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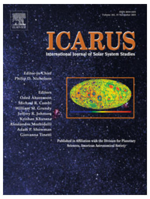

Observational constraints on the identification of shallow lunar magmatism: Insights from floor-fractured craters

L.M. Jozwiak[a,*], J.W. Head III[a], G.A. Neumann[b], L. Wilson[c]

[a] Dept. Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, United States
[b] Solar System Exploration Div., NASA Goddard Space Flight Center, Greenbelt, MD 20768, United States
[c] Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK

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ABSTRACT

Floor-fractured craters are a class of lunar crater hypothesized to form in response to the emplacement of a shallow magmatic intrusion beneath the crater floor. The emplacement of a shallow magmatic body should result in a positive Bouguer anomaly relative to unaltered complex craters, a signal which is observed for the average Bouguer anomaly interior to the crater walls. We observe the Bouguer anomaly of floor-fractured craters on an individual basis using the unfiltered Bouguer gravity solution from GRAIL and also a degree 100–600 band-filtered Bouguer gravity solution. The low-magnitude of anomalies arising from shallow magmatic intrusions makes identification using unfiltered Bouguer gravity solutions inconclusive. The observed anomalies in the degree 100–600 Bouguer gravity solution are spatially heterogeneous, although there is spatial correlation between volcanic surface morphologies and positive Bouguer anomalies. We interpret these observations to mean that the spatial heterogeneity observed in the Bouguer signal is the result of variable degrees of magmatic degassing within the intrusions.

1. Introduction

Floor-fractured craters (FFCs) are a small subset of lunar craters with anomalously shallow, fractured floors (Schultz, 1976; Jozwiak et al., 2012). FFCs range in diameter from ~10 to 200 km and frequently exhibit volcanic morphologies within the crater interior (vents, pyroclastic deposits, deposits of mare material). FFCs exhibit non-axisymmetric floor uplifts that are associated with a wide range of floor morphologies (Jozwiak et al., 2012); smaller FFCs typically exhibit more domed floors, while larger FFCs generally exhibit flatter floors. These two floor morphologies represent end-member cases with all crater floor morphologies existing on a continuum between these end-members (Jozwiak et al., 2012). FFCs are morphologically interpreted to be formed by the intrusion of a magmatic body beneath the crater floor (e.g. Schultz, 1976) formed by the propagation of a dike from depth that then stalls in the underdense brecciated region beneath the crater, and then spreads laterally to form a sill (Maccaferri et al., 2011; Jozwiak et al., 2015a). This hypothesis is supported by morphologic and morphometric observations of the craters (Jozwiak et al., 2012; 2015a) made using LROC-WAC (Lunar Reconnaissance Orbiter Camera—Wide Angle Camera) (Robinson et al., 2010) images and LOLA (Lunar Orbiter Laser Altimeter) topographic data (Smith et al., 2010). Key morphologic observations supporting the magmatic intrusion hypothesis include: volcanic morphologies within the craters (vents, pyroclastic deposits, deposits of mare material) and non-axisymmetric floor uplift (Jozwiak et al., 2012). Two key morphometric parameters supporting the magmatic intrusion hypothesis are the wide range of crater diameters affected by the process (~10–200 km), and the preservation of short wavelength topography (i.e. crater rim crest heights) despite the significant relaxation of long wavelength topography (i.e. depth of the crater floor) (Jozwiak et al., 2012). Recent implicit finite-volume modeling supports the hypothesis that FFCs are formed by the intrusion of a volcanic body beneath a pinned elastic sheet (the overlying crust) (Thorey and Michaut, 2014).

It has long been proposed that the use of sufficiently high resolution gravity data could aid in understanding the mechanism by which floor-fractured craters form (Schultz, 1976), as well as in the identification of subsurface magmatic bodies that do not produce identifiable surface morphologies. Thus far, the identification of FFCs has always relied on surface morphologic evidence due to the low spatial resolution of available gravity data. The GRAIL (Gravity Recovery and Interior Laboratory) (Zuber et al., 2013) mission provides, for the first time, gravity field data of sufficient spatial resolution to investigate the gravity anomaly properties associated with FFCs.

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[*] Corresponding author. Tel.: +1 6303191615.
E-mail address: lauren_jozwiak@brown.edu (L.M. Jozwiak).

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Current analyses using the GRAIL data have focused on statistical assessments of Bouguer gravity anomalies associated with lunar impact craters. The Bouguer gravity anomaly is derived from the free-air gravity anomaly, but includes a correction for the gravitational signature of topography; thus, the resulting solution emphasizes density variations within the body. Soderblom et al., (2015) and Thorey et al., (2015) used the residual Bouguer anomaly for craters, which is computed by subtracting the average of the Bouguer anomaly from the floor of the crater from the average Bouguer anomaly from an annulus outside the crater, yielding the Bouguer anomaly relative to the surrounding region. Soderblom et al., (2015) examined the Bouguer gravity signatures of ~1200 complex highland craters and observed that the residual Bouguer anomalies of these craters are generally negative, but that the magnitude scales with crater diameter such that larger craters have more negative Bouguer anomalies. The data show that the range of Bouguer anomalies is ∼ ± 30 mGal (Soderblom et al., 2015). Thorey et al. (2015) performed a statistical analysis of Bouguer anomalies of FFCs compared with nearby complex craters. They determined that on average, FFCs have a more positive crater floor Bouguer anomaly than complex craters.

