Solar System Exploration Division, GSFC Code 690

GRAIL-identified gravity anomalies in Oceanus Procellarum: Insight into subsurface impact and volcanic/magmatic structures on the Moon

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Introduction: Lunar gravity anomalies.

- Four distinctive positive Bouguer gravity anomalies are identified in Oceanus Procellarum. They are similar in:
  - -Diameter (~100-120 km).
  - -Gravitational amplitude (>100 mGal contrast).
  - -Shape (approximately circular in planform).
- Previous work has suggested that these four positive gravity anomalies may be due to:
  - -Lava-filled impact craters [1].
  - -Subsurface volcanic sills [2].
- New, higher-resolution GRAIL data [3] allow for the re-analysis of these anomalies.
- Understanding the subsurface density structures that contribute to these anomalies is important in order to discuss regional impact and volcanic histories, and the evolution of the lunar crust in Oceanus Procellarum.

Objectives.

1. Constrain subsurface structures that contribute to the four positive Bouguer gravity anomalies.
2. Discuss the hidden impact and volcanic histories of the Moon.

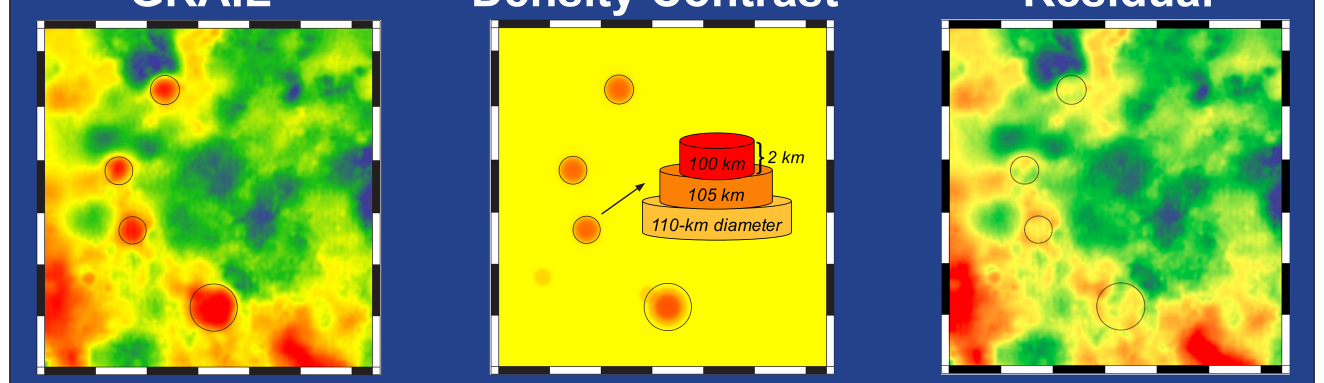
Methods.

GEOLOGIC ANALYSES.

- Six geologic end-member scenarios are explored to analyze the four observed gravitational anomalies.
- Impact crater parameters [e.g., 4] are estimated to consider the role of filled and buried impact craters.
- Analyses of the generation, ascent, and eruption of magma [5-6] are used to guide both the modeling of subsurface magmatic structures and also the interpretation of surface volcanic features.

FORWARD GRAVITATIONAL MODELING.

GRAIL - Density Contrast = Residual



- We obtain Bouguer anomalies from GRAIL gravity data [3] by removing the surface topography attraction, assuming a crustal density of 2800 kg/m³ [7].
- We use a bulk density of 3150 kg/m³ for the maria, as was suggested for basalt of intermediate Ti-content [2].
- We remove the longest wavelength variations in crustal structure, windowing the anomalies to spherical harmonic degrees 6-660.
- The density contrasts for each geologic scenario are modeled as a series of cylinders with finite thicknesses, with a range of infill and intrusion density contrasts between 150 and 600 kg/m³ to model the anomalies.
- The total modeled gravity anomaly is the sum of the gravity from different subsurface load scenarios.

