Modeling magma oceans in the laboratory: Accounting for free-slip conditions at the top boundary of an analog convection experiment

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Résumé

During the early formation of rocky planets, heat due to collisions, core formation, and radioactive decay may have melted their silicate mantle, forming a magma ocean (MO). Upon magma ocean solidification, volatiles in the MO are progressively outgassed, forming a secondary atmosphere.
Most coupled MO-atmosphere models assume quasi-instantaneous degassing of the MO, in equilibrium with the atmosphere (e.g., Elkins-Tanton 2008, Lebrun et al. 2013, Nikolaou et al., 2019). However, the outgassing efficiency can be limited by the fact that fluid parcels containing dissolved volatiles need to reach small pressures corresponding to shallow exsolution depths for bubbles to form and volatiles to be outgassed.

Recent studies, using both numerical and analog models (Salvador & Samuel, 2023; Walbecq et al., 2025), revealed that relaxing this hypothesis can result in a significant delay in the exsolution of volatiles, leading to shorter duration of the MO stage. However, the analog model used in the aforementioned study had rigid boundaries along all sides, which does not accurately reflect the dynamics of a magma ocean, for which free-slip conditions at least at the top boundary are more relevant. The presence of free-slip boundary conditions can impact the velocity field near the surface, which is of particular importance for the volatile outgassing problem considered.
We therefore studied a fluid convecting under a thin layer of less dense, immiscible fluid, with a strong viscosity contrast between both. This allows neglecting shear stresses along the top boundary. We mapped the velocity field in 3D using particle tracking velocimetry and compared the results of analog and numerical experiments. We evaluate the ability of this approach to mimic free-slip boundary conditions for convective flow in a tank with rigid walls.

Mots-Clés: atmosphere, boundary conditions, convection, experimental techniques, magma ocean, planetary dynamics

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