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Fractional Crystallization Of The Basal Magma Ocean: Consequences For Present-day Mantle Structure

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The crystallization of the Basal Magma Ocean (BMO) sets the stage for the long-term evolution of terrestrial planets and may leave behind large-scale thermochemical structures in the lower mantle. Previous work shows that a FeO-enriched molten layer or basal magma ocean (BMO) is stabilized at the core-mantle boundary of large rocky planets such as Earth for a few billion years. The BMO itself is expected to freeze by fractional crystallization (FC) because it cools very slowly. However, the fate of BMO cumulates has not yet been systemically explored.

To explore the fate of the BMO cumulates in the convecting mantle, we explore 2D geodynamic models with a moving-boundary approach. Flow in the mantle is explicitly solved, but the thermal evolution and related crystallization of the successively crystallizing BMO (i.e., below the moving boundary) are fully parameterized. The composition of the crystallizing cumulates is self-consistently calculated in the FeO-MgO-SiO_2 ternary system according to Boukaré et al. (2015). In some cases, we also consider the effects of Al_2O_3 on the cumulate density profile. We then investigate the entrainment and mixing of BMO cumulates by solid-state mantle convection over billions of years as a function of BMO initial composition and volume, BMO crystallization timescales, distribution of internal heat sources, and mantle rheological parameters (Rayleigh Number and activation energy). We vary the initial composition of BMO by manipulating the bulk molar fraction of FeO, MgO, and SiO_2, e.g. considering BMO compositions such as pyrolite, lower-mantle partial melts of pyrolite (after 50% batch crystallization), or Archean Basalt.

For all our model cases, we find that most of the cumulates (first ~90% by mass) are efficiently entrained and mixed through the mantle. However, the final ~9% of the cumulates are too dense to be entrained (either fully or partially) over the age of the Earth, and rather remain at the base of the mantle as a strongly FeO-enriched solid layer. Unless the initial thickness of the BMO is ≤100 km, this strongly enriched and intrinsically dense layer should cover the CMB globally. We highlight that this outcome of BMO fractional crystallization is inconsistent with the geophysical constraints. Our results suggest that the BMO was either very small initially or did not crystallize by end-member FC. An alternative mode of crystallization may be driven by an efficient reaction between a highly-enriched last-stage BMO with the overlying mantle. Such reactive crystallization may be much faster than FC of the BMO, as it is driven by chemical disequilibrium instead of (slow) planetary cooling.