ANALYSIS OF THORIUM CONCENTRATION ANOMALIES ON THE LUNAR SURFACE Jingyi Zhang[1,2], Jianzhong Liu[1*], James W. Head[2*], Ross W. K. Potter[2,3]. [1]Center for Lunar and Planetary Science, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, China, (liujianzhong@mail.gyig.ac.cn), email: zhangjiangyi@mail.gyig.ac.cn, [2]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912 USA, (james_Head@brown.edu) [3]Clarivate Analytics, London, UK.

Introduction: Most lunar evolution models predict that fractional crystallization of a lunar magma ocean will produce a layer of melt enriched in incompatible elements such as K, REE, and P (i.e., KREEP) [1]. Some workers [2] have proposed that the surficial distribution of Th, which has been measured on a global-scale [3,4,5], can be used as a proxy for determining the global distribution of KREEP. The Th and FeO distributions are also used to divide the lunar surface into three main Terranes: Procellarum KREEP (PKT), Feldspathic Highland (FHT) and South Pole-Aitken (SPAT) [2]. Here, we use the boundary of PKT in [6].

There are obvious highTh abundance locations in the PKT, but almost none in FHT, and only medium-Th concentrations in parts of SPAT (Figure 1). The lateral extent and distribution of the residual magma ocean "KREEP" layer is currently a matter of debate. On the basis of the asymmetry of the Th distribution, some workers suggested that the Procellarum region is the oldest lunar impact basin, the formation of which may have caused the accumulation of KREEP-rich residual liquid on the nearside; in contrast, the lunar farside generally lacks the same high abundances of Th and other KREEPy elements [7,8]. Other mechanisms have been proposed to explain the asymmetry of KREEP materials, including inhomogeneous differentiation of the magma ocean [9], and antipodal effects of impact [10].

In this analysis, we use impact craters and basins superposed on the ancient lunar crust to document the 3-D (lateral and vertical) extent of Th in PKT and SPA in order to establish the geometry and potential evolution of the KREEP layer. We use the relations between transient cavity depth or diameter and crater excavation depth given by Potter [11] and Melsoh [12] to obtain sampling depth data. We then assess the three-dimensional geometry of Th concentrations in the PKT and compare the relations between PKT and SPA as a basis for a hypothesis to explain Th distribution and characteristics.

Data: We use a synthesis of data from remote sensing, geomorphologic mapping, and comparative analysis. Thorium abundance from the Lunar Prospector mission [13] are merged with an altimetric shaded relief map [14] and crater depth/diameter from the LPI Lunar Impact Crater Database [18].

Results: The Th abundance map shows that the high-Th areas are 1) mainly related to Imbrium ejecta (Fra Mauro Formation-FMF) and/or post-Imbrium KREEP volcanism in the PKT, and 2) concentrated at the location of young impact craters in mare and highlands regions (Figure 1) [15]. We studied several such craters located on highlands and mare regions (Figure 1; Table 1), including Mairan, Kepler, Aristarchus, Aristillus, Copernicus and Plato. In particular, the high-Th concentration regions are near Mairan, Kepler, Aristarchus, and Aristillus. However, not all craters on Imbrium ejecta show high-Th concentrations. Copernicus and Plato, which are located on the FMF and the Imbrium rim respectively, show relatively low Th values, suggesting that the high-Th terrain does not exist below the surficial FMF in these areas. Craters within Mare Imbrium generally show lower Th abundance than those on the highlands (suggesting that they are excavating maria, not Th-rich FMF or crust), with two exceptions - Timocharis and Autolycus. These two craters appear to excavate through Th-poor maria and into Th-rich Imbrium basin deposits (FMF etc., Table 1). A second concentration of Th is within Mare Ingenii in SPA (Figure 3a). This concentration shows peaks at two impact craters, Brikeland (81.4 km diameter) and Oresme V (56.1 km diameter) (Figure 3b).

Discussion: There exists a higher Th abundance in PKT than its surrounding areas, which suggests that KREEP materials are mainly concentrated in the subsurface of the PKT [2,6,16,17], perhaps throughout the crust. In the PKT, combining these high-Th craters and their excavation depths (Table 1), we found that craters on the highlands (mostly FMF) show the highest Th abundances, except Copernicus and Plato, the excavation depths of which are deeper than other high-Th locations. We thus interpret the Th concentration to have been excavated by the Imbrium impact and distributed only onto the very shallow surface of the highlands (FMF) and thus much less abundant at deeper depth. There are two craters that show relatively high Th abundance in Imbrium (Figure 2). The high-Th values of Aristillus impact ejecta (Autolycus values may due to Aristillus ejecta) and Timocharis crater ejecta, both located in the maria, show high Th even though the mare is many hundreds of meters thick. We therefore suggest that both penetrated through the mare basalts of the Imbrium basin and excavated underlying Th-rich material =. This lends support to the model of the Th rich material being concentrated primarily in Imbrium basin ejecta deposits and related impact melt and KREEP volcanism, independent of the lunar mare fill. In SPA, observed Th anomalies occur on the central, more mafic floor of the basin (Figure 3) suggesting that their formation is related to basin formation and is likely indigenous [18].

