Resolving the Primary Cause for Floor-Fractured Craters on the Moon Using GRAIL and LOLA Data

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Introduction

Floor fractures are found in relatively few craters on the moon and the cause of their formation is a mystery. There are two proposed ideas for the cause of these fractures. The mechanism causing floor fractured craters has been hypothesized to be either magmatic intrusions or viscous relaxation. Due to the lack of gravity data in early studies, a definite answer was not determined. Recently, gravity data from the Gravity Recovery and Interior Laboratory (GRAIL) has provided new insight into how floor fractured craters form. For example, Thorey et al. (2015) used GRAIL data to suggest the magmatic intrusion hypothesis is more likely. In this research, we expand on the previous work to further ascertain which of these proposed hypotheses is best supported by the data. Because magmatic intrusions would lead to a difference in gravity anomalies between floor fractured craters and normal craters that viscous relaxation would not produce, the results of our comparisons has allowed us to conclude the probable cause of floor-fractured craters. Floor-fractured craters were measured to have a higher gravity anomaly difference between the crater and its immediate surroundings compared to non-floor-fractured craters with similar properties. This leads to the conclusion that magmatic intrusion is the cause of floor-fractured craters. This experiment is important because it allows for a better understanding of lunar surface activity.

Background

- Floor fractures are a series of cracks on the floor of a crater.
- Magmatic intrusion and viscous relaxation are two proposed causes of floor fracturing in craters.
- **Magmatic Intrusion:** Magma approaches the surface by filling existing cracks under the surface and forms dikes. When the magma reaches a level where it can no longer expand upwards, the overlying crust expands laterally and forms cracks on the surface (Jozwiak, 2012).
- **Viscous Relaxation:** This is when heat below the surface causes the rock below a crater to rise unevenly with a dome-like shape. This expanding rock behaves in a viscous way. The rock on the surface can not expand this way so it cracks, forming the floor-fractures (Solomon, 1982).
- Information gathered by the Gravity Recovery and Interior Laboratory (GRAIL) satellites and the Lunar Orbiter Laser Altimeter (LOLA) data set were used in this study.
- GRAIL provided precise measurements of the moon's gravitational anomalies. LOLA provided accurate elevation readings.
- This data was accessed through ASU's Java Mission-planning and Analysis for Remote Sensing (JMARS) program.

Methods

- Floor-fractured craters (FFC's) with significant gravity anomalies were selected for our study.
- Pertinent "Comparison Craters" without floor fractures, but otherwise similar to the FFC's were selected as a control.
- GRAIL data was accessed in JMARS to measure the gravitational anomalies of both FFC's and non FFC's.
- Floor-fractured craters were found in the LOLA Data archive.
- By applying the GRAIL layer (measured in mGals) on the Moon using JMARS, we analyzed every pixel on/surrounding the FFCs and non FFCs and averaged all the gravity readings.
- The percent difference between the crater and the surrounding lunar surface was calculated.
- Comparing the gravity difference between the FFCs and their corresponding non FFCs using a Student's t-Test will help to determine which hypothesis is supported by the data.

Research Question

What is the primary mechanism causing floor-fractured craters on the Moon?

Hypothesis

The cause of floor-fractured craters is magmatic intrusion, as models of viscous relaxation do not match altimetric measurements of FFC's. Additionally, FFC's occur near mare filled basins, which are known locations of magmatic activity (Jozwiak, 2012).

Table 1. List of the Defining Characteristics for Each Class of FFC[a]

Crater Class	Class Characteristics
1	Deep floor, radial/concentric fractures, crescent shaped patches of mare material along walls, central peak complexes
2	Well-defined wall scarp, uplifted central region/convex up floor profile, concentric fractures
3	Wide moat between crater wall scarp and crater interior, radial/polygonal fractures, terracing on wall opposite the nearby mare
4a	V-shaped moat, radial/concentric fractures, convex up floor profile
4b	V-shaped moat with pronounced inner ridge on the interior side, subtle fractures, irregular convex up floor profile
4c	V-shaped moat, hummocky interior
5	Degraded crater walls, radial/polygonal fractures
6	Mare-flooded interiors, concentric fracture pattern near wall

[a]Craters in each class need not possess all of the listed characteristics, although they must possess a majority in order to be classified.

Figure 1: The crater class scheme for the floor-fractured crater (Jozwiak, 2012).

