STRUCTURE AND ORIGIN OF THE MARTIAN LATITUDE DEPENDANT MANTLE REVEALED BY ICE EXPOSING SCARPS.
N. Le Becq[1], S.J. Conway[1], A. Grau Galofre[1], S. Byrne[2], N. Mangold[1], V. Bickel[3], C. M. Dundas[4], V. G. Rangarajan[5], L. L. Tornabene[6]. [1]LPG, Univ. Nantes, France (noe.le-becq@univ-nantes.fr). [2]LPL, University of Arizona, USA. [3]CSH, University of Bern, Switzerland. [4]Astrogeology Science Center, USGS, Flagstaff, USA. [5]German Aerospace Center (DLR), Germany. [6]IESE, University of Western Ontario, Canada.

Introduction: Assessing the nature and distribution of water ice in the mid-latitudes of Mars is fundamental for the understanding of the planet's recent climate history [1], and for characterizing ice reservoirs as a resource for future sustainable human exploration [2].

Martian mid-to-high latitudes are covered by a young smooth deposit that drapes the topography: the "latitude dependent mantle" (LDM) [3, 4, 5]. Almost continuous above 55° latitude, it becomes thinner, degraded and discontinuous towards lower latitudes, disappearing around 30°. Numerous observations [2 and references therein] indicate that the LDM contains at least 46% of water ice by volume [6]. While this ice is usually covered by a layer of dry regolith several centimeters thick, instances of exposure occur on back-wasted scarp faces, allowing the ice and internal structure of the mantle to be explored [7, 8, 9]. These ice exposing scarps (IES) are located at the head of triangular depressions and face directly towards the poles, as shown in Fig. 1. They expose a stratified, relatively bluish-colored material visible year-round in HiRISE and CaSSIS color images, which CRISM observations have confirmed to be water ice with < 1% contamination [7]. Recent models suggest that IES are actively retreating at a rate of a few mm per year [10].

In this work, we build on the efforts of [7, 8] by completing the mapping of IES across the entire planet and studying in detail their morphology, context, and the characteristics of the exposed ice. This analysis aims to shed light on the origin of the LDM, its internal structure, and the global distribution and internal stratification of near-surface ice deposits in Martian mid-latitudes.

Datasets and approach: We surveyed the ~5 m/pix MurrayLab CTX mosaic [11] at mid-latitudes (40° to 65°) searching for IES with the same morphological characteristics described in [7, 8]. We also conducted a complimentary IES scan using a neural network based on [12]. Individual IES were outlined as polygons, with a polyline placed along the ridgeline on the steep pole-facing scarp, and a further straight line placed orthogonal to the ridgeline ending at the furthest equatorward extent. We then used HiRISE and CaSSIS images to examine IES colours and any existing internal stratigraphy, and to look for smaller scale morphological details such as polygons and boulders in the depression. We investigated the topographic context of the IES with the gridded MOLA elevation product at 128 pix/deg. Finally, we produced and used HiRISE DTMs with a resolution of ~1 m/pix for 26 IES to produce their topographic profile and to estimate depression depths and volumes by extrapolating surrounding topography as in [6]. We also generated orthoimages to measure the stratigraphic layer thicknesses and their frequency of occurrence using fast Fourier transform (FFT) and wavelet analysis.

Results: We mapped 231 IES, 178 of which are located in the northern hemisphere, with the majority in Milanković crater (117). The neural network scan did not reveal any unknown IES locations, underlining the completeness of our global inventory. Despite being larger in number, the northern IES tend to be smaller (333 m long on average) than their southern hemisphere counterparts (860 m on average). Southern hemisphere IES are up to a few kilometers long, with the longest measuring 6560 m (Fig. 2), and are mostly located in

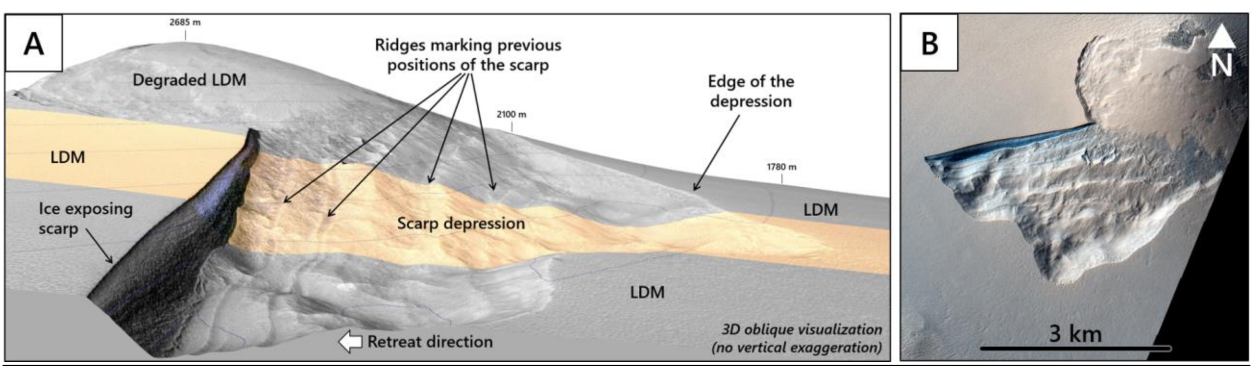

Fig. 1: A – Labelled oblique view of south IES 02 (SC02). This 3D scene with no vertical exaggeration has been produced from a HiRISE DTM and the associated orthoimages (ESP_057571_1245 / ESP_057782_1245). **B –** CaSSIS color image (MY36_019654_301, RGBwPAN) of SC02 at Ls = 212.1° showing the depression with the retreat ridges, and the bluish scarp highlighted by seasonal CO_2 frost.

