RADAR-STRATIGRAPHIC AND MODELING EVIDENCE FOR GROWTH AND EPISODIC RETREAT OF THE NORTH POLAR LAYERED DEPOSITS, MARS.

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Introduction: The North Polar Layered Deposits (NPLD) of Mars have long been considered to contain an important record of recent climate; however, age constraints and links to orbital forcing have not been established. Orbital radar sounding has provided a new ability to probe the interior of polar deposits on Mars. A few of the many long-standing questions [1] regarding Planum Boreum have now been answered as a new perspective on its long-term evolution has emerged. These advances have come about primarily from examining large-scale stratigraphic relationships previously hidden from view, combined with decades of previous studies that provide critical context.

It is increasingly evident that the NPLD have been shaped by the same processes acting today, namely deposition and erosion resulting from surface-atmosphere interactions. Paleoclimate modeling can link changes in orbital parameters to atmospheric conditions and surface temperatures in order to predict the temporal and spatial patterns of ice accumulation. We show that the overall accumulation history of the NPLD as represented by the internal radar stratigraphy is, to first order, consistent with a model that produces a north-polar ice mass with evidence for two major retreat episodes. This is a modified version of a recently-published ice-growth model [2] that only produces a stable north-polar ice mass after 4 Ma.

Radar Sounding: Radar sounding by SHARAD on Mars Reconnaissance Orbiter [3] has enabled the mapping of the uppermost surface of the basal unit (BU) [4,5] and internal structure of the overlying NPLD [4,6]. While bulk composition has been constrained by radar to be ~95% water ice [4,7], radar reflectors are assumed to arise from variations in dust content that impact the dielectric properties of the layers [6,8].

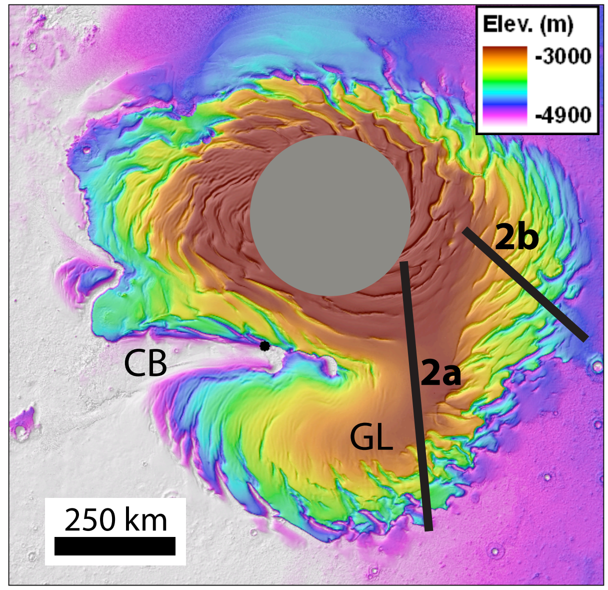

Figure 1. Shaded-relief Planum Boreum surface derived from MOLA data. GL = Gemina Lingula; CB = Chasma Boreale. SHARAD profiles shown in Fig. 2 indicated with solid lines.

Dominant Processes: Ice flow has previously been proposed as a significant factor in shaping the overall morphology of Gemina Lingula (GL; Fig. 1) [9-11]. However, the analysis of internal radar stratigraphy including a 3-dimensional flow model contradicts this [12]. Deformation by glacial flow therefore appears to not have impacted stratigraphy in a signifi-

