# DEVELOPMENT AND EVOLUTION OF EXPOSED ICY LAYERS AT MARS' NORTH POLE THROUGH SPACE AND TIME.

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**Introduction:** One of the main open issues in Mars cryospheric science is that of characterizing the mass balance of the polar ice deposits, a critical step to interpret the record of climate preserved within them [1]. Current knowledge of the exchange of $H_2O$ and dust between the surface and atmosphere is not yet sufficient to explain whether the North Polar Layered Deposits (NPLD) are experiencing growth or loss at present-day. Transport of water and dust onto/out of either polar cap is variable spatially and temporally on seasonal to decadal and longer timescales, and the processes driving this variability are not well understood. Characterizing the modification of the present-day polar cap surface is an indispensable step in deciphering the cap's complex evolution, and thereby interpreting the environmental records preserved within.

Combining observations and modeling, we investigate the processes and factors contributing to the evolution of the north polar cap in an attempt to gain insight into recent amounts of sublimation at the north pole. Specifically, we use sites within the spiral troughs that dissect the NPLD [2], which exhibit lateral and vertical variations in the layers, to disentangle the effects of slope, slope aspect (i.e., orientation), and layer properties on the ice stability.

**Study site:** We examine a unique trough site, N0 (Fig. 1) [3, 4], which is mantled by dust to the west but is dust-free to the east, with gradational dust coverage in-between. The dust-free east wall has a steeper slope with an average MOLA derived slope of 6°, and aspect 112° from north, while the dust veneer-covered west wall has an average slope of 3° and aspect of 84° (Fig 1). Overlapping CTX and HiRISE observations show the dust veneer is perennial between Mars Years 28–34 [5] at this location. The nature of this trough site offers a unique opportunity to investigate the cause of variability across layers and its effect on polar trough evolution if extrapolated over longer timescales.

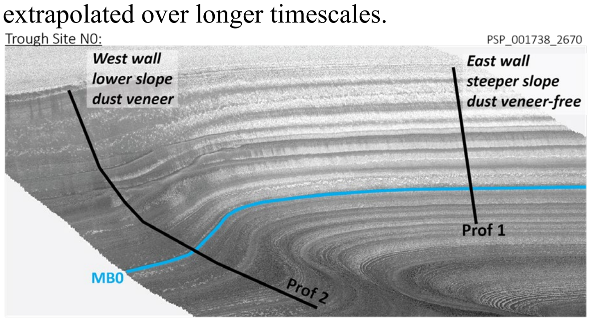


*Fig. 1.3D Northeast view of N0 (87.1N, 92.8E) from a HiRISE DTM (V.E. 7x). Traced in blue is MB0, which is the first MB identified by [6]. Black lines trace our east and west profiles.*

**Observational evidence for laterally nonuniform ice loss:** The dark-toned, regionally traceable layers of the NPLD, known as marker beds (MBs) [3,4,6], are characterized by their ablation-resistant nature (thought to be due to higher dust content, and protective, indurated lag [7,8]). This causes the MBs to protrude from the trough wall relative to the lighter-toned layers that typically sandwich them [4,7,9].

We use the difference in the erosional resistance between layers to calculate vertical protrusion profiles (protrusion normal to surface vs. elevation), similar to those in [2,4]. Protrusion profiles were derived from elevation profiles taken near perpendicular to layer strike from HiRISE Digital Terrain Models (DTM), (Fig. 2). For details on the protrusion profile method and analysis at N0, see [10].

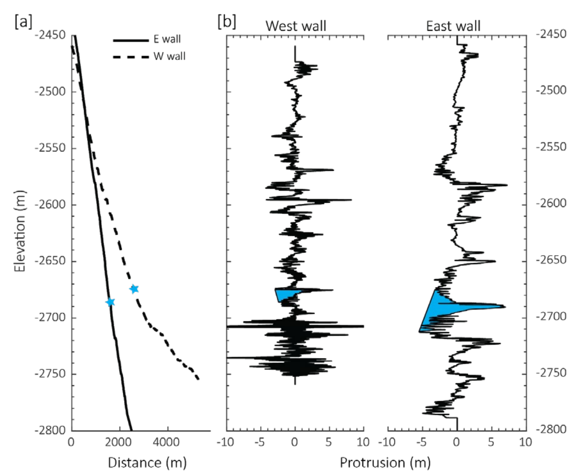


*Fig. 2. [a] HiRISE DEM elevation profiles from the east and west wall sites (see Fig. 1). [b] Protrusion profiles derived from the elevation profiles in [a]. Blue = MB0 location for reference.*

We found that protrusion gradually but significantly decreases for the stratigraphically lower MBs from east to west [10]. These MBs (MB1, MB0, MB-1, MB-2, MB-3, [4]) exhibit a decrease of ~5.5m, 4m, 4m, 3.5m, 2.5m, respectively [10]. The lateral change in protrusion is a function of the erosional resistance of the MB (controlled by dust content and induration) and the total sublimation difference between the MB and the bounding, lighter-toned strata. Wall orientation and slope, and dust cover – and thus, albedo – contribute to the spatially nonuniform ice sublimation. However, it remains to be disentangled whether the driving factor is the trough topography or the persistent dust presence, as well as when, or how long it took for the lateral difference in layer expression to occur from these observations.

We test the hypothesis that the lateral change in dust cover at this site is due to the change in slope and orientation (aspect angle) of the trough wall. These properties affect the amount of solar insolation imparted on the surface and, therefore, the ice's stability. As ice sublimates, the dust embedded within it gets left behind, growing a "lag" deposit on the surface. We also test whether the dust veneer originated via deposition through aeolian from the atmosphere or via erosion of layer lag and in-situ redeposition downslope.

