# AN IMPACT ORIGIN OF THE LUNAR PROCELLARUM KREEP TERRANE.

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**Introduction:** The lunar South Pole–Aitken (SPA) basin is the largest and oldest recognized impact basin on the Moon [1]. Located on the farside hemisphere (Fig. 1), SPA is nearly antipodal to the nearside geochemical province referred to as the Procellarum KREEP Terrane (PKT) [2, 3]. (KREEP is a geochemical component named for its enrichment in incompatible elements including Potassium (K), Rare Earth Elements (REE), and Phosphorous (P) [4]). The PKT represents an as-of-yet unexplained compositional asymmetry on the lunar surface, but the relative position of the two regions may be indicative of the SPA impact playing a role in forming the PKT [5].

Large basin-forming impacts create substantial thermal anomalies in planetary interiors [6, 7]; we demonstrate here that the SPA impact-induced thermal anomaly would have greatly influenced lunar thermochemical evolution, leading to an interior asymmetry and offering an explanation for the existence of the PKT.

**Thermochemical Evolution Model:** We used the 3-D spherical finite element thermochemical evolution code CitcomS with tracer-based composition tracking [10-12]. The SPA impact is simulated by prescribing a global temperature increase which varies radially from the point of impact, calculated using a Hugoniot-release model of impact shock-induced heating [6]. We limit shock-induced temperatures by the mantle solidus, as the timescale of impact melt crystallization is short compared to the timescale of thermochemical convection [7, 13].

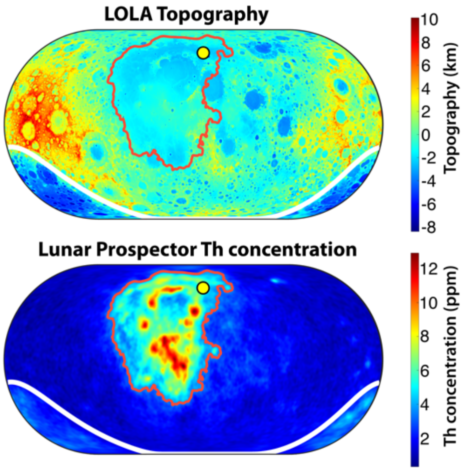

**Figure 1:** Lunar maps centered on the nearside: (top) topography [8]; (bottom) Th abundance [9]. PKT outlined in red, defined by 3.5 ppm Th contour [2]. SPA basin ellipse outlined in white and basin-center antipode marked by a yellow circle [3].

*Initial Conditions.* The silicate portion of the Moon is hypothesized to have fractionally crystallized from a lunar magma ocean (LMO); we initialized our simulations with temperature and composition structures consistent with this hypothesis. Toward the end of solidification, a global layer of dense, low-viscosity, KREEP-rich material is expected beneath the crust and above a cumulate mantle [4, 14, 15]. The unstable mantle density structure created by fractional LMO crystallization may have undergone gravitational overturn [14], although it has been suggested that at least some of the late-stage cumulates would remain underlying the crust [15]. The timing of the SPA impact relative to this potential overturn is unknown, so we consider both pre- and post-overturn lunar interior structures adapted from model results of LMO evolution [14]. The composition structures are vertically stratified and laterally uniform.

In order to explore the general character and variability of the SPA thermal anomaly's effects, we considered 15 additional simulations with a variety of temperature and composition structures based on reasonable limits for the lunar interior [e.g. 14-18].

**Results:** As Figure 2 illustrates, the large thermal anomaly resulting from the SPA impact drives buoyant upward flow and leads to formation of a mantle plume beneath the impact site. Degree-1 convection disrupts preexisting convection patterns and lasts until the thermal anomaly buoyantly spreads and flattens to a uniform thickness. Once degree-1 convection stagnates, a thermal hemispheric asymmetry is left behind, sometimes lasting until the present.

In the pre-overturn impact scenario, buoyant flattening of the thermal anomaly as well as forcing from the farside mantle plume drive shallow lateral flow for ~200 Myr, transporting late-stage LMO cumulates laterally toward the nearside. The nearside late-stage cumulate layer thickens by around 15 km (Fig. 3). Deep material is entrained in the upwelling and mid-depth material is entrained in the downwelling.

In the post-overturn impact scenario, late-stage cumulates surround the core and have much lower viscosity than the overlying mantle, leading to layered convection. The farside mantle plume that forms after the SPA impact remains within the low-viscosity layer (rising to a depth of approximately 350 km), so degree-1 convection and shallow lateral flow are mainly driven by buoyant flattening of the impact-induced thermal anomaly. The inverted post-overturn temperature profile lessens the depth extent of the thermal anomaly, so the timescale and vigor of degree-1 convection depend highly on the mantle thermal gradient.

The patterns described above and shown in Figure 2 develop consistently across the parameter space tested in all simulations. In cases where the compositional structure is laterally uniform at the time of impact, an interior asymmetry with initially deep material remaining in the farside hemisphere develops in addition to the shallow asymmetry created by lateral subcrustal flow.

**Implications:** The KREEP component detected in the PKT is proposed to be derived from partial melting of incompatible-rich late-stage LMO cumulates [4], so the surface distribution of KREEP could be representative of its subsurface distribution. Pre-SPA interior heterogeneities may have shifted the center of KREEP concentration, or the obliquity of the SPA impact [3, 5] may have shifted the center of the associated thermal anomaly [19], but our models indicate that concentration of late-stage LMO cumulates beneath the nearside lunar crust is highly likely.

