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MARTIAN INTRUSIONS:
POSSIBLE SITES AND IMPLICATIONS

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Abstract. Both the Moon and Mars exhibit volcanic modification of impact craters characterized by subfloor intrusions that either lift the old crater floor or result in extrusions of lava. Endogenic modification of martian craters, however, probably has involved interactions between such intrusive bodies and permafrost, as suggested by differences between lunar and martian floor-fractured craters. Such interactions raise the interesting possibility for hydrothermally concentrating ores in a manner analogous to the Sudbury structure on the Earth that may be consistent with interpretations of Viking lander results.

Introduction

Localized crustal weaknesses created by impact craters represent primary pathways for basaltic volcanism on the Moon. Such volcanic centers are expressed by mare-filled craters with unbreached rims ranging in size from smaller than 10 km in diameter to the largest basins. In addition, over 200 lunar craters exhibit floor fractures and other tectonic modifications that provide important clues for the distribution, timing, and the style of volcanism associated with the much larger lunar basins (e.g., *Pike,* 1971; *Schultz,* 1976). Mars (*Schultz et al.,* 1973) and perhaps Mercury (*Schultz,* 1977) also exhibit impact craters with endogenic modifications. Consequently, where flow termini and other indicators of endogenic processes are absent or ambiguous, floor-fractured craters may provide a record of a major stage in the thermal history of the planet.

Crater-Centered Intrusions on the Moon and Mars

The volcanic and tectonic history of Mars is considerably more complex than the volcanic history of the Moon. Nevertheless, the early stages of martian volcanism resulted in certain cratered plains resembling the lunar maria that were tentatively identified in Mariner 6 and 7 images (*Schultz and Ingerson,* 1973) and subsequently mapped from Mariner 9 images (*Carr et al.,* 1973). The existence and distribution of over 80 floor-fractured craters on Mars strengthen the gross similarity of this early eruptive phase on the two planets. Martian craters exhibiting floor fracturing typically occur within the cratered plains and cratered southern highlands near the borders of vast smooth plains units of the northern hemisphere (Figure 1). More specifically, they appear to be restricted to the "plateau plains" described by *Wilhelms* (1974) from Mariner 9 images and *Spudis and Greeley* (1977) from Viking Orbiter images. Similarly, on the Moon, floor-fractured craters predominantly occur within the cratered highlands near the margins of the maria. Notable exceptions on Mars occur near Valles Marineris and at the apparent source of sinuous channels. These interesting exceptions are discussed later.

By analogy with endogenically modified craters on the Moon, many martian floor-fractured craters may indicate the sequence of inundation of irregular basaltic plains. The location of such craters in the cratered highlands on the margins of the plains suggests that such lava plains expand not only by passive encroachment of lavas from remote vents, but also by active, parasitic eruptions within pre-existing impact craters. This analogy is strengthened by the lava-filled martian crater in Figure 3 that exhibits many similarities to the lunar basalt-filled and floor-fractured craters summarized above and discussed in more detail by *Schultz* (1976). Moreover, many martian craters that appear to be filled with airborne deposits may represent basalt-filled or basalt-capped crater floors only mantled by such deposits (*Schultz et al.,* 1973). The close association of martian floor-fractured craters and the plateau plains mapped by *Spudis and Greeley* (1977) could indicate a more specific epoch of martian volcanism prior to plains formation but after the period of intense impact cratering.

Figure 1 reveals that a cluster of floor-fractured craters occurs adjacent to Valles Marineris and the region eastward: tectonic features not found on the Moon. Some of these examples interconnect with the margin of Coprates Chasma, an eastern extension of Vales Marineris, and the chaotic terrain to the east. But numerous examples are not connected, thereby suggesting that their modification is related to the formation of these terrains by an endogenic link and not a simple result of surficial processes, e.g., aeolian erosion or undercutting. Moreover, the distribution of such craters suggests an extension of this endogenic process generally to the east and along a NE-SW trend, reflecting lineament trends and unconnected segments of chaotic terrain (*Schultz and Ingerson,* 1973). As is clear from Figure 1, the north-trending system of channels is not accompanied by floor-fractured craters. This exclusion further supports an origin of such channels distinct from but related to the canyon systems to the south: for example, erosion due to fluid release associated with endogenic sources near Valles Marineris/Coprates-Chasma systems (*McCauley et al.,* 1972; *Schultz et al.,* 1973; *Baker and Milton,* 1974; *Masursky et al.,* 1977). *Sharp* (1973) also argued that the chaotic terrain could have developed by subsurface movement of magma and enhanced by ground ice deterioration.

