THE NATURE OF THE GRAVITY ANOMALIES ASSOCIATED WITH LARGE YOUNG LUNAR CRATERS

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Abstract. The negative Bouguer anomalies (i.e., mass deficiencies) associated with four young lunar craters are analyzed. Model calculations based on generalizations made from studies of terrestrial impact structures suggest that the major contribution to the Bouguer anomaly for these lunar craters is due to a lens of brecciated material confined within the present crater rim crest and extending vertically to at least a depth of one-third the crater rim diameter. Calculations also reveal a systematic variation in the magnitude of the mass deficiencies with the cube of the crater diameter.

Introduction

This paper is concerned with the subsurface structure of large, young lunar craters as inferred from the gravity data obtained from line-of-sight tracking of lunar spacecraft. To date, most studies pertaining to lunar craters have been limited to a description of the surficial geology based on orbital photography combined with inferences drawn from studies of terrestrial impact features. We are presently performing a quantitative analysis of the gravity anomalies associated with lunar craters of various sizes and ages and utilizing this data to place constraints on the possible subsurface structure associated with these features. The gravity data used in our analysis consists of the line-of-sight component of the accelerations experienced by a spacecraft in a close lunar orbit [*Sjogren et al.*, 1972]. The strategy adopted in this research is to understand first the nature of the gravity anomalies associated with the youngest and freshest appearing lunar craters, and then to apply this knowledge as an aid in understanding the older, more modified lunar craters. This paper summarizes the results for only the youngest lunar craters analyzed.

Several investigators have previously used this method to study lunar craters [e.g., *Gottlieb et al.*, 1970]. The present work deals with a more detailed consideration of the gravity and topographic data [*Phillips et al.*, 1977] and will report on results of a more quantitative nature for a larger number of lunar craters than given in earlier investigations.

Four lunar craters are included in our analysis: Eratosthenes (58 km rim diameter), Copernicus (92 km), Theophilus (100 km), and Langrenus (132 km). These craters are all post-Imbrian in age. In basic form, they are characterized by relatively flat floors and have well developed central peaks and terraced interior walls. The depth to diameter ratios for these craters range from 0.02 to 0.04.

Analysis of the Bouguer Anomalies

This research begins with one of the basic conclusions of *Phillips et al.* [1977] who applied topographic corrections to the gravity data and showed that a pronounced negative Bouguer anomaly (i.e., a mass deficiency) is associated with each of the young craters listed above. We will show that the major component of the mass deficiency for each of these craters extends laterally outward to approximately the present crater rim and vertically to a depth of roughly one-third of the present crater rim diameter. The uncertainty in the vertical extent is primarily due to the uncertainty in the value of the density contrast between these craters and their surroundings and is also due to an uncertainty in the exact geometry of the anomalous mass.

From analogy with terrestrial impact craters, we interpret this low density region as the brecciated and crushed material formed essentially *in situ* to distinguish it from the fallout debris. That is, the major component of the Bouguer gravity anomaly is target material which has been extensively broken up and crushed but has not undergone a great deal of mixing. Model calculations indicate that the rim deposits associated with these large lunar craters are a relatively minor component to the total gravity anomaly. Calculations also indicate that material transported by the inward collapse of the transient crater walls may be an important component of this large brecciated region; however, this material cannot be the sole component nor the dominant component of the anomalous mass.

To estimate the amount of this material resulting from the inward collapse of the crater walls we postulate the existence of a transient cavity stage during the formation of these caraters in which they were similar in form to the much smaller bowl-shaped craters. The original shape is reconstructed from the present shape by removing material from the center of the crater and building up the crater walls [*Settle* and *Head*, 1976; *Malin* and *Dzurisin*, 1977]. This procedure leads to estimates for the maximum thickness of this collapse material which is roughly 10% of the present crater rim diameter. This estimate is independent of the detailed shape of the transient cavity.

