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Observational Constraints on the Identification of Shallow Lunar Magmatism: Insights from
Floor-fractured Craters

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28 Abstract:

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

42 Keywords: Moon, Geophysics, Volcanism

43 I. Introduction:

44 Floor-fractured craters (FFCs) are a small subset of lunar craters with anomalously
45 shallow, fractured floors [Schultz, 1976; Jozwiak et al., 2012]. FFCs range in diameter from ~10-
46 200 km and frequently exhibit volcanic morphologies within the crater interior (vents,
47 pyroclastic deposits, deposits of mare material). FFCs exhibit non-axisymmetric floor uplifts that
48 are associated with a wide range of floor morphologies [Jozwiak et al., 2012]; smaller FFCs
49 typically exhibit more domed floors, while larger FFCs generally exhibit flatter floors. These two
50 floor morphologies represent end-member cases with all crater floor morphologies existing on a
51 continuum between these end-members [Jozwiak et al., 2012]. FFCs are morphologically
52 interpreted to be formed by the intrusion of a magmatic body beneath the crater floor [e.g.
53 Schultz, 1976] formed by the propagation of a dike from depth that then stalls in the underdense
54 brecciated region beneath the crater, and then spreads laterally to form a sill [Maccaferri et al.,
55 2011; Jozwiak et al., 2015]. This hypothesis that is supported by morphologic and morphometric
56 observations of the craters [Jozwiak et al., 2012; 2015a] made using LROC-WAC (Lunar
57 Reconnaissance Orbiter Camera- Wide Angle Camera) [Robinson et al., 2010] images and
58 LOLA (Lunar Orbiter Laser Altimeter) topographic data [Smith et al., 2010]. Key morphologic
59 observations supporting the magmatic intrusion hypothesis include: volcanic morphologies
60 within the craters (vents, pyroclastic deposits, deposits of mare material) and non-axisymmetric
61 floor uplift [Jozwiak et al., 2012]. Key morphometric parameters supporting the magmatic
62 intrusion hypothesis include the wide range of crater diameters the process affects (~10-200 km),
63 and the preservation of short wavelength topography (i.e. crater rim crest heights) despite the
64 significant relaxation of long wavelength topography (i.e. depth of the crater floor) [Jozwiak et
65 al., 2012]. Recent implicit finite-volume modeling supports the hypothesis that FFCs are formed

66 by the intrusion of a volcanic body beneath a pinned elastic sheet (the overlying crust) [Thorey
67 and Michaut, 2014].

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

76 Current analyses using the GRAIL data have focused on statistical assessments of
77 Bouguer gravity anomalies associated with lunar impact craters. The Bouguer gravity anomaly is
78 derived from the free-air gravity anomaly, but includes a correction for the gravitational
79 signature of topography; thus, the resulting solution emphasizes density variations within the
80 body. Soderblom et al. [2015] and Thorey et al. [2015] used the residual Bouguer anomaly for
81 craters, which is computed by subtracting the average of the Bouguer anomaly from the floor of
82 the crater from the average Bouguer anomaly from an annulus outside the crater, yielding the
83 Bouguer anomaly relative to the surrounding region. Soderblom et al. [2015] examined the
84 Bouguer gravity signatures of ~1200 complex highland craters and observed that the residual
85 Bouguer anomalies of these craters are generally negative, but that the magnitude scales with
86 crater diameter such that larger craters have more negative Bouguer anomalies. The data show
87 that the range of Bouguer anomalies is $\sim \pm 30$ mGal [Soderblom et al., 2015]. Thorey et al.,
88 [2015] performed a statistical analysis of Bouguer anomalies of FFCs compared with nearby
89 complex craters. They determined that on average, FFCs have a more positive crater floor
90 Bouguer anomaly than complex craters.

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

105 understanding of the floor-fractured crater intrusion formation process. Finally, we seek to
 106 address if Bouguer gravity data can be used in the identification of previously unrecognized
 107 shallow magmatic bodies on the Moon.

108 II. Predictions of FFC Gravity Signal:

109 The impact cratering process is generally assumed to produce a negative Bouguer
 110 anomaly within the crater, as a consequence of the intense fracturing and brecciation that occurs
 111 as a result of the impact-induced shock waves [e.g. Phillips et al., 1978]. This negative Bouguer
 112 anomaly has been observed in both terrestrial [e.g. Pilkington and Grieve, 1992] and young lunar
 113 craters [Dvorak and Phillips, 1977]. Recent studies using GRAIL data support the observation
 114 that the residual Bouguer anomaly in the crater generally exhibits increasingly negative values
 115 with increasing crater diameter [Soderblom, et al., 2015, submitted]. Results from the GRAIL
 116 mission suggest that the lunar crust has a density of 2560 kg/m^3 with an average porosity of 12%
 117 [Wieczorek et al., 2013]. Measurements of lunar basalt from Apollo samples, place the density of
 118 lunar basalts at $2900\text{-}3200 \text{ kg/m}^3$ depending on the TiO_2 content [Kiefer et al., 2012]. Thus, a
 119 crustal magmatic intrusion (like that proposed to be present below FFCs) composed of basaltic
 120 material is significantly denser than the average lunar crustal density, and is therefore predicted
 121 to produce a large positive Bouguer anomaly.

122 Before investigating the observed Bouguer anomaly of FFCs, we first model the
 123 predicted maximum anomaly using a simple Bouguer plate model for the archetypal FFCs
 124 Humboldt, Alphonsus, and Vitello. The model consists of a crater and surrounding subsurface
 125 environment with standard lunar crustal density, $\rho_c=2560 \text{ kg/m}^3$, and a magmatic sill beneath the
 126 floor of the crater composed of lunar basalt, $\rho_m=3000 \text{ kg/m}^3$. We assume that the degree of floor
 127 uplift represents the thickness of the intrusion, w_m [e.g., Jozwiak et al., 2012], and so we estimate
 128 w_m by subtracting the observed crater depth, d , from the theoretical crater depth, d_t . We find d by
 129 measuring the elevation difference between the average rim-crest height and floor elevation with
 130 LOLA data, and d_t is estimated from the fresh-crater depth-diameter relationships found by Pike
 131 [1980].