Modified craters unconnected to nearby canyons suggest an internal origin related to the development of the martian canyonlands, but floor fractures become more numerous and commonly wider where such craters connect with the canyonlands and chaotic terrains. Moreover, in these latter examples, a moat encircling the broken floor plate is typically well developed. These two styles of modification contribute to the differences between the lunar and martian fracture patterns (Table 1). Vents for basalts and pyroclastics within lunar floor-fractured craters typically are localized along the margins of the old crater floor (e.g., the craters Gassendi, Alphonsus, Atlas). Consequently, the development of wide moats within modified martian craters reflects not only floor movement, but perhaps evaporation and drainage of melted trapped ice at these locations. Figure 4 illustrates an example where a wide annular moat has developed along the old floor/wall contact of a large subdued crater. Fluid release through two breached segments of the wall probably enlarged the moat. Figure 2b shows a crater with complex fracture patterns that also may be related to fluid release, evaporation, or subsidence. Extensive and closely spaced polygonal fractures within craters intersected by the chaotic terrain are interpreted as differential collapse and rafting of segments of the old crater floors owing to lateral release of lava and/or water.

More common expressions of a similar but less catastrophic process may be the sinuous channels that appear to emanate from the rim region of certain old martian craters (*Schultz and Ingerson,* 1973; *Stockman,* 1976; *Pieri,* 1976). Several mare-flooded and floor-fractured craters on the Moon exhibit peripheral fractures and vents, the latter represented by head pits of sinuous lava channels and dark-haloed pits (*Schultz,* 1976). These sites of structural weakness are believed to be related to the original impact event but dilated during advanced stages of crater modification. Moreover, studies of the terrestrial impact crater, Manicouagan, reveal a broad region of extensive impact-induced jointing and possible peripheral fractures (*Murtaugh,* 1975). Sites such as these should provide easy paths for percolating water trapped within the martian cratered terrain to escape slowly in response to the local thermal anomaly associated with the intrusions. If such a process has occured, then the distribution and timing of the distribution and timing of small channels mapped by *Pieri* (1976) may reflect an ancient period of heating that, like the Moon, was localized within certain craters but, unlike the Moon, first resulted in water-eroded channels down the crater rim and filling of the crater floor with sediments.

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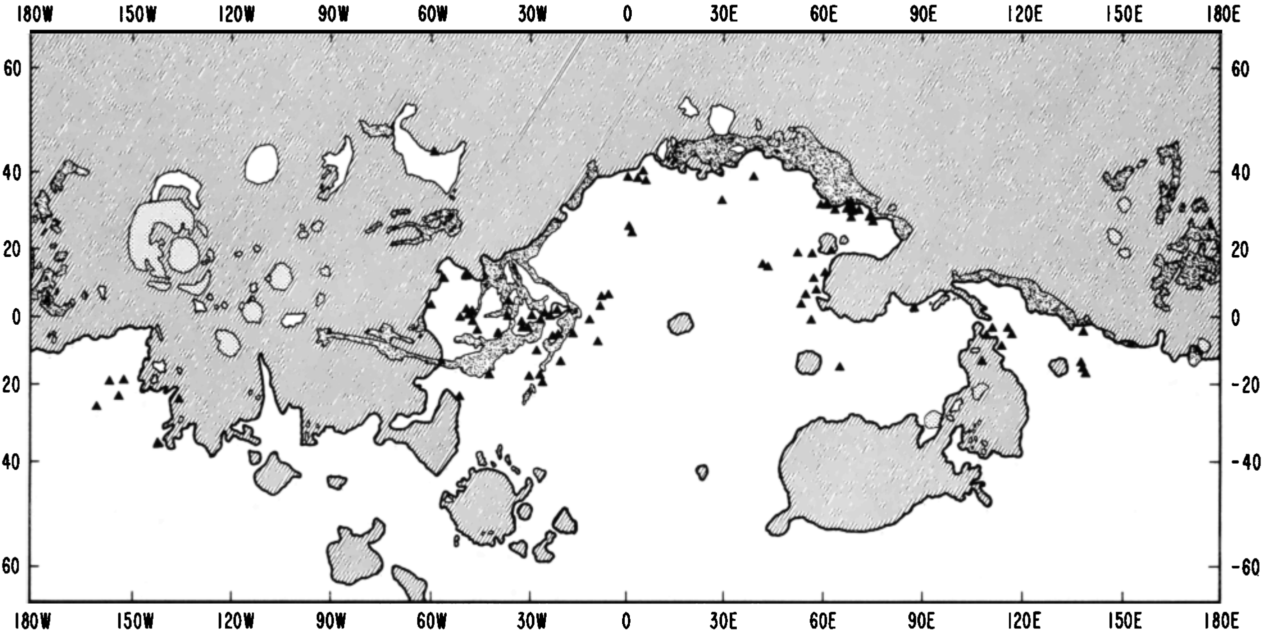

