STRUCTURE AND FORMATION OF THE LUNAR FARSIDE HIGHLANDS: IMPLICATIONS FOR GLOBAL CRUSTAL EVOLUTION. I. Garrick-Bethell[1], F. Nimmo[1], and M. A. Wieczorek[2], [1]Department of Earth and Planetary Sciences, University of California, Santa Cruz, CA 95064, igarrick@ucsc.edu. [2]Institut de Physique du Globe de Paris - Sorbonne Paris Cité, Paris, France.

Introduction: The high topography of the lunar farside highlands makes up a large part of the Feldspathic Highlands Terrane (FHT), the largest of the Moon's three major geologic provinces [1]. Because the farside highlands may be a relic of very early thermal processes, understanding their structure and formation may help constrain models of global lunar evolution and magma ocean processes in general [2]. Theories for the formation of the farside highlands include South Pole-Aitken (SPA) basin ejecta deposits, asymmetric nearside/farside cratering [3], and asymmetric crustal growth [4]. However, to date there has been no quantitative description of the farside highlands, and therefore models that describe their formation are poorly constrained.

Here we show that the farside highlands topography and crustal thickness follow a functional form that implicates tides in their formation [5]. This finding has a number of implications for the global-scale formation, evolution, and structure of the lunar crust [5, 6]. It also demonstrates for the first time that tidal heating is important in lunar thermal evolution [7].

Function fits to farside highlands topography and crustal thickness: Starting on the approximate center of the farside highlands, we took great circle profiles of topography using different azimuths, and averaged the terrain between these azimuths. These azimuth-averaged profiles produced "swaths" of topography and crustal thickness data. Five swaths are shown in Figs. 1a-d. The swaths presented were chosen to illustrate the dependence of the shape of the farside highlands on azimuth, starting location, and width of the swath.

We fit a number of functions to the topography and crustal thickness swaths, over 95-105° of arc. We found that a $\cos^2(x)$ function produced high quality fits and was superior to a number of other functions, such as cosine, exponential, and polynomial functions. However, two other observations allow us to conclude that the terrain is indeed described by a $\cos^2(x)$ or degree-2 function. Firstly, in Fig. 1 we also plot data in the opposite direction of the swaths ("prediction direction"), and plot the best-fit $\cos^2(x)$ function over this non-fitted data. In swaths 1-3, it is clear that the best-fit function does a good job of predicting terrain in the non-fit direction, a strong indicator that the function is a good choice. The second observation is that the majority of the decrease in farside topography takes place over 90°, as expected from a $\cos^2(x)$ function. In several swaths, there is evidence for inflection at 0° and 90°, as required for a global degree-2 function.

Formation age of the farside crust: The fact that both topography and crustal thickness follow the same function suggests that the crustal thickness is largely compensated. This is supported by the regional lack of free air gravity anomalies. This state of compensation also suggests a very ancient origin for the terrain, likely during the crystallization of the crust. A frozen fossil tidal bulge could not have produced the majority of the terrain, since the amplitude of the topography change is too large, and large crustal thickness variations are not produced by a fossil bulge.

Effect of SPA or other basin ejecta: Because basin ejecta deposits are not predicted to be emplaced in a degree-2 pattern, it is unlikely the topography of the farside highlands is related to a basin.

Tidal heating: Predominantly degree-2 crustal thickness variations similar to those in the farside highlands may arise in tidally heated satellites with subsurface liquid oceans, such as Europa [8] and Titan. The subsurface ocean decouples the crust from the mantle, and leads to high tidal dissipation in the crust's warm base. This dissipation heats the crust, such that the crust will be thinner relative to its thickness without dissipation [8]. Because dissipation is greatest at the poles, and least at the equatorial 0° and 180° longitudes, the crust becomes thinner, and thicker in those locations, respectively, for low obliquity orbits. Similar to Europa, the Moon once possessed an ocean beneath its crust during the magma ocean epoch.

Heating model: We modeled tidal dissipation in a floating anorthositic crust, using an anorthosite rheology, and different values for the lunar eccentricity, semimajor axis, late-stage magma ocean temperature, and background heat flow into the base of the crust (details in [1]). It is difficult to constrain many of these parameters, but when dissipation is sufficiently high, a crustal thickness pattern similar to the observed crustal thickness emerges (Fig. 2). The model accounts for a unique region labeled "X" in all figures.

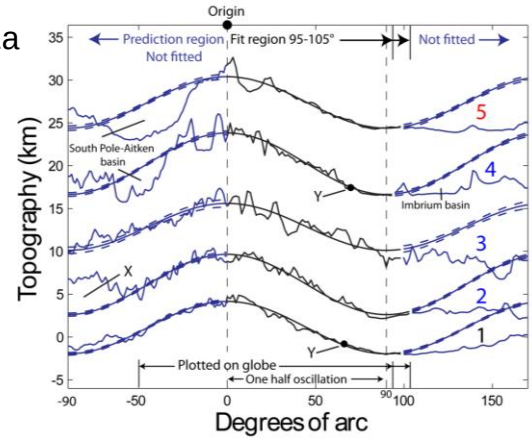
Implications: There are a number of important implications of this model: 1) The region that follows a $\cos^2(x)$ function extends significantly into the nearside and crosses mare regions in Oceanus Procellarum and Mare Frigoris. These mare units are a part of the Procellarum KREEP Terrane (PKT) and suggest parts of the PKT and FHT have a common crustal structure. 2) The mapped $\cos^2(x)$ region is also continuous across

the border of the putative Procellarum impact basin, and therefore may place constraints on whether or not this basin actually exists. 3) The geometry of the region permits us to determine the paleo sub- and anti-Earth points, with several implications for lunar orientation and the degree-1 structure of the Moon [6].

