THE DISTRIBUTION OF TH ON THE MOON'S SURFACE. LARRY A. HASKIN, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, One Brookings Drive, St. Louis, MO 63130 (lah@levee.wustl.edu)

Our present knowledge of the Th distribution at the Moon's surface is sketchy. It consists mainly of two bands of data taken by the Apollos 15 and 16 γ-ray experiments [1, 2], augmented by ground-truth measurements on Apollo and Luna samples and on lunar meteorites [3]. Gamma-ray maps show a broad area of high Th concentration in the Imbrium-Procellarum region, which we refer to as the High-Th Oval Region [4]. The Imbrium impact occurred within this region. Here, we show that the global pattern of highland surface Th concentrations is consistent with that expected for Imbrium ejecta deposits. Outside of the High-Th Oval Region itself, Imbrium ejecta produced deposits that are a mixture of Th-rich Imbrium ejecta and Th-poor, pre-existing crustal material. Inside the High-Th Oval Region (including the Apollos 12 and 14 sites), Imbrium ejecta mixed with Th-rich crustal material. We suggest that except where younger Orientale ejecta diluted them, or mare basalt flows covered them, Imbrium ejecta deposits remain largely intact. Later gardening of their surfaces has not obscured the pattern of their Th concentrations.

Imbrium ejecta were voluminous. If the excavation cavity was standard (depth/diameter ~0.1 and a parabolic shape less ~10 vol%, [5]), ejecta from the smallest Imbrium event (transient crater radius, R_{tr}, 335 km, e.g.,[6]) would have covered the Moon's surface to a depth of ~280 m and ejecta from the largest (R_{tr} 485 km) to a depth of ~850 m, if distributed uniformly (not including dilution through mixing with substrate (i.e., the materials onto which the ejecta fell). The distribution is not uniform, of course, but falls off exponentially away from the transient crater rim. Material from the Imbrium Basin should thus be found moonwide in substantial amounts. As the ejecta originated in the High-Th Oval Region, they should be (for the Moon) rich in Th. The probable contribution of lunar nearside ejecta to the Th budget of the farside highlands has been noted by others [e.g., 7], but not quantitatively.

Here, we model the thickness of Imbrium ejecta deposits as a function of distance from the Imbrium crater, using the equations of crater scaling [8-12]. We assume ballistic transport of primary ejecta fragments, which produce secondary craters when they impact into the Moon's surface [e.g., 13]. This produces global ejecta deposits that consist of mixtures of ejecta and substrate. Fig. 1 shows the predicted *average* deposit thicknesses as a function of distance from the primary crater for values of R_{tr} of 335 and 485 km. For each value, these predictions should be accurate to about ±50%. The modelling was done for a single ejecta launch angle of 40°; modelling results are sensitive in detail but not in general aspect to choices of model parameters (see[12]).

Proportions of Imbrium ejecta in deposits near the basin rim are high mainly because ejecta landing there have low velocities and impact the surface relatively gently, and because the surface density of the infalling ejecta is high; little substrate is thus mixed into the deposits. At greater distances, infalling ejecta excavate more substrate per mass of ejecta fragments, and surface densities of ejecta are lower; ejecta deposits consist mainly of substrate. Coverage of the lunar surface by Imbrium deposits would be more heterogeneous than the average values given by the model because ejecta travelling distances of a few R_{tr} or more mainly congregate into rays. Deviation from average conditions for a lunar basin the size of Imbrium is not a major concern for the comparisons made here because Th concentrations were averaged over large areas of the Moon's surface by the Apollo γ-ray experiments. Some deviations from the average are expected, nonetheless; they should be greatest at the broad region where the curves in Fig. 1 are near their minima (roughly, 2,000 to 4,000 km from Imbrium). Beyond ~4,000 km, rays converge, so deposit thicknesses and proportions of Imbrium ejecta increase, achieving high values near the antipode [14].

Fig. 2 shows the predicted proportions of Imbrium ejecta in the deposits as a function of distance from Imbrium. These proportions decrease with distance up to ~3,800 km. Beyond that point, the proportion of Imbrium ejecta in the deposits increases owing to ray convergence. Th concentrations of those deposits can be estimated if average Th concentrations of the Imbrium ejecta and the preexisting substrate are assumed (Fig. 2). We use 5 ppm for the ejecta (in the range of Th-rich mafic impact melt breccias [Avg. 7 ± 4, [15]), and 0.1 ppm for the substrate. Fig. 2 also shows Th concentrations determined by the Apollo γ-ray experiments [16] for highland regions lying outside the High-Th Oval Region. Most data points fall between the two theoretical curves. The data show the predicted steep decrease with distance from Imbrium, the broad minimum, and the rise caused by ray convergence beyond about 4,000 km. A spike of high Th concentrations occurs near the Van de Graaff craters not far from the antipode; these high Th concentrations can in principle be reached by the convergence of ejecta [14].

