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# Distinct erosional progressions in the Medusae Fossae Formation, Mars, indicate contrasting environmental conditions

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ABSTRACT

The form of erosional remnants of the Medusae Fossae Formation (MFF) on Mars provide evidence of their development progression and implicate two spatially distinct environments in the equatorial regions of Mars. Ubiquitous yardangs are clearly the product of strong unidirectional winds acting over time on variably indurated deposits. Yardang orientation is used as a proxy to map regional and local wind direction at meso-scale resolution. In other, more limited areas not subjected to strong unidirectional winds, randomly oriented kilometer-scale mesas and buttes are found to be remnants of progressive cliff recession through mass wasting as support is lost from within the MFF lithology at its margins. The differing processes that dominate the formation of the distinctive landforms have implications for meso-scale variations in climate that remain unresolved by current modeling efforts. Additionally, the variability of erosional forms within the deposit emphasizes the overall complexity of this extensive formation.



## 1. Introduction

Erosional remnants on the surfaces of planetary bodies are valuable as a record of past and current climatic and geologic processes on the planet. Among the most obvious features on the surface of Mars are erosional remnants like yardangs and less-than-kilometer-scale mesas. They provide insight into erosional processes and material properties of the formations on which they are found, such as the abundant yardangs in the Medusae Fossae Formation (MFF) that have been attributed to the mildly indurated nature of the MFF lithology and the presence of strong unidirectional winds (Schultz and Lutz, 1988; Scott and Tanaka, 1982; Mandt et al., 2008). To date, less-than-kilometer-scale mesas have been noted by very few authors, with little insight provided as to their source or significance (Bradley and Sakimoto, 2001; Zimbelman and Patel, 1998).

As part of a comprehensive survey of 713 images of the MFF from the Mars Orbiter Camera (MOC) of the Mars Global Surveyor (MGS), we have inferred material properties that suggest that the lithology of the MFF is largely that of an ignimbrite (Mandt et al., 2008). Herein we focus on the development and evolution of yardangs and less-than-kilometer-scale mesas and show that both are produced by a sequence of erosional stages that suggest differing processes for formation that are distinct from each other. The mechanism for forming yardangs is well understood (e.g. Breed et al., 1979) and their development within the MFF provides indications of local climatic conditions and material properties within the MFF. The mechanism for forming the mesas is a strong indicator of material properties and shows a lack of the strong unidirectional winds that formed the yardangs. Both forms require a lithology that is indurated in its upper parts and more friable in its lower portions. The separation of areas dominated by these respective forms is on the scale of 50–350 km, suggesting contrasting local environmental conditions at this spatial scale.

## 2. The MFF

Many geologic formations on Mars have origins that have yet to be agreed upon. One of the most prominent of these is the MFF, a deposit located along the equator stretching between 240° and 170°E Longitude. It is commonly described as enigmatic because its origin has been the subject of debate for decades. The MFF is located in the Amazonis Planitia region and lies between two major volcanic centers: Tharsis and Elysium (Fig. 1). In all places where they are in contact, the southern portion of the MFF overlies the

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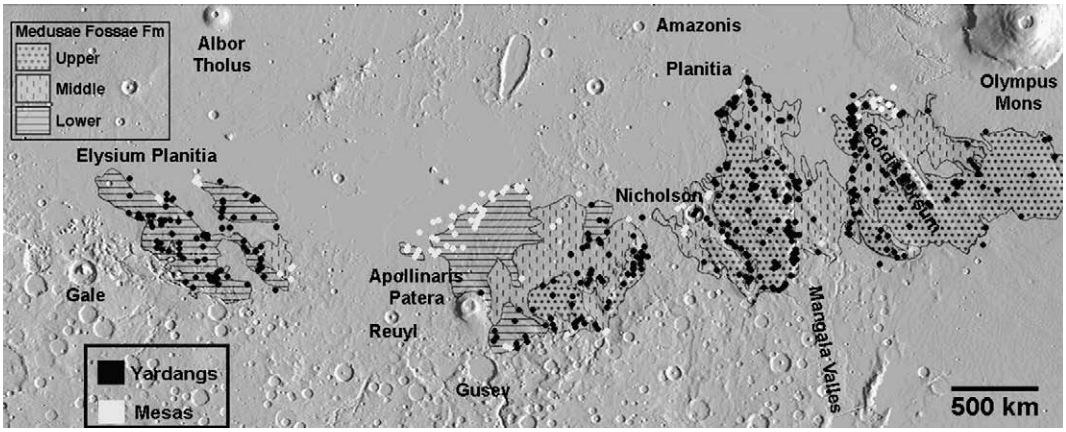