Fig. 1. Distribution of floor-fractured craters on Mars based on Mariner 9 images shown on a simplified geologic terrain map modified from *Carr et al.*, (1973). Striated regions indicate plains materials; dotted regions indicate major volcanic constructs; stippled regions indicate fretted and chaotic terrains.

The global distribution of such channels may provide an important and sensitive record of a stage in the thermal history of Mars.

Concluding Remarks and Possible Implications

Thus there are at least three contributing processes inferred to produce martian floor-fractured craters. First, floor uplift and/or subsidence perhaps result from an intrusion of magmas most likely at the fracture/breccia interface beneath an old impact crater, in direct analogy with lunar floor-fractured craters. Evidence supporting this process is the location of martian craters similar to lunar craters adjacent to lava-flooded plains and the morphology of lava-inundated craters. Second, localization of intrusions beneath an old crater floor in a manner analogous to lunar floor-fractured craters melted and perhaps volatized trapped ices accumulated within an old impact crater. Such a process may have enhanced the development of concentric fractures around the floor. Rapid melting resulted in breaching of the crater rim and possible rafting of the crater floor; less rapid melting associated with intermittant intrusive episodes resulted in percolation through the heavily jointed and fractured region surrounding the old unbreached impact crater. In addition, percolation through the crater wall modified (filled) but not necessarily fractured the old crater floor. A third process not directly addressed above involves water (?) that undercuts an endogenically inactive crater and breaks up the crater floor plate. In this case, the crater is not intruded but is nevertheless affected.

Mariner 9 and now Viking images reveal that craters in a wide range of degradation have been modified by endogenic processes (Figure 2), from

Fig. 2a. Floor-fractured crater (90 km diameter) on Mars on the margin of Isidis Planitia (266°, 5°N) that exhibits many of the same characteristics of lunar floor-fractured craters: elevated central peak complex, moat at floor/wall contact. Viking frame 67B65.

Fig. 2b. Complexly fractured floor of 55 km diameter crater (44°, 50° S). Style of crater modification is different from that of lunar floor-fractured craters: wide and elevated hummocky wall region, radial patterns associated with hills and ridges. NASA press release (S-76-27777).

TABLE 1. Comparison of Fracture Patterns in Lunar and Martian Craters
(total number of lunar craters = 206; total number of martian craters = 82)

	Concentric	Radial (% of patterns – including combinations of patterns)	Polygonal	Concentric Depression (% of floor-fractured craters)
MOON	72%	11%	33%	(10%)
MARS	42%	7%	52%	(26%)
	• magma withdrawal • ring-like intrusion • foundering of floor	• upward-directed primary stress from intrusive body	• multiple periods of uplift and subsidence • multiple intrusions • inhomogeneous floor (altered stress field) • rafting of broken floor blocks due to subfloor erosion or sapping	• elevation of floor plate • foundering of wall zone into magma reservoir • erosion due to sapping by evaporated or melted ice at floor/wall contact

craters with degraded rims to craters with preserved hummocky ejecta facies. The latter type of modified crater suggests that the modification process is relatively recent, possibly corresponding to the late stages of martian volcanism. The style of crater modification is also generally similar to that of lunar floor-fractured craters. Both lunar and martian floor-fractured craters rarely exhibit radial fractures beyond the crater rim, thereby indicating an intrusion localized beneath the crater floor. Polygonal patterns are much more common on Mars than on the Moon. Moreover, concentric fracture patterns are less characteristic of martian craters although the development of a concentric depression or moat encircling the floor is twice as common on Mars as on the Moon. Examples on both planetary bodies exhibit shallow crater floors with elevated and dropped central peaks, the latter expressed as a central depression. Table 1 compares the fracture patterns and postulated causes.

