OVERTURN OF ILMENITE-BEARING CUMULATES ACTIVATED BY NON-LINEAR MANTLE RHEOLOGY

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Introduction: The overturn of ilmenite-bearing cumulates (IBC) following the cristallization of the lunar magma ocean provides a suitable explanations for the extensive volcanism on the lunar nearside [1, 2], the magnetic field anomaly before $\sim$ 3.6 Ga [3], and the low-viscosity zone in the deep mantle [4, 5]. However, the rheological conditions needed for the overturn are still problematic. The stagnant lid – the cold and stiff part on the top of the mantle – can easily entrap IBC and prevent this dense layer from sinking downwards [6]. Due to the importance of IBC overturn for the interpretation of the thermo-chemical evolution of the Moon, it is critical to constrain the rheological conditions under which the overturn of IBC can take place.

This work aims at constraining the dynamics of IBC overturn in the context of non-linear mantle rheology associated with dislocation creep. Taking place via the migration of imperfect lattice structures, dislocation creep results in an effective viscosity depending not only on temperature but also on strain rate. The mobilization of IBC layer thus provides a feedback to weaken the rheology itself. Furthermore, recent experiments suggest that ilmenite is a rheologically weak and non-linear component in the ilmenite-olivine mixture. The presence of ilmenite can thus affect the rheology of the IBC layer and facilitate its overturn [7].

Methods: We modeled the dynamics of IBC overturn by using the finite-volume mantle convection code GAIA [8]. We used a half-cylindrical domain with a radial resolution of 4.5 km and a lateral resolution varying from 1.5 km at inner boundary to 13 km at outer boundary. The outer boundary is assumed to be isothermal and free-slip. The inner boundary is considered to be free-slip and its temperature is updated by using the energy conservation equation of core cooling. The initial density profile, initial temperature profile and initial heat production rate profile were determined by using the software alphaMELTS [9, 10] with which we simulated the crystallization of the lunar magma ocean. We assumed a core radius of 390 km [11] and used a bulk composition according to Longhi et al. [12].

We considered two rheological models: a pure mantle diffusion-creep rheology and a composition-dependent rheology coupling mantle diffusion-creep, mantle dislocation-creep, and ilmenite dislocation-creep. For the latter, we adopted the isostress mixing model (the so-called Reuss model) to blend different types of rheology. We assumed rheological data based for ilmenite and olivine derived from laboratory experiments [7, 13] and varied the reference viscosity of the lunar mantle at a reference temperature of 1600 K between 10^{19} and 10^{21} Pa s.

Results and Discussions: We track the development of overturn by using the volumetric fraction of foundered IBC, i.e.

$$\psi_{ibc} = \frac{V_{ibc} - V'_{ibc}}{V_{ibc}} \tag{1}$$

where V_{ibc} is the total volume of IBC, V'_{ibc} is the volume of entrapped IBC. Figure 1 shows the time variation of ψ_{ibc} for different modeling cases. With a pure mantle diffusion-creep rheology, the overturn of IBC cannot take place unless the reference viscosity decreases to 10^{19} Pa s. In contrast, if the dislocation creep of mantle and ilmenite are coupled, more than 90 vol. % IBC mobilizes at last for all three reference viscosity values. This suggests that dislocation creep can tends to promote the overturn of IBC.

If the viscosity of IBC layer is lower than the viscosity of underlying mantle cumulates by four orders of magnitude, a hemispherical overturn of IBC can take place [14]. This so-called degree-one overturn hypothesis provides an explanation to the focusing of KREEP materials on the lunar nearside. In all modeling cases, we did not observe the overturn taking place in the form of a degree-one structure. As an example, Figure 2 shows snapshots of chemical composition in the modeling case with composition-dependent rheology and a reference viscosity of 10^{21} Pa s. As can be seen from this figure, the precipitation of IBC occurs via small-scale diapirs throughout the overturn phase.

Conclusions: As recognized earlier by Elkins-Tanton et al. [6], the overturn of IBC depends strongly on the rheology of the lunar mantle. Considering only mantle diffusion-creep, the overturn of IBC cannot take place unless the reference viscosity decreases to 10^{19} Pa s. Considering dislocation creep of mantle rocks and ilmenite leads to a complete IBC overturn for reference viscosities between 10^{19}–10^{21} Pa s suggesting an important role for this type of deformation in controlling the early dyanamics of the lunar mantle.

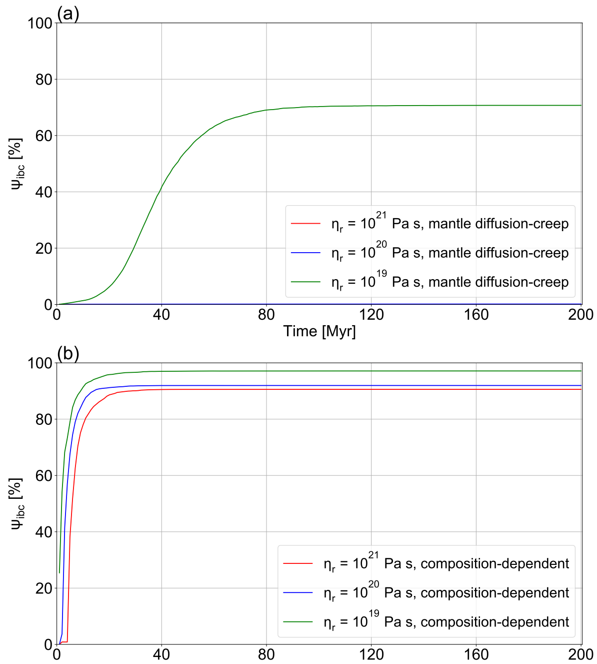

Figure 1: Time evolution of foundered IBC fraction (ψ_{ibc}) for pure diffusion-creep rheology (a) and composition-dependent rheology (b).

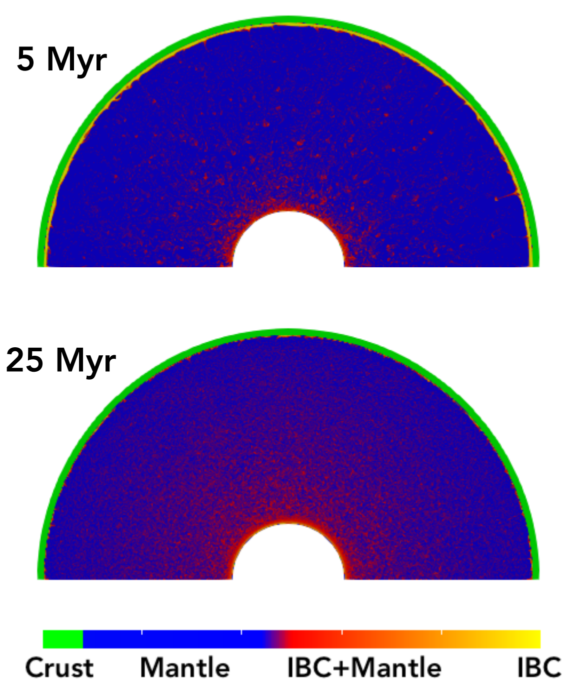

Figure 2: Snapshots of chemical composition at different times for the case with a reference viscosity of 10^{21} Pa s.

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