**Fig. 1.** MOLA shaded relief with map showing locations of images with yardangs (black) and collapse features and mesas (white). Upper, middle and lower member boundaries based on Scott and Tanaka (1986) and Greeley and Guest (1987). Boundaries of map stretch from 120° to 230°W Longitude and 15°S to 15°N Latitude. The Tharsis region is on the far right side of the map.

dichotomy boundary (Sakimoto et al., 1999, Bradley et al., 2002): a great circle inclined 28° to the equator that divides the northern lowlands from the southern, cratered highlands (Greeley and Guest, 1987). The MFF is considered to be one of the youngest deposits on Mars based on stratigraphic relationships (Scott and Tanaka, 1986; Greeley and Guest, 1987; Head and Kreslavsky, 2004; Hynek et al., 2003).

A wide variety of hypotheses have been proposed for the geologic origin of the MFF: ignimbrites (Scott and Tanaka, 1982; Mandt et al., 2008), aeolian deposits (Greeley and Guest, 1987), paleopolar deposits (Schultz and Lutz, 1988), exhumed fault rocks (Forsythe and Zimbelman, 1988), carbonate platform (Parker, 1991), rafted pumice deposits (Mouginis-Mark, 1993), lacustrine deposits (Malin and Edgett, 2000), ash fall tuff (Tanaka, 2000; Bradley et al., 2002; Hynek et al., 2003), and deposits associated with a subsurface aquifer (Nussbaumer, 2005). Most of these origins have been challenged by later work and only the ash fall tuff, aeolian (loess), and the ignimbrite hypotheses remain most viable after examination of recent datasets. Based on the material properties evident in the formation, we have argued that an ignimbrite origin is the most likely of the three remaining viable hypotheses (Mandt et al., 2008). In addition to providing information about the nature of the MFF lithology, the observations documented in this paper outline evidence for the development of two prominent erosional remnant forms of the MFF and the dissimilar environmental conditions required to form both of them.

## 3. Methods

The MOC Narrow Angle images we used had a typical resolution of one to three meters per pixel (e.g., Malin and Edgett, 2001). Though newer missions are providing higher resolution images, MOC was chosen for the present study due to the extent of its coverage of the MFF, which allows a synoptic analysis of the formation. This approach is important because this formation spans more than one-fourth of the equatorial circumference of the planet and thus could have considerable variability at the scale of high resolution images. The extent of coverage by MOC images allowed us to produce maps of the yardangs and kilometer-scale mesas in order to evaluate the formation as a whole.

Each of the images was studied individually and within the context of its location on a Mars Odyssey Thermal Emission Imaging System (THEMIS) mosaic (e.g., Christensen et al., 2004). Maps were created identifying the locations of images showing mesas and yardangs within the MFF to highlight their extent throughout the formation (Fig. 1), and the inferred wind direction based on yardang orientation (Fig. 2a). We then examined the 541 images associated with yardangs and 96 images associated with collapse features and mesas to develop models for their formation.

## 4. Yardangs

Yardangs are the most commonly observed feature in the MFF; they form fields covering very large areas. Yardangs are linear aerodynamic forms formed by aeolian erosion, and they are best developed in arid regions (Breed et al., 1979). They can be as large as many kilometers in length and 100–200 m high (Ward, 1979). Terrestrial yardangs formed by a strong unidirectional wind eroding lithologically consistent material are "ideal" in form when they are well-streamlined, and typically have an aspect ratio (length to width) of about 3:1 (McCauley et al., 1997), but terrestrial examples are found with aspect ratios as high as 50:1 in the Altiplano-Puna of the Central Andes. The degree of induration and the vertical induration profile plays a major role in aspect ratio, and properties such as jointing and layers with different degrees of induration can also alter the morphology of a yardang (Mandt et al., 2008).

We have found that there is an erosional progression in the development of yardangs from initiation as v-shaped depressions to proto-yardangs and then fully fledged yardangs. The v-shaped depressions, interpreted to be deflation hollows caused by the removal of less resistant material (Bradley et al., 2002), are observed in areas dominated by yardangs. The depth of these depressions ranges from 10–50 m and a progression from the depressions to the yardangs can be seen as illustrated in Figs. 3 and 4. The yardangs in the MFF appear to be initiated through deflation/excavation that exposes a resistant block of material that is subsequently sculpted into an aerodynamic landform in a well understood process (e.g. Breed et al., 1979).

