FLOOR-FRACTURED CRATERS ON THE TERRESTRIAL PLANETS – THE MARTIAN PERSPECTIVE

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ABSTRACT

Floor-fractured craters appear to occur on all the cratered terrestrial planets. Their floors are typically raised as a whole, or they are cut into large elevated blocks. The floors exhibit radial, concentric and/or polygonal fractures, occasionally mixed with volcanic features. The craters occur almost always next to large regional volcanic provinces, indicating an intimate relationship with endogenic activity. This paper reviews shortly the multitude of past work done on the floor-fractured craters in the inner Solar System. We also provide the preliminary results of a new survey done on Martian floor-fractured (and related) craters.

1. INTRODUCTION

Fractured floors are a type of anomalous features which can be found in impact structures. Instead of ‘regular’ flat floors with just peak rings, pits or occasional slumps from the walls, they exhibit intense modification of the crater interiors, including fracturing and uplifting [1]. They occur near large regional volcanic provinces, indicating an intimate relationship with them. Floor fractures occur only in some impact craters (FF craters) but not in most. Thus they are representations of endogenic processes, which emerge into view only through impact structures and special conditions. This is probably caused by the combination of the undercrater environment, e.g. the subcrater fracture zone, and its occurrence just in the “right” place and time.

2. DESCRIPTIONS AND CLASSIFICATIONS

FF craters are a diverse group, which can be classified using several properties. Although generally similar from planet to planet, they do occur in slightly varying forms, indicating the environment they reside in.

2.1. Basic types

Much of the fundamental observational data on the FF craters have been gathered from the Moon [e.g. 1-5]. The idealized floor-fractured impact crater exhibits both concentric and radial crevasses/troughs, with an additional circumferal moat near the crater rim. [1] found that the FF craters are generally clearly shallower and tend to often have 2-3 times smaller rim to peak ring elevation differences than unmodified craters in the same region, indicating that the FF crater floors have been uplifted by some process. There are, of course, several deviations from the basic form, and classifications can be used to categorize the features.

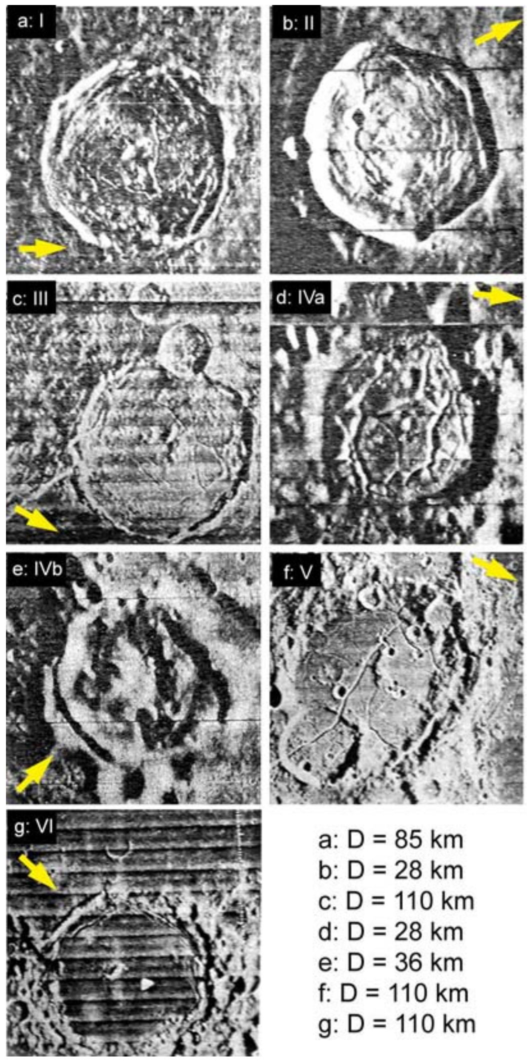

Fig. 1. Examples of fractured-floor crater classes I-VI (see text). Yellow arrows show rough estimation of Sun direction. Modified from [1].

