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Proposed Running Head: Mapping Medusae Fossae Formation outliers

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ABSTRACT

The Medusae Fossae Formation (MFF) is an extensive deposit ($2.2 \times 10^6 \text{ km}^2$, Bradley et al., (2002)) of wind-eroded material of widely debated origin, which unconformably overlies a considerable area of the crustal dichotomy boundary on Mars. The MFF shows a variety of layering patterns, erosional styles and channel-like forms and has been mapped into five main outcrops and three geological members according to exposure and stratigraphy (Scott and Tanaka, 1986; 1987; Zimbelman et al., 1996). Away from the three main lobes are numerous outliers of MFF materials. These have mainly been reported in the northern lowlands regions (Watters et al., 2007b; Keszthelyi et al., 2008) but few studies have examined the possibility of MFF outliers on high ground south of the dichotomy boundary. We have searched Mars Orbiter Camera Narrow Angle (MOC NA) images for outliers in this region. Our observations show that there are many MFF outliers on the southern highlands. The characteristics of the outliers indicate materials which overlie the underlying terrain for they appear widely in dips, craters and topographic lows. The surfaces are typified by yardang fields and have a similar patchy and discontinuous nature to materials of the upper member of the MFF. Most have consistent lineation orientations across the wider area which match the dominant orientation of yardangs in the main MFF outcrops. Furthermore, elevation data shows that the maximum, minimum and mean elevations of these newly discovered outliers are closest to those of the upper member of the MFF. We therefore conclude that these deposits are MFF outliers and that they probably represent remnant upper member material. We suggest that there might be two possible explanations for these outliers: 1) the MFF had a much greater pre-erosional extent than previously estimated, or 2)

Materials from the main outcrops were eroded and then blown south to accrue in the highland areas, where they were subsequently reworked. We suggest that the topography of the region favors the first option. We outline an “overflowing” layer-cake deposition model, in which layers of sediment stacked up against the dichotomy boundary until they reached the topographic level of the highlands. Further materials (that went on to become upper-member MFF material and outliers) were then deposited across a wider area, including south of the dichotomy boundary. Severe erosion subsequently removed much of this material.

Keywords: Mars; Mars, Surface; Geological processes;

1 Introduction

1.1 The Medusae Fossae Formation

The Medusae Fossae Formation (MFF) is an extensive but discontinuous geological unit that can be found across approximately a quarter of the equatorial region of Mars (130-240 E, 15 N-15 S; (Bradley et al., 2002)). Its E-W length, which extends from the Amazonis Planitia area, to the southern Elysium Planitia is ~ 5500 km (Tanaka, 2000). The deposit overlies the crustal dichotomy between the older Southern highlands and the younger Northern lowlands, with a N-S extent of several 100 km, reaching locally up to 1000 km (Tanaka, 2000). The MFF comprises five primary outcrops or lobes (Fig. 1), which themselves are mapped into three stratigraphic members: lower, middle and upper, with an estimated total area of $2.2 \times 10^6 \text{ km}^2$ (Bradley et al., 2002). It is possible that these lobes represent the degraded remnants of a once continuous deposit (Bradley et al., 2002).

Fig. 1

Morphologically, the Medusae Fossae Formation materials are typified by a discontinuous, highly eroded appearance (Fig. 2), and it is commonly agreed that they are fine grained and friable in nature (Zimbelman et al., 1996; Zimbelman et al., 1997; Tanaka, 2000; Bradley et al., 2002; Bridges et al., 2007; Mandt et al., 2007; Mandt et al., 2008b; Carter et al., 2009; Kerber and Head, 2009). This long-standing interpretation is rooted in the observed prevalent aeolian erosional features indicating modification of its surface and by inference from thermal inertia measurements (Zimbelman et al., 2003).

Current interpretations of its age, based upon relative stratigraphy (Scott and Tanaka, 1986; Tanaka et al., 1992; Zimbelman et al., 1999; Bradley et al., 2000; Tanaka, 2000; Bradley et al., 2002; Shockey et al., 2004) and measurements of the size frequency distribution of impact craters (Werner, 2005; Allen and Gregg, 2007; Hartmann, 2007; Smith et al., 2008), places the MFF as a geologically young unit of Amazonian age. On the other hand, it has been argued that local stratigraphic relationships (Kerber and Head, 2009) indicate deposition may have been sporadic over a much longer period and that initial emplacement may have been as early as the Hesperian (Schultz and Lutz, 1988; Head and Kreslavsky, 2001; Head and Kreslavsky, 2004; Schultz, 2007; Kerber et al., 2008; Kerber and Head, 2009).