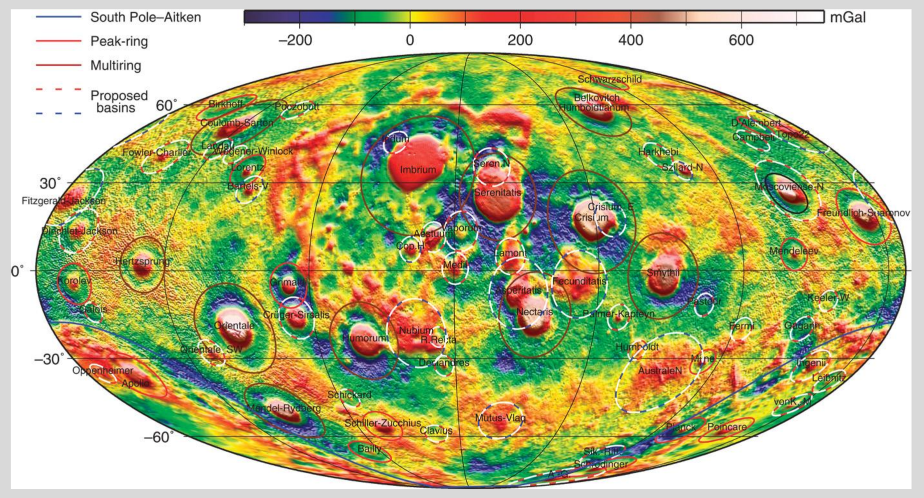


Figure 2: Colorized gravity anomaly map of the moon.

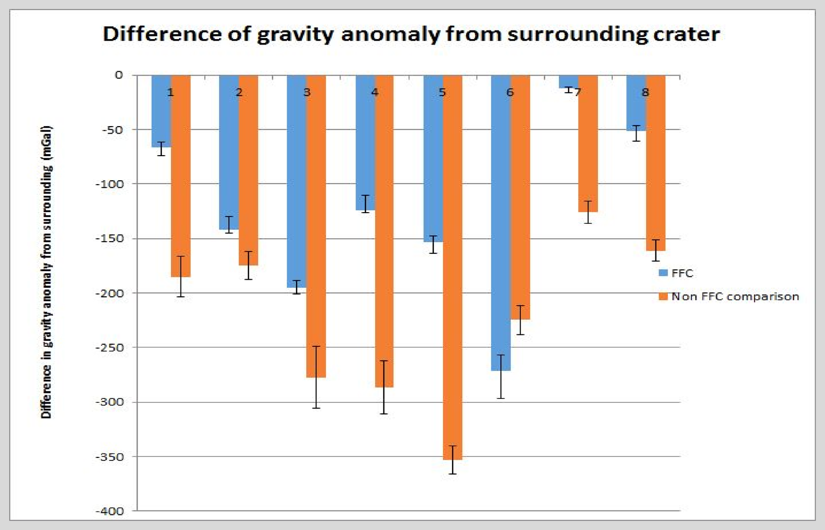
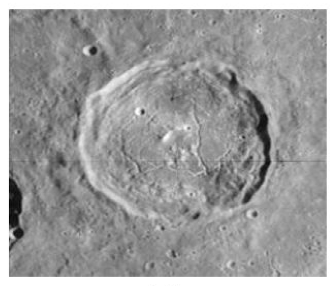


Figure 3: There is a significant difference between the local gravity anomaly (difference from surrounding gravity) of FFCs and non-FFCs, P<.05.

Data

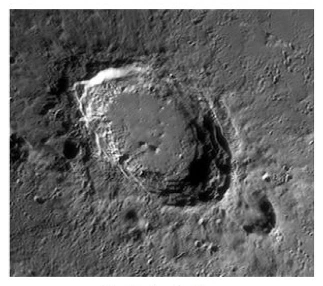
Table 1: All of the data that was utilized throughout this research.