Classification by [1] puts the Lunar FF craters into six types, representing degrees of modification, initial appearance and size, and possible different crater origins. In short, they are (see Fig. 1 for reference):

I) 16 fresh-looking deep large craters (D ~50-120 km); central peaks and concentric/radial fracture patterns; elongate pits and dark mantle deposits in fractures near the wall; typically near shallow maria, only two individuals in the highlands.
II) 23 shallow small craters (D ~20-40 km); hummocky floors and fractures; near/within maria.
III) 37 shallow small craters (D ~20-100 km); wide U-shaped moats next to crater wall; a symmetric ridge borders the raised floor plate; cones and fissures are common; near maria.
IV) 92 small craters (D ~20-30 km); narrow V-shaped moats with a ridge bordering it; ridge can be higher than the crater rim (class IVb; 7 craters). Situated mostly at great distances from the maria.
V) 25 medium-size craters (D ~70 km); relatively unmodified; polygonal/concentric fractures; deep or shallow depending on post-impact modification stage prior to fracturing; near the maria.
VI) 13 craters (D ~20-120 km); fractured mare or mare-like plains; fractures polygonal, radial or concentric; some low-relief hummocks.

Many Lunar floor-fractured craters also exhibit dark mantling, cone structures placed on and immediately next to the fractures, and occasionally fresh floor units overlying the older fractured terrain; these have been interpreted as volcanic units [e.g. 1,2,6,7].

2.2. Martian deviances

On Mars, the basic FF crater form is the same as on the Moon (Fig. 2a), though some exhibit properties not found elsewhere. [8-10] showed that these craters have a more extensive and wider system of fractures (Fig. 2b), which they interpreted as volatile-induced enhancement of the fracture formation. Additionally, the Martian craters exhibit more often a polygonal fracture system, indicating repeated periods of floor uplift and subsidence [8].

Additionally, two other crater types found on Mars should be mentioned here, as they are related to the FF craters. Firstly, craters with chaotic floors (CF craters) occur in the same regions (see chapter 3 for details on the distribution). These crater floors are so heavily dissected that instead of fractures, they rather exhibit deep floors with only remnant mesas and knobs inside (Fig. 2c). Often the "craters" themselves are so highly modified that they can only be interpreted as ancient remains of impact craters, as they have no rim or ejecta blanket. The chaotic regions are described and discussed in detail e.g. in [11 and references therein]. Together with the FFs, the CFs have been interpreted to create a sequence of crater modification stages [12]. Smallest FF fractures and moats seemingly develop and larger concentric and radial fissures of the fully grown FF craters. Continuing this deformation, they cut the crater floor into pieces; in the end this results in a CF crater-like circular depression with a chaotically dissected floor, which often ends up with partly collapsed or totally destroyed walls [e.g. 11,13].

Secondly, regions harbouring FF craters also exhibit crater floors with irregular depressions (ID craters, see Fig. 2d) [14-16]. These depressions have typical depths of 50-300 m, and are mostly small compared to the parent crater (cover usually <20% of crater diameter). The depression walls exhibit layers, indicating a sedimentary origin of the surrounding material; usually the craters with IDs are rather shallow compared to average fresh craters. This is seen as evidence for crater filling by deposited materials. However, these depressions are typically not found outside impact craters. The ID craters are usually not connected with any fluvial or major tectonic features directly capable of explaining the depressions. The ID craters often occur on the outskirts of the FF crater clusters, and ostensibly continue the FF-CF sequence. However, it must be emphasized that this proposed sequence does not necessarily represent a proven developmental continuum.

