# FATE OF TH- AND TI-BEARING LUNAR MAGMA OCEAN CUMULATES IN THE AFTERMATH OF MAJOR BASIN-FORMING IMPACTS.

M. J. Jones[1] (matthew_jones@brown.edu) and A. J. Evans[1], [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02906.

**Introduction:** Many ancient geochemical, geodetic, and geophysical features of the Moon—including hemispheric asymmetries in surface composition and interior mass distribution—have been characterized by remote-sensing and in-situ observations yet remain incompletely explained. Some hypotheses relate these observations to late-stage cumulates emplaced through fractional crystallization of a global lunar magma ocean [1–3]. The late-stage cumulates would have included a Ti-rich ilmenite bearing layer as well as a final residuum enriched in incompatible elements such as potassium (K), rare earth elements (REE), phosphorous (P) (a.k.a., KREEP), and thorium (Th) [1–3], thus imparting the residuum with a unique geochemical fingerprint and elevated concentrations of heat-producing elements.

Recent numerical geophysical experiments suggest that mantle convection patterns catalyzed by the massive South Pole–Aitken (SPA) impact >4.3 billion years (Gyr) ago [4] likely controlled the spatiotemporal evolution of the Th-, Ti-, and KREEP-bearing late-stage cumulate layer [5,6]. However, there are a wide array of possible fates for the late-stage cumulate layer throughout and following convection catalyzed by the SPA impact (and, potentially, other major lunar basin-forming impacts) [5]. The spatiotemporal evolution of the cumulate layer depends on several poorly constrained characteristics of the early lunar interior [5]. Some of the major influencing parameters include: the initial mantle temperature profile, $\bar{T}_0$; the mantle reference viscosity, $\eta_0$; the energy of the impact (i.e., the impact scenario); and the viscosity of the cumulate layer relative to the mantle reference viscosity, $A$. Because of the influence of the layer's viscosity, another influencing parameter is the initial thickness of the cumulate layer, $H$.

This study aims to characterize: (1) the influence of the parameters listed above on the timescale and spatiotemporal evolution of the late-stage cumulate layer; and (2) the variety of final configurations of the cumulate layer, which can be compared to present-day lunar observations to potentially constrain the early interior state of the Moon. Using 3-D spherical finite element simulations, preliminary results show that the massive and ancient SPA impact would have sequestered magma ocean cumulate material in the nearside within 300–600 million years (Myr) and the smaller, later Serenitatis impact may have influenced lunar interior evolution given a sufficiently low lunar upper mantle viscosity at the time of impact.

**Methodology:** We conduct more than 30 simulations of lunar interior evolution, either without a basin-forming impact or after a pulse of heat is added to the mantle by a basin-forming impact (either SPA or Serenitatis; impact parameters from [7,8] and [9], respectively). We use a modified version of the 3-D finite element thermochemical evolution code CitcomS [10–12] that includes an analytical model of impact-induced shock heating [13]. Our methodology and model formulation is explained in greater detail in [5]. Table 1 summarizes this study's chosen parameter values and combinations thereof.

**Preliminary Results and Discussion:** From preliminary results, our simulations show a range of timescales and final configurations of the late-stage cumulate layer.

In general, $\bar{T}_0$ and $\eta_0$ appear to have the greatest influence on how rapidly the upper mantle flows away from the site of impact (entraining the cumulate layer and sequestering it toward the impact antipode). In cases where impact heating catalyzes hemisphere-scale convection, lateral upper mantle flow leads to a moderate to significant asymmetric distribution of the cumulate layer within 300–600 Myr. A warmer upper mantle and lower $\eta_0$ decrease the time needed for an asymmetry to develop. Scenarios with $\eta_0 = 10^{22}$ Pa·s typically do not develop any notable mantle convection by 1 Gyr.

With respect to the spatial configuration of the cumulate layer, the major influencing parameters appear to be the impact scenario, $H$, and $\bar{T}_0$. In many scenarios, with or without impact heating, hemisphere-scale convection leads to downwelling that entrains the cumulate layer. However, without impact heating, the configuration of the downwelling cumulate layer is simply linked to the configuration of the initial temperature perturbation (a requisite feature of these convection models, separate from the impact heating perturbation). In scenarios with SPA impact heating, cumulate downwelling (if present) consistently occurs within the antipodal hemisphere (e.g., Fig. 1), although $H$ influences when and where downwelling begins (greater $H$ leads to earlier downwelling over a broader area). Serenitatis impact heating has variable results, ranging from only a small perturbation of the cumulate layer close to the impact, to equatorial (e.g., Fig. 1) or antipodal downwelling.

In both impact scenarios, as lateral upper mantle flow "pushes" the cumulate layer toward the antipode of impact heating, a thicker cumulate layer (i.e., greater $H$)

leads to earlier downwelling at the edges of the layer than at the center (i.e., the impact antipode). This effect appears to be exaggerated given a warmer upper mantle.

