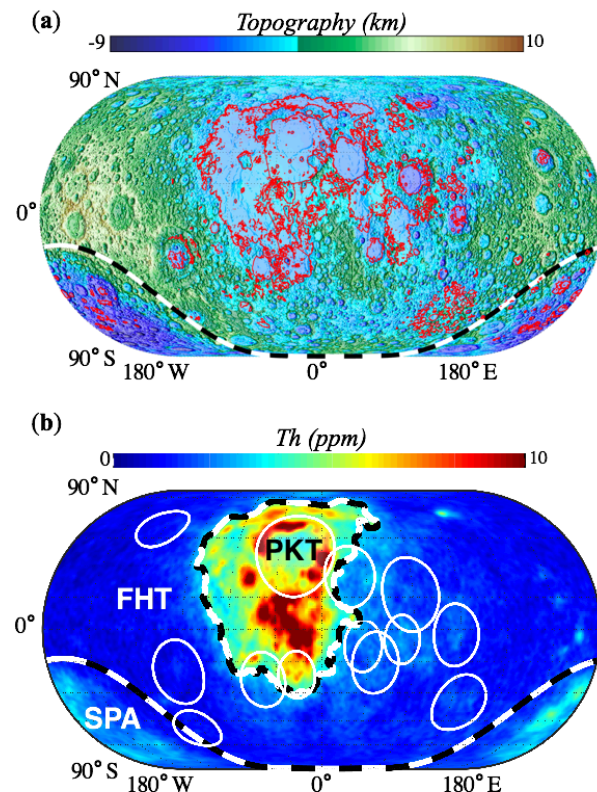


**THE LUNAR GEOCHEMICAL ASYMMETRY: IMPLICATIONS FOR KREEP AND MAGMA OCEAN CRYSTALLIZATION.** Alexander J. Evans<sup>1</sup>, Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA, alexander\_evans@brown.edu.

**Introduction:** Our fundamental understanding of lunar evolution is grounded in the theory that the Moon underwent an early, extensive magma ocean near the end of its primary accretion phase [1–3]. This theory explains well the compositions and ages associated with the lunar crust [2], however, the last stages of magma ocean crystallization have yet to be reconciled with the observed surface geochemical distribution, particularly that of lunar KREEP [4–6]. KREEP — a geochemical component with a high abundance of incompatible elements such as *K*, *Rare Earth Elements*, and *P* — is the residuum from the magma ocean that crystallized beneath the less dense, feldspathic crust [3]. As a result of the high enrichment of radioactive elements such as potassium, thorium, and uranium within KREEP material, the primary distribution and subsequent evolution of lunar KREEP has significant implications for the thermal and chemical evolution of the Moon [7].



**Figure 1.** Lunar maps of (a) topography (km) [11] with surface volcanic deposits (outlined in red; [12]) and (b) surface Th (ppm; [13]). The Feldspathic Highlands Terrane (FHT), South Pole-Aitken (SPA) basin, and Procellarum KREEP Terrane (PKT) are labeled in (b) and delineated (black and white). Basins with diameters larger than 650 km are outlined (b). Modified after [14].

Although the magma ocean is expected to have occurred globally [1,2], KREEP lithologies are found almost exclusively on the lunar nearside surface associated with high thorium abundances (Figure 1b) [4]. Several theories relying on giant impacts [9] and asymmetric evolution of the crystallized magma ocean cumulates [10] have been proposed to explain the apparent localization of surface KREEP, and other late-stage magma ocean cumulates such as ilmenite, within the Procellarum KREEP Terrane (PKT). However, the present-day observed asymmetry of KREEP at the lunar surface is heavily biased by Imbrium ejecta, mare volcanism, and other surface effects [e.g., 8; Figure 1]. Accordingly, it is not known whether the observed surface geochemical asymmetry in thorium is reflective of an asymmetry in the original subsurface distribution of KREEP or other processes.

Herein, basins that excavated beneath the lunar crust are used to determine: (1) whether an asymmetry in the primary subcrustal KREEP layer is required to explain the observed surface KREEP distribution and (2) the degree of subsurface KREEP asymmetry required to reproduce the observed surface geochemical asymmetry. For the preliminary analyses below, the South Pole-Aitken and Imbrium basins are primarily considered.

