Dielectric Properties of the Medusae Fossae Formation and Implications for Ice Content

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Abstract. The extensive Medusae Fossae Formation (MFF) along the dichotomy boundary on Mars has geologic features indicative of wind erosion of low-density material. There is evidence suggesting a water ice component, but with considerable uncertainty linked to the unknown MFF porosity and compaction behavior. We use SHARAD radar sounder data to estimate the real permittivity and loss tangent of MFF deposits, and compare these to a model for sediment compaction and to the properties of ice in mid-latitude glaciers. In areas along the margins of Eumenides Dorsum, between Gordii Dorsum and Amazonis Mensa, and in northwest Zephyria Planum, the loss tangent is about 0.001 at 170 m and plateaus at about 0.003 for 310-550 m thickness. The real dielectric constant across the study areas ranges from 2 to 3. We propose that the MFF is a two-layer deposit, with 300-600 m of fine-grained, self-compacting material above up to 2 km of minimally compacting, low-loss material. The lower unit could be ice-free and very coarse-grained, but we see no evidence of extensive sand exposed by erosion. The lower layer might instead be ice-rich and protected from sublimation by the dry cover. The volume of cover relative to a high ice content in the lower layer implies hybrid MFF formation as glacial or polar layered deposits capped by a dry, perhaps pyroclastic ash, component.

Plain Language Summary

The Medusae Fossae Formation (MFF) on Mars covers a vast area along the boundary between the rugged southern highlands and the smooth northern plains. While the MFF appears to be thick sediments or volcanic ash slowly eroding in the martian winds, how this material was emplaced remains mysterious. Most intriguing is evidence suggesting that some areas of the MFF may contain water ice. In this work we use sounding radar data from the SHARAD instrument on the Mars Reconnaissance Orbiter to probe up to 600 m below the surface and measure the electrical properties of the MFF material. The results suggest that the shallow parts of the MFF deposits are very porous and compress readily under their own weight. To match deeper probing by the MARSIS instrument on Mars Express requires a second layer of either vast porous deposits or ice-rich material protected from sublimation by the dry sediments.

I. Introduction

The Medusae Fossae Formation (MFF) spans a ~5000 km region along the martian dichotomy boundary. The deposit comprises the large massifs Amazonis Mensa, Eumenides Dorsum, Lucus Planum, Aeolis Planum, Zephyria Planum, and Gordii Dorsum, and lower-lying materials with a range of areal coverage. Estimates of MFF deposit volume range from 1.4x10^6 km^3 [Bradley et al., 2002] to 1.9x10^6 km^3 [Hynek et al., 2003]. Long inferred to be comprised of friable, low-density material, the MFF exhibits extensive wind erosion features such as yardangs, and is an evident source of sediments both regionally [Morgan et al., 2015] and perhaps planet-wide [Ojha et al., 2018]. Its deposition has been attributed to a range of mechanisms, with many authors proposing pyroclastic or ignimbrite eruptions [e.g., Bradley et al., 2002; Hynek et al., 2003; Zimbelman and Griffin, 2010; Kerber et al., 2011] including possible rafting of pumice southward from Olympus Mons [Mouginis-Mark and Zimbelman, 2020]. In any case, the MFF is likely characterized by a mix of primary depositional features, with ages stretching back to the Hesperian period, and by units comprising reworked material eroded from these earliest deposits [e.g., Kerber and Head, 2010; 2012, Zimbelman and Scheidt, 2012]. A major question, however, is the degree to which the MFF contains a significant amount of water ice [Watters et al., 2007], perhaps as paleo-polar features [e.g., Schultz and Lutz, 1988].

Ice is relatively transparent to radar signals in the frequency range used for subsurface sounding, so instruments like the Mars Express Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) [Picardi et al., 2004; Jordan et al., 2009] and the Shallow Radar (SHARAD) on the Mars Reconnaissance Orbiter [Seu et al., 2007] can probe up to several km in polar and glacial materials. Signal penetration of up to 2500 m was observed for the Medusae Fossae Formation using MARSIS [Watters et al., 2007], and SHARAD may “see” subsurface interfaces down 800 m or more. Data from both radar sounders suggest a low real dielectric constant and loss tangent for the MFF that could be consistent with an ice component [Carter et al., 2009a; Campbell and Morgan, 2018].

In this work we combine the larger set of SHARAD observations collected since the Carter et al. [2009a] study with a new multi-band data processing technique [Campbell and Morgan, 2018] to study the variations in MFF physical properties with depth. We first use SHARAD data to estimate the real dielectric constant of the material for locations with different thicknesses. We then apply the multi-band data analysis technique, and a previously demonstrated power versus time-delay method, to MFF areas where strong subsurface echoes can be detected, in particular the region of gently sloping deposits between Amazonis Mensa and Gordii Dorsum. In this area the topography of the unit changes gradually enough for a detailed study of the dependence of loss on thickness. Through comparison to exponential compaction model predictions and the dielectric properties of other Mars terrain types, including debris-covered glaciers, we assess the need for a water ice component to explain the MFF properties.

II. Medusae Fossae Study Regions

We analyze SHARAD observations of three areas of the Medusae Fossae Formation (Fig. 1). Located between the highly elevated Gordii Dorsum and Amazonis Mensa, the first study region consists of a broadly lobate deposit that terminates within the Hesperian plains units of southern Amazonis Planitia (Fig. 2). Following the nomenclature of Carter et al. [2009a], we term this region as MFF_{GA}. Portions of MFF_{GA} are bisected by a prominent cliff face 300-400 m high (delineated in Fig. 2). The cliff structure suggests that the original surface of the deposits has regressed laterally via the removal of an upper layer of material. SHARAD signals penetrate only the thinner parts of the MFF_{GA} unit northwest of the cliff, which gradually thins to a contact with the plains (Fig. 3). Figure 4 shows a representative SHARAD track over the deposit, revealing the single (though sometimes intermittent) reflector that extends from the northern terminus of the MFF_{GA} and continues beneath much of the deposits. As the reflectors begin at the terminus of the MFF_{GA} we interpret them to represent the transition between the base of the MFF_{GA} and underlying Amazonis Planitia (Hesperian-age) plains. Several SHARAD tracks also indicate that this subsurface horizon extends beneath Amazonis Mensa, implying that despite the dramatic variations in elevation, the MFF_{GA} and Amazonis Mensa are part of a single MFF deposit that likely also includes Gordii Dorsum. Analysis of MARSIS data for this area [Watters et al., 2007] showed two subsurface reflectors at greater depth than the interface mapped by SHARAD, which may indicate interlayering of plains-forming lava flows and primary or reworked MFF material [Morgan et al., 2015].

