Long-Wavelength Convection in the Moon with a Weak Lower Crust. A. Bellas and S.J. Zhong, Department of Physics, University of Colorado at Boulder.

Introduction: On the Moon, mare basalts erupted extensively on the near-side or Earth-facing side, covering approximately 30% of the surface area, but are scarce on the far-side. Eruption of the maria occurred predominantly between ~3.9 and 3.0 Ga and they appear to have a deep source (>350km depth) based on petrologic evidence [1,2]. The distinct morphological difference in impact basins on the near-side and far-side also suggests a different thermal state between the interiors of each lunar hemisphere [3]. These observations provide compelling evidence of long-wavelength thermal processes in the Moon, which may provide crucial insight into early lunar thermal and dynamic evolution.

Previous studies demonstrated that gravitational instability may occur at predominately degree-1 harmonic (i.e., hemispheric asymmetric structure) when relatively dense magma ocean residual material [4], ilmenite-rich cumulate, sinks into the mantle or the mixture of ilmenite cumulates and olivine-orthopyroxene rises back to the surface [5]. However, these degree-1 instability processes require either a small lunar metallic core [4] that may be inconsistent with seismic studies [6] or unusually large viscosity contrast between the ilmenite cumulates and the underlining mantle [5]. More realistic 3-D mantle convection simulations with temperature-dependent viscosity showed the difficulties in achieving degree-1 convective structure [7].

The goal of this study is to explore a simple model of mantle convection, but with a distinctly different mechanism from these previous studies, that can self-consistently explain why mare basalts erupted principally on the Moon's nearside. We conduct 2D finite element simulations, and show for the first time that a weak lower crust allows long-wavelength mantle convection to dominate flow in a body with a stagnant lid with wavelength that corresponds to spherical harmonic degree-1.

Crustal rock may be much weaker than mantle rock at equal temperature [8], and in the early Moon, temperature at the Moho is significantly higher than present-day. We propose a global, weak lower crust in the early Moon accommodates deformation by channel flow, and provides a free-slip surface boundary condition for the lunar mantle. We demonstrate that even with a relatively simple model (one that relies on temperature-dependence of viscosity and a weak lower crust), long-wavelength convection is readily produced, provided that the lithospheric mantle can mechanically decouple from the stagnant lid, and has a viscosity contrast in a specific range.

Model: We conduct finite element simulations in 2D Cartesian geometry using Citcom to solve the equations of conservation of mass, momentum, and energy in the Boussinesq approximation with infinite Prandtl number. The aspect ratio of the box is 1:6. We vary Rayleigh number (Ra) which governs the vigor of convection from 10^5 to 10^7, and change the nondimensional viscous activation energy (E) which controls the sensitivity of viscosity to temperature from 0 to 15. We allow each simulation to run until it has reached steady state, and take the Fourier transform of temperature to determine the dominant wavelength of the flow structure.

We conduct a series of purely thermal calculations which consider only the lunar mantle, and impose a free-slip boundary condition at the surface with weak lower crust in mind. We find that the viscosity contrast across the lithosphere has a controlling effect on the wavelength of convection (similar to [9]).

We extend purely thermal to thermo-chemical convection with a compositionally distinct crust, and impose high viscosity at the surface and low viscosity in the lower crust. The goal is to demonstrate consistency between purely thermal and thermo-chemical models for the same Ra and viscosity contrast across the mantle-lithosphere. Then, the simpler, purely thermal models can be used to map the range of parameters in which mode-1 convection dominates the flow (i.e., a single convection cell occupies the entire 2-D box).

Results: *Purely Thermal Models:* The lunar Moho is the surface boundary in these models. Figure 1 shows the final flow structure for a model with Ra = 10^6 and E=11 from an initial state with top and bottom thermal boundary layers. The flow evolves from short wavelength structures to a steady state with dominantly mode-1 convection.

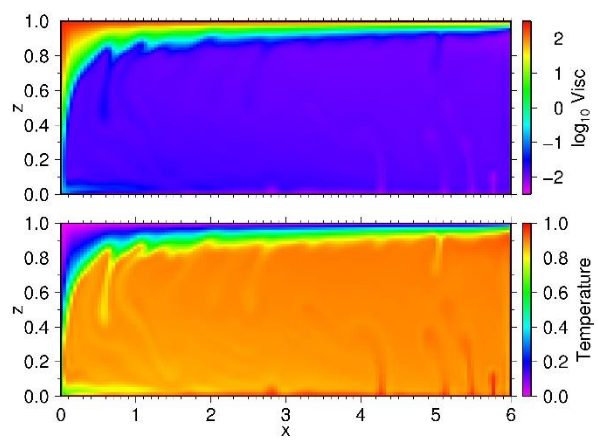

Figure 1. Nondimensional viscosity and temperature for Ra = 10^6 and E=11. The flow is dominated by a single convection cell, or the fundamental mode (consistent with degree-1).