132 Using the simplifying assumptions of the Bouguer plate model, the maximum predicted
 133 BA is given by eq. 1,

$$134 \quad BA = 2\pi(\rho_m - \rho_c)Gw_m, \quad (1)$$

135 where G is the gravitational constant. The results of this analysis for the crater Humboldt,
 136 Alphonsus, and Vitello are given in Table 1, and represent the maximum possible BA for each of
 137 these craters before subsequent band-filtering of the data. As expected, the BA is highly
 138 dependent on intrusion thickness, and is predicted to be in the range of tens to a few tens of mGal
 139 for w_m values between a few hundred meters and a few kilometers, consistent with the values
 140 generated by Thorey et al. [2015] from synthetic FFC geometries. The magnitude of the BA

141 predicted to be present at FFCs is thus well within the resolution of the GRAIL instrument
 142 (0.001 mGal) [Zuber et al., 2013].

143 Table 1:

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

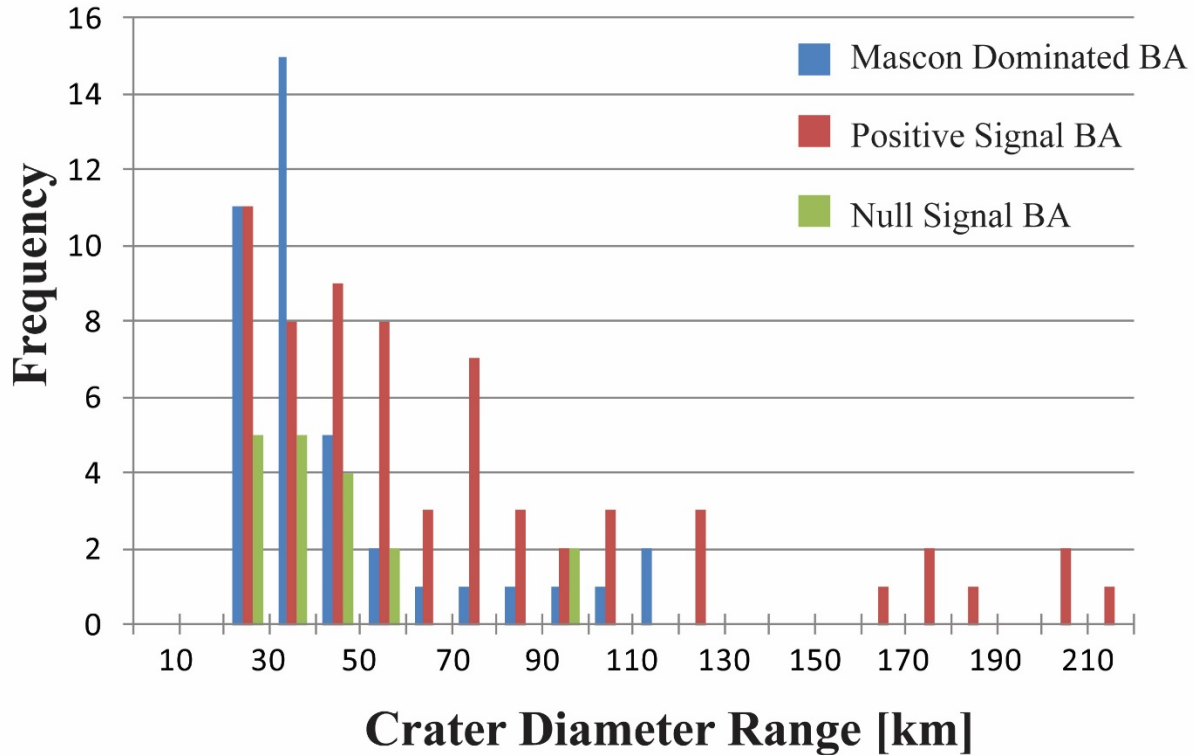
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145 III. Observations of FFC Bouguer Anomalies:

146 We conducted a survey of observed BA within FFCs using the Jozwiak et al. (2012)
 147 global catalog of FFCs (N = 170) and the GRGM900c Bouguer gravity solution [Lemoine et al.,
 148 2014] in the ArcGIS system. The resolution of the 900c model is $\sim 6 \text{ km}^2$ [Lemoine et al., 2014],
 149 although due to the dominance of noise in the highest order terms, the data are limited to degree
 150 600 which has a block size of $\sim 9 \text{ km}^2$. The data were not filtered in any way beyond this, and
 151 the color stretch was applied to the entire range of lunar data, $\sim +600 \text{ mGal} - \sim -300 \text{ mGal}$. As a
 152 result of the model resolution, FFCs with diameter $< 20 \text{ km}$ were excluded from this analysis, as
 153 the floor region is oftentimes at or below the model solution resolution. This diameter restriction
 154 brings the number of observed craters to 122, 72% of the original catalog [Jozwiak et al., 2012].
 155 The observations fell into three broad categories: 1) mascon dominated, 2) positive signal, 3)
 156 null signal; the frequency distribution of the data are shown in Figure 1. Many FFCs are located
 157 inside, or along the edges of large impact basins, consequently the Bouguer anomaly of the crater
 158 is completely overwhelmed by the gravity signal of the basin, these are termed “mascon
 159 dominated”, and account for 33% (40 craters) of the craters observed. The designation “positive
 160 signal” is used to identify craters that possess a positive central Bouguer anomaly, broadly
 161 correlated with the crater floor region, and account for 52% (64 craters) of the observed craters.
 162 The final category is “null signal” which denotes craters where the Bouguer anomaly is
 163 indistinguishable from the regional Bouguer anomaly. The threshold for distinction between
 164 “positive signal” and “null signal” is $\pm 5 \text{ mGal}$, which is a function of the global data color
 165 stretch, and represents distinct, discrete color values in the stretched dataset. The “null signal”
 166 designation is found predominately in smaller craters, $D < 50 \text{ km}$, and accounts for 16% (18
 167 craters) of the observed population. It is important to note that these categories are observational
 168 in nature and do not represent a statistical assessment of the magnitude of BA found in these
 169 FFCs; we direct readers seeking such a treatment to Thorey et al. [2015].