Although Bradley et al. (2002) conducted a statistical analysis of yardang direction with the goal of evaluating the lithology of MFF material and concluded that wind direction was not the sole determinant of yardang orientation, this is in contrast to other studies on Mars that show that yardangs reflect the orientation of strongly unidirectional winds (e.g., Ward, 1979; Mandt et al., 2008). Moreover, studies of terrestrial yardangs have shown that yardang orientation strongly reflects wind direction (Bailey et al., 2007; de Silva et al., 2009). We therefore believe that the orientation of the yardangs can be used as a proxy for the dominant wind direction that formed them. Our analysis thus presents the first high

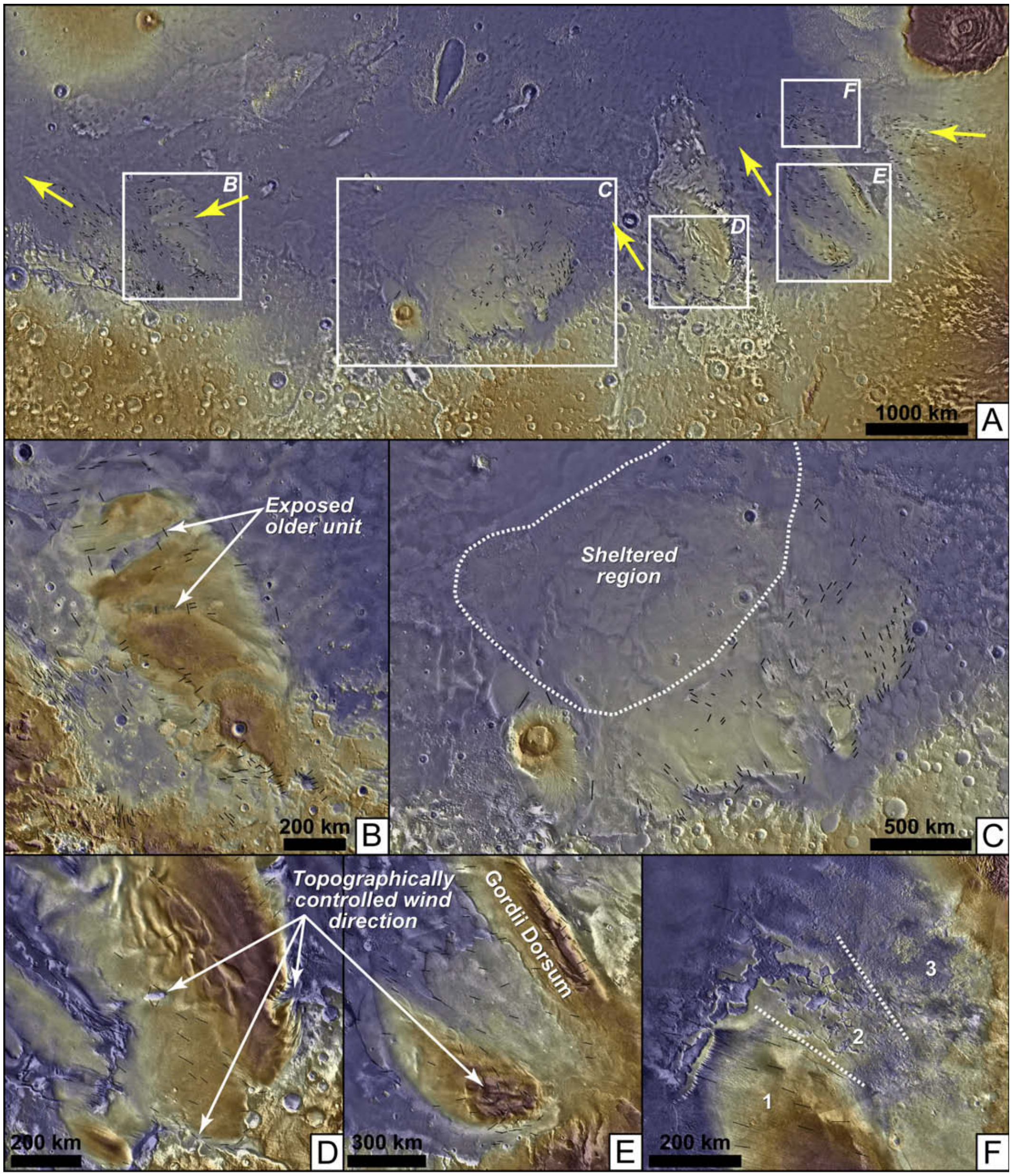


**Fig. 2.** MOLA topography overlain on Viking mosaic of the MFF. (a) Overview of entire formation. Black lines indicate yardang orientation that was used as a proxy for wind direction. Yellow arrows suggest dominant wind direction and white boxes outline the enlarged portions below. (b) Enlarged view of the western portion of the MFF. The yardang orientation shows an exposed layer that provides evidence of changing climatic conditions in this region over time. (c) Central portion of