Lunar floor-fractured craters: Classification, distribution, origin and implications for magmatism and shallow crustal structure

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Lunar floor-fractured craters: Classification, distribution, origin and implications for magmatism and shallow crustal structure

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[1] Floor-Fractured Craters (FFCs) are a class of lunar craters characterized by anomalously shallow floors cut by radial, concentric, and/or polygonal fractures; additional interior features are moats, ridges, and patches of mare material. Two formation mechanisms have been hypothesized—floor uplift in response to shallow magmatic intrusion and sill formation, and floor shallowing in response to thermally driven viscous relaxation. This study combines new Lunar Orbiter Laser Altimeter (LOLA) and Lunar Reconnaissance Orbiter Camera (LROC) data to characterize and categorize the population of FFCs and map their distribution on the Moon, and uses variations in floor-fractured crater morphology and regional distribution to investigate the proposed formation mechanisms. The population of FFCs was categorized according to the classes outlined by Schultz (1976). The distribution of these FFC categories shows an evolution of crater morphology from areas adjacent to lunar impact basins to areas in the lunar highlands. We propose that this trend is supportive of formation by shallow magmatic intrusion and sill formation—crustal thickness determines the magnitude of magmatic driving pressure, and thus either piston-like floor uplift for high magnitude, or a convex floor profile for low magnitude. Predictions from previous studies modeling viscous relaxation are inconsistent with the observed altimetric profiles of FFCs. Hence our analysis favors FFC formation by shallow magmatic intrusion, with the variety of FFC morphologies being intimately linked with location and crustal thickness, and the driving pressure of the intrusion. Data from the GRAIL (Gravity Recovery and Interior Laboratory) mission will help to test these conclusions.


1. Introduction and Background

[2] Floor-Fractured Craters (hereafter referred to as FFCs) are characterized by their shallow, often plate-like floors and contain radial, concentric, and/or polygonal fractures; additional interior features can include moats, ridges, pits of mare material, and dark-haloed pits. These craters were first described in detail by Schultz [1976], who examined them using Lunar Orbiter and Apollo images, and established a classification system based primarily on observed morphological differences between floor fractured craters and fresh unaltered impact craters. Schultz [1976] defined six sub classes for FFCs, summarized in Table 1. A map showing the distribution of all FFCs over the lunar surface was published by Schultz [1976], although the map did not distinguish between the different classes of FFC for individual points and a list of craters with coordinates and classification was not provided.

[3] As described by Schultz [1976], FFCs share several characteristics, most notably their fractures. The fractures can be radial, concentric, or polygonal, with the differences contributing to the definition of the different categories of FFCs. FFCs are also characterized by a shallow floor, although the shallowing varies widely between craters, anywhere from 20 to 85% of the predicted crater floor depth [Schultz, 1976]. On the basis of new image and altimetry data from the Lunar Reconnaissance Orbiter (LRO) we have undertaken a detailed analysis of the global distribution and characteristics of FFCs in order to 1) revisit and assess the
classification scheme of Schultz [1976], 2) provide more quantitative data on crater morphometry, 3) assess the global distribution of FFCs and members of their subclasses, and 4) revisit and reassess theories of origin (e.g., viscous relaxation or magmatic intrusion and piston-like uplift). The proposed theories of origin predict different end-member morphologies, such as the height of the crater rim crest, although it is difficult to distinguish the processes by purely quantitative standards, because the exact amount of deformation experienced may vary widely by crater. We first describe the classification scheme of Schultz [1976], outline the major theories of origin, describe the data sets used in our analyses, and then address the four goals outlines above.

1.1. Classification Scheme of Schultz [1976]

Although FFCs share broad characteristics, they can be readily divided into subcategories based on their morphology; Schultz [1976] described six subcategories for FFCs. We found these categories to be accurate classifications, and employ the descriptions when classifying FFCs. A summary of subclass characteristics is presented in Table 1.

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

*Craters in each class need not possess all of the listed characteristics, although they must possess a majority in order to be classified.*
Class 4c (Figure 6): Although alluded to by Schultz [1976], these types of craters were not previously a separate category of FFC. We find, however, that the class is different enough from 4a and 4b to merit its own sub-category.

The diameters of class 4c craters range from 8 km to 39 km with an average diameter of 15 km. In a manner similar to other class 4 craters, 4c craters contain a “v” shaped moat, but beyond this similarity, their characteristics are different.

Figure 1. Class 1 floor-fractured craters. (a) Crater Humboldt shown with LOLA topography overlain with LROC-WAC image data. Distinguished as a Class 1 FFC by the dark patches of mare material along the wall, and the radial and concentric floor fractures. (b) Transect of Humboldt, indicated by the line from A-A’ in Figure 1a. Marked on the profile are the locations of the class 1 FFC features. (c) Size-frequency of Class 1 FFCs, binned by diameter; Class 1 FFCs are among the largest. (d) Areal distribution of Class 1 FFCs.
Figure 2. Class 2 Floor-fractured craters. (a) Crater Vitello shown with LOLA topography overlain with LROC-WAC image data. Class 2 distinguishing features include the strong concentric fractures and the uplifted central region. (b) Transect of Vitello, indicated by the line from A-A’ in Figure 2a. Marked on the profile are the locations of class 2 FFC features, note also the smooth transition between crater wall and crater floor, and the uplifted central crater region. (c) Size-frequency distribution of Class 2 FFCs binned by diameter, like a majority of the FFC population, they range between 10 and 50 km in diameter. (d) Areal distribution of Class 2 FFCs.
Figure 3. Class 3 floor-fractured craters. (a) Crater Gassendi shown with LOLA topography overlain with LROC-WAC image data. Class 3 is distinguished by a flat, plate-like floor, a wide moat, and radial/polygonal fractures. (b) Transect of Gassendi, indicated by the line from A-A’ in Figure 3a. Marked on the profile are the locations of class 3 FFC features, note in Gassendi the terracing on the crater wall opposite the basin, and the pronounced moat on the crater wall adjacent to the basin. (c) Size-frequency distribution of Class 3 FFCs, although a wide range of diameters occur, the majority of Class 3 craters are 30–40 km in diameter. (d) areal distribution of Class 3 FFCs; they are located almost exclusively just inside basins, or at basin margins.
Figure 4. Class 4a floor-fractured craters. (a) Crater Bohnenberger shown with LOLA topography overlain with LROC-WAC image data. Class 4a is distinguished by a “v”-profile moat, radial or concentric fractures, and a convex-up crater floor. (b) Transect of Bohnenberger, indicated by the line from A-A’ in Figure 4a. Marked on the profile are the locations of class 4a FFC features, note despite the large fracture cutting through the center of the crater floor, the floor has an overall convex up profile. (c) Size-frequency distribution of Class 4a FFCs. (d) Areal distribution of Class 4a FFCs; note that Class 4a FFCs are more uniformly located beyond basin margins, and into the lunar highlands.
Figure 5. Class 4b floor-fractured craters. (a) Crater Gaudibert shown with LOLA topography overlain with LROC-WAC image data. Class 4b is distinguished by a “v”-profile moat with a very pronounced inner ridge occasionally higher than the crater rim crest, a hummocky convex up central floor region, and subdued fractures. (b) Transect of Gaudibert, indicated by the line from A-A′ in Figure 5a. Marked on the profile are the locations of class 4b FFC features, note how the ridge nearly matched the elevation of the crater rim crest. (c) Size-frequency distribution of Class 4b craters. (d) Areal distribution of Class 4b FFCs, as with Class 4a, they are located farther from the basin margins than Class 3 FFCs.
Figure 6. Class 4c floor-fracture craters. (a) Unnamed crater located at 56.3 S, 143.9 W shown with LOLA topography overlain with LROC-WAC image data. Class 4c is distinguished by a "v"-profile moat, although the interiors vary between craters, and floors can be either convex up or concave down in profile. (b) Transect of the crater located at 56.3 S, 143.9 W, indicated by the line from A-A’ in Figure 6a. Marked on the profile are the locations of class 4c FFC features. (c) Size-frequency distribution of Class 4c craters, the vast majority having diameters 10–20 km. (d) Areal distribution of Class 4c FFCs.
The interiors are shallower than fresh craters, and appear flat, although most have a slightly concave up floor profile. The surface is hummocky and largely lacking fractures. The texture of the floor varies between craters, but they are united by evidence of post emplacement modification. Class 4c craters are often small and unnamed, and occasionally difficult to identify as craters. A named example of a Class 4c crater is Colombo M, the Class 4c characteristics of the crater located at 56.3S, 143.9W are shown in Figure 6a.

