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Compositional Fractionation of Terrestrial Magma Oceans

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Abstract

Terrestrial planets are thought to evolve through episode(s) of large-scale melting early in their history. For example, the moon-forming giant impact has released large amounts of kinetic energy to sustain the formation of a deep and extensive "magma ocean" in the Earth's mantle [1]. Studying the crystallization and fractionation of magma oceans (MO) can provide constraints for the initial condition and thermochemical evolution of solid-state mantle convection in terrestrial planets. While simplified models of MO crystallization have been developed for various planets in our solar system [2], these models are often limited by the lack of our understanding of the interior structure of these planets. Here, we model compositional fractionation and convective mixing during crystallization of the Earth's MO, and compare model predictions with seismological constraints in terms of the thermochemical structure of the modern Earth's deep mantle [3]. Through this comparison, we identify melting and melt-rock reaction processes in the early Hadean mantle. Finally, we apply our model to other terrestrial planets such as Mars.

1. Introduction

Compositional fractionation of the MO within a terrestrial planet leads to unstable stratification within the cumulate layer that progressively grows upwards [2]. This unstable stratification results from progressive iron enrichment in the MO, and thus in the coexisting cumulate layers. However, the effects of convection and related partial melting in the growing cumulate layer during MO crystallization remain to be explored. Here, we use geodynamic models with a moving-boundary approach to study convection and mixing within the growing cumulate layer(s), and subsequently, in the fully-crystallized terrestrial mantle [3].

2. Results

For fractional crystallization, pronounced iron-enrichment upwards leads to incremental cumulate overturns during MO freezing and hence efficient cumulate mixing, except for the most Fe-enriched final-stage cumulates, which remain unmixed and persist for billions of years near the base of the mantle. Less extreme crystallization scenarios can lead to somewhat more subtle stratification and more pervasive mixing. However, MO cooling models indicate that fractional crystallization should have been dominant at least during the slow final stages of MO freezing. The long-term preservation of strongly iron-enriched cumulates at the base of the Earth's mantle as predicted by MO fractional-crystallization models is inconsistent with seismic constraints, which point toward moderate enrichment of deep-mantle rocks.

To address this inconsistency, we evaluate the potential effects of melting processes in the Hadean upper mantle. For example, partial melting in the convecting upper-mantle cumulates may have diluted the final-stage shallow MO to moderate the Fe-enrichment of related final-stage cumulates (see Figure 1). Also, we estimate that Fe-rich final-stage cumulates sink as small km-size diapirs, and that they should undergo thermal equilibration and melting during sinking. After reaction of these Fe-rich melts with the host rock, the resulting moderately Fe-enriched hybrid rock assemblages may further sink to be preserved in the deep mantle through the present day. The long-term preservation of such moderately Fe-enriched rock assemblages (due to MO dilution, melt-rock reaction or both) can reconcile the physical properties of the large low shear-wave velocity provinces (LLSVP) in the lower mantle.

If multiple episodes of MO stabilization and crystallization have occurred during the progressive accretion of our planet, multiple reservoirs of enriched cumulates may be preserved in the deep mantle. Some of these reservoirs would predate the

Moon-forming giant impact and preserve primordial $^{182}W/^{184}W$ characteristics. Such a scenario may explain the preservation of $^{182}W/^{184}W$ anomalies in Archean and modern igneous rocks.

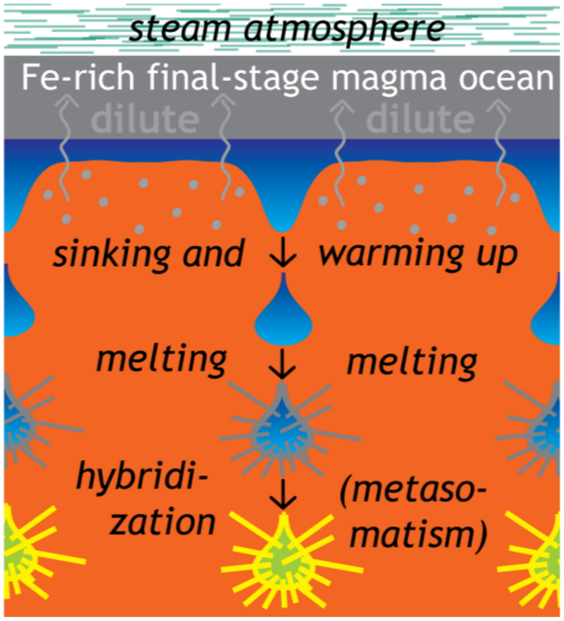

Figure 1: Cartoon illustrating the fate of final-stage MO cumulates. Fe-rich cumulates that form in the shallow final-stage MO are predicted to sink as small diapirs to thermally equilibrate and melt during sinking. The resulting moderately Fe-enriched lithological assemblages that consist of a mix of refrozen melts, hybrid rock and ambient mantle may make up the present-day LLSVPs, in particular if the final-stage MO had been modified by partial melts of the convecting cumulate layers (light grey arrows).

3. Discussion and Conclusions

By comparing the predictions of models of MO fractionation and cumulate convection with seismic constraints for the deep Earth, we reveal the operation of melting and/or melt-rock reaction processes in the early Hadean mantle. Integrated geodynamic and thermodynamic modeling will be required to better characterize these processes, and test predictions with geophysical and geochemical constraints. The viability of melting and melt-rock reaction processes in other terrestrial planets depends on the lifespan of the shallow MO, which is controlled by the thickness of the overlying atmosphere, and thus related to planet mass. For example, on small planets with little or no atmosphere, such as Mars, the MO may have cooled sufficiently fast to outpace cumulate convection and related secondary melting processes, and to form strongly Fe-enriched final-stage cumulates that are preserved in the Mars mantle until the present-day. This hypothesis is testable with future missions that may bring more than just one seismometer to our red neighbor planet.

References

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