170 The results of this analysis suggest that there is some indication in the standardly released
 171 Bouguer gravity field for an association of positive Bouguer anomalies with floor-fractured
 172 craters, as would be predicted. Despite this, the assessment technique is non-ideal for
 173 conclusively identifying a link between Bouguer anomalies and shallow magmatic bodies on the

174 Moon. The two largest complications to analysis are 1) the inclusion of low-degree, high-
 175 magnitude terms in the gravity solution (e.g. mascons) which overpower the smaller signal of
 176 shallow magmatic intrusions, and 2) the coarse resolution and averaging over features of interest
 177 smaller than several 10s km². Consequently, we turn to more advanced data filtering techniques
 178 to better isolate the gravity contributions of small, shallow magmatic bodies.



179

180 Figure 1: Qualitative, observational assessment of floor-fractured crater Bouguer anomaly for all floor-fractured
 181 craters with $D > 20$ km. Analysis yielded three categories of observed Bouguer anomaly: (1) mascon dominated, (2)
 182 positive signal, (3) null signal. (1) Mascon dominated signals were observed in craters located at the edges or
 183 interiors of basins, and are consequently characterized by the overwhelming basin Mascon gravity signature. (2)
 184 Positive signal denotes craters which possessed a positive Bouguer anomaly in the floor region, which was observed
 185 to be qualitatively higher than the regional Bouguer anomaly. (3) Null signal denotes craters with no inherent,
 186 identifiable Bouguer anomaly that is distinct from the regional Bouguer anomaly. Floor-fractured craters taken from
 187 Jozwiak et al., [2012]. Gravity data are the GRGM900c Bouguer gravity solution for the GRAIL data.

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189 IV. Band-filtered Bouguer Anomaly:

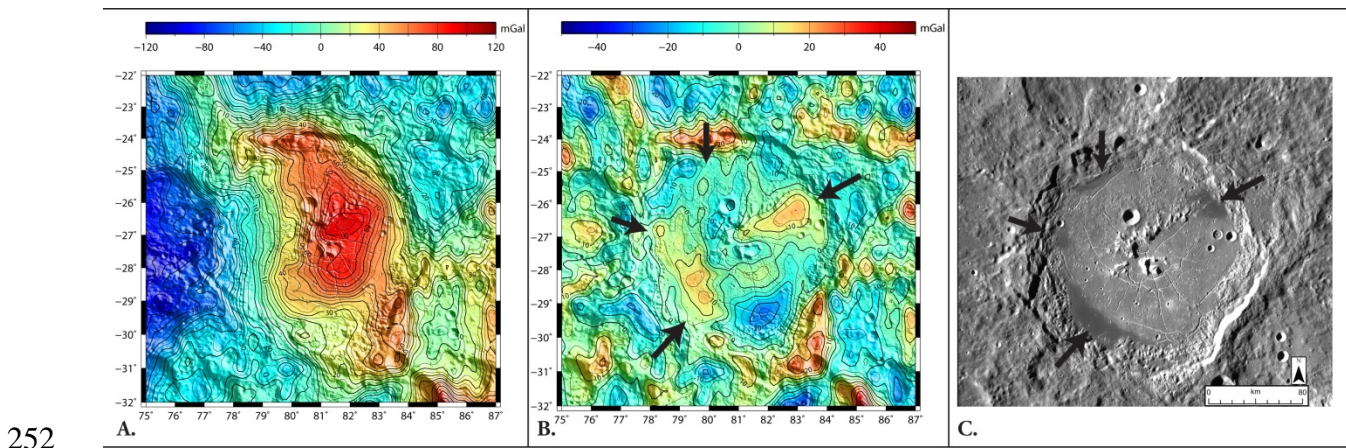
190 The previous analysis with the GRGM900c Bouguer contains the spherical harmonic
 191 solutions for all degrees through degree 900. Gravity fields are dominated by low-degree
 192 contributions associated with long-wavelength perturbations to the gravity field and by
 193 perturbations to surfaces of density discontinuities (e.g. core-mantle boundary and the Moho)
 194 [Wahr, 1996]. This is also true of the Moon where below degree 80, most of the gravitational

195 signal is not attributable to topography, but rather to long-wavelength interior variations [Zuber
 196 et al., 2013]. Smaller-scale density variations, such as those associated with FFC intrusions, are
 197 only resolvable using the higher-order spherical harmonic solutions. Using the HigenX program,
 198 we band-filter the GRGM900c Bouguer spherical harmonic solution to degree 6-600 and also
 199 degree 100-600 solutions (Figure 2) to better emphasize the density anomalies within the crust.
 200 For both solutions, the upper limit of degree 600 was selected because it represents the highest
 201 degree solution with strong correlation and RMS power [Lemoine et al., 2014]. We selected a
 202 lower degree limit of degree 6 to remove spherical harmonic contributions from lunar oblateness
 203 and deviations in the center of mass, but retain most contributions to the gravity field from
 204 density disturbances in the crust and mantle. For the second model solution, a lower limit of
 205 degree 100 was selected to preferentially exclude gravity disturbances originating in the mantle,
 206 and thus focus on gravity disturbances in the crust. The degree 100-600 solution has a block size
 207 of ~ 9 km, and filtering the anomalies below degree 100 attenuates disturbances deeper than 34
 208 km by a factor of 7.4 or more. Thus we assume that gravity anomalies in the degree 100-600
 209 solution arise exclusively from density variations within the lunar crust, although mantle plug
 210 contributions could still be present in very large craters located in regions of thin crust (e.g.,
 211 Oppenheimer). These density variations could be the result of compositional variation (e.g.
 212 basalt instead of anorthosite), or the result of variations in porosity. Because of the retention of
 213 high-magnitude low-degree mantle contributions, the degree 6-600 solution has difficulty
 214 showing low-magnitude, high-order features. This can be seen in a comparison of the dynamic
 215 range displayed in the degree 6-600 solution (Fig. 2a) as compared to the degree 100-600
 216 solution (Fig. 2b). The constrained scale of the degree 100-600 solution allows us to focus on
 217 gravity disturbances with magnitude variations of < 5 mGal, which are muted to the point of
 218 invisibility in the degree 6-600 solution.