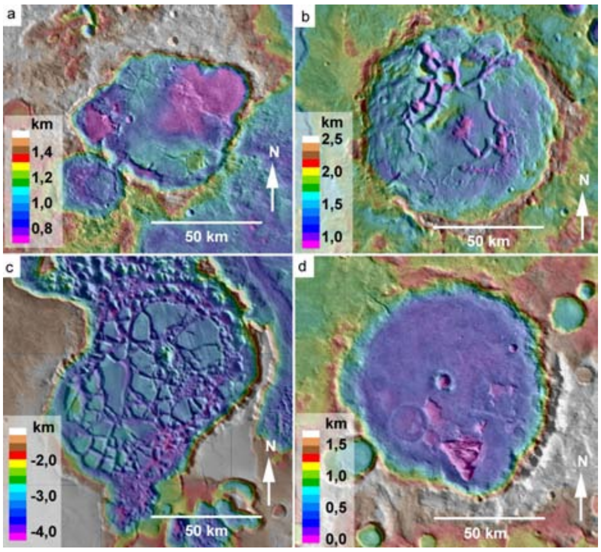

Fig. 2. Martian FF craters shown in Viking MDIM2 detail with MOLA colors. **a)** Narrow concentric / radial crevasses along the border of an uplifted central plate (16 °N, 56 °E); note the southern edge moat. **b)** Wider fissures (3°N, 53°E) common only to Mars. **c)** This chaotically fractured crater pair (3 °N, 331 °E) has a broken northern rim and a connection to nearby fluvial channel. The fracture patterns still retain the crater shapes. **d)** 3-part irregular depression complex (32 °S, 41 °E); a triangle-shaped S portion and two shallower irregular depressions NE and NW from it.

Although irregular and very diverse as a group, directional patterns do emerge from the depressions; many of the depression walls are straight. These ID walls are usually either 1) radial or concentric to the parent crater, or 2) straight and parallel to each other within a cluster of ID craters in particular regions [17]. This may indicate that the ID formation is controlled, enhanced or enabled in the first case by the crater structure itself, similar to the radial and concentric FF fractures. In the second case they appear to be controlled by a regional trend - the main direction was radial to the nearby Hellas region [17]. Similar regional patterns are also observed e.g. in the distribution of polygonal crater wall directions [18,19].

3. FRACTURED CRATER DISTRIBUTIONS

3.1. Moon

On the Moon 206 craters have been recognized to be floor-fractured [1]. They are situated on a relative narrow region on the highlands, surrounding the mare regions. Mainly those belonging to class IV are additionally spread around farther away from the maria. The distribution differs considerably from that of the global crater population, inferring their close relationship with the mare development [1].

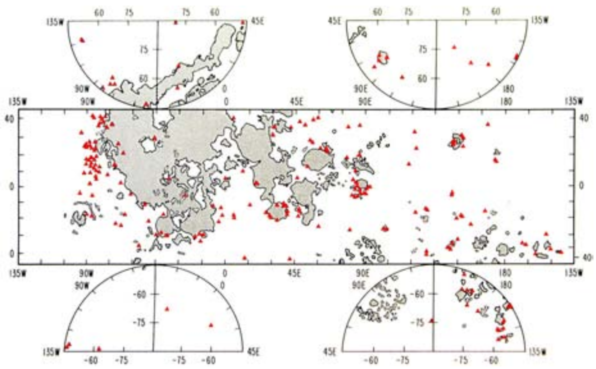

Fig. 3. Distribution of floor-fractured craters (red triangles) on the Moon relative to the maria (grey) and the highlands (white). Note the dense clusters near some of the large basins. Modified from [1].

3.2. Mars

Martian floor-fractured craters are mostly distributed along a narrow band south of the dichotomy boundary in Arabia Terra (0-45 °N, -15-120 °E) and at the mouths of Valles Marineris and the adjacent outflow channels (-20-10 °N, 305-355 °E). 80 FF craters were found and categorized using Mariner 9 and preliminary Viking data [8]. A newer search, using standardized Viking MDIM2 and MGS MOLA data, revealed a total of 111 FF craters [15,16], strengthening the same regional trend as found before (Fig. 4). At the same time, additional 69 CF craters were recognized to lie at the northern sides of the regional FF clusters - generally directly on the dichotomy boundary.