**Modeling sublimation:** To assess ice stability, we use a 1-D semi-implicit thermal conduction model that simulates surface energy balance and transfer of heat between subsurface layers. We then calculate the amount of ice that would sublimate from the trough wall following [11, 12] and simulate forced convection by winds, with a nominal wind speed of 10 m/s (consistent with measurements by [13]). Sublimation of ice also leads to growth of the lag, implemented following [14], which insulates the underlying ice and makes it harder for further sublimation to occur. Additional details about the calculations in the model can be found in [11, 15].

To understand the processes that lead to layer protrusion and the cause of lateral variability, we model ice stability between the east and west wall locations. This was done by modeling the sublimation for two different layer types at each wall, as illustrated in Fig. 3. Locally near this marker bed, the slope (derived from the HiRISE DTM) is 11° along the east wall and 6° along the west wall. We analyze ice stability and amount of sublimation at present-day and throughout the last 500 kyr using orbital solutions from [16].

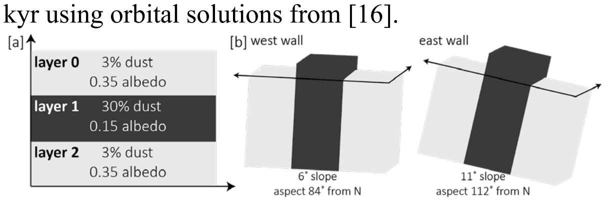


*Fig. 3. [a] 2D cartoon representation of the initial layer properties assumed in the 1-D semi-implicit thermal conduction model. Layer 1 is akin to MB0 in Fig. 1 & 2, [b] 3D cartoon representation of layers exposed on the west side (Fig. 1 – Prof. 2) and east side of the trough wall (Fig. 1 – Prof. 1).*

**Model results:** Figure 4 shows the results of modeling the sublimation of the layers along both walls (dashed vs solid lines). We find that under nominal conditions, at present-day, ice along the trough wall is very stable. This remains true for both east and west walls even when the wind speed is increased to 20 m/s, the highest values reported in [13]. This result suggests that the difference in slope and aspect between the two areas does not significantly affect the amount of sublimation.

While we find that the ice has been very stable in the recent past, there have been times (corresponding to higher obliquities) when the layers could have undergone meaningful amounts of sublimation. Albedo plays an important role, with Layer 1 experiencing an order of magnitude more sublimation than the other layers. At 379 ka, we find Layer 1 would sublimate ~7 cm/yr and Layer 2 ~7 mm/yr. Over 100 years, the observed difference in relief between layers (the protrusion) could be generated. The difference could also, for example, be created in ~600 years as recently as 79 ka.

These results, however, raise more questions than they answer. If solely due to differential sublimation of exposed surface ice, the model results show the brighter (and more stable to sublimation) Layers 0 and 2 should be protruding, which is the opposite of what is observed in the protrusion profiles.

Lastly, because the east wall is oriented more southward, it experiences more direct insolation, and thus more sublimation and corresponding lag growth. However, the west wall is the one with the dusty veneer coating it. Therefore, we rule out the hypothesis that the veneer was formed in situ as a dust lag.

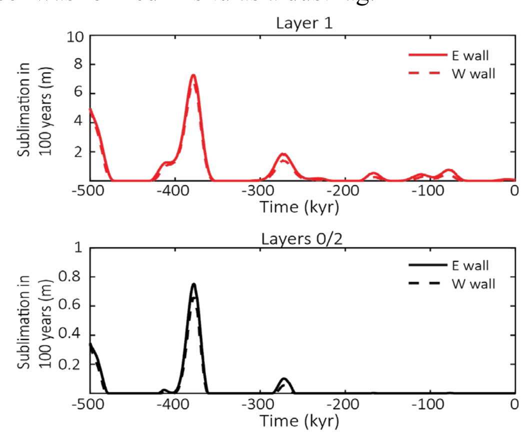


*Fig. 4: Amount of sublimation modeled to occur over 100 years on exposed icy layers at each of the orbital conditions of the past 500 kyr (0 is at present-day).*

**Outstanding Questions and Future Work:**

Additional processes must be at play to explain the disparities between the model and observations. We find that a lag deposit on the order of mm to cm can easily form during one the instability bursts, which would shut down any further sublimation (unless the lag is occasionally removed). Understanding the processes and timing for possible alteration to the lag or perennial veneer development will be important to deciphering the role sublimation plays in altering the polar landscape.

**References:** [1] Becerra, P., et al. (2020) Nat. Astro. 4, 566; [2] Smith, I. B. & J. W. Holt, (2010) Nature, 465; [3] Fishbaugh, K. E., et al. (2010) GRL, 37; [4] Becerra, P., et al (2016) JGRP, 121; [5] Clancy, R. T., et al. (2000) JGR, 105; [6] Malin, M. C. & K. S. Edgett (2001) JGRP, 106; [7] Becerra, P., et al. (2017) GRL, 44; [8] Hvidberg, C. S., et al. (2012) Icarus, 221; [9] Fishbaugh, K. E., et al. (2010) Icarus, 205; [10] Pascuzzo, A. C., et al. (2020) LPSC, 51, abs#2914 [11] Bramson, A. M., et al (2019) JGRP, 124; [12] Dundas, C. M. & S. Byrne (2010) Icarus, 206; [13] Smith, I. B. & A. Spiga (2018) Icarus, 208; [14] Schorghofer, N. (2010) Icarus, 208; [15] Bramson, A. M., et al. (2017) JGRP, 122; [16] Laskar, J., et al. (2004) Icarus, 170

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