Fig. 2

Importantly, the origins of the MFF remain uncertain, despite numerous studies (including (Parker, 1991; Zimbelman et al., 1996; Zimbelman et al., 1997; Bradley et al., 2002; Ivanov et al., 2003; Head and Kreslavsky, 2004; Shockey et al., 2004; McColley et al., 2005; Shockey and Zimbelman, 2005; Bridges et al., 2007; Watters et al., 2007a; Mandt et al., 2008a; Mandt et al., 2008b; Basilevsky et al., 2009; Carter et al., 2009; Kerber and Head, 2009) that have constrained the age, distribution and material properties. These studies have resulted in a variety of hypotheses for the formation mechanism of the MFF, some of which are summarised in Table 1. Over time, some of these hypotheses have been discounted based on newer evidence (see the review of Mandt et al., 2008b). Recent radar data in particular suggest that the dielectric properties of the MFF indicate the materials to be either dry, low density deposits (for example ash)

or ice-rich deposits of some kind (Head, 2001; Nussbaumer, 2007; Watters et al., 2007a; Carter et al., 2008; Kerber et al., 2008; Keszthelyi et al., 2008).

The most prominent surficial features of the MFF are tapered ridges called yardangs, aeolian features carved in areas of easily erodible materials (Greeley and Iverson, 1985, p134). Yardangs occur ubiquitously over the formation, often in large clusters or fields, as is typical for these features on Earth (Greeley and Iverson, 1985, p135). They have distinctive planform morphology, often described as an “inverted ships hull” shape (Greeley and Iverson, 1985, p135). Some studies have also investigated the progressional development of yardangs, linking them with other surface features including mesas and troughs (Mandt et al., 2008a). The presence of yardangs and their characteristics underpin much of the work herein, both because they are a readily identifiable signature of the MFF surface type, and also because they are an indicator of paleo wind direction.

1.2 Outlier occurrence of MFF materials

The MFF is extensively and intensively eroded and, in a number of large areas, completely or partially stripped away. Such stripping can reveal features such as exhumed craters and lavaflows (Zimbelman et al., 1996; Zimbelman et al., 1997). In many cases, these underlying features appear to be minimally altered and well-preserved (Sakimoto et al., 1999). This characteristic erosion is of great importance not only because it results in surface features which are in many cases unique to this area of Mars

but also because the erosional history of the formation is fundamental to understanding its origins, particularly as it appears to postdate all other units in the region (Irwin et al., 2004).

Close study of the five main outcrops has found them to be stratigraphically and topographically complex, although several studies have acknowledged that the mislocation of member and formation boundaries has probably been an unavoidable by-product of the combination of poor data quality and the varying levels of erosion across the outcrops (Bradley et al., 2002; Sakimoto et al., 1999). A qualitative study of erosion rates for the formation has been made utilizing pedestal crater height measurements and their distance from the main outcrops (Allen and Gregg, 2007). Results from this suggested a non-linear rate of erosion. Studies of the paleo extent of the formation have also been made, using gridded topography and assuming a single pre-existing mass of MFF material, which estimated an area of $5 \times 10^6 \text{ km}^2$ prior to erosion (Bradley et al., 2002).

Over the surfaces between and around the main outcrops are numerous examples of apparent outlying MFF materials. Outlying materials are defined in this case as examples of surface morphology and erosional characteristics similar to those observed on type examples of MFF materials within the main outcrops (Watters et al., 2007a; Keszthelyi et al., 2008). These outliers may be clustered or isolated and the consistency of their surfaces has been used to infer that the present-day discontinuous MFF outcrops were once a laterally continuous stratigraphy (Hynek et al., 2003). Such outliers have taken the form of eroded remnants (Hynek et al., 2003), extensions of the formation

upslope (Sakimoto et al., 1999) and layers overlying the central peaks of nearby craters (Zimbelman et al., 2003).

