An indigenous origin for the South Pole Aitken basin thorium anomaly

Ian Garrick-Bethell and Maria T. Zuber

Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

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[1] The northwest portion of the Moon's South Pole-Aitken basin contains an anomalously high abundance of thorium as determined by Apollo and Lunar Prospector gamma-ray spectroscopy. The anomaly's proximity to the antipode of the Imbrium basin has led several investigators to suggest that the anomaly is the result of convergence of thorium-enriched ejecta from the Imbrium impact. Examination of this complex region with new higher-resolution thorium data and several other datasets reveals that a convergence of ejecta cannot explain the anomaly. Alternatively, we propose an indigenous and likely ancient source. **Citation:** Garrick-Bethell, I., and M. T. Zuber (2005), An indigenous origin for the South Pole Aitken basin thorium anomaly, *Geophys. Res. Lett.*, *32*, L13203, doi:10.1029/2005GL023142.

1. Introduction

[2] It is generally believed that as the Moon differentiated, plagioclase feldspar floated to the top of a magma ocean to form the anorthositic crust, while mafic minerals condensed to form the mantle. During this process trace incompatible elements concentrated in an unincorporated magma ocean residue, eventually crystallizing last as the minerals observed in KREEP-rich rocks (i.e. enriched in potassium, rare earth elements and phosphorus). Among the elements found in KREEP, thorium is also abundant and serves as an adequate surrogate for detection of incompatible elements and KREEP. The global distribution of thorium is heterogeneous, with the strongest surficial expression found on the nearside in the Procellarum KREEP Terrane (PKT), centered around the Imbrium basin [*Jolliff et al.*, 2000]. The farside as a whole has far fewer expressions of significant abundances of thorium. The South Pole-Aitken (SP-A) basin contains most of the farside thorium in an oval shaped region centered at approximately (48°S, 188°E) [*Garrick-Bethell*, 2004], with abundances peaking at 3.8 μg/g in the northwest anomaly region, Figure 1 [*Lawrence et al.*, 2003]. Aside from the Compton-Belkovich region [*Lawrence et al.*, 2003], the SP-A thorium anomaly represents the highest concentration of thorium on the farside.

[3] Noting the anomaly's proximity to the antipode of the Imbrium basin, and its rough association with units of "grooves and mounds", *Stuart-Alexander* [1978] suggested that the anomaly is due to a convergence of thorium-enhanced ejecta from the nearside Imbrium basin. Models of ejecta deposition indicate that significant amounts of primary ejecta should land at the antipode [*Moore et al.*, 1974; *Haskin et al.*, 1996; *Haskin*, 1998]. *Wieczorek and Zuber* [2001] proposed on the basis of simple ejecta modeling that the Serenitatis basin is a more likely source of the thorium anomaly than the Imbrium basin. *Haskin et al.* [2004], however, have alternatively suggested that ejecta from Imbrium or Serenitatis is unlikely to produce the observed pattern. If the above impact-origin hypotheses are not correct, the SP-A thorium anomaly would have important implications for the thermal and chemical evolution of SP-A and the farside of the Moon. Here we show that an ejecta origin is untenable on the basis of careful analysis of a variety of data.

2. Data

[4] Thorium abundance data comes from an updated version of low altitude (average 30 km) measurements of the Lunar Prospector gamma-ray spectrometer (LP-GRS) [*Lawrence et al.*, 2003]. Briefly, measured gamma-ray counts from 32-second spectra were binned onto a 0.5 × 0.5 degree/pixel grid, and smoothed to reduce statistical scatter with an equal area smoothing algorithm. The full width at half maximum (FWHM) of the LP-GRS becomes $\sim$(80 km)^2 under the smoothing operations, with a full width at full maximum (FWFM) of 240 km (FWFM defined as where the spatial response function falls to 1%).

[5] Topography data are from the Clementine laser altimeter. The 0.25 degree/pixel grid of interpolated elevation is obtained from filtered along-track range data [*Smith et al.*, 1997]. Clementine five-band UV-VIS multispectral image strips are taken from the published CDs and mosaiced together with the United States Geological Survey Map-a-Planet software at a maximum resolution of 100 meters/pixel [*Pieters et al.*, 1994]. In order to obtain qualitative mineralogical information from the multispectral images in an RGB color format, we utilized a ratio technique proposed by *Pieters et al.* [2001]. Under this scheme, noritic low-Ca pyroxene lithologies appear red ("band curvature"), high-Ca pyroxene and/or olivine rich materials are shown in green ("band tilt"), and blue tones represent anorthositic and/or mature materials ("band strength"). A shaded relief basemap from *Rosiek and Aeschliman* [2001] is also utilized.