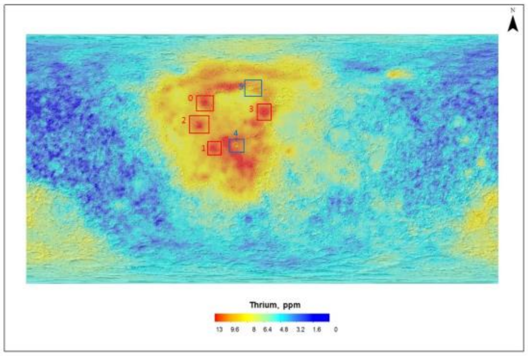

Figure 1. Thorium abundance from Lunar Prospector gamma-ray spectrometer overlain on LOLA hillshade map. Red and blue square boxes show high-Th and low-Th concentrations, respectively. 0 is crater Mairan; 1-Kepler; 2-Aristarchus; 3-Aristillus; 4-Coperncius; 5-Plato.

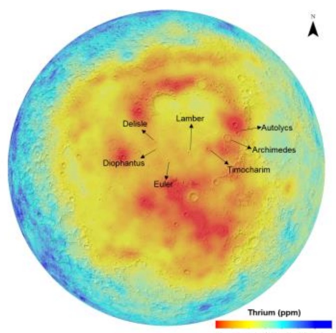

Figure 2. Craters analyzed within Imbrium.

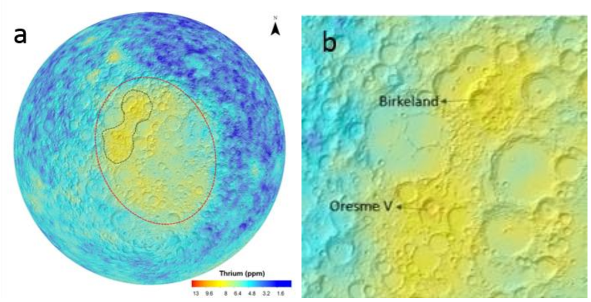

Figure 3. Thorium abundance from Lunar Prospector gamma-ray spectrometer overlay the LOLA hillshade map. (a) Red dashed oval represents approximate contour of SPA which shows relatively higher Th concentration than the around FHT. Green dashed polygon represents the highest Th value region in SPA, centered on two impact craters. (b) Birkeland and Oresme V crater in SPA with peak Th abundances.

Interpretation: Based on these stratigraphic and geometric relationships, we interpret the high Th distribution in PKT and SPA to be related to sequential oblique and near-vertical impacts. First, an oblique impact formed a Procellarum basin, removing much of the upper and middle crust in the area and bringing the residual KREEP-rich layer close to the surface. This was followed by formation of the SPA basin by oblique impact [10], similarly removing much of the upper and middle crust and exposing the KREEP-rich lower crust covered by SPA impact melt. Subsequently, the more-vertical Imbrium basin impact penetrated into the shallow KREEP layer, ejecting it to form the FMF and related Th-rich ejecta and impact melt deposits. Later mare volcanism buried the KREEP-rich deposits under hundreds of m to km of lava. In the SPA basin, similar vertical impacts Brikeland and OresmeV excavated Th-rich material from below the melt sheet to create the locally high Th anomalies. In summary, this interpretive scenario attributes the origin of the PKT and SPA Th anomalies to sequential impact processes, requiring no additional processes to concentrate KREEP in the SPA or PKT terrain at depth, in agreement with [20]. Analysis of the young Procellarum mare basalt samples schedule to be returned by Chang'E 5 will provide a test of this hypothesis.

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Table 1. Craters studied.

Name	Diameter (km)	Apparent depth(km)	Trainsent crater depth(km)	Excavation depth(km)
Diophantus	17.57	2.801	5.72	1.91
Delisle	24.83	1.897	7.67	2.56
Euler	26.03	1.924	7.99	2.66
Kepler*	31	1.999	8.88	2.96
Lambert	30.12	2.012	9.04	3.01
Timocharis*	34.14	2.09	10.06	3.53
Autolycus*	38.8	2.174	11.23	3.74
Aristarchus*	42	2.193	11.51	3.84
Mairan*	34.49	2.184	11.83	3.94
Aristillus*	54.37	2.407	14.94	4.98
Archimedes	81.04	2.798	20.97	6.99
Copernicus	96	2.846	24.24	8.08
Plato	100.68	2.859	25.22	8.41

*Craters which highlighted in red represent high-Th craters in PKT

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