[11] Class 5 (Figure 7): Class 5 craters are old, degraded craters with strong radial, concentric, and/or polygonal fractures cutting their floors; they have diameters ranging from 12 km to 177 km, with the vast majority between 45 km and 100 km. The interiors of these craters are old highland material, and often contain slumps from the degraded walls. Like the rest of the crater, the rim crest is heavily degraded. Examples of Class 5 craters include Von Braun, Repsold, and Alphonsus. Figure 7a shows the Class 5 features of crater Von Braun.

[12] Class 6 (Figure 8): Class 6 craters are easily identified by their distinctive interiors which are completely flooded by mare material; excluding the extreme diameters of 5 km and 700 km, Class 6 FFC diameters range between 50 km and 200 km. Additionally, Class 6 craters have a distinctive concentric fracture pattern close to their wall scarp. Some craters have central peaks and radial fractures, although these are not requirements. Examples of Class 6 craters include Pitatus and Fracastorius, and the Class 6 features of crater Pitatus are shown in Figure 8.

1.2. Theories of Origin of FFCs

[13] There are currently two proposed formation mechanisms for FFCs: magmatic intrusion leading to sill formation [Brennan, 1975; Schultz, 1976; Wichman and Schultz, 1995] and viscous relaxation [Masursky, 1964; Daněš, 1965; Cathles, 1975; Schultz, 1976; Hall et al., 1981; Dombard and Gillis, 2001]. The process of magmatic intrusion has been modeled by Johnson and Pollard [1973], a schematic for this process is shown in Figure 9. Energy from the initial crater impact forms a highly fractured region and brecciated lens beneath the crater [Baldwin, 1963; Roddy, 1968; Roddy, 1977]. A magma filled crack (dike) propagates upward from the magma source region in the mantle [Wilson and Head, 1981]. When the propagating dike reaches this level, it ceases vertical propagation and begins to spread laterally. The magma then spreads beneath the crater forming an axisymmetric sill broadly consistent with the dimensions of the crater floor. The sill then begins to grow vertically, uplifting the overlying crater floor; eventually the pressure becomes sufficient to cause piston-like uplift of the crater floor. Depending on the extent of the intrusion, additional faults, graben, and mare units may be formed on the crater walls and floor [Schultz, 1976]. Schultz [1976] examines this proposed process extensively, and shows models for increasing amounts of crater modification in response to a growing intrusion, including the formation of graben and terraces and the floor fractures observed in the craters.

[14] On the other hand, the shallow crater floors and floor fractures could be the result of viscous relaxation, sketched in Figure 9b. Viscous relaxation occurs when high thermal gradients within a given region lead to a decrease in material strength and a corresponding relaxation in the regional topography, particularly the long-wavelength topography [Daněš, 1965; Baldwin, 1968; Cathles, 1975; Hall et al., 1981; Dombard and Gillis, 2001]. In the most basic system, that which assumes constant Newtonian viscosity, viscosity decreases with depth (a result of temperature increasing with depth), and as a result, long wavelength features, such as the crater depression, tend to relax; this results in an apparently shallower crater depth and an upbowed floor [Parmentier and Head, 1981; Hall et al., 1981; Solomon et al., 1982; Dombard and Gillis, 2001]. The lunar crust can also be modeled as an extended Maxwell solid whose rheology has three components: linear elasticity (as seen in constant Newtonian viscosity models), solid state ductile creep, and plasticity [Albert et al., 2000]. Modeling the crater system using this more complex elastoviscoplastic relaxation process, results in the same relaxed topography and bowed floor as seen previously, but with the addition of floor fractures. These floor fractures are the result of a cold shallow crust containing the crater overriding warmer, less viscous deeper material. The system strain created by this situation leads to upward flexure of the bottom of the crater floor, and this flexure causes bending stresses on the crater floor that may yield floor fractures [Dombard and Gillis, 2001]. Both the Newtonian viscosity model [Parmentier and Head, 1981; Hall et al., 1981; Solomon et al., 1982; Dombard and Gillis, 2001] and elastoviscoplastic model [Dombard and Gillis, 2001] have been used to model the effects of viscous relaxation on craters, but are limited by the accuracy of input parameters describing the lunar rheology, and the assumption of axisymmetric deformation.

[15] A problem arises then in determining which of these mechanisms formed floor-fractured craters, as both mechanisms are predicted to produce the large-scale characteristic features of the craters. Our study uses the new high-resolution topographic and image data from the Lunar Orbiter Laser Altimeter (LOLA) and Lunar Reconnaissance Orbiter Camera-Wide-angle Camera (LROC-WAC), respectively, to analyze the smaller-scale characteristics that define the different classes of FFC, and also to characterize and plot the distribution of these classes on the lunar surface. This distribution, and the high-resolution data allow us to investigate in a new way the formation of FFCs, in particular the ability of the proposed theories to explain the distribution of FFC types, and the more detailed differences in addition to the fundamental differences from fresh craters illustrated by their shallow floors and floor-fractures.

