

**Instability and Distribution of Ilmenite-rich Cumulates after the Overturn of an Initially Stratified Lunar Mantle.** N. Zhang, E. M. Parmentier, Y. Liang, Department of Geological Science, Brown University, 02912, RI. (Nan\_zhang@brown.edu)

**Introduction and motivation:** Several lines of evidence suggest that lunar mantle is chemically, isotopically, and lithologically heterogeneous. The heterogeneities are ancient and were formed during large-scale differentiation events, such as the solidification of a globally distributed lunar magma ocean (LMO) and subsequent cumulate mantle overturn [1,2]. Mixing of distinct early and late LMO cumulates results in a hybrid cumulate mantle [3]. Partial melting of such chemically and lithologically heterogeneous mantle source regions gives rise to a diverse range of basaltic magmas and cumulate rocks observed on the surface of the Moon [2,4]. Evidence for a heterogeneous lunar mantle is overwhelming, including major element data (e.g., very low-Ti to high-Ti basaltic samples), incompatible trace element patterns, selected incompatible trace element ratios, and isotopic variations and covariations [1, 4, 5, 6]. At least three distinct components in the (overturned) lunar mantle have been recognized: early harzburgitic cumulate, late ilmenite-bearing cumulate, and KREEP. Although the notation of a heterogeneous lunar mantle has been widely accepted in the lunar sciences community, the nature and distribution of hybridized mantle sources are still poorly understood.

The early evolution of the ilmenite-bearing cumulates and KREEP has been constrained by an overturn of an initially stratified lunar mantle. In one endmember case, downwellings caused by the ilmenite-rich cumulates entrain the urKREEP from the top and form a mixed layer consisting of olivine, opx, and KREEP-ilmenite-rich cumulates (MIC) at the core-mantle boundary. After the overturn, the evolution of the ilmenite-bearing cumulates and KREEP is complicated and, maybe controversial. MIC that sinks rapidly to the core-mantle boundary is both denser than overlying mantle and richer in U, Th, and K. With heating due to radioactive decay, MIC may become buoyant, rise toward the surface, and create melt as it decompresses. The buoyant rise of MIC have been widely used to explain a variety of lunar observations [7-9]. However, one previous model [10] suggests that a significant part of the MIC may remain at the CMB or form a stable outer core. The inversion of lunar free oscillation data indicates a density structure that may be compatible with a metallic core surrounded by stable ilmenite-rich cumulates [11]. Moreover, if the MIC begins to melt before it becomes buoyant, the downward migration of dense Fe-rich melt at high pressure may concentrate heat producing elements toward the core-mantle

boundary. If solid-state convection cannot maintain subsolidus temperatures in the MIC, this will affect the amount of MIC that can rise buoyantly and the role that this may play in lunar evolution.

This study focuses on the instability of MIC on the CMB and the distribution of the Ti-rich materials may affect the dynamics of the lunar mantle. The instability of MIC is explored by a 3-D numerical mantle convection model and an analytic thermal evolution model. The evolution of thermal and chemical structures, especially for the degree-one structure, in the lunar mantle is investigated. For numerical models with unstable MIC, the spatial and temporal distributions of the Ti-rich materials are presented.

**Model formulation:** The numerical models solve the conservation equations of mass, momentum, energy, and composition in a 3-D spherical shell that has outer radius of 1740 km and inner radius of 400 km (i.e., core mantle boundary). The mechanical boundary conditions on the top and bottom are free-slip. For the thermal boundary condition, the top surface is fixed to 0°C while the bottom accounts for the heat capacity and cooling of the core. The latter has generally been neglected in earlier studies. The lunar mantle has two compositional layers, the MIC at the bottom and overlying mantle above it. The MIC layer is initially more dense than the overlying mantle while it is continuously heated.

**Results I:** The instability of the MIC layer on the CMB. For the instability of the MIC layer, we focus on the influence of the temperature-dependent viscosity. We compute a series of cases with viscosity contrast due to temperature from  $10^5$  to  $10^7$ . Our results show that the behavior of the MIC layer depends on its viscosity. With a weakly temperature-dependent viscosity ( $\Delta\eta=10^5$ ), the MIC layer has relatively large viscosity and transports heat slowly. Hence, the MIC layer becomes thermally buoyant after 250 Ma and forms a degree-one thermochemical upwelling. However, with a strongly temperature-dependent viscosity ( $\Delta\eta=10^7$ ), the MIC has smaller viscosity and transports heat efficiently. The MIC layer becomes much more stable and is only slowly entrained to the ambient mantle. Finally, our analytic thermal evolution models also predict these different thermal evolutions for the MIC layer due to the different viscosity contrast.

**Results II:** The temporal and spatial distributions of MIC materials. For the case with a major plume, the MIC materials re-distribute in the lunar mantle with

the evolution of the plume. And the distribution shows interesting temporal and spatial variations. When the plume head reaches to the bottom of cold lithosphere at 264 Ma, the MIC materials start to accumulate surrounding the center of the plume head at this shallow depth. With 150 Ma of accumulation (i.e., 414 Ma of model calculation), the MIC materials cover an area with a radius of  $20^\circ$  from the plume center (Fig. 1a).