The viscosity contrast across the lithosphere plays a critical role in controlling the wavelength of convection. To summarize the results from a large number of model runs, we present the power spectrum of the temperature field as a function of viscosity contrast in Figure 2. Mode-1 dominates the flow structure for models with Ra = 10^6 when the viscosity contrast across the lithosphere is in the range $3x10^1$ to $3x10^4$. For a contrast of 10, mode-1 and -3 are equally strong. For contrast >$3x10^4$, the lithosphere quickly becomes too strong to participate in the flow, and short wavelength features begin to dominate. The range of viscosity contrast which produces mode-1 dominant flow is similar for models with Ra = 10^5 and 10^7.

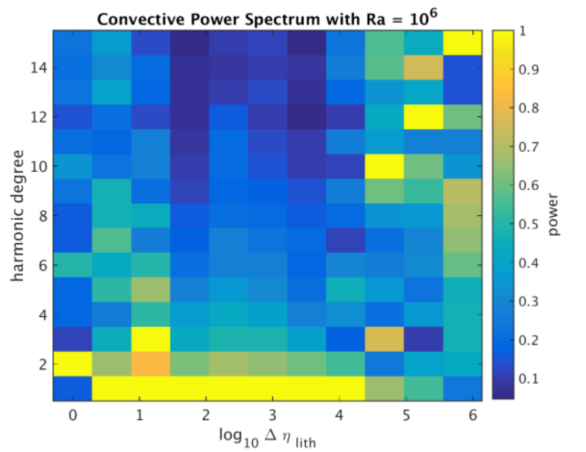

Figure 2. The power spectrum of temperature for models with Ra = 10^6, a range in viscosity contrast from 0 to 6 orders of magnitude (or E from 0 to 15).

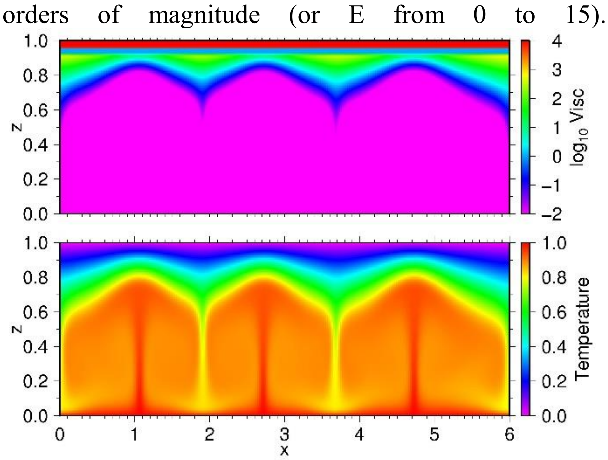

Figure 3. Nondimensional viscosity and temperature for Ra =10^4, E=18 and an artificially imposed stagnant lid and weak lower crust.

Thermo-chemical Models: The lunar surface is the upper boundary in these models. We test these preliminary cases with lower Ra, and limit the viscosity within the range 10^{-2} to 10^4 to increase the rate of convergence. We also do not advect the crust, but will allow for crust thinning and thickening in future calculations. Figure 3 shows the final flow structure for a model with Ra = 10^4 and E=18. The initial short wavelength features lengthen to eventually produce a mode-3 dominant flow. The viscosity contrast across the mantle-lithosphere is almost 5 orders of magnitude. Comparing with Figure 2, this viscosity contrast produces mode-10 dominant flow with some significant contribution at mode-3 for purely thermal, free-slip surface conditions. We consider this result promising, and will continue to explore models with higher Ra and lower E to map out the range in which a single convection cell dominates the flow.

Discussion: Thermo-chemical models with a weak lower crust and stagnant lid are a more complete representation of lunar convection than purely thermal models. Based on preliminary results, we hypothesize the artificially imposed weak lower crust will produce results consistent with a free-slip boundary at the Moho.

The following discusses purely thermal models with a free-slip surface boundary condition. For small viscous activation energy, the lithosphere becomes unstable quickly after reaching the cold upper boundary such that convection cells have approximately unit aspect ratio (characteristic of isoviscous flow). For a critical range in viscosity contrast, the temperature dependence of viscosity strengthens the lithosphere such that it resists downwelling until it has traversed the domain. This produces one major upwelling and one major downwelling region, consistent with degree-1 convection. For viscosity contrasts >~$3x10^4$, the lithosphere becomes strong enough to resist gravitational instability altogether, and the flow rapidly devolves into short-wavelength structures in the convecting mantle.

In conclusion, since mode-1 convection is robustly produced for a broad range of viscous activation energy and Ra, we find that it is quite likely for a long-wavelength flow to emerge in the early Moon and produce the mare basalts. We will continue this study to demonstrate the lunar hemispherical asymmetry can be reproduced by a simple model with two controlling features: temperature-dependent viscosity, and a weak lower crust.

References: [1] J. Delano (1986) *JGR 91*, 201-213. [2] Morota et al. (2011) *EPSL 302,* 255-266. [3] K. Miljković et al. (2013) *Science 342*, 724-726. [4] M.E. Parmentier et al., (2002) *EPSL 201*, 473-480. [5] S.J. Zhong et al., (2000) *EPSL 177*, 131-140. [6] R. Weber et al. (2011) *Science 331*, 309-312. [7] N. Zhang et al. (2017) *GRL 44*, 6543–6552. [8] N. Carter and M. Tsenn, (1987) *Tectonophysics 136*, 27-63. [9] A.K. McNamara and S.J. Zhong (2005) *GRL 32*, L0130.