VESTIGES OF A LUNAR ILMENITE LAYER REVEALED BY GRAIL GRAVITY DATA. W. Liang[1], A. Broquet [1], J. C. Andrews-Hanna[1], N. Zhang[2], M. Ding[3], A. J. Evans[4]. [1]Lunar and Planetary Laboratory, University of Arizona (wl463@arizona.edu), [2]Key Laboratory of Orogenic Belts and Crustal Evolution, Peking University, [3]State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, [4]Department of Earth, Environmental, and Planetary Sciences, Brown University.

Introduction: Models of the late stages of lunar magma ocean crystallization predict a layer of dense Ti-rich ilmenite-bearing cumulates (IBCs), as well as the concentration of potassium, rare earth elements, and phosphorous (KREEP) and heat-producing elements in the late stage liquids of the magma ocean. However, while remote sensing and geochemical evidence for the concentration of both Ti-rich material [1] and KREEP-rich [2] material within the nearside Procellarum KREEP terrane (PKT) exists, physical evidence for the subsurface distribution of these materials and their evolution through time has been lacking.

Also within the nearside mare region, a large set of linear to arcuate gravity anomalies (henceforth referred to as PKT border anomalies; Fig. 1a) was revealed by gravity data from the GRAIL mission [3]. The PKT border anomalies have been interpreted as the expression of lava flooded rift valleys or the plumbing system of the maria [3], and differ from the linear anomalies elsewhere interpreted as stalled dikes in the crust [4], but their origin remains uncertain.

Here we explore a new explanation for the origin of the PKT border anomalies – that they are remnants of the dense IBCs that formed in early lunar history, most of which subsequently sank into the mantle. One proposed catalyst of the scenario is the South Polar Aitken (SPA) basin-forming impact, which resulted in high-temperature anomalies that triggered mantle overturning and the migration of the global IBC layer to the nearside [5, 6]. The resulting gravitational instability of the IBC layers is modelled to manifest as sheetlike downwellings as the IBC sinks into the mantle. Residual bodies left at the base of the crust are predicted to form a polygonal pattern of intersecting elongated bodies with triangular cross-sections that remain today [5]. To first order, the scale and pattern of the modeled residual IBC material (Fig. 1b) resembles that of the PKT border anomalies, and the presence of dense IBCs is consistent with the positive gravity and negative gravity gradients.

In this study, we use GRAIL gravity data together with models of the overturn of the ilmenite-rich materials to reveal, for the first time, the vestiges of the nearside ilmenite layer. First, we use the predicted IBC distribution from the mantle overturn models [5] to forward model the gravity. We then quantify the cross-sectional geometry of the structures using Markov Chain Monte Carlo (MCMC) algorithms. Finally, we inverted the topography and gravity of the PKT border anomalies to solve for the corresponding thickness of the IBCs.

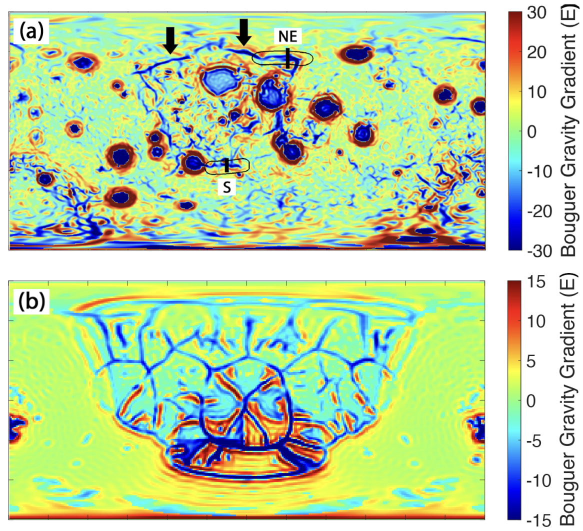

Figure 1. (**a**) Bouguer gravity gradient showing the PKT border anomalies (arrows), and the regions selected as the gravity profile for MCMC analysis highlighted. (**b**) Modeled [5] Bouguer gravity gradient after mantle overturn and IBC downwelling

Methods: In the MCMC models, we assume that the residual IBC material has the form of an inverted triangular prism, based on the model predictions [5]. The lengths were set to the horizontal lengths of the individual gravity anomalies, and the top depth is set to the estimated PKT region crust-mantle interface depth of 25 km. The models then vary the vertical thicknesses and horizontal widths of the density anomalies, in order to match average gravity profiles across the northeast (NE) and southern (S) border anomalies. The mantle and IBC densities are assumed to be 3400 and 3700 kg/m^3 [5], respectively.