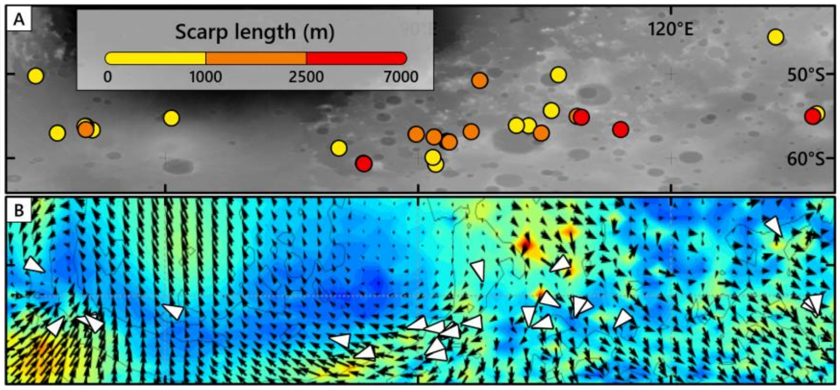

Fig. 2: A - Distribution of 51 IES in Promethei Terra. **B** - Downslope direction of the hillslope hosting the IES (white arrows) overlaid on a wind direction map at Ls=120°, from the Mars Climate Database [13, 14].

Promethei Terra with only two outlier-IES located in southwest Argyre.

Topographic context. We find that IES mostly occur on 3° to 15° slopes. Furthermore, IES depressions are located either at the boundary between a gentle slope (e.g. crater floor) and a steeper slope (e.g. crater wall), or at the transition between the upper concave slope and the lower convex slope.

Also, we find that the downslope direction of the hillslope hosting the IES broadly aligns with the current winter wind direction (Fig. 2). Because the regional pattern of past atmospheric circulation for higher obliquities remains broadly similar to the current pattern around Hellas [13, 14], we cannot constrain whether this relationship is linked to current or a past wind direction.

Depression depths. We find that the deepest IES depressions exceed 150 m and are located in the southern hemisphere. On average, northern hemisphere IES depressions are 72 m deep, *vs.* 113 m for southern hemisphere ones. Shallow IES have bedrock at the bottom, and so indicate areas where ice-rich deposits are thinner.

Layers. Analysis of the exposed layers reveals that their geometry and thickness vary greatly from one IES to another, even when the IES are only a few kilometers apart. The thinnest and most complex layering is only observed in the southern hemisphere. Our preliminary measurements on these IES with thin layers reveal typical spacings of 4-8 m. Layers are regularly spaced, and are observed to slightly warp around rocky obstacles and infill depressions. Their variable dip angles are suggestive of niveo-eolian deposits [15].

Discussion: IES at the global scale are located in regions predicted to have: i) high ice accumulation rates and volumes according to climate model studies [1], and ii) subsurface ice located closest to the surface, as indicated by thermal observations [16]. Areas of high ice accumulation may be the regions where the LDM would be the thickest. At a smaller scale, the position of the IES within their host hillslopes and the correlation with wind direction suggests that these are local areas of maximum ice accumulation. If we assume an atmospheric origin (snow/dust deposition) for the ice, leeward slopes should accumulate thicker drifting snow/ice. Our estimates show this drift could be >180 m thick. The snow-drift hypothesis is also consistent with the layering we observe in the IES, which shares notable similarities with niveo-eolian deposits. This drifting hypothesis suggests that the thickness of the LDM should be highly variable depending on the local context (e.g. slope and aspect), and this is a key consideration if this ice is ever to be used as a resource for human exploration of Mars.

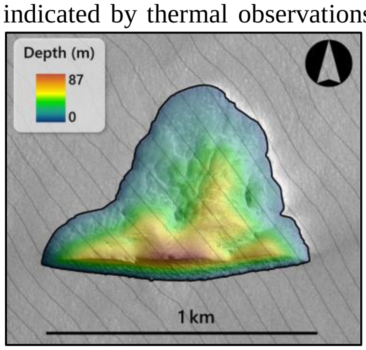

Fig. 3: Depth of an IES depression at 148.1°W, 54.2°N. The deepest point is at the base of the scarp. 10 m contour lines show the interpolated paleo-topography.

Conclusion: Based on our observations of IES, we suggest an atmospheric wind-drifted origin for the ice in the LDM with alternating snow and dust layers depending on climate forcing. We suggest that the LDM has a highly variable thickness, for example hillslopes in Promethei Terra can have thicknesses from 51 m to 186 m. This implies spatial variability in the internal structure of the LDM which is a key factor to consider for using LDM ice as a resource for human exploration of Mars.

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