No obvious evidence on the nearside: The process that sculpted the farside highlands should have also operated on the nearside. However, the geologic history of the nearside is more complex. The nearside is both more volcanic and enriched in heat producing elements. It is plausible that a large-scale thermal and compositional event (e.g. [9]) may have greatly modified the same tidally-driven processes on the nearside. Regardless, the ancient farside highlands has retained a record of early tidal processes that took place during crystallization of the crust, and provide a new framework for assessing early crust building on the Moon.

References: [1] Jolliff, B.L. et al. (2000), *JGR* 105, 4197. [2] Shearer C.K. et al. (2006), *Rev. Mineralogy and Geochem* 60, 365. [3] Wood, J. A. (1973) *Moon* 8, 73. [4] Wasson, J. T. & Warren, P. H. (1980), *Icarus* 44, 752. [5] Garrick-Bethell, I. et al. (2010), *Science* 330, 949. [6] Perera, V. et al., this volume. [7] Peale, S.J. & Cassen, P. (1978), *Icarus* 36, 245. [8] Ojakangas, G. W. & Stevenson, D. (1989), *Icarus* 81, 220. [9] Parmentier, E. M., et al. (2002), *EPSL* 201, 473.

1a



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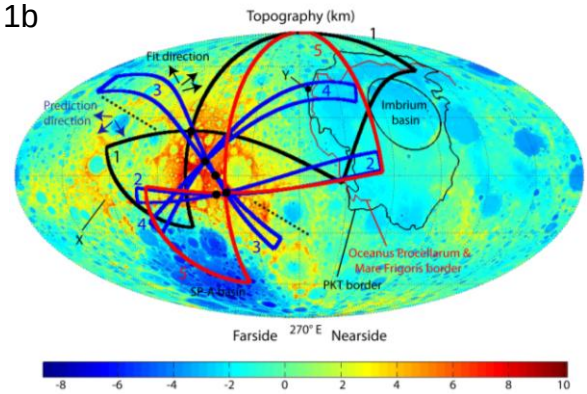

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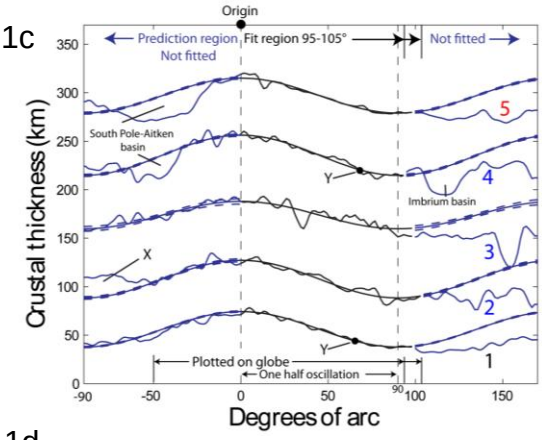

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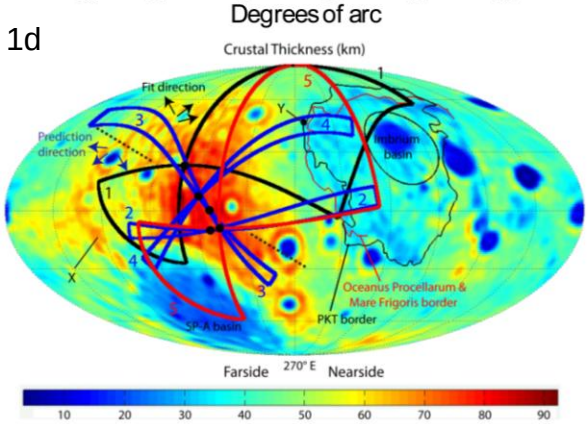

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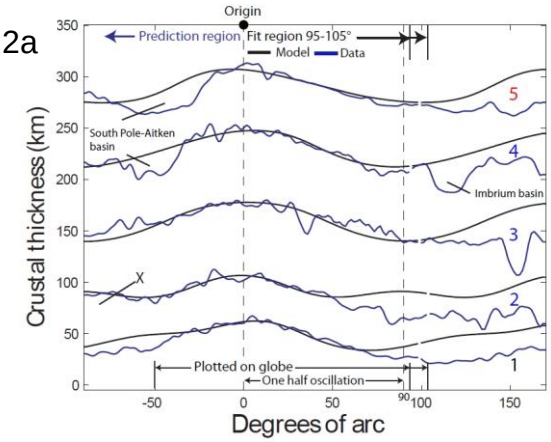

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