**Methodology:** For each basin of rim diameter  $D$ , the observed surface thorium concentration  $[\text{Th}]_{\text{obs}}$  within the continuous ejecta blanket region (annulus bounded by  $0.5 \times D$  and  $D$ ) is presumed to be representative of the mean thorium concentration of material excavated by the basin. Using the outline of surface volcanic deposits in Figure 1a,  $[\text{Th}]_{\text{obs}}$  is corrected to exclude measurements within the maria. Excavation diameters of 721 km for Imbrium [15] and 850 km and 1200 km [16] for South Pole-Aitken are considered, respectively. The excavation cavity is approximated as a parabolic shape, with a depth of 10% of the excavation diameter [17], such that the observed thorium distribution can be related to the crust, KREEP, and mantle layers via the following relation:

$$[\text{Th}]_{\text{obs}} = \frac{[\text{Th}]_K V_K + [\text{Th}]_M V_M + [\text{Th}]_C V_C}{V_{\text{ex}}}$$

The thorium concentration  $[\text{Th}]$  and volume  $V$  for the excavated portions of the crust, mantle, and KREEP layers are denoted with subscripts  $C$ ,  $M$ , and  $K$ , respectively. The sum of the volumes of the excavated layers in the above equation is equivalent to the total excavation volume  $V_{\text{ex}}$ . To be consistent with models of lunar magma ocean crystallization [2], the subsurface KREEP layer is

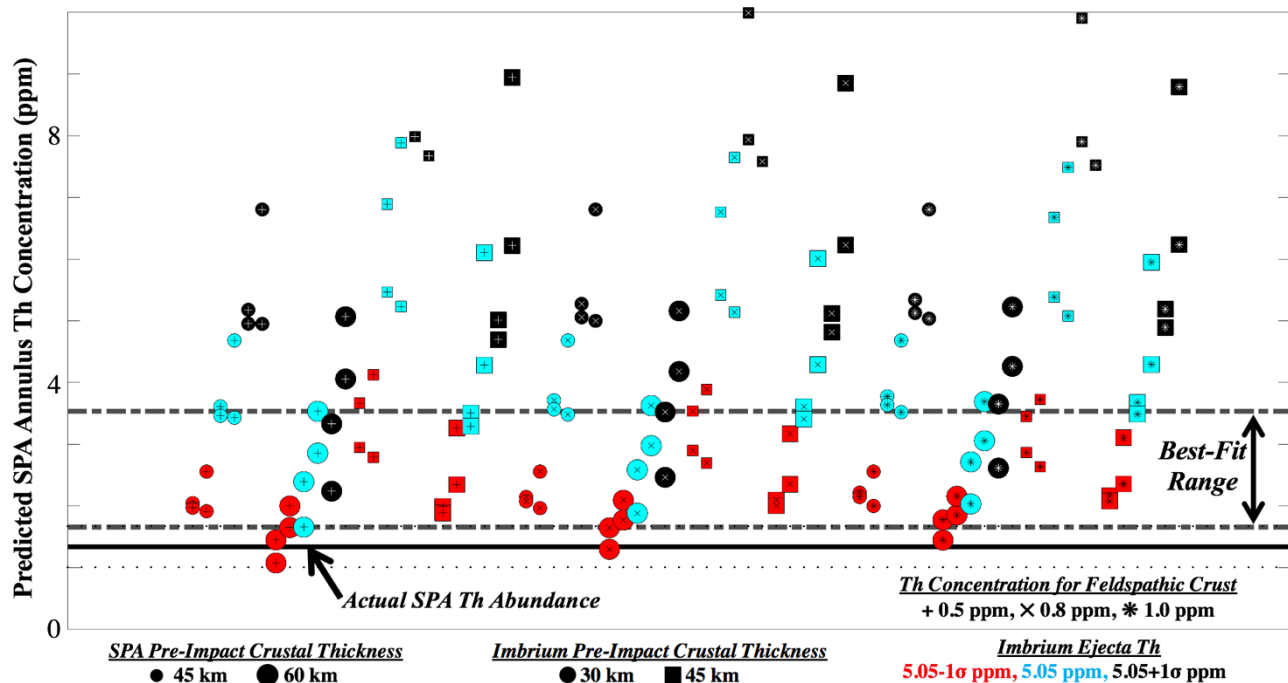
considered to be immediately beneath the feldspathic crust and above the mantle.

