THE GEOPHYSICAL NATURE OF THE PROCELLARUM REGION OF THE MOON AS REVEALED BY GRAIL GRAVITY DATA.
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Introduction: The Procellarum region is a broad area on the nearside of the Moon that is characterized by low elevations [1], relatively thin crust [2], and high concentrations of heat-producing elements [3]. The Procellarum KREEP terrain (PKT) likely experienced a unique history because of the enhanced heat flow. Procellarum has been interpreted as an ancient impact basin approximately 3200 km in diameter [4, 5] on the basis of photogeologic interpretations of basin rims and rings. Here we use data from the Gravity Recovery and Interior Laboratory (GRAIL) mission [6] to examine the subsurface structure of Procellarum. The results reveal a quasi-rectangular pattern of border structures, interpreted as volcanically flooded rift valleys intersecting at 120°-angle triple junctions.

Methodology and results: We examined the subsurface structure of the Procellarum region using GRAIL Bouguer gravity data (gravity field corrected for the contributions of surface topography [6]) and gravity gradients (second horizontal derivatives of the Bouguer potential [7]). The Procellarum region is revealed to be bounded by narrow belts of negative gravity gradients (Fig. 1) and positive gravity anomalies, indicating narrow zones of positive density contrast in the subsurface. We inverted the gravity field in the spherical harmonic domain under the assumption that the anomalies arise from variations in the thicknesses of both the maria and underlying crust. The results suggest the presence of elongated mare-filled depressions in the feldspathic crust, with widths of ~150 km and depths of 2–6 km, underlain by crust-mantle interfaces that have been uplifted by up to 8 km (Fig. 2).

These inversion solutions are consistent with thickening of the maria over linear depressions formed by crustal thinning, as would occur in volcanically flooded rift valleys. The branching of anomalies of the western border structure and the triple-junction intersections at some corners are consistent with the behavior of planetary rifts. The elevated heat flux in the PKT [8] coupled with passive mantle upwelling during rifting would have led to widespread partial melting of the underlying mantle, so extensional tectonics would have been accompanied by dike intrusion and volcanism. These structures are interpreted as the magma plumbing system of many of the nearside maria, which served as conduits connecting magma reservoirs to the surface. The Procellarum border structures are the only known lunar structures consistent with large-scale rifting of the crust.

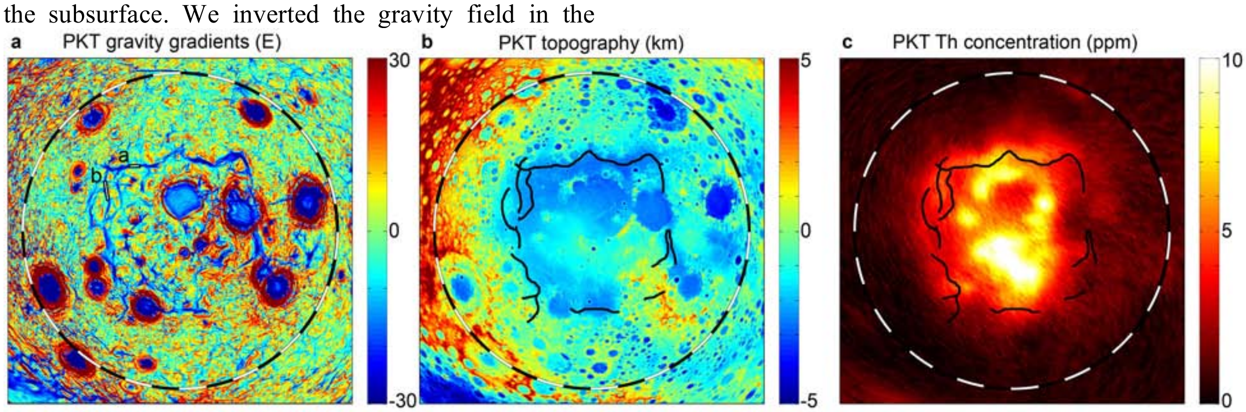

Figure 1. Polar projections centered on the Procellarum region of the Moon in (**a**) Bouguer gravity gradients, (**b**) topography [1], and (**c**) Th abundance [3]. Circle is 180° in diameter divided into 10° increments. The border structures are traced in black in **b** and **c**. The locations of structures analyzed for profiles in Fig. 2 are shown in **a**.

In a polar projection centered on the PKT, the border structures delineate a quasi-rectangular shape (Fig. 1). The short arcuate rim segments of the proposed Procellarum basin are seen in the GRAIL data to be a small fraction of this continuous set of well-expressed structures that trace out a polygonal pattern consisting of predominantly straight sides and angular intersections. The northeast and northwest corners of the structure deviate from the proposed circular basin rim [4] by 215 km and 175 km, respectively. This quasi-rectangular pattern is in contrast with the circular or elliptical shapes of all other large impact basins [9], including the hemispheric-scale Borealis basin on Mars [10]. Furthermore, the negative gravity gradients of the border structures do not match the signatures of known impact basins, which are characterized by paired positive and negative gradients of equal amplitude along the rims and negative gradients throughout the basin interiors. Thus, the structures bordering the PKT are not compatible with their interpretation as marking the rim of a basin.

