BOUNDING AND CONTEXTUALIZING VERTICAL DISTRIBUTION OF KREEP IN THE MOON'S UPPER CRUST. J. N. Levin[1], A. J. Evans[1], J. Andrews-Hanna[2], I. J. Daubar[1]. [1]Brown University, Providence, RI. [2]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ. (janette_levin@brown.edu)

Introduction: KREEP (short for Potassium (**K**), Rare Earth Elements (**REE**), and Phosphorous (**P**)) refers to lunar material enriched with incompatible elements [1,2]. Its distribution is an important clue to untangling the early history of lunar evolution (e.g., the aftermath of the lunar magma ocean). The highest abundances of KREEP observed on the lunar surface are found in the Procellarum KREEP Terrane (PKT), the high-thorium region on the lunar nearside [3].

Gamma-ray spectroscopy measurements of surface thorium concentration are often used as a proxy for KREEP. However, as gamma-ray spectroscopy is limited to the top meter of the surface [4], the true vertical and lateral distribution of KREEP within the lunar crust remains poorly understood. Here, we constrain the thickness and thorium concentration of a potential KREEP-rich layer to depths of several kilometers by measuring Th abundances ([Th]) in complex craters with diameters of up to 200 km [5].

Ejecta from the Imbrium impact has been proposed as the source of much of the current thorium distribution on the lunar surface [11]. We use peak [Th] as a function of distance from Imbrium alongside a model of basin ejecta to constrain the thorium concentration of the possible KREEP-rich reservoir excavated by the Imbrium impact. Finally, we compare predicted ejecta thickness of Imbrium with our reconstructed KREEP layer thickness.

Data Analysis: We use the instrument response function and thorium abundance data from the Lunar Prospector Gamma Ray Spectrometer (LP GRS) to measure and compare true surface thorium abundances (TSTAs) of the interior and ejecta of individual craters [4,6]. For subsequent analyses, we exclusively consider craters where the ejecta TSTA is greater than the interior TSTA by a statistically significant amount (Fig 1). Specifically, we only consider craters where the TSTA differences between the crater ejecta and crater interior regions exceed the [Th] variance of the crater region, defined by an annulus extending 300 km from the outermost edge of the continuous ejecta. To simplify density and composition considerations, we exclude all LP GRS pixels within mare for this analysis [7]. A total of 344 craters fit our criteria (Fig. 2).

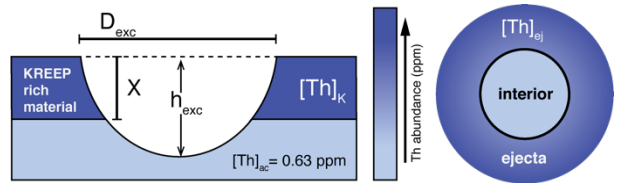

Figure 1: Schematic of a crater with a greater [Th] in ejecta than interior (right), modeled as an impact into a high thorium KREEP-rich layer overlaying thorium-poor anorthosite (left).

Bounding KREEP Layer Properties: To constrain parameters for a KREEP layer, we compare observed ejecta TSTAs to modeled ejecta [Th] calculated using a mixing model. We consider a scenario where a crater impacts into a layer of KREEP (thickness X and abundance $[Th]_K$) overlying anorthositic crust with bulk

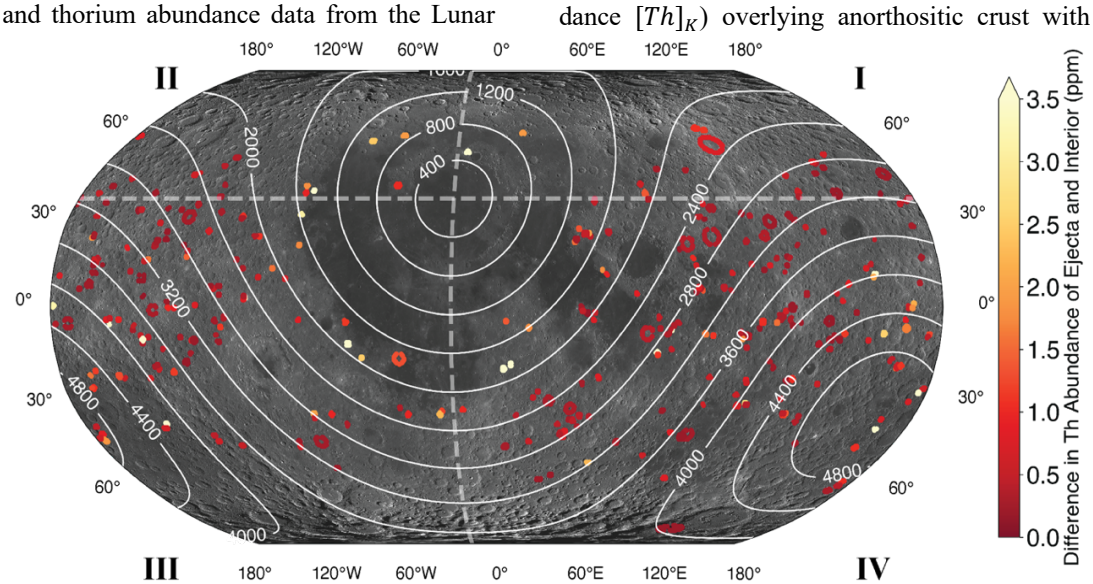

Figure 2: 344 final craters used in our analysis. Regions of Interest are defined using Imbrium-centric quadrants (dashed grey lines), labeled I - IV, and contours based on distance (km) from the center of Imbrium (solid white lines).