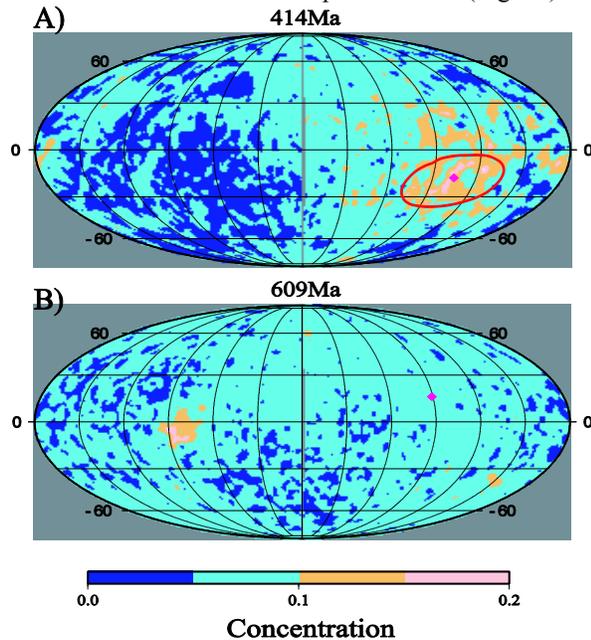


Figure 1. The distributions of the MIC materials at 414 Ma (A) and 609 Ma (B) at depth 120 km.

The MIC material keeps ascending through the plume conduit to the shallow depth. When the plume first reaches to the bottom of lithosphere at 264 Ma, the MIC concentration shows a peak at 150 km depth in the plume (Fig. 2, green curve). As the MIC materials migrate to the top, the MIC at the lower mantle is gradually drained by the plume. When most of the MIC is drained into the plume at 414 Ma, the concentration profile in the plume show the maximum at the 150 km depth and the minimum at the CMB (Fig. 2, yellow curve). When the model runs to 609 Ma, most MIC materials migrate to a shallow depth and interestingly concentrate at the major downwelling (Fig. 1B) while the concentration profile in the plume of upwelling shows a flat distribution (Fig. 2, red curve). This MIC distribution is probably caused by the reduced thermal buoyancy of MIC because the abundance of radioactive elements decays with time.

**Results III: Density anomalies.** From our numerical models, we can calculate the density anomalies at different time and depth. This can provide a test if our prediction is consistent with the gravity measurement for the present day. However, our model can only be calculated through  $\sim 1$  Gyrs because the lunar mantle

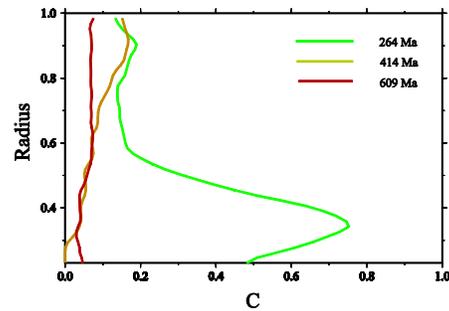


Figure 2. The concentrations of MIC with depth for different time. The concentration profiles are quantified in the plume with a radius  $20^\circ$ .

temperature decreases to  $< 1000^\circ\text{C}$  and our viscosity contrast can not be maintained large enough for a stagnant lid convection after 1 Gyrs. Here we compute the density anomalies at the depth 120 km at 1,100 Ma of our model calculation. We believe that after the lunar mantle becomes much colder, the density anomalies may be frozen in the lunar mantle to the present day. The density anomalies show a high density at the major downwelling (Fig. 3). We suggest that this large density anomaly may be observed in the present-day gravity measurement.

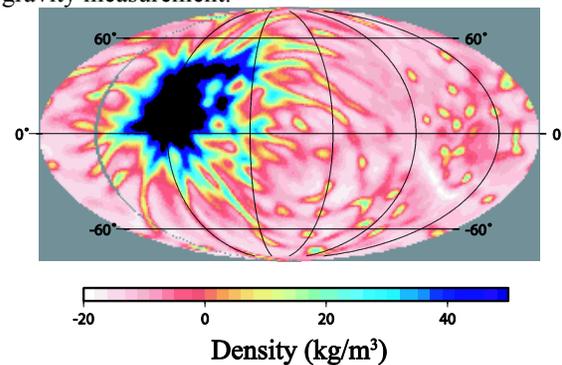


Figure 3. The density anomalies at 120 km depth at 1100 Ma.

**References:** [1] Snyder et al., (2000), Origin of the earth and moon, 361-395. [2] Shearer et al., (2006), *Reviews in Mine. & Geochem.*, 60, 365-518. [3] Ringwood and Kesson, (1976), *Proc. Lunar Planet Sci. Conf. 7*, 1697-1722. [4] Papike et al. (1998) In: *Planetary Materials*. Chapter 5, pp1-234.. [5] Hughes et al., (1988), *GCA*, 52, 2379-2391. [6] Hughes et al., (1990) *Proc. Lunar Planet Sci. Conf.* [7] S. Zhong, Parmentier E.M., and Zuber M., (2000) *Earth Planet. Sci. Lett.*, 177, 131-140. [8] D. Stegman, Jellinek A. M., Zatman S., Baumgardner J. and Richard M. (2003) *Nature*, 421, 143-145. [9] M.J. Krawczynski and Grove T. L. (2008) *LPS XXXIX*, abstract # 1231. [10] J. de Vries, van den Berg A., and van Westrenen W. *Earth Planet. Sci. Lett.*, 292, 139-147. [11] A. Khan and Mosegaard K., (2001) *GRL*, 28, 1791-1794.