WIDESPREAD SHALLOW WATER ICE ON MARS AT HIGH AND MID LATITUDES.

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Introduction: Future crewed missions to Mars are scheduled by NASA approximately for the mid-2030's, and would rely on *In-Situ Resource Utilization* (ISRU), especially for water. H_2O in the form of ice is abundantly present on Mars, but not necessarily in exploitable quantities or easily accessible depths at mid-to-low latitudes. For the scientific community, mid/high latitudes subsurface water ice deposits hold the promise to constrain volatile transport models and climate conditions at other epochs, could be currently involved with various active geomorphological processes, and likely impacts near-surface habitability.

When present close to the surface in multi-dm thick units, water ice behaves as a heat capacitor, absorbing and storing energy during spring and summer, resulting in slightly lowered surface temperatures at these seasons. Inversely, during the fall/winter, this heat is released and surface temperatures are slightly higher. The magnitude of this effect is modulated by the depth to the water ice table and can be predicted theoretically. The analysis of global and local-scale thermal infrared data can be used to derive water ice depths, and this approach has proven reliable to map water ice distribution at sub-meter vertical scales [1,2,3]. Here, we leverage MCS data available since 2006, derive the properties of the dry overlying (insulating) regolith, and we map the depth *d* [m] of its interface with the top of the water ice table.

The mapping results are shown in Fig. 1. Results are not presented at low latitudes (35°N-35°S) where seasons are not well pronounced and where the seasonal equatorial cloud belt influences the cyclical temperature signal that is leveraged by the method. Water ice might still be present at these locations, even at shallow depths, but the current approach and numerical tools used here are not optimized for this task. This limitation also includes retrievals in the southern mid-latitudes, where spring corresponds to the dusty season, i.e., a period of buffered surface temperatures (and therefore warmer nighttime temperatures) damping the trend we seek to identify, as well as in low thermal inertia (TI) regions ($TI < 120$ J m^{-2} K^{-1} $s^{-1/2}$) where small unmodeled atmospheric forcings result in large temperature variations. False positives are undoubtedly reported in Fig. 1 where shallow subsurface material with ice-like thermophysical properties is present. Such material could correspond to competent bedrock or large rocks present across 10's of km laterally (mapping resolution of our work), for example from buried lava flows or ejecta units, but they have been shown to be relatively rare on Mars, and not latitude-dependent.

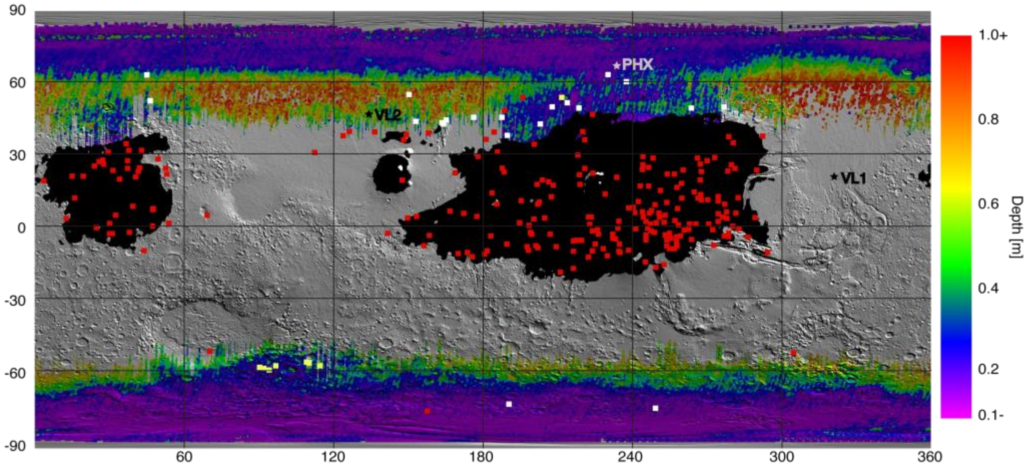

Figure 1: MCS derived depth to the top of the water ice table *d* and MOLA shaded relief (background), mapped at 3 ppd (~20km at the Equator). Low thermal inertia regions ($TI < 120$ J m^{-2} K^{-1} $s^{-1/2}$) are masked out. PHX, VL1, and VL2 indicate the landing site locations for Phoenix, Viking Lander 1, Viking Lander 2. White dots indicate fresh ice exposing impact craters (red dots no ice identified). Yellow dots indicate exposed water ice along cliff scarps.