Our results robustly show a connection between a known event in lunar history (i.e., the SPA basin-forming impact) and a process which transports and concentrates KREEP in the lunar nearside. The post-overturn scenario requires further examination, but it shows the same degree-1 convection patterns as the pre-overturn scenario. Furthermore, all models show a mechanism by which a deeper lunar interior asymmetry could form. Such a mantle asymmetry could affect characterizations of the interior of the Moon, e.g. a mantle density asymmetry would change values of crustal thickness [20] or could lead to true polar wander. A mantle geochemical asymmetry created by degree-1 convection could also lead to observable surface features, such as azimuthally varying Mg# due to the vertical gradient in mantle Mg# from fractional LMO crystallization [14].

The major reorganization of lunar interior dynamics caused by the SPA impact has not yet been fully factored into studies of lunar thermochemical evolution. However, we demonstrate here that this process has broad implications for the geologic history of the Moon.

**References:** [1] Evans A. J. et al. (2018) *JGR: Planets, 123,* 1596-1617. [2] Jolliff B. L. et al. (2000) *JGR: Planets, 105*, 4197-4216. [3] Garrick-Bethell, I. and Zuber, M. T. (2009) *Icarus, 204,* 399-408. [4] Warren P. H. and Wasson J. T. (1979) *Rev. Geophys. Space Phys., 17,* 73-88. [5] Schultz, P. H. and Crawford, D. A. (2011) *GSA Special Paper 477,* 141-159. [6] Watters W. A. (2009) *JGR, 114,* E02001. [7] Roberts, J. H. and Arkani-Hamed, J. (2012) *Icarus, 218,* 278-289. [8] Smith, D. E. et al. (2010) *GRL, 37,* L18204. [9] Lawrence, D. J. et al. (2003) *JGR: Planets, 108,* 5102. [10] Tan E. et al. (2006) *Geochem. Geophys. Geosys., 7,* No. 6. [11] Zhong S. et al. (2000) *JGR: Solid Earth, 105,* 11063-11082. [12] McNamara A. K. and Zhong S. (2004) *JGR: Solid Earth, 109,* B07402. [13] Reese, C. C. and Solomatov, V. S. (2006) *Icarus, 184,* 102-120. [14] Elkins-Tanton L. T. et al. (2011) *Earth Planet. Sci. Letters, 304,* 326-336. [15] Elkins-Tanton, L. T. et al. (2002) *EPSL, 196,* 239-249. [16] Dygert, N. et al. (2016) *GRL, 43,* 532-540. [17] Zhang, N. et al. (2013) *JGR: Planets, 118,* 1789-1804. [18] Evans, A. J. et al. (2014) *JGR: Planets, 119,* 2013JE004494. [19] Wakita, S. et al. (2019) *GRL, 46,* 2019GL085174. [20] Wieczorek M. A. et al. (2013) *Science, 339,* 671-675.

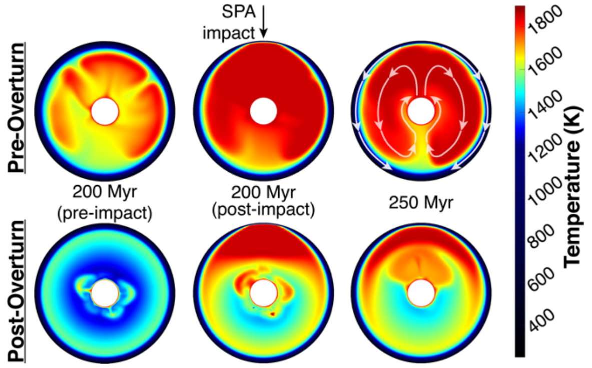

**Figure 2:** 2-D temperature cross-sections of lunar thermochemical evolution simulations showing the pre- (top) and post- (bottom) mantle overturn initial condition scenarios. Timesteps shown are immediately before (left) and after (center) emplacement of the SPA-induced thermal anomaly and 50 Myr after emplacement (right). The SPA impact is simulated vertically down at 200 Myr based on the ≥4.3 Ga constraint on the age of the SPA basin [1]. Arrows showing the induced degree-1 convection pattern are overlain on the 250 Myr pre-overturn cross-section.

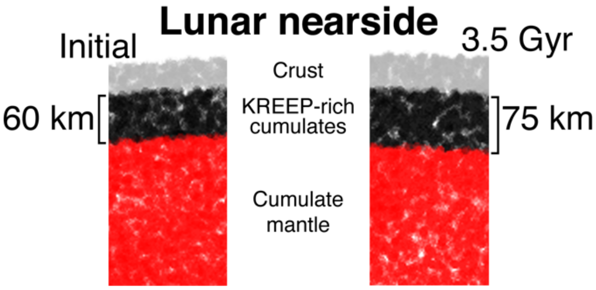

**Figure 3:** Adjacent 2-D cross-sectional slices of tracer composition from the pre-overturn SPA impact thermochemical evolution simulation. Shallow lateral flow induced by the SPA thermal anomaly (Fig. 2) leads to ~15 km of thickening of the KREEP-rich late-stage LMO cumulates.