219 In Figure 2 we compare the solutions for the degree 6-600 solution (Fig. 2a) and degree
 220 100-600 solution (Fig. 2b) for the crater Humboldt (27.2°S , 80.9°E), $D = 207$ km (Fig. 2c). The
 221 degree 6-600 solution has much higher magnitude gravity disturbances, including a broad 100
 222 mGal gravity anomaly dominating a large portion of the crater floor region. This is consistent
 223 with the gravitational signature of an uplifted mantle plug, a signature which is observed in
 224 craters with $D > 218 \pm 17$ km [Soderblom et al., 2015]. In the degree 100-600 solution the broad
 225 positive anomaly we associated with the uplifted mantle plug is no longer observed. Instead,
 226 numerous lower magnitude gravity disturbances emerge and appear heterogeneously distributed
 227 throughout the crust in the field of view. The low-magnitude nature of these anomalies is
 228 problematic when observed in the degree 6-600 solution because the magnitudes of the low-
 229 degree anomalies are significantly larger and overwhelm the intrusive volcanic signal. In section
 230 II we calculated theoretical maximum magnitudes for the BAs associated with FFC intrusions,
 231 and all of these magnitudes are an order of magnitude smaller than the typical BA displayed by
 232 low-degree mantle features like mascons. Thus, although the degree 6-600 band-filtered solution
 233 eliminates some of the noise from the GRGM900c Bouguer model, it does not prove useful in
 234 the identification of small-scale magmatic anomalies. For this reason, we now focus on the

235 results of the degree 100-600 band-filtered solution, which greatly attenuates the low-degree,
 236 high-magnitude contributions to the gravity field.

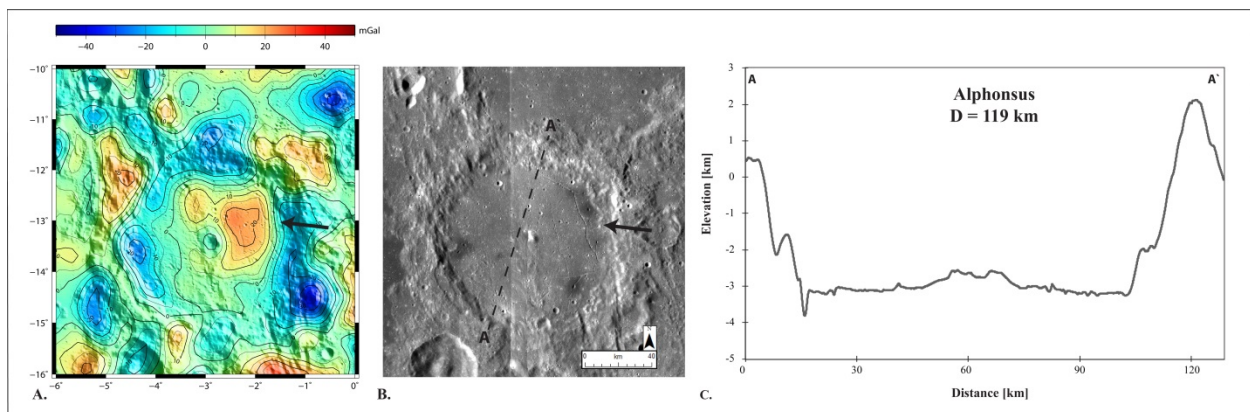
237 Within the crater Humboldt, there emerge two regions of positive gravity anomalies with
 238 magnitudes of ~ 15 mGal . These regions are broadly correlated with the surface locations of 3 of
 239 the observed mare deposits on the floor of Humboldt crater. The mare deposits are indicated by
 240 black arrows in both the degree 100-600 solution (Fig. 2b) and the LROC-WAC image of
 241 Humboldt crater (Fig. 2c). None of these surficial volcanic deposits would be expected to
 242 produce a gravity anomaly of the observed magnitude because of their limited thickness ($<$ few
 243 hundred meters). We suggest this correlation of positive gravity anomaly regions with regions
 244 hosting volcanic morphologies could be indicative of the subcrater magmatic body which
 245 produced the surface volcanic deposits. We note, however, that numerous Bouguer anomalies of
 246 comparable magnitude are present (outside of the crater) which are not associated with surface
 247 volcanic features. The provenance of these exterior anomalies cannot be explained by
 248 associations with any unique surface morphologies We instead focus our attention on Bouguer
 249 anomalies arising in the crater floor region, because for these anomalies we have a hypothesis for
 250 the main contribution to the Bouguer anomalies—the density changes associated with the sub-
 251 crater shallow magmatic intrusion.



253 Figure 2: A comparison of band-filtered Bouguer gravity solutions for the crater Humboldt ($D = 207$ km) (27.2°S ,
 254 80.9°E). **A**) The band-filtered Bouguer solution from degrees 6-600 reveals a broad, high positive anomaly slightly
 255 offset from the center of the crater. Due to the large diameter of Humboldt, some portion of this anomaly is
 256 attributable to mantle uplift processes [Soderblom et al., 2015]. **B**) The band-filtered Bouguer solution from degrees
 257 100-600 represents almost exclusively crustal density variations. The surface volcanic deposits on the floor of
 258 Humboldt have been marked with black arrows. The large anomaly observed in **A**. has been removed by the
 259 filtering; instead, three smaller provinces of positive Bouguer anomaly emerge. These three regions are spatially
 260 correlated with surface volcanic morphologies in Humboldt. **C**) LROC-WAC image of Humboldt crater with the
 261 surface volcanic deposits indicated by black arrows, as in **B**. The band-filtered Bouguer solutions were generated
 262 from the GRGM900c Bouguer solution to GRAIL data.

