A SIMPLE HISTORY OF LUNAR TRUE POLAR WANDER. I. Garrick-Bethell[1,2], [1]Department of Earth and Planetary Sciences, University of California, Santa Cruz (igarrick@ucsc.edu), [2]School of Space Research, Kyung Hee University, Yongin, Gyeonggi 17104, South Korea.

Introduction: The orientation history of the Moon is important for constraining a number of early geophysical processes, including crystallization of the crust, formation of the lithosphere, the geometry of the lunar dynamo, and the accumulation of volatiles in polar regions. Recently, Garrick-Bethell et al. (2014) inferred the history of true polar wander by examining the topography of the Moon, when the South Pole-Aitken (SPA) and other large basins are ignored [1]. They found that when this topography was rotated into its principal reference frame and analyzed with the associated gravity field, the lunar shape was consistent with the crust being sculpted by tidal heating and deformation. Therefore, this reference frame represents one of the earliest epochs in lunar history, when the crust was still growing. However, they left open the problem of what drove the Moon to its present orientation, suggesting the eventual formation of density anomalies, due to regions such as the Procellarum KREEP Terrane (PKT), were a plausible explanation. Such anomalies would have given rise to the component of gravity that has no topography expression, and thus arisen during an epoch when the lithosphere was strong.

More recently, Siegler et al. (2015, 2016) derived a paleopole location from the antipodal nature of hydrogen deposits on the north and south poles [2, 3]. Interestingly, the paleopole found by Siegler et al. (2016) is only 9 degrees apart in longitude from the one implied by topography: (84.5°S, 318°E) (in the southern hemisphere) for hydrogen, and (54°N, 309°E) for topography. Siegler et al. (2016) found that a model for PKT's density structure could explain the location of their hydrogen paleopole.

The similar longitude of the topography and hydrogen paleopoles could imply that the Moon's orientation history was relatively simple: an initial reference frame recorded signatures of early tidal processes, after which a combination of SPA and density anomalies associated with the PKT drove the Moon's pole to its present position. Here we assess this hypothesis further by examining the Moon's gravity field outside of the PKT. In particular, we estimate the degree-2 spherical harmonics (and thereby the inertia tensor) outside of PKT, so that we can estimate where the pole of the Moon would be located if the PKT had not formed.

Methods: We fit spherical harmonics to the GRAIL gravity potential [4] outside of the PKT, assuming a PKT center of (30°N, 325°E), and PKT radii ranging from 1000 to 1900 km (Figure 1). These radii were chosen based on the thorium distribution in the PKT (Figure 2). We use harmonics from degree zero, up to a maximum of 3 to 8, according to the methods of [1]. As the size of the PKT is increased, the "hole" created by the PKT allows for higher frequency harmonics to fill in this region unconstrained, possibly leading to unrealistic degree-2 solutions, due to the non-orthogonal nature of these functions when calculated on an incomplete sphere (a similar effect was discussed in [1]) . Therefore, we check for the consistency of degree-2 fits across fits up to different maximum degrees. (Also, ultimately, to produce a fully consistent solution, the combined gravity and topography field of Garrick-Bethell et al. (2014) should be recalculated outside of the bounds of the PKT border used here. However, the resulting changes are expected to be small, since the topography of PKT is very modest compared to the topography of SPA, and topography is used to derive the paleopole).

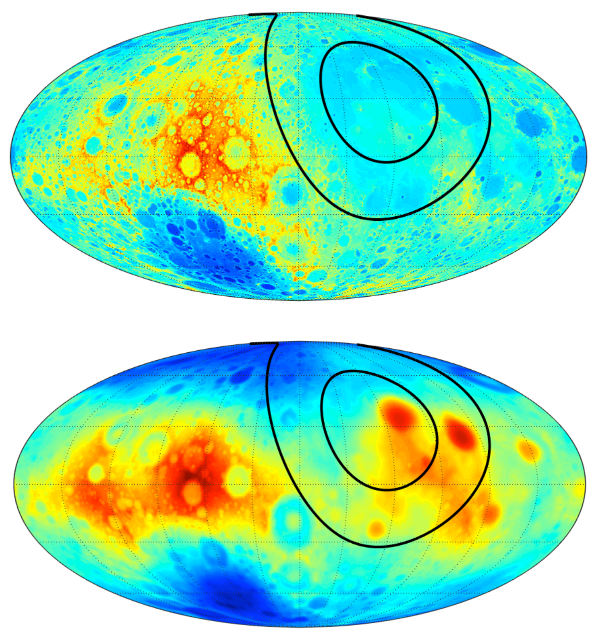

Figure 1. Lunar topography and gravity potential (from LOLA and GRAIL, respectively) showing the range of PKT sizes used in the analysis (black lines). The scale limits are -8.7 to 10.3 km, and -2.9 to 3.0 × 10^{-4} *GM*, respectively. The right side is the nearside. Only the gravity field is used here to derive the Moon's paleopole without the PKT.