The second study region is situated to the west of MFF_{GA}, along the northwest margin of Eumenides Dorsum (Fig. 5). A single subsurface reflector is present below Eumenides Dorsum in three SHARAD tracks that cross the boundary between the deposit and the surrounding plains (Fig. 6). As is the case with MFF_{GA}, we interpret these reflectors as the boundary between the base of Eumenides Dorsum and the underlying plains. Our third study region is a deposit in northern Zephyria Planum (Fig. 7), on the margin of a thick unit studied by Watters et al. [2007] using MARSIS data and termed “North Hill” (Fig. 8). A study by Carter et al [2009a] using SHARAD data also revealed the presence of a subsurface reflector below North Hill. Directly to the north of Zephyria Planum is the youngest known lava flow on Mars [Jaeger et al., 2010] that forms part of the Elysium Planitia volcanic complex (Fig. 7). Morgan et al. [2015] identified the subsurface contact between an outlier of MFF material (noted on Fig. 7-8) and the young lava directly to the north of Zephyria Planum. The presence of MFF material on top of very young flows (~10 Ma, Jaeger et al., [2010]) suggests the recent removal and redistribution of MFF material from the main deposits to the surrounding terrain [Morgan et al., 2015].

III. Measurement of the Real Dielectric Constant

Radar reflections in sounder observations arise from a transition in the real dielectric constant, ε', typically linked to a difference in density and/or composition across an interface. The real dielectric constant also determines the speed of light in the material, $c_m = c/\sqrt{\varepsilon'}$, where c is the speed of light in vacuum. The round-trip time delay between the surface and a subsurface interface at depth H is thus:

$$\Delta T = \frac{2H}{c}\sqrt{\varepsilon'} \qquad (1)$$

The time delay is an integral of properties, over the full thickness of the deposit, which comprise changes in density or mixing of materials such as sediment, ice, or void space. Where H can be measured from topographic data, (1) yields an estimate for this "apparent" dielectric constant with uncertainties set by the time resolution of the sounder. In locations where the true thickness is less certain, a common method is to estimate ε' from the value that best "flattens" the subsurface interface (e.g., a plains unit below the MFF or a valley floor beneath glacier-like lineated fill) or matches the trend of nearby plains [e.g., Plaut et al., 2009].

For the MFF_{GA}, we compared the time delay recorded in multiple SHARAD tracks with that of Mars Orbiter Laser Altimeter (MOLA) point data (Fig. 3). Adjusting the permittivity to match an extrapolation of the adjoining plains provides an ε' between 2 and 3. We also used daytime data which run SE-NW and thus trace a profile through the MFF_{GA} unit into Amazonis Planitia (Fig. 9). Extending the slope of these plains beneath the MFF material and correcting for different dielectric values shows that the basal interface is well matched by a value of ε'=3 for the thicker portions (maximum depth ~260 m), while the thinner section to the north is overcorrected and may require a dielectric constant closer to 2.

For the Eumenides Dorsum study region our best estimate of the real dielectric constant is obtained by comparing a track through the deepest areas seen by SHARAD (34655_01) with a parallel track over plains 54 km west (19148_01). Matching the plains elevation in an overlay of the two tracks, we see that the gentle upward trend of topography from north to south is well matched by correcting the subsurface material for $\varepsilon' = 3$ (Fig. 10). There is no clear evidence for a lower dielectric value in the thinner parts of Eumenides, but the surface topography changes rapidly enough to potentially obscure any subtle difference. At this dielectric constant the maximum depth probed by SHARAD is ~400 m.

For a combination of several MFF units, including those of northern Zephyria Planum, Watters et al. [2007] estimated an effective real dielectric constant in units 500-2500 m thick of 2.9±0.4, and Carter et al. [2009a] estimated a value of 3.0 from SHARAD track 5898_03 in a unit <500 m thick. Investigating the MFF outlier north of Zephyria Planum, Morgan et al. [2015] found an ε' of 1.6-2.2 in a deposit about 100 m thick (Fig. 8). Two tracks, 18042_02 (Fig. 11) and 22011_01 (Fig. 12), suggest that the minimum dielectric constant could be 2.0-2.5 in thicker material to the south. We assume that the "plains" which appear to extend below the MFF are capped by the much younger lava flows evident in images. Permittivity values >2.0 for 18042_02 yield a sloping interface that is progressively less consistent with the tracks to either side, and there is no reason to expect such a change in plains slope at precisely this location. The same approach for deposits in track 22011_01 (Fig. 12) yields a best estimate of ε'=2.5. The maximum penetration delay of 6 μs on track 18042_02 corresponds to 640 m at ε'=2.0 or 570 m for ε'=2.5. SHARAD track 22011_01 also reveals an internal reflector in the MFF (Fig. 12).

IV. Measurement of the Dielectric Loss

The imaginary component, ε'', of the complex dielectric constant, ε, determines the loss experienced by a radar signal as it propagates through a medium. The loss tangent, tanδ, is the ratio of the imaginary to the real components of ε and is strongly dependent on material composition [Ulaby et al., 1986; Carrier et al., 1993]. We measure that depth-averaged loss tangent for the MFF through two methods. The first is based on differences in SHARAD echoes within separate frequency bands [Campbell and Morgan, 2018], while the second is based on the reduction in echo strength with delay for interfaces in radargrams processed with the full SHARAD bandwidth [e.g., Campbell et al., 2008].

Multi-band Analysis

SHARAD transmits a “chirp” radar signal that spans a 10-MHz bandwidth between 15 MHz and 25 MHz. The frequency bandwidth allows for compression of a long transmit signal to a finer time resolution: in this case a 15-m one-way spatial resolution in vacuum. In geologic materials, that resolution scales from about 11 m where $\varepsilon' = 2$ to 5 m in dense rock where $\varepsilon' = 8$. During the data processing, any sub-band of the full chirp range may be used to create the radargram (delay time versus along-track distance), with commensurate degradation of the vertical resolution. Campbell and Morgan [2018] show that the differences in interface echo strength between radargrams from different sub-bands correlate with the loss tangent of the overlying materials. In particular, for sub-bands centered on 17.5 MHz and 22.5 MHz, the loss tangent is given by:

$$tan\delta = \frac{-\ln(\Delta P)}{31.5\Delta T} \qquad (2)$$

where ΔT is the round-trip delay in μs from the surface to the base of the layer, and ΔP is the ratio of echo power in the high-frequency and low-frequency components.