the MFF showing two distinct environmental regimes. The lower portion has abundant yardangs formed by strong unidirectional winds while the outlined "sheltered" portion shows no evidence of the unidirectional winds. (d and e) Enlarged view of the east-central portion of the MFF showing areas where topography has clearly controlled the direction of the wind. (f) Enlarged view of the region north of the Gordii Dorsum showing the transition region, area 2, located between a region of yardangs subjected to strong unidirectional winds, area 1, and a region with collapse features and the resulting mesas and buttes, area 3.

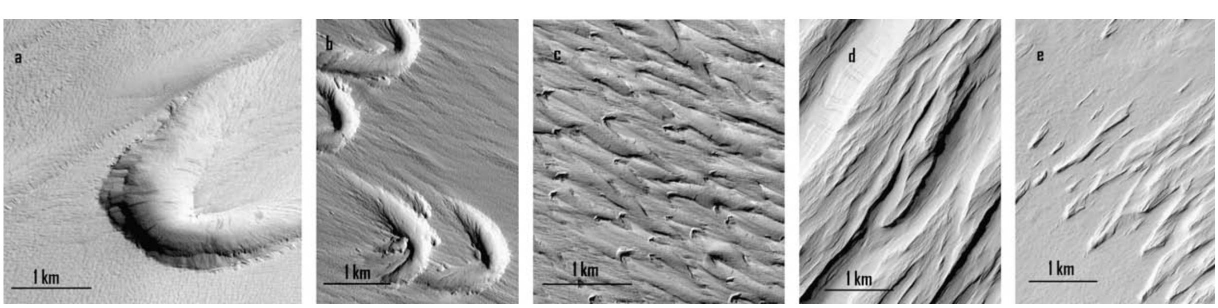


**Fig. 3.** Erosional progression from v-shaped depressions to yardangs. All images are illuminated from the bottom left and north is up. (a) MOC E10-00390, centered at 156°W and 1°N, showing a single v-shaped depression. (b) MOC M07-00371 centered at 163°W and 4.5°N, showing a cluster of v-shaped depressions. (c) MOC M21-01904 centered at 148°W and 0.5°N, showing yardangs with remainders of v-shaped depressions at the tip. (d and e) MOC E03-01400 centered at 173°W and 2.5°S, showing fully formed curvilinear yardangs. Image (d) shows the remainder of an elongated v-shaped depression.