The majority of these previously observed outlier occurrences have been on the northern lowlands above the dichotomy boundary and in the immediate vicinity of the main outcrops. Few studies have examined such MFF outliers south of the dichotomy boundary; however, some 300 m of MFF material was observed by (Bradley et al., 2000) to be draped over the Labou Vallis channel terraces and to cover some of the channel floor. Labou Vallis is a channel of about an average 900 m deep and 6 km wide (widening to 18 km downstream), which lies just to the southeast of MFF lobe D in Fig. 1. The aim of our work is to explore the region further south to detect whether MFF outliers exist on the topographically high, cratered highlands, whether there are sufficient outliers to indicate that the MFF previously extended further south than its currently agreed extent, and whether any such new data provides evidence on the origin of the formation.

2. Approach

We have systematically searched Mars Orbiter Camera (MOC) Narrow Angle (NA) images (Malin and colleagues, 1998) for evidence of the existence of materials of similar morphology to that defined for the Medusae Fossae Formation. We have found many examples of such materials and have analyzed their morphology, distribution and azimuthal trends. Using these data, we sought to establish whether a consistent

stratigraphy existed between these outliers and therefore whether the outliers do indeed represent degraded MFF deposits. In addition to MOC NA data, we have also used Mars Reconnaissance Orbiter Context Imager (CTX) images.

2.1 Definition of Medusae Fossae Materials

Key to the mapping process was establishing a defined set of morphologic criteria for identifying MFF textures. Such definition needed to take into account the differing levels of erosion over the five main outcrops and the different members exposed, each of which has slightly different surface morphology. In this case, the definitions were derived from close study of appropriate images and from the member definitions as given in previous work (Head and Kreslavsky, 2001). The morphology of previously identified outliers (Hynek et al., 2003; Sakimoto et al., 1999; Zimbelman et al., 2003) was also taken into account. Figure 2 show examples of the range of morphologies seen across the five main outcrops of the MFF.

Established examples of MFF material as observed in MOC NA images were catalogued for each of the five outcrops. The MOC NA images were judged to be the best resolution for the task (averaging roughly 3 m/pixel), based upon image assessment and previous works. These were then used as the baseline for geomorphological definition of the MFF materials being searched for. The surface descriptions of the three stratigraphic divisions of the formation, as given by (Head and Kreslavsky, 2001), are summarised in Table 2.

Table 2

MFF materials of all three stratigraphic members commonly drape over the underlying materials and are lightly cratered (Bradley and Sakimoto, 2001; Bradley et al., 2002; Zimbelman et al., 1996). The principal surface feature of all members of the MFF materials are yardangs and yardang fields. The majority of these yardangs trend in one of two dominating directions (NW-SE or NE-SW), although they do also occur N-S and E-W. The morphology of the yardangs can vary greatly in detail (Mandt et al., 2008b), but they are distinctive enough to be easily identified.

Other notable MFF surface features include mesas (Mandt et al., 2008a; Mandt et al., 2008b) and pits and pit chains (often interpreted as collapse features) (McColley et al., 2005; Mandt et al., 2008a; Mandt et al., 2008b; Mandt et al., 2009).

Ultimately, the morphologic criteria for identification were summarized as:

1. discontinuous nature
2. the presence of yardangs, either individually or in fields; unidirectional and bidirectional
3. other erosional and aeolian modification features
4. the presence of ripple and ridge features; unidirectional and bidirectional
5. pits and pit chains, often progressing into mesa formation.

2.2 Initial transect survey

A preliminary survey was performed to quickly search for possible MFF outliers across the widest longitude range possible. Five transect lines were constructed which passed through one of the five main MFF lobes and extended into the region southward of the formation. These transects were overlain on a map of the image footprints using a GIS (Geographical Information System). By studying any image within 50 km of these transects, a relatively small number of images could be quickly assessed to establish any potential occurrences of outliers. This also provided a cross section of images from within each of the established MFF lobes enabling us to create a bank of comparison images of MFF morphology. Each transect started a short distance north (between 100 and 200 km) of the main MFF lobe and then continued a longer distance south (between 750 km and 1000 km depending on the transect position) (Fig. 3).

Fig. 3

Each selected image was examined and the presence of MFF material recorded. Given the nature of the transect lines, almost all of the positive identifications were, as expected, recorded within the five main outcrops themselves, and in the immediate surroundings areas on the lowlands. The vast majority of images with no trace of MFF material were distributed across the southern highland regions. However, some apparent outlying MFF materials were found in one area of the southern highlands: the southern region of Transect 5 in the vicinity of the Mangala Valles region. For this reason, we initiated a more in-depth study of all the images in this region.