For each relevant segment of a SHARAD radargram, we first trace the surface and subsurface interface locations in delay time from the full-bandwidth radargram (0.1 μs resolution). The two sub-band images are formed by windowing the desired part of the received spectrum, leading to a time resolution of 0.2 μs; both delay resolution values are broadened by Hann windowing used to limit sidelobes in the range-compressed echoes. After subtracting the background noise, we tabulate the high- and low-frequency subsurface echoes for each radargram frame and calculate a loss tangent from (2). Combining all of the ΔT-tanδ pairs for a given major deposit, we average the tanδ values in bins 0.4 μs wide for all frames where echoes in both channels are at least 3 dB above the noise. In order to assure a reasonable reduction of the uncertainties due to radar speckle, only values from bins with at least 50 frames are used in the analysis. Since each frame is already a 7-look product, the resulting uncertainty is about 5% (the inverse square root of 350 looks).

From SHARAD observations to date we identify 10 tracks that cross the MFF_{GA} area and have sufficient signal-to-noise ratio (SNR) on the subsurface reflector to enable the multi-band technique (Table 1). The center values of five 0.4-μs width bins with >50 samples for the collected frames range from 2.0 μs to 3.6 μs in delay. If the effective real dielectric constant were 3, then these delays correspond to a thickness range of 170 m to 310 m. Figure 13 shows the loss tangent results with their standard errors on the mean presented in logarithmic format (Table 3). At very low loss and with ~50 samples the lower end of the loss value can be unbounded, but the more important attribute is the upper uncertainty limit.

Over the 170 m to 310 m thickness range the MFF_{GA} loss tangent increases from about 0.001 to 0.003 (Fig. 13). As a second test, we averaged all of the data from $\Delta T<3$ μs and $\Delta T>3$ μs, yielding tanδ values of 0.0016 and 0.0026. Figure 13 also illustrates the general range of loss values identified by Campbell and Morgan [2018] for sedimentary and lava flow materials in Elysium, Amazonis, and Arcadia Planitiae. We have plotted a strictly illustrative dashed line showing how an increasing tanδ precludes subsurface interface detections when the total loss at some round-trip delay exceeds the data SNR.

We obtained four well-populated delay bins (at 3.2, 4.0, 4.4, and 4.8 μs) from three closely spaced tracks over a portion of Eumenides Dorsum (Fig. 5), which cluster about tanδ~0.003. In the northwest Zephyria Planum area, the limited number of frames led to use of 0.8-μs bins to obtain the 50 required samples. The loss tangent rises more slowly with delay (i.e., thickness), and reaches a maximum depth-averaged value of 0.002 at 6.4 μs (550 m when $\varepsilon' = 3$). Finally, we calculated a mean loss tangent from closely spaced tracks over a lineated valley fill deposit and a lobate debris apron in the Deuteronilus Mensa region that Plaut et al. [2008] and Holt et al. [2008] suggest have significant ice content (Figs. 14-15). At 5.2 μs to 6.8 μs, the average loss tangent value is ~0.003, with little evidence for a dependence on thickness (450 m to 600 m if ε'=3) (Fig. 13). This is consistent with the tanδ=0.002-0.003 range reported by Campbell and Morgan [2018] for similar glacial units, and to the upper end estimate for the north polar layered terrain by Grima et al. [2009].

Power Loss Versus Delay Analysis

The MFF_{GA} deposit is banked against Amazonis Mensa and Gordii Dorsum such that the elevation and slope of the underlying base is not certain. As an alternate method to estimate tanδ, we can study the change in radar echo power in the full-bandwidth radargrams as a function of time delay. The method does not require a known thickness for the material [Campbell et al., 2008]. Binning the data by delay and averaging the power, we define a linear least-squares fit to the loss in dB per μs. The power loss at any given delay is a function of the loss tangent:

$$\frac{P}{P_o} = exp\left(\frac{-2\pi c\Delta T tan\delta}{\lambda}\right) \qquad (3)$$

The slope of the power change, *S*, in dB per μs, is related to the loss tangent by (with λ=15 m):

$$tan\delta = -\ln\left(10^{S/10}\right)\frac{\lambda}{2\pi c} \approx -0.008 \ln\left(10^{S/10}\right) \quad (4)$$

Figure 16 shows the power as a function of delay for the tracks crossing MFF_{GA} (Table 2) where at least 25 frames with signal-to-noise ratio >5 dB are averaged in each 0.2-μs delay bin. Also plotted are lines with slopes corresponding to tanδ=0.0016 for a break-point in round-trip delay of <2.3 μs, and to tanδ=0.0026 for ΔT>2.3 μs. The reasonable fit of the two slope values with the depth-dependent power shows an agreement between the multi-band and power-versus-delay methods.

Unlike the multi-band method, surface roughness can play a role in defining the change in subsurface power with delay. For example, the average surface return as a function of delay is shown on Fig. 16, where the echo changes are due to some combination of surface roughness and near-surface density. If lower surface echoes are due to roughness, then we expect less energy to reach the subsurface, while lower density can improve the transmission of energy into the material. In studies of the effect of surface roughness on power transmitted into a medium, Pinel et al. [2011] and Schroeder et al. [2015] show that the transmitted signal retains a greater degree of phase coherence than the energy reflected from the surface, and the impact of roughness is further diminished for low-density shallow material. A study of roughness effects on the ratio of SHARAD subsurface to surface echo power is needed to clarify these behaviors, but here we simply suggest that roughness is not a first-order effect in the fits to the MFF loss tangent.

V. Modeling of Physical Properties

The SHARAD loss tangent results (Section IV) present a "rise-and-plateau" behavior (Fig. 13), implying that the physical properties which drive changes in tanδ remain almost unchanged past about 300 m (MFF_{GA}) to 600 m (Zephyria Planum) thickness. Composition plays a major role in loss tangent variability, particularly between basaltic material and ice [e.g., Campbell and Morgan, 2018]. The effect of density changes is less well characterized at low tanδ values and SHARAD frequencies [e.g., Carrier et al., 1993], but the observed loss must increase as the fraction of void space is reduced.