The lunar mantle thorium concentration is lower than that of the crust and KREEP layers by at least a factor of  $\sim 20$  [3]. Therefore, the middle term in the above equation is insignificant and can be neglected. For the crust, a range of Th concentrations (0.5, 0.8, and 1.0 ppm) and pre-impact thicknesses (30, 45, and 60 km) are considered [e.g., 3, 15, 16]. Th concentrations for the feldspathic crust and KREEP layer are considered to be the same at the pre-impact sites of both Imbrium and SPA. The KREEP layer has a constant global thickness for each model scenario (5, 27, and 42 km). The crustal thickness ranges are permitted to vary independently at each pre-impact site. In each scenario, the term  $[\text{Th}]_K$  is globally varied to ensure that  $[\text{Th}]_{\text{obs}}$  matches observations at Imbrium. Ultimately, this allows predictions to be made for  $[\text{Th}]_{\text{obs}}$  at SPA that can then be compared to observations.

**Discussion and Summary:** Our results from the range of scenarios described above are shown in Figure 2. For the best-fit impact parameters predicted by previous workers for SPA and Imbrium [15, 16], we find that a factor of 1.2–2.6 more subsurface KREEP may have existed beneath the pre-impact site of Imbrium compared with the pre-impact site of SPA. Most interestingly, we also find that the observed asymmetry in thorium concentration and KREEP at the lunar surface does not re-

quire a greater amount of KREEP beneath the lunar near-side. Instead, the surface geochemical asymmetry may have been the result of the known global variation in crustal thickness and the expected difference in depths of excavation for the Imbrium and SPA impacts. Furthermore, if the South Pole–Aitken basin impacted into the Moon prior to the final crystallization of the lunar magma ocean, as suggested by the results of [14], a less-concentrated KREEP-rich layer would have been excavated at SPA compared to Imbrium, resulting in lower thorium concentrations than those predicted in Figure 2.

**References:** [1] Warren P. (1985) *Annu. Rev. Earth Planet. Sci.*, 13, 201–240. [2] Elkins-Tanton L. T. et al. (2011) *Earth Planet. Sci. Lett.*, 304, 326–336. [3] Warren P. H. and Wasson J. T. (1979) *Rev. Geophys.*, 17, 73–88. [4] Jolliff B. L. et al. (2000) *J. Geophys. Res.*, 105, 4197–4216. [5] Borg L. E. et al. (2015) *Meteorit. Planet. Sci.*, 50, 715–732. [6] Wilhelms D. E. (1987) *USGS Prof. Paper 1348*. [7] Wiczorek M. A. and Phillips R. J. (2000) *J. Geophys. Res.*, 105, 20417–20430. [8] Haskin, L. A. (1998) *J. Geophys. Res.*, 103, 1679–1689. [9] Cadogan P. H. (1974) *Nature*, 250, 315–316. [10] Parmentier E. M. et al. (2002) *Earth Planet. Sci. Lett.*, 201, 473–480. [11] Barker M. K. et al. (2016) *Icarus*, 273, 346–355. [12] Nelson D. M. et al. (2014) *LPS XLV*, 2861. [13] Lawrence D. J. et al. (2003) *J. Geophys. Res.*, 108, 5102. [14] Evans A. J. et al. (2018) *J. Geophys. Res.: Planets*, 123, 1–22. [15] Miljković K. et al. (2016) *J. Geophys. Res.: Planets*, 121, 1695–1712. [16] Melosh H. J. et al. (2017) *Geology*, 45, 1063–1066. [17] Melosh H. J. (1989) *Oxford Monogr. Geol. Geophys.*



**Figure 2.** Predictions for thorium concentration in an annulus surrounding SPA assuming that both the crustal thorium concentration and subcrustal KREEP thorium abundance were the same at the pre-impact sites of Imbrium and SPA, respectively. A range of predictions are shown for varying Th concentrations in the crust (0.5, 0.8, and 1.0 ppm), pre-impact crustal thicknesses at Imbrium and SPA (30, 45, and 60 km), thorium concentration in Imbrium ejecta (2.76, 5.05, and 7.34 ppm). Variations based on SPA transient diameter and KREEP layer thickness are not uniquely distinguished by symbols or colors.