The maximum depth of brecciation is estimated from a survey of terrestrial impact structures to be roughly one-third the crater rim diameter [*Innes*, 1961; *Shoemaker*, 1960; *Dence et al.*, 1968]. Outward from this brecciated zone lies a region of cracked and fractured country rock. The extent of this region as revealed by anomalously low seismic velocities is roughly one crater diameter beyond the rim [*Ackerman et al.*, 1975]. This peripheral region does not contribute significantly to the gravity anomaly since an insufficient amount of void space is created at this distance from the point of impact.

The lateral extent of the anomalous low density region for the lunar craters can be roughly determined. We do this by testing two extreme cases. In one case, the low density material is confined within the crater *floor* diameter. In the other case the low density material is confined within the crater *rim* diameter. The floor diameter is ~60% of the rim diameter.

Four model calculations, including the effect of topography, for a single profile across the crater Langrenus are shown in Figure 1. The gravity data and the topographic contribution are also shown. A crustal density of 2.7 gm/cm^3 was used in evaluating the topographic contribution. The choice of this value is not critical in our analysis. In each calculation the low density material is represented by a paraboloid with the dimensions given in Figure 1. The geometry of each model with respect to the present crater shape is shown in Figure 2. Once the geometry of the anomalous mass has been specified, we solve for the density contrast required to reproduce the observed gravity signature including the effect of the surrounding topography.

The first two models shown in Figure 2 represent extreme cases of material collected by the inward collapse of the original crater wall. This material is confined to lie within the crater floor in the first model and to lie within the crater rim in the second. The postulated transient bowl-shaped stage is schematically shown in the first model. The third and fourth models represent the extreme cases of the combined effects of collapsed material and of an underlying brecciated

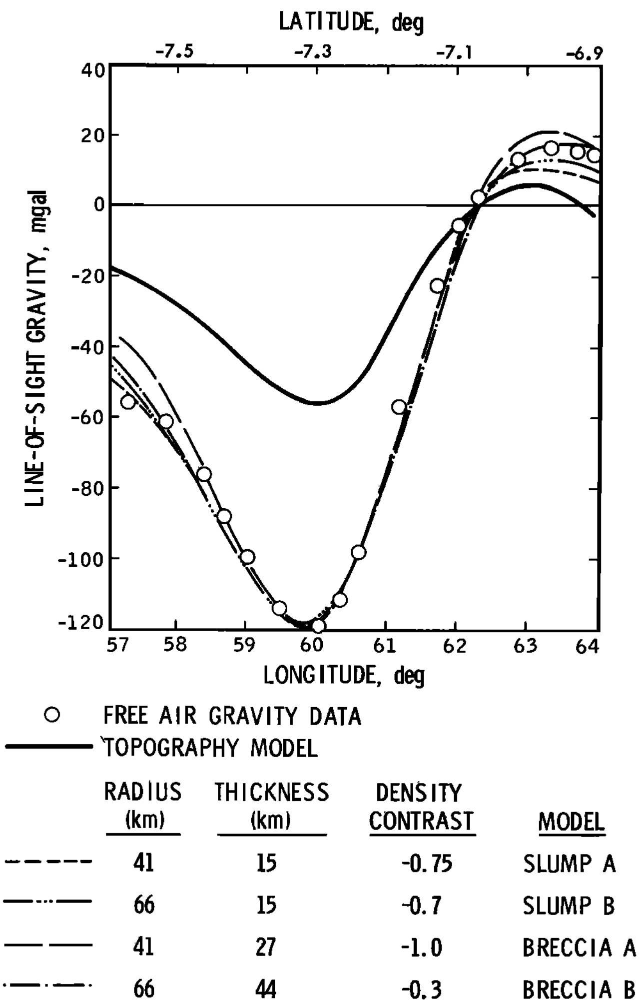

Fig. 1. Comparison of four model calculations described in the text with the observed gravity data for a single profile across the crater Langrenus. The sum of the gravity effects of the subsurface and topographic models are matched to the free air data