Number	Name of FFC	FFC Class	Location	Diameter (km)	Gravity anomaly (mGal)	Standard error	Average surrounding gravity	Standard error	Difference from surrounding	Name of Comparison Crater	Location	diameter (km)	Gravity anomaly (mGal)	Standard error	Average surrounding gravity	Standard error	Difference from surrounding	Difference of differences from surrounding
1	Alphonsus	5	2.85°E,13.39°S	110.54	-124.91	4.369	-58.849	7.849	-66.061	Stöfler	5.93°E, 41.24°S	129.8774	-140.039	5.19	44.926	18.631	-184.965	118.904
2	Atlas	1	44.38°E, 46.74°N	88.116	-99.643	11.75	41.933	3.234	-141.576	Aristoteles	17.32°E, 50.24°N	87.567	-132.173	10.922	42.276	12.863	-174.449	32.873
3	Compton	5	103.91°E, 56.31°N	164.628	-195.678	6.268	-0.675	5.579	-195.003	Heaviside	166.77°E, 10.44°S	164.463	-103.205	36.866	174.179	28.183	-277.384	82.381
4	Einstein	1	271.83°E, 16.70°N	181.473	-153.813	13.443	-29.75	2.198	-124.063	Kovalevskaya	129.44°W, 30.86°N	113.709	-200.649	19.792	86.038	24.226	-286.687	162.624
5	Humboldt	3	81.25°E, 27.03°N	199.459	-123.865	5.375	29.557	10.062	-153.422	Longomontanus	21.88°W, 49.55°S	145.497	-244.255	9.187	108.687	12.6	-352.942	199.52
6	Karpinskiy	5	166.87°E, 72.66°N	91.403	-297.882	14.61	-26.579	25.384	-271.303	Seares	147.23°E, 73.74°N	99.502	-212.574	13.239	12.093	13.239	-224.667	-46.636
7	Pitatus	6	13.5°W, 29.9°S	100.628	-80.389	1.802	-67.96	3.898	-12.429	Lomonosov	98.28°E. 27.35°N	90.69	-84.183	13.535	41.656	10.506	-125.839	113.41
8	Repsold	5	78.6°W, 51.3°N	108.654	-60.879	4.884	-9.828	9.953	-51.051	Xenophanes	82.00°W, 57.49°N	117.572	-130.038	17.558	31.168	9.841	-161.206	110.155



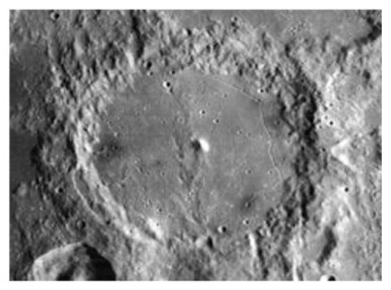
Atlas

Lat & Long: 44.38°E, 46.74°N
Diameter: 88.116 km
Crater Class: 1
Mare or Highland: Highland
Average Gravity of Crater: -99.643 mGals
Average Gravity of Surrounding: 41.933 mGals
Gravity Difference: -141.576 mGals



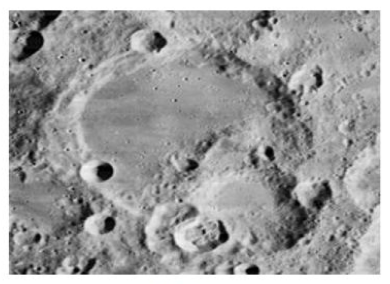
Aristoteles

Lat & Long: 17.32°E, 50.24°N
Diameter: 87.567 km
Mare or Highland: Highland
Average Gravity of Crater: -132.173 mGals
Average Gravity of Surrounding: 42.276 mGals
Gravity Difference: -174.449 mGals



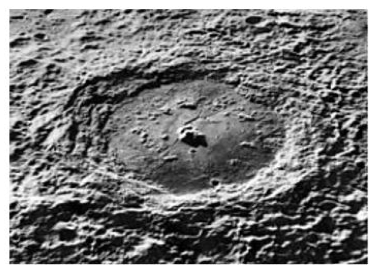
Alphonsus

Lat & Long: 2.85°E,13.39°S
Diameter: 110.54 km
Crater Class: 5
Mare or Highland: Highland
Average Gravity of Crater: -124.910 mGals
Average Gravity of Surrounding: -58.849 mGals
Gravity Difference: -66.061 mGals



Stöfler

Lat & Long: 2.03°W, 25.51°S
Diameter: 129.8774 km
Mare or Highland: Highland
Average Gravity of Crater: -140.039 mGals
Average Gravity of Surrounding: 44.926 mGals
Gravity Difference: -184.965 mGals



Compton

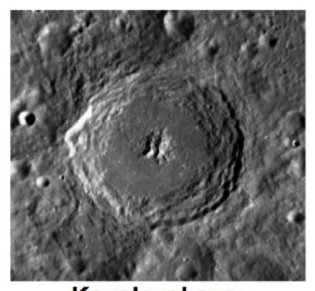
Lat & Long: 103.91°E, 56.31°N
Diameter: 164.628 km
Crater Class: 5
Mare or Highland: Highland
Average Gravity of Crater: -195.678 mGals
Average Gravity of Surrounding: -0.675 mGals
Gravity Difference: -195.003 mGals

