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**A SINGLE PLUME UPWELLING ON LUNAR NEAR SIDE THAT PROVIDES A SOURCE FOR TITANIUM-RICH VOLCANISM.** Y. Zhao[1], Ana-Catalina Plesa[2], Doris Breuer[2], Matthieu Laneuville[3], Wim van Westrenen[1], [1]Faculty of Science, Vrije Universiteit Amsterdam, the Netherlands, [2]Department of Planetary Physics, German Aerospace Center (DLR), Berlin, Germany, [3]Earth-Life Science Institute (ELSI), Tokyo Institute of Technology, Tokyo, Japan, email y.zhao@vu.nl

**Introduction:** The most striking feature of the lunar surface is the dichotomy between the near side and the far side. The mare basalts that cover about a third of the near-side surface are present on only 1% of the far side. The Lunar Prospector mission discovered that the distribution of thorium on the lunar surface is concentrated in the Procellarum KREEP terrain (PKT), whose location strongly correlates to that of a nearside mare basalt region [1], and to a lesser extent in the far-side South Pole–Aitken basin. The lack of KREEP signatures in the material ejected from many large far-side impact basins implies that the source of KREEP is concentrated in the near-side hemisphere [2].

The asymmetrical distribution of mare basalts and KREEP on the lunar surface has been proposed to be due to a single-plume upwelling toward the near side. Zhong et al. [3] argued that this upwelling stems from dense ilmenite-bearing cumulates (IBC) that sank to the core-mantle boundary from under the crust where IBC crystallized in the late stages of lunar magma ocean solidification. The IBC contains high concentrations of heat-producing elements, making it thermally buoyant enough to rise after the initial sinking. Parmentier et al. [4] studied the Rayleigh-Taylor instability developed in a dense layer lying on top of another layer, simulating the gravitationally unstable IBC after the solidification of the lunar magma ocean. They suggested that spherical harmonic degree 1 is the fastest growing instability when the top layer is sufficiently thick, and when the viscosity of the top layer is ~4 orders of magnitude lower than the underlying mantle.

This study aims to investigate the possibility of localizing key ingredients for lunar volcanic activities, including sources for titanium and radioactive elements, to the near side of the Moon after solidification of the magma ocean, using numerical models that simulate both the downwelling of IBC and the upwelling that give rise to volcanism. In particular, we describe our preliminary results using asymmetrical crustal thickness and distribution of KREEP as an initial condition.

**Numerical method:** Our numerical models are performed in a 2-D cylindrical domain. The lunar mantle is simulated using the Boussinesq approximation as a fluid with infinite Prandlt number. Finite volume code Gaia [5] is used to solve the conservation equations of mass, momentum, and energy. The advection of chemical components is implemented using the particle-in-cell method [6]. The mantle domain is heated from within by radioactive decay and from below by a cooling core. A reference viscosity of $1x10^{20}$ Pa s is used, resulting in a thermal Rayleigh number of $1x10^{7}$. We use a fine mesh with a radial resolution of 1.7 km throughout the domain. More than 90 million tracers are used to track various material properties, including density, viscosity and concentrations of heat-producing elements.

Our models start when the lunar magma ocean has solidified. The stratified cumulates are characterized by varying density, viscosity, and distribution of heat-producing elements [7]. Viscosity is computed by using a temperature- and pressure-dependent Arrhenius law for diffusion creep. In addition to that, IBC have their viscosities one order of magnitude lower than calculated from the Arrhenius model, taking into account the low viscosity of ilmenite [8]. For density and concentration of heat-producing elements, we use a weighted arithmetic average according to their concentration when different chemical components are mixed. Viscosity is combined to a product of the viscosity of all compositions to the power of their relative concentration.

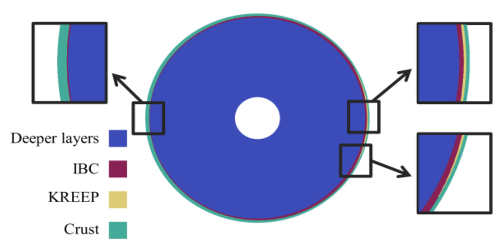

*Figure 1. The asymmetrical distribution of crustal thickness, IBC, and KREEP in the initial condition.*

The crust has a thermal conductivity of 1 W/m/K, taking into account the low thermal conductivity of plagioclase, and the porous top layers of the crust. The initial crustal thickness is a minimum of 20 km on the near side and a maximum of 40 km on the far side, and we use a sine function to model its variation. KREEP, having the same density and viscosity as IBC while containing higher concentrations of heat-producing elements, is localized in a cylindrical cap of 40 degrees, which mimics the PKT region subsurface. Its thickness is 20 km where crustal thickness is 20 km, and gradually decreases to 0 towards the PKT edge. Figure 1 shows these initial conditions.

experiments will further test the effects of a range of other parameters, including the reference viscosity, which may also play an important role in the convective pattern.

