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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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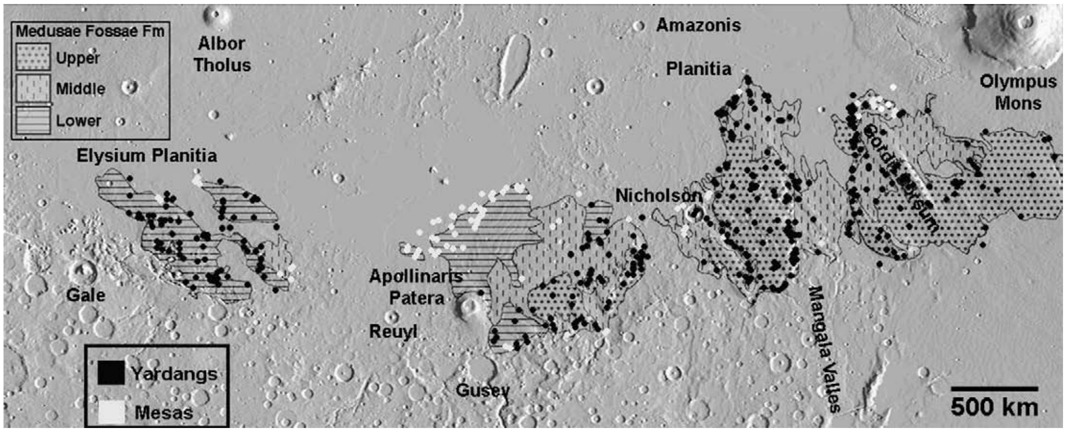

Fig. 1. MOLA shaded relief with map showing locations of images with yardangs (black) and collapse features and mesas (white). Upper, middle and lower member boundaries based on Scott and Tanaka (1986) and Greeley and Guest (1987). Boundaries of map stretch from 120° to 230°W Longitude and 15°S to 15°N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