ATMOSPHERIC ICE-DUST PRECIPITATION AND VOLCANIC TERRAIN: CONSTRAINING THE ORIGIN AND EVOLUTION OF GROUND ICE AND OF PERIGLACIAL LANDFORMS IN UTOPIA PLANITIA, MARS.

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Introduction:

A variety of putative periglacial-landforms have been observed at the mid-latitudes of Utopia Planitia (UP): small-sized and non-sorted polygons, small-sized sorted-polygons and circles, gelifluction lobes and, most importantly for our work, scalloped flat-floored depressions [e.g. 1-9].

On Earth, the origin and evolution of periglacial (cold-climate and non-glacial) landforms requires the antecedent presence of "permafrost," (water-based) "ground ice" or, in some instances, "ice-rich permafrost," as well as a transformational mechanism, e.g. freeze-thaw cycling [10].

"Permafrost" is ground that has been frozen for at least two years; "ground ice" refers to all types of ice forming in permafrost or in ground that is freezing; "ice-rich permafrost" occurs where "the volume of ice in the ground ***exceeds*** the total pore volume that the ground would have under natural unfrozen-conditions" [10].

On Mars, the presence of "ground ice" is hypothesised wherever the putative periglacial-landforms noted above are observed; contrarily, as will be explained below, the thermokarst-like depressions are unique in that they alone require the presence of ice-rich permafrost to form [1,5,10].

Currently, ideas on the origin of ground ice or of ice-rich permafrost in UP range from the deposition and accumulation of atmospherically precipitated ice-dust (water ice either nucleated on and/or intimately mixed with atmospheric dust) [e.g. 11-15] to water vapour-diffusion [e.g. 16-20].

Below, we suggest that neither of these sets of ideas or hypotheses, in and of themselves, is sufficiently robust to generate ground ice or ice-rich permafrost from the near-surface to tens of metres of depth at the mid-latitudes of UP. By contrast, we propose a three-fold (ice-rich) permafrost formation-hypothesis that integrates the deposition and accumulation of atmospherically-precipitated ice-dust, episodic freeze-thaw cycling and the presence of a high porosity, low-albedo volcanic substrate.

Ground-ice depth in UP:

Scalloped, flat-floored depressions are ubiquitous at the mid-latitudes of UP and incise terrain that is thought to be ice-rich [1,4-5,21] (Fig. 1). Depression depths extend from metres to decametres and their distribution often covers tens of kilometres [1,4-5,21]. Invariably, small-sized polygons, possibly the result of thermal-contraction cracking [1-5,20] and perhaps underlain by ice-wedges at the margins [22], cross-cut the depressions.

Some workers believe that the morphology of the depressions, their spatial association with the small-sized (non-sorted) polygons, and their possible embayment within ice-rich permafrost are suggestive of flat-floored thermokarst basins absent of water (or alases) in "wet" periglacial landscapes on Earth [1,5]. Alases occur where ice-rich terrain has undergone thermal stress, thawed, lost water by evaporation or drainage and has settled (or subsided) to a new equilibrium depth below the original datum [10,23].

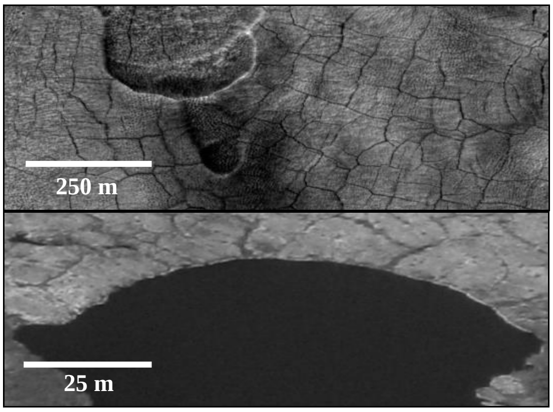

Fig. 1a: Flat-floored depressions and small-sized polygons (HiRISE PSP_007384_2225, 42.224^0N; 86.322^0E, ~25cm/pixel. Image credit: NASA/JPL/UofA. **Fig. 1b:** Thermokarst lake and marginal small-sized polygons, some of whose troughs are filled with water. (Tuktoyaktuk Coastlands, Canada). Image credit: R.J. Soare.