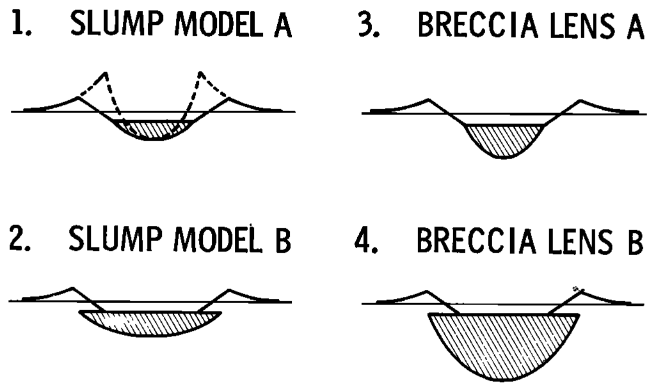

Fig. 2. Four proposed models for the mass deficiency associated with lunar craters. Dashed line outlines the postulated transient cavity geometry

region. In each case, the brecciated region extends to a depth of one-third its diameter. In the third model, the brecciated region is confined within the crater floor, which may correspond to the diameter of the transient bowl-shaped crater referred to earlier [e.g., *Malin* and *Dzurisin*, 1977]. The last model represents a brecciated region extending outward to the present crater rim.

There is no preferred model based on the degree of fit to the data. Our criterion for accepting or rejecting models relies on the value of the density contrast required to reproduce the observed gravity signature. An upper bound of -0.3 to -0.4 gm/cm^3 can be placed on acceptable values for the density contrast. This bound is based on the largest density contrasts determined for terrestrial impact craters [*Innes*, 1961] and on the density change measured for a lunar microbreccia subjected to a peak static pressure of 40 kilobars and then unloaded to zero confining pressure [*Stephens* and *Lilley*, 1970.]. In addition, larger values are deemed unacceptable, since for each proposed model the anomalous mass must extend at least a few tens of kilometers into the lunar crust. At these depths the confining pressures will begin to close the microcracks [e.g., *Todd et al.*, 1973] and, hence, reduce the porosity created by the impact.

Making use of this upper bound, only the last model listed in Figure 1 is acceptable. This model also represents the largest spatial extent of brecciation determined from studies of terrestrial impact features. If these two bounds are not to be violated, then there is *not* a major positive component to the observed gravity anomalies associated with these craters. The results of model calculations for all four lunar craters are shown in Table I. Also tabulated here are the mass deficiencies and the density contrasts reported for five terrestrial impact craters.

The values in Table I are displayed graphically in Figure 3. This is a log-log plot of the mass deficiency versus the present crater rim diameter and has not been corrected for the enlargement of craters larger than ~10 kilometers by large scale slumping. This correction may decrease the crater diameter up to 30 to 40%. This diagram is essentially model independent in that no assumptions have been made about the detailed density structure except to assume that the anomalous mass is a near surface feature.

Table I. Mass Deficiencies Associated with Impact Craters

	Diameter D_r (km)	Mass Deficiency ΔM (gm)	Density Contrast (gm/cm^3)	Source
Terrestrial Impact Craters				
Meteor Crater	1.2	-3×10^{13}	-0.12	*Regan* and *Hinze* [1975]
Holleford	2.3	-3×10^{14}	-0.23	*Innes* [1961]
Brent	3.5	-9×10^{14}	-0.17	*Innes* [1961]
Deep Bay	12	-2×10^{16}	-0.17	*Innes* [1961]
Ries Basin	22	-7×10^{16}	-0.2	*Dennis* [1971]
Lunar Impact Craters				
Eratosthenes	58	-8×10^{18}	-0.3	This study
Copernicus	92	-4×10^{19}	-0.4	This study
Theophilus	100	-5×10^{19}	-0.4	This study
Langrenus	132	-8×10^{19}	-0.3	This study

