OBLIQUITY, ICE SHEETS, AND LAYERED SEDIMENTS ON MARS: WHAT SPACECRAFT OBSERVATIONS AND CLIMATE MODELS ARE TELLING US.

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Introduction: The Mars Odyssey Gamma-Ray Spectrometer (GRS) data [1,2,3] present a quandary: On the one hand, large deposits of (inferred) water ice are located where thermal models suggest they would form and best be protected, e.g., if deposited during periods of higher obliquity [4,5] (Figure 1). On the other hand, the volume mixing ratios (~70%) [1,2,3] are so high that diffusive deposition of water in regolith pore space (which is the process assumed by these models) cannot be the primary formation mechanism. Furthermore, given that the water is inferred to be so close to the surface (less than a few 10's of cm's) [1], it must be in communication with the atmosphere on time scales that are geologically relatively short (10^3-10^6 years); therefore the water cannot be archaic. Considering the GRS data, images of mantled, fretted, and disaggregated terrain [6,7,8] (Figure 2), and new climate modeling of Mars' orbital cycles [9] (Figure 3), we are led to an alternate conclusion about the ice deposits: that they form as subaerial ice sheets. This scenario not only provides a simple explanation for these observations, but may also help explain the formation of globally distributed, sedimentary layered deposits.

The Challenge of Understanding the GRS Water Observations: GRS has yielded compelling evidence for the existence of massive water ice deposits just centimeters beneath the Martian surface at latitudes poleward of ~60° [1,2,3] (Figure 1). The locations of these deposits is gratifyingly similar to predictions based on thermal models [4,5]. Implicit in such models is the idea that water diffuses through the interconnected pore spaces of the regolith; freezing, adsorbing, and subliming in response to orbit-driven thermal forcing and the supply of water to and from the atmosphere. As obliquity changes, the thermal forcing at the surface and the total water vapour available at the surface also change, yielding different geographical distributions of subsurface water stability [4,5].

These models predict stable subsurface water ice deposits that change with orbital parameters, but maximum volume mixing ratios do not exceed 40%, even for carefully chosen, poorly consolidated regolith. The amount of water inferred to be present

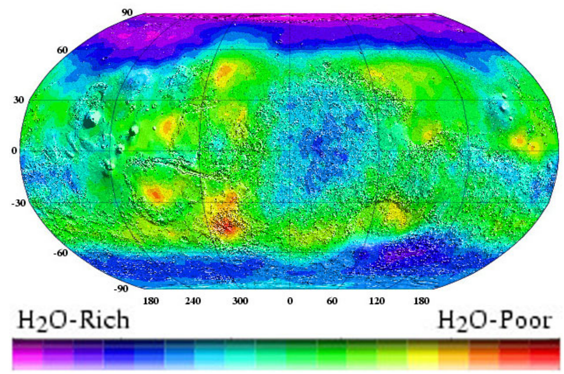

Figure 1: Qualitative map of near-sub surface water ice distribution *(from GRS LPL web site)* [1,2,3].

from the GRS data, however, is extremely high--as much as 70% by volume. It may be possible to reconcile the measurements and models by choosing the lowest bounds on the measurements and the highest (unlikely) estimates of regolith pore capacity. Nevertheless, the idea that water, trapped in regolith pore space, alone explains the GRS observations appears to be suspect.

Surface Water Ice Deposition: We propose that ice sheets form at the surface, with diffusion into the subsurface being of secondary importance. Recent modeling of Martian perennial ice sheets with a full General Circulation Model (GCM) [9] suggests that water ice is deposited on the growing ice sheets during winter, forming relatively thick annual deposits at the surface. As Mars' orbital elements vary, the latitudes favoured for perennial water ice change, with ice sheets being stable at mid- and lower latitudes when the obliquity is high [10,11,12,13]. As orbital elements trend to lower obliquity, formerly stable lower-latitude deposits become unstable with respect to the poles. Over an obliquity cycle, the model suggests that as much as a few 10's of meters of water ice can form at non-polar latitudes (the exact location depending on orbital elements, the history of where surface ice was formerly stable, and on surface thermal properties) [9]. At 35° obliquity, which characterized the last high obliquity extremum, the favoured latitudes for perennial ice extend to below ~60° (Figure 3). As such, we suggest that the observed GRS water ice may be a fossil remnant of that period.

