

## The relative roles of boundary layer fractionation and homogeneous fractionation in cooling basaltic magma chambers

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Quantitative understanding of chemical evolution of magmas in crustal magma reservoirs is one of the main goals of petrology, and has been investigated using experimental, thermodynamic, and field-based approaches. However, predictions of chemical evolution of magmas in a cooling magma body are still challenging. This is because, in crustal magma chambers, various kinds of instability occur as a consequence of heat transfer from the magma to the cool crust and chemical differentiation of magmas proceeds through a complex interplay of dynamic processes. Magmatic differentiation can proceed both by fractionation of crystals from the main molten part of the magma body (homogeneous fractionation) and by mixing of the main magma with fractionated melt derived from low-temperature mush zones (boundary layer fractionation). The difficulty of predicting the chemical differentiation path of magma arises partly from the fact that the differentiation trend caused by homogeneous fractionation could be fairly different from the trend resulting from boundary layer fractionation. The chemical path of the main differentiating magma is thus controlled by the relative contributions of homogeneous fractionation and boundary layer fractionation. In view of the above, this study examines how the two different kinds of fractionation processes take place in a cooling basaltic magma chamber, using a thermodynamics-based mass balance model considering homogeneous fractionation and boundary layer fractionation.

The model considers thermal and chemical evolution of magma in a cooling magma chamber. The model was designed to specifically examine chemical evolution of the main magma body. Therefore, modeling of physical processes is somewhat simplified, and thermal evolution of the main magma is simply approximated as a function of a constant cooling rate. Compositional evolution of the main magma proceeds through gravitational separation of crystals present in the main magma (homogeneous fractionation) and through mixing with the fractionated melt extracted from the mush zones (boundary layer fractionation). Multi-component thermodynamic models are used to link thermal and chemical evolution of the magma.

Model calculations show that boundary layer fractionation cannot be a dominant fractionation mechanism when magma chambers are located at low pressures (less than  $\sim 50$  MPa) or when magmas are less hydrous (less than  $\sim 1$  wt.%), such as mid-ocean ridge basalt and intraplate basalt, because of the low efficiency of melt transport from the mush zones to the main magma. Therefore, magmas evolve principally by homogeneous fractionation. If crystal-melt separation does not occur effectively in the main magma, the magma becomes crystal-rich in the early stages of magmatic evolution. On the other hand, boundary layer fractionation can occur effectively when magmas are hydrous (more than  $\sim 2$  wt.%), such as arc basalt, and the magma chambers are located at depth (more than  $\sim 100$  MPa). Because the melt derived from mush zones is enriched in alkalis and H<sub>2</sub>O, crystallization from the main magma is suppressed by mixing with the mush melt as a consequence of depression of the liquidus temperature. Therefore, homogeneous fractionation is more effectively suppressed in magma chambers in which boundary layer fractionation is more active. If magmatic differentiation proceeds primarily by boundary layer fractionation, magmas can remain free of crystals for long periods during magmatic evolution.

Quantitative understanding of chemical evolution of magmas in crustal magma reservoirs has been extensively challenged, but it appears that few models have considered both homogeneous fractionation and boundary layer fractionation. This study demonstrates that, to develop a general model for reliably predicting chemical paths of differentiating magmas, it is necessary to consider boundary layer fractionation and its interplay with homogeneous fractionation.