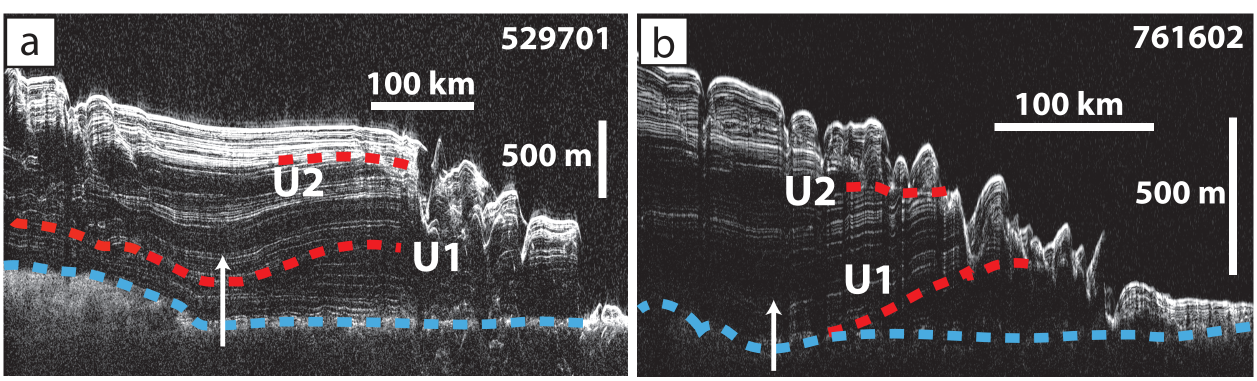

Figure 2. Representative SHARAD data from the NPLD showing the major stratigraphic unconformities. (a) observation 5297, and (b) observation 761602. See Fig. 1 for locations. Base of NPLD indicated with dashed blue line. Major stratigraphic unconformities indicated with dashed red lines. Vertical arrows point to infilling (thicker layers) of the now-buried chasma that was created during the U1 hiatus. Truncated layers on outer margin (right side, Fig. 2a) indicate retreat of ice cap southern margin, likely during most recent erosional episode.

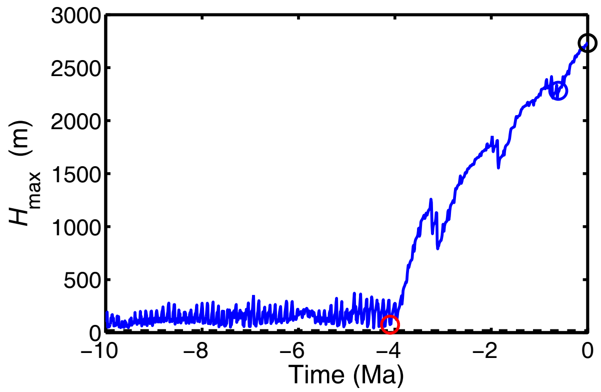

Figure 3. *Growth of north polar ice as predicted by MAIC-2 model [2]. Note presence of large erosional events at ~ 3.2, 1.9 and 0.7 Ma.*

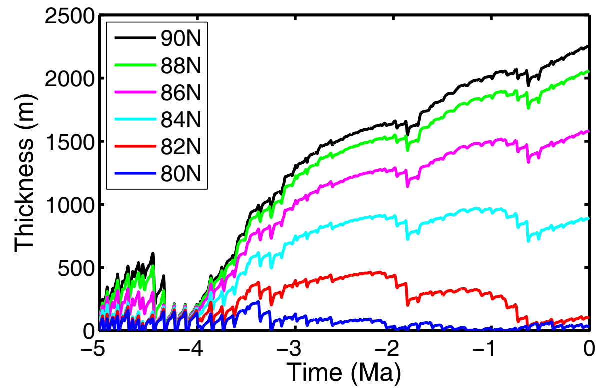

Figure 4. *Results of MAIC-2 model (only past 5 Myr shown), under assumption that only north polar ice volume is exchanging with atmosphere starting at 10 Ma. Ice thickness shown for discrete latitudes between 80°N and 90°N. Erosional event at ~ 3.2 Ma is less prominent, while those at ~1.9 and 0.7 Ma are more still significant.*

cant way. This is in contrast to mid-latitude glacial features that have clear viscous-flow morphologies [13-15] and are estimated to be at least 100 Myr old and therefore have experienced extreme variations in obliquity [16]. Lack of significant NPLD flow provides a different constraint on its thermal history.

Likewise, there is no evidence yet identified in radar stratigraphy to support basal melting of NPLD from enhanced geothermal flux or brittle deformation on large scales. Furthermore, sedimentary structures indicate that aeolian processes have played a major role throughout PB's history. This is clearly a dominant force at work both within the basal unit [17] and in the uppermost NPLD.

In the higher portions of the NPLD, stratigraphic structures indicate the first appearance of spiral troughs and their subsequent migration during deposition ([18], Fig. 1b). This process appears to have continued until the present. This finding and the unique inter-trough stratigraphy negates hypotheses relying on recent incision to create the troughs and supports an origin with katabatic winds as a critical driver [19].

