On the Distribution of Th in Lunar Surface Materials. Larry A. Haskin, Jeffrey J. Gillis, Bradley L. Jolliff, and Randy L. Korotev, Department of Earth and Planetary Sciences and the McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130. lah@levee.wustl.edu

Preliminary values for global Th concentrations [1] based on Lunar Prospector data [2] are used here to assess further the hypothesis that most of the Th of the Feldspathic Highlands Terrane (FHT) might have been ejected from the Procellarum KREEP Terrane (PKT) [3] by the Imbrium event [4]. Figure 1 shows the concentrations of Th on the non-mare surfaces of two terranes (the PKT and the FHT) [3] and for the mixture of mare and non-mare materials for a third terrane (the South Pole–Aitken Terrane, SPAT) as a function of distance from the center of Mare Imbrium. Each point represents an equal-area pixel, $5° \times 5°$ in size at the equator.

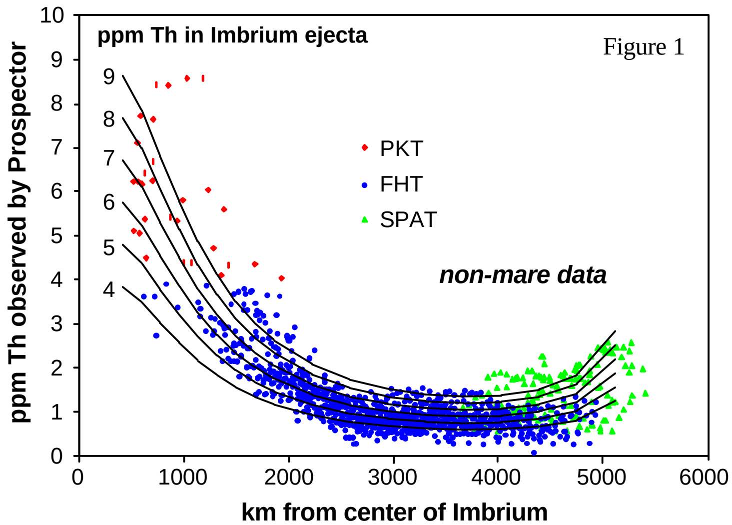
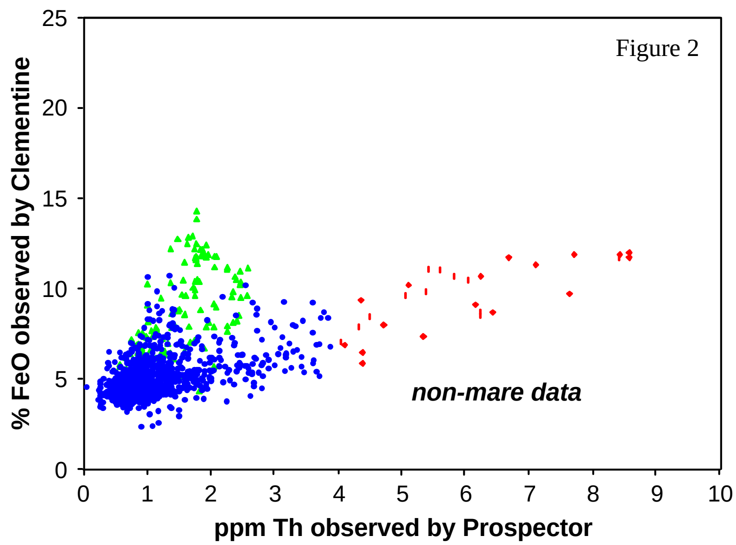


Figure 2 is a plot of ppm Th against wt.% FeO constructed from the Clementine FeO values of [5]. We use the (outermost) 4 ppm Th contour to represent the boundary of the Procellarum KREEP Terrane (calibration of [1]). Most of the terrain within the border of that contour has been resurfaced. The red points in Fig. 2 are for the mainly non-mare locations within the PKT. They form a linear array that extends toward the cluster of points for the FHT. The least-squares line for those points has a slope of 0.98, an intercept of 3.8, and a correlation coefficient of 0.77. The line is not shown as its significance is uncertain, but its value of ~0.4 ppm Th is what we expect for the average for FHT minimally contaminated with Imbrium ejecta [6]. Moreover, the iron value at low Th of 4.2 wt.% FeO for the line is similar to the average estimated for the FHT based on the feldspathic lunar meteorites [6]. Pixels within the PKT that correspond mainly to volcanically resurfaced terrain are not included in this analysis. Most high-Th pixels (4–9 ppm) represented in Fig. 2 are from the furrowed massifs and Fra Mauro formation surrounding the Imbrium basin. As these materials are the most proximal continuous Imbrium deposits, they consist mainly of Imbrium ejecta. The variation in their Th concentrations illustrates that the ejecta (and hence the target) were not uniform in composition. We model the more distal ejecta assuming the same range in variability of Th applies to them, using the method of [7]. This leads to the family of curves shown in Fig. 1. Each curve models ejecta of a single Th concentration. All curves are based on a single value of the transient crater radius, 370 km, as derived from a geophysical model by [8]. The curves show the spread in Th concentration we can reasonably expect for the Imbrium ejecta deposits, and the data at any given distance span the same range of concentration as the curves. A fundamental requirement of the Imbrium ejecta hypothesis is that large areas do not exist outside the family of Th curves, and such is the case.