2. Data Set and Analysis of FFCs

[16] The data used in this analysis were drawn from LOLA and LROC-WAC data sets. The LOLA data set that served as a global lunar base map was composed of tiles at 512 m/pixel resolution. This basemap was overlaid with a hillshade generated from the 512 m/pixel LOLA data, and LROC-WAC imagery. The craters Humboldt (1), Vitello (2), Gassendi (3), Bohnenberger (4a), Gaudibert (4b), Von Braun (5), and Pitatus (6) were identified as exemplary for their class (listed in parentheses), because they contained all or a majority of the defining characteristics for their specific class. Profiles of these craters (Figures 1b 2b, 3b, 4b, 5b, 6b, 7b, and 8b) were compiled from the gridded data to investigate the variations in crater morphometry between FFCs and fresh craters.
Figure 7. Class 5 floor-fractured craters. (a) Crater Von Braun shown with LOLA topography overlain with LROC-WAC image data. Class 5 is distinguished by a flat plate-like floor, radial or polygonal fractures, and an old, degraded appearance. (b) Transect of Von Braun, indicated by the line from A-A’ in Figure 7a. Marked on the profile are the locations of Class 5 FFC features, note the extremely flat floor and prevalent wall slumps. (c) Size-frequency distribution of Class 5 craters, a large span of diameters are present, and are mostly larger than a majority of FFCs. (d) Areal distribution of Class 5 FFCs, note locations close to basin margins, in particular to the west of Oceanus Procellarum.
(Figure 10), as well as between FFC classes. The results of these analyses are described in the following section. A global search for FFCs was undertaken using the LROC and LOLA databases. An initial list of currently recognized FFCs was compiled using the global distribution map of Schultz [1976]; this list was then used as a guide for corroboration of the currently identified FFCs and identification of any previously unidentified FFCs found in our global search. We identified

Figure 8. Class 6 floor-fractured craters. (a) Crater Pitatus shown with LOLA topography overlain with LROC-WAC image data. Class 6 is distinguished by a mare-flooded interior and a concentric fracture pattern near the crater wall. (b) Transect of Pitatus, indicated by the line from A-A' in Figure 8a. Marked on the profile are the locations of Class 6 FFC features. (c) Size-frequency distribution of Class 6 FFCs, which are larger than average FFCs. (d) Areal distribution of Class 6 FFCs, note proximity to basins.
approximately 10–20 previously unnoted FFCs, and removed approximately 10 from the existing lists because the LOLA and LROC data showed that the craters did not share the characteristics of FFCs. Using the LOLA and LROC-WAC global data, craters were located, and those that fit the characteristics of FFCs were recorded in a newly generated list of all lunar FFCs, provided as auxiliary material to this paper.\(^1\) The morphology of individual craters was studied in detail using both LOLA altimetry and LROC Narrow-Angle Camera (NAC) image data. These analyses were all carried out using the ArcGIS program platform.

2.1. Floor-Fractured Crater Diameter Distribution and Morphometry

[17] The diameter frequency distribution of FFCs (Figures 1c, 2c, 3c, 4c, 5c, 6c, 7c, and 8c) highlights the predominance of FFCs with diameters between 10 km and 40 km. This could have implications for the preferential scale of activity for the FFC formation mechanism. Current gravity data resolution cannot define gravity anomalies in areas as small as a majority of these craters. However, GRAIL (Gravity Recovery and Interior Laboratory) mission data will acquire data at this scale, and could reveal the formation mechanism, as will be discussed in section 3.3.

[18] For detailed morphologic and morphometric characterization, a representative crater was selected from each FFC class (Figure 10); these craters were selected because they contained all of the identifying characteristics of their class, thus providing an end-member example for each class, and assisting comparisons between classes. These representative FFCs were then compared to Copernican-aged craters.

\(^1\)Auxiliary materials are available in the HTML. doi:10.1029/2012JE004134.

Figure 9. Diagrammatic cross-sectional representations of a fresh complex crater and the predictions of two candidate crater modification processes proposed to explain the characteristics of floor-fractured craters. (a) Fresh complex craters are characterized by a depth-diameter (d/D) relationship of approximately d = 1.04d\(^{0.301}\) [Pike, 1980], and an exterior rim crest height (h) that represents the height of the crater rim crest above the level of the surrounding uncratered substrate. Exterior crater rim crest height is a combination of structural uplift and ejecta thickness and is represented in this diagram by a horizontal dashed line labeled ORCH (original rim crest height) for reference in b and c. The crater interior is characterized, from the rim crest inward, by wall terraces formed by rim slumping in the terminal stages of the cratering event, impact melt overlying a breccia lens emplaced in the terminal stages of the impact event as impact melt settled to the crater floor above the breccias lens, and a central peak, uplifted and emplaced in the latter part of the excavation and modification phase. (b) Complex craters undergoing viscous relaxation [e.g., Hall et al., 1981; Dombard and Gillis, 2001] experience a wavelength-dependent change in topography. Long-wavelength topography (in this case, at the scale of the crater itself) decreases in amplitude, while short-wavelength topography, such as the central peaks of the shape of the rim crest itself, is much less affected. This results in an overall decrease in the depth of the crater (d) and a decrease in the original rim crest height (ORCH), as the original crater topography smooths out at long wavelengths. Local (short-wavelength) topographic features, such as the central peaks and the crater rim crest tend to remain prominent, however. Evidence for a fresh complex crater undergoing viscous relaxation (Figure 9b) would be a decrease in both the crater depth (d) and the crater exterior rim crest elevation (h), and a distinctive crater interior topographic profile [e.g., Dombard and Gillis, 2001]. (c) Floor-fractured craters have also been interpreted as complex craters intruded by dikes and sills [e.g., Schultz, 1976; Wichman and Schultz, 1996]. In this scenario, a dike propagating vertically from the mantle toward the surface encounters a low-density breccias zone at the base of the crater floor, becomes neutrally buoyant [see Head and Wilson, 1992], and spreads laterally to form a sill. Continued pressurization of the sill causes vertical thickening and uplift of the crater floor and central peaks, with the most extreme deformation focused at the lateral margins of the sill. The predicted result of sill emplacement is the fracturing and faulting at the margins of the crater floor, uplift of the floor and central peaks (with some associated floor deformation), formation of a marginal trough or moat as the crater floor is elevated above the base of the wall terraces, and a decrease in the value of (d), the depth to the crater floor. In the sill intrusion model, the exterior rim height, h, should remain unaltered. These predictions of the behavior of complex impact craters (Figure 9a) that have undergone either viscous relaxation (Figure 9b), or sill intrusion and floor uplift (Figure 9c), can be used to distinguish the origin of floor-fractured craters using new image and altimetry data.
The motivation for this comparison was twofold: 1) to quantify the morphologic differences between FFCs and normal fresh craters to assess the differences and their geographic locations at the craters, and 2) to use these data to help determine the formation mechanism of FFCs.

Copernican craters were used because they represent the youngest lunar craters [Wilhelms, 1987], and as such have undergone the least deformation and modification, and for the purposes of comparison can be used to represent fresh impact craters.

Figure 10. LROC-WAC images of Floor-Fractured craters and the Copernican-aged, un-modified impact craters they were compared against. (a) Crater Gassendi compared against (b) Crater Tycho; (c) Crater Taruntius compared against (d) Crater Aristillus; (e) Crater Gaudibert compared against (f) Crater Kepler; (g) Crater Vitello compared against (h) Crater Glushko; (i) Crater Humboldt compared against (j) Crater Hausen (Eratosthenian-aged).
Figure 11. Plot of frequency of floor depth for craters (a) Gassendi, a FFC, and (b) Tycho, an un-modified impact crater. In Figure 11a, Gassendi is a Class 3 FFC and has a much broader spectrum of frequent floor depths, indicating a floor that is wider and flatter than the floor of crater Tycho (Figure 11b). Tycho displays narrow bands of frequent floor depths corresponding to the classical bowl-like shape of impact craters.

