ESTIMATE AND EXPRESSION OF WATER ICE IN POLAR SAND DUNES.

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Introduction: The most extensive sand dune deposits on Mars encircle the north-polar residual water-ice deposit. The Olympia Undae, located between 130° and 245° E and 78° and 83° N is the largest sand sea on Mars covering an area of 185,00 Km^2 [1]. Although the dunes have been studied extensively using visible and infrared imaging data of the Viking orbiters [e.g., 2, 3-6], many fundamental issues regarding the origin, evolution, and internal structure of the dunes remain unknown. Omega and CRISM data confirm that there is a strong calcium sulfate signature (most likely gypsum) in the dune surface sediments in the eastern part of the dunefield that decreases westwards [7-9]. More recently, hydrated minerals have been detected throughout the north polar region including many of the deeper chasma and re-entrants in Planum Boreum [10]. Here we estimate the hydrogen content of the Olympia Undae and explore the dune-scale geomorphic features of north polar dunes to explain concentrations of hydrogen detected.

Hydrogen signature: We use two data sources in our analyses. First, neutron currents were measured using the Mars Odyssey Neutron Spectrometer. Second, seasonally varying temperatures were measured using the Thermal Emission Spectrometer. Details of this approach are outlined in Feldman *et al* [11]. Both the neutron and thermal infrared data are best represented by a two-layered model having a water-ice equivalent hydrogen content of 30±5% in a lower semi-infinite layer, buried beneath a relatively desiccated upper layer that is 9±6 g/cm^2 thick (about 6 cm depth at a density of 1.5 g/cm^3).

Dune geomorphology: We use High Resolution Imaging Science Experiment (HiRISE) images to detect dune-scale geomorphic signatures (Fig. 1b).We present four features that suggest induration of the dune sediments and potential sublimation of dune volatiles.

Indurated layers and arcuate ridges: Narrow, often curvilinear ridges protrude from the windward slope of dunes on Mars. These may be indurated layers that are exposed when windward-side erosion occurs. On Earth, induration is know to result from geochemical process [12] and from layers of frozen sand, ice and snow in dunes [13].

The remnants of partially eroded dunes that moved across the area are preserved as arcuate ridges. These may mark the base of the windward slope, slipface or may outline the entire position of the dune (Fig.1a). Similar features are found upwind of dunes on Earth. They can be formed as vegetation traps sediment [14], geochemical induration of sediment during periods of high groundwater or interdune flooding [12], or they result from ice induration of dune sediment [15].

Sinkholes: Circular depressions that resemble sinkholes are located periodically along dune crests (Fig. 1c). These circular depressions are found on polar desert dunes on Earth and are formed by the sinking/collapse of surface sediment due to a loss in volume of underlying volatiles [16]. Their position along the dune crest and not elsewhere may be linked to larger diurnal insolation receipts at that location on the dune. These features identify locations of potential denivation, but do not necessarily map out the potential full extent of subsurface volatiles.

Tensional fissures: Sinuous, narrow, rectilinear and branching depressions are observed on the lee face of the larger dunes (Fig. 1d). These features suggest cohesion of the surface sediments and the operation of tensional stresses. They are similar to tensional cracks reported on dune surfaces in polar deserts. On Earth, the cohesion is a function of moisture content (from snowmelt). The source of tensional stress is a loss of subsurface volatile volume [16]. On Mars, cohesion of the surface sediment may be provided by crusting [17, 18].

Are these signatures a product of geochemical induration? The neutron and thermal infrared data coupled with the dune geomorphology suggest that the dunes contain a relatively desiccated top layer, which overlays a hydrogen-enriched lower layer. A stratigraphic model that is consistent with all three data sets is that the dunes contain a surface dry layer which overlays a niveo-aeolian lower layer.

However, the origin of the hydrated signature is under discussion. Two of the geomorphic features presented here may be consistent with a geochemical cementation process (protruding indurated layers and arcuate ridges). However, the crestline pits suggest a loss of volume, triggered by melting, evaporation or sublimation of volatiles that are located close to the surface. If the indurated laminae, arcuate ridges and tensional fissures are due to the presence of hydrated minerals,require repeated episodes of (melt)water production and this presents a challenge under current polar climatic scenarios.

The multispectral data indicate the presence of hydrated minerals on the surface (*i.e.* ≤ 20 μm depth). Neutron data detect a hydrogen signature at greater depth (6cm) and the geomorphic features allow a potentially deeper view into the internal composition of the dunes. Based on our combined approach our preferred hypothesis is that the dunes contain niveo-aeolian deposits. These are deposits of wind-driven snow, sand, and dust [19]. They consist of inter-bedded sand and ice that are often indurated and resistant to erosion [20]. They are preserved by rapid burial of precipitated snow and frost layers by rapidly aggrading sand. On Mars water ice may be emplaced in the dune by the diffusion of water vapor or by direct precipitation of snow and ice crystals.

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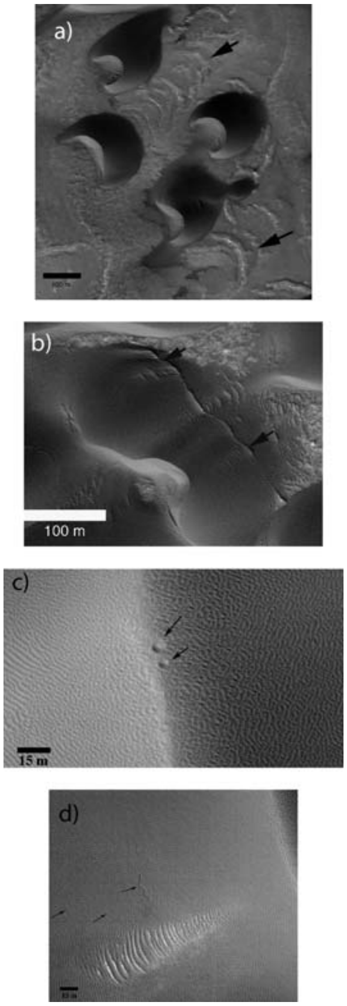

Figure 1 a) Arcuate ridges upwind of barchan dunes in Chasma Boreale mark the former dune position. (PSP_1374_2650. b) Indurated layer protruding from the windward slope (PSP_1374_2650). c) Section of dune crest from black arrows indicate locations where the dune crest has been altered by hypothesized sublimation pit formation. (PSP_001736_2605).d) Tensional crack development on a dune lee slope (PSP_001736_2605).