263 We extend our band-filtering analysis to all FFCs with $D > \sim 100$ km, including the
 264 craters Oppenheimer, Humboldt, Janssen, Gauss, Petavius, Compton, Cleomedes, Nernst,

265 Alphonsus, Gassendi, Repsold, Posidonius, and Schlüter. We focused our analysis on larger
 266 craters ($D > 100$ km) so as to maximize the spatial block resolution over the crater floor region.
 267 In the regions outside of the craters, we observed a persistently heterogeneous signal in the
 268 degree 100-600 filtered Bouguer solution. Inside of the craters, we also observed heterogeneities
 269 in the gravity disturbances. However, much like our observations at Humboldt, the regions of
 270 positive gravity disturbances on the crater floor appear to be spatially correlated with either
 271 surficial volcanic morphologies (i.e. mare deposits and pyroclastic deposits) or heavily fractured
 272 floor regions. The crater Alphonsus demonstrates some degree of spatial correlation between
 273 regions with positive Bouguer anomalies on the crater floor and surficial volcanic morphologies
 274 (Fig. 3). Alphonsus hosts several well-defined fractures and pyroclastic deposits in the eastern
 275 half of the crater floor, with a large portion of the pyroclastic deposits located in the northeast
 276 portion of the crater floor. This region is spatially correlated with a large positive Bouguer
 277 anomaly located in the eastern half of the crater, and concentrated in the northeastern part of the
 278 crater floor (arrows in Fig. 3). Despite the correlations in the northeast portion of the crater floor,
 279 the pyroclastic deposit located in the southeastern portion of the crater floor correlates to a region
 280 of approximately 0 mGal BA, and the pyroclastic deposits in the western portion of the crater
 281 floor are adjacent to a regional BA low.

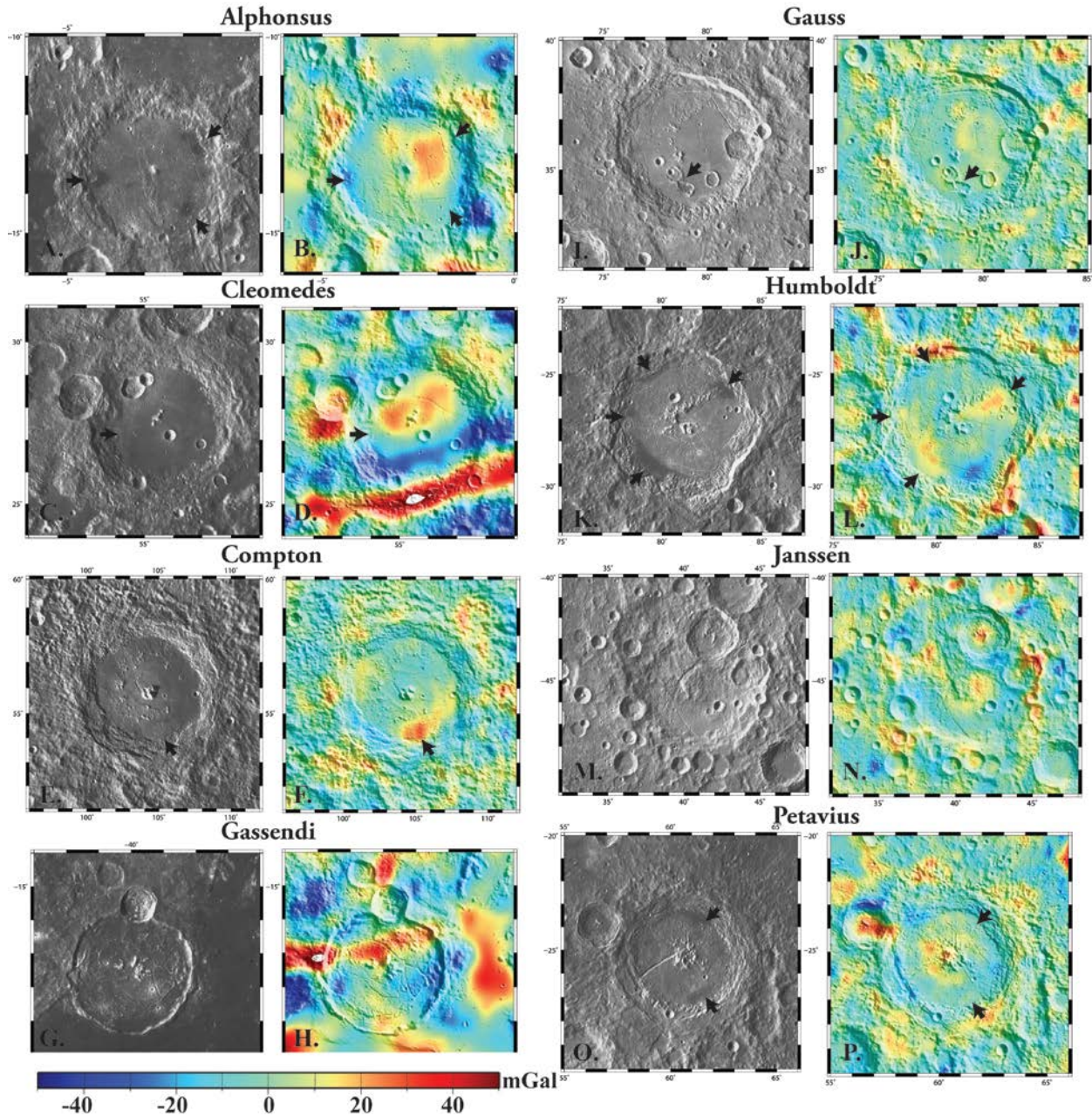


282
 283 Figure 3: The crater Alphonsus ($D = 119$ km) (13.4°S , 2.8°W) **A**) degree 100-600 band-filtered Bouguer anomaly
 284 reveals a broad positive Bouguer anomaly within the crater floor, and a concentrated region of higher Bouguer
 285 anomaly in the northeast quadrant of the crater, indicated by the black arrow. This anomaly corresponds spatially
 286 with a region of numerous fractures and pyroclastic deposits on the crater floor, indicated by the arrow in **B**.
 287 Conversely, neither the pyroclastic deposit in the southeast portion of the crater floor, nor the deposits in the western
 288 portion of the crater floor correlate with strong positive BA. **C**) A topographic profile across Alphonsus shows a flat
 289 floor, indicating uniform uplift across the crater floor. **A**) Generated from GRGM900c Bouguer solution to GRAIL
 290 data. **B**) LROC-WAC (Lunar Reconnaissance Orbiter Camera- Wide Angle Camera) image. **C**) LOLA (Lunar
 291 Orbiter Laser Altimeter) data.