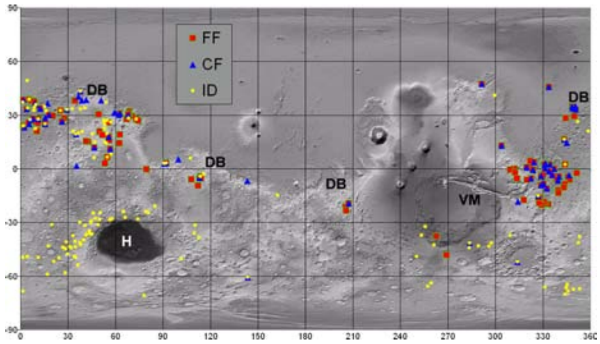

Fig. 4. Distribution of Martian craters with floor-fractures (red boxes), chaotic floors (blue triangles) and floors with irregular depressions (yellow circles). The main concentration of FF, CF and some ID craters is near the dichotomy boundary (DB) and the mouth of Valles Marineris (VM), and the separate cluster of IDs near the Hellas basin (H). Data from [16].

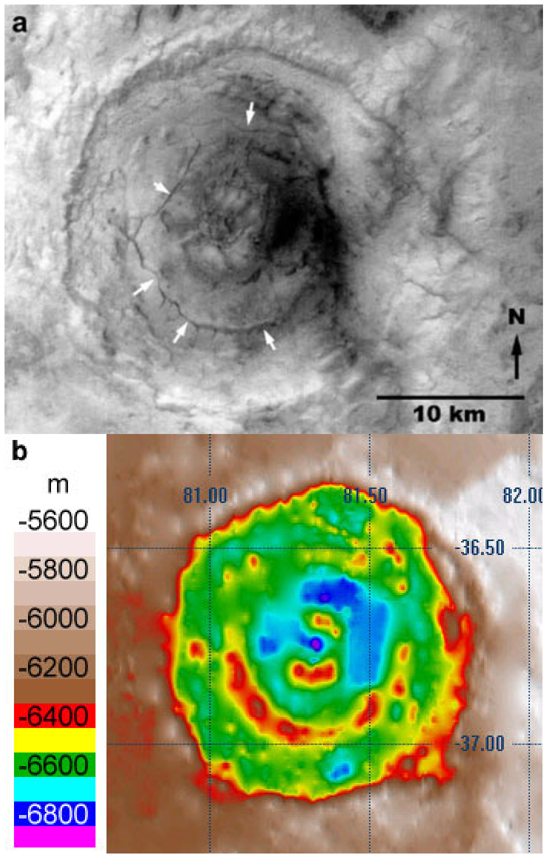

Fig. 5. a) Newly found 52-km Martian floor-fractured crater (36.7 °S, 81.2 °E); arrows show the concentric fracture system with radial branches. HRSC orbit 49, modified from [21]. **b)** MOLA topography; noted fractures lie on the concentric >200 m high ridge top.

Additional 129 ID craters were identified; roughly 1/3 of which are situated in or immediately adjacent to the Arabia Terra FF clusters, while 2/3 lie in a separate distinct faction north and west the Hellas basin with a 'tail' in Noachis Terra thinning out towards Argyre [14-17,20-23]. Continuing this work, one FF crater was identified (and a few proposed) on the floor of the southern Hellas impact basin (Fig. 5) [16,21], perhaps indicating that also the Hellas floor has been volcanically active and not just flooded with lavas from nearby volcanic centers, Hesperia and Malea Plana.

3.3. Other planets

Mercury has been imaged only partly, and with a rather poor ~1 km pixel resolution. Because of this, no definite floor-fractured craters have yet been identified there. However, [24] found several good candidates searching for intracrater dark haloes or other color variations indicating post-impact emplacement of mafic materials onto the floor. They did find several crater floors with contrasting deposits, and additionally a few rimmed moat-like depressions (see Fig. 6). However, all the found structures are either ambiguous or just at the edge of resolution. Thus, more detailed data is needed for proof of Mercurian FF craters.