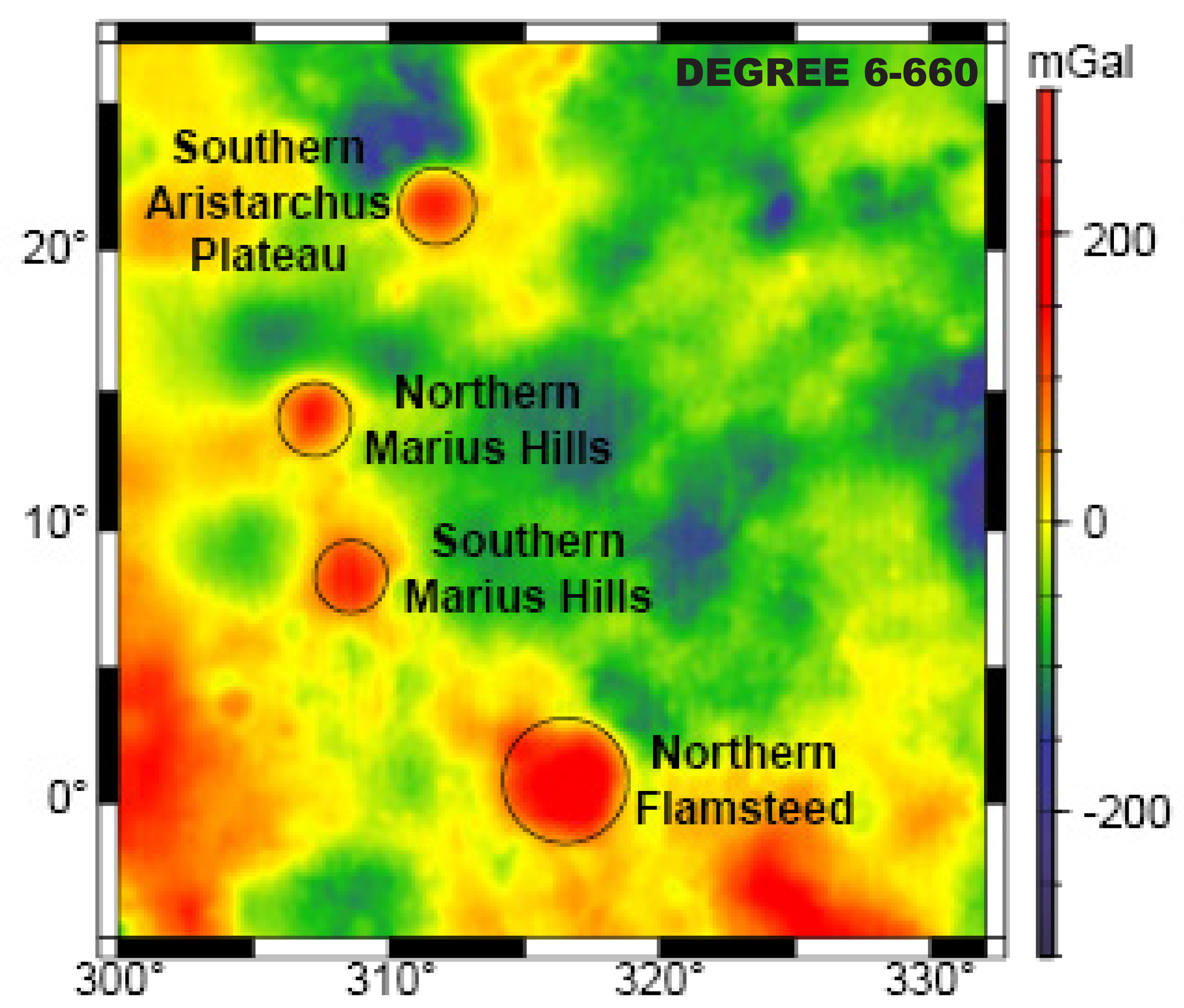
References.

[1] Evans A. J. et al. (2016) *GRL, 43*, 2445–2455. [2] Kiefer W. S. (2013) *JGR Planets, 118*, 733–745. [3] Zuber M. T. et al. (2013) *Science, 339*, 668–671. [4] Kalynn J. et al. (2013) *GRL, 40*, 38–42. [5] Wilson L. and Head J. W. (2017) *Icarus, 283*, 146–175. [6] Head J. W. and Wilson L. (2017) *Icarus, 283*, 176–223. [7] Besserer J. et al. (2014) *GRL, 41*, 5771–5777. [8] Jozwiak L. M. et al. (2012) *JGR, 2012*, JGR, 117, E11005. [9] Jozwiak L. M. et al. (2017) *Icarus, 283*, 224–231. [10] Wilson L. and Head J. W. (2002) *JGR, 107*, E8. [11] Wilson L. and Head J. W. (1981) *JGR, 86*, 2971–3001.