The ejecta model curves begin just outside the edge the Imbrium transient crater and extend most of the way to the Imbrium antipode. The steep decrease in Th concentration is caused by the higher proportion of local material in the ejecta deposits with increasing distance from Imbrium. As distances from Imbrium increase, the deposits become increasingly discontinuous because the ejecta arrive as filaments or rays. Beyond ~3600 km, however, as these



rays converge, surface density, average thickness, and Th concentrations of deposits increase. Later gardening by smaller craters has little effect on the average Th concentration because it mainly reworks the thick deposits. The Th signal of the ejecta is presumably obscured where it fell into topographic lows that were later resurfaced with mare basalt. It is evident that the general pattern of decrease in surface Th concentration in the FHT with distance from the Imbrium basin is matched to first order by the predictions of the model. Thorium concentrations of several pixels within the PKT lie well above the curves. The PKT is not uniform in Th concentrations. The highest-Th points are for the Fra Mauro region and part of the Carpathians that, while certainly bearing Imbrium ejecta deposits, were already rich in Th, so materials excavated there did not dilute the Imbrium-derived Th as was the case in the Feldspathic Highland Terrane.

As seems always to be the case for global phenomena, a single explanation even if basically correct seldom fits all the data. The main part of the rise in Th concentrations predicted by the model to occur from convergence of Imbrium ejecta at distances nearing the Imbrium antipode occurs, but only within the confines of the South Pole–Aitken basin, where its significance is ambiguous because it might reflect Th in indigenous SPAT floor material. Points at the farthest distances from Imbrium but lying outside the SPAT basin do not show a similar rise in Th concentration, but they nevertheless lie within the confines of the model curves; i.e., their positions are consistent with the model prediction. A preliminary examination of the distribution of Th within SPA reveals that the areas of highest Th [1] do not correspond uniquely with mare basalt deposits on the basin floor. This relation would imply that the Th bearing unit with SPA is either inherent in the local basin floor material or is foreign material deposited inside the basin. Further examination of the stratigraphic relation between the Imbrium ejecta deposits and the older SPA basin should reveal which units carry the high-Th material. Although the Imbrium ejecta deposits are younger than the SPA basin, their identification and their relationship to Th concentrations within that basin have yet to be worked out. We conclude that the predictions of the model overall are consistent with the Prospector data, although the model is not necessarily a unique explanation of the Th distribution.

We believe that the pixels shown in Figs. 1 and 2 represent FHT regolith that is mostly free of extensive contamination by mare material. Many of the pixels not included in Figs. 1 and 2 have sufficiently low FeO concentrations to indicate that they contain a substantial component of PKT or FHT material. A rough correction for this "contamination" can be made by assuming FeO and Th concentrations for the PKT and FHT contaminants, then estimating values for Th concentrations of the mare basalt components of these pixels. This was done as follows: For pixels within the boundary of the PKT, a value for non-mare materials of 10% FeO and 8 ppm Th was assumed. For pure mare basalt, 20% FeO was assumed [9]. The fraction of mare basalt in the average soil represented by each pixel was then calculated by mass balance from the FeO concentration. If the estimated fraction of mare basalt was high enough (>30%) that the mare component would significantly influence the Th concentration of the mixture, then a Th concentration for the mare basalt component was computed. The estimated Th concentrations for O. Procellarum vary, but many are >4 ppm, indicating that high Th concentrations are indigenous to the lavas and do not arise from surface contamination by low-FeO, high-Th ejecta. For pixels well outside the PKT, values in the range of 4–6% FeO and 0.4–1.5 ppm Th were assumed for the FHT component [8]. The resulting estimates all suggest that most of these maria contain ~2–4 ppm Th, significantly more than the surrounding FHT regoliths, indicating substantial amounts of Th in the mare basalt source regions outside the PKT (see also [3]).

Conclusions: The Th concentrations of the Feldspathic Highlands Terrane estimated from the Prospector count-rate data are generally consistent with the hypothesis that most of the Th was emplaced there as Imbrium ejecta. The composition of the ejecta was probably variable, and the range of Th concentrations found for the massifs surrounding M. Imbrium is adequate to explain the spread observed for the FHT. Most pixels within the Procellarum KREEP Terrane represent resurfaced areas, and their FeO concentrations are high enough to require that the lavas themselves have elevated Th concentrations. The high Th concentrations of these mare basalts suggest that Th anomaly of the PKT may extend to the depth of the source regions for mare basalts. The high concentrations of Th would explain why the PKT exhibits the greatest amount of resurfacing on the Moon [see also 10]. The mare regions within the FHT are "contaminated" with substantial FHT material; when a correction is made, the mare basalts have estimated Th concentrations of ~2–4 ppm. This estimate suggests that even the mare source regions well outside of the PKT contain a significant amount Th and at these levels might be responsible for partial remelting the magma ocean olivine-pyroxene cumulates.

Acknowledgment: This work was supported in part by NASA grant NAG5-4172.

References: [1] Gillis et al. (1999), this vol.; [2] Lawrence et al. (1998), *Science* **281**, 1484–1489; [3] Jolliff et al. (1999), this vol. (terranes); [4] Haskin (1997) *J. Geophys. Res.* **103**, 1679–1689; [5] Lucey et al. (1998) *J. Geophys. Res.* **103**, 3679–3699; [6] Korotev (1999), this vol. (feldspathic upper crust); [7] Moss et al., in prep; [8] Wieczorek and Phillips (1999) *J. Geophys. Res.*, in press; [9] Korotev (1998), *J. Geophys. Res.* **103**, 1691–1701; [10] Wieczorek and Phillips (1999) this vol.