REASSESSING THE FORMATION PROCESS OF LUNAR FLOOR-FRACTURED CRATERS.

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Introduction: Lunar floor-fractured craters (FFCs) are a subset of ~170 lunar craters with floors that have been uplifted and fractured [1, 2]. In addition to the uplifted, fractured floors, FFCs host numerous associated morphologies including volcanic morphologies (such as mare deposits and pyroclastic deposits), fracture morphologies, and topographic profiles which have allowed the craters to be further divided into 8 morphologic subclasses [1, 2].

Early theories postulated that the deformation could result from either viscous relaxation of the crater floor [e.g. 3, 4], or the intrusion of a magmatic body beneath the crater [e.g. 1]. However, several recent studies [2, 5, 6, 7] leveraging data from the Lunar Reconnaissance Orbiter (LRO) [8] and Gravity Recovery and Interior Laboratory (GRAIL) [9] missions have shown that the observed deformation patterns can be conclusively linked to the subcrater magmatic intrusion hypothesis. While several of those works [2, 5] have subsequently outlined a phenomenological framework for the formation sequence of floor-fractured craters, these schematics are seemingly incongruous with terrestrial finite-element models of sill formation [e.g. 10, 11], and are also not detailed enough to account for the wide range of morphologies observed in the FFC subclasses.

In this work, we present the two possible modes of FFC intrusion formation, and then use detailed geomorphologic studies of FFCs to distinguish the likely mode of formation. Finally, we also present a hypothesis for the origin of the FFC morphologic subclasses and identify remaining open questions.

Subcrater Magmatic Intrusion Formation: The canonical process of FFC formation [1, 2, 5, 7] is described by the following steps: 1) a dike propagating from depth encounters a density or rheological boundary in the heavily brecciated region beneath a crater, 2) the dike ceases vertical propagation, but excess pressure in the magma causes lateral fracturing and magma propagation, forming a sill, 3) the sill extends to the edges of the crater floor, where increased overburden pressure from the walls causes propagation to cease, 4) magma continues to fill the sill resulting in a laccolith beneath smaller craters (D < 40 km), and a tabular sill beneath larger craters (D > 40 km). The resulting idealized cross-section for this process is shown in Fig. 1. The crux of the problem lies in the ambiguity of the sill formation process and how it relates to the final intrusion morphology (i.e. laccolith vs. tabular sill), and in particular, whether the floor uplift observed in large floor-fractured craters is the result of so-called “piston-like uplift”.

Discrete intrusion formation. The formation model we have termed “discrete” is described, and detailed schematically in both [1] and [2]. Conceptually, this model envisions the sill propagating to the full horizontal extent before large-scale vertical uplift of the floor occurs. Focusing only on the effects for larger craters, this model would suggest shallow degrees of fracturing in the center of the crater floor, with the greatest degree and depth of fracturing localized near the edge of the crater floor, where the piston-uplift has occurred. The model allows for the near uniform thickening of the sill, encourages dike propagation at the edges of the sill, and accommodates a “piston-like” i.e. wholescale uplift of the crater floor.

Continuous intrusion formation. In contrast, the formation model we have termed “continuous” has arisen from recent modeling efforts including finite element modeling of terrestrial sill formation [10, 11], and numerical modeling of dike propagation in lunar settings [7]. This model suggests that following the cessation of dike propagation, the laterally propagating sill proceeds to grow laterally while simultaneously inflating vertically. In this way the horizontal and vertical growth of the sill occur synchronously, although the degree of horizontal growth far exceeds vertical growth. In larger craters this would manifest as greater degrees and depths of fracturing near the center of the crater floor with increased fracture shallowing closer to the crater walls. This model disfavors the notion of a coherent “piston-like” uplift of the crater floor, rather it allows for partial or otherwise piece-meal uplifts of the floor. The model also allows for both laccolith-style and sill-style FFCs to be considered as part of a formation continuum, as opposed to bifurcating end-members.