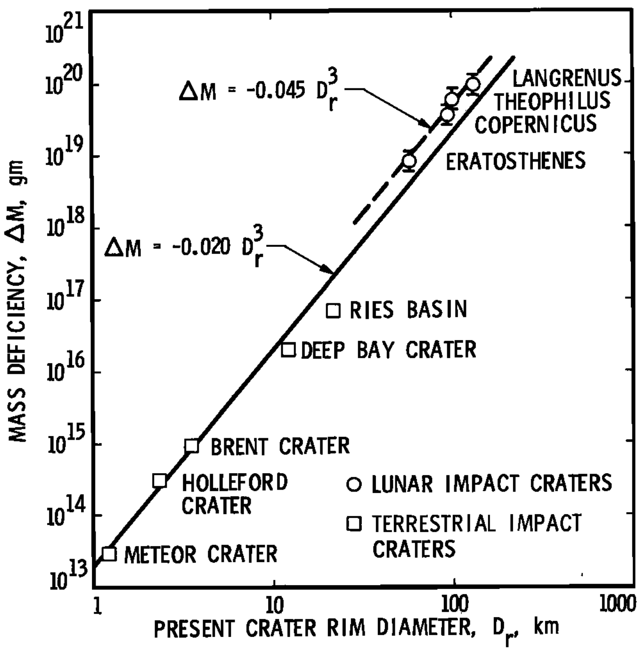

Fig. 3. The variation of the mass deficiency with the present crater rim diameter for lunar and terrestrial impact craters

Drawn in Figure 3 are lines relating the mass deficiency to the cube of the crater diameter. The four lunar craters closely follow this trend while this cubic relation establishes an upper bound for the partially eroded terrestrial impact craters. Note that all of the lunar craters fall above the line drawn through the terrestrial craters. If a single line is drawn through the terrestrial and lunar craters, then the mass deficiency would increase faster than the cube of the crater diameter. When a correction is made for the enlargement of these lunar craters by slumping, the discrepancy between the mass deficiencies for the lunar and terrestrial craters cannot be totally reconciled by simply accounting for low density material which has been eroded away from the more degraded terrestrial impact craters (e.g., rim deposits). This may indicate that the amount of brecciation is significantly larger for lunar craters than for terrestrial craters.

Discussion

Several aspects of lunar crustal history are implied by these results.

By our adpoted upper bounds on model geometry and density contrast, large scale volcanic or plutonic processes were not induced or triggered by these relatively youthful impact events, since, as mentioned earlier, such activity would have partially masked the negative component to the gravity anomaly. Similarly, magmatic material has not ascended through the crust in the vicinity of these craters since the time of their formation. This statement is not necessarily true for older lunar craters which, in some cases, have non-negative gravity anomalies associated with them [*Phillips et al.*, 1977].

On a more subtle level, the upper lunar crust must have undergone extensive reconsolidation or compaction since the last stage of heavy bombardment of the lunar surface. Our results indicate a significant density contrast presently existing between these young lunar craters discussed here and their surroundings. An interpretation of the lunar seismic data suggests that microcracks and fractures presently exist to a depth of 25 kilometers [*Simmons et al.*, 1973]. Together these two results imply that a process has acted on the upper lunar crust to remove the major part of the porosity generated by the last stage of heavy bombardment, but has not totally removed the fractures and cracks produced by this event. We propose four possible processes which may be responsible for this reconsolidation or compaction. They are shock lithification [*Short*, 1966], compaction by seismic shaking, hot pressing of material [*Simonds*, 1973], or reconsolidation by igneous processes. These first two processes are mechanical in nature and the latter two are the result of the thermal environment.

It is not the intent of this paper to evaluate these various possibilities. We do suggest that the compaction or reconsolidation process may be related to one of the major geologic events in lunar history, such as the formation of the multiringed basins or the emplacement of the mare basalts. Some light on this problem may be provided from our current analysis of the gravity anomalies associated with the older lunar craters.