292 We continued our analysis of the degree 100-600 band-filtered gravity solution to several
 293 of the floor-fractured craters with $D > 100$ km (Fig. 4), we examined both the degree of
 294 heterogeneity, and also correlations between gravity anomalies and surface volcanic
 295 morphologies (mare deposits and pyroclastic deposits [Gaddis et al., 2003]). The craters

296 Gassendi (Fig. 4g, h) and Cleomedes (Fig. 4c, dm), which are located at the edges of Humorum
297 and Crisium basin, respectively, show large magnitude, linear positive anomalies. These are
298 interpreted as large, older circumbasin dikes, first identified in GRAIL data by Andrews-Hanna
299 et al. [2013], and are not related to the shallow intrusions we are addressing here. The data show
300 a general correlation of positive Bouguer anomalies beneath regions hosting volcanic surface
301 morphologies. Examples of this can be seen in the eastern half of Alphonsus (Fig. 4a, b),
302 Compton (Fig. 4e, f), Gauss (Fig. i, j), Humboldt (Fig. k, l), and Petavius (Fig. o, p). However
303 notable deviations occur in the western half of Alphonsus, and in Cleomedes crater. Neither
304 Gassendi crater, nor Janssen crater have surface volcanic morphologies, although both do have a
305 broadly positive interior Bouguer anomaly.

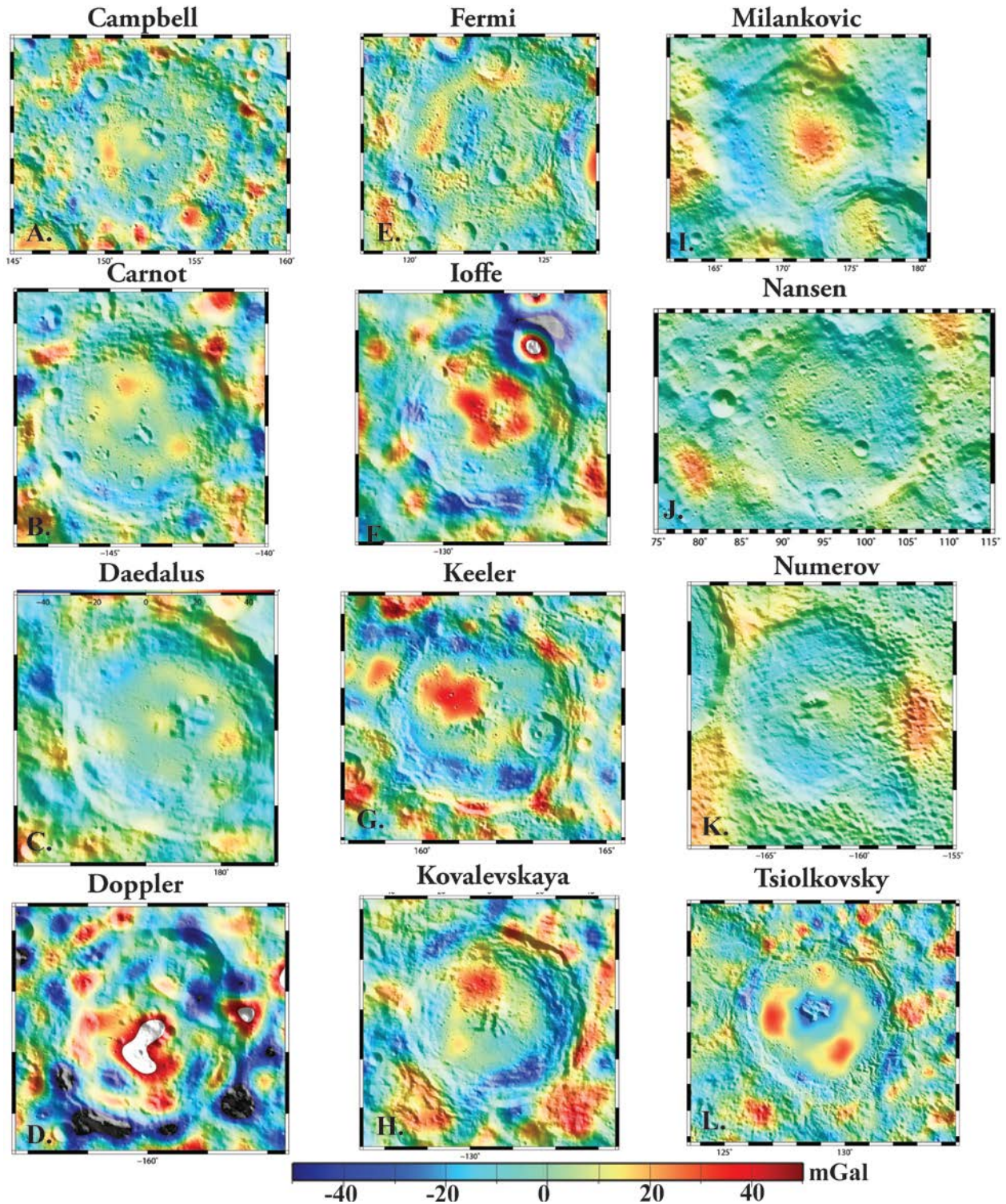
306 Given the extreme heterogeneity we observed in the FFC Bouguer anomaly, we
307 examined whether or not the statistically observable difference between FFC and complex crater
308 Bouguer anomalies [Thorey et al., 2015] was observable in the individual data, either in terms of
309 overall magnitude or in terms of degree of heterogeneity. We examined a randomly selected set
310 of complex craters with $D > 100$ km, and stratigraphic ages spanning from the pre-Nectarian to
311 Upper Imbrian, which represent the range in stratigraphic ages for most FFCs [Jozwiak et al.,
312 2015a] (Fig. 5). We applied the same band-filtering technique that was applied to the FFCs. We
313 found that the regions outside of the craters maintained similar levels of heterogeneity observed
314 in regions outside of FFCs. Inside the crater, the gravity anomalies display heterogeneities
315 similar to those observed on the floors of FFCs. Unlike FFCs, however, there is no observed
316 spatial correlation of gravity anomalies with surface morphologies in the complex craters. We
317 note that because the complex craters lack many of the distinctive floor morphologies of FFCs,
318 the lack of correlation between morphologic features and gravity anomalies is unsurprising.
319 When viewed next to FFCs (Fig. 4), it is difficult to identify complex craters (Fig. 5) using only
320 the observed gravity anomalies. Although FFCs have a more positive Bouguer anomaly than
321 complex craters on average [Thorey et al., 2015], the heterogeneous nature of the lunar crust (as
322 seen through gravity data) necessitates that geologic data (such as LOLA and LROC) be used in
323 conjunction with the gravity data to verify the presence of suspected magmatic intrusions.