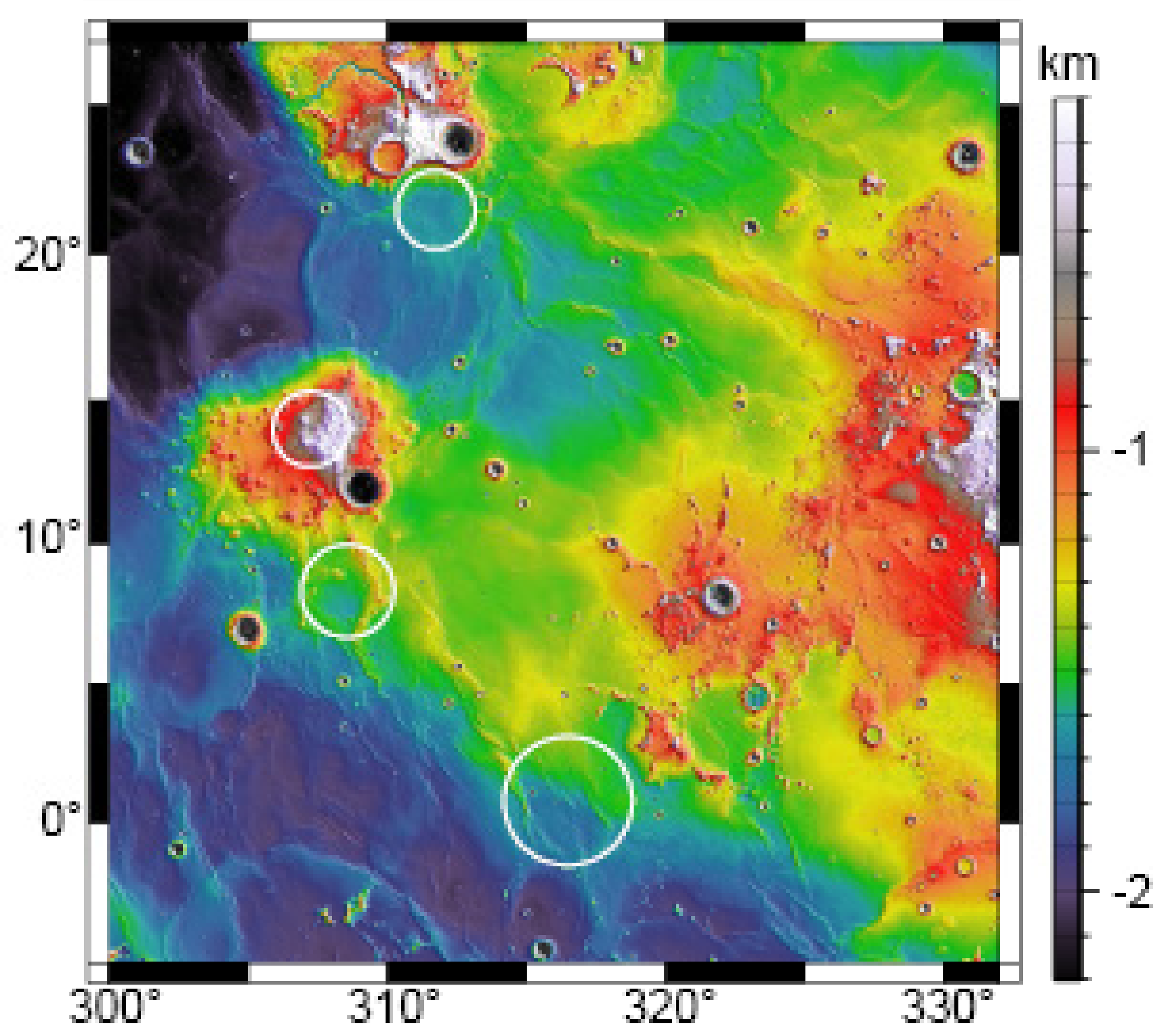
Acknowledgment: This work is supported by NASA under Grant Number NNX16AT19H issued through the AS&ASTAR Graduate Fellowship.

Positive Bouguer gravity anomalies.

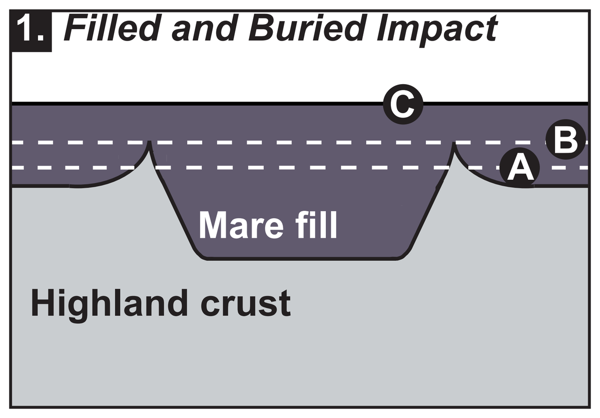
GRAVITATIONAL SIGNATURE.

