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Reactive Crystallization of the Basal Magma Ocean: Consequences for present-day mantle structure

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Terrestrial planets evolve through multiple magma-ocean stages during accretion and differentiation. Magma oceans become progressively enriched upon fractional crystallization (FC). The resulting upwards enrichment of the cumulate package drives gravitational overturn(s), and ultimately stabilizes a FeO/SiO_2-enriched basal magma ocean (BMO). Alternatively, a ~pyrolitic BMO may be formed due to a liquid-solid density crossover at high pressures. In either case, the slowly cooling BMO is highly likely to freeze by FC, which implies strongly FeO-enriched final-stage BMO cumulates. Such a layer with density anomalies >2,000 kg/m³ is expected to remain stable at the base of the mantle, inconsistent with geophysical constraints.

Using a thermodynamic model [1], we here investigate the chemical consequences of an alternative scenario, in which the BMO interacts with (partially) molten basaltic material in the lower mantle. We refer to such a scenario as reactive crystallization (RC). Any recycled crust in the Hadean/Archean is likely to have undergone (partial) melting in the hot lowermost mantle, and therefore mixed with the BMO. We find that the first BMO cumulates due to RC are Mg-rich bridgmanite (~$MgSiO_3$). With progressive addition of basaltic material, Al_2O_3 becomes enhanced in the BMO to promote FeO-disproportionation, leading to loss of elemental Fe to the core and crystallization of $FeAlO_3$. With ongoing cooling, the BMO starts effectively shrinking, and final BMO cumulates are similar in composition (i.e., slightly more enriched) as basalt. The associated intrinsic density anomalies are just 300~350 kg/m³. These predicted densities and cumulate compositions are in very good agreement with the geophysical signatures of seismically-observed large low-velocity provinces [2]. In turn, the predicted final composition of the BMO itself may correspond to that of seismically-detected ultra-low velocity zones.

Our results imply that large rocky planets such as Earth, Venus or even Super-Earths may host only a rather short-lived BMO due to efficient crustal recycling. In turn, small stagnant-lid planets with limited crustal recycling, such as e.g. Mars, may host longer-lived BMOs. These predictions have important implications for the long-term thermal and chemical evolution of terrestrial planets.

[1] Boukaré et al. (2015), *JGR--Solid Earth*
[2] Vilella et al. (2015), *Earth Planet. Science Lett.*