On Earth, a rough rule-of-thumb is used to estimate the minimum depth of ice-rich permafrost where alases are observed [23]. For example, if the ice-volume of the permafrost is 50% and an alas shows a depth of ~30m, then based on the volumetric loss of water entailed by the formation of an alas, the minimum depth of the ice-rich permafrost would be ~60m [adapted from 23].

As noted above, the alas-like landforms in UP reach tens of metres of depth [4-5,21]. If the "alas" analogue is valid, then the putative ice-rich permafrost in which the Martian depressions are rooted could reach anywhere from tens to and even beyond ~100m, depending upon the assumed ice-volume in the substrate. Interesting as this might be, a key question remains unanswered: by which means has the permafrost become ice-rich to such depths? Heretofore, two main formation-hypotheses have been proposed: (a) the “ice-dust hypothesis; and, (b) the “vapour-diffusion” hypothesis. Here we discuss these hypotheses and provide a new alternative: (c) atmospheric ice and lithic sediments.

(a) The “Ice-Dust” Hypothesis:

The “ice-dust” hypothesis can be broken up into two components: 1) ice-dust deposition and accumulation (mantle formation); and, 2) periglacial modifications of the accumulated ice-dust (mantle deformation). With regard to the former, numerous workers have suggested that changes in the spin axis of Mars during the very Late Amazonian Epoch have induced the atmospheric precipitation of ice-dust in the northern hemisphere [12-15]. This has engendered the cyclical or episodic formation of a metres- to decametres-thick mantle [4,6,8-9,11-15,23-24]. Subsequently, insolation induces the partial sublimation of the mantle and this, in turn, triggers the formation of polygonal cracks and flat-floored depressions [4,6].

This hypothesis implies that the lithic component of the periglacial mantle comprises dust-sized grains (a few microns or less). By contrast, the subsidence associated with the formation of an alas on Earth is the result of “***excess ice***” being lost from the pore space of ice-rich permafrost or sediments [10]; typically, this comprises silt to sand sized (ten μm up to a mm) grains. As “dust” shows pore space an order of magnitude smaller than that of water (or of frozen water), water cannot fill the pore space of dust.

The hypothesized episodic deposition and accumulation of “ice dust” in the northern hemisphere of Mars is more akin to the deposition and accumulation of snow, followed by the formation of glacial ice by firnification. The thaw or sublimation of this glacial ice would not generate steep-sided pits. Thus, the type of thaw-induced subsidence associated with alas formation on Earth does not run parallel with the sublimation-driven loss of ice in a putative “ice-dust” mantle on Mars.

(b) The Vapour-Diffusion Hypothesis:

It has been hypothesised that during recent periods of high obliquity as much as 30-40% of the available pore space in the upper few metres of the regolith poleward of the Martian mid-latitudes could have been filled by atmospheric water-vapour; this would form ground ice, stable at or near the surface as long as surface and near-surface temperatures remain below the atmospheric frost point [16-17]. Once initiated, the rapid accumulation of ice in the pore space of the near-surface regolith would impede transport to depth, leaving the regolith below the upper few metres largely dessiccated [16-17]. When and if the surface and near-surface temperatures rise above the atmospheric frost-point, the ground ice would diffuse back into the atmosphere.

In periglacial environments such as the Dry Valleys of the Antarctic, ice-rich or ice-cemented permafrost seemingly produced by vapour transport has been observed [25-26]. However, the icy permafrost does not extend beyond one metre of depth [25-26]. This is consistent with the theoretical constraints of the Mars vapour-diffusion hypothesis. Writ large, vapour diffusion alone seems incapable of generating the ground-ice depths required to initiate and develop the formation of the alas-like landforms on Mars.