Heaviside

Lat & Long: 166.77°E, 10.44°S
Diameter: 164.463 km
Mare or Highland: Highland
Average Gravity of Crater: -103.205 mGals
Average Gravity of Surrounding: 174.179 mGals
Gravity Difference: -277.384 mGals

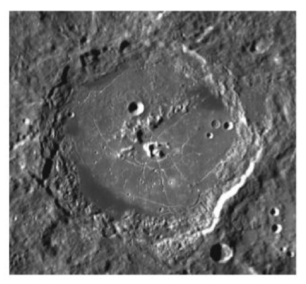
Einstein

Lat & Long: 271.83°E, 16.70°N
Diameter: 181.473 km
Crater Class: 1
Mare or Highland: Highland
Average Gravity of Crater: -153.813 mGals
Average Gravity of Surrounding: -29.750 mGals
Gravity Difference: -124.063 mGals



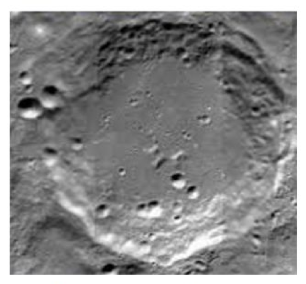
Kovalevskaya

Lat & Long: 129.44°W, 30.86°N
Diameter: 113.709 km
Mare or Highland: Highland
Average Gravity of Crater: -200.649 mGals
Average Gravity of Surrounding: 86.038 mGals
Gravity Difference: -286.687 mGals



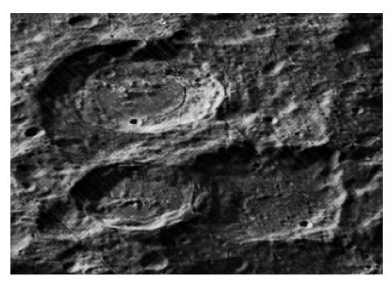
Humbolt

Lat & Long: 81.25°E, 27.03°N
Diameter: 199.459 km
Crater Class: 3
Mare or Highland: Highland
Average Gravity of Crater: -123.865 mGals
Average Gravity of Surrounding: 29.557 mGals
Gravity Difference: -153.421 mGals



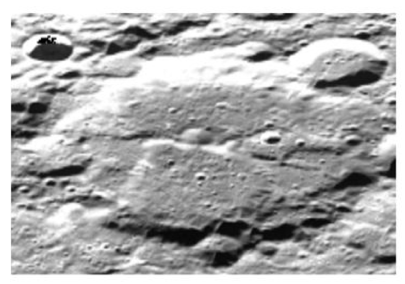
Longomontanus

Lat & Long: 21.88°W, 49.55°S
Diameter: 145.497 km
Mare or Highland: Highland
Average Gravity of Crater: -244.255 mGals
Average Gravity of Surrounding: 108.687 mGals
Gravity Difference: -352.942 mGals



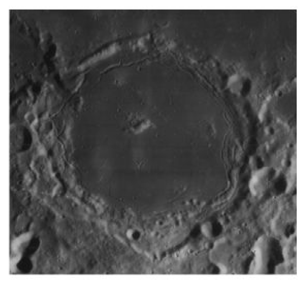
Karpinkskiy

Lat & Long: 166.87°E, 72.66°N
Diameter: 91.403 km
Crater Class: 5
Mare or Highland: Highland
Average Gravity of Crater: -297.882 mGals
Average Gravity of Surrounding: -26.579 mGals
Gravity Difference: -271.302 mGals



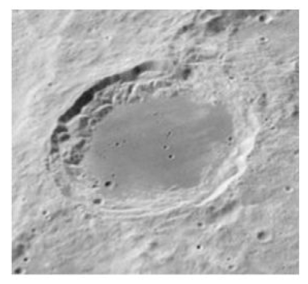
Seares

Lat & Long: 147.23°E, 73.74°N
Diameter: 99.502
Mare or Highland: Highland
Average Gravity of Crater: -212.574 mGals
Average Gravity of Surrounding: 12.093 mGals
Gravity Difference: -224.667 mGals



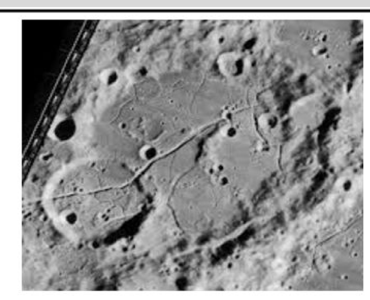
Pitatus

Lat & Long: 13.5°W, 29.9°S
Diameter: 100.628 km
Crater Class: 6
Mare or Highland: Highland
Average Gravity of Crater: -80.389 mGals
Average Gravity of Surrounding: -67.960 mGals
Gravity Difference: -12.429 mGals