Conclusions and Summary

A quantitative analysis of the gravity anomalies associated with four large young lunar craters is reported. Each of the lunar craters analyzed here has a very pronounced negative Bouguer anomaly associated with it. Model calculations based on generalizations made from studies of terrestrial impact structures suggest that the major contribution to the Bouguer anomaly for these lunar craters is due to a large lens of brecciated material confined within the crater rim and extending vertically to at least a depth of one-third the crater rim diameter. Uncertainty in the exact geometry of this zone leads to a depth range of one-half to one-fourth of the diameter. Independent of exact shape, model calculations also reveal for the lunar craters a systematic variation in the magnitude of the mass deficiency with the cube of the crater diameter.

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References

Ackerman, H.D., R.H. Godson and J S Watkins, A seismic refraction technique used for subsurface investigations at Meteor Crater, Arizona, *J Geophys Res*, *80*, 765-775, 1975.

Dence, M.R , M.J S. Innes, and P.B. Robertson, Recent geological and geophysical studies of Canadian craters, In *Shock Metamorphorism of Natural Materials*, B.M French and N.M. Short (eds.), 339-362, 1968.

Dennis, J.G., Ries structure, Southern Germany, A review, *J Geophys Res.*, *76*, 5394-5406, 1971.

Gottlieb, P , P.M. Muller, W.L. Sjogren, and W R. Wollenhaupt, Lunar gravity over large craters from Apollo 12 tracking data, *Science*, *168*, 477-479, 1970.

Innes, M J S , The use of gravity methods to study the underground structure and impact energy of meteorite craters, *J. Geophys. Res.*, *66*, 2225-2239, 1961.

Malin, M. and D. Dzurisin, Modification of fresh crater landforms Evidence from the Moon and Mercury, in revision for *J. Geophys Res.*, 1977.

Phillips, R.J., E.A Abbott, W L. Sjogren, and S.H. Zisk, Simulation gravity modeling to spacecraft tracking data. Analysis and application to lunar crater anomalies, submitted to *J. Geophys. Res.*, 1977.

Regan, R.D. and W.J. Hinze, Gravity and magnetic investigations of Meteor Crater, Arizona, *J Geophys. Res.*, *80*, 776-788, 1975

Settle M. and J.W Head, The role of rim slumping in the modification of lunar crater morphometry, in *Lunar Science VII*, The Lunar Science Institute, Houston, 794-796, 1976.

Shoemaker, E.M , Penetration mechanics of high velocity meteorites, Illustrated by Meteor Crater, Arizona, Int'l Geol. Cong., XXI Session. *Structure of the Earth's Crust and Deformation of Rocks*, 418-434, 1960.

Short, N M , Shock lithification of unconsolidated rock materials, *Science*, *154*, 382-384, 1966.

Simmons, G , T Todd and H. Wang, the 25-km discontinuity Implications for lunar history, *Science*, *182*, 158-161, 1973.

Simonds, C.H., Sintering and hot pressing of Fra Mauro composition glass and the lithification of the lunar breccias, *Am J. Sci*, *273*, 428-439, 1973.

Sjogren, W.L., P Gottlieb, P.M. Muller and W R. Wollenhaupt, S-Band transponder experiment, in *Apollo 15 Preliminary Science Report*, NASA SP-289, 20-1 to 20-6, 1972.

Stephens, D.R. and E.M. Lilley, Loading-unloading, pressure-volume curves to 40 kilobars for lunar crystalline rock, microbreccia, and fines, *Proc Apollo 11 Lunar Science Conf.*, *Geochimica et Cosmochimica Acta*, Suppl 1, *3*, 2427-2434, 1970.

Todd, T., H. Wang, D. Richter and G. Simmons, Unique Characterization of Lunar Samples by Physical Properties, in *Lunar Science IV*, The Lunar Science Institute, Houston, 731-733, 1973.

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