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The fluid dynamics of crystal settling and flotation in a lunar magma ocean

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Abstract

The smoking-gun evidence for a lunar magma ocean is the anorthosite-rich highlands on the Moon, which are thought to have formed by flotation of buoyant plagioclase crystals in a solidifying magma ocean. A puzzling aspect of this idea is that plagioclase only appears in the crystallization sequence during the late stages of solidification, i.e. once the magma ocean is approximately 70-80 % solidified [1], which is difficult to reconcile with the fluid-dynamical constraints on crystal settling.

The goal of this study is to gain insights into the differentiation history of the lunar magma ocean by investigating the fluid-dynamical conditions that govern crystal settling or flotation. Our approach complements earlier work [2,3] by employing direct numerical simulations to fully resolve flow at the scale of the crystals and by focusing primarily on the non-turbulent boundary layers of the lunar magma ocean. We find that the relative settling of two mineral phases with different densities is hindered substantially already at low to moderate crystal fractions, because the frequency and duration of crystal collisions increases rapidly with crystal fraction. We hypothesize that tidal heating and cumulate overturn may have been critical in facilitating plagioclase flotation.

1. Introduction

Early Apollo-era results led to the realization that immediately following accretion the Moon underwent extensive melting. The solidification processes in the resulting magma ocean hold important clues to today's Moon: The anorthositic lithology of the lunar crust is thought to have formed by plagioclase flotation, the mare basalts might be the result of the sinking of more dense and mafic silicates and KREEP could represent highly evolved fluids during the last stretches of magma ocean solidification.

One of the biggest uncertainties in connecting these pieces of observational evidence to the fluid dynamics and geochemistry of magma ocean solidification concerns the ability of individual crystals to settle or float. Here, we investigate the fluid dynamical conditions under which flotation or settling is possible. Motivated by experimental evidence [4], we focus primarily on crystal segregation in the non-turbulent boundary layers (see Fig. 1).

2. Method

At the planetary scale, flow in magma oceans is driven by thermal convection. At the scale of individual crystals, the temperature differential is negligible and the dynamics of crystalline suspensions is governed by the Navier-Stokes equation in the fluid and rigid body motion in the solid phase (see Fig. 1). We have developed and

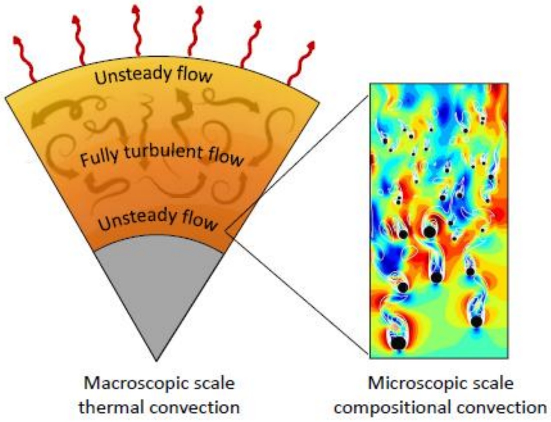

Fig. 1: Convective regimes during the early stages of solidification in a lunar magma ocean. Left: At the planetary scale flow is driven by thermal convection. Flow is turbulent for most of the depth range of the magma ocean. Right: The degree to which crystals can settle out of suspension in the non-turbulent boundary layer is dominated by compositional convection.

benchmarked a numerical method to fully resolve the solid-fluid coupling between crystals and magma ocean flow from first principles, i.e. without assuming an approximate drag law or settling speed. The existence of an ambient flow field is captured in our simulations by specifying inflow and outflow along the boundaries such that mass is preserved.

3. Results

We investigate the fluid dynamical factors determining crystal settling for a wide range of suspensions that might have arisen during the solidification of the lunar magma ocean. These include dilute as well as non-dilute suspensions, different crystal size distributions and crystal populations with variable density and shape.

Our main findings regarding the fluid dynamical conditions for crystal segregation are: (1) The relative settling of two mineral phases with different densities is hindered substantially already at low to moderate crystal fractions, because the frequency and duration of crystal collisions increases rapidly with crystal fraction. We argue that crystal collisions play an important role in magma-ocean solidification, both because they transfer kinetic energy from fast to slow moving crystals and because they convert kinetic energy to heat through viscous dissipation. (2) Crystal settling is facilitated greatly by skewed as compared to homogeneous crystal-size distributions, even if the mean size of the skewed is much smaller than that of the homogeneous crystal-size distribution. (3) The degree to which mineral phases with different densities may segregate depends primarily on the relative sizes of the various mineral phases and only to second order on the density. Maximum settling efficiency is achieved only if density and size are correlated; if density and size are inversely correlated, crystal settling may yield an unstable density stratification in the cumulate pile.

Our simulations indicate that crystal settling was probably very efficient during the early stages of lunar magma ocean solidification, particularly as long as olivine was the sole crystallizing phase. Once other mineral phases join the crystallization sequence, settling speeds are reduced and the differentiation of the crystals in the resulting cumulate pile is likely incomplete. Fluid dynamical separation of different mineral phases towards the late stages of solidification is greatly hindered by both the high crystal fraction and the relatively large number of mineral phases in suspension. We hypothesize that the heat released by the initiation of cumulate overturn and potentially tidal heating might have been critical in facilitating plagioclase flotation. The resulting melting event reduces the solid fraction in suspension, creating a thin spherical shell of mixed liquid, which would then fractionate very slowly.

6. Summary and Conclusions

Our simulations indicate that the overall crystal fraction is the rate-limiting factor for crystal settling or flotation in solidifying magma oceans. The main mechanism through which crystal segregation is hindered at finite crystal fractions collisions between crystals, which redistribute kinetic energy among the suspended crystals. This insight implies that crystal segregation is efficient only during the early stages of magma ocean solidification. Fractionation during the last stretches of solidification, such as plagioclase flotation on the Moon, likely requires both an insulating shell and a heating event.

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