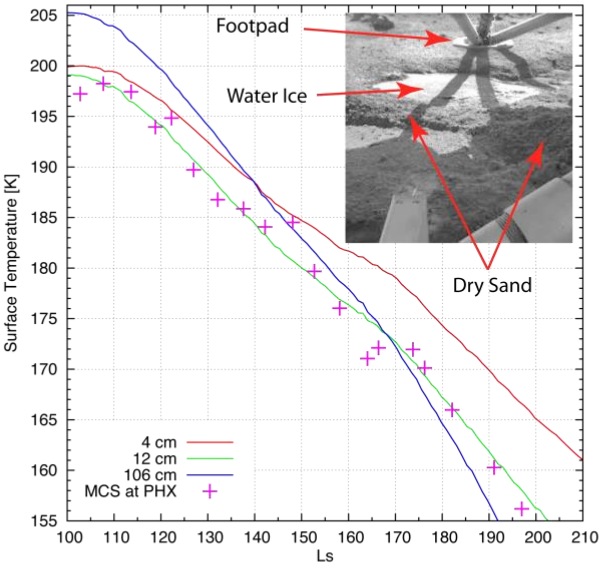

Figure 2: Example of surface temperatures at the Phoenix landing site location (68.2°N, 234.2°E). The best match between the model and MCS data is obtained with a water ice table at 12 cm below the surface. A subsection of the "holy cow" mosaic (upper right -modified from [*4*]) shows the water ice table exposed under the lander, where mobile sand-like material had been displaced upon landing. Trenches near the lander found water ice at variable depths below the surface.

Discussion: Shallow water ice (i.e., within the top ~1m) is most likely involved as its spatial distribution in Fig. 1: 1) mimics maps of high near-surface H concentrations at polar and most mid-latitudes, 2) matches the occurrence and approximate excavation depth of ice-exposing craters, 3) correlates with the observation of icy cliffs, 4) fits the depth to the water ice table exposed at the Phoenix lander (Fig. 2), without identifying shallow ice at depths attained by both Viking landers trenches, 5) overlaps with regions associated with high near-surface radar permittivity signatures (in Arcadia Planitia and Deuteronilus Mensae), and 6) is associated with periglacial geomorphological features.

In addition, the analysis of THEMIS data (not shown here) acquired at strategically selected seasons confirms the great lateral variability of depth identified by [1,2], even at lower latitudes than reported in [1], and suggests that isolated patches of shallow water ice may persist at latitudes lower than those reported in Fig. 1., especially associated with steep pole-facing slopes. Although the prospect of tropical water ice availability [4] would also open additional potential exploration sites, steep slopes are generally avoided for engineering/safety reasons.

Such widespread shallow water ice represents an enabling breakthrough for future crewed missions to Mars. Abundant water just a few centimeters below the surface at latitudes as low as 35°N (as opposed to possibly meters deep based on radar data), at low elevation (-4 km), medium thermal inertia (i.e., 200-300 J m^{-2} K^{-1} s$^{-1/2}$ indicative of sandy –as opposed to dusty- material) and generally smooth terrains (i.e., not limited to steep cliffs or sublimation-driven depressions) is crucially important. Of course, it is understood that landing site certification requires vastly more criteria than just those.

The water ice identified in Fig. 1 is not stable everywhere at the lowest latitudes reported here under the current conditions, but matches closely modeled ice stability maps generated for other epochs, especially when the water vapor content of the atmosphere would have been much higher than today's. If this is the case, future mapping work should focus on confirming the presence of subsurface water ice predicted by model at even lower latitudes, because 1) landing at the lowest latitudes is generally most preferable for engineering constraints, and 2) shallow ice there may be most sensitive to the environmental conditions that led to its deposition and persistence until today. *Special Regions* of increased potential sensitivity to biological contamination might need to be revisited.

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