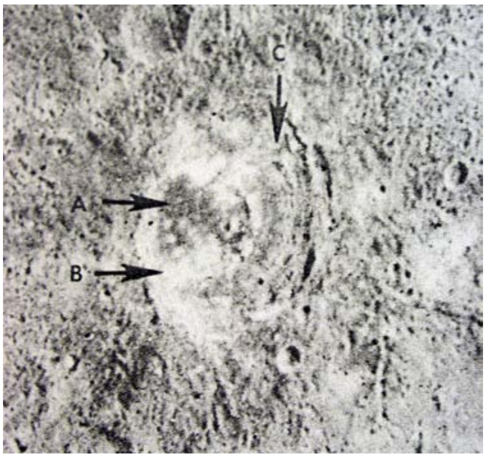

Fig. 6. (left) The Mercurian 120-km crater Zeami (2°S, 148°W) shows dark (A) and bright (B) regions on its floor. C shows a possible rimmed moat, similar to those of the Lunar FF craters. Modified from [24].

Both **Venus'** and Earth's geologic records have been cut off by the intense resurfacing phenomena reworking the planets. Thus, the most ancient and cratered surfaces are mostly wiped out on both planets. However, according to the online databases, over 942 craters remain on Venus [25,26]. Out of these, only a few probable FF craters have been recognized [27-29].

Earth has preserved only 174 impact structures recognized (proven) so far [30], but still two large terrestrial craters exhibit features which can be interpreted as being result of the floor-fracturing processes. [31] proposed that the 55 km central floor of the Manicouagan structure was uplifted by a post-impact tabular magmatic body leaving behind the circular moat we see today. They also state that the outer ring structure of Manicouagan was produced by a ring dike intrusion originating from that magma. However, the authors do admit that their idea is not entirely airtight.

The Sudbury structure has offset dikes, which have been taken by [32] to represent post-impact magma injections. They continue to state that the dike pattern may reflect the flexural uplift of the crater floor during its post-formation isostatic movement, showing resemblance to Lunar floor-fractured craters. They also acknowledge that the source is probably not an independent endogenic intrusion; instead it is an independent injection from the impact melt sheet body. [33] indeed recognize that the dikes are genetically related to the igneous complex in the impact crater. However, they conclude that it was caused by the collapse of the transient cavity and subsequent back-injection of impact-caused melting or by peak ring formation during rebound.

4. FORMATION MODELS FOR THE FRACTURED FLOORS

The morphology of the FF craters suggests that they have undoubtedly been modified by an endogenic process uplifting the crater floor [e.g. 1]. Judging from their distribution, this is apparently related to regional volcanism, but the mechanism is under some debate.

Classically there are two models, which have been used to explain the floor-fracturing of some craters; 1) laccolith intrusions traversing along subcrater fracture patterns and 2) viscous relaxation of the crater floor over time. Both mechanisms can explain the development of the observed features in individual floor-fractured craters, but they have distinctly different implications for the nature of local crustal conditions during crater modification. Below we summarize the model ideas but do not go deep into model implications. These models have been studied and compared thoroughly in [34,35].

4.1. Intrusion model

In the intrusion model, laccolith protrudes through the fractured undercrater zone directly or indirectly into the subcrater brecciated region. This causes a small magma chamber to form into the subcrater brecciated region (inside the transient crater). Subsequently the floor is uplifted *en bloc* and fractures occur on the floor surface. If the volcanism reaches the surface, some flooding of the crater floor may occur. Thus the FF craters indicate sites of individual intrusions, in a region / time when large subsurface magma chambers and/or surface mare /lava plains units are emplaced [1,2,34,36].