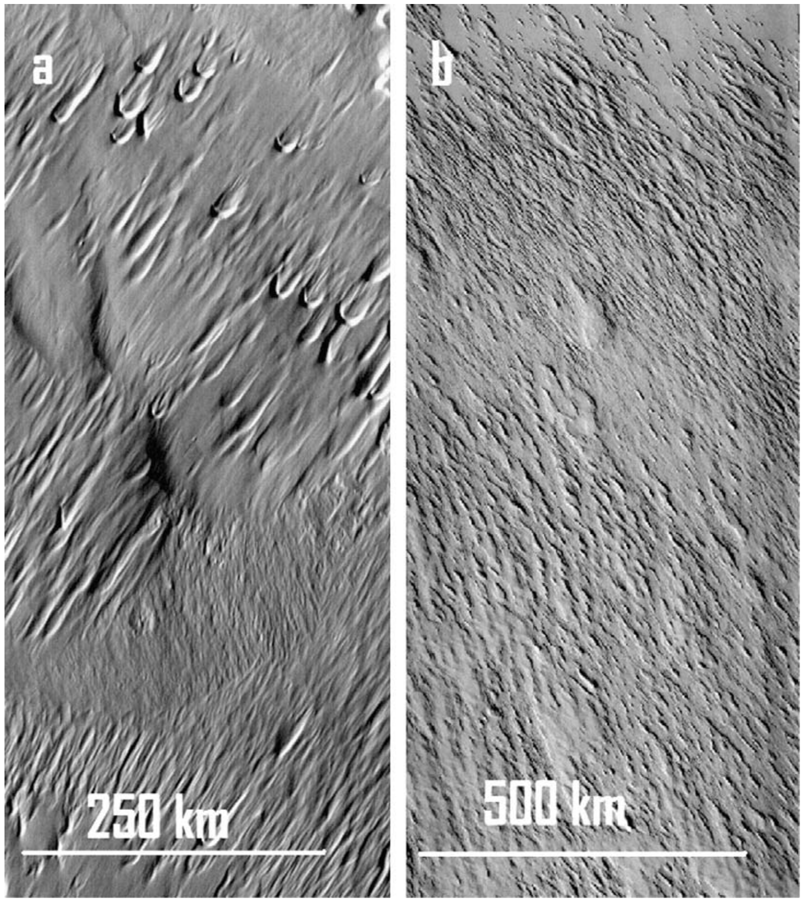


**Fig. 4.** THEMIS images (Christensen et al., 2004) showing yardang erosional progression at larger scale. Illumination is from the lower left in both images. (a) THEMIS daytime infrared image I10241007, centered at 204°W and 3.6°N, showing progression from v-shaped depressions to curvilinear yardangs and (b) THEMIS visible V01054003, centered at 201°W and 11.2°N, showing erosional progression from feathered scarps (bottom of image) to curvilinear yardangs.

resolution graphical presentation of wind direction in the MFF region. In the areas with v-shaped depressions, the prominent wind direction is inward from the point of the v. Fully-developed yardangs form a linear shape in the prominent wind direction, are wider on the side facing the wind and narrower in the tail. The primary wind direction in the area of the MFF differs from one section of the formation to another (Fig. 2a). The far western portion (westward of 200°W Longitude) has been eroded by a predominantly east–west wind. In Fig. 2b, the majority of the yardangs are oriented in the ENE–WSW direction. Some yardangs are oriented perpendicular to this direction and are at a lower elevation. This suggests erosional exposure of an underlying layer with yardangs that formed prior to deposition of the layer overlying these yardangs. It is clear from this that the wind direction when the older yardangs formed was perpendicular to the most recent wind regime. The central portions (between 150° and 180°W Longitude) of the MFF have been eroded by a wind that appears to be coming off of the dichotomy boundary while the far eastern portion (eastward of 150°W Longitude) has been exposed to winds coming off of the Tharsis rise. Evidence of topographic influence on the wind is clearly seen (Fig. 2b, d and e).

## 5. Collapse features and mesas

Chains of pits and trenches, referred to as collapse features, with size scales ranging from one to tens of kilometers are ob-

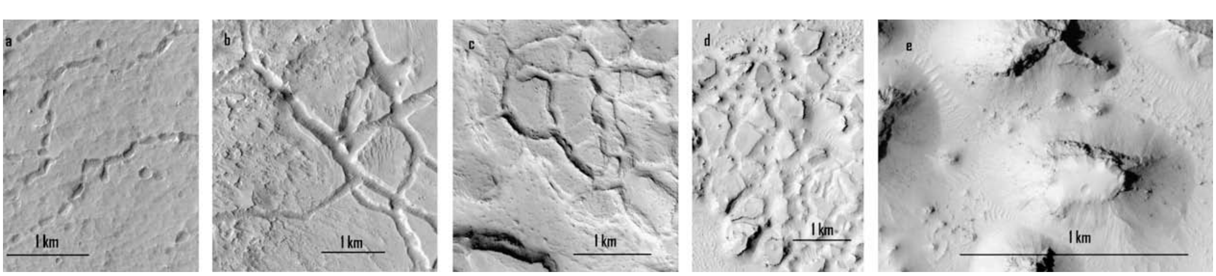


**Fig. 5.** Erosional progression from troughs to mesas. All images are illuminated from the bottom left and north is up. (a) MOC E03-01084, centered at 181°W and 15°N, showing chains of pits formed by probable subsurface collapse. (b) MOC E05-02396, centered at 182°W and 2.3°N, showing similar collapse features that have progressed to deeper trenches. (c) MOC E10-01357, centered at 147°W and 13°N, showing the development of individual mesas as the deepening of the trenches progresses. (d) MOC E04-02348, centered at 213°W and 3.3°N, showing a group of mesas resulting from this progression. (e) MOC E05-01356, centered at 213°W and 3.3°N, showing heavily eroded buttes at the final stages of this erosional progression.

