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Compositional fractionation of terrestrial magma oceans

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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 un-stable stratification within the cumulate layer due to progressive iron enrichment upwards, but the effects of convection and partial melting in the growing cumulate layer during MO freezing remain to be explored. Here, we use geodynamic models with a moving-boundary approach to study convection and mixing within the grow-ing cumulate layer and in the fully-crystallized mantle.

For fractional crystallization, progressive 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 our models is inconsistent with seismic constraints.

To address this inconsistency, we evaluate the potential effects of melting processes in the Archean upper man-tle. 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, particularly in the presence of a thick early steam atmosphere. Also, we find that Fe-rich final-stage sink as small km-size diapirs and infer that they should thermally equilibrate to undergo melting during sinking. After reaction of these melts with the host rock, the resulting moderately iron-enriched hybrid rock assemblages may further sink to be preserved in the deep mantle through the present day. Such moderately iron-enriched rock assemblages can better reconcile the physical properties of the large low shear-wave velocity provinces (LLSVP) in the lower mantle. The potential for melting and melt-rock reaction processes in other terrestrial planets depends on the lifespan of the shallow MO, and thus likely to atmospheric composition and ultimately to planet mass.