Crater diameter was calculated using a 3-point circle fit. On each crater, three points were selected on the rim crest and then used to form a circle. The selected points were spaced in equidistant locations on the rim crest around the crater; the points were also selected to avoid areas where the crater wall or rim crest had been modified by post-impact events, such as additional crater impacts on the rim. Most of the craters were not perfectly circular, so to account for this, each crater was fit three times, and the average of these fits was taken as the crater diameter.

Given the precision of LOLA data, 30 m spatial resolution and 1 m vertical resolution [Smith et al., 2010; Zuber et al., 2010], detailed crater floor depth measurements were made. In each crater, profiles were taken from rim crest to rim crest trending west-east, northwest-southeast, and southwest-northeast; these data were compiled and a depth frequency plot was constructed with depths binned in 25 m intervals. Although the plots showed significant variation in shape between Copernican craters and FFCs, in both cases the most frequent floor depth was used to represent the average floor depth for the crater. Copernican craters such as Tycho have a narrow frequency peak at the deepest depths corresponding to their crater floor (Figure 11b), and in many cases the deepest floor depth was also the most frequent. In FFCs, however, there is a larger spread of depths for the crater floor (Figure 11a). This spread arises from floor fractures, which expose small areas of greater depth, as well as occasional wall slumps and convex floor profiles. To mitigate these contributions, the most frequent floor depth was used to represent the average floor depth.

Using ArcGIS, a line was traced along the entirety of the rim crest, a corresponding profile generated, and from this an elevation for the average rim crest height was obtained. It should be noted that when tracing the rim crest, areas with post-impact modification to the rim crest, such as subsequent cratering, were omitted. From the terrain surrounding the crater, profiles were taken to represent the average background elevation. This average elevation was then subtracted from the background elevation to yield the exterior rim crest height.

Crater classes were assigned using a combination of qualitative and quantitative methods. Crater morphology was the largest factor in crater classification. Craters displayed a majority of class-specific characteristics (Table 1) that allowed them to be categorized. At times there is ambiguity between the morphologic characteristics of a crater, at which point LOLA topography was used to generate detailed crater profiles. These profiles resolved the crater classification, as they revealed finer scale crater features that helped to distinguish between different classes, for example the presence of a moat to distinguish between Class 2 (Figure 2) and Class 4 (Figure 4).

2.2. FFC and Fresh Crater Comparison

Floor Fractured Craters exhibit distinct morphologic differences from fresh impact craters. Many of the differences are localized to the crater floor. All classes of FFC contain fractures on their floors. The fractures vary in width depending on the crater class; the fractures also vary in orientation, and can be radial, concentric, or polygonal. Many of the fractures, especially the larger ones are interpreted to be graben.

Certain classes of FFC have moat features (Figures 3a, 3b, 4a, 4b, 5a, 5b, 6a, and 6b) with Figure 12 depicting this specific type of morphologic feature. Wide moats (Figures 3a, 3b, and 12a) are separated from the central crater floor by concentric fractures or strong topographic differences. Topographically, the moats are either flat, or slope down toward the wall scarp forming a broad “U” shape. Wide moats comprise, on average, 40% of the crater floor; although other crater morphologies, such as terraces, can decrease the percent of floor coverage. Other craters have a narrow moat feature that has a characteristic “ν” shaped profile (Figures 4a, 4b, 5a, 5b, 6a, 6b, 12b, and 12c). This moat type is identified in topographic profile by the “ν” shape formed between the interior crater wall and the domed central crater floor region. In Class 4b craters, this moat is bounded on the inside by a ridge (Figures 5b and 12c). The ridge varies in height from almost indistinguishable from the elevation of the interior crater floor (Figures 4b, 6b, and 12b) to being near the height of the crater rim crest (Figure 5b). We note
that not all Class 4a and 4c craters have a discernible ridge feature; however, they do all have the “v” profile.

FFCs have distinctly broad, shallow floors, although the floor can tend to be concave up (Figure 6b), concave down (Figure 2b), or flat to irregular in topographic profile (Figures 3b and 7b). This is distinctly different from fresh craters which display the classic parabolic profile (Figure 11b) and do not have a distinct central floor region except central peaks at larger diameters.

**Figure 12.** LOLA topographic profiles depicting the range of FFC moat morphology. (a) Wide moat from crater Haldane. The interior of crater Haldane is has a visually distinct flat central region surrounded by a clear wide moat, indicated in the LOLA topographic profile. (b) “V” profile moat without an inner ridge from crater Bohnenberger. Note how the meeting of the wall scarp and the domed central crater floor create a “v” shape, for which the “v” profile moat is named. (c) “V” profile moat with an inner ridge from crater Gaudibert. Crater Gaudibert hosts the most topographically distinct inner ridge, with the elevation of the inner ridge exceeding the crater rim crest in places. The “v” moat is created by the meeting of the crater wall with the ridge material.
This fundamental difference in crater floor interior between fresh craters and FFCs is readily observed in floor depth versus frequency distributions as shown in a comparison of the depth frequency distributions for FFC Gassendi, and the Copernican-aged crater Tycho (Figure 11). Fresh crater depth distributions (Figure 11b) show a frequency spike corresponding to the crater rim crest, a small one at the central peak (if present), and then a large spike at the deepest floor depth. On rare occasion there are a few depths deeper than the most frequent depth, however, they are negligible by comparison. FFC crater depth distributions (Figure 11a), on the other hand, display the spikes at the rim crest height and central peak, but have a spread of very frequent depths, with the most frequent values corresponding to the broad uplifted central crater floor depth. There is a significant frequency of depths deeper than the most frequent one, and these depths come from the interior of the fractures and also the moats present in certain classes.

Comparison of the fresh (Tycho) and floor fractured (Gassendi) craters (Figure 11) also readily shows that the range of depths is very different, with Tycho having almost twice the topographic range as Gassendi. Indeed, the new data confirm that FFCs typically differ from fresh impact craters in their depth to diameter ratio (Figure 13). Pike [1980] demonstrated a relationship between crater diameter and crater depth for lunar craters (red squares in Figure 13). FFCs are shallower than fresh craters, and thus follow a shallower regression when depth is plotted against diameter (blue diamonds in Figure 13). This was noted by Schultz [1976], and is corroborated by the LOLA data measured (Figure 13). We also investigated the depth to diameter ratio for individual FFC classes, plotting approximately 70% of the craters for each class. All classes had a shallower regression than would be predicted by Pike [1980]; however, there were no observable trends beyond this shallower relationship. We make these data available in the auxiliary material.

Pike [1980] also documented a relationship between crater diameter and exterior crater rim crest height in fresh craters (red squares in Figure 14). FFCs plot along this same regression (blue diamonds in Figure 14), demonstrating that the modification to FFCS occurred primarily to their floor, not their rim (compare Figures 11a and 11b and Figures 13 and 14). This relationship holds true even for FFCs with an inner ridge, such as Class 4b, demonstrating further that the modification occurs primarily in the central floor region of the crater.

