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A long-lived lunar magma ocean

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1. Introduction

The moon is thought to originate from a collision between the early Earth and a Mars-sized impactor. Such a giant impact would have left a large quantity of the lunar mantle molten, resulting in a global magma ocean. A large part (about 80%) of the lunar magma ocean (LMO) solidifies in around 1000 years by efficient radiative heat loss at its molten surface, until a solid crust forms by flotation of plagioclase. The heat is then lost by conduction through the growing crust, which is a much less efficient regime, delaying the complete solidification of the LMO to a few tens of millions of years. However, the lunar anorthositic crust formed over a time span of ~200 Myr [1], still longer than what LMO solidification models suggest. Based on the observation that the LMO solidification time scale is compatible with solid cumulates overturn, we show that secondary melting generated by hot plumes after onset of solid-state convection below the solidifying LMO represents an important heat source for the LMO by extracting hot melt from the cumulates into the LMO, that can suffice to delay the complete solidification by about 200 Myr.

Furthermore, the onset of solid-state convection in the solidifying cumulates help entrain the late crystallized Ilmenite bearing cumulates (IBC) into the mantle before a stiff stagnant lid forms and traps the IBC. This constitutes an alternative sinking mechanism to the usually assumed post-solidification overturn.

2. Model

We use the model described in [2] to perform 2D and 3D simulations of solid-state convection on the cumulates below a self-consistently solidifying LMO. The initial structure of the mantle is computed from fractional crystallization of a global LMO using alphaMELTS, and the solidification of the LMO and the growth of the flotation crust are parametrized by solving the energy conservation equilibrating the outgoing heat flux through the crust with the incoming conductive and "heat piping" heat fluxes as well as the internal heating of the LMO from radioactive decay. Figure 1 represents how the different systems (core, solid cumulates, LMO and crust) are thermally coupled.

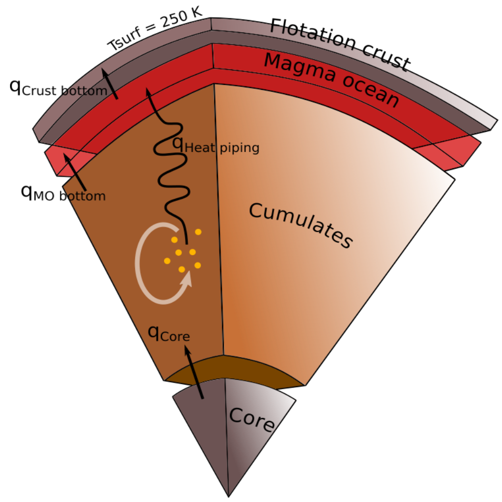

Figure 1: Thermal couplings between the different layers of the system. The thermal energy is conserved for each of the four systems, the interfacial heat fluxes (black arrows) and the surface temperature providing the boundary conditions. The heat piping flux originates from the melting induced by solid-state convection in the cumulates (white arrow). Internal heating by radioactive decay is also included.

3. Results

We investigate the influence of heat piping on the LMO's crystallization duration and the entrainment of IBC in the lunar mantle.

3.1. LMO duration

We varied the reference viscosity of the lunar mantle as a parameter, causing different overturn time scales and convective intensities, resulting in different heat piping efficiency. While, for a high reference viscosity

(~10^{22} Pa s) no overturn occurs during LMO solidification and the heat piping flux is zero, lower (but still realistic) values of the reference viscosity (~10^{19} Pa s) result in rapid onset of solid-state convection generating an intense heat piping flux due to decompression melting in the cumulates. This supplementary heat source significantly prolongs the LMO duration, up to ~200 Myr, matching the isotopic age measurements of the lunar crust.

3.2. IBC entrainment

Entrainment of the late crystallized IBC is needed to produce the Moon's surface high-Ti mare basalts and picritic glasses by secondary melting [3]. However, the IBC crystallize at low temperature and remain trapped in the stagnant lid in models where solid-state convection starts after the whole lunar mantle is solid [3]. We showed in a previous work [2] that onset of solid-state convection during the magma ocean solidification provides an efficient means to mix composition heterogeneities inherited from fractional crystallization. We show that when cumulates overturn occurs during LMO solidification, a substantial part of the IBC is entrained in the bulk convecting mantle, and Ilmenite is present in re-melting plumes even long after the end of the LMO solidification.

References

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