**Conclusions:** In summary: the lunar mantle temperature profile and reference viscosity exert a controlling influence on the rapidity of lunar upper mantle flow and—in the case of basin-forming impacts—impact-antipodal sequestration of Th-, Ti-, and KREEP-bearing magma ocean cumulates. The impact scenario, initial cumulate layer thickness, and initial mantle temperature profile exert a controlling influence on the spatiotemporal configuration of the cumulate layer. With a lower mantle reference viscosity (in our study, $10^{20}$ Pa·s), SPA impact heating consistently transports the cumulate layer to the antipodal hemisphere. Under the same conditions, the Serenitatis impact (and by proxy, similarly sized lunar basin-forming impacts) could have influenced the subsurface distribution of important geochemical fingerprints such as KREEP/Th or Ti, though further investigation is required.

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**References:** [1] P. H. Warren and J. T. Wasson (1979) *Rev. Geophys.*, *17*, 73–88. [2] P. H. Warren (1985) *Ann. Rev. Earth Planet. Sci.*, *13*, 201–240. [3] L. E. Nyquist and C.-Y. Shih (1992) *Geochim. Cosmochim. Acta*, *56*, 2213–2234. [4] A. J. Evans et al. (2018) *J. Geophys. Res. Planets*, *123*, 1596–1617. [5] M. J. Jones et al. (2022) *Sci. Adv.*, *8*, eabm8475. [6] N. Zhang et al. (2022) *Nat. Geosci.*, 1–5. [7] R. W. K. Potter et al. (2012) *Icarus*, *220*, 730–743. [8] A. J. Trowbridge et al. (2020) *Icarus*, *352*, 113995. [9] E. Bjonnes et al. (2022) *LPSC LIII*, 1551. [10] S. Zhong et al. (2000) *J. Geophys. Res.*, *105*, 11063–11082. [11] E. Tan et al. (2006) *Geochem. Geophys. Geosyst.*, *7*, Q06001. [12] A. K. McNamara, and S. Zhong (2004) *J. Geophys. Res.*, *109*, B07402. [13] W. A. Watters et al. (2009) *J. Geophys. Res.*, *114*, E02001.

**Table 1:** All model parameters and associated values that were varied between scenarios. Model scenarios used in this study include all combinations of the below parameters, except as noted.

| **Parameter** | $\bar{T}_0$ | $\eta_0$ | ***Impact*** | $\eta(T)?^a$ | $A$ | $H^b$ |
|---|---|---|---|---|---|---|
| **Values** | *Mixed (1600 K)*<br>*Solidus* | $10^{20}$ *Pa s*<br>$10^{22}$ *Pa s* | *None*<br>*SPA*<br>*Serenitatis* | *Yes*<br>*No* | $10^0$<br>$10^{-2}$ | 25 *km*<br>50 *km*<br>100 *km* |

$^a\eta(T)$ column represents whether viscosity, $\eta$, depends on temperature, $T$. Note: $\eta(T)$ is only *Yes* when *Impact* is *SPA* or *Serenitatis.*

$^bH$ = 25 km and $H$ = 100 km are not used when $A$ was $10^0$.

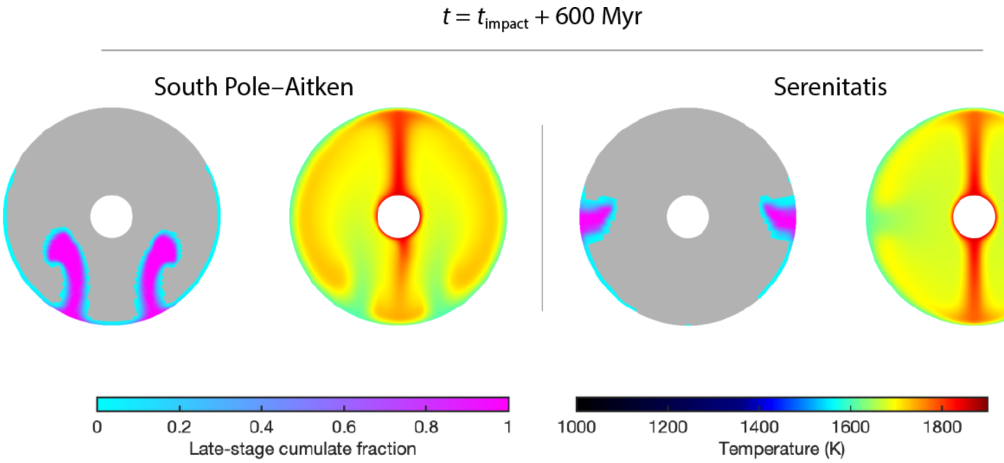

**Figure 1:** 2-D cross-sectional plots from 3-D spherical simulations of lunar mantle evolution at 600 Myr after heating from the South Pole–Aitken (SPA) (*left panel*) and Serenitatis (*right panel*) basin-forming impacts. Each panel shows composition (*left*) (with late-stage cumulate material in pink and blue and other mantle material in grey) and temperature (*right*). Cross-sections in each panel are oriented so that the basin-forming impact point is at the north pole. Aside from the impact scenario, these simulations share the same model parameters: $\bar{T}$ = *Mixed (1600 K)*; $\eta_0 = 10^{20}$ Pa·s; $A = 10^0$; $H$ = 50 km.