Results for the real dielectric constant (Section III) offer modest evidence for a trend with thickness in the MFF consistent with a rise-and-plateau behavior. Deposits of the outlier north of Zephyria Planum have ε' values of 1.6-2.2, while other deposits up to 640 m thick range from 2.0 to 3.0. Watters et al. [2007] suggest little further increase in ε' as a deposit exceeds about 500 m thickness. The real part is generally dominated by density (ρ in gm/cm^3) with a typical behavior of $\varepsilon' = 2^{\rho}$ [Campbell and Ulrichs, 1964; Ulaby et al., 1988; Carrier et al., 1993]. There are exceptions to this relationship, including lower values of ε' for sandstones and higher values linked with iron and titanium content in basalts [Ulaby et al., 1988]. We assume that compositional differences of lithic material are not significant in comparing real permittivity values across the MFF.

One simple explanation for the rise of the loss tangent and the real dielectric constant is self-compaction in the MFF material. An often-used model for self-compaction of sediments expresses porosity with depth, *z*, in a medium as:

$$\phi = \phi_0 \exp(-z/K) \quad (5)$$

where K is a scale parameter that captures the depth at which the porosity is about 36% of its near-surface value, ϕ_o. In the similar Athy model [1930], K is a function of compressibility, gravity, and density [Watters et al., 2017], but for this study we are interested only in the first-order range of the scaling depth. Ideally we would compare the predictions of a density-versus-depth model to the observed loss tangent, but there is no similar expression to that for the real permittivity.

The apparent real dielectric constant is an integral over the full depth of the material, H:

$$\varepsilon'_{app} = \left[\frac{1}{H}\int_0^H \sqrt{\varepsilon'(z)}\, dz\right]^2 \quad (6)$$

and we can link this to the porosity function (5) through:

$$\rho(z) = \rho_o(1 - \phi(z)) \quad (7)$$

where ρ_o is the density of the grains alone (i.e., zero porosity). To illustrate possible variations in apparent ε' with thickness, we choose two values for K. As an upper-end example, we adopt the ~1800 m value used for sand under Mars conditions by Watters et al. [2017]. Dust and ash have lower K values of about 300 m and 800 m, respectively, and we take an average of 500 m for a second example. Figure 17 shows the numerical solution of (6) for two values of ϕ_o (40% and 60%) and K (500 m and 1800 m) when ρ_o=2.8, corresponding to a "solid" rock dielectric constant of ~8. The latter is a conservative value for basalt, consistent with low-end estimates for lava flows in the Tharsis Montes [Carter et al., 2009b; Simon et al., 2014].

From these plots, we infer that no single value of K can explain both a significant rise in density (and thus ε') for the first 300-600 m and a plateau in density beyond that thickness. To obtain low near-surface permittivity and a rise in the first few hundred meters requires that the near-surface porosity be quite high and K be relatively low (fine-grained material). The slower rise in tanδ with thickness for northwestern Zephyria Planum (Fig. 13) may be due to modestly larger grain sizes than found in the MFF_{GA} or Eumenides deposits, or to a near-surface porosity higher than 60%. To maintain a plateau beyond ~600 m requires a higher value of K in the range of larger, sand-sized particles. It also requires the compressibility to be significantly lower than that of a well-sorted sand [see Watters et al., 2017]. Our interpretation is that the MFF is a two-layer deposit when the thickness is greater than 300-600 m, with the upper layer undergoing self-compaction and the lower layer being nearly incompressible.

VI. Discussion

The nature of the material beneath the proposed upper layer is the key question arising from our results. Prior studies have shown that the current surface of the MFF is friable and readily eroded by the wind. The fine-grained weathering products are then distributed over very large areas. Significant self-compaction of the upper layer while keeping the apparent $\varepsilon' \leq 3$ is readily within the range of exponential compaction models for grain sizes similar to volcanic ash [Watters et al., 2017]. In order to be dry (ice-free) material but not undergo significant compaction for a thickness of up to 2000 m, grain sizes in the lower layer must be much larger than those of the upper layer. Based on results shown in Fig. 17, sand-sized particles could provide the appropriate dielectric behavior. Ojha and Lewis [2018] used gravity data to infer a bulk density of 1765±105 kg/m^3 for the MFF, which is generally consistent with this model. A concern is the need for very coarse-grained sand with low compressibility, and we do not observe widespread sand or dune fields at the margins of the MFF.

A second scenario postulates a minimally compacting lower layer of mixed ice and lithic material. The fraction of ice needs to be high to maintain a bulk average real dielectric constant at the high end of the MARSIS estimate. This interpretation is bolstered by the loss properties of massive ice in lobate debris aprons and lineated valley fill (Fig. 13) and by the presence of pedestal craters in the region that Schultz and Lutz [1988] and Kadish et al. [2009] suggest formed in a volatile-rich target. Progressive thinning of the upper MFF would allow increased sublimation loss such that the ice-rich layer remains at depth until the total thickness reaches the "dry" limit of 300-600 m. There is also some support for this model of ice at depth in measurements of hydrogen abundance.

Data from the Mars Odyssey Neutron Spectrometer were used by a number of teams to estimate the hydrogen abundance in about the upper meter of the surface, and from there to model the weight percentage of water (as ice or hydrated minerals) [Boynton et al., 2002; Mitrofanov et al., 2002; Feldman et al., 2004]. From Feldman et al. [2004], the MFF lies along the northern boundary of a band of ~6-9% water abundance extending to ~30^{o} S. Work to improve the spatial resolution of the data with an image reconstruction method increased the water-equivalent hydrogen content to >10% in some western MFF regions such as Zephyria Planum, while the eastern areas remained in a similar range with earlier estimates [Wilson et al., 2018]. To explain the hydrogen abundance in the western MFF, Wilson et al. [2018] proposed that relatively young water ice deposited during obliquity changes may be protected by dust or duricrust.

If ice-rich material is present at depth, it is difficult to form the fine-grained upper 300-600 m solely from sublimation of an original glacial or polar layered deposit when the expected ice fraction is high. One possibility is that the Medusae Fossae Formation is a hybrid deposit, where parts of an extensive, thick, ice-rich unit was capped by a later "dry" component, perhaps through pyroclastic volcanism. The currently existing ice at depth would thus reflect the interplay of large-scale Hesperian glacial or PLD deposition with favorably timed volcanic eruptions that buried and preserved the ice through subsequent obliquity cycles.

