O in melt inclusions from olivine phenocrysts and in quench glasses from the same samples are compared in Fig. 7. In all the MORB samples, the H$_2$O concentrations of inclusions are similar to those of glasses, indicating the negligible influence of degassing on the melt composition. This is consistent with the evidence of the H$_2$O-undersaturated character of MORB melts (Jambon, 1994). In contrast, the significant enrichment of inclusions in H$_2$O as compared to glasses was observed in the mantle magmas of suprasubduction zones. This fact indicates a significant water loss due to magma degassing in this geodynamic environment, and is consistent with the evidence for the presence of a water-bearing fluid phase in them (Sobolev and Danyushevsky, 1994).

H$_2$O in Primary Mantle Melts

Suprasubduction settings. The highest water contents were found in the mantle magmas formed above a subducted slab, as shown in Fig. 8. Taking into account the effect of crystal fractionation on increasing the concentration of H$_2$O in the residual melt, we may conclude that the maximum H$_2$O contents of melt inclusions from suprasubduction magmas significantly (by a factor of 2–3) exceed those of quench glasses. This implies that the values published earlier for the water flux in island-arc systems based on glass compositions (Thompson, 1992) are appreciably underestimated: compare the value of 1 wt % used by Thompson for a water content in magma and 2–3 wt % obtained in this work. This, in turn, results in revising the balance between subducted and recycled water, and suggests that most of the water entrained in a subduction zone could be recovered in an igneous processes, a possibility rejected by Thompson (1992).

Mid-ocean ridges. The H$_2$O abundances of the mantle magmas of mid-ocean ridges are significantly lower than those of the magmas of suprasubduction zones, and agree with the estimates based on quench glasses. However, another result unexpectedly appeared after studying melt inclusions demonstrating independent behavior of H$_2$O and elements with similar degrees of incompatibility (K, La, Ce) (Fig. 9), which were not detected in quench glasses. The regular relationships between the concentrations of water, K, La, and Ce reported for MORB glasses in a number of previous studies [see the review of Michael (1995)] were not observed in the inclusions with extreme abundances of incompatible elements. Roughly constant H$_2$O contents were measured in melt inclusions from the same samples from a number of the world’s regions, in spite of the considerable variations of incompatible element contents. Such water behavior cannot be explained by melting processes or variations in the composition of mantle source regions, because the partition coefficients of water and the mentioned incompatible ele-

![Fig. 7. Correlation between the H$_2$O concentrations in the melt inclusions from olivine phenocrysts and in glasses from the same samples. 1—basalts of mid-ocean ridges; 2—boninites; and 3— island arc tholeiites. To eliminate the effect of olivine and clinopyroxene fractionation, the concentrations of H$_2$O are normalized to Al$_2$O$_3$ contents. The lines show constant ratios of H$_2$O contents in the inclusions and glasses. The data of this work and of Sobolev and Chausson (1996) are plotted.](image)

![Fig. 8. H$_2$O and MgO contents in the melt inclusions from magnesian olivines. See Fig. 7 for symbol explanations. The shaded area shows the compositions of Cenozoic glasses from suprasubduction zone environments, the empty field shows modern basalts from mid-ocean ridges and ocean islands (Sobolev and Chausson, 1996). Only maximum H$_2$O contents in each sample are plotted for the magmas of suprasubduction zones. The data from this work and Sobolev and Chausson (1996) are plotted.](image)
ments between melt and crystal phases are similar (Michael, 1995). The observed phenomenon may be supposed to result from the buffering of the H$_2$O content in the mantle magmas of mid-ocean ridges by a water-bearing phase, essentially free from other incompatible elements. This phase may be represented by a CO$_2$-rich fluid, whose presence was ascertained by magmatic fluid inclusions found in the phenocrysts of all studied MORB samples (Sobolev et al., 1988; and author’s unpublished data).

CONCLUSION

1. The application of secondary ion mass spectrometry and electron microprobe analysis demonstrated that melt inclusions in magnesian olivine are capable of preserving information on the composition and formation conditions of the primary melts and the products of their mixing, as well as on the initial H$_2$O contents of the mantle melts. This information is completely or partially obliterated from the compositions of rocks and glasses by the processes of mixing, contamination, degassing, and crystallization differentiation.

2. It was shown that the typical oceanic basalt of the Mid-Atlantic Ridge formed through the mixing of primary melts generated by the critical melting of a mantle column, more than 50 km thick. The melting commenced in the presence of garnet and proceeded in an open system which could retain no more than 2–3 wt % melt. Primary melts were mixed in magma chambers during crystallization and, probably, also during their transport through the mantle.

3. The initial H$_2$O contents of suprasubduction zone magmas are no less than 2–3 wt %, which exceeds the previous estimates by a factor of 2–3.

4. No correlation was found in the primary MORB magmas between the concentrations of H$_2$O and elements with a similar degree of incompatibility (La, Ce, K), which may be indicative of the continuous interaction of melts with a water-bearing carbon dioxide fluid.

ACKNOWLEDGMENTS

The author thanks S.A. Simakin (Institute of Microelectronics, Russian Academy of Sciences, Yaroslavl’) and N.N. Kononkova (Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences) for ion and electron microprobe analyses, respectively. N. Shimizu (WHOI, USA) and M. Chaussidon (CRPG, France) greatly influenced the author’s concepts of the use of secondary ion mass spectrometry. This work was supported by the International Science Foundation, grants no. MNN000 and MNN300 and the Russian Foundation for Basic Research, projects no. 93-05-8895 and 96-05-66014.

Fig. 9. Comparative geochemical behavior of H$_2$O and elements similar in the degree of incompatibility with respect to melts for glasses and inclusions from MORB.

1–3—melt inclusions in olivine from the basalts of the Mid-Atlantic Ridge: 1—region at 9°N (table); 2—FAMOUS region (author’s unpublished data); 3—region at 14°–15°N (unpublished data, courtesy of O.P. Tsameryan, Vernadsky Institute of Geochemistry and Analytical Chemistry). All ratios are chondrite-normalized after Anders and Greshes (1989). The contents of H$_2$O and K were normalized to 85 and 83 ppm, respectively. The shaded fields are the compositions of MORB glasses after Michael (1995).
REFERENCES