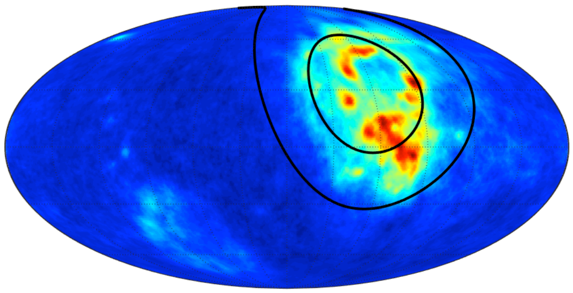

Figure 2. Thorium distribution used to define the PKT radii and center used in the analysis. The scale is from -0.3 to 11.6 ppm Th. Black lines show PKT radii of 1000 and 1900 km.

Results: When degree-2 gravity terms are calculated using fits up to a maximum degree of 5 to 8, the degree-2 solution becomes unstable for PKT sizes > 1200 km in radius (see above). Therefore, we focus on the results from maximum fit degrees of 3 and 4. For these fits, the implied paleopoles all fall along a line that nearly connects the topography paleopole and the hydrogen paleopole (Figure 3). They also fall nearly along the line of paleopoles calculated by Siegler et al. (2016), who used a density anomaly model to approximate the effect of PKT. Therefore, our results support their conclusions.

While the above results from fits up to degrees 3 and 4 are encouraging, the paleopoles are located in opposite hemispheres for each of these cases. The divergent answers arise in part because rotations in either of these directions yield only small changes in degree-2 harmonics, due to their orientation. Future work will focus on resolving this ambiguity. However, it is still important that the results from both maximum fit degrees of 3 and 4 fall on the same great circle path, as it indicates the axis of rotation induced by the PKT.

Discussion: Using the results from the degree-3-maximum fits, without the PKT, the Moon's paleopole would have been located closer to the paleopole inferred from topography without large basins (Figure 3). The location of the paleopole inferred without PKT increasingly approaches the topography paleopole as the size of the PKT is increased. This implies that without the PKT and the Moon's large basins (mostly SPA), the two paleopoles would be nearly coincident. This paleopole would represent the Moon when it was still forming its crust, and had not yet experienced any significant symmetry breaking events. In turn, this implies that the Moon's history of true polar wander may be describable almost entirely by two events: the formation of the Moon's largest basins, plus the PKT. The fact that the hydrogen paleopole falls along the same great circle as the PKT-free paleopoles and topography paleopole is independent evidence that supports this history.

Conclusions: The observation that the hydrogen and topography paleopoles fall along nearly the same longitude may not be a mere coincidence. Instead, it may imply the epochs of their formation are linked, in particular by the formation of the PKT. If the Moon did experience a relatively simple history of true polar wander, as outlined here, it would have applications to understanding the wide distribution of paleopoles derived from magnetic anomalies [5, 6] (see also [7], this volume). In particular, it could imply that these paleopoles are not paleopoles at all, but rather represent a dynamo that was not oriented along the spin axis.

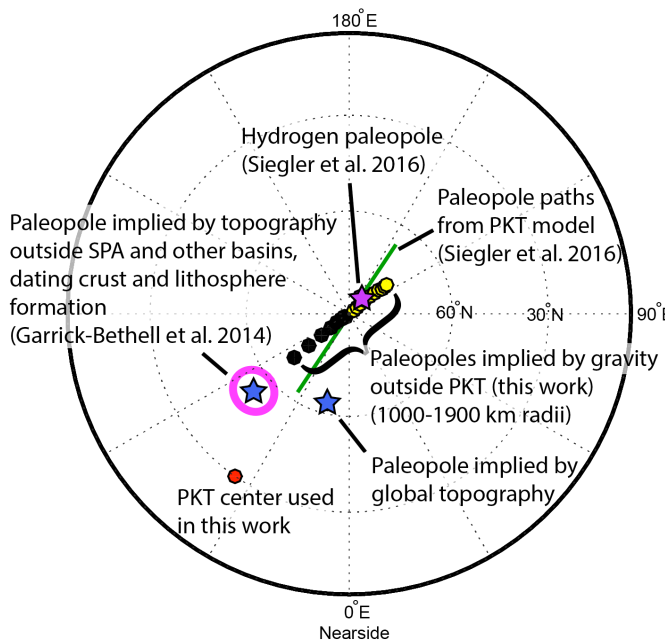

Figure 3: Paleopoles inferred from topography (with and without large basins) and polar hydrogen, compared with paleopoles inferred from the formation of the PKT. The PKT paleopoles found here represent the Moon's gravity field (including SPA), without the PKT. Yellow points are from a maximum fit degree of 4, black points are from a maximum fit degree of 3, and distance from the present pole increases with increasing PKT size, up to 1900 km radius. The hydrogen paleopole, topography paleopole, and PKT paleopoles are nearly on the same great circle.

References: [1] Garrick-Bethell et al. (2014), *Nature* 512, 181. [2] Siegler et al. (2015), *LPSC* 46^{th}, abstract 2675. [3] Siegler et al. (2016), *Nature*, in press. [4] Zuber et al. (2013), *Science* 339, 668. [5] Takahashi et al., 2014, *Nat Geosci*. 7, 409. [6] Arkani-Hamed & Boutin, 2014, *Icarus* 237, 262. [7] Nayak et al. 2016, this volume.