served at the edges of the MFF, where the apparent thickness is less than 250 m, assuming the base material below the entire formation is relatively flat (Watters et al., 2007; Carter et al., 2009). At the very edges of the deposit, less-than-kilometer scale erosional mesas coincide with areas where the collapse features are seen. MOC images (Figs. 5 and 6) show a clear progression from collapse features to mesas. The evolution appears to begin with pit chains and trenches forming by collapse. The collapsed material is, as a result, of a less cohesive nature and more susceptible to aeolian erosion and mass wasting. Over time these features become deeper and wider, eventually leaving only the mesas. Images of this progression suggest that the top layer of material is more indurated than the material below it, as evidenced by the way the polygonal forms remain during the removal of material and appear to tilt (as shown in Fig. 6). Blocks at the bases of many mesas in the highest resolution images also support a more lithified top layer as the more friable base layer is removed. Recent modification of fine material is evident in the dunes between, and on top of, the mesas suggesting that aeolian processes may play a recent role in local erosion of materials.

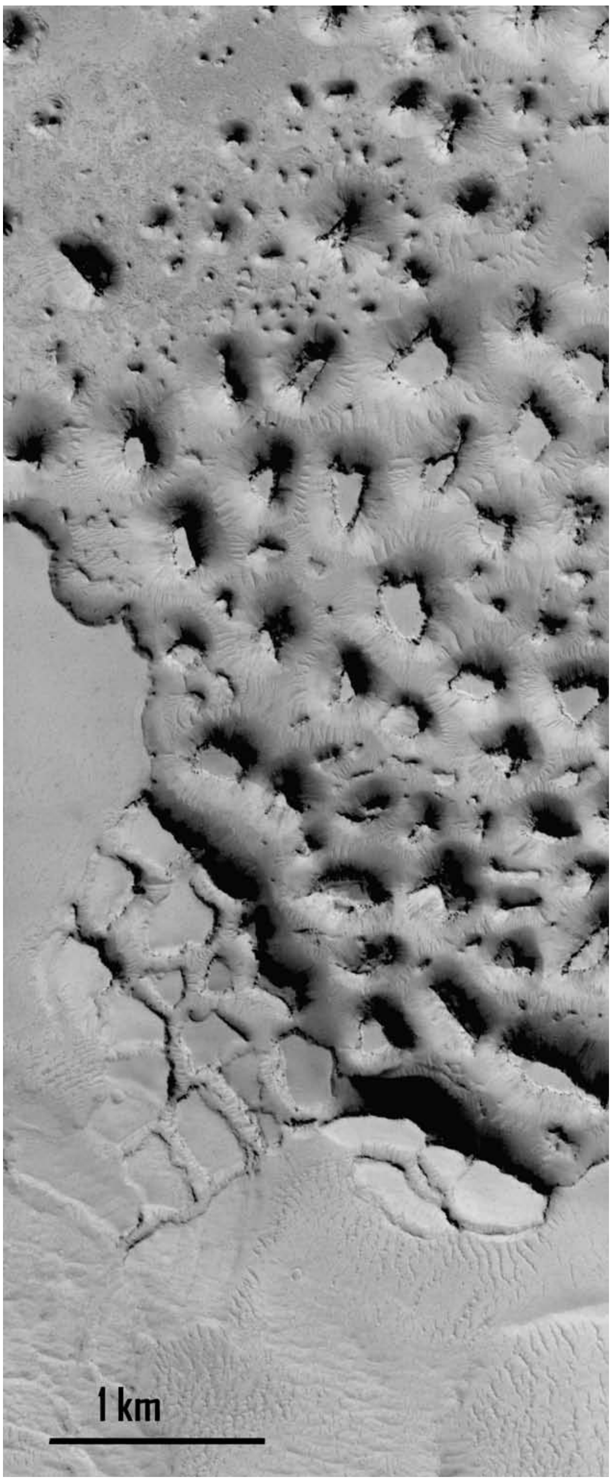


**Fig. 6.** MOC E11-02357, centered at 211°W and 2.4°N, showing full progression from collapse features to mesas. Blocks at the base of the buttes suggest an indurated layer overlying a more friable base layer.

The regions dominated by collapse features and mesas are spatially separated from yardangs by 50–350 km (Figs. 1 and 2c), although some transition zones between the two regions can be seen in Viking mosaics (Fig. 2f). Regions showing collapse features and mesas are clearly not exposed to a strong unidirectional wind because such a mechanism would shape the mesas into yardangs and erase much of the evidence of collapse.