These statistical analyses support the hypothesis that there exist high density intrusions beneath floor-fractured craters, resulting in positive Bouguer anomalies. Thus far, the identification of floor-fractured craters and other shallow intrusive magmatic features (e.g. dikes) has been confined to places where they produce identifiable surface morphologies. The use of high-resolution gravity data could provide a new tool for the identification of shallow magmatic bodies on the Moon both in regions of suspected magmatic activity (e.g. beneath floor-fractured craters and graben), and also in regions where no surface expression was observed. Previous studies (Thorey et al., 2015) have shown that positive Bouguer anomalies can be associated with floor-fractured craters when the group is statistically analyzed in aggregate. We seek to address whether Bouguer anomalies can be used as analytic tools on individual targets. To this end, we begin by assessing several Bouguer anomaly gravity products for regions of known subsurface magmatic processes (i.e. floor-fractured craters) to determine the utility of gravity data in identifying small, shallow magmatic bodies on the Moon. We then explore how the observed correlations between the Bouguer gravity data and the observed morphologies inform our understanding of the floor-fractured crater intrusion formation process. Finally, we seek to address if Bouguer gravity data can be used in the identification of previously unrecognized shallow magmatic bodies on the Moon.

2. Predictions of FFC gravity signal

The impact cratering process is generally assumed to produce a negative Bouguer anomaly within the crater, as a consequence of the intense fracturing and brecciation that occurs as a result of the impact-induced shock waves (e.g.Phillips et al., 1978) This negative Bouguer anomaly has been observed in both terrestrial (e.g. Pilkington and Grieve, 1992) and young lunar craters (Dvorak and Phillips, 1977). Recent studies using GRAIL data support the observation that the residual Bouguer anomaly in the crater generally exhibits increasingly negative values with increasing crater diameter (Soderblom, et al., 2015), submitted. Results from the GRAIL mission suggest that the lunar crust has a density of 2560 kg/m^3 with an average porosity of 12% (Wieczorek et al., 2013). Measurements of lunar basalt from Apollo samples, place the density of lunar basalts at 2900–3200 kg/m^3 depending on the TiO$_2$ content (Kiefer et al., 2012). Thus, a crustal magmatic intrusion (like that proposed to be present below FFCs) composed of basaltic material is significantly denser than the average lunar crustal density, and is therefore predicted to produce a large positive Bouguer anomaly.

Table 1
Intrusion dimensions and maximum predicted Bouguer anomaly.

Crater name	Diameter [km]	d [m]	d_t [m]	w_m [m]	BA [mGal]
Humboldt	207	3200	5200	2000	36
Alphonsus	119	3500	4400	900	16
Vitello	44	2500	3200	700	13

Before investigating the observed Bouguer anomaly of FFCs, we first model the predicted maximum anomaly using a simple Bouguer plate model for the archetypal FFCs Humboldt, Alphonsus, and Vitello. The model consists of a crater and surrounding subsurface environment with standard lunar crustal density, $\rho_c = 2560\,\mathrm{kg/m^3}$, and a magmatic sill beneath the floor of the crater composed of lunar basalt, $\rho_m = 3000\,\mathrm{kg/m^3}$. We assume that the degree of floor uplift represents the thickness of the intrusion, w_m (e.g., Jozwiak et al., 2012), and so we estimate w_m by subtracting the observed crater depth, d, from the theoretical crater depth, d_t. We find d by measuring the elevation difference between the average rim-crest height and floor elevation with LOLA data, and d_t is estimated from the fresh-crater depth-diameter relationships found by Pike (1980).

Using the simplifying assumptions of the Bouguer plate model, the maximum predicted BA is given by Eq. (1),

$$BA = 2\pi\,(\rho_m - \rho_c)Gw_m, \tag{1}$$

where G is the gravitational constant. The results of this analysis for the craters Humboldt, Alphonsus, and Vitello are given in Table 1, and represent the maximum possible BA for each of these craters before subsequent band-filtering of the data. As expected, the BA is highly dependent on intrusion thickness, and is predicted to be in the range of tens to a few tens of mGal for w_m values between a few hundred meters and a few kilometers, consistent with the values generated by Thorey et al. (2015) from synthetic FFC geometries. The magnitude of the BA predicted to be present at FFCs is thus well within the resolution of the GRAIL instrument (0.001 mGal) (Zuber et al., 2013).

3. Observations of FFC Bouguer anomalies

We conducted a survey of observed BA within FFCs using the (Jozwiak et al. 2012) global catalog of FFCs ($N = 170$) and the GRGM900c Bouguer gravity solution (Lemoine et al., 2014) in the ArcGIS system. The resolution of the 900c model is ~6 km^2 (Lemoine et al., 2014), although due to the dominance of noise in the highest order terms, the data are limited to degree 600 which has a block size of ∼ 9 km^2. The data were not filtered in any way beyond this, and the color stretch was applied to the entire range of lunar data, ~+600 mGal—~–300 mGal. As a result of the model resolution, FFCs with diameter < 20 km were excluded from this analysis, as the floor region is oftentimes at or below the model solution resolution. This diameter restriction brings the number of observed craters to 122, 72% of the original catalog (Jozwiak et al., 2012). The observations fell into three broad categories: 1) mascon dominated, 2) positive signal, 3) null signal; the frequency distribution of the data are shown in Fig. 1. Many FFCs are located inside, or along the edges of large impact basins, consequently the Bouguer anomaly of the crater is completely overwhelmed by the gravity signal of the basin, these are termed “mascon dominated”, and account for 33% (40 craters) of the craters observed. The designation “positive signal” is used to identify craters that possess a positive central Bouguer anomaly, broadly correlated with the crater floor region, and account for 52% (64 craters) of the observed craters. The final category is “null signal” which denotes craters where the Bouguer anomaly is indistinguishable from the regional Bouguer anomaly. The threshold for distinction between

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