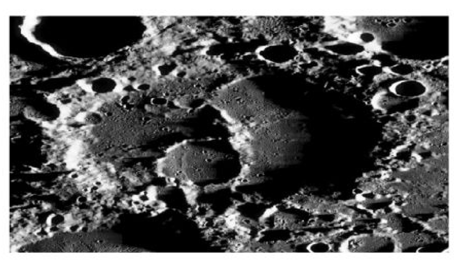
Lomonosov

Lat & Long: 98.28°E, 27.35°N
Diameter: 90.69 km
Mare or Highland: Highland
Average Gravity of Crater: -84.183 mGals
Average Gravity of Surrounding: -125.839 mGals
Gravity Difference: -125.839 mGals



Repsold

Lat & Long: 78.6°W, 51.3°N
Diameter: 108.654 km
Crater Class: 5
Mare or Highland: Highland
Average Gravity of Crater: -60.879 mGals
Average Gravity of Surrounding: -9.828 mGals
Gravity Difference: -51.051 mGals



Xenophanes

Lat & Long: 84.4°W, 53.9°N
Diameter: 117.407 km
Mare or Highland: Highland
Average Gravity of Crater: -137.135 mGals
Average Gravity of Surrounding: 34.392 mGals
Gravity Difference: -171.527 mGals

Conclusion

- The data obtained and analyzed in this study through GRAIL and LOLA supports the hypothesis that magmatic intrusions are the cause of FFCs.
- When comparing the local gravity anomaly (difference from surrounding) between the FFCs and non-FFCs, the conclusion was made that there is a significant difference between the gravity of FFCs and non-FFCs, P<.05.
- Data analysis showed that magmatic intrusions cause floor-fractures in craters. Since local gravity anomaly of FFCs was higher than non-FFCs, magmatic intrusion is supported and viscous relaxation is not.
- This is because magmatic intrusion involves spreading dense basalt and viscous relaxation involves expansion of existing rock. Magmatic intrusions' dense rock would cause a trend of higher gravity in FFC's, which was confirmed in our study. Gravity anomaly of FFCs being lower than gravity anomaly of non-FFCs would indicate viscous relaxation.

Future Research

- The additional analysis of craters as well as the compositional data of these crates can be analyzed to further augment our research.

References

Crawford, I.A., *et al*. (2014). Lunar exploration: opening a window into the history and evolution of the inner Solar System. *Philosophical Transactions of the Royal Society, 372*(212).

Impact Cratering, (January 6, 2016). URL: *http://www.lpi.usra.edu/exploration/education/hsResearch/moon_101/ImpactCratering.pdf*

Jozwiak, L. M., et al. (2012). Lunar Floor-Fractured craters: Classification, Distribution, Origin and Implications for Magmatism and Shallow Crustal Structure. *Journal of Geophysical Research, 117,* 1-23.

Kaprinsky Floor Fractures, (January 6, 2015). URL: *http://lroc.sese.asu.edu/posts/685*

Liang Q, Chen C, Huang Q, et al. (2009). Bouguer gravity anomaly of the Moon from CE-1 Topography Data: Implications for the Impact Basin Evolution. *Sci China. 52*(12), 1867-1875.

LOLA Data Archive, (January 6, 2016). URL: *http://imbrium.mit.edu/LOLA.html*

Lunar Pioneer: Oblique view of Karpinskiy floor fractures. (n.d.). Retrieved February 08, 2016, from http://lunarnetworks.blogspot.com/2013/08/oblique-view-of-karpinskiy-floor.html

NASA's GRAIL Creates Most Accurate Moon Gravity Map, (December 7, 2015). URL:*http://www.jpl.nasa.gov/news/news.php?feature=3613*

Neumann, G. A., *et. al.* (2015). Lunar impact basins revealed by Gravity Recovery and Interior Laboratory measurements. *Science Advances, 1*(9).

Nozaki, K. (2006). The Generalized Bouguer Anomaly. Earth Planets Space, *58*, 287-303.

Solomon, S.C., et al. (1982). The Evolution of Impact Basins: Viscous Relaxation of Topographic Relief. *Journal of Geophysical Research. 87*(B5), 3975-3992.

Thorey, C., Michaut, C., and Wieczorek, M. (2015). Gravitational Signatures of LunarFloor-Fractured Craters. Earth and Planetary Science Letters, 424, 269-279.