GRAIL-IDENTIFIED GRAVITY ANOMALIES IN PROCELLARUM: INSIGHT INTO SUBSURFACE IMPACT AND VOLCANIC STRUCTURES ON THE MOON.

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Introduction: Oceanus Procellarum on the Moon hosts four positive Bouguer gravity anomalies (PBGA): S*outhern Aristarchus Plateau*, *Northern* and *Southern Marius Hills*, and *Northern Flamsteed* (***Fig. 1***). These four PBGAs span a region ~700 km in N-S extent, and are all similar in diameter (~100–120 km), gravitational amplitude (>100 mGal contrast), and shape (approximately circular in planform). The northernmost anomaly is located just southeast of the Aristarchus Plateau (AP), and has been interpreted as a buried ~100 km-diameter impact structure nearly completely filled with mare lava, with a few locations of protruding crater rim crest [e.g., 1–2]. This *Southern Aristarchus Plateau* anomaly is adjacent to the broad AP topographic rise, which contains a wide variety of sinuous rilles and extensive pyroclastic deposits [e.g., 3], but no PBGAs are present within the rise itself. To the south, the next two PBGAs, named *Northern and Southern Marius Hills*, coincide with extensive volcanic features, including domes, cones, flows, and sinuous rills of the Marius Hills volcanic complex [e.g., 4]. The southernmost of the PBGAs in our analysis, *Northern Flamsteed* coincides with topographic ridges trending northwest in the direction of Marius Hills, but is located ~300 km from the southern Marius Hills anomaly. These four, spatially associated PBGAs are important in understanding the impact and volcanic/plutonic history of the Moon, in a region of elevated temperatures due to the Procellarum KREEP Terrane [5].

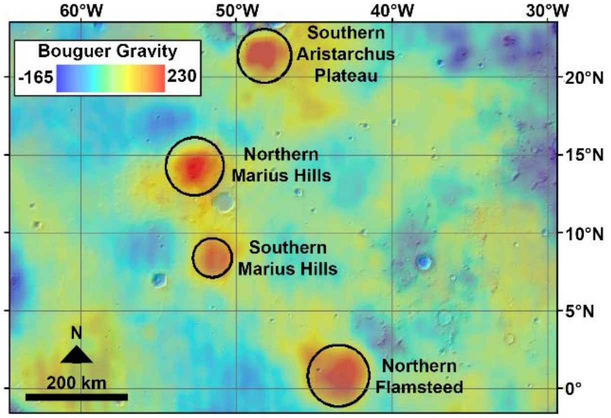

Fig. 1. *Four positive Bouguer gravity anomalies in Oceanus Procellarum. GRAIL-derived GRGM900c [6] Bouguer spherical harmonic solution to degree 6-660 is displayed overlying LOLA [7]-derived hillshade.*

Analysis of gravity data is an excellent approach for characterizing the subsurface crustal and interior structure of a planetary body. The very high resolution of the Gravity Recovery and Interior Laboratory (GRAIL) data [8] approaches the scale of many geologic features, and with these data together, the interpretation of PBGAs can be made more confidently. Here we explore seven geologic endmember scenarios (***Fig. 2***) to compare to the four observed PBGAs in the Procellarum region: (1) filled and buried impact crater, (2) mantle upwelling at the crust-mantle boundary, (3) a buried crater with combined floor-fractured crater (FFC) intrusion and surface mare fill [9], (4) an intruded volcanic sill or shallow magma reservoir [10], (5) a swarm of radial dikes surrounding or above a magma source region [11], (6) a concentration of vertical dikes over a deeper mantle intrusion [12], and (7) tectonic thickening by mare ridge/arch lava overthrusting [13].

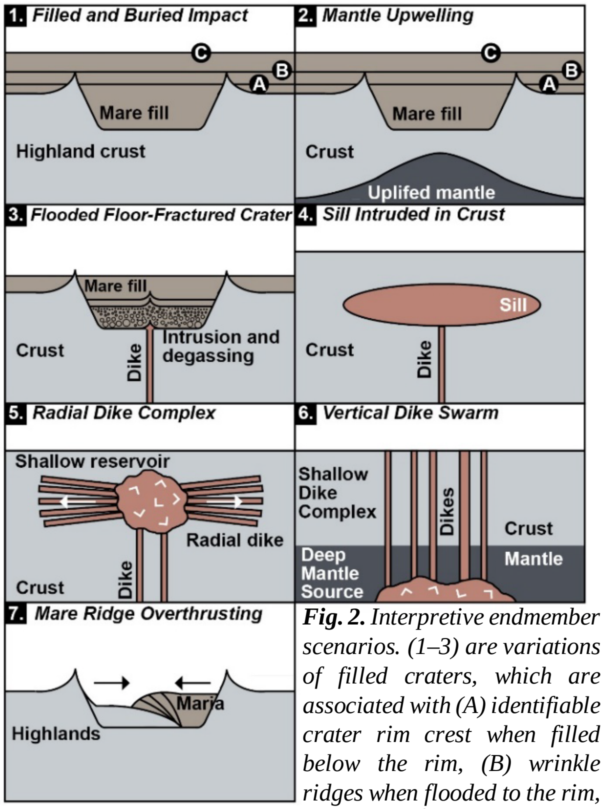

Fig. 2. *Interpretive endmember scenarios. (1–3) are variations of filled craters, which are associated with (A) identifiable crater rim crest when filled below the rim, (B) wrinkle ridges when flooded to the rim, and (C) no topographic expression when flooded over. (4–6) are variations of magmatic intrusions. (7) is tectonic thickening.*