324

325 Figure 4: Images of eight floor-fractured craters compared to the degree 100-600 band-filtered Bouguer anomalies
 326 for each crater. Surface volcanic morphologies including mare deposits and pyroclastic deposits (as identified in
 327 Gaddis et al. [2003]) are noted with black arrows in both the visual image and the band-filtered gravity solution. All
 328 craters display a heterogeneous Bouguer anomaly. Many of the regions beneath and adjacent to surface volcanic
 329 morphologies are correlated with regions of positive Bouguer anomaly, although there are notable exceptions in the
 330 western part of Alphonsus crater and in Cleomedes crater. Alphonsus crater image (a), gravity (b); Cleomedes
 331 crater image (c), gravity (d); Compton crater image (e), gravity (f); Gassendi crater image (g), gravity (h); Gauss
 332 crater image (i), gravity (j); Humboldt crater image (k), gravity (l); Janssen crater image (m), gravity (n); and
 333 Petavius crater image (o), gravity (p). All visual images are LROC-WAC images in sinusoidal projection, centered
 334 on the crater center longitude.

335



336

337 Figure 5. GRAIL Bouguer gravity data band-filtered to degree 100-600 for 12 complex lunar craters. All craters data
 338 are shown at the same scale, which is consistent with the scale used in Fig. 4. The complex craters exhibit a variety
 339 of heterogeneities in the band-filtered degree 100-600 solution, however, these heterogeneities are not correlated
 340 with any distinct surface morphologies. The exception is the crater Tsiolkovsky (l), which has significant mare
 341 flooding over the entirety of the crater floor, and still displays some degree of heterogeneity, likely associated with

342 varying mare deposit thickness. A) Campbell, B) Carnot, C) Daedalus, D) Doppler, E) Fermi, F) Ioffe, G) Keeler,
 343 H) Kovalevskaya, I) Milankovic, J) Nansen, K) Numerov, L) Tsiolkovsky.

344 V. Discussion:

345 Both the morphologic analyses of FFCs [e.g. Jozwiak et al., 2015a] as well as statistical
 346 assessments of FFC Bouguer anomalies [Thorey et al., 2015] support the hypothesis that FFCs
 347 are formed by the intrusion of a magmatic body beneath the crater. The spatially heterogeneous
 348 Bouguer anomalies observed within individual craters, however, vary significantly from the
 349 spatial BA pattern predicted from both simple plate models (eq. 1) and synthetic sill models
 350 [Thorey et al., 2015], which both assume an axisymmetric sill intrusion geometry. The deviation
 351 between the spatial pattern (and magnitude) of observed Bouguer anomaly from the predicted
 352 Bouguer anomaly suggests that the model neglects some facet of the intrusion process. Possible
 353 hypotheses to explain the observed Bouguer anomaly heterogeneity include (1) spatial variations
 354 in intrusion geometry (i.e., an intrusion that does not extend beneath the entire crater floor, but is
 355 instead discretely located); and (2) spatial variations in intrusion density. In the case of variations
 356 in intrusion geometry, the intrusion does not fill the entire crater floor, but is instead located
 357 directly beneath the regions which have a positive Bouguer anomaly. We find this hypothesis
 358 unlikely because morphologic and morphometric analyses of FFCs [Jozwiak et al., 2012]
 359 indicate that the intrusions extend to the edges of the crater floor, and deform the entire overlying
 360 floor region, uplifting it either into a domed morphology or lifting the entire floor region in a
 361 competent piston-like fashion (Fig. 3c).

362 In the second scenario, the observed heterogeneity in the Bouguer anomaly may be the
 363 result of density variations within the intrusion. The evolution of magmatic intrusions involves a
 364 number of processes including solidification/contraction, crystal settling, bubble formation, and
 365 degassing [e.g. Marsh, 1989]. These last two processes, in particular, have a large effect on
 366 overall intrusion density, as there can be a large difference in the densities of degassed and non-
 367 degassed basalt. The listed basalt densities of 2900–3200 kg/m³ [Kiefer et al., 2012] represent
 368 completely degassed basaltic samples. New research on returned Apollo glass samples, however,
 369 has revealed a significant volatile component in pre-eruption lunar magmas [Saal et al., 2008].
 370 An additional and more volumetrically significant source of volatiles in shallow lunar magmatic
 371 intrusions is CO. CO is produced in the shallow lunar subsurface via pressure-dependent
 372 reduction reactions between metal oxides (i.e. Cr₂O₃, FeO, and Ti₂O₃) and C_{graphite} in the melt
 373 [Sato, 1979; Fogel and Rutherford, 1995]. During the dike propagation process, bubbles will
 374 collect in the low-pressure dike-tip environment, forming a magmatic foam [Head et al., 2002;
 375 Wilson and Head, 2003].