3. Results

3.1. Anomaly Description

[6] Figure 1 shows the thorium enhancement lies in the northwest corner of SP-A and ranges in concentration from 2.5 to 3.8 μg/g. The enhanced region can be divided into two northeast-southwest trending regions which we refer to as North and South Lobes. The lobes each have concentrations over 3.5 μg/g near their centers, with South Lobe

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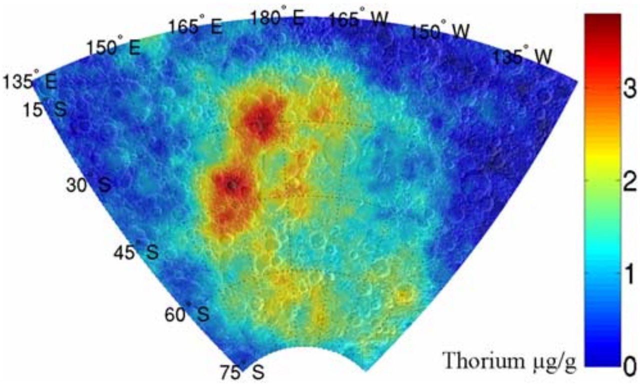

Figure 1. Map of thorium content in the South Pole-Aitken basin, in μg/g.

being slightly higher, peaking at 3.8 μg/g. Thorium level contours ranging from 2.5 to 3.5 μg/g illustrate this morphology, and serve hereafter as a convenient quantitative means of characterizing the extent of the anomaly, Figure 2. The total anomaly area with regions of thorium above 2.5 μg/g is approximately 202,000 km^2. We note that the western edge of the two lobes is continuous with the western edge of the entire inner SP-A thorium deposit (cf. Figure 1).

3.2. Correlation With Mapped Unit of Grooves

[7] Smoothed thorium data shows that correlation with the mapped Imbrian unit of grooves, mounds and dissected crater walls (unit Ig) attributed to the Imbrium impact [*Stuart-Alexander*, 1978], is seen only in North Lobe (Figure 2a). To the northwest of North Lobe a large area greater in size than the FWHM thorium footprint is nearly filled with the mapped unit Ig, including the northwestern walls of Ingenii. However, the thorium signature falls to values below 1.0 μg/g in this region. In South Lobe unit Ig is hardly present except for several instances of crater wall dissection. Instead, Nectarian "rolling terra" constitutes the majority of South Lobe, as is the case for much of the interior of SP-A.

3.3. Relations With Eratosthenian Craters

[8] Figure 2b shows that the highest abundance of thorium in South Lobe is associated with an unnamed 50-km-diameter Eratosthenian crater at (40°S, 165°E) [*Stuart-Alexander*, 1978], herein referred to as South Crater. In North Lobe the high thorium abundances are correlated with the mapped ejecta units of Birkeland (30.2°S, 173.9°E, 82.0 km) [*Blewett et al.*, 2000], but the thorium pattern is not as circular as for South Crater. Focusing on South Crater, we calculate from its diameter a crater depth of 3.4 km [*Pike*, 1974], and a depth of excavation of 1.1 km (from experiments of *Stoffler et al.* [1975]). Thus if earlier-emplaced ejecta from Imbrium is responsible for the thorium deposit at South Crater, the ejecta would have to be at least 1.1 km thick to have remained exposed at the bottom South Crater and its immediate surroundings. Despite the fact that a purported ejecta blanket at least 1.1-km-thick fell in the vicinity of South Crater, there are no mapped Imbrian ejecta units bordering South Crater (Figure 3). Dissected crater walls of purported Imbrian origin are not present in the pre-Nectarian crater underlying South Crater, or in the larger pre-Nectarian crater Oresme (42.4°S, 169.2°E, 76.0 km) to the southeast. In the crater Obruchev (38.9°S, 162.1°E, 71.0 km) the northern walls bordering Mare Ingenii show signs of dissection, but the walls closest to South Crater do not. If we use the more general numerically-derived crater scaling laws of *Croft* [1980] we calculate the depth of excavation of South Crater to be 5.0 km. An Imbrium ejecta blanket of this thickness would have

