The origin of typical NMORB: The evidence from a melt inclusions study

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Introduction

In the recent studies mid-ocean ridge basalts (MORBs) are frequently regarded as mixtures of separate fractions of melt generated in mantle columns which are highly permeable even for small amounts of melt. This view is based on the theoretical models (e.g. McKenzie and Bickle, 1988), abyssal peridotite studies (e.g. Johnson *et al.*, 1990) and discovery of ultra-depleted melts (UDM) as inclusions in the high-Mg olivine in NMORBs (Sobolev and Shimizu, 1993; Sobolev *et al.*, 1994). The present paper reports results of a detailed study of the same NMORB sample in which the first UDM was found, showing that the process of MORB formation is recorded in melt inclusion compositions and could be revealed by microbeam analysis techniques.

Samples and methods

Typical NMORBs sampled on an undisturbed segment of Mid-Atlantic Ridge at 9N, 39.5W were studied. Two samples investigated here were obtained in a single dredge and are almost identical in petrography and compositions of minerals and matrix glasses. They consist of 20–30% phenocrysts of olivine (Fo_{90-87}), plagioclase (An_{86-80}), clinopyroxene (Mg# 89–87) and spinel (Cr# 38–47), and 80–70% of glass. Primary inclusions in 120 olivine phenocrysts were analyzed for major elements with electron probe (at Vernadsky Institute) and for trace elements with ion microprobe (at WHOI).

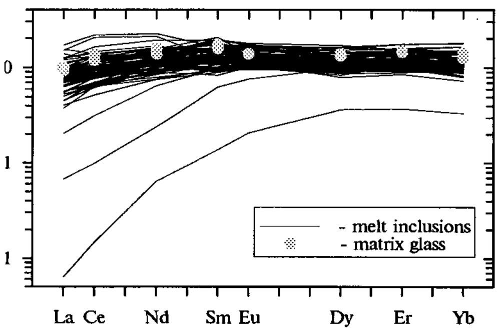

FIG. 1. *REE* in melt inclusions and matrix glasses from samples 649/C and 649/11 normalized to chondrite from Anders and Grevesse, 1989. The most depleted inclusion is from Sobolev and Shimizu (1993).

Results

As it is shown in Figs. 1 and 2, the analyzed inclusions display a dramatic range in incompatible element concentrations and ratios in the same rock sample. The observed ranges are: 0.05–1.3 for $(La/Sm)_n$, 850–80 for Ti/Zr, and 0.3–6.9 for Zr/Y. These ranges exceed considerably those known for MORB whole rocks and glasses. However, the majority of melt inclusions (around 90%) fall well within the typical NMORB composition ranges and are similar to the matrix glasses (Ti/Zr = 99-102; $(La/Sm)_n$ = 0.58–0.59; Zr/Y = 3.0). The rest (10%) of the melt inclusions show either significant depletions or enrichments in highly incompatible elements. Almost all such inclusions were found in the high-Mg olivine phenocrysts (Fo higher than 88.5, see Fig 2. UDM were found in 3% of population and are similar to those described previously (Sobolev and Shimizu, 1993 and Sobolev *et al.*, 1994). A new type of inclusions with humped *REE* patterns (Fig 3) and depletions in Y and *HREE* (termed YDM) were found in 7% of the population. The Zr/Y ratios of these inclusions vary between 4 and 7, markedly exceeding the range for typical NMORB.

The melt inclusions in high-Mg olivine (Fo > 89) corrected for the effects of post-entrapment growth of olivine manifest multiple saturation with Ol-Opx-Cpx-(Pl or Sp), based on the criteria of Kinzler and Grove (1992). Pressures and temperatures of such equilibria range from 4 to 15 kbar (most between 7 and 10 kbar) and from 1240°C to 1350°C. The highest pressure and temperature estimates are characteristics for the YDM inclusions, whereas the lowest are for the most depleted UDM.