2.3 Local area survey

We defined a large study area that covered part of transect 4 and 5 (Fig. 4). Each of the >350 MOC NA images that fell within this region was selected, downloaded and processed using US Geological Survey “ISIS” software prior to being loaded into a GIS. These images were examined individually, a record kept of any possible MFF materials and these data converted into a shape-file within the GIS. Where possible, the direction of inferred yardang-forming winds was also recorded as described in more detail in section 3.3 below.

Fig. 4

We also utilized new CTX images in the defined study area. These were also processed in ISIS and ingested into the GIS. CTX images have generally poorer spatial resolution than MOC NA (6m/pixel as opposed to up to 1m/pixel) but each image covers an area 1-2 orders of magnitude larger than MOC NA. Additionally, although MOC NA coverage is well-distributed but covers only a low percentage of continuous area, the CTX coverage is patchy but provides a larger total coverage (Fig. 5). In some areas the CTX coverage is almost continuous. We analyzed the morphology, extents and directionality trends of MFF outliers in CTX images in the same way as we did using MOC NA data.

Fig. 5

3. Results

3.1 General observations

The new southern outliers observed in the images are characterized by extreme degradation. They most commonly occur in dips and troughs and on channel and crater floors, and often become visibly more eroded, or in fact missing completely, across nearby areas (Fig. 6). Additionally, they occur across eroded older craters, particularly on the raised edges (Fig. 7). Occasionally, the MFF-like materials terminate at scarp edges, such as crater interior slopes, but then continue at the base of the slope.

Fig. 6

Fig. 7

The texture is typified by pronounced ridges, interpreted as fields of yardang features, overlying smoother material in most cases. However, there are examples where traces of MFF materials overlie rough textures.

Although the dominant directional trend, defined by the general orientation of the yardang features, was observed to be diagonally NW-SE or SE-NW, there were other orientations observed, including NNW-SSE, NNE-SSW and N-S. There were also a number of examples where bi-directionality or multi-directionality occurred, in some of these cases resulting in a crosshatch appearance (Fig. 8). Detailed observation of yardang morphology was used to establish specific wind direction as described in section 3.3.

Fig. 8

Superficially, the morphology of many outliers in the Mangala Valles study area is similar to examples of MFF upper member materials that occur primarily toward the southern edges of lobes D and E where they are observed in > 20 MOC NA images. Both these materials (Fig. 9a) and the outliers (Fig. 9b) exhibit an extremely degraded appearance, are preferentially concentrated in local topographic lows and contain small (c. 30m width) and very tightly packed yardang features, sometimes with poorly defined crosshatching. In general, though, the outlier morphologies do not completely match any of the previously described MFF member materials, but have enough similar features for us to be confident that we are dealing with the same formation. The implications of the similarity of some outliers to some Lobe D and E upper member terrains are further discussed in section 4.

Fig. 9

3.2 Distribution

The distribution of outlying deposits is both patchy and discontinuous, as far as can be judged from the sparse and non-uniform image coverage. We found examples of both isolated outliers and of clusters of near-continuous MFF-material. Many of the larger outlier extents are in close proximity to smaller outliers and show a clear relationship to each other.

Pitted patches, wherein the materials have numerous teardrop-shaped pits across them, resembling negative form yardangs (also seen on the main outcrops) appeared

frequently. These materials then grade into the more typical raised texture at the eroded edges of these patches. Isolated and lightly-clustered yardangs are often found at the edges of individual outliers, becoming less intensely clustered the further from the outlier concerned.

Overall, the outliers were most commonly found to the south of, and straddling, the crustal dichotomy, positionally between the bases of the two easternmost MFF outcrops (Fig. 10). It is also here that the largest continuous area was mapped, over a significant section west of the downstream Mangala Valles. Occurrences in channel floors were also common. To the west, many outliers, some of continuous extent, were observed in the highland region south of lobe D, particularly across and within craters. Another notable continuous example is that which lies in the furthest east corner of the study area, on a relatively high but smooth region, south of lobe E. Further south within the study area, the outliers become more sparse and eroded, often comprising only trace extents. For example, several small outliers occurred on the relatively flat area bounded to the west by Mangala Valles and to the east by a large range of hills; this area is shown close up in Fig. 11.