4.2. Relaxation model

The elastic or "elastoviscoplastic" relaxation model requires the crustal viscosity to be quite low at depth. This in turn would enable the impact crater to search a new equilibrium state after its formation, and create the features seen today. This model requires that the crustal viscosity scheme is somehow altered either locally or regionally near the affected craters. This is thought to occur at time periods of active (mare) volcanism, and thus the floor-fractured craters would reflect the extent and intensity of regional heating [37,38]. The fractured crater floor is at the roughly same elevation as the exterior mare elevation, suggesting isostatic adjustment. This scheme has later been modelled [34,35,39] and proven to be unsatisfactory in explaining all the FF features [35]. Not all impact craters of similar size, age or location are affected by this modification process. Thus it is felt that internal magma plumbing, rather than isostatic adjustment, controlled the crater modification [24].

4.3. Enhancement by volatiles

The wider Martian FFs and chaotic crater floors are generally thought to be the result of volcano-ice/water interaction [8-11,13]. In this scenario, water (or possibly CO_2?) trapped in the subsurface reacts to the raised temperatures induced by the magmatic intrusion. It is melted, and either flows through subsurface drainage systems [see 11 for details], evaporates into the atmosphere or escapes through fluvial channels on the surface. The craters with the widest floor-fractures are indeed sometimes connected to small or medium-sized fluvial outlets, and the CF craters are the usual starting points of major outflow channels.

If the craters with irregular depressions found on Mars indeed are related to FF craters, the occurrence of a major ID cluster around Hellas basin can be explained. In our view, this also requires the presence of volatiles in the sediments filling the parent crater. The proposed sequence is as follows. 1) A crater forms, and later becomes partly filled with volatile-laden sediments. 2) A laccolith injection occurs, forming a magma chamber beneath the crater floor, raising it and its general temperature. 3) The volatiles in the sediments warm up and become mobile; they are either pumped out through a subsurface drainage system (as no surface tracks are visible), or they vaporize straight into the atmosphere. 4) The volume left by the removed volatiles is collapsed, where applicable, controlled by regional /local stress patterns.

5. DISCUSSION

As for Mars, the discovery of a floor-fractured crater inside the giant Hellas impact basin may indicate that the region is or at least has been more active volcanically than has previously been believed. This is further supported by the interpretation that the ID craters, abundant in the region, may in fact be a continuation of the FF-CF sequence [15]. Additionally, the thorough analysis of one ID crater pair on the Hellas rim [22] showed at least a possibility of long distance dikes propagating and penetrating into the crater floor. The floor of the Hellas basin is often covered by dense cloud layers and dust in the atmosphere – it has only recently been imaged thoroughly with a good resolution by the HRSC, THEMIS and MOC cameras. Thus, a more detailed search of the Hellas rim and floor craters for signs of fracturing (as well as other possible volcanic features) will provide new insight to both 1) the large scale modification of the crust by a Hellas size impact, and 2) regional interaction between volcanism and volatile-rich subsurface.

The eminent search for floor-fractured craters on all terrestrial planets, their categorization and interpretation done in the 1970's and early 80's [1-5, 8-10, 24, 31, 37-38] is an extremely good basis for work using new data and new methods at hand today. As recently acquired data has shown [21], not all floor-fractured craters have previously been recognized, e.g. due to resolution constraints. The apparent absence of terrestrial FF craters may provide interesting clues to the crater formation and later modification – why do no FF craters appear to occur on Earth? Would the best place to create such a crater be a tectonic plate border with abundant volcanism, and if so, how quickly is the crater destroyed? The datasets accumulated on our own impact structures should be looked into carefully, to see if some of the modified craters may in fact have been floor-fractured. This applies to all terrestrial planets; new space probes have recently imaged the Mars and Moon with unprecedented spectral and spatial resolutions, and in a few years several missions will extend our knowledge of both Mercurian and Venusian surfaces.

Whatever the mechanism, the FF crater formation is intimately related to regional volcanism, possibly magmatic intrusions. They are found on all terrestrial planets in one form or another. Thus, they can be used as indicators and study tools of deep-seated regional endogenic activity. Furthermore, as the crater floor is uplifted and fractured, more detailed studies of e.g. the fractures and moats themselves will reveal also much more information, being natural cross-sections through the stratigraphy of the crater floor.

6. ACKNOWLEDGEMENTS

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