The inversion of gravity and topography for the IBC layer thickness first solves for the global mare and crustal thicknesses [7,8]. Next, the mare and crustal thicknesses were interpolated across the border anomalies from the surrouding values to yield a smooth transition. A new gravity model is then generated using the crust and mare thickness models, and the difference between the modeled and observed gravity is inverted to return the thickness variations of the IBC layer.

Results: The forward models of the IBC material return gravity gradient maps (Fig. 1b) that reveal polygonal structures of negative gravity gradients, which is consistent with what is observed in the lunar gravity gradients. The model gravity gradients are ~10 E (~30%) weaker than the observations, but the magnitudes of the modeled anomalies are sensitive to the assumed density contrast between mantle and IBCs. The linear segments comprising the polygonal pattern observed in the gravity data (Fig. 1a) are larger than predicted by the overturn models (~2200 km and ~1000 km, respectively), and the overturn model predicts a polygonal network of anomalies over a broader area. However, the horizontal length scale of the downwellings resulting in the polygonal patterns depends on the assumed viscosity contrast between mantle and IBCs [5], with larger viscosity contrasts predicting longer lineations and larger polygons (e.g., ~1800 km for a viscosity contrast of 10^{-3}). Later impacts may have also modified the structures.

The MCMC models (Table 1) return best fit thicknesses and widths of ~35 km and ~220 km, respectively. These values are consistent with the ilmenite migration model [5], which predicts residual IBC bodies with thickness and widths of ~15-40 km, and ~100-300 km, respectively.

The global gravity and topography inversion returns similar results (Fig. 2a) to the MCMC models and are consistent with the overturn model predictions, with predicted maximum thicknesses of 36 and 35 km for the NE and S anomalies, respectively. The mantle overturn models (Fig. 2b) predict a thin residual layer of IBCs throughout the PKT region, which will be included in future gravity-topography inversions.

Anomaly	Height (km)	Width (km)	RMS (mGal)
NE	33.6 (139+89.3,-96.8)	211 (122+93.3,-67.0)	10.1
S	38.6 (128+69.0,-82.9)	226 (119+74.3,-61.7)	8.01

Table 1. Best-fit and (mean 1σ) MCMC height and width (km), and best-fit misfit (mGal) for the two selected anomalies .

Conclusions: The PKT border anomalies revealed by the GRAIL data are features unprecedented in scale and pattern. However, this polygonal pattern of linear gravity anomalies with angular intersections strongly resembles the pattern of the final residues of sheetlike downwellings of ilmenite-bearing cumulates predicted by mantle overturn models [5]. Our MCMC models and gravity and topography inversion show that the PKT border anomalies can be explained by a local thickening of a residual IBC layer by 40 to 60 km, which is consistent with results from models of mantle overturn and IBC downwelling. Differences in the lengthscale of the lineations may indicate a greater viscosity contrast between the mantle and IBCs.

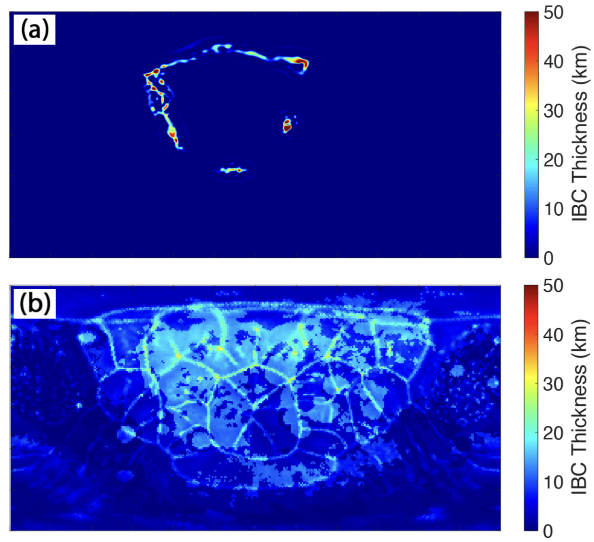

Figure 2. (a) Inverted IBC layer thickness using GRAIL gravity and LOLA topography. (b) Predicted IBC layer thickness from the reference model of the effects of the SPA impact [5]

The interaction between the PKT border anomalies and the impact basins can be used to help constrain the timing. Our interpretation is that the border anomaly pattern was not influenced by Serenitatis, which implies that they predate that impact event. The estimated ages of Serenitatis and SPA of ~4.22 Ga [9] and 4.25 Ga [10] may bracket the overturn event.

The implications of these results are significant, as they provide the first physical evidence for the subsurface distribution and evolution of the dense ilmenite bearing cumulates predicted by models of magma ocean crystallization. The overturn of the buoyantly unstable magma ocean cumulates was one of the defining events in the evolution of the lunar interior, but has previously been understood primarily based on compositional evidence. The gravity observations place a new constraint on the nature and timing of this event.

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