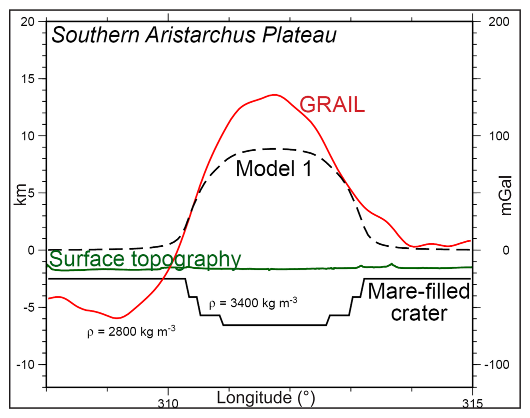


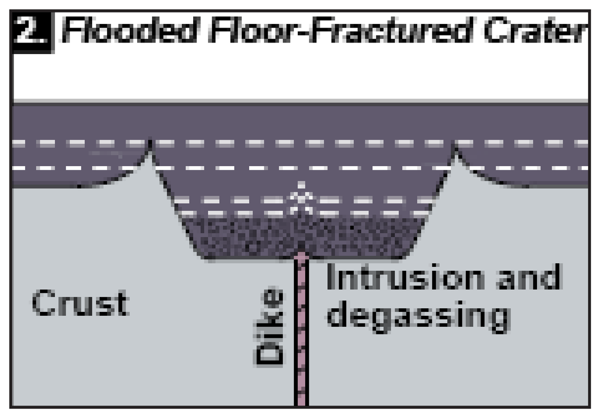
SURFACE TOPOGRAPHY.

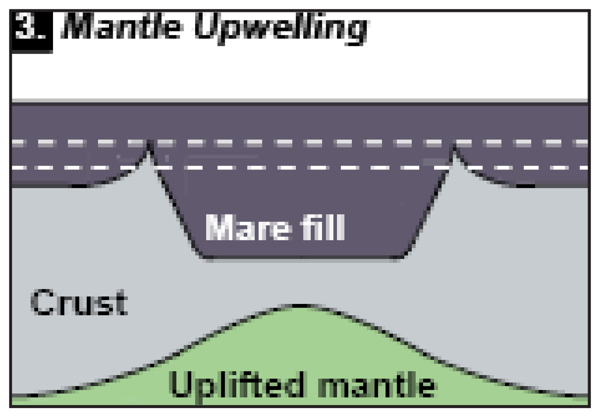


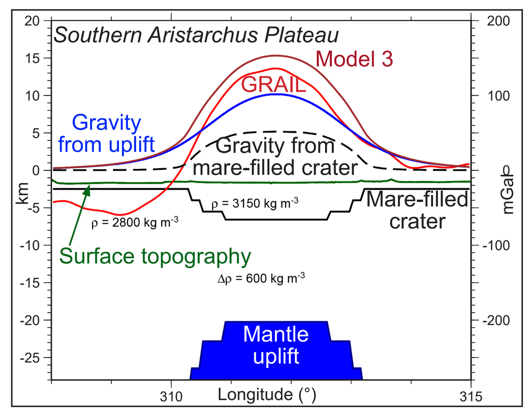
Results: Filled and buried impact craters.











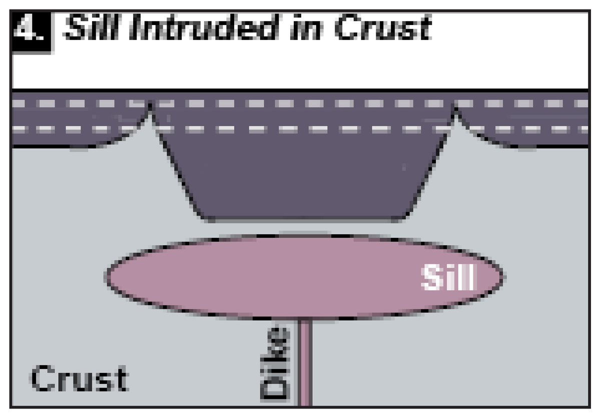
CASES 1 & 2: NOT FAVORED.