A study of the lower member of the MFF, with a specific focus on a region containing a large number of collapse features and lacking yardangs (McColley et al., 2005), interpret the collapse features to be troughs created by subsurface collapse due to the release of volatiles. This region is mapped as the 'sheltered region' outlined in Figs. 2b and 1 shows that these features cover a very extensive area. Collapse features are seen all over the surface of Mars at varying scales and shapes. The larger-scale collapse features have been shown to form by collapse due to an underlying fault or fracture system (Wyrick et al., 2004).

## 6. Discussion

The formation of yardangs is well understood, and our observations of the yardangs of the MFF are consistent with yardang formation in differentially indurated lithologies on Earth (de Silva et al., 2009). Where a well-indurated capping layer is present, yardang formation proceeds at local anomalies that expose the less indurated layer. Knobs and reentrants can expose the lower softer layers that subsequently get preferentially excavated by the wind, armed with saltating particles. As the depression develops in the softer material, excavation focuses within the rim of the growing depression, creating local eddies and turbulence (Breed et al., 1979). As the indurated upper layer forms a resistant caprock, the wind becomes bifurcated, producing v-shaped depressions that result in the development of the yardang form. Where an indurated capping layer is present, mega-yardangs (Goudie, 2007) of extreme aspect ratio can develop, aided by sculpting, through block collapse of the upper indurated parts while poorly indurated lithologies produce smaller, less well-defined yardangs (de Silva et al., 2009). Strong unidirectional winds and a lithology with a vertical induration profile are the primary factors that result in the mega-yardang formation in the MFF.

The mesas and buttes represent different phenomena, though the lithology of the material in which the collapse features, mesas and buttes form resembles that in which the yardangs form: fine-grained with evidence of upper layers of caprock in many areas. Collapse features similar to the ones found in the MFF have been observed at much larger scale elsewhere on Mars, and have been interpreted to be the result of dilational faulting and fracturing (Wyrick et al., 2004). In the case of the MFF collapse features, dilational faulting and fracturing could possibly account for the original collapse features. The fact that they are only found at the margins of the deposit may mean that the fracture systems are only exposed near the surface at locations where the thickness is least, and therefore become susceptible to further mass wasting and erosion. We suggest that the collapse is driven by the removal of support from within the lithology, along the margins of the deposit.

The association of the collapse features and mesas with cliff recession is striking. The mesas and buttes are clearly remnants of larger forms that are left behind as the cliff recedes (Fig. 6), and this removal of material is facilitated by the formation of the pit chains. We propose that this has taken place due to loss of material, and hence support, from within the deposit near their margins, rather like sapping of groundwater in terrestrial deposits, only in this case it is a material property inherent to the MFF. These collapse features have been suggested to be the result of release of volatiles (McColley et al., 2005), and if the MFF is predominantly ignimbrite (Scott and Tanaka 1982, 1986; Mandt et al., 2008), volatiles could have been trapped during the formation process and later released. However, volatiles in ignimbrites typically escape upwards. These volatiles have two sources; magmatic volatiles contained in the juvenile (magmatic) material usually pumice, and external gas (trapped and ingested ambient air, gas from combustion of vegetation, water) that may be incorporated into the flows as it moves. Observations of historical eruptions in 1902 Mt. Pelée, Martinique, in 1980 at Mt. St. Helens, Washington, in 1991 at Mt. Pinatubo in the Phillipines, and in 1992 at Volcan Lascar, Chile, emphasize the presence of massive ash clouds above the moving pyroclastic flows. These observations confirm sedimentological data from ancient deposits that indicate that gas loss is continuous during the flow process (Sparks, 1978; Wilson, 1984). Juvenile gas is released as pumice is broken and crushed during flow and external gas is streamed upwards through the flow. However, post depositional gas loss may actually account for most of the gas loss from ignimbrites; this is enhanced if an external gas source like surface water is present (e.g. Keating, 2005). This is evidenced by vertical gas escape structures and vapour phase alteration profiles in ancient deposits, and active degassing of the upper surfaces of historic ignimbrites such as those described above. Active degassing months to years after deposition has been observed, while qualitative and quantitative thermal and chemical considerations suggest time scales of at least decades to maybe centuries for complete cooling and degassing of thick (many tens of meters) (e.g. Ross and Smith, 1961; Sheridan and Ragan, 1976; Riehle et al., 1995). The pathways for gas loss are usually strongly indurated and recrystallized, due to vapor phase devitrification and crystallization, and sintering in upper zones ignimbrites (Cas and Wright, 1992; de Silva, 1989; de Silva et al., 2009). These pathways would not be weak areas along which pits could develop; therefore a different mass loss process to post depositional degassing of ignimbrite is required.

