MARSIS SUBSURFACE RADAR SOUNDING OF MEDUSAE FOSSAE FORMATION DEPOSITS ON MARS: ICE RICH OR ICE POOR, THAT IS THE QUESTION.

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Introduction: The Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) onboard the European Space Agency's Mars Express spacecraft [1] has successfully probed the polar layered deposits (PLD) [2], the Hematite-Bearing Plains (HBP) and Etched Plains (EP) deposits of Meridiani Planum [3], and the Medusae Fossae Formation (MFF) [4] (Fig. 1). The radar sounder data delineates the subsurface interface between PLD, HBP-EP, and MFF deposits and the underlying terrain. The PLD at the south and north poles are known to be ice-rich deposits. The HBP-EP of Meridiani are deposits of basaltic sand [5] likely deposited in an aqueous environment [6]. Compaction models indicate that the relatively low dielectric constant of the Meridiani Planum deposits is consistent with a thick layer of ice-free, porous, basaltic sand [3]. The MFF deposits are the most mysterious, and their origin the most controversial of the three. They are broadly distributed deposits confined to the dichotomy boundary (Fig. 1) and are thought to be either volcanic ashfall deposits [7−9], eolian sediments [10,11], or an ice-rich deposit analogous to the PLD [12,13]. Electrical properties derived from MARSIS and SHARAD radar sounder data do not rule out ice-rich MFF deposits [4, 14−16], and reprocessed epithermal neutron data from the Mars Odyssey Neutron Spectrometer suggest MFF deposits may contain >40% water equivalent hydrogen [17]. Here, we present newly acquired MARSIS sounder data that shows evidence of layering in multiple units of MFF, and we apply compaction models that challenge reported low bulk densities for MFF and the interpretation that the deposits are thick accumulations of highly porosity, ice-free volcanic ash [18].

The MARSIS Radar Sounder: The MARSIS instrument is a multi-frequency synthetic aperture orbital sounding radar that operates in four frequency bands between 1.3 and 5.5 MHz in its subsurface modes. Its free-space range resolution is ~150 m, and the cross-track and along-track footprint sizes range from 10 to 30 km and 5 to 10 km, respectively [1]. The most commonly used operating mode is SS3, consisting of 2 frequency bands and 3 Doppler filters collected on the dipole antenna channel [19]. Onboard processing in this mode includes pre-summing and conversion of digitized radar echoes to one-byte integers. The instrument also has the capability to collect raw data in 2 frequency bands stored in flash memory (FM). In FM mode, the along-track distance covered is typically ~100 to 250 km, much less than in the SS3 mode. The normal FM radargrams have gaps in coverage, giving the radargrams a picket fence appearance. The super-frame (SFM) mode provides continuous coverage at the expense of along-track distance, typically <100 km.

New MARSIS MFF Observations: During the northern hemisphere night campaign over the summer of 2018, SS3 and targeted FM and SFM data for MFF deposits were collected. SS3 orbits over the three largest contiguous MFF deposits (Lucus Plunum, Medusae Fossae-Eumenides Dorsum, and Amazonis Mensa-Gordii Dorsum) show evidence of layering (Fig. 1, 2). Previously, layering had only been detected in the Amazonis Mensa-Gordii Dorsum deposits [4, 20]. Two distinct subsurface echoes are found in orbits 18703 and 18644 over Lucus Plunum and Medusae Fossae-Eumenides Dorsum, respectively (Fig. 2). An FM orbit 18664 also shows two subsurface echoes in Medusae-Eumenides deposits. Three subsurface echoes are detected in orbit 18611 over Amazonis Mensa-Gordii Dorsum (Fig. 2), consistent with layers found in earlier SS3 orbits (10121 and 10216). Weak subsurface echoes in a SFM orbit 18460 over one of the westernmost MFF deposits, Zephyria Planum, may be evidence of layering in these deposits (Fig. 3). The detection of layers in the largest units of MFF indicates that layering is not confined to isolated sections [18] but is a pervasive property of MFF deposits.

Compaction Models for MFF Deposits: The change in porosity as a function of depth in a geologic material can be described by an exponential decline [21,22], and this relation has been applied to the porosity of the lunar [23] and martian [24] crusts. Adapting Athy's Law formulated with effective stress, the porosity ϕ as a function of depth is given by

$$\phi = \phi_o e^{-k(\rho g z)}$$

where ϕ_o is the initial porosity, k is the compressibility or the inverse of the bulk modulus of the material, ρ is the uncompacted density, g is the acceleration due to gravity, and z is the depth [3]. This equation allows the expected decrease in porosity with depth of specific geologic materials on Mars to be modeled and avoids the need for the use of empirically derived constants. The relationship between bulk density ρ_b and porosity ϕ is given by $\rho_b = (1 - \phi)\rho_p$ where ρ_p is the density of the particles.