Fig. 10

Fig. 11

3.3 Orientation

We found that the meter-scale resolutions of both MOC NA and CTX images were insufficient for more detailed analysis of the morphologies of the MFF erosional

features. For example, ascertaining the exact orientation of the yardangs, and thus the wind direction, was difficult. We therefore used 25cm/pixel High Resolution Imaging Science Experiment (HiRISE) data (McEwen and colleagues, 2007) to derive wind direction from yardang morphology. Figure 12, showing a yardang in HiRISE image PSP_007973_1750, provides an example of how morphology was used to infer wind direction. Although the morphology is sometimes ambiguous and the HiRISE coverage somewhat sparse, we measured yardang orientations for 21 examples in the newly discovered southern outliers. The inferred wind directions are shown in Fig. 13. The dominant wind directions were found to be SW and NE, which mirrors those which were inferred from visual assessment of the main MFF lobes D and E. We suggest that this match between inferred wind directions reinforces the interpretation that the outliers we have mapped are MFF material, and thus were deposited and reworked under similar climate conditions as that of the main MFF lobes. The simplest explanation is that these outliers are the remnants of a previously larger MFF that extended much further south than previously thought.

Fig. 12

Fig. 13

3.4 Stratigraphy

The Medusae Fossae Formation, by definition, consists of several different stratigraphic units (Scott and Tanaka, 1986) and the central lobe (C) is the only one on which all three of these units can be identified. The division into the three members is extremely important in regard to relating the stratigraphy of the outliers to that of the

main lobes. The style of deposition of each member is uncertain. For example, it has not been demonstrated that deposition occurred sequentially in a “layer cake” scenario (nor if such a scenario included periods of erosion resulting in unconformities) or instead if the depositional processes were spatially and temporally heterogeneous. Furthermore, the crosshatching appearance resulting from bidirectionality in the yardangs could indicate differing stratigraphic layers within the materials themselves (Kerber and Head, 2009). We suggest that two possibilities exist: 1) that the new outliers are representative of one specific member of the Medusae Fossae Formation, or 2) that their morphology represents the highly degraded form of any of the MFF members.

To test these hypotheses, polygonal shapefiles were created in a GIS that represented the extents of the MFF outliers discovered in both the MOC NA and CTX images. These data can be seen in Fig. 10. Further shapefiles were created to represent the extent of each individual lobe, as well as the extents of the individual members within them. Elevation statistics were then computed using these shapefiles to delineate the areas in which the topographical data were analyzed. We used the gridded 128 pixel per degree Mars Orbiter Laser Altimeter (MOLA) topography data (Smith and colleagues, 1998).

The elevation data, summarized in Fig. 14, show that the maximum, minimum and mean elevations of the newly discovered outliers are closest to those of the upper member of the MFF. This is not surprising given that we are searching an area of higher and more variable altitude, but as discussed in section 3.1, the outliers share morphologic characteristics with a subset of the upper member materials. Together with the elevation

trends, this might suggest that the outliers are more likely to be remnants of the upper member than the middle or lower members.

Fig. 14

4. Discussion

The morphology and patchy, discontinuous nature of the newly identified outlier materials are very similar to MFF outliers found around areas of the upper member on lobes D and E. The characteristics of the outliers are indicative of materials which initially draped the underlying terrain since they appear widely in dips, craters and topographic lows.

The extent shapefiles (Fig. 10) illustrate the widespread aspect of the outlier spatial extents. They are most common in the north of the study region, with relatively smaller extents in the more southern areas - often only tiny outcrops. If the outliers represent the remnants of a once continuous layer, the Medusae Fossae Formation might once have extended up to 870 km south of the crustal dichotomy boundary (Fig. 15), and these areas have since been very heavily eroded.

Fig. 15

The elevation statistics (Fig. 14) show that the elevation trends for the outlier materials around Mangala Valles are most similar to those of the upper member of the MFF. This could represent skewing due to the underlying topography, given that the

outliers rest upon the southern highlands, but these results may suggest that the outliers are representative of upper member MFF materials. The similarity in morphology between certain areas of the upper member and some of the outliers further supports this possibility.