The location of the structures at the edge of the PKT suggests that the elevated heat flux in this region [8] may have played a role in the extension inferred from the gravity modeling. Although the PKT was always warmer than its surroundings, it would have cooled at a greater rate due the declining radiogenic heat production. The cooling and thickening lithosphere would then have experienced thermal contraction, driving extension at its margins. A finite difference model was used to represent the conductive thermal evolution of the Moon, given the equivalent of 10 km of KREEP basalt at the base of a 40-km-thick crust within a spherical cap 2000 km in diameter [8, 11]. The model predicts a temperature decrease of the PKT relative to its surroundings of >600 K between 4.0 and 3.0 billion years ago (Ga). The stresses resulting from the thermal contraction of the lithosphere and the buoyancy-driven pressure from the underlying mantle between 4.0 and 3.0 Ga were calculated with an elastic finite element model [12]. Cooling and contraction of the lithosphere within the PKT resulted in predicted extension throughout the lithosphere at the edge of the PKT, consistent with the inferred crustal rifting.

In order to explain the observed rectilinear pattern of structures, it is necessary to break the azimuthal symmetry. Volumetric contraction beneath a free surface generates fracture patterns with characteristic corner angles of 120°, resulting in six-sided contraction polygons at a range of scales. However, as the size of the structure becomes large relative to the radius of the planet, surface curvature becomes important. A polygon with 120° corner angles will have five or four sides when the lengths of the sides reach 32° or 80° of arc, respectively. The mean length of the PKT border structures is 2150 km or 71° of arc, and the angles of the vertices range from 109° to 125°. Thus, at the scale of the PKT, a set of linear rifts intersecting at 120°-angle junctions around a contracting cap will form a quasi-rectangular structure.

Conclusions: GRAIL Bouguer gravity anomalies and gravity gradients reveal a pattern of narrow linear anomalies that border the Procellarum region and are interpreted to be the frozen remnants of lava-filled rifts and the underlying feeder dikes that served as the magma plumbing system for much of the nearside mare volcanism. The discontinuous surface structures that were earlier interpreted as remnants of an impact basin rim are shown in GRAIL data to be a part of this continuous set of quasi-rectangular border structures with angular intersections, contrary to the expected circular or elliptical shape of an impact basin [9]. These structures are interpreted as having formed in response to the cooling and contraction of the PKT that resulted from the declining radiogenic heat production.

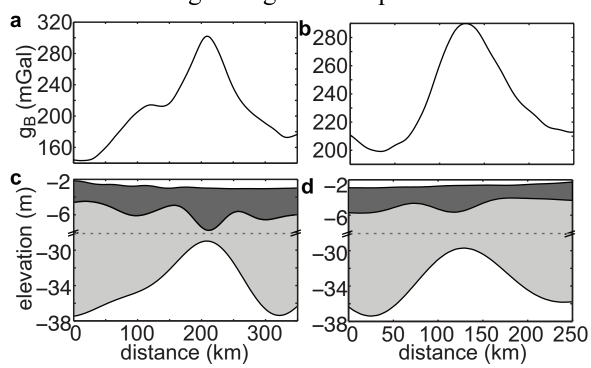

Figure 2. Profiles of the Bouguer gravity and modeled crustal structure, showing variations in the thickness of the maria (dark gray) and feldspathic crust (light gray) beneath two of the border structures.

References: [1] Smith D. E., et al. (2010) *GRL 37,* L18204, doi:10.1029/2010GL043751. [2] Wieczorek M. A., et al. (2013) *Science 339,* 671-675. [3] Jolliff B. L., et al. (2000) *JGR 105,* 4197-4216. [4] Whitaker E. A. (1980) in *Multi-ring Basins: Formation and Evolution,* LPI, 105-111. [5] Cadogan P. H. (1974) *Nature 250,* 315-316. [6] Zuber M. T., et al. (2013) *Science 339,* 668-671. [7] Andrews-Hanna J. C., et al. (2013) *Science 339,* 675-678. [8] Wieczorek M. A. and Phillips R. J. (2000) *JGR 105,* 20,417-20,430. [9] Andrews-Hanna J. C. and Zuber M. T. (2010) in *Large Meteorite Impacts and Planetary Evolution IV: GSA Special Paper 465*, 1-13. [10] Andrews-Hanna J. C., et al. (2008) *Nature 453,* 1212-1215. [11] Grimm R. E. (2013) *JGR 118,* 768–777, doi:10.1029/2012JE004114. [12] Melosh H. J. and Raefsky A. (1980) *Geophys. J. R. Astron. Soc. 60* 333-354.