Letter

Rafted pumice: A new model for the formation of the Medusae Fossae Formation, Mars

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ABSTRACT

The Medusae Fossae Formation (MFF), Mars, could be deposits of materials originally formed as hyaloclastites erupted from vents which formed the basal units of Olympus Mons volcano, and subsequently collapsed as landslides to form the aureole materials. These low density hyaloclastites subsequently floated on the northern sea as pumice rafts and drifted to the southwest, where they encountered the boundary of the southern highlands to form the MFF.

1. Introduction

The Medusae Fossae Formation (MFF) covers ~2.2 million km$^2$ of Mars with an estimated volume of ~1.4 million km$^3$ (Bradley et al., 2002), with several large outcrops extending around the equator (Fig. 1). MFF deposits were initially divided into three subunits, all Amazonian in age (Scott and Tanaka, 1986; Greeley and Guest, 1987). However, more recent investigations have shown that at least some parts of the MFF are Hesperian (Schultz and Lutz, 1988; Kerber and Head, 2010; Zimbelman and Scheidt, 2012).

The origin and physical attributes of the MFF remain enigmatic despite >40 years of study. Most investigators advocate an explosive volcanic origin, with the similarity between terrestrial ignimbrites and some MFF outcrops being the most popular (Mandt et al., 2008, 2009; de Silva et al., 2013). Alternative origins include paleo-polar deposits (Schultz and Lutz, 1988), eroded carbonate platform materials (Parker, 1991), or massive deposits of ash (Kerber et al., 2011; Hynek et al., 2003). Kerber et al. (2011) proposed that the MFF was produced by explosive volcanic eruptions at Apollonaris Mons, but in their model only fine particles (30–60 μm) would be transported to the distances associated with the MFF, and so their hypothesis requires either a significant amount of reworking of the ejecta while in the plume (Wilson and Head, 2007) or an abundance of small, highly fragmented, ash particles to create such a deposit. The source of the volatiles (and, thus, magma chemistry) required for such large-scale explosive eruptions early in Mars’ history is not clear, but it is possible that the mantle could have started out fairly wet and then became progressively drier as volatiles were outgassed but never replaced due to the absence of plate tectonics (Balta and McSween, 2013).

Gravity and topographic data for the MFF provide direct constraints on the material density (Ohja and Lewis, 2018), with a bulk density of 1765 ± 105 kg m$^3$. When combined with sounding radar data (Carter et al., 2009), this density rules out the presence of ice as the cause of the unusual radar permittivity (Muhleman et al., 1991; Watters et al., 2007). Instead, the density implies a dry and highly porous rock unit (Ohja and Lewis, 2018) suggesting products of pyroclastic eruptions; thus the MFF could be more than ~2 orders of magnitude larger than the largest terrestrial pyroclastic deposit. Such a conclusion, of course, has major implications for magma chemistry, the volatile history of Mars, and the influence of volcanism on the atmosphere.

An alternative origin for the MFF is proposed here, namely that these materials are the result of water-rafted pumice which originated from the Olympus Mons (OM) aureole materials. Mouginis-Mark (1993) first proposed this idea in abstract form. Since this time, there have been several terrestrial examples of large present-day sea-rafted pumices in the Pacific Ocean (Shane et al., 1998; Jutzeler et al., 2014) which helped motivate this study. Data from Mars missions over the past >18 years have also strengthened the idea that there was once an ocean which impacted the geologic history of the NW flanks of OM (De Blasio, 2011, 2018).

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2. Proposed model

The hypothesized new origin for the MFF involves five steps (Fig. 2):

1. The base elevation of OM is ~2 km relative to Mars datum (Smith et al., 2001). If local ice deposits existed early in the evolution of OM, it is possible that the basal units were produced by explosive phreatomagmatic activity (Head et al., 1976; Hodges and Moore, 1979). By analogy with terrestrial eruptions, vast amounts of hyaloclastite could have been produced (Head and Wilson, 2002), and is a characteristic of the submarine portion of Hawaiian volcanoes (Schiffman et al., 2006). Inspection of the lower flanks of OM supports this interpretation as there are no visible lava flows exposed within the eroding escarpment face, which shows numerous slope lineations suggesting unconsolidated material that slumps easily (Mouginis-Mark, 2018). Originally, these hyaloclastites remained close to the vent as no spatially-extensive body of water existed at this time.

2. This basal hyaloclastite layer is buried by lava flows as OM grew to sufficient height that the vent became disassociated from the local ice or water. A comparable sequence was observed during the 1964 eruption of Surtsey, Iceland (Thorarinsson, 1967). In order to float (Step 4), this hyaloclastite must retain a low bulk density despite the subsequent overburden pressure.

3. Parts of the lower flanks of OM subsequently collapsed, potentially as giant landslides (Lopes et al., 1980; McGovern et al., 2004; De Blasio, 2011, 2018) forming the aureole lobes. This appears to be possible if they are made of weak hyaloclastites which cannot support the lavas on the upper flanks. Depending upon the origin of the landslides (submarine or subaerial?) the dispersal of the hyaloclastite may have been restricted to the local area at this time.

4. After (or during) the period of emplacement of the aureole materials, a shallow sea existed around the base of OM and flooded the aureole lobes (De Blasio, 2011). Low density material within the aureole would then float, forming “pumice rafts”. This would have been similar to floating pumice rafts documented for Pacific eruptions (Shane et al., 1998; Jutzeler et al., 2014), but differs in that terrestrial pumice rafts have only been observed concurrent with eruptions rather than being generated by remobilization after the eruption stops.