Data from two regions fall below the lower curve: the "western limb" and the "western farside" (nomenclature of [16]). At the western limb, the Orientale Basin and its ejecta deposits cover or dilute the Imbrium deposits. The lower than expected Th concentrations suggest that the Orientale event did not excavate into Th-rich material such as we propose for the High-Th Oval Region. Most points for the western farside also fall below the theoretical curve. Interpreted in terms of the suggested Imbrium origin for most of the Th in the highlands, the western farside highlands along the groundtrack of the γ-ray experiment may be a region with a lower than average amount of Imbrium rays. Alternatively, the ejecta landing in that area may have been less Th-rich than the average value used in the modelling. There is no similar dearth of Th for the "highlands eastern limb" region at the same distance from Imbrium as the western farside highlands, and all data for the more distant "eastern farside" highlands lie between the curves and show the upturn expected to result from ray convergence. The Apollo γ-ray data thus are consistent with an Imbrium origin for most of the Th at the Moon's highland surface. The quality of the agreement is surprisingly good, given that the modelling yields only average values and that it has been extended out to distances of 11 (large Imbrium) and 16 (small Imbrium) transient crater radii, beyond the well tested range of the crater-scaling equations.

If the High-Th Oval Region is the main source of KREEPy material on the Moon and KREEPy ejecta are the main source of Th at the lunar highland surface, then potassium should be distributed in the same way. Indeed, K concentrations as determined by the Apollo γ-ray experiments [17] correlate with Th concentrations as expected. Also, if the High-Th Oval Region is a mafic province, Imbrium ejecta should also be a significant source of Fe at the lunar surface. Iron concentrations [18, 19] do not correlate with Th concentrations, however. Meteoritic and mare basalt components of the highland regolith are responsible for part of the discrepancy but not all of it. Mafic highland materials excavated from basins other than Imbrium appear to be present. If so, this result strengthens the case for an Imbrium source of most lunar surface Th (and K), because it suggests that other impacts excavated deeply enough to extract Fe-bearing mafic materials, but that those materials did not contain appreciable Th. Th data from the Lunar Prospector should test these possibilities.

References: [1] Metzger et al., Science 179, 800-803, 1973; [2] Metzger et al., PLPSC8, 949-999, 1977; [3] Haskin and Warren, Lunar Sourcebook 357–474, 1991; [4] Haskin et al., this volume; [5] Melosh, Impact Cratering, Oxford Univ. Press, 245 pp., 1989; [6] Spudis, The Geology of Multi-Ring Impact Basins: The Moon and Other Planets. Cambridge, 263 pp., 1993; [7] Wasson and Warren, Icarus 44, 752-771 1980; [8] Holsapple and Schmidt, J. Geophys. Res. 87 1849-1870, 1982; [9] Housen et al., J. Geophys. Res. 88 2485-2499, 1983; [10] Schmidt and Housen, Int. J. Impact Eng. 5, 543-560, 1987; [11] Holsaple, Ann. Rev. Earth Planet. Sci. 21 333-373, 1993; [12] Moss et al., Meteoritics, subm.1996; [13] Oberbeck et al., PLSC5 111-136, 1974; [14] Haskin et al., LPS27, 501-502, 1996; [15] Korotev, Geochim. Cosmochim. Acta 58 3931-3969, 1994; [16] Metzger et al., PLPSC8 949-999, 1977; [17] Parker et al., LPS12 811-812, 1981; [18] Bielefeld et al., PLSC7 2661-2676, 1976; [19] Davis, J. Geophys. Res. 85 3,209-3,224, 1980.

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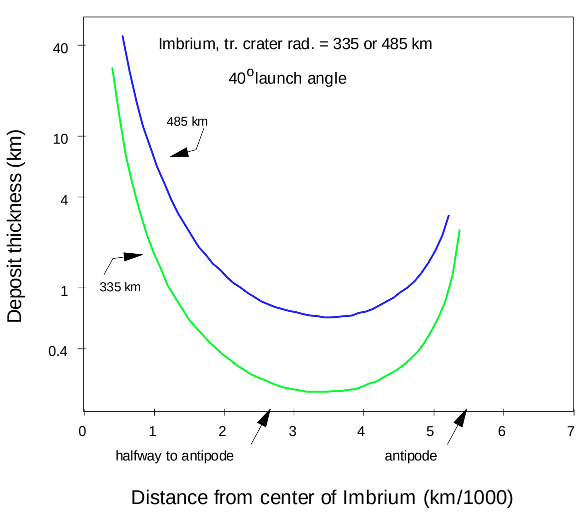

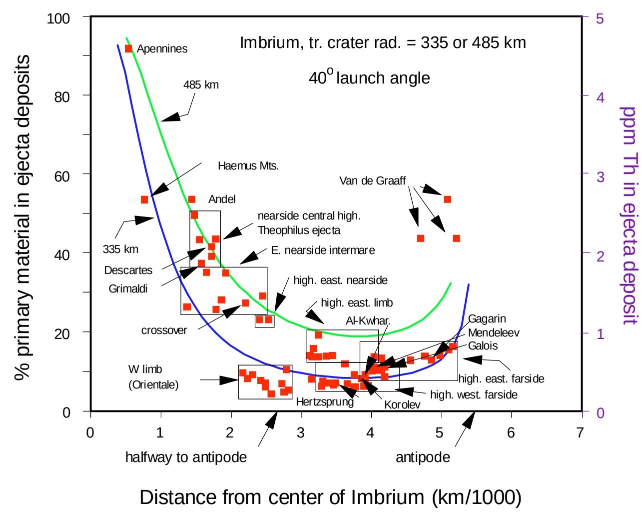

Fig. 1. Modelled average thickness of Imbrium ejecta deposits versus distance from the center of the Imbrium basin.

Fig. 2. Curves show estimated percent of Imbrium ejecta and ppm Th in the deposits (assuming 5 ppm for Imbrium ejecta) versus distance from the center of the Imbrium basin. Data points from the Apollos 15 and 16 orbiting γ-ray experiments [2].