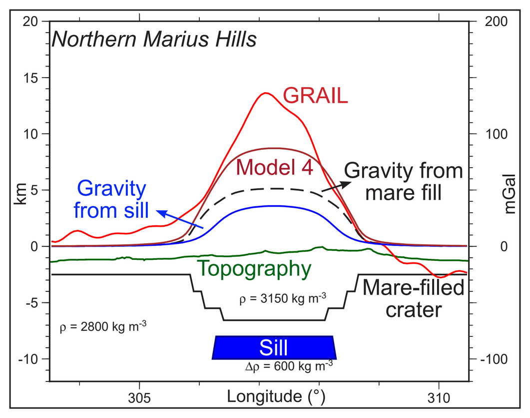
- Does not provide enough density contrast.
- Uplift caused by inflation and concentric fractures [8] are not observed.
- Anomalies are high magnitude and concentrated, in contrast to the gravitational signatures that are associated with FFCs [9].

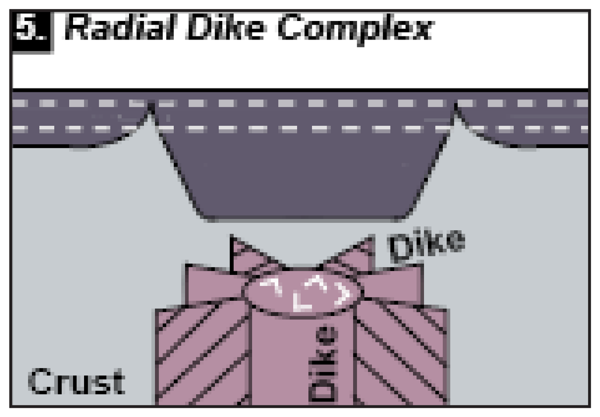
CASE 3: FAVORED.

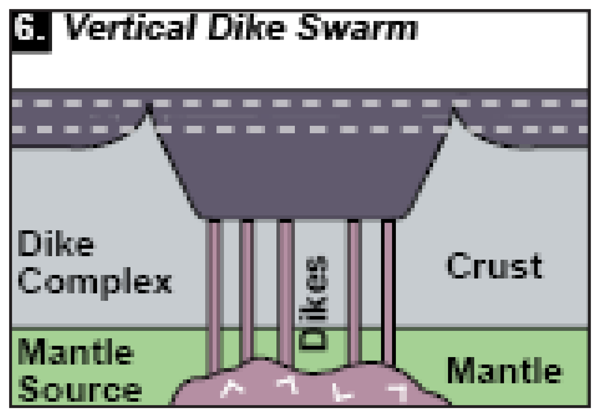
- Provides enough density contrast.
- Consistent with postulated buried craters [1].
- 2.8-3.5 km of mare fill + 5-7 km of mantle uplift.
- Requires crustal thickness of 18-28 km.

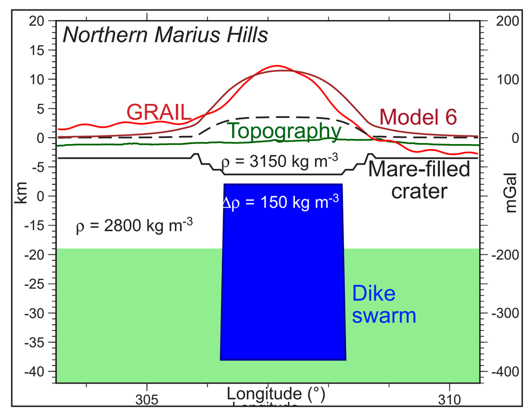
Results: Volcanic and magmatic intrusions.











CASES 4 & 5: NOT FAVORED.

- Does not provide enough density contrast.
- Horizontal, subsurface sills beneath the Marius Hills anomalies require a thickness >10 km in order to match the observed signal.
- Surface tectonic effects, radial fractures, or graben [6, 10] are not observed.

CASE 6: FAVORED.

- Provides enough density contrast.
- Consistent with ascent and eruption of maria [6].
- Feeds the Marius Hills complex with 10+ dikes.
- Crust occupied by 25% dikes [11], fed by mantle.

Conclusions.

1. **GRAIL data presented here permit higher resolution gravity modeling than in previous studies.**
2. **We demonstrate that the four positive Bouguer gravity anomalies in Oceanus Procellarum require a deep density contrast in order to correspond to the magnitude of the signal.**
3. **This density contrast is consistent with either impact rebound (CASE 3: *S. AP and N. Flamsteed*) or a mantle source region supplying a vertical dike swarm (CASE 6: *N. and S. Marius Hills*).**
4. **These anomalies are important in understanding the impact and volcanic/plutonic history of the Moon, specifically in a region of thin crust and elevated temperatures.**