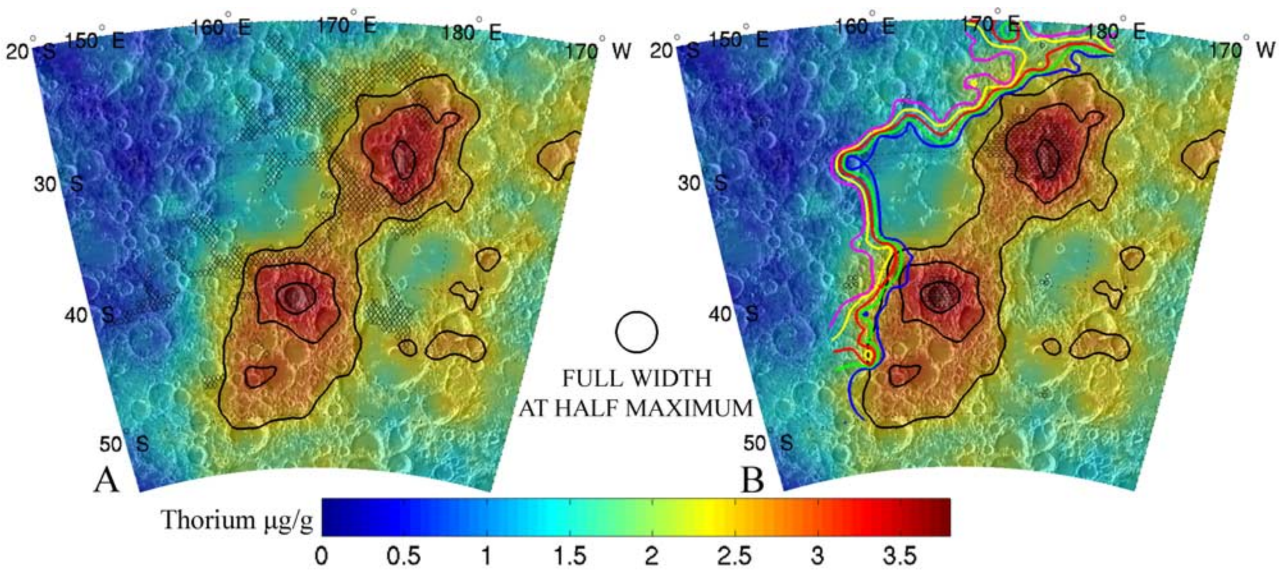

Figure 2. 2.5–3.5 μg/g thorium contours in intervals of 0.5 μg/g, shown in black. (a) Small black diamonds represent mapped units of grooves and mounds from *Stuart-Alexander* [1978]; (b) small black circles represent units of Eratosthenian craters from *Stuart-Alexander* [1978], and multi-color contours show basin topography from −3000 to −1000 m, increasing westward in 500 m intervals.

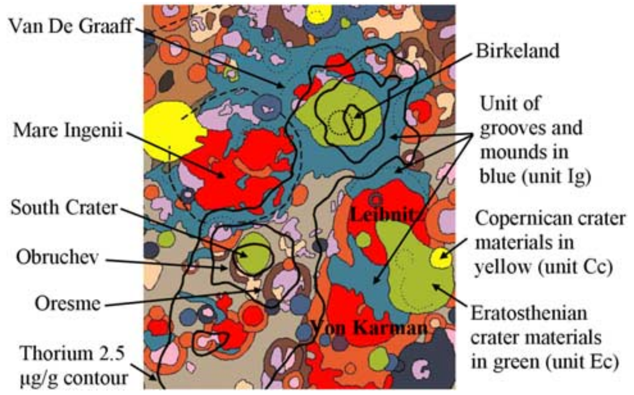

Figure 3. Geologic map of the anomaly region with superimposed thorium contours from Figure 2.

exceeded the depth of all pre-Imbrian craters currently observed inside the anomaly, likely filling the smaller ones completely, which is not observed.

3.4. Topography

[9] Figure 2b shows that the western edge of the thorium anomaly is well aligned with topographic contours defining the inner part of the basin. Level contours between −1000 and −3000 m can be followed from approximately (23°S, 180°E) to (47°S, 158°E), over a distance of approximately 1200 km. The same contours also wrap around much of SP-A and the Ingenii basin, which appears to have impacted on the border of SP-A's inner topographic depression. The northeast trending orientation of North and South Lobe is most likely due to correlation with this topographic trend in the same direction. Such strong correlation and bounding by terrain would not be expected if the material fell randomly as ejecta, but is more consistent with a process related to basin formation.