VII. Conclusions

We used SHARAD radar sounder data to estimate the real permittivity and loss tangent of MFF deposits, and compared these to a model for sediment compaction and to the properties of ice in mid-latitude glaciers. In areas along the margins of Eumenides Dorsum, between Gordii Dorsum and Amazonis Mensa, and in northwest Zephyria Planum, the loss tangent is about 0.001 at 170 m and plateaus at about 0.003 for 310-550 m thickness. The real dielectric constant across the study areas ranges from 2 to 3. We propose that the MFF is a two-layer deposit, with 300-600 m of fine-grained, self-compacting material above up to 2 km of minimally compacting, low-loss material.

The lower unit could comprise ice-free, very coarse-grained, sand-sized particles with low compressibility, consistent with estimates of MFF bulk density, but we do not see extensive sand exposed by erosion and this would provide no source for the measured hydrogen abundance. An alternative is that the lower layer is predominantly ice-rich and protected from sublimation by the dry cover. This model is supported by the properties of mid-latitude glaciers and perhaps by the observed hydrogen abundance, but is not in line with the bulk density values from gravity analysis. The volume of cover relative to a high ice content in the lower layer may imply hybrid MFF formation as glacial or polar layered deposits capped by a dry, perhaps pyroclastic ash, component. Resolving these questions will be aided by additional SHARAD observations in a rolled attitude to increase the SNR and allow multi-band analysis of deeper reflections.

Acknowledgments

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Data availability. The raw SHARAD Experiment Data Records used in this study are available from the PDS Geoscience Node (https://pds-geosciences.wustl.edu/mro/mro-m-sharad-3-edr-v1/mrosh_0001/). Radargrams used for measurement of time delay to the basal interface of MFF units (Table 2) are also available on the PDS (https://pds-geosciences.wustl.edu/mro/mro-m-sharad-5-radargram-v1/mrosh_2001/browse/tiff/). The ancillary GEOM files of this archive contain latitude and longitude coordinates matched to the X_1 and X_2 locations noted in the tables (https://pds-geosciences.wustl.edu/mro/mro-m-sharad-5-radargram-v1/mrosh_2001/data/geom/). Processed radargrams in the high-frequency and low-frequency bands for tracks noted in Table 1 are archived at https://smithsonian.figshare.com/articles/dataset/Archive_of_Multi-Band_SHARAD_Radargrams/12582593. Note that these radargrams are identical in along-track location to the PDS full-band images (https://pds-geosciences.wustl.edu/mro/mro-m-sharad-5-radargram-v1/mrosh_2001/data/rgram/), with the exception of a 0.075-μs delay resolution and thus 1800 image rows rather than 3600. MOLA data used in Figure 3 are on the PDS (https://pds-geosciences.wustl.edu/missions/mgs/mola.html).

References

Athy, L. F. (1930). Density, porosity, and compaction of sedimentary rocks. *American Association of Petroleum Geologists Bulletin, 14*, 194–200. https://doi.org/10.1306/3D93289E-16B1-11D7-8645000102C1865D

Boynton, W. V., Feldman, W. C., Squyres, S. W., Prettyman, T. H., Bruckner, J., Evans, et al. (2002). Distribution of hydrogen in the near surface of Mars: Evidence for subsurface ice deposits. Science, 297, 81– 85. doi:10.1126/science.1073722

Bradley, B. A., Sakimoto, S. E. H., Frey, H., & Zimbelman, J. R. (2002). Medusae Fossae Formation: New perspectives from Mars Global Surveyor. *J. Geophys. Res.*, *107*, E8, 5058. https://doi.org/10.1029/2001JE001537

Campbell, B. A., & Morgan, G. A. (2018). Fine-Scale layering of Mars polar deposits and signatures of ice content in non-polar material from multi-band SHARAD data processing. *Geophys. Res. Letters*, *45*, 1759-1766. https://doi.org/10.1002/2017GL075844

Campbell, B. A., Carter, L. M., Phillips, R. J., Plaut, J., Putzig, N., Safaeinili, A., Seu, R., Biccari, D., Egan, A., & Orosei, R. (2008). SHARAD radar sounding of the Vastitas Borealis Formation in Amazonis Planitia. *J. Geophys. Res*., 113, E12010. doi:10.1029/2008JE003177

Carter, L. M., Campbell, B. A., Holt, J. W., Phillips, R. J., Putzig, N. E., Mattei, S., Seu, R., & Okubo, C. H. (2009b). Dielectric properties of lava flows west of Ascraeus Mons, Mars. *Geophys. Res. Letters*, 36. doi:10.1029/2009GL040749

Carter, L. M., Campbell, B. A., Watters, T. R., Phillips, R. J., Putzig, N. E., Safaeinili, A., Plaut, J. J., Okubo, C. H., Egan, A., Seu, R., Biccari, D., & Orosei, R. (2009a). Shallow Radar (SHARAD) sounding observations of the Medusae Fossae Formation. Mars, *Icarus*, 199, 295-302. Doi:10.1016/j.icarus.2008.10.007

Feldman, W.C., Prettyman, T. H., Maurice, S., Plaut, J. J., Bish, D. L., Vaniman, D. T., et al. (2004). Global distribution of near-surface hydrogen on Mars. *J. Geophys. Res*. 106, E09006. doi:10.1029/2003JE002160

Grima, C., Kofman, W., Mouginot, J., Phillips, R. J., Herique, A., Biccari, D., Seu, R., & Cutigni, M. (2009). North polar deposits of Mars: Extreme purity of water ice. *Geophysical Research Letters*, 36, L03203. https://doi:10.1029/2008GL036326

Holt, J. W., Safaeinili, A., Plaut, J. J., Head, J. W., Phillips, R. J., Seu, R., Kempf, S. D., Choudhary, P., Young, D. A., Putzig, N. E., Biccari, D., & Gim, Y. (2008). Radar sounding evidence for buried glaciers in the southern mid-latitudes of Mars, *Science*, Vol. 322 (5905), pp. 125-1238. https://doi: 10.1126/science.1164246

Hynek, B.M., Phillips, R. J., & Arvidson, R. E. (2003). Explosive volcanism in the Tharsis region: Global evidence in the martian geologic record. *J. Geophys. Res.*, *108*, E9, 5111. doi:10.1029/2003JE002062

Jaeger, W. L., Keszthelyi, L. P., Skinner, J. A., Milazzo, M. P., McEwen, A. S., Titus, T. N., Rosiek, M. R., Galuszka, D. M., Howington-Kraus, E., & Kirk, R. L. (2010). Emplacement of the youngest flood lava on Mars: A short, turbulent story. *Icarus*, *205*(1), 230–243. https://doi.org/10.1016/j.icarus.2009.09.011