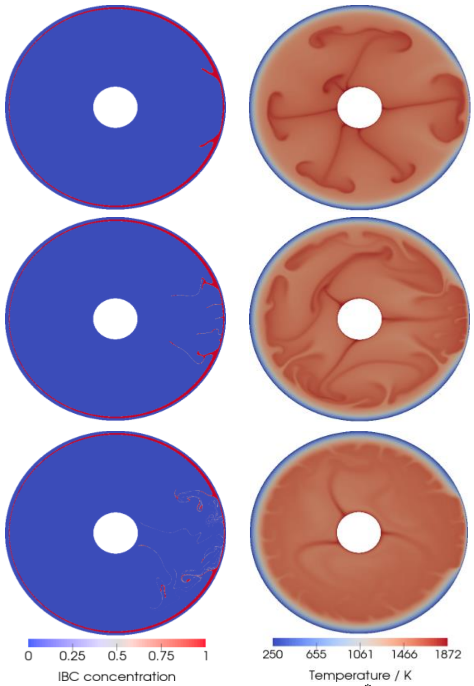


*Figure 2. model results using $E^*$=300 kJ/mol. Here IBC concentration includes both the IBC and KREEP in Figure 1.*

**Results:** Two sets of model results are shown in Figures 2 and 3, corresponding to activation energies $E^*$ of 300 kJ/mol and 100 kJ/mol, respectively, in the Arrhenius viscosity model. Both models show the sinking of dense IBC in two diapirs that correspond to the edges of the PKT region. An upwelling remains under the PKT region, due to the region's high heat production, though the convective pattern evolves differently in the two models. We can see from Figure 2 that when $E^*$=300 kJ/mol, the onset of convection is driven by several upwellings at the core-mantle boundary (CMB). When $E^*$=100 kJ/mol, as shown in Figure 3, the onset of convection is driven by sinking IBC. During the sinking of IBC along the edges of PKT, an upwelling is formed underneath the PKT. Foundered IBC at the CMB are then brought up by the near-side upwelling, providing a source of titanium and heat-producing elements to the near side.

**Discussion and conclusion:** Our preliminary results show that the behavior of IBC overturn under an asymmetrical initial condition is sensitive to the temperature dependence of viscosity. When $E^*$=100 kJ/mol, foundered IBC is brought to the surface through a near-side single-plume upwelling. This mechanism may explain titanium-rich sources for nearside volcanism. Our continued numerical

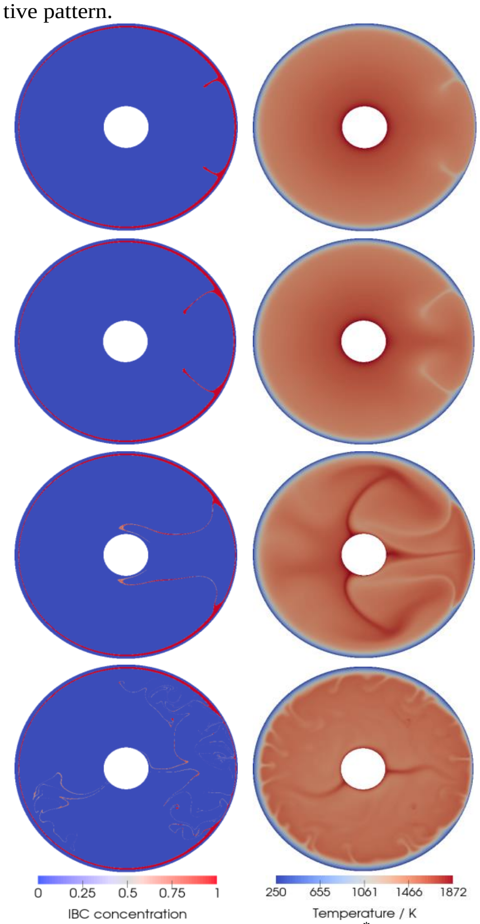


*Figure 3. model results using $E^*$=100 kJ/mol. Here IBC concentration includes both the IBC and KREEP in Figure 1.*

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**References:** [1] Jolliff B. L. et al. (2000) *JGR*, 105, 4197–4216 [2] Warren P. H. (2001) *GRL.*, 28, 2565–2568 [3] Zhong S. et al. (2000) *EPSL*, 177, 131–140 [4] Parmentier E. M. et al. (2002) *EPSL*, 201, 473–480 [5] Plesa A-C. et al., (2012) In: Rueckemann, C.-P. (Ed.), *IGI Global*, 302–323 [6] Hüttig C. et al. (2013) *PEPI*, 220, 11–18 [7] de Vries J. (2012) Chapter 5, *PhD diss*, Utrecht University. [9] Dygert N., et al. (2016) *GRL*, 43, 532-540