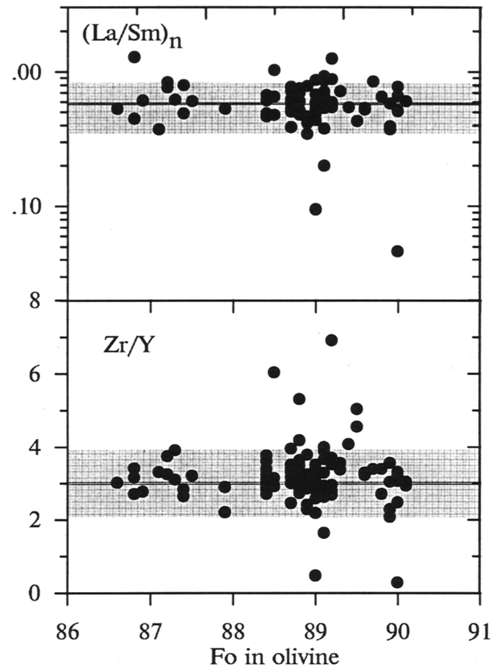

FIG. 2. Trace elements ratios in melt inclusions versus composition of host olivine. The line parallel to x-coordinate represent the compositions of matrix glasses. The shaded area indicate the ratios similar to matrix glasses within accuracy of ion probe analyses.

Discussion

As discussed previously (Sobolev and Shimizu, 1993; Sobolev *et al.*, 1994) and inferred from the data presented here, the UDM inclusions in high-Mg olivines correspond to unmixed instantaneous melts formed by critical (continuous) melting of depleted Sp-lherzolite mantle with small amounts (0.5–3 wt.%) of melt retained in the residue. The calculated extent of melting to produce UDM varied from 10 to 18 wt.%. The NMORB inclusions and matrix glasses could be interpreted as pooled melt samples of all fractions produced by this process. However, the YDM inclusions could not be formed by this process. They require a significant amount of garnet (up to 5 wt.%) in the melting source and could be easily produced by low degree of critical melting of garnet lherzolite, followed by minor mixing with the UDM (Fig 3). Thus, these melts could represent, in part, instantaneous melts formed by small degree melting at pressures greater than 20 kbar as proposed previously by Salters and Hart (1989)

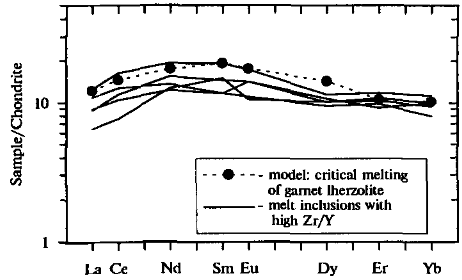

FIG. 3. The Y depleted melt inclusions (YDM). The model represent mixture between instantaneous melt formed by critical melting of garnet lherzolite with 2 wt.% of melt in residue and degree of melting 5 wt.% with 30 wt.% of UDM (Sobolev and Shimizu, 1993).

and Shimizu and Hassler (1993). As the majority of melt inclusions even in the most Mg-rich olivine (Fo 90) are NMORB type, one can speculate that mixing of instantaneous melts already occurred before crystallization of primary melts. However, we have found around 10% of potentially unmixed instantaneous melt inclusions in high-Mg olivines (Fig. 2). Also, we observed, in two olivine phenocrysts, geochemically different types of inclusions (UDM and NMORB in one and YDM and NMORB in the other) trapped in the same crystal. This suggests that in some cases the mixing of instantaneous primary melts occurs in magma chambers or conduits during crystallization of early phenocrysts, and instantaneous melts could survive during migration in the mantle. Dominance of YDM over UDM (7:3) could be explained by greater survivability of the former in mixing due to its high trace elements concentrations.

Conclusion

The data reported here suggest that typical NMORB magmas originated as a mixture of instantaneous melts formed in the mantle column at list 50 km thick by critical (continuous) melting with small amounts of residual melts (0.5–3 wt.%). The estimated degree of melting varies from around 5% at high pressures (greater than 20 kbar) in the presence of garnet as residual phase to 18% at low pressures (4 kbar). Mixing of instantaneous primary melts occurs mostly before crystallization and more rarely in magma chambers or conduits during growth of early olivine phenocrysts.