Reconciling Magma-Ocean Crystallization Models with the present-day Structure of the Earth’s mantle

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Terrestrial planets are thought to experience episode(s) of large-scale melting early in their history. Studying the crystallization and fractionation of terrestrial magma oceans (MO) can provide constraints for the initial condition and thermochemical evolution of solid-state mantle convection. MO fractionation leads to unstable stratification within the cumulate layer due to progressive iron enrichment upwards, but the effects of incremental cumulate overturn that may occur during MO crystallization remain to be quantitatively explored. Here, we use geodynamic models with a moving-boundary approach to study convection and mixing within the growing cumulate layer, and thereafter within the resulting, fully-crystallized mantle. For fractional crystallization, pronounced stratification leads to incremental cumulate overturns during MO freezing and hence efficient cumulate mixing, except for the most iron-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. Based on scaling relationships, however, we infer that final-stage Fe-rich MO cumulates should thermally equilibrate during overturn and sinking, and hence undergo melting and reaction with the host rock. The resulting moderately iron-enriched hybrid rock assemblages should be preserved in the deep mantle through the present day. In contrast to the original strongly-enriched final-stage cumulates, moderately iron-enriched hybrid rock assemblages can much better reconcile the physical properties of the large low shear-wave velocity provinces in the present-day lower mantle. Thus, we reveal Hadean melting and rock-reaction processes by integrating simplified MO crystallization models with the present-day seismic snapshot.

Keywords: Magma Ocean, Large-Low Shear Wave Velocity Province, Lower Mantle