However, the outliers are not always morphologically similar to the upper member materials. Therefore, we suggest that either a) both the outliers and the morphologically similar upper member materials are examples of eroded areas of upper member deposits, or b) both are examples of aeolian materials eroded from elsewhere on the MFF and subsequently reworked. The first option is somewhat supported by observations of spatially related morphologies on the upper members and the outliers, which could be taken to represent a slightly earlier progressional stage in the erosion: some tightly packed yardang features possess morphologic characteristics that indicate a history of less severe erosion than in the outliers. While we cannot discount the second option, we suggest that aeolian materials on Mars more commonly collect in topographic lows than remain deposited on topographic highs, and therefore suggest that this is less likely than the first option.

If the mapped outliers do represent upper member materials, we then can combine a simple layer cake stratigraphic model, in which it is assumed that each member of the MFF was deposited sequentially, with the “sediment trap” hypothesis of Irwin et al (2004) where the crustal dichotomy acted to trap sedimentary materials. Here we propose a scenario in which deposition occurred on the highlands following deposition in the lowlands to the north. In this hypothesis, the deposits sequentially stacked up against the

boundary, eventually reaching the height of the southern highlands. The latter stage upper member deposits then ceased to be confined by the topographic boundary, “overflowed” it and were deposited across the nearby highlands. The topography seen today shows evidence the products of severe erosion of this “overflowed” layer-cake deposition style. The layer cake model for the MFF may be oversimplified as it does not take into account observed complexities of the member stratigraphies (Sakimoto et al., 1999; Bradley et al., 2002; Kerber and Head, 2009).

We can use our new estimate of the paleo extent of the MFF in this region to derive the volume of additional material here before erosion. To do this, we have assumed that the greatest former extent of the MFF in this region was as shown in Fig. 16, and that its uppermost surface was at the same height as the majority of the outliers we have found on the southern highlands. This is clearly an over-simplification, but there seems little alternative. Using the GIS, we have estimated a maximum removed paleovolume of $5.7 \times 10^6 \text{ km}^3$ for a region including Lobes D and E and the outliers we have presented here (Fig. 16). This assumes a very basic uniform layer-cake structure with vertical sides. Calculations of the volumes of the two easternmost MFF lobes, using a basal elevation of -3300, suggest current volumes of 6.6×10^5 and $8.9 \times 10^5 \text{ km}^3$ for lobes D and E respectively. The lobe volumes are also notably higher than would be suggested by the total current volume for the formation of $1.4 \times 10^6 \text{ km}^3$ as calculated by Bradley et al. (2002), who used similar basal elevation. The same authors estimated a paleo-area for the entire formation at $5 \times 10^6 \text{ km}^2$, compared to our total calculations of $2.14 \times 10^6 \text{ km}^2$ for the area shown in Fig. 16 alone.

Our results show that the MFF paleovolume is about three times higher than that seen today. The volume of removed material is particularly interesting when compared to Hayward et al.'s (2007) estimate of only 3600 km³ for the global dune field volume on Mars, as it raises the question of where all this material has gone. The answer to this question is not immediately obvious, but it is possible the removed material can be found in the form of surface regolith, crater infill or perhaps even buried sediments in the northern plains.

Our results support the hypothesis that the Medusae Fossae Formation was once present over a much larger area than is currently visible and suggest that the MFF contained an even larger volume of material than previously thought (e.g. Bradley et al., 2002).

The hypothesis that the highland outliers are progressively more eroded and more widely spaced towards the south of the study area could indicate either that the southern areas underwent more extreme erosion than the northern areas or that the deposition thickness decreased to the south. This latter interpretation could fit with both the “overflow” hypothesis presented above and the hypothesis of southern reworked deposits, particularly if they were preferentially laid down close to the boundary due to wind conditions. Overall, this would mean that either only the upper member of the Medusae Fossae Formation extended a significant distance south or that the MFF itself did not originally extend south but that the products of its erosion did.

5. Conclusions

Based upon the work done to date, and led by the definitions given in Section 3.1, we infer that eroded materials observed over the Mangala Valles region are examples of outlying Medusae Fossae Formation materials. Trends in yardang direction on both the MFF and the outliers tend to support this conclusion.

The topographic distribution of the outliers is most similar to the upper member of the MFF. Morphologically, there is similarity between some outliers and some upper member terrains in lobes D and E.

