POLAR IS IN THE EYE OF THE BEHOLDER: ICE-RICH UNITS ACROSS THE MID-LATITUDES OF MARS.

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Introduction: In addition to water's necessity in sustaining human life, H_2O is also the most valuable Martian resource due to its utility in conversion to fuel. Surface ice exists on Mars in plentiful volumes at the poles. However, polar locations, with their extremely cold temperatures and long, dark winter nights make these locales less viable for both robotic and crewed exploration. Therefore, knowledge of the distribution and properties of water ice at warmer and sunnier non-polar latitudes is vitally important for future exploration of the planet. In addition to water ice's importance as an in situ resource, understanding the distribution, properties, and stability of non-polar ice (including its emplacement and evolution) has important scientific implications as a record of Martian climate processes.

The Subsurface Water Ice Mapping (SWIM) Project [1–3] supports an effort by NASA's Mars Exploration Program to determine in situ resource availability by integrating data and analyses from numerous missions and instruments. Here, we present the results of focused mapping and analysis of subsurface radar reflectors found within observations by SHARAD, the Mars Reconnaissance Orbiter (MRO) Shallow Radar [4], which senses the deepest (>15 m) of the instruments whose data were considered by the SWIM Project.

Radar Mapping: SHARAD transmits a signal swept from 25 to 15 MHz, yielding a wavelength in free space of 15 meters [4]. When the radar wave encounters material interfaces with a contrast in the dielectric properties (e.g., boundaries between atmosphere and surface or layers in the subsurface), a portion of the radar wave is reflected back toward the instrument, causing an increase in the power sensed at that delay time. In locations where the depth to a reflecting interface can be estimated from topographic measurements, that depth and time delay measured with SHARAD can be used to constrain the relative dielectric constant, also referred to as the real dielectric permittivity ($\boldsymbol{\varepsilon}'$), of the material through which the radar signals have traveled. This property provides constraints on composition. Values close to 3 are consistent with pure water ice [5] while values approaching 6–12 are consistent with basaltic, ice-poor regolith or bedrock [6]).

As part of the SWIM Project, we mapped subsurface radar interfaces throughout the northern hemisphere and estimated $\boldsymbol{\varepsilon}'$ based on surrounding topographic features, when possible, at the locations of the reflectors (Fig. 1).

Ice Consistency and the SWIM Equation: To enable a quantitative assessment of how consistent (or inconsistent) diverse remote sensing datasets are with the presence of buried ice across these regions, we introduce the concept of ice consistency values for each dataset [1–3]. A consistency value of +1 means that the data are wholly consistent with the presence of ice, 0 means that the data give no indications of the presence or absence of ice, and -1 means that the data are wholly inconsistent with the presence of ice. Based on our dielectric constants estimates, we calculated the radar dielectric consistency values, C_{RD}, as follows:

$C_{RD} = +1$ where $\boldsymbol{\varepsilon}' \leq 3$
$C_{RD} = ½ (5 – \boldsymbol{\varepsilon}')$ where $3 \leq \boldsymbol{\varepsilon}' \leq 7$ ($C_{RD}=0$ where $\boldsymbol{\varepsilon}'=5$)
$C_{RD} = -1$ where $\boldsymbol{\varepsilon}' \geq 7$

The SWIM Team also developed the SWIM Equation [1–3] to combine the consistency values from each dataset considered in the SWIM Project (subscripts N = neutron detected hydrogen, T = thermal signature, G = geomorphology, RS = radar surface reflectivity, and RD = radar dielectric using subsurface reflectors). The resulting composite ice consistency provide a tangible representation of the overall likelihood of ice, C_i:

$$C_i = (C_N + C_T + C_G + C_{RS} + C_{RD}) / 5$$

Results: The radar subsurface reflector mapping yielded nine *radar units* across the northern hemisphere. The median dielectric permittivity estimates $\boldsymbol{\varepsilon}'$, corresponding C_{RD}, and full SWIM Equation C_i result for each of these units are provided in Table 1 (below).

Mapped Radar Units	$\boldsymbol{\varepsilon}'$	C_{RD}	C_i
Arcadia Unit 1 Main Plains	4.1	0.45	0.37±0.16
Arcadia Unit 2 Layered Ejecta Crater (LEC)	4.2	0.4	0.34±0.10
Utopia Unit 1 Thermokarstic Mesas	2.9	+1	0.05±0.12
Utopia Units 2–5	3.2	0.9	0.18±0.11
Utopia Units 6–10	8.1	-1	-0.04±0.14
Utopia Unit 11	8.3	-1	-0.14±0.13
Onilus LDA/LVF/CCF	3	+1	0.22±0.16
Onilus Unit 1 Upper Plains Mantle	4	0.5	0.03±0.09
Onilus Unit 2 Misc. Mantle	5.2	-0.1	0±0.13