Compaction curves for three commonly cited geologic deposits on Mars, well-sorted sand, volcanic ash, and silicate (lunar-like) dust, are modeled. The physical properties of these materials (i.e., *k* and ρ) are well established [see 3]. The maximum thickness of the major MFF deposits varies from less than 1 km up to ~2.5 km [see 4]. Compaction curves indicate that well-sorted sand experiences the least and silicate dust the most reduction in porosity and increase in density with depth. Volcanic ash at a depth of 1,000 m reaches a density of ~2.4 gm/cm^3, and at 2,000 m reaches a density of nearly 2.8 gm/cm^3 (Fig. 4). The real dielectric constant ε' of MFF deposits with a depth-averaged bulk density >2.4 g/cm^3 is >5, much larger than the value of ~3 inferred from MARSIS and SHARAD data [4,14,25]. Thus, the possibility that MFF deposits are ice-rich cannot be ruled out. The presence of layering in all the major MFF deposits establishes an additional key similarity to PLD.

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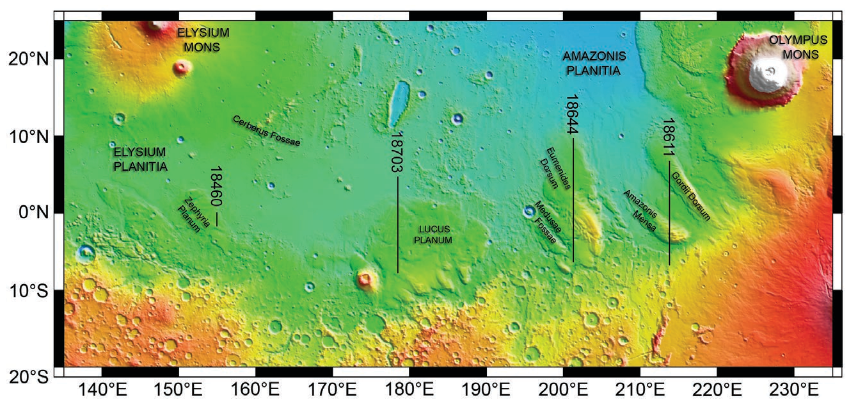

Figure 1. Medusae Fossae Formation deposits along the dichotomy boundary. The approximate locations of MARSIS orbit tracks 18460, 18703, 18644, and 18611 are indicated by black lines.

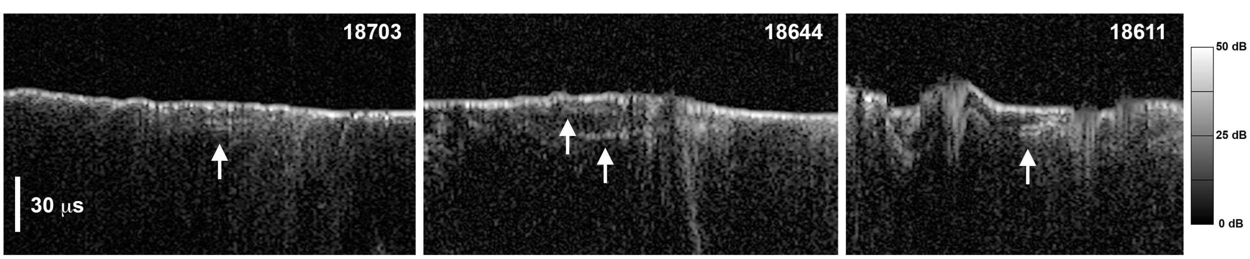

Figure 2. Radargrams showing MARSIS SS3 mode data for orbits 18703 (band 4), 18644 (band 2), and 18611 (band 1) where echoes are plotted in time-delay versus position along the orbit. Multiple subsurface echoes (arrows) are offset in time-delay from the surface echo and are interpreted to be nadir reflections from layers in the MFF deposits. Locations of the radargrams are shown in Fig. 1.

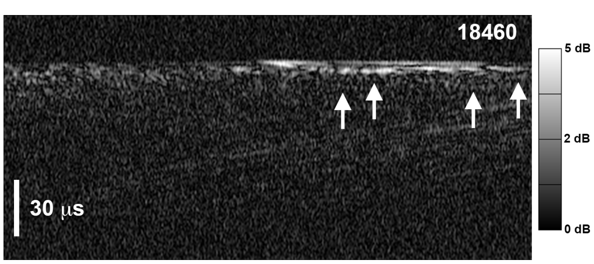

Figure 3. Radargram showing MARSIS super-frame FM data for orbit 18460 (band 2) where echoes are plotted in time-delay versus position along the orbit. Subsurface echoes (arrows) are offset in time-delay from the surface echo. The upper and lower arrows indicate echoes interpreted to be layering in the MFF deposits of Zephyria Planum.

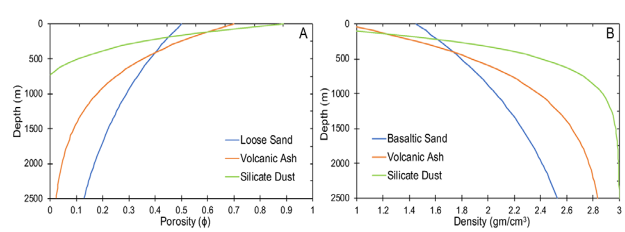

Figure 4. Compaction and density curves for three geologic materials: a loose basalt sand (blue), a volcanic ash (red), and a silicate dust (green). (A) The compaction model incorporates the compressibility of the materials and acceleration due to gravity of Mars (see 3 for the material parameters). (B) Change in bulk density as a function of depth for the compacting geologic materials.