We suggest that there are two possible explanations for the presence of these outliers:

1. The MFF had a much larger pre-erosional extent than previously thought.
2. These materials were initially eroded from the main northern MFF, transported southward by wind, deposited onto the highlands and then subsequently reworked.

At the moment, we suggest that the first option is the more likely one, which corresponds also with results from recent mapping work by Zimbelman (2010) in the western Medusae Fossae. We present an “overflowing” layer-cake model for deposition in which approximately horizontal stacks of sediment built up north of, and against, the dichotomy boundary until they attained the topographic level of the highlands. Subsequent materials (that went on to become upper-member MFF material and outliers) were then deposited across a wide area, including well south of the dichotomy. Severe erosion then removed much of the deposited material. We also present some basic paleo-area and paleovolume

estimations that imply that the Medusae Fossae Formation once covered an area much larger than any previous estimates.

We conclude that the MFF was probably emplaced by airfall and windblown deposition of fine sediments. Deposition as episodic ignimbrites, fine grade aeolian materials (Zimbelman et al., 2003; Mandt et al., 2007) or as ice-rich deposits laid down during periods of high obliquity (Head, 2001; Head and Kreslavsky, 2001; Head and Kreslavsky, 2004; Nussbaumer, 2007) therefore seem the most likely models for formation.

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1 **Figure captions**

2

3 Figure 1: Global DEM (128ppd) demonstrating the spatial context and extent of the
4 Medusae Fossae Formation (MFF). The black polygons in the local subset represent the
5 rough boundaries of the individual lobes of the formation. The crustal dichotomy
6 boundary and the MFF's adjacent position can be clearly seen. Image credit:

7 NASA/MSSS/USGS.

8

9 Figure 2: Examples morphology from each of the five lobes of the MFF. a - Lobe A in
10 MOC NA image M07/02180 (214.38°, 1.46°), b - Lobe B in MOC NA image E16/02285
11 (207.71°, 1.98°, c - Lobe C in MOC NA image M07/02913 (176.09°, -5.95°), d - Lobe D
12 in MOC NA image M03/01027 (159.49°, 7.34°), e - Lobe E in MOC NA image
13 E04/02109 (145.45°, -4.15°). These represent just a small subset of the range of
14 morphologies seen across the formation. Image credit: NASA/JPL/MSSS.

15

16 Figure 3: Spatial context of the transect lines used in the initial survey. A - Transects 1
17 and 2 through lobes A and B, b - Transect lines 3, 4 and 5 through lobes C, D and E.
18 Image credit: NASA/MSSS/USGS.

19

20 Figure 4: Spatial context of the Mangala Valles region in relation to the Medusae Fossae
21 Formation eastern lobes (D and E) and transect lines 4 and 5. The polygonal area

represents the area used for the local survey of images. Image credit:

NASA/MSSS/USGS.

Figure 5: MOC NA and CTX coverage for the survey area within the polygon. It can be seen that the spacing of the coverage for the area is quite discontinuous (up to 400 m for CTX, up to 500 m for MOC NA). Note also the areas of continuous local areal coverage for CTX. Image credit: NASA/MSSS/USGS.

Figure 6: Example of the discontinuous and degraded Medusae Fossae outlier materials found in the Mangala Valles region (MOC NA image E16/02118 153.50°, 4.42°). Note how the materials trend SE-NW. Image credit: NASA/JPL/MSSS.

Figure 7: Example of the Medusae Fossae outlier materials that occur over two underlying and flattened craters (MOC NA image R10/01181 211.83°, -15.01°). Note how in some outliers, the materials are less degraded on the raised edges and follow the dominant SE-NW orientation. Image credit: NASA/JPL/MSSS.

Figure 8: Example of bidirectionality of the yardang ridges in the outlier materials, wherein degradation has resulted in a crosshatch appearance (M07/00807 156.41°, -10.8°).

The two directional trends in this case are SE-NW and SW-NE. Image credit:

NASA/JPL/MSSS.

Figure 9: Comparison of degraded upper member materials on lobe D (a – MOC NA image E11/01999 156.61° , -7.58°) with an example of the outlier materials (b – MOC NA image R11/04489 148.34° , -6.43°). Both show a rough SE-NW directional trend in the yardang ridge features and preferentially occur in topographic lows. Image credits: NASA/ MSSS.