5. The floating pumice raft was then transported to the southwest by the wind until it encountered a “coastline” represented by the southern highlands boundary. Of course, no detailed knowledge of the paleo-meteorology of Mars exists, but Banfield et al. (2015) found that combinations of reasonable atmospheric pressure and wind could have influenced the surface of a paleo-ocean. Successive cycles of this process (flank collapse to produce an aureole lobe followed by flooding and pumice floatation) created multiple MFF deposits, which have subsequently undergone extensive erosion to produce the observed diversity of MFF units (i.e., massive-looking or at other times finely layered). Differences in the orientation of yardangs within the MFF (de Silva et al., 2013) demonstrates that wind has been an important factor in the erosion of the MFF, so that aeolian transport of pumice rafts appears plausible.

3. Potential next steps

This “floating pumice” hypothesis for MFF does not require any large volcanic vents or volatile-rich magmas, which have been issues for the proposed copious ash originating from the Tharsis volcanoes (Hynek et al., 2003), or the injection of ash high into the atmosphere (Glaze and Baloga, 2002; Kerber et al., 2011). Instead, it is proposed here that the OM vent complex was in contact with ice or water during the earliest eruptive phases. Such a common origin could explain the remarkable similarity of the MFF over distances of thousands of kilometers, which Hynek et al. (2003) attributed to explosive volcanism. Thus the materials which now form the MFF would only require a single magma source.
in the early history of OM. What the model does require is a shallow sea which persisted (perhaps episodically) over a sufficiently long period to span the time for MFF formation (Kerber and Head, 2010; Zimbelman and Scheidt, 2012). Supporting this idea of a persistent (or periodic) sea, an extended time period for aureole formation has been advocated by De Blasio (2018) on the basis of a channel-fan on the western aureole which was eroded prior to other phases of aureole lobe emplacement.

How can this new idea be tested? First, if the MFF material is rafted pumice, it would have to mark the highest levels of the shallow sea along the boundary of the southern highlands—does this make sense? Currently, the different components of the MFF have base elevations between −2.5 km and −1.0 km, so that a shallow sea would appear possible. The lack of clear evidence for shorelines (Banfield et al., 2015; Sholes et al., 2019) is problematic, but this elevation range is similar to the water level (−2.3 km) inferred by De Blasio (2018) for the emplacement of the western aureole lobe from OM. This is true for the base of MFF, but the current upper surface of the MFF (which can exceed 3700 m above datum; Hynek et al., 2003) means that something (wind?) was needed to “pile up” the rafted pumice once it started to accumulate at the dichotomy boundary. The identification of climbing dunes within the MFF would support this idea.

Second, De Blasio (2018) noted that there is a mismatch between the volume “missing” from the lower flanks of OM and that of the aureole materials. Further investigations should strive to determine if adding the volume of the MFF, with suitable allowances for changes in the bulk density of the material, makes the aureole volume more consistent with the volume missing from the lower volcano flanks.

Third, evidence of welding within the MFF would be a fatal observation for the rafted pumice model, as one would expect everything to be transported cold and as individual pieces of pumice. To date, no
structures uniquely consistent with materials emplaced at high temperatures (i.e., welded ignimbrites displaying columnar jointing; Mandt et al., 2008, 2009) have been found.

Fourth, is there any morphologic evidence within the aureole lobes for the removal of fines by marine processes? The aureole lobes display a variety of structures and block orientations, and the ubiquitous presence of slope lines and lack of layering within the blocks supports the idea that the lobes comprise unconsolidated materials (Mouginis-Mark, 2018). The channel fan identified by De Blasio (2018) indicates water flow within the aureole, but no clear evidence for removal of material from the surface of the lobes (such as “plucking” of lobes flooded by the sea) has yet been identified.

Fifth, gravity and topographic data (Ohja and Lewis, 2018) demonstrate that the current bulk density of the MFF (1765 ± 105 kg m⁻³) is too high to allow the material to float. Our model would require post-emplacement compaction of the pumice by less than a factor of two, and requires the pumice to remain buoyant for sufficient time (weeks, months?) to be transported hundreds of kilometers. Given that the MFF may be 2–3 km thick, self-compaction to a density greater than that of water may be possible. It would be productive to test if there are density variations across the MFF which might indicate different degrees of compaction.

4. Conclusions

We may never know if any Tharsis volcano experience phreatomagmatic activity early in its evolution. Nevertheless for our “rafted-pumice model” to be valid, it seems most likely that OM was the source of the pumice. Were the aureole lobes to be the source of the MFF units, then some of these materials would have to be transported >4000 km from the aureole lobes to the westernmost extent of the MFF close to Gale Crater. Unfortunately, extensive bed load across the MFF and aureole materials precludes a direct correlation (or lack thereof) of their compositions, but it may sometime be possible to search for spectral matches between the aureole and MFF.

The relative age of the MFF units compared to the hypothetical northern ocean may be a problem for the rafted-pumice model. However, as observed by numerous investigators (Mandt et al., 2009; Zimbelman and Griffin, 2010; Morgan et al., 2015) the MFF appears to be extensively reworked, so that the date at which the materials were originally transported to the current location may be earlier than their inferred Amazonian and Hesperian ages (Kerber et al., 2011; Zimbelman and Scheidt, 2012).

We contend that our model solves some of the issues implied by the MFF being volcanic ash or ignimbrite, because the MFF volume is very large and would require highly explosive eruptions from volcanoes which today only display evidence for effusive activity. The model is also consistent with processes which might explain the origin of the basal escarpment of OM and the aureole lobes, as well as the idea that Mars once had shallow oceans in the northern lowlands. It is therefore hoped that future observations and models may test some of the ideas associated with the rafted-pumice hypothesis.

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References


