Goldschmidt 2021 Abstract
https://doi.org/10.7185/gold2021.4839

Crystallization sequence of a Basal Magma Ocean in light of geophysical and geochemical constraints

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Terrestrial planets evolve through multiple magma-ocean stages during accretion and differentiation. Magma oceans become progressively enriched in FeO upon fractional crystallization (FC), which should be dominant at least in the upper mantle. The resulting upwards enrichment of the cumulate package drives gravitational overturn(s), and ultimately stabilizes a FeO-enriched basal magma ocean (BMO). Alternatively, a BMO may be stabilized due to a liquid-solid density crossover at high pressures. In any case, the slow-freezing BMO is expected to evolve subsequently due to FC, but the consequences on mantle heterogeneity and evolution have not yet been systematically explored.

Here, we investigate these consequences. For FC, the first ($MgSiO_3$) cumulates are entrained by mantle convection, but final FeO-enriched cumulates stabilize a layer at the base of the mantle due to extreme density anomalies of >500 kg/m^3. This layer is several 10s of km thick (or ~7% of the initial BMO volume), inconsistent with geophysical observations. Alternatively, the BMO may evolve due to reactive crystallization (RC). As long as the BMO-mantle boundary remains exposed due to the entrainment of cumulates, the BMO reacts with mantle pyrolite due to chemical disequilibrium. The final RC sequence consists of two discrete layers: the first is Mg-rich bridgmanite (~$MgSiO_3$); the second is a moderately FeO-enriched pyrolite. The first layer is entrained by mantle convection due to its intrinsic buoyancy, but may resist efficient mixing due to its intrinsic strength, thereby potentially providing an explanation for seismic scatterers/reflectors and ancient geochemical reservoirs. The second layer is swept up into thermochemical piles due to moderate density anomalies, providing a candidate origin for large low shear-velocity provinces. In an alternative scenario with dominant RC between the BMO and subducted Archean crust, thermochemical piles would be enhanced in fO_2 and Al-bearing bridgmanite, consistent with geophysical estimates.

Our results imply that large terrestrial planets such as Earth, Venus or even Super-Earths may host only a rather short-lived BMO due to efficient RC (instead of inefficient cooling for FC). In turn, small rocky planets, such as Mars, may host a longer-lived BMO. These predictions have important implications for the long-term thermal/chemical evolution of terrestrial planets.