Figure 10: Map showing the recorded occurrences of MFF outlier materials and the spatial extents of these examples. The largest continuous extent can be seen in the north of the study area and extending to the north of it, between lobes D and E of the main formation, with other the main occurrences clustered in the north west of the area. Towards the south of the study area, the extents become considerably smaller and more widely spaced. Image credit: NASA/MSSS/USGS.

Figure 11: Close-up of a portion of Fig. 10, which gives closer look at a section of the study area in which the outlier spatial extents are much smaller, and in fact largely typified by traces occurrences. The exception to this trend is the relatively large extent which extends across the range of hills in the east of the image. Image credit: NASA/MSSS/USGS.

Figure 12: A example of yardang morphology used to infer paleo-wind direction in a section of HiRISE image PSP_007973_1750 (209.6° -4.9°) showing a yardang in the MFF material. Note the inverted “ships hull” shape. In yardang morphology, the blunt

nose is the windward face, whilst the tapered tail is the leeward face and so the dominant wind direction in this case can be inferred as SE-NW. Typically the blunt windward face may also be undercut although this is not obvious in this image. Image credit:

NASA/JPL/University of Arizona.

Figure 13: Map showing the dominant orientation/wind direction trends are inferred from examination of yardang morphology in selected HiRISE images. Comparative orientations are also given for areas of lobes D and E. The most commonly occurring wind direction is SE-NW, with also a number of instances of NW-SE. In a few cases, a completely different orientation can be seen in the materials – either SW-NE or NE-SW – and in others, the crosshatching as seen in Fig. 8, occurs. Image credit:

NASA/MSSS/USGS.

Figure 14: Chart showing the derived elevation statistics for the differing Medusae Fossae Formation exposures, including each main lobe, the different members within these lobes and the outliers observed in the Mangala Valles region. The hollow circles represent the mean elevations, whilst the extent bars describe the minimum and maximum elevation ranges. The outlier elevation trends are most similar to those of the upper member and Lobe E (typified by the upper member).

Figure 15: Map showing the potential paleo extent of the Medusae Fossae Formation, encompassing Lobes D, E and the outliers. This was inferred from the outlier extents as

90 shown in Fig. 10 and assumes a continuous layer of deposit across the area. This extent
91 was used as the basis for paleovolume calculations. Image credit: NASA/MSSS/USGS

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Fig 1

Fig 2

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— Transect lines

Fig 3b

Survey polygon — Transect lines

Fig 5

Survey polygon MOC NA footprints CTX footprints

Fig 6

ACCEPTED MANUSCRIPT

Fig 7

ACCEPTED MANUSCRIPT

Fig 8

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Fig 9a

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Fig 9b

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Fig 12

Survey polygon —> Dominant orientation

Fig 15

Tables

Hypothesis	Source
Ignimbrite/ash flow deposits	(Zimbelman et al., 1996; Tanaka, 2000; Zimbelman et al., 2003; Hynek et al., 2003; Shockey et al., 2004; Mandt et al., 2007; Kerber et al., 2008)
Pyroclastic material	(Zimbelman et al., 1997; Bradley et al., 2002; Zimbelman et al., 2003; Hynek et al., 2003; Mandt et al., 2007; Kerber et al., 2008)
Aeolian deposits (indurated)	(Zimbelman et al., 1997; Zimbelman et al., 2003; Mandt et al., 2007)
Ancient polar layered deposits	(Head, 2001)
Ice-rich deposits laid down during periods of high obliquity or outflow channel formation	(Head, 2001; Head and Kreslavsky, 2001; Head and Kreslavsky, 2004)
Carbonate platforms	(Parker, 1991)

Table 1: A selection of the proposed origin hypotheses for the Medusae Fossae Formation. For more detail, please see Mandt et al. (2008b)

Member	Surface characteristics
<i>Upper (Amu)</i>	Discontinuous but widespread; smooth to rolling; ridges and grooves in some localities; curved margins; overlies the dichotomy boundary up to elevations of ~ 0.5 km (~3.5 km above surrounding plain)
<i>Middle (Amm)</i>	Rougher and more eroded than Upper, cut by joints and intersecting joints; appears heavily dissected and modified at all scales; has sections of highly modified teardrop hills separated by valleys
<i>Lower (Aml)</i>	Smooth to rough; highly eroded; darker in colour

Table 2: Summary of the surface characteristics of Medusae Fossae geological members
(Head and Kreslavsky, 2001)