On the Moon, extensive floor fracturing and floor uplift may be culminated by the capping of the uplifted floor by mare basalts. The thinness of the basalt cap is suggested by the unburied central peak, the summit of which may extend above the crater rim (e.g., the lunar crater, Posidonius). Moreover, the rim region of such extensively modified craters may exhibit considerable structural modifications expressed by flat-topped rims and concentric graben as well as expanded volcanic modification expressed by both head pits of sinuous rilles (e.g., on the rims of Prinz, and Marius) and dark-haloed craters along concentric fractures (e.g., Haldane) outside the modified crater rim. Remnants of such crater-localized volcanism typically occur within the irregular maria (e.g., the ringed plain, Flamsteed) and may have been responsible for a non-trivial volume of basalts. Just as crustal weaknesses from a single major impact basin such as Imbrium provided the primary conduits for extensive eruptions and the formation of a circular mare, numerous smaller impact craters provided multiple extrusive centers that contributed to the formation of the irregular maria, such as Oceanus Procellarum. Floor-fractured craters in the cratered highlands peripheral to these maria indicate less extensive volcanic modifications from an exposed precursory stage of regional mare inundations (*Schultz*, 1976).

In summary, the early crustal history of Mars seems generally similar to that of the Moon: extensive impact cratering followed by emplacement of extensive lava plains. On the Moon, pre-existing impact craters and basins played an important role in controlling vent location. The possibility that water/ice existed in the martian crust creates an interesting

Fig. 3. Lava-filled (90 km diameter) crater south of Tharsis near 140°, 10° S. Exposed central peak, flat-topped rim profile, and rim graben resemble lunar mare-filled and modified craters. Viking Orbiter Frame 41B56.

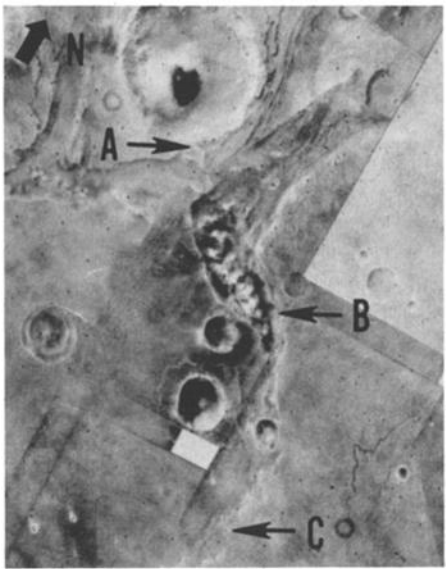

Fig. 4. Subdued crater (85 km diameter) with wide discontinuous moat and channels (59°, 4° N). Floor exhibits little evidence of uplift, yet moat development is clear. Arrow A indicates earlier stage of moat and related channel formation; arrow B indicates later stage. Old crater floor/wall boundary without moat development is indicated by arrow C. Viking Orbiter Frames 79A62, 80A31, 80A32, 80A33, 80A34.

complication whereby these craters became release centers for such volatiles and fluids during global heating. Inorganic chemical analyses from the Viking sites suggest that the most probable constituents of the martian soils include iron-rich smectites, carbonates, iron oxides, and sulfate minerals that are consistent with interaction between mafic magmas and subsurface ice as suggested by *Toulmin et al.*, (1977). Moreover, the high sulfur content, now interpreted as sulfates, suggests the possible existence of hydrothermally concentrated sulfide-rich ore bodies at depth. Interactions of igneous reservoirs beneath impact craters with crustal water/ice may make the concentration of hydrothermally derived ores possible and the existence of rich resources such as the Sudbury-type structures, as interpreted by *French* (1970), commonplace. The complex albedo contrasts associated with several martian floor-fractured craters may indicate hydrothermal deposits and possible sites for such ore concentrations. Further detailed analysis from Viking Orbiter images will permit further bracketing the time of the proposed crater modifications and their relation to martian geologic history.

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