### 2.3. FFC Areal Distribution

A plot of the entire population of FFCs on the lunar surface (Figure 15) shows that the majority of FFCs are located in close vicinity to the lunar maria and the mare-filled impact basins, with a significant population also located in the South Pole Aitken basin, and in the highlands, especially the highlands west of Oceanus Procellarum. This distribution was also noted by Schultz [1976] but the distribution of the subclasses was not given there. We will examine the distribution of individual FFC classes and use this as a basis to assess further the proposed formation mechanisms.

Class 1 FFCs (large craters with radial and concentric fractures, and wall-adjacent patches of mare material) (Figure 1d) do not constitute a large population (8 craters), and with one exception, are not located directly adjacent to basins. This location away from direct basin edge contact is intriguing given that the hallmark of Class 1 FFCs are the patches of mare material along the crater wall margins (Figure 1a). This supports the hypothesis that the Class 1 FFCs were formed by magmatic intrusion as opposed to viscous relaxation, if the mare patches are areas where the intruding magma reached the surface.

Class 2 FFCs (medium size craters with strong concentric fractures) (Figure 2d) do not constitute a large population (8 craters), and with one exception, are not located directly adjacent to basins. This location away from direct basin edge contact is intriguing given that the hallmark of Class 2 FFCs are located along the edges of maria and basins, with a few also located inside the South Pole Aitken (SPA) basin. There is no apparent correlation between the age of the FFC and the age of the basins. The distinguishing feature of Class 2 craters, concentric fractures around an uplifted central region (Figure 2b), can be explained as uplift caused by either magmatic intrusion or viscous relaxation. There are five Class 2 FFCs located in highland regions. Several of these resemble Class 4 FFCs, however, lack the “v” shaped moat (compare Figure 2b with Figure 5b). It is unclear if this is a reflection.
of different formation mechanisms, or simply a difference in how the mechanism manifests itself in different lunar regions or substrates.

Class 3 FFCs (wide moat with a shallow floor and radial and polygonal fractures) (Figure 3d) are localized to the edges and close interiors of basins and mare units. The distinguishing morphology of this class is a wide moat (Figures 3a and 3b); in craters located at the edges of basins, the moat is more pronounced on the basin interior side (Figures 3a and 3b), and occasionally contains mare units. Proximity of these craters to large impact basins could implicate a role for thermal processes linked to basin formation. Localized thermal anomalies associated with heat of impact and geotherm uplift in the short term basin modification phase could create environments conducive to viscous relaxation of subsequently formed craters [e.g., Hall et al., 1981]. The distribution of these FFCs, however (Figure 3a), indicates that they form adjacent to basins with a wide range of formation ages (e.g., Humorum, Nubium, Nectaris, Crisium, Imbrium, Serenitatis, etc.) [Fassett et al., 2012], and thus a basin-related thermal anomaly is unlikely to have persisted long enough to retain regional geothermal fluxes sufficient to influence viscous relaxation of later craters [e.g., Bratt et al., 1985a, 1985b]. A more direct correlation is with the time of emplacement of the actual mare deposits themselves [e.g., Hiesinger et al., 2010].

Figure 14. External rim crest height versus diameter relationship for FFCs plotted with the same relationship for fresh impact craters. The crater populations used are shown in Figure 9. Note both FFC and fresh crater populations follow the same trend.

Figure 15. Areal distribution of all FFCs. FFCs tend to be located near mare-filled basins and impact basin margins, although there is also a significant population located in the lunar highlands. There is also a relationship between FFC class and location, as seen Figures 1d, 2d, 3d, 4d, 5d, 6d, 7d, and 8d.
Percent relaxation of a crater undergoing viscous relaxation, as a function of diameter and time, modeled under reasonable lunar thermal conditions. Little to no relaxation occurs for craters under 80 km diameter, a majority of FFCs, and at the longest timescales craters modeled with the largest diameter experience less than 10% relaxation. (From Dombaard and Gillis [2001].)

[33] Class 4a FFCs (small craters with “V” profile moat and radial or concentric fractures) (Figure 4d), are the most numerous of Class 4 craters. They are located generally near mare basin margins, although as in cases such as west of Oceanus Procellarum, they are not necessarily at the edges of an impact basin. There is also a significant population of 4a FFCs scattered throughout the highlands. These craters contain both a “v” shaped profile occasionally with a subtle inner ridge, and distinct radial and/or concentric floor fractures (Figures 4a and 4b). Uplift alone does not uniquely indicate a specific formation mechanism. However, the addition of the “v” profile (Figure 4b), suggests an area that may be defined by a subsurface magmatic intrusion that uplifted the central region of the crater, producing the “v” shaped moat in the uplift process. Long wavelength viscous relaxation might favor more subtle topographic variations.

[34] Similar to Class 4a, Class 4b (small craters with “V” profile moat, a pronounced inner ridge, and subdued fractures) (Figure 5d) craters are located primarily away from impact basins; indeed Class 4b craters are found to the outside of Class 4a craters relative to mare-filled basins, suggesting a relationship of Class 4a craters and Class 4b craters as a function of increasing distance from an impact basin. The distinguishing morphologic features of 4b craters (Figure 5a) are the pronounced “v” profile moat (Figure 5b), a very high inner bounding ridge (Figure 5b), and a hilly interior with subtle radial fractures (compare Figure 5b with other class profiles). If we postulate that Class 4b craters (Figure 5) are simply a spatial evolution of Class 4a craters (Figure 4), the different morphology could be a result of thicker crust, warping and muting the effects of the magmatic intrusion. At the same time, the generally muted and sinuous topography of 4b craters could be a result of deformation by viscous relaxation.

[35] Class 4c (small craters with a “V” profile moat) (Figure 6d), is the only class in this study not distinctly classified or mentioned in the original Schultz [1976] classification. Craters of Class 4c are located away from the mare, though not necessarily deep in the lunar highlands in a manner similar to some of the Class 4a craters (Figure 4d). As mentioned previously, the craters have varied morphology, although all share a nominal “v” profile moat, shallow floor, and a fractured and/or hilly textured interior (Figures 6a and 6b). There is nothing specific in their spatial distribution or morphology to favor formation by either viscous relaxation or magmatic intrusion.

[36] Class 5 craters (degraded craters with radial and polygonal fractures) (Figure 7d) are numerous (32 craters), and a majority are located in the highlands west of Oceanus Procellarum, although in positions closer to the mare than the Class 4 craters in this region (Figure 4d). They are located throughout highlands north of Mare Crisium, and a scattering of other places. The defining features of members of this class are their old, degraded appearance with strong radial and occasionally concentric fractures (Figures 7a and 7b). The degraded nature of the crater suggests an older age for the host crater than other FFCs. The prevalence of these craters near, but not on, the edge of Oceanus Procellarum could be indicative of a relationship between the modification of these new Class 5 FFCs and the formation of Oceanus Procellarum, or the emplacement of mare units in Oceanus Procellarum [e.g., Hiesinger et al., 2010]. Although the highly subdued features of the crater (Figure 7a) may be the result of viscous relaxation, the generally flat floor profiles of Class 5 craters (Figure 7b) are not consistent with the flexure associated with viscous relaxation processes [Hall et al., 1981].

