Stability of a thin mushy layer within a convecting magma ocean

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Résumé

The solidification within a deep convecting magma ocean (MO) is a key process that significantly shaped the Earth's interior. This process is responsible for the separation between compatible elements that prefer the solid phase (e.g., Mg, Cr) and incompatible elements which prefer the liquid phase (e.g., Al, Na, Fe). The solidification depth is governed by the geotherm and the melting curves. Crystal settling could then occur towards neutral buoyancy depths where crystals are paradoxically more easily entrained by the flow. Both chemical composition and cooling dynamics contribute to the buoyancy of a crystal layer. Depending on the crystal buoyancy relative to molten magma, different scenarios may emerge: Bottom/up solidification or mid-mantle solidification making a basal magma ocean possible.
As the vigor of the thermal convection in the magma ocean tends to prevent the sedimentation of the solid grains, a detailed understanding of the overall dynamical behavior of this solid phase flow segregation is required. We develop numerical models using COMSOL Multiphysics to monitor the chemical and thermal evolution of a convecting and crystallizing magmatic reservoir. These models solve the Navier-Stokes and heat transfer equations considering the Euler-Euler method to monitor the dispersed multiphase flow. Our study focuses on the vicinity of the solid boundaries where the flow is less turbulent and gradually slows down until the local flow speed becomes comparable to the settling speed of the crystals. The Rayleigh numbers investigated in our study range between 10$ˆ6$ and 10$ˆ8$. We also model the compatible/incompatible elements transfers by implementing a time dependent density difference between the mineral phase and the residual liquid phase.
Our models show that the ability of the crystal fraction to disperse within the domain is strongly dependent on the crystal size, the density difference and the magma viscosity. Two regimes emerge: sedimentation regime or suspension regime. We show that the critical value of the convection/buoyancy stress ratio separating these two regimes (1) depends on the viscosity of the reservoir and (2) is smaller than proposed by Solomatov et al. (1993). Hence, during the early crystallization of a magma ocean, suspension should be the dominant process.

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