Geomorphological Analysis: In order to investigate these two hypotheses, we performed a series of detailed geomorphological analysis on 4 FFCs: Humboldt (morphologic class 1), Vitello (morphologic class 2), Bohnenberger (class 4a), and Alphonsus (morphologic class 5) [2]. Here we will focus on the results for the crater Humboldt (D = 207 km, 80.9° E, 27.2° S). Using the combined LOLA-Kaguya Terrain Camera DEM [12], we produced a contour map of the crater floor, to better assess the degree and uniformity of floor uplift. We observed that, although seemingly flat, the floor of Humboldt is actually subtly domed; the central region of the crater floor is ~1.5 km higher than the edges of the crater floor. This doming is reminiscent of more traditionally laccolithic FFCs, such as Vitello; however, the vast expanse of the Humboldt crater floor obscured this topographic signature. We then used the Kaguya terrain camera mosaic [13] combined with the LOLA/Kaguya DEM [12] to investigate the morphologic and morphometric variations in the Humboldt floor fractures. We observed 5 fracture styles distributed across the crater floor (Fig. 2): graben, deep V, shallow V, pit chains, and inferred fractures (identified using detrended LOLA data). The distribution of fracture styles indicates that the largest degree of fracturing/greatest uplift occurred in the center of the crater floor, and fracture profiles become shallower with increasing proximity to the crater wall. Additionally, the cross-cutting relationships between the concentric and radial fracture segments suggest synchronous, or near-synchronous formation. Taken together, the fracture morphologies and the floor topography clearly favor the “continuous” intrusion formation model.

Similarly, the geomorphological assessment of Vitello and Bohnenberger favor the continuous formation model. The analysis of Alphonsus suggests that the original crater floor of Nectarian-aged Alphonsus [14] is buried beneath several meters of ejecta from the nearby Imbrium basin [15], obscuring the initial floor topography. The presence of such unconsolidated regolith substrate would similarly shallow and obscure the floor fractures, as evidenced by the abundance of shallow V fractures and inferred fractures within Alphonsus.

Conclusions: The current literature on FFC formation suggests two possible pathways for sill/laccolith formation—one where tabular sills and laccoliths represent discrete endmembers of initial sill formation, and one where they exist on a continuum that is largely a function of intruded magma volume and crater diameter. Detailed geomorphological analysis of several representative floor-fractured craters suggests that the floor and fractured morphologies support the continuous model of intrusion formation. Although a seemingly subtle distinction, this clarification has important ramifications, as it implies that all FFCs are subject to the same formation and evolution process, and that there is not one formation process for large FFCs and another one for small FFCs. Furthermore, this distinction suggests that the recognized FFC morphologic subclasses may simply be manifestations of differences in the crater initial conditions such as crater wall/terrace morphology or proximity to mare deposits. We are now working towards an integrated model of FFC formation wherein we consider the FFC sub-classes as variations in initial setting, and are also establishing a generalized list of criteria (beyond simply the presence of fractures) for identifying shallow magmatic intrusions on the Moon and other terrestrial bodies.

Figures:

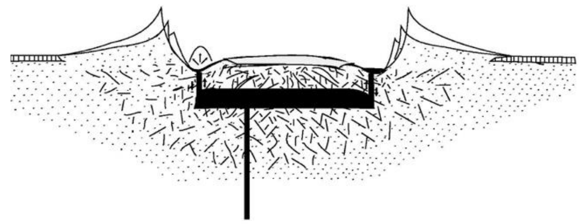

Figure 1: Schematic cross-section of a large (D > 40 km) FFC. This figure emphasizes the piston-like uplift formation theory, although the relative thickness of the magmatic intrusion is not to scale. From: Jozwiak et al. (2015) [5].

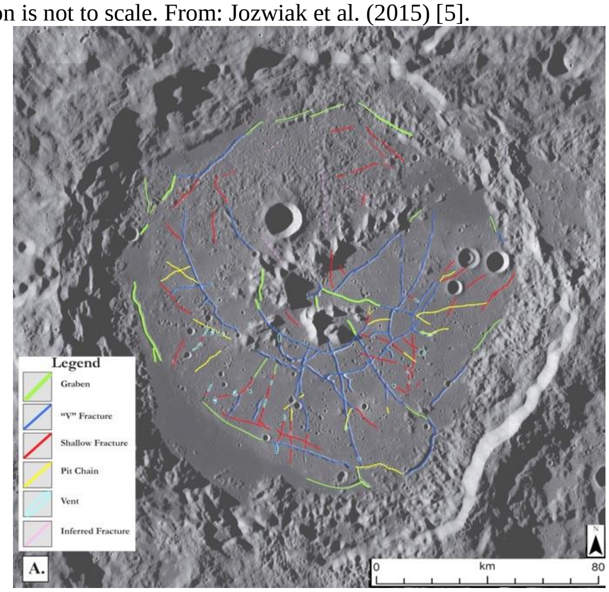

Figure 2: Map of fracture morphology for the FFC Humboldt. The deep, V-fracture morphology dominates interior portions of the crater floor, while shallow V-fractures dominate the outer portions. This pattern is consistent with the continuous intrusion formation scenario.

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