The objective of our study is to constrain the subsurface structures that contribute to the four PBGAs through combined analysis of high-resolution GRAIL gravity data [8] and recent geologic analyses [e.g., 12]

(***Figs. 1, 2***). Previous work on this region was restricted to lower resolution Lunar Prospector gravity data [10], which is likely to have resulted in a substantial underestimation of the mass anomaly magnitude.

Methodology: We use GRAIL gravity data [8], which at long wavelengths largely indicate variations in compensation state and thickness of the crust [14]. We first remove the attraction of surface topography assuming a crustal density of 2800 kg/m^3 [15] that is characteristic of the nearside mare region to obtain Bouguer anomalies. Regional admittance modelling [15] suggests that the basaltic maria covering the surface are considerably denser than the average lunar highlands (bulk density of 2550 kg/m^3). We use a bulk density of 3150 kg/m^3 for the maria, as was suggested for basalts of intermediate Ti-content in Marius Hills [10]. We remove the longest wavelength variations in crustal structure, windowing the anomalies to spherical harmonic degrees 6-660 (corresponding to 8-km to 900-km half-wavelengths), and explore a range of infill and intrusion density contrasts between 150 and 600 kg/m^3 to model the anomalies.

Gravitational modeling results: We test the hypothesis that the four PBGAs are the expressions of basalt-filled, preexisting craters (***Fig. 2.1***), and find that excessive (a factor of ~2) density contrasts are required to match the circular anomalies, given well-known constraints on crater depth. Mapped mare-filled craters, such as the 112-km-diameter Flamsteed P located south of *Northern Flamsteed*, do not show a significant gravity anomaly, casting further doubt on the filled impact crater scenario (***Fig. 2.1***) for the four PBGAs. Thus, mare-filled craters alone cannot reasonably produce the observed PBGAs, not even for *Southern AP*, where a protruding rim crest is visible.

If filled craters were intruded by a sill to produce a FFC (***Fig. 2.3***), then concentric fractures would be expected [16], but these are not observed. It is possible that such patterns were subsequently covered by mare fill. However, FFCs are also associated with spatially heterogeneous, low-magnitude (~10's of mGal) gravity anomalies [9], and this, too, is inconsistent with the four PBGAs in our study region (***Fig. 1***).

We also find that intrusive sills or radial dike complexes (***Figs. 2.4, 2.5***) require considerable volumes at shallow depths in order to produce the observed anomalies, and thus, would be likely to produce observable surface tectonic effects [12]. The density contrast provided by shallow volcanic sills or dike complexes (***Figs. 2.4, 2.5***) alone cannot account for the large, relatively compact PBGAs, and require an excessive factor of ~2 in density contrast to match the anomalies. Thus, it is unlikely that underlying magma chambers are the sole source of the anomalies, as suggested by [10] for both *Marius Hills* anomalies.

The four PBGAs show no clear association with wrinkle ridges, as expected from tectonic thickening (***Fig. 2.7***) due to a fault or series of faults and overall crustal shortening. Thus, we do not favor this scenario.

We find the best gravitational solution is (1) a vertical dike swarm (***Fig. 2.6***), (2) mantle upwelling associated with mare-filled craters (***Fig. 2.2***), (3) or some combination of the two. (1) *Dike swarms:* In this scenario, the crust is occupied by ~25% dikes to correspond to the GRAIL-derived signal. The dikes have a density contrast of 150 kg/m^3, or 25% of the 600 kg/m^3 explored in our model. It has been suggested that the upper limit for the fraction of crust occupied by dikes is 37–50% by volume, but that the crust is likely to be occupied by much less [17]. The presence of dikes is indeed required to feed the mare basalt deposits observed at the four sites. The addition of a deep mantle reservoir is necessary in our forward model to increase the overall density contrast and correlate with the magnitude of the anomalies. (2) *Mantle upwelling:* Mare-filled craters (***Fig. 2.2***) are consistent with the circular shapes of the four anomalies and the protruding crater rim crest at *Southern AP*. Coupling ~2 km of mare infill with ~10 km of mantle uplift produces the required density contrast for the four anomalies. This region of Oceanus Procellarum is characterized by relatively thin crust [18], which may have resulted in preferential mantle uplift following impacts in this region.

Conclusions: The GRAIL data [8] presented here permit higher resolution gravity modeling than in previous studies [10]. Coupled with geologic analyses [12], we determine that the four PBGAs (***Fig. 1***) are due to surface mare fill, subsurface dikes, and a deep density contrast, caused by either a volcanic mantle reservoir or impact-related mantle uplift.

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