Dusty Ice Sheets: Thermal models indicate that water ice would sublime as quickly as it condensed, leaving little trace. However, we suggest that modest amounts of atmospheric dust deposited with the ice will collect near the surface of the subliming water ice, forming a progressively thicker lag. Thermal and diffusive blanketing by this lag will protect the ice sheets, allowing a fraction of each deposit to persist long after (~10^5-10^7 years) its latitude has become unfavourable for stable surface water ice. A lag a few 10's of cm in thickness would isolate the ice from the diurnal thermal wave, thereby vastly increasing the ice sheet stability. A lag of this thickness requires that the top few meters of ice (that sublime) contain a few percent dust content, which seems plausible given that higher obliquity states are probably associated with higher-than-present atmospheric dust content. Such a lag appears to blanket the southern polar layered deposits [14,15].

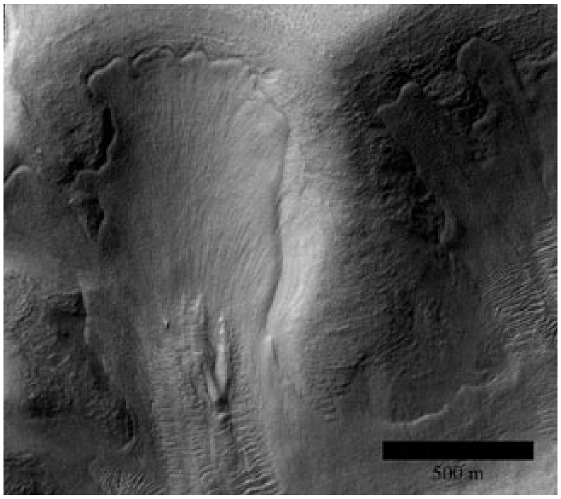

Figure 2: Volatile rich material in the high southern latitudes indicated by apparent flow down channel wall.

We therefore believe that the GRS observations don't reveal water ice deposited in pore space below a preexisting surface, but an ice sheet(s), covered by a lag, overlaying a preexisting surface. The existence of mantled ice sheets in the high latitudes of Mars where the GRS water abundance is highest appears plausible on the basis of imaging observations [6,7]; indeed, some of these observations suggest the presence of more extensive and now substantially de-volatilized deposits at even lower latitudes [6]. We note that this scenario suggests something foundational to our understanding of Mars climatic and geologic history: that ongoing volatile redistribution due to changes in obliquity and other orbital elements can generate extensive sedimentary deposits of ice and/or lag. Accumulation of these units may be an important mechanism in the formation of mid-and low-latitude layered terrains [8].

Discussion: Our conceptual model of global-scale ice sheets on Mars carries several implications. First, the ice sheets would be relatively thin (only a few 10's of m can be deposited over a single obliquity cycle [9]) and as such, the amount of water inferred from the top few meters of the high-latitude subsurface cannot be extrapolated to significant depth when estimating the global water abundance. Second, the climate mechanisms involved in *polar* layered terrain formation may also be creating geological records at other locations on the Martian surface. Finally, this framework naturally extends to explain the layered sedimentary deposits widely distributed on Mars [8], requiring only the action of observed, ongoing climate system components and not extensive periods of stable liquid water.

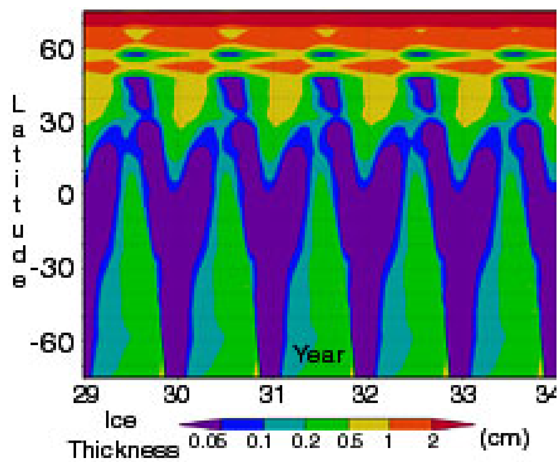

Figure 3: GCM [9] predicts perennially stable surface water ice poleward of 60°N latitude when obliquity is 35°. Color is zonally averaged surface ice thickness. Model years 29-34 are shown.

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