Jordan, R., Picardi, G., Plaut, J., Wheeler, K., Kirchner, D., Safaeinili, A., Johnson, W., Seu, R., Calabrese, D., Zampolini, E., Cicchetti, A., Huff, R., Gurnett, D., Ivanov, A., Kofman, W., Orosei, R., Thompson, T., Edenhofer, P., & Bombaci, O. (2009). The Mars express MARSIS sounder instrument. *Planetary and Space Science*, *57*(14), 1975–1986. https://doi.org/https://doi.org/10.1016/j.pss.2009.09.016

Kadish, S.J., Barlow, N. G., & Head, J. W. (2009). Latitude dependence of Martian pedestal craters: Evidence for a sublimation-driven formation mechanism. *J. Geophys. Res. 114*, E1000. doi:10.1029/2008JE003318

Kerber, L., & Head, J. W. (2012). A progression of induration in Medusae Fossae Formation transverse aeolian bedforms and extensive reworking. *Earth Surface Processes and Landforms, 37*, 422-433 doi:10.1002/esp.2559

Kerber, L., & Head, J. W. (2010). The age of the Medusae Fossae Formation: Evidence of Hesperian emplacement from crater morphology, stratigraphy, and ancient lava contacts. *Icarus, 206*, 669-684. doi:10.1016/j.icarus.2009.10.001

Kerber, L., Head, J. W., Madeleine, J-B, Forget, F., & Wilson, L. (2011). The dispersal of pyroclasts from Apollinaris Patera, Mars: Implications for the origin of the Medusae Fossae Formation. *Icarus, 216*, 212-220. doi:10.1016/j.icarus.2011.07.035

Mitrofanov, I., Anfimov, D., Kozyrev, A., Litvak, M., Sanin, A., Tret'yakov, V., Krylov, A., Shvetsov, V., Boynton, W., Shinohara, C., Hamara, D., & Saunders, R. S. (2002). Maps of subsurface hydrogen from the High Energy Neutron Detector. Mars Odyssey, *Science Express, 297*, 78– 81. doi:10.1126/science.1073616

Morgan, G.A., Campbell, B. A., Carter, L. M., & Plaut, J. J. (2015). Evidence for the episodic erosion of the Medusae Fossae Formation within the youngest volcanic province on Mars. *Geophys. Res. Letters, 42*, 7336-7342. *doi:10.1002/2015GL065017*

Mouginis-Mark, P.J., & Zimbelman, J. R. (2020). Rafted pumice: A new model for the formation of the Medusae Fossae Formation, Mars. *Icarus, 343*, 113684. doi:10.1016/j.icarus.2020.113684

Ojha, L., Lewis, K., Karunatillake, S., & Schmidt, M. (2018). The Medusae Fossae Formation as the single largest source of dust on Mars. *Nat. Commun. 9*, 2867. doi:10.1038/s41467-018-05291-5

Ojha, L., & Lewis, K. (2018). The density of the Medusae Fossae Formation: Implications for its composition, origin, and importance in martian history. *J. Geophys. Res., 123*, 1368-1379. doi:10.1029/2018je005565

Picardi, G., Biccari, D., Seu, R., Marinangeli, L., Johnson, W. T. K., Jordan, R. L., Plaut, J. J., Safaeinili, A., Gurnett, D. A., Ori, G. G., Orosei, R., Calabrese, D., & Zampolini, E. (2004). Performance and surface scattering models for the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS). *Plan. Space Science, 52*, 149-156. doi:10.1016/j.pss.2003.08.020

Plaut, J. J., Safaenili, A., Holt, J. W., Phillips, R. J., Head, J. W., Seu, R., Putzig, N. E., &. Frigeri, A. (2009). Radar evidence for ice in lobate debris aprons in the mid-northern latitudes of Mars. *Geophysical Research Letters, 36*, L02203, https://doi:10.1029/ 2008GL036379

Schroeder, D.M., Grima, C., & Blankenship, D. D. (2015). Evidence for variable grounding-zone and shear-margin basal conditions across Thwaites Glacier, West Antarctica. Geophysics, 81, WA35-WA43, doi:10.1190/GEO2015-0122.1

Schultz, P. H., & Lutz, B. A. (1988). Polar wandering of Mars. *Icarus, 73*, 91-141. doi:10.1016/0019-1035(88)90087-5

Seu, R., Phillips, R. J., Biccari, D., Orosei, R., Masdea, A., Picardi, G., Safaenili, A., Campbell, B. A., Plaut, J. J., Marinangeli, L., Smrekar, S. E., & Nunes, D. C. (2007). The SHARAD sounding radar on MRO. *J. Geophys. Res*., 112, E5. doi:10.1029/2006JE002475

Simon, M., Carter, L. M., Campbell, B. A., Phillips, R. J., & Mattei, S. (2014). Studies of lava flows in the Tharsis region of Mars using Shallow Radar (SHARAD). *J. Geophys. Res., 119*, 2291-2299. doi:10.1002/2014JE004666

Tanaka, K. L., Skinner Jr., J. A., Dohm, J. M., Irwin III, R. P., Kolb, E. J., Fortezzo, C. M., Platz, T., Michael, G. G., & Hare, T. M. (2014). Geologic map of Mars: U.S. Geological Survey Scientific Investigations Map 3292. scale 1:20,000,000, pamphlet 43 p., https://dx.doi.org/10.3133/sim3292

Ulaby, F. T., Moore, M. K., & Fung, A. K. (1986). Microwave Remote Sensing, Active and Passive. Norwood, Mass: Artech House.