3.5. Mare-Thorium Relations

[10] The most visually prominent feature of the thorium anomaly is that it is well defined by the eastern border of Mare Ingenii. When combined with the topographic contours described in Section 3.3, the two features completely outline the western portion of the anomaly (Figure 2b). We interpret this relationship to be due to mare cross-cutting a thorium-enriched subsurface that may extend approximately halfway into the Ingenii basin from the east. In a survey of all SP-A mare units we find that the majority are adjacent to or within the thorium anomaly. Total amounts of 68 percent of mare by volume, and 50 percent of mare by area are found either inside the 2.5 μg/g thorium contour, or with some component within 50 km of the exterior of the contour (including all of Mare Ingenii, and mare in the craters Leibnitz and Von Karman), based on mare volumes and areas from *Yingst and Head* [1997]. We also note from the morphometric studies of *Yingst and Head* [1997] that Mare Ingenii has an approximate depth of 1.6 km, which places an upper limit on the thickness of the purported Imbrium ejecta. This thickness is less than the ejecta thickness estimate of 5.0 km implied by South Crater's maximum excavation depth (Section 3.2).

3.6. Multispectral Images

[11] Using the multispectral ratio technique outlined in Section 2, we can compare the gross mineralogy of the thorium anomaly to nearside geologic units attributed to Imbrium basin ejecta (similar in spirit to *Spudis and Fessler* [2002]). Figure 4a shows that the thorium anomaly appears mostly green in both mare and non-mare regions, implying significant materials of mafic character. The anomaly region is similar to the mineralogy of SP-A as a whole. The Fra Mauro Formation, units mapped as Fra Mauro materials, and the Apennine backslope formations are all believed to have been deposited by the Imbrium event [*Wilhelms and McCauley*, 1971]. From

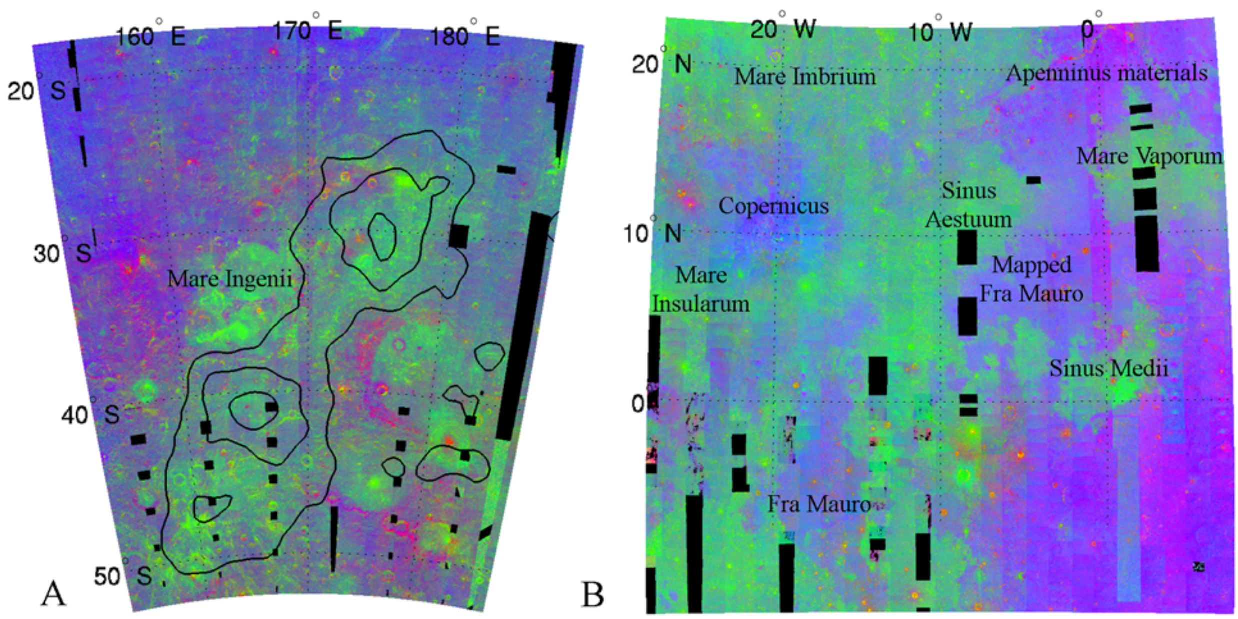

Figure 4. Multispectral ratio used to reveal dominant rock types. (a) Thorium anomaly; (b) imbrium ejecta formations.

