Volcanic Origin of Medusae Fossae Formation from Gravity and Topography Data.

L. Ojha[1] and K. Lewis[1], S. Karunatillake[2] [1]Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, MD, 21211. [2]Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA, 70803. (Corresponding author: Lujendra Ojha LUJU@JHU.EDU)

Abstract: The Medusae Fossae Formation (MFF) is one of the largest and youngest layered deposits on the Martian surface. The origin of MFF is unknown and several processes including volcanic, aeolian and ice-related mechanisms have been proposed as depositional mechanisms. We localize the gravity and topography signature of MFF and place a direct constraint on its density. We find MFF to be composed of relatively low-density units (1500-1800 kg m^{-3}). When combined with RADAR measurement of MFF's dielectric constant, the density measurement rules out the presence of ice in MFF. Surface elemental data indicates that MFF is enriched in Cl and S. Based on the relatively low density of MFF and enrichment of major volcanic elements, we propose that MFF was deposited by explosive volcanic eruptions. The mass of MFF is found to be two orders of magnitude higher than the largest terrestrial pyroclastic deposit making it the largest known pyroclastic deposit in the solar system.

Introduction: The Medusae Fossae Formation is one of the most extensive geologic units on the Martian surface that may have been deposited due to pyroclastic activity. MFF stretches from ~140°E to 240°E near the hemispheric dichotomy between Amazonis and Elysium Planitia and has a relatively young surface exposure age [1]. Based on the imagery and elevation data from the Mars Orbiter Camera (MOC), and Mars Orbiter Laser Altimeter (MOLA), the areal extent of MFF is estimated to be 2E6 km^2, but could have once covered an area greater than 5E6 km^2, making it one of the largest sedimentary deposits on the Martian surface [2]. Based on crater counting, and stratigraphic relations, the emplacement age of the lowermost MFF has been dated to be Hesperian with significant chemical and physical alteration and subsequent deposition occurring into the Amazonian [3].

The origin and the depositional history of MFF are not completely understood and several geological processes have been proposed to explain MFF's formation including: paleo-polar deposits [4], ignimbrite deposits [5], pyroclastic or aeolian materials [6], and ashfall [2]. The Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) instrument onboard the Mars Express spacecraft found MFF to have a relatively low dielectric constant of ~2.9 ± 0.4, which was inverted for a maximum depth-averaged bulk density of 1900 kg/m^3; both ice-rich and non-ice material with low dielectric constant were considered as plausible compositions for the MFF [7]. The Shallow Radar (SHARAD) onboard the Mars Reconnaissance Orbiter also found a similarly low permittivity of ~3.0 [8].

Based on RADAR data [7,8] and stratigraphic observations and modeling [2], the most favored formation scenario for MFF involves explosive volcanic processes that deposited low-density welded or interlocked pyroclastic deposits on the Martian surface. However, direct measurement of MFF's density to corroborate this hypothesis has not been available to date. In this work, we place a direct constraint on the density of MFF using topography data from the Mars Orbiter Laser Altimeter (MOLA), and the spherical harmonic gravity field of Mars.

Methodology: The spherical harmonic gravity field of Mars [9] expanded to degree and order 120, and MOLA topography [10] were used to compute admittance and correlation spectra. Localized gravity and topography estimates within our region of interest were obtained by multiplying the global gravity and topography fields of Mars by a bandlimited localization window. Because of the non-circular, and relatively small extent of MFF, we created a series of custom localization windows of shape A optimally concentrated within our region of interest on the sphere using Slepian functions [11,12].

The estimated admittance spectra were compared to synthetic admittance spectra to constrain the load-density and the elastic thickness. We constructed numerous forward models by assuming that the lithosphere is a thin shell that deforms elastically in response to surface loads. We solved for the best fitting elastic thickness and load-density by calculating the root-mean-square (RMS) between the forward models and the observed admittance spectra.

Results: We localized the gravity and topography fields using a single-taper window with bandwidths between 25° – 50°. Synthetic admittance spectra were created and compared with the observed admittance spectra to constrain the load density and the elastic thickness. The elastic thickness is essentially unconstrained, but as elastic thickness increases, load-density with lowest RMS within 1-σ of the observed admittance corresponds to 1500 – 1800 kg m^{-3} (Fig. 1). The relatively low-density of the MFF, especially compared to the bulk crust in this area, implies

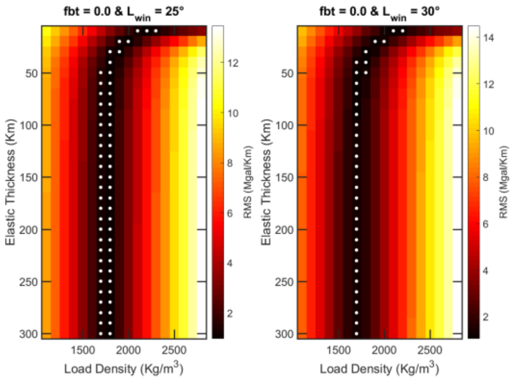

Fig. 1. *(R.M.S) difference between observed and modeled admittance as a function of elastic thickness and load density. The solutions within 1-σ of the observed admittance are denoted with white dots.*