376 The presence of pyroclastic deposits in many FFCs [e.g. Gaddis et al., 2003] provides
 377 ready evidence for the degassing of FFC magmatic intrusions. Using the observed range of
 378 pyroclastic material from the source vent, we can calculate the average gas volume fraction of
 379 the foam. The crater Alphonsus hosts several pyroclastic deposits with an average radius of 3-4

380 km [Head and Wilson, 1979]. The average velocity of pyroclastics, v , can be calculated from the
 381 following equation [Head et al., 2002; Wilson and Head, 2016],

$$382 \quad R = \frac{v^2}{g} \quad (1)$$

383 where R is the deposit radius in meters and g is 1.62 m/s^2 , the lunar acceleration due to gravity.
 384 The velocity can then be used to calculate the magmatic volatile gas fraction, n , from equation 2,

$$385 \quad n = \left[\frac{v^2 m (\gamma - 1)}{2 Q T \gamma} \right]^{\frac{1}{2}} \quad (2)$$

386 which represents a compromise between adiabatic gas expansion and gas expansion in a
 387 Knudsen regime [Wilson et al., 2014; Wilson and Head, 2016]. In this application, m , the gas
 388 molecular weight, is 28 kg mol^{-1} , Q , is the universal gas constant, $8314 \text{ J K}^{-1} \text{ kmol}^{-1}$, T is the
 389 magmatic temperature, 1500 K , and γ is the ratio of gas specific heats, 1.28 (a weighted average
 390 of the two most common volatiles species, CO and H_2O) [Wilson et al., 2014; Jozwiak et al.,
 391 2015b].

392 From this analysis, the average range of pyroclasts in Alphonsus suggests a gas fraction
 393 of 0.0345 , a volume fraction of 72.8% [Jozwiak et al., 2015b], which is well within the range of
 394 critical gas volume fraction for bubble collapse observed experimentally by Jaupart and
 395 Vergnolle [1989]. The density of CO at magmatic temperatures and pressures is 40 kg/m^3
 396 [Wilson et al., 2014], which combined with the basalt, results in a foam density of 845 kg/m^3 .
 397 The overall intrusion density can thus be deduced from a simple linear mixing of magmatic foam
 398 volume and degassed magma volume. For example, assuming a degassed basalt density of 3000
 399 kg/m^3 , and intrusion with 5% foam would have an overall density of $\sim 2900 \text{ kg/m}^3$, whereas an
 400 intrusion with 25% foam would have an overall intrusion density of $\sim 2450 \text{ kg/m}^3$. Thus, the
 401 amount of magmatic foam within an intrusion can have a significant effect on the intrusion
 402 density and by extension, the observed Bouguer anomaly. This hypothesis is also supported by
 403 the spatial correlation of surface volcanic morphologies with positive Bouguer anomalies. The
 404 volcanic features provide direct evidence of degassing within the underlying intrusion,
 405 suggesting that the removal of the magmatic foam component (through degassing) results in a
 406 higher positive Bouguer anomaly. In regions where there are no surficial volcanic morphologies,
 407 there is no direct evidence for the removal or collapse of the magmatic foam component, which
 408 results in a lower density for the region in question, and a correspondingly lower magnitude
 409 Bouguer anomaly. Although the wide range of observed Bouguer anomalies in complex craters
 410 [Soderblom et al., 2015] prevents the back-calculation of the foam volume in any given
 411 intrusion, work is ongoing to determine the amount of magmatic foam generated during the
 412 magma ascent process [Wilson and Head, 2016]. Future work may then provide constraints on
 413 the volume of solidified foam remaining within the intrusion [Jozwiak et al., *in prep*].

414 VI. Conclusions:

415 Morphologic studies using LROC and LOLA data provide evidence that the class of
416 lunar craters called floor-fractured craters is formed by the intrusion of a magmatic body beneath
417 the crater floor [Jozwiak et al., 2012, 2015a]. This interpretation is broadly supported by recent
418 modeling work [Thorey and Michaut, 2014] and statistical analysis of floor-fractured crater
419 Bouguer anomalies, which are on average more positive than those measured within complex
420 craters [Thorey et al., 2015], consistent with the intrusion of a high density magmatic body
421 beneath the crater floor. Although high resolution gravity data from GRAIL was initially
422 postulated to provide a powerful analytic tool for these shallow magmatic intrusions, our analysis
423 shows that great care must be exercised when applying gravity data to the investigation of
424 shallow lunar magmatism. Our simple Bouguer plate modeling shows that, while the subcrater
425 magmatic intrusions are capable of producing Bouguer anomalies resolvable by the GRAIL
426 instrument, the overall magnitude of these anomalies is significantly smaller than most of the
427 low-degree, high-magnitude contributions to the gravity field. This is borne out by assessments
428 using both the raw GRGM900c Bouguer gravity model and a band-filtered degree 6-600
429 solution. In both of these analyses, although there was some correlation of floor-fractured craters
430 with positive Bouguer anomalies, the correlation was not strong enough to serve as a predictive
431 tool. To remove the effects of low-degree contributions to the gravity field, we also explored a
432 band-filtered degree 100-600 gravity solution. When observed using the degree 100-600 solution
433 craters displayed a spatially heterogeneous Bouguer anomaly signal, which is inconsistent with
434 the predicted Bouguer anomaly based on the inferred intrusion morphology [Jozwiak et al.,
435 2012] and on synthetic gravity modeling [Thorey et al., 2015]. The heterogeneities within the
436 crust can be attributed to some combination of compositional variations and porosity variations.
437 We observe, in the degree 100-600 solution, that within floor-fractured craters, regions of
438 relatively high magnitude, positive Bouguer anomalies are spatially correlated with surface
439 volcanic morphologies. We postulate that the observed heterogeneities in the Bouguer anomaly
440 of floor-fractured craters arise as a natural consequence of the intrusion evolution and degassing
441 process, wherein heterogeneous degassing of a magmatic foam results in localized areas of high
442 Bouguer anomalies. Future work seeks to constrain the volume of foam produced during the dike
443 propagation process, and its applicability to the evolution of shallow magmatic intrusions.

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