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Conditions for segregation of a crystal-rich layer within a convective magma ocean

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The vigor of the thermal convection in a terrestrial magma ocean tends to prevent the sedimentation of the solid grains. Understanding of the overall dynamical behavior of this solid phase segregation is required to anticipate the solidification mechanisms in the early Earth mantle. We develop numerical models using COMSOL Multiphysics to monitor the crystal fraction evolution of a convecting magmatic reservoir. Our models show that the ability of the crystal fraction to disperse within the domain strongly depends on the crystal size, the density difference and the magma viscosity. Two regimes can be identified (sedimentation or suspension regimes) separated by the critical value of the convection/buoyancy stress ratio (Sh_c). Our 2D numerical models (1) illustrate the non-linear dependence of Sh_c on the viscosity and (2) show that Sh_c can reach smaller values than obtained from 3D analog models (Solomatov et al., 1993). These results illustrate that, during the early crystallization of a magma ocean, suspension could be the dominant process favoring an equilibrium crystallization.

We then investigate the implications of our models on the mechanism of magma ocean solidification after a major melting event on an Earth-like planet. In particular we discuss the possibility of Bridgmanite segregation depending on its buoyancy (positive or negative). To that aim, we compare the density difference between the MO and the solid crystal (Dr_{MO}) calculated for different compositions and the critical density contrast (Dr_{crit}) (derived from our numerical models) above which crystal segregation is likely to occur. We define the relevant set of parameters; including the P-V-T equations of state of coexisting melt and bridgmanite in the mushy MO. We observe that bridgmanite grains are unlikely to segregate in a mantle of pyrolite composition. However, bridgmanite segregation is more likely to occur at the bottom of a MO enriched in SiO_2, compared to pyrolite. When a solidifying layer contains 60% of bridgmanite and 40% of melt, we observe a significant SiO_2enrichment with increasing mantle depth in a primitive mantle. This feature is compatible with seismic and geochemical observations.