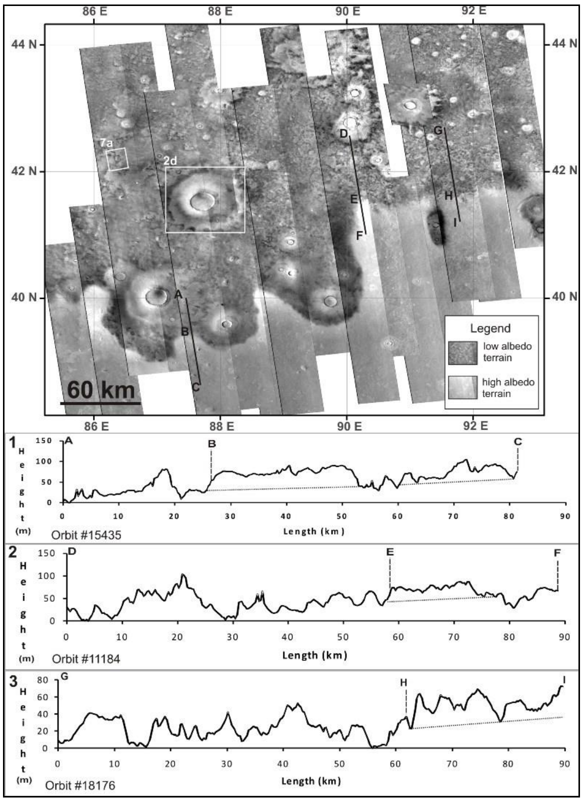

Fig. 2. CTX composite image (~8m/pixel) overlain with three MOLA profiles. The image highlights the changes of topography observed where the relatively low-albedo (dark-toned) terrain in which putative periglacial-landforms are embedded and the relatively high-albedo (light-toned) terrain adjacent to these landforms occur in proximity. Generally, the darker-toned terrain occurs at a lower elevation than the lighter-toned terrain; a height difference of ~35m is estimated based on the difference in average height between the lighter and darker-toned terrain in transect A-C - see the dashed line (A-B) and the dashed-dotted line (B-C) in MOLA profile 1. CTX image credits: NASA/JPL/MSSS [27].

(c) Atmospheric Ice and Lithic Sediments:

Our recent work has shown that at the mid-latitudes of UP dark-toned terrain has/is been/being modified by periglacial processes [27]. That is to say, the small-sized polygons and flat-floored scalloped-depressions widely observed in the region incise terrain that is relatively dark-in-tone compared to light-toned (presumably dusty terrain) that lies to the south (Fig. 2). At HiRISE resolution (~25cm/pixel) the light-toned terrain shows no small-sized polygons or flat-floored scalloped depressions. Moreover, the light-toned terrain occurs at a higher elevation than the darker-toned terrain **(Fig. 2)**, partially fills some of the scalloped depressions that incise the latter, and clearly mantles the dark-toned terrain where the two terrains intercept one another (Fig. 3).

At local and regional scales these observations suggest that the light-toned terrain lies above the dark-toned terrain in a stratigraphical column. This is inconsistent with the main stratigraphical assumption of the ice-dust hypothesis: that the dusty lighter-toned terrain underlies the small-sized polygons and the scalloped depressions and is cross-cut by them.