Watters, T. R., Leuschen, C. J., Campbell, B. A., Morgan, G. A., Cicchetti, A., Grant, J. A., Phillips, R. J., & Plaut, J. J. (2017). Radar sounder evidence for a thick, porous, and ice free deposit in Meridiani Planum Mars. *Geophys. Res. Letters*, 44, 9208-9215. doi:10.1002/2017GL074431

Watters, T. R., Campbell, B. A., Carter, L. M., Leuschen, C. J., Plaut, J. J., Picardi, G., Orosei, R., Safaeinili, A., Clifford, S. M., Farrell, Ivanov, A. B., Phillips, R. J., & Stofan, E. R. (2007). Radar sounding of the Medusae Fossae Formation Mars: Equatorial ice or dry, low-density deposits? *Science, 318,* 1125-1128. doi:10.1126/science.1148112

Wilson, J. T., Eke, V. R., Massey, R. J., Elphic, R. C., Feldman, W. C., Maurice, S., & Teodoro, L. F. A. (2018). Equatorial locations of water on Mars: Improved resolution maps based on Mars Odyssey Neutron Spectrometer data. *Icarus, 299*, 148-160. doi:10.1016/j.icarus.2017.07.028

Zimbelman, J.R., & Scheidt, S. P. (2012). Hesperian age for western Medusae Fossae Formation, Mars. *Science 336*, 1683. https://doi.org/10.1126/science.1221094

Zimbelman, J.R., & Griffin, L. J. (2010). HiRISE images of yardangs and sinuous ridges in the lower member of the Medusae Fossae Formation, Mars. *Icarus, 205*, 198-210. doi:10.1016/j.icarus.2009.04.003

Table 1. SHARAD Tracks Used for Multi-band Loss Analysis

SHARAD Track	X_1	X_2	Min ΔT (μs)	Max ΔT (μs)	N pts >3 dB
LVF/LDA					
52582_01	1000	1070	2.25	6.15	64
35334_01	984	1059	4.31	7.39	66
24429_01	1062	1148	3.11	7.24	85
38433_01	980	1059	4.46	7.54	71
45106_01	458	533	4.95	6.86	74
7169_02	4119	4178	5.14	6.86	59
Eumenides Dorsum					
27429_03	3152	3326	0.64	5.85	174
34655_01	3057	3286	1.46	4.73	208
26796_01	3240	3376	1.91	5.14	121
Zephyria Planum					
18042_02	1262	1326	2.7	5.59	56
19176_02	1383	1456	3.79	6.26	65
47527_02	3426	3482	2.59	4.13	41
22222_02	2218	2274	2.1	5.78	57
19809_02	3479	3526	5.33	6.83	43
20165_02	2289	2328	5.33	5.51	40
MFF_{GA}					
5197_02	1167	1269	1.73	2.03	101
5764_01	1138	1259	1.88	2.25	121
24211_01 (23^o roll)	3224	3348	2.4	2.66	125
24422_01 (23^o roll)	3175	3363	2.4	2.93	188
24211_01 (23^o roll)	3369	3462	2.48	3.49	85
24000_01	3232	3436	2.35	3.04	190
32347_02	3272	3463	3.19	3.38	139
59617_02	1927	2101	3.19	3.53	169
27323_02	1702	1981	2.96	3.53	189
27534_02	1799	1934	3.49	4.13	41
26901_01 (23^o roll)	1672	1779	2.55	3.98	95

Each row represents a trace along the designated X_1 to X_2 frames of a US SHARAD Planetary Data System radargram. The corresponding range of round-trip delay, and the number of frames with signal-to-noise ratio >3 dB, are noted. Rolled observations indicated by their maximum MRO roll angle.

Table 2. SHARAD Tracks Used for Time-Delay Loss Analysis of MFF_{GA}

SHARAD Track	X_1	X_2	Gain Factor (dB)
3641_01	960	1297	-0.08
5197_02	1086	1157	+1.21
5764_01	1039	1113	+1.37
24000_01	3232	3436	+2.61
27323_02	1702	1981	+1.81
27534_02	1683	2038	+1.86
32347_02	3121	3245	+2.23
32703_01	3130	3434	+2.25
34760_02	3116	3452	+2.20
59617_02	1774	1794	+2.03

SHARAD track number and range of radargram frames (X_1 to X_2) of a US PDS radargram for analysis of the average surface and subsurface echo strengths in delay bins of 0.4 μs width (Fig. 17). All data are collected during night operations. Gain correction factors come from analysis of effects of solar array and high-gain antenna gimbal angles on the effective gain of the SHARAD observations [Campbell et al., "Gain Calibration of Mars Reconnaissance Orbiter Shallow Radar (SHARAD) Data for Subsurface Probing and Surface Reflectivity Studies", in preparation].

Table 3. Loss Tangent Values for Geologic Units

Geologic Unit Designation	Delay (μs)	Loss Tangent	Standard Error
MFF_{GA}	2.0	0.0007	0.0008
	2.4	0.0009	0.0006
	2.8	0.0023	0.0004
	3.2	0.0027	0.0003
	3.6	0.0026	0.0004
Eumenides Dorsum	3.2	0.0039	0.0010
	4.0	0.0047	0.0006
	4.4	0.0038	0.0006
	4.8	0.0031	0.0005
LDA/LVF	5.2	0.0035	0.0004
	5.6	0.0028	0.0004
	6.0	0.0029	0.0004
	6.4	0.0037	0.0005
	6.8	0.0030	0.0003
Zephyria Planum	3.2	0.0004	0.0007
	4.8	0.0006	0.0005

	5.6	0.0008	0.0004
	6.4	0.0021	0.0004

Values from multi-band analysis presented in Figure 13.

Fig. 1. Map of Medusae Fossae Formation SHARAD study sites, noted by grey ovals. Background image is color-coded MOLA topography.

Fig. 2. SHARAD tracks (Table 1) that cross the MFF_{GA} unit (boundary marked by white line) between Amazonis Mensa and Gordii Dorsum. The colors within the tracks represent the time delay between the surface and the subsurface reflector interpreted to be the base of the unit. The white dashed line traces the prominent cliff face that bisects the MFF_{GA}. Trace of topographic transect from Fig. 3 is noted between A and A'. From the data in Fig. 4, we infer that the reflector beneath MFF_{GA} is continuous with that under Amazonis Mensa, such that the two units represent a single geologic entity emplaced on top of Late Hesperian plains. Late Hesperian plains unit boundary from Tanaka et al. [2014].

Fig. 3. Cross-sectional profile of the MFF_{GA} unit from MOLA topography along transect A - A' in Fig. 2. Inferred locations of the base interface from SHARAD observations are shown by triangles, where their vertical positions are calculated based on a value for the real dielectric constant. Red dotted line shows an interpolation of plains to the north beneath the MFF material. Based on this analysis we favor a dielectric constant of ~3 for the thicker portion of the unit. The black diamonds represent averaged MOLA point values within a 3-km radius of the transect line (chosen to match a SHARAD Fresnel zone). The red circles represent the surface elevation directly above the SHARAD tracks and were estimated by extrapolating from the nearest MOLA point data. Tracks used to obtain the data in this figure are: (5197_02, 5764_01, 24211_01, 24222_01, 59901_01, 39112_01, 20000_01, 3641_01, 32347_02, 59617_02, 59690_01, 40319_01, 27332_02, 27534_02, 26901_01, 46332_01, 2652_01, and 59762_01).