average $[Th]_{crust}$ of 0.63 ppm [8] (Fig.1). A complex crater excavates a parabolic cavity with diameter D_{exc} and height h_{exc} which are calculated from the observed crater diameter using established crater-scaling laws [9,10]. We calculate the [Th] of ejected material for a suite of varying KREEP-layer properties (X, $[Th]_K$), and compare our model results to observed TSTA values. We calculate a range of best-fit target properties for each crater individually, and group results into Regions of Interest (ROIs) to analyze broader trends.

For this study, we choose ROIs to explore the thickness of a top-layer of KREEP as a function of distance from Imbrium by dividing the surface into four Imbrium-centric quadrants, and each quadrant into ROIs bounded by contours of Imbrium (Fig. 2). In each ROI, the maximum ejecta TSTA is taken to be the minimum possible $[Th]_K$. The root-mean-square of best-fit models from each crater in the ROI is used to bound the maximum thickness of a KREEP layer with concentration $[Th]_K$.

Modeling Imbrium Ejecta: Imbrium ejecta deposits are a mix of primary material ejected during the impact event and local material excavated by the secondary impacts. We use a ballistic sedimentation model to calculate the ratio of primary ejecta to local material as a function of distance from Imbrium [11–13] (Fig. 3a). Modeled thicknesses of total Imbrium ejecta deposits are within the bounds of calculated surface KREEP layer thickness (Fig. 3a).

To estimate the thorium distribution of Imbrium ejecta deposits, we consider the scenario wherein the Imbrium impact event excavated a high-thorium reservoir [12]. For a given value of primary material [Th], we use the ratio of primary-to-local material from the ballistic sedimentation model to calculate [Th] of total Imbrium ejecta deposits as function of distance from Imbrium. The resulting [Th] vs. distance curves are compared to $[Th]_K$ bounds calculated from our Imbrium-centric ROIs. To exclude possible contributions from the South-Pole Aitken Basin, we use the domain bounded by Imbrium's coherent blanket ejecta radius (720 km) and the distance of minimum Imbrium ejecta thickness (3300 km) for our best fit calculations. The resulting best fit [Th] for the material excavated by Imbrium is ~31 ppm (Fig. 3b).

Our thorium distribution calculation relies on the simplification that outside of the immediate impact region, most of the upper lunar crust was anorthositic at the time of the Imbrium impact. It has been shown that a localized upwelling of KREEP-bearing material in the PKT could have been induced by the South-Pole Aitken-forming impact [14,15]. This upwelling could serve as the source of KREEP-rich material at the Imbrium impact-site. Our results show that the first-order measure of thickness of surface KREEP is well explained by Imbrium ejecta deposits.

Discussion and Future Work: Smaller scale patterns in the thickness and [Th] of the KREEP layer could be caused by preexisting giant impact ejecta or subsequent impact events. Non-impact related thorium anomalies (i.e. Compton Belkovich complex) are also a potential source of variation [7]. In the future, we will consider different ROIs to explore patterns in vertical and spatial KREEP distribution. A modified version of the technique will also be applied to determine the depth of buried KREEP layers across the Moon.

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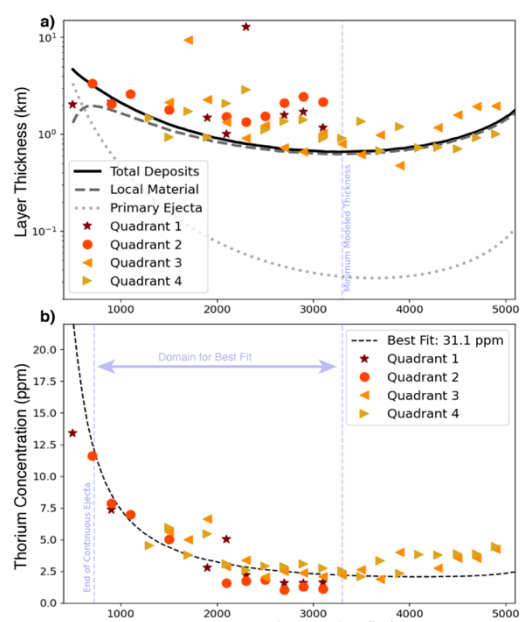

Figure 3: a) Maximum KREEP layer thickness measurements from ROIs compared to modeled Imbrium ejecta deposits. b) Minimum KREEP layer [Th] from ROIs and the best-fit model of Imbrium ejecta concentration