that it is either highly porous, or contains a large fraction of ice. If ice is present in MFF, along with rock and air, then the bulk dielectric constant of MFF can be approximated using a power-law $((K_{bulk})^{1/\gamma} = F_{ice}*(K_{ice})^{1/\gamma} + F_{air}*(K_{air})^{1/\gamma} + F_{rock}*(K_{rock})^{1/\gamma})$, where F is the volume-fraction, K is the material's dielectric constant and γ is 2.7 [14, 15]. Assuming the dielectric constant of ice, rock and air to be 3, 8, and 1 respectively, a range of ice-rock-air mixtures can yield bulk dielectric constant of 2.9 ± 0.4 as measured by MARSIS (Fig. 2). Assuming a grain density ρ_s of 3000 kg m-^{3}, the average Martian atmospheric density ρ_a of 2E-2 kg m^{-3} and a water-ice density ρ_{ice} of 934 kg m^{-3} and that bulk-density is a linear combination of these materials, none of the solutions that satisfy the dielectric constraint can satisfy the density constraint of 1500-1800 kg m^{-3} (Fig. 2). If ice is assumed to be absent in MFF, then the bulk-dielectric constant can be related to the bulk-density of the air-rock mixture via the alternate relation $K = 1.96^d$, where d is the bulk-density if g cm^{-3}. The range of K observed by MARSIS (2.9 ± 0.4) yields a bulk-density in the range of 1300-1800 kg m^{-3} which is in excellent agreement with our density estimate of MFF (Fig. 2).

Conclusions: The presence of ice is inconsistent with the joint constraints of our density and previous RADAR measurements [7, 8]. In the absence of significant amounts of ice, the dielectric constant of MFF and our density estimates require a highly porous rock unit, consistent with pyroclastic ashfall and/or ignimbrites. A volatile-rich magma is necessary for an explosive eruption, and therefore the presence of a major pyroclastic deposit on Mars will be important in understanding the evolution and volatile content of the Martian interior. The largest explosive eruption on Earth (Fish Canyon Tuff) produced >10^{16} kg of deposits. Given our density constraint of 1500-1800 kg m^{-3}, and an estimated volume [2] of 1.4E6 km^3, the total mass of MFF ranges from 2.1 E18 kg to 2.5 E18 kg, which is two orders of magnitude higher than the mass of Fish Canyon Tuff deposit. In the absence of any evident subduction regions on Mars, recycling of near-surface and atmospheric volatiles such as water or carbon dioxide into the planet's interior would not have been a major geological process. Therefore, any volatiles involved in pyroclastic eruptions on Mars must have been primordial and sourced from the planet's interior.

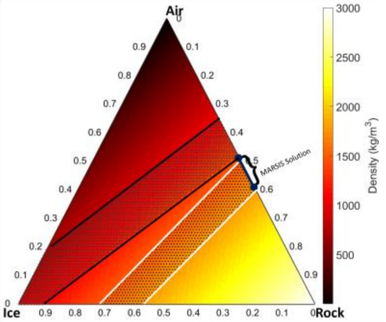

Fig. 2. *Ternary diagram of bulk density for a range of mixtures of ice, rock and air. The white lines outline density in the range of 1500-1800 kg m^{-3}. The black lines outline the solution for dielectric constant between 2.9 ± 0.4.*

The Gamma Ray Spectrometer (GRS) onboard the Mars Odyssey has observed an elevated concentration of chlorine in MFF [17] that has been hypothesized to be due to acidic volcanic fog. Furthermore, a recently compiled elemental map also shows that MFF is highly enriched in sulfur, the source of which could be due to volcanic degassing of S in the easternmost MFF section [18]. The enrichment of major volcanic elements along with the measured low-density of MFF is most consistent with a volcanic origin.

References:[1]Tanaka et al., (2014). doi:10.3133/sim329 [2]Bradley et al., *J. Geophys. Res*. 107, 5058. [3]Kerber & Head (2010). *Icarus* 206, 669–684. [4]Schultz & Lutz (1988). *Icarus* 73, 91–141. [5]Scott & Tanaka (1982). *J. Geophys. Res.* 87, 1179–1190. [6]Tanaka 2000. *Icarus* 144, 254–266. [7]Watters et al., *Science.* 318, 1125–1128. [8]Carter et al., *Icarus* 199, 295–302. [9]Konopliv et al. (2016). doi:10.1016/j.icarus.2016.02.052. [10]Wieczorek et al. (2015). doi:10.5281/zenodo.20920. [11]Dahlen & Simons (2008). *Geophys. J. Int.* 174, 774–807. [12]Slepian, D. (1983). *SIAM Rev*. doi:10.1137/1025078. [13]Grott & Wieczorek (2012). *Icarus* 221, 43–52. [14]Bramson et al. (2015). *Geophys. Res. Lett*. 42, 1–9. [15]Stillman et al. (2010). *Phys. Chem. B* 114, 6065–6073. [16]Kerber et al. (2011). *Icarus* 216, 212–220. [17]Keller et al. (2007). *J. Geophys. Res. E Planets* 112. [18]Karunatillake et al. (2009). *J. Geophys. Res. Planets* 114.