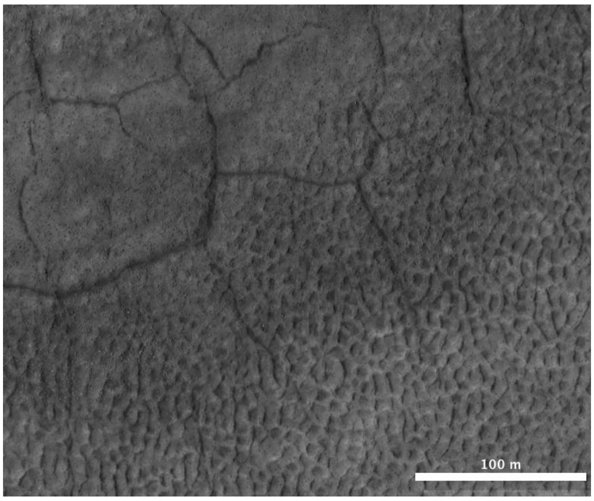

Fig. 3: Example transition from mantle to underlying darker, bolder-topped periglacial terrain in dark-toned area near point "E" in Fig. 2 (HiRISE ESP_017260_2225 42.153^{0}N; 89.970^{0}E, ~25cm/pixel). Image credits: NASA/JPL/UofA.

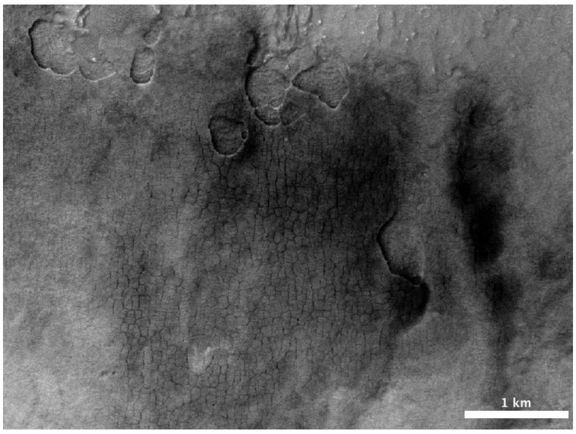

Fig. 4: Dark splotches, interpreted as drifted sediments, and small scalloped depressions located between "D" and "E" in Fig. 2 (CTX P18_008254_2212_XN_41N269W, ~8m/pixel). Image credits: NASA/JPL/MSSS.

At high-spatial resolution, the dark-toned terrain exhibits sub-meter boulders and drifts of dark wind-blown sediment (Figs. 3-4). As these drifts rarely form aeolian bedforms, this suggests that the sediment is likely smaller than sand-sized (e.g. silt-sized). In addition, several of the larger scalloped depressions exhibit possible layering (observed on their walls) (Fig. 5). These characteristics are not consistent with a pure "ice-dust" deposition scenario.

We propose that these periglacially-modified terrains are composed of ice-rich sedimentary layers, formed from the near-concurrent (almost syngenetic) deposition of sediments and atmospherically precipitated ice/snow. In this scenario, the ice/snow would have been deposited on top of the sediments; then, by means of melting, water could have percolated through the underlying sediments and frozen in situ, forming ice-rich permafrost. The syngenetic formation of ice-rich permafrost is commonplace on Earth, for example, at the mid-latitudes of Alaska [e.g. 28]. However, this scenario begs the question: "What is the sediment type and wherefrom does the sediment originate?"

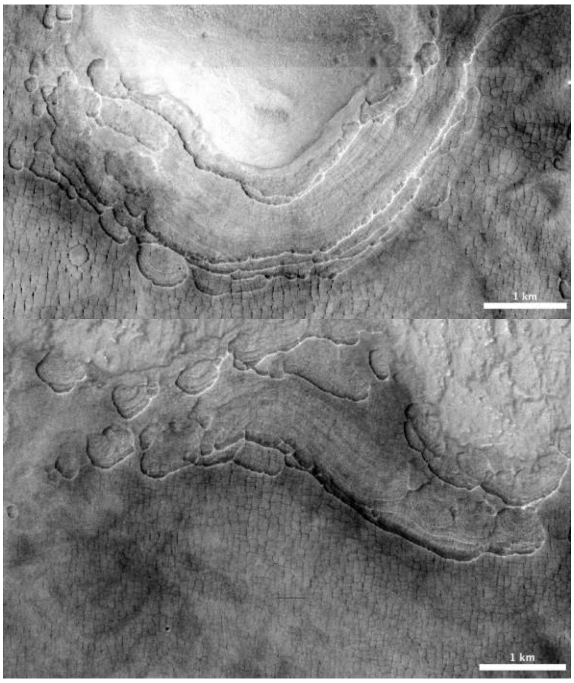

Fig. 5: Possibly layered walls in scalloped depressions (bottom) near point "D" in Fig. 1 (CTX P19_008465_2235 _XN_43N272W; P18_008254_2212_XN_41N269W, 8m/pixel). Image credits: NASA/JPL/MSSS.