[37] There is a small population of Class 6 FFCs (mare-flooded interiors with concentric fractures along the outer edge of the crater floor) (Figure 8d) and they are all located at the edge of a mare filled basin. This is not surprising because Class 6 craters are defined by their smooth, mare flooded interiors (Figure 8a). The other identifying feature of these craters is their distinct concentric fracture pattern around the edge of the crater interior (Figures 8a and 8b). As with the other craters, this fracture pattern is not sufficient in itself to distinguish between a magmatic intrusion or viscous relaxation origin; their proximity to maria could suggest a formation mechanism involving magmatic processes or viscous relaxation due to the heat of basin formation or magmatic filling.

3. Implications and Models for FFC Formation

[38] In this section we present the major characteristics of FFCs that might help to distinguish between an origin by viscous relaxation and intrusion (Figures 16–19), and make further assessments to assist in this distinction.

3.1. Formation Mechanism Implications of Crater Morphology and Morphometry

3.1.1. Floor Depth

[39] The key morphologic and morphometric feature of FFCs is their shallow floor (Figures 11a, 11b, and 13), which could be produced by either viscous relaxation or magmatic intrusion. We compile in Table 3 the difference in the average crater depth and the theoretical depth of an unmodified crater.
of that diameter [Pike, 1980]. These values could either be interpreted as the amount of viscous relaxation or the postulated intrusion thickness. Investigations into the amount of topographic relaxation necessary to reproduce crater shallowing have been undertaken by both Dombard and Gillis [2001] and Wichman and Schultz [1995]. Model results for percent crater relaxation as a function of crater diameter under reasonable estimates of lunar conditions (Figure 15) show that the model predicts little to no shallowing over the range of FFC diameters. Dombard and Gillis [2001] conclude that “lunar crustal rocks are simply too rigid to have accommodated substantial relaxation over the age of the Moon.”

3.1.2. Exterior Rim Crest Height

The similarity of fresh crater and FFC exterior rim crest heights (relative to external topography) is an additional morphologic feature that makes FFC formation due to viscous relaxation improbable. The process of viscous relaxation affects primarily long wavelength topography, and thus the crater floor; it also affects the elevation of the crater rim crest, although this is not itself a long wavelength topographic feature. Figures 13 and 14 show the depth versus diameter and external rim crest height versus diameter, respectively, for both fresh craters and FFCs. The shallower depth versus diameter relationship combined with the unchanged rim crest height versus diameter relationship, demonstrate that the FFC modification process worked to shallow the floor without degrading any of the other crater morphologic features.
structure features. This morphology is more indicative of the piston-like uplift predicted by magmatic intrusion than the feature-muting predicted by viscous relaxation (compare Figures 17 and 19). Furthermore, models of viscous relaxation show that the level of relaxation needed to replicate the shallow floor of FFCs change the elevation of the rim crest, making it higher than unmodified craters in the case of moderate shallowing, and greatly lowering the rim crest in the case of extreme crater shallowing (Figure 17) [Hall et al., 1981].

3.1.3. Crater Symmetry

[42] Models of viscous relaxation also assume axisymmetric deformation of craters [Hall et al., 1981], a result rarely observed in FFCs. Most FFCs have generally uneven rim crests, although this does not preclude formation by viscous relaxation, as later deformation could have caused the asymmetry of the rim. However, as described above, the regions of intact crater rim crest are widely consistent with rim crest heights of unmodified craters (Figure 14). Hence the uneven rim crests are likely the result of other crater degradation processes and not due to the FFC formation mechanism. The interiors of FFCs also show heterogeneity. Class 3 craters in particular, often have extensive wall slumping and terracing on one side of the crater interior with a corresponding wide moat on the other side separated by a rather flat central floor region (Figures 3a and 3b). These craters are often located on the edges of mare, and thus the asymmetric nature could be reflective of the initial local topography, dipping in toward the basin interior. Class 2 craters have a convex up interior (Figure 2b), and examples such as Vitello have a distinctly elevated central floor, however, this elevated floor is not axisymmetric. Due to the high resolution of the LOLA data, we were able to determine that none of the crater profiles observed in this study were axisymmetric, although observed profiles of fresh craters were, to a larger extent, axisymmetric.

3.1.4. Crater Floor

[42] Several of the FFC floor profile types appear less consistent with viscous relaxation, or more consistent with magmatic intrusion. FFC classes 1 (Figure 1b), 3 (Figure 3b), 5 (Figure 7b), and 6 (Figure 8b) all have flat, plate-like floor profiles. Models for viscous relaxation show a convex floor responding to flexural uplift, or a sinuous floor that has been warped by the process of viscous relaxation (Figure 17) [Hall et al., 1981; Dombard and Gillis, 2001]. Class 4 craters, in particular class 4b craters, display uplifted or warped floor profiles (Figure 5b), however, their diameters do not exceed approximately 40 km, well below the range of even minimal modification from viscous relaxation (Figure 16) [Dombard and Gillis, 2001].

3.1.5. Crater Moat

[43] One of the most important discrepancies between half-space models of viscous relaxation profiles seen in both Hall et al. [1981] and Dombard and Gillis [2001], is the inability to produce moats of any shape in the crater interiors (Figure 16). Steep “v” profile moats (Figures 4b and 5b) and wide moats (Figure 3b) are key defining features of Class 4 and Class 3 FFCs respectively, and thus models of viscous relaxation must be further refined, or perhaps combined with other mechanisms, in order to produce these key features of FFCs.

[44] Alternatively, the moat could be interpreted as a proxy for the dimensions of the underlying intrusion. In this scenario, the intruding dike encounters highly brecciated rock beneath the crater (Figure 18), where it then stalls and forms a sill (Figure 19). The observed uplifted region of the crater interior (Df in Figure 19) would then show the lateral extent of the intrusion. In all observed FFCs the floor uplift is confined to the interior of the crater, and in some cases (as seen in Figure 2), the uplifted section represents only a portion of the crater interior. The exact nature of this density barrier beneath the crater is unknown, but its nature and composition has important implications for the intrusion formation hypothesis. It is hypothesized that the cratering process results in a highly fractured, brecciated lens beneath the crater (Figure 18). This brecciated region is less dense than the magma in the propagating dike, thus halting the vertical propagation of the dike due to neutral buoyancy having been reached, and causing horizontal growth and sill formation. Although generally conceptualized from terrestrial craters, experiments and modeling (Figure 18), the exact morphology and extent of this brecciated lens remains unknown. The floor of FFCs often contains an uplifted

Table 2. Constants and Related Parameters Used in the Calculation of Intrusion Flexural Thickness, and Driving Pressure, Listed in Table 3

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Assumed Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_m</td>
<td>Young’s Modulus (basalt)</td>
<td>7.03 *10^10 Pa</td>
</tr>
<tr>
<td>ν_m</td>
<td>Poisson’s Ratio</td>
<td>0.25</td>
</tr>
<tr>
<td>B_m</td>
<td>Elastic Modulus of Country Rock, E/(1−ν)^2</td>
<td>7.47 *10^10 Pa</td>
</tr>
<tr>
<td>k</td>
<td>Magma Yield Strength</td>
<td>10^7 N/m²</td>
</tr>
<tr>
<td>g</td>
<td>Lunar gravitational acceleration</td>
<td>1.62 m/s²</td>
</tr>
<tr>
<td>ρ_m</td>
<td>Magma Density</td>
<td>2900 kg/m^3</td>
</tr>
<tr>
<td>γ_m</td>
<td>Unit Magma weight (ρ_m g)</td>
<td>4700 kg/m^2</td>
</tr>
</tbody>
</table>

*From Wichman and Schultz [1996].