Recent Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) data consistent with either an ice-rich or very porous deposit (Watters et al., 2007), raising the possibility that ice is subliming at the exposed front of the MFF, although analysis of the Shallow Radar (SHARAD) does not interpret the data to show strong evidence of ice within MFF (Carter et al., 2009). If ice were to sublime, a volume deficit could be created and result in formation of collapse features and subsequent cliff recession. Such a scenario is an attractive possibility, potentially supporting the paleopolar deposit origin of the MFF (Schultz and Lutz, 1988). However, laboratory results of the dielectric properties presently are not able to distinguish between a fine-grained dry deposit and a porous material where the void spaces are filled with water ice (Watters et al., 2007; Carter et al., 2009), so that at present the radar sounding results are unable to provide direct evidence of either the presence or the absence of ice from within MFF. In any case, both volatile release and ice sublimation would likely have produced a more ubiquitous pattern of pit distribution rather than the polygonal fractured patterns as indicated by the pit chains and troughs. It is possible that volatile release or ice sublimation could have been preferentially emplaced and transported through higher-permeability faults and fractures, but it is not required for the polygonal pit chain and trough formations.

The loss of support from within the MFF to produce the collapse features at the edge of the formation remains problematic. Because ice sublimation and volatile loss do not provide good explanations, we are unsure of what material is being lost out of the margins of the MFF to produce the collapse structures, mesas and buttes. Nonetheless, because the mesas and buttes form in material with similar lithology to the yardang material but lack the aerodynamic form of the yardangs shows that there is not a strong unidirectional wind in the areas where the mesas and buttes form. This suggests local climate variability within the region where the MFF is found.

Current models of circulation on Mars show generally westward winds for this region, northwest in the northern spring and summer and southwest in the northern summer (Zurek, 1992; Fenton, 2003). Our observations of the yardangs along with previously documented variations in yardang orientation (Bradley et al., 2002) show spatial variations that suggest a more complex surface pattern (Fig. 2a), and long-term variation in primary wind direction between one episode of deposition and the next (Fig. 2b). Topography clearly plays an important role in near-surface winds (Fig. 2d and e). We note that some workers (Anderson et al., 1999) have attempted to look at erosion vs. deposition on the surface of Mars with a $25 \times 40$ km resolution wind model, but found no correlation to specific geologic features. Our observations of the difference between mesas and yardangs in the MFF suggest that local environmental conditions vary on the spatial scale of 50–350 km in the equatorial region of Mars (Fig. 2f).

The differing erosional processes also have important implications for analysis and mapping of the MFF. This formation was originally mapped into three members of one formation (Scott and Tanaka, 1986; Greeley and Guest, 1987), but is typically addressed as a single entity (e.g. Parker, 1991). Across its expanse of over 5000 km there exist enormous differences in the overall thickness of the deposits, and in their degree of degradation showing that the MFF is not a homogenous unit (Mandt et al., 2008). The variations in erosional style documented here further emphasize how diverse MFF is. This emphasizes the importance in recognizing the MFF for what its name implies, a "formation" – a lithostratigraphic division consisting of two or more members, each of which consists of two or more beds (Barnes and Lisle, 2004, p. 94). Formations consist of a variety of materials that have contributed to their final composite state.

## 7. Conclusions

Mesas and yardangs in the MFF on Mars are the final result of progressive erosional processes that are unique to each feature. The yardangs are streamlined by a dominant locally unidirectional wind, but no streamlining is seen in the mesas, buttes and associated collapse features suggesting the absence of a strong unidirectional wind in these areas. The development of mesas and buttes from collapse features due to progressive recession of the margin of the MFF through removal of support from the interior of the lithology is important to understanding the lithology of the MFF material when not degraded by a strong unidirectional wind. This variability of erosional forms within the deposit emphasizes the overall complexity of this extensive formation that must be taken into account when evaluating its origin and the recent (Amazonian) geological history of this region of Mars.

As seen by the erosional progressions illustrated above, aeolian processes dominate for yardangs while collapse and mass wasting in response to loss of support from within the deposits produces the mesas. The spatial separation of mesas from yardangs suggests quite different local environmental conditions in their respective locations within the equatorial region of Mars. These erosional features are revealing environmental variability at a scale not yet incorporated into current wind modeling.

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