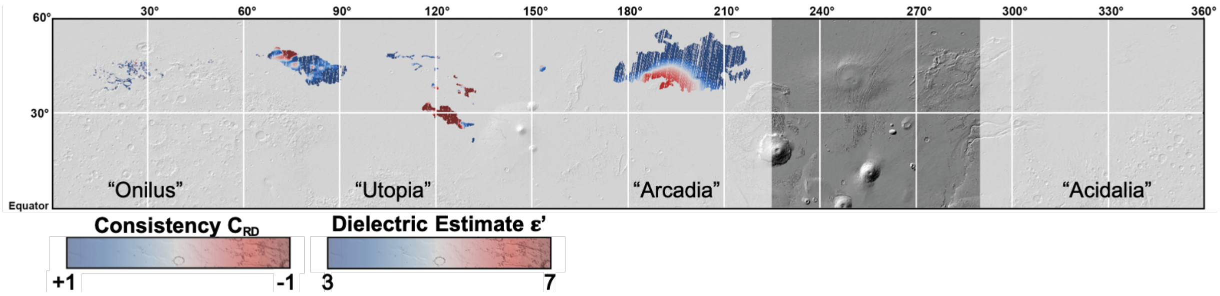

Figure 1. Map showing location of radar subsurface reflectors mapped in The SWIM Project, with colorbar representative of the dielectric permittivity estimates and corresponding ice consistency value from our radar analysis, C_{RD}.

Our dielectric estimates and SWIM Equation results suggest multiple units across the northern mid-latitudes of Mars that may contain ice: *Arcadia Unit 1 Main Plains* (widespread reflector previously mapped in [7] which cuts across multiple large-scale volcanic units mapped by [8]); *Arcadia Unit 2 LEC* (reflector present around a large Layered Ejecta Crater west of Phlegra); *Utopia Unit 1 Thermokarstic Mesas* (reflectors previously mapped in [9] and interpreted by [8] to be ice-rich loess and periglacial terrain); *Utopia Units 2–5* (sinuous feature within lacustrine deposits perhaps modified by thermokarst [8]); *Onilus LDA/LVF/CCF* (reflectors mapped beneath large glacier-like landforms – lobate debris aprons, lineated valley fill, and concentric crater fill – previously mapped in [10], and includes regions mapped by [11]); *Onilus Upper Plains Unit Mantle* (reflectors associated with an LDA-mantling unit identified by [12]); *Onilus Northern Plains Mantles* (reflectors associated with miscellaneous layered mantle).

Meanwhile, our dielectric estimates and ice consistency values for Utopia Units 6–11 are indicative of basaltic, ice-free materials, corroborated by the geologic mapping of [8] which interpreted these regions as lava flows from Elysium Mons and Olympus Mons.

Role of Densification Processes on Observed Heterogeneities: There are numerous lines of evidence that Martian mid-latitude ice is heterogenous, both laterally and vertically. Lateral variations in bulk dielectric permittivity can be observed in Figure 1. Geomorphologic features support the presence of vertical heterogeneities, which our bulk permittivity estimates do not capture. Such features include the scalloped terrain associated with Utopia "Thermokarstic Mesas Unit" [9], terracing in simple craters throughout Arcadia "Main Plains Unit" [7], and a scarp exposure in northern Arcadia of a ~100 meter-thick deposit of massive ice [13].

Microstructural ice evolution through sintering is a possible mechanism for generating heterogeneities in ice, especially given its strong dependency on temperature and grain size (e.g., [14]). The primary stages of sintering are characterized by growth of the contact region ("neck") between grains and mass redistribution forming grain agglomerates (Stage 1 from [15]) and densification via the shrinkage of isolated pores after the ice has become a cohesive aggregate (Stage 3 from [15], with Stage 2 being a transitional period between stages). Negligible densification occurs during Stage 1.

Smaller and warmer grains sinter faster. At 200 K, 100 and 200 micron grains take ~2 and 9 years, respectively, to complete Stage 1 (neck growth) [14]. At 170 K, the same modification for 100 and 200 micron grains takes ~350 and 1500 years, respectively [14]. Annual average temperature at the top of northern mid-latitude ice deposits (which are insulated under dust) are likely around 190–210 K throughout the last ~20 Myr of Mars' history [16], suggesting the initial neck growth phase will occur quickly under Martian conditions.

In contrast, the densification stage occurs over much longer timescales [14], which are not well constrained for planetary environments. We are working to address this knowledge gap using laboratory experiments of ice under different thermal and atmospheric conditions to build on the sintering model of [14]. We will present preliminary results of this model, especially as it pertains to creating heterogeneities within ice across the Martian mid-latitudes. We will explore the role that diurnal, seasonal, and orbital thermal cycling may play in the formation of subsurface density gradients and relate results to observations of ice heterogeneities.

References: [1] SWIM Data Products, swim.psi.edu [2] Morgan et al. (2019) LPSC Abstract #2918. [3] Putzig et al. (2019) 9th Int'l Conf. on Mars Abstract #6427. [4] Seu et al. (2007) JGR, 112. [5] Ulaby, Moore, & Fung (1986) Microwave Remote Sensing, active and passive. [6] Campbell and Ulrichs (1969) JGR, 74. [7] Bramson et al. (2015) GRL, 42. [8] Tanaka et al. (2014) Geologic map of Mars: USGS Map 3292. [9] Stuurman et al. (2016) GRL, 43. [10] Petersen et al. (2018) GRL, 45. [11] Levy et al. (2014) JGR-Planets, 119. [12] Baker & Head (2015) Icarus, 260. [13] Dundas et al. (2018) Science, 359. [14] Molaro et al. (2018) JGR-Planets, 124. [15] Swinkels & Ashby (1981) Acta Metallurgica, 29. [16] Bramson et al. (2017) JGR-Planets, 122.