Table 3. For Each Listed Crater, the Theoretical Driving Pressure Needed to Form the Intrusion, as Well as the Flexural Thickness of the Intrusion [Johnson and Pollard, 1973]

<table>
<thead>
<tr>
<th>Crater</th>
<th>Crater Class</th>
<th>Crater Diameter (D)</th>
<th>Intrusion Radius (a)</th>
<th>Intrusion Thickness (w_m)</th>
<th>Magma Driving Pressure (P_0)</th>
<th>Flexural Thickness (T_v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gassendi</td>
<td>3</td>
<td>109.67 km</td>
<td>47.58 km</td>
<td>1.97 km</td>
<td>11.34 MPa</td>
<td>4.20 km</td>
</tr>
<tr>
<td>Tarutius</td>
<td>3</td>
<td>58.66 km</td>
<td>14.00 km</td>
<td>0.811 km</td>
<td>7.10 MPa</td>
<td>0.92 km</td>
</tr>
<tr>
<td>Gaudibert</td>
<td>4b</td>
<td>33.99 km</td>
<td>5.76 km</td>
<td>0.14 km</td>
<td>5.95 MPa</td>
<td>0.49 km</td>
</tr>
<tr>
<td>Vitello</td>
<td>2</td>
<td>41.71 km</td>
<td>11.69 km</td>
<td>1.03 km</td>
<td>4.28 MPa</td>
<td>0.58 km</td>
</tr>
<tr>
<td>Humboldt</td>
<td>1</td>
<td>203.65 km</td>
<td>48.03 km</td>
<td>1.60 km</td>
<td>10.20 MPa</td>
<td>4.40 km</td>
</tr>
</tbody>
</table>

*The diameter was calculated using 3 points to fit a circle around the crater rim crest. The intrusion thickness (w_m) was calculated to be the difference in the crater floor depth from the depth of an unmodified crater of the same diameter, calculated using Pike [1980].
central region, distinct from the central peak region (Figure 2b). Combining this observation with the magmatic intrusion hypothesis, this uplifted floor region could yield information about the morphology, and in particular the lateral extent of the brecciated lens. For the five FFCs whose morphometry was studied in detail, the uplifted central floor region covered approximately 50% of the entire crater floor. The uplifted region of crater Gassendi was approximately 86% of the crater floor, however, the terraces on the northern wall of Gassendi (Figure 3a) obscure the edge of the moat, possibly affecting this result. Similarly, in crater Gaudibert, it is unclear whether or not the inner ridge constitutes part of the uplifted central region. If only the central most region of Gaudibert is considered (Figure 5b), the percent floor uplift is 33%, however, if the ridge is included in the uplifted region, the percent uplift becomes 58%. The discrepancy with both of these craters arises from the nature of their moat features, and the unknown origin of these features. It remains to be determined if moat formation is related to the extent of the brecciated lens, or is formed as the result of another facet of dike intrusion and sill formation. High-resolution gravity data from the GRAIL mission may help to resolve this question.

3.1.6. Floor Slope
[45] From crater profiles, regardless of the overall floor profile shape (excepting features such as graben), the absolute floor of the crater is approximately level, varying by only tens of meters (e.g., Figures 3b, 4b, and 7b). The background elevation, however, slopes by as much as hundreds of meters over a region approximately 100 m in length, especially near basin edges. This can be observed in Figure 3b, where the basinward rim crest of Gassendi is at a lower elevation primarily due to the lower elevation of the region, but despite this the overall topographic profile of Gassendi is flat. Although it is unlikely that viscous relaxation is dependent on regional slope, the regional slope would still be reflected in the final relaxed crater. Uplift from magmatic intrusion, on the other hand, would not only be independent of regional slope, but also would erase the record of such a regional slope in the area the intrusion is active.

3.1.7. Summary
[46] The key morphologic properties of FFCs include the floor depth, rim crest height, interior crater symmetry, presence or absence of a moat, and the texture and slope of the crater floor. These properties would all be affected by the initial FFC formation mechanism, and the LOLA and LROC-WAC data allow these properties to be investigated in regards to the proposed formation hypotheses. All of the above listed properties favor FFC formation by magmatic intrusion and sill formation, while remaining ambiguous, or unfavorable in relation to formation by viscous relaxation.

3.2. Implications of Crater Areal Distribution for Formation Mechanisms

3.2.1. Crater Size
[47] The distribution of FFCs appears to favor formation by intrusion rather than viscous relaxation for the following reasons. In order for the amount of viscous relaxation seen in FFCs to occur, locally high thermal gradients are required; though feasible for areas near the mare, such high thermal gradients would be more difficult to explain in the lunar highland regions [Hall et al., 1981; Wichman and Schultz, 1995; Dombard and Gillis, 2001]; however, the distribution of FFCs (Figures 1d, 2d, 3d, 4d, 5d, 6d, 7d, 8d, and 15), shows that FFCs occur not only along the edges of the lunar basins, but also occur as significant populations in the lunar highlands. Moreover, a majority of these highland craters are Class 4 FFCs, which (excluding crater Stoney, D = 45 km), have diameters less than 40 km; this small size would require an extremely high thermal gradient to cause modification by viscous relaxation than gradients known from other data [e.g., Dombard and Gillis, 2001]. FFC distribution also places severe constraints on the extent of potential thermal gradients. In areas such as the crater located at (51.29°N, 121.67°W) (Figure 15), a FFC is observed within the vicinity of an older, unmodified crater, implying an extremely localized thermal gradient that would modify the younger crater, yet leave the older crater undisturbed.

3.2.2. Kopff and Orientale
[48] One possible example of a FFC that could have formed via viscous relaxation is Kopff, located in Mare Orientale. Whitten et al. [2011] proposes that Kopff formed ~10 m.y. after the Orientale basin, excavating the upper layer of the solidified Orientale melt sheet. In this case Kopff would have formed at a time when the local thermal gradient was still relatively high, allowing for topographic relaxation before the crater was subsequently flooded by volcanic material. The rim crest height of Kopff is approximately 10% shallower than would be predicted given its diameter, however, this is still within the trend range for FFC rim crest heights. The depth to diameter ratio for crater Kopff also follows the trend for FFCs, and is plotted as the black square in the Class 3 Depth v. Diameter plot found in the auxiliary material. However, as a broader FFC formation mechanism, this process would only be applicable to craters formed inside basin regions and very soon after basin formation or mare emplacement. These characteristics fit only a very small subset of all FFCs, those being the set of Class 3 FFCs which are contained within lunar basins, and often covered in mare material. However, it should be noted that these craters (such as Runge) have prominent wide moat features and plate-like central floor regions, features unsupportive of formation by viscous relaxation.