Fig. 4. Portion of SHARAD Track 24211_01 over the MFF_{GA} deposit. Northeast is at left, southwest to the right. Image width 910 km. Arrows denote the extent and range of delay for the MFF_{GA} material to the east of Amazonis Mensa. Note that the plains base reflection extends under Amazonis Mensa. The yellow arrow denotes clutter echoes that might be mis-interpreted as a shallower subsurface interface. For this track, SHARAD was operated with MRO in a rolled configuration to optimize the signal to noise ratio. The round-trip delay values correspond to thicknesses of 110 m to 230 m if the real dielectric constant is 3.

Fig. 5. SHARAD tracks 26796_01, 27429_03, and 34655_01 along the northwest margin of Eumenides Dorsum. Only those portions of the tracks that have strong subsurface reflections are noted in white. The track 19148_01 used as a reference for the topography of the plains in Fig. 10 is shown in yellow. Note that there is no subsurface reflection in this track.

Fig. 6. Representative SHARAD track across Eumenides Dorsum (34655_01). Image width 920 km. Vertical axis is in time delay, so the basal reflector appears to slope downward as the MFF

material thickens. Arrows denote round-trip signal delay between the surface and base at three locations. For a real dielectric constant of 3, these correspond to thicknesses of 220 m, 390 m, and 745 m. Cross sections of Eumenides Dorsum with corrections to depth are shown in Fig. 10.

Fig. 7. SHARAD tracks (Table 1) across the northern Zephyria Planum study area. White segments show the portions of each track where a subsurface reflector is used for the loss tangent analysis. Note the location of the MFF outlier investigated by Morgan et al [2015] and the proximity of the youngest Mars lava flow unit [Jaeger et al 2010].

Fig. 8. Representative SHARAD track (19176_02) across MFF in Zephyria Planum. Image width 460 km. Vertical axis is in time delay, so the basal reflector appears to slope downward as the MFF material thickens. Arrow denotes round-trip signal delay between the surface and base of the deposit termed "North Hill". For a real dielectric constant of 3, this maximum value corresponds to a thickness of 545 m. Note the thin outlier just left (north) of the main deposit.

Fig. 9. Portion of SHARAD track 59901_01 showing a dayside profile (southeast at left, northwest at right) of the MFF_{GA} deposit. In each figure the vertical scale in the subsurface is adjusted for the speed of light in the material as characterized by the real dielectric constant. The yellow line is an extension of the plains slope from the north. The deeper areas toward the left match that projected plains level for a dielectric constant of 3.0, while the over-correction of the base level in the thinner section may indicate a value closer to 2.0. Image width 510 km. The short vertical lines mid-way down the slope occur where the ionospheric delay correction is uncertain.

Figure 10. SHARAD radargrams for track 34655_01 over western Eumenides Dorsum and track 19148_01 covering plains and low MFF deposits to the west (see Fig. 5 for track locations). There is no subsurface reflection in 19148_01, which is used solely to establish a reference for the regional topography. The plains trend in track 19148_01 is well matched when 34655_01 is corrected for a dielectric constant of 3 in the MFF material (lower panel). Image width 690 km.

Fig. 11. SHARAD track 18042_02 with dielectric corrections to convert round-trip delay to depth. A value of 2.0 best "flattens" the base to match the plains regions to the north (left).

Fig. 12. SHARAD track 22011_01 with dielectric corrections to convert round-tip delay to depth. A value of 2.0-2.5 best "flattens" the base to match the plains regions to the north (left). A possible internal reflector (i.e. an interface within the deposit) is labeled in the figure for $\varepsilon'=2.5$.

Fig. 13. Loss tangent values for sites discussed in the paper. Note the rapid rise in loss tangent (from <0.001 to 0.003) for the MFF_{GA} materials (green circles) over the 2-3 μs delay range, and the slower rise toward the same maximum for Zephyria Planum (purple triangles). Eumenides Dorsum (red squares) has properties similar to those of lineated valley fill and lobate debris aprons (blue diamonds). The range of values for other mid-latitude deposits are shown by the two horizontal bars at upper left. Sediments in Amazonis Planitia or mantling units in Arcadia Planitia have values of 0.010-0.015 in the 1-2 μs range while lava flows in Elysium Planitia may be as high as ~0.03 [Campbell and Morgan, 2018]. The dashed line illustrates the general trend toward smaller radar penetration depth as the loss tangent increases.

Fig. 14. SHARAD tracks across lineated valley fill (45106_01, 7169_02) at top and lobate debris aprons (52582_01, 35344_01, 24429_01, 38433_01) at bottom. These tracks are used to derive the LDA/LVF values shown in Fig. 13 (Table 1).

Fig. 15. Representative radargrams of lineated valley fill (SHARAD 45106_01) and lobate debris aprons (SHARAD 24007_01, close to those in the lower panel of Fig. 14). Image width 310 km. Arrows note the bounds of the subsurface interfaces used in this study. Images have not been corrected for the dielectric constant in the subsurface material.

Fig. 16. Radar echo power versus round-trip time delay for the surface (cyan triangles) and subsurface (blue crosses) over the MFF_{GA} unit. The blue dashed line represents a fit using a loss tangent of 0.0016 from the multi-band analysis of data for delay <2.3 μs, while the red dashed line has a slope for a loss tangent of 0.0026 from data for >2.3 μs.

Figure 17. Apparent real dielectric permittivity as a function of unit thickness for different values of near-surface porosity, ϕ_o, and compression scaling factor, *K*. Blue lines are for ϕ_o =0.4, red lines for ϕ_o =0.6. Solid lines correspond to *K*=500 m (fine grains with a high rate of compaction with increasing depth) and dashed lines to *K*=1800 m (coarse grains with a low rate of compaction with increasing depth). The "solid" rock density corresponds to a dielectric constant of ~8. The green shaded box marks the range of MFF permittivity values from SHARAD data. The blue shaded box indicates the bounds from MARSIS observations. Note that an increase in permittivity from 2 to 3 in the first few hundred meters requires fine material (red solid line), while maintaining a value of ~3 to 2000 m requires much coarser material (red dashed line).