Figure 4b it is apparent that under the same image stretch the mineralogy of these regions is much bluer than the thorium anomaly region, meaning there is more anorthositic and/or weathered material. Green areas surrounding the bluer units are Mare Imbrium, Mare Insularum, Mare Vaporum, Sinus Medii, and Sinus Aestuum.

4. Discussion

[12] An alternative explanation to the antipodal ejecta hypothesis is that the anomaly is a province of slightly elevated thorium that was exposed by the SP-A impact event. This would explain the thorium correlation with inner-basin topography contours and the mafic mineralogies characteristic of SP-A's interior, while resolving the contradictions of association with the Imbrium unit Ig. An indigenous source explains the position and orientation of the anomaly lobes in relation to the entire SP-A thorium region, without invoking oblique nearside impacts [*Wieczorek and Zuber*, 2001]. South Crater may have excavated thorium-rich indigenous material that had been covered by and mixed with ejecta from subsequent basins and craters [*Lawrence et al.*, 2003]. Beyond South Crater however, the lack of apparent association with any other features suggests that the deposit is an ancient province of material that has been homogenized by aeons of meteoroid bombardment. To the west of the pre-Nectarian Ingenii basin, we find low concentrations of thorium that would seem to contradict an ancient thorium province, which would have been ejected westward by the Ingenii impactor. However, Ingenii's western half is outside the anomaly's western edge (Figure 2b), where thorium is low and topography changes significantly. To the east, Ingenii would have contributed thorium-enriched ejecta to the anomaly region, in addition to the ejecta from Von Karman (44.8°S, 175.9°E, 180.0 km), and Leibnitz (38.3°S, 179.2°E, 245.0 km). To the east of Von Karman and Leibnitz we observe some thorium above 2.5 μg/g (Figure 2), which may be freshly exposed by local Copernican and Eratosthenian craters. The mare that fills Von Karman and Leibnitz appears to border loosely the eastern edge of the anomaly, implying that thorium may also be present beneath these craters.

[13] Thorium and other heat-producing elements at depth could provide the heating necessary for the extensive amount of mare flooding found around the anomaly (Section 3.4). Notably, this region not only contains most of the SP-A mare deposits, but a significant fraction of all farside volcanism. Work by *Hawke and Spudis* [1980] suggests that the thorium may be a result of extrusive volcanism, although the generally lower thorium abundances we observe in the nearby mare units contradict this idea. For insight into the relationship between thorium, mare materials, and non-mare materials, we look to the nearside PKT. The PKT is heavily enriched in radioactive elements that are believed to have led to most of the nearside's volcanism [*Jolliff et al.,* 2002]. In the PKT a topographically high circum-Imbrium ring of non-mare terrain surrounds Mare Imbrium materials that are relatively lower in thorium, though nonetheless enriched compared to terrain outside of the PKT [e.g., see *Lawrence et al.*, 2003]. Similarly, in the SP-A thorium anomaly, non-mare thorium rich materials surround mare that is relatively lower in thorium, but enriched when compared to terrain outside of SP-A. Thus in both cases, KREEP-related heating and volcanism apparently do not have to produce mare materials as rich in KREEP as adjacent non-mare crustal materials.

[14] As for the mapped units of Imbrium ejecta, all of the above analysis indicates that they are not directly related to the region's enhanced thorium. These distinct and complex features may be unique local disturbances related to early Imbrian volcanism, the convergence of an antipodal impactor's seismic energy [*Schultz and Gault*,1975], or a combination of both [*Boslough et al.*, 1986].

5. Conclusions

[15] The characteristics of the thorium anomaly can be linked to known geologic features and basin structures. When considering local geology, geophysics, and composition, as well as the merely rough correlation with mapped Imbrium ejecta deposits, we conclude the anomaly is an indigenous unit, likely emplaced at the time of basin formation. This region is important to understanding the nearside-farside dichotomy in REE, styles of lunar volcanism, and the general evolution of the SP-A basin.

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I. Garrick-Bethell and M. T. Zuber, Earth, Atmospheric, and Planetary Sciences, MIT, 77 Massachusetts Avenue, Cambridge, MA 02139, USA. (iang@mit.edu)