3.3. Magmatic Intrusion Models

[49] Using the dimensions of the crater, and material constants, a theoretical driving pressure for the magma can be calculated to provide a more quantitative assessment of the magmatic intrusion model, represented schematically by Figure 19. The intrusion thickness, $w_m$, is taken to be the depth difference between the crater’s theoretical unmodified depth (calculated using Pike [1980]), and the current depth of the crater, which was interpreted to be the most frequent crater floor depth. The axisymmetric radius of the intrusion, $a$, was measured from the uplifted region of the crater interior, a region that was easily identifiable from the crater profile. The dimensions of the modeled intrusion are listed in Table 3, and a schematic of the crater parameters is given in Figure 19. The physical assumption of the model from which the equations are derived, is that the uplifted crater floor is supported entirely by the underlying intrusion; for a full derivation we direct the reader to Johnson and Pollard...
was calculated
to be
the driving pressure and flexural
thickness of the overlying crust (or roof), $T_\text{cr}$,
\begin{equation}
    P_d = \left(2k/a + \gamma_m\right),
\end{equation}
From this driving pressure, equation (2) $[\text{Johnson and Pollard, 1973}]$ was used to calculate the flexural thickness of the overlying crust:
\begin{equation}
    P_d = (5.33w_mB_mT_\text{cr})/a^4,
\end{equation}
Results of these calculations are displayed in Table 3.

Both the magmatic driving pressure and flexural thickness scale with crater diameter, as would be expected. These calculations are similar to those of $\text{Wichman and Schultz [1995]}$, wherein the driving pressure and flexural thickness for Taruntius was modeled. The values presented here are lower than those predicted by $\text{Wichman and Schultz [1995]}$; however, this is expected given the refined topography data available for this study.

The calculated magma driving pressures shown in Table 3 are feasible for an intrusion stalled several kilometers below the surface. An intrusion beneath crater Gassendi, for example would require a driving pressure of 11.34 MPa. $\text{Head and Wilson [1992]}$ calculate that a magma overpressure greater than 15.1 MPa is necessary to penetrate the nearside crust. Thus the model is consistent with the dike not penetrating the floor of Gassendi. The two largest craters modeled (Gassendi and Humboldt), also have the largest flexural thickness (Table 3), this could be attributed to a larger brecciated lens formed during crater formation and modification stage.

In the magmatic intrusion model (Figure 19), a dike propagates from the mantle, and is halted by a density boundary at the base of the brecciated lens. The dike has a specific driving pressure necessary to fracture the anorthositic crust $[\text{Jolliff et al., 2006}]$ and raise the negatively buoyant magma. However, upon reaching the lower density zone of the brecciated lens, the driving pressure is no longer great enough to support vertical propagation, and the dike stalls. Then the dike propagates laterally forming a sill, and eventually a laccolith. Remaining questions include the exact nature of this density boundary and how it relates to the stratigraphy underneath the overlying crust (Figure 18). Detailed gravity data for these craters, such as that which will be provided by GRAIL, could help determine definitively whether FFCs are formed by intrusion and uplift or by viscous relaxation. Young non-FFCs have been observed to have large negative Bouguer gravity anomalies $[\text{Sjogren et al., 1972; Scott, 1974; Janle, 1977; Dvorak and Phillips, 1977}]$, whereas the older FFCs Humboldt and Petavius have, for their size, smaller negative Bouguer anomalies relative to young non-FFCs $[\text{Dvorak and Phillips, 1978}]$. The mass accommodated by the floor uplift is not enough to account for the decreased Bouguer anomaly according to models in $\text{Dvorak and Phillips [1978]}$. One interpretation for this disparity is that intruding magma below the crater floor also contributes to the diminishment of the Bouguer anomaly underneath FFCs. Future work will focus on analyzing the enhanced gravity data in conjunction with the FFC classes and distributions to elucidate a more detailed formation model for FFCs.

4. Conclusions

The availability of Lunar Reconnaissance Orbiter LOLA topographic data and LROC images has made possible a detailed investigation of FFCs, and a more quantitative approach to their classification. The depth versus diameter relationship of the FFCs is distinctly shallower than the same regression for fresh craters (Figure 13); however, both FFCs and fresh craters share the same relationship between external rim crest height and diameter (Figure 14). Detailed crater profiles allow for the observation of crater structures that justify the further classification of FFCs into 6 subclasses. The distribution of these classes across the lunar surface has implications for both their formation and also the geothermal environment in which they evolved. This distribution of FFC classes supports formation by magmatic intrusion as the crater morphologies evolve from regions adjacent to impact basins into the lunar highlands. Further work should be done to investigate quantitatively this relationship. Of the two proposed formation mechanisms for FFCs, viscous relaxation and magmatic intrusion, we favor magmatic intrusion on the basis of the data outlined above. Other works $[\text{Wichman and Schultz, 1995; Dombard and Gillis, 2001}]$ have shown the rheological improbability of formation by viscous relaxation, and this work shows that the morphologic and morphometric features observed are inconsistent with viscous relaxation, and instead support magmatic intrusion. Detailed models of the evolution and emplacement of these intrusions can be carried out with the availability of this highly detailed data set, and data from the GRAIL (Gravity Recovery and Interior Laboratory) mission will help to test and refine these conclusions.

In this work we focus solely on Lunar FFCs, we note that floor-fractured craters have been identified on both Mars $[\text{Schultz, 1978; Korteniemi et al., 2006}]$ and on Mercury $[\text{Schultz, 1977; Head et al., 2009}]$. Martian floor-fractured craters exhibit morphological characteristics such as shallow, fractured floors and moats; however, the floors of many of these craters have been highly dissected, and the overall morphologies of these craters have been heavily influenced by interactions with ice in the crustal material $[\text{Korteniemi et al., 2006; Schultz and Glicken, 1979; Costard and Dolfus, 1987; Sato et al., 2010}]$. $\text{Schultz [1977]}$ identified several candidate FFCs on Mercury in images from the Mariner 10 mission, using albedo differences within the crater floor region as an identifying feature. In images from the first flyby of the MESSENGER mission, $\text{Head et al. [2009]}$ identify a single candidate floor-fractured crater, similar in morphology to lunar Class 4 FFCs, with a floor region consisting of two upbowed lobes, and an association with nearby plains of volcanic origin. This crater remains the only analogous floor-fractured crater observed in the global coverage of Mercury with the MESSENGER MDIS imagery. It is postulated that the lack of floor-fractured craters on Mercury is indicative of a planetary structure that does not favor small scale intrusive volcanism; rather the thin mantle of Mercury seems to favor large-scale flood basalt style eruptions $[\text{Head et al., 2012}]$. 
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References


Reddy, D. J. (1968), Shock Metamorphism of Natural Materials, Mono, Baltimore, Md.