Constraints on the Origin of the Sediments:

(1) Composition: Vis/near-IR spectra from the OMEGA imaging spectrometer have been used to show that the composition of the dark sediments covering much of the northern lowlands, including the mid-latitudes of UP, largely is weathered iron-bearing glass [29-30]. Previous studies have suggested either an explosive volcanism or impact origin for these widespread sediments [31-32].

(2) Grain size: As discussed above, periglacial features form most readily in silt to sand sized (10 µm-1 mm) sediments; based on the lack of aeolian bedforms where the surficial sediments in our study region accumulate the surficial sediments appear to be smaller than sand sized (probably silt).

(3) Depth: As discussed above, in order for

"alases" to form the depth of the underlying ice-rich sediments minimally must comprise tens of meters of depth and, potentially, more than 100 meters.

Possible Sediment-Origin Scenarios:

Based on the glass-rich nature of the visible portion of the UP sediments, these deposits could be consistent with either melt-rich impact ejecta or volcaniclastic sediments (ash, pyroclastics, etc.).

(1) Impact Ejecta/Melt: Impact ejecta/melt from distal sources likely has contributed to sedimentation in the northern plains but may not be sufficient to produce the thick deposits here. Several authors [31-32] have proposed that there should be globally distributed melt-droplets (sub-mm size) on Mars even from relatively small craters. These same studies have suggested that an ejecta layer on the order of tens of μm to mm thick should be deposited every 10,000-100,000 years on average, given current cratering rates. Although these ejecta events could cause accumulation of tens to hundreds of meters of material, it would require hundreds of millions to billions of years, effectively approaching the full Amazonian time-period. We cannot rule out fully an impact origin for these sediments but other sources may be more plausible.

*(2) Volcaniclastic debris:*The glass-rich composition of the sediments also could be consistent with glassy sediments due to explosive volcanism. Modeling of explosive volcanism on Mars has shown that these eruptions produce dispersed deposits of silt to sand-sized grains [33]. Based on these models, both Alba Mons and Syrtis Major could produce ash deposits in this region of UP, and in particular, Alba Mons tends to create thicker deposits localized to this portion of UP. Alternatively, the source of the eruption could have been more local. For instance, putative super-volcanoes have been recently identified in Arabia Terra, which have morphologies indicative of explosive activity [34]. These constructs may also have acted as a contributor to ash-fall deposits in UP.

In contrast to the impact scenario presented above, a volcanic origin for these deposits would imply a relatively-short timescale for deposition. If a major volcanic-event coincided with (or perhaps motivated) a period of enhanced precipitation in UP, this could produce the near-concurrent deposition of sediments and ice that may be required to form these large periglacial deposits. Furthermore, volcaniclastics tend to have high porosities, which can lead to deep permafrost layers [35].

Conclusions:

We have employed morphology and landscape context as the basis for identifying UP's scalloped depressions as putative alases. If the analogy is correct, then the depth of the Martian landforms can be used to infer the depth of ground ice in the region, which we estimate to be on the order of many tens of metres, and possibly more than 100 meters. On Earth, alas formation is rooted in ice-rich permafrost. We have shown that hypotheses relying on the atmospheric deposition of ice dust or of vapour diffusion cannot form ice-rich permafrost to tens of metres of depth and, thus, are unsatisfactory.

We propose that the ice-rich permafrost in our study region originated as nearly concurrent layers of silt sized sediments and meteorically or atmospherically precipitated ice/snow. Based on the composition and extent of the sediments, we favor a volcanic interpretation for their origin, but cannot fully rule out an impact source.

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