Accumulation History: Stratigraphy within the NPLD indicates the dominance of processes that are sedimentary in nature; therefore we use large-scale stratigraphic unconformities to define the major depositional sequence boundaries. At least three large-scale depositional sequences are preserved (Fig. 2), each of which is bounded by an erosional event [20]. The lower of these (U1; Fig. 2) is mapped across Planum Boreum to reveal the early appearance of Chasma Boreale [21]. A higher unconformity found in the saddle region east of Chasma Boreale indicates a later period of regional erosion (U2; Fig. 2). In both instances, the lateral extension of reflectors bounding these unconformities are conformal under the main lobe of Planum Boreum, indicating that these erosional epochs may have been relatively short-lived and limited in extent.

Evidence does, however, exist for significant retreat of the NPLD margin in the region of Gemini Scopuli prior to the most recent episode of deposition. This may be coeval with the erosional event that created the uppermost unconformity.

Overall, the stratigraphy indicates a relatively simple accumulation history, with continuous deposition in the center of the deposits and either two or three large-scale (but relatively brief) hiatuses interrupting deposition and creating erosional surfaces in the lower latitudes of Planum Boreum. The youngest spiral troughs initiated above the upper unconformity, but some are older, indicating that the conditions required for trough formation are not necessarily connected to net deposition or erosion. This is consistent with a cyclic step model for troughs [22].

Climate Modeling: A latitudinal model of Martian surface temperature, atmospheric water transport and surface glaciation was developed (MAIC-2; [2]) to estimate global surface-ice mass balance for the past 10 Myr. This model uses as input the periodic changes in insolation derived from predictions of Mars' orbital parameters [16]. Maximum ice thickness at the north pole is shown in Figure 3, demonstrating that a positive accumulation is not achieved until after 4 Ma. This is due to mean obliquities higher than ~35° prior to ~ 5 Ma, and entirely consistent with previous modeling results indicating a similar age for the north polar cap [23]. Significantly, the model predicts three large-scale erosional events that interrupt relatively continuous accumulation in the past 4 Ma (Fig. 2).

We modified the modeling scenario of [2] in a few ways to further investigate this relationship. The primary modification was to assume that the NPLD has dominated the planetary water budget for the past 10 Myr. This was based on evidence for both the basal unit of Planum Boreum and the SPLD being much older than the NPLD [24] and therefore largely sequestered prior to 10 Ma. We used an NPLD volume determined by mapping the base of the NPLD with SHARAD [4,5] and differencing from the current surface. This volume was 803,550 km^3.

We also introduced a slight bias toward deposition in the northern hemisphere, based on the topographic gradient that influences Hadley cell circulation. The results of this modified scenario are shown in Fig. 4. This shows that the basic evolution including timing is the same, but there are differences. A significant buildup of ice just prior to 4 Ma exists but does not persist, and the oldest of the three retreat events is diminished in amplitude. The younger two, at ~1.9 and ~0.7 Ma still exist in the model. This is, to first order, highly consistent with our finding of at least two large-scale erosional events within the internal stratigraphy of the NPLD.

It is also clear from the variation of modeled ice growth with latitude (Fig. 4) that the effects of these erosional events are stronger below 86°N than at higher latitudes, although erosion is apparent even to 90°N. The model slightly over-predicts current surface temperatures at high latitudes [2] so this effect could result in an overestimate of modeled sublimation rates nearest the pole.

Future work: Quasi-periodic sub-sequences within the NPLD's major depositional sequences are indicated by groupings of radar reflectors into "packets" (Fig. 2a) as well as the reflectors themselves which often have very regular spacing. If the first-order correlation with the model holds, then these sub-sequences should correlate to smaller fluctuations in insolation parameters that impact atmospheric dust content. The dynamics of dust entrainment, transport and deposition are complex and poorly understood, but this is an important area of future work to further refine the correlation between modeled ice deposition and observed stratigraphy. Latitude dependence on accumulation patterns observed with radar stratigraphy can provide further constraints for modeling [24].

Conclusions: The internal radar stratigraphy of Planum Boreum contains a rich record of deposition, erosion, aeolian processes and compositional variations that can be linked to past climatic conditions through modeling. Significant challenges remain for such an effort, but the observed radar stratigraphy is consistent with a fairly straightforward model predicting northern polar ice growth and retreat episodes with net accumulation beginning after 4 Ma.

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References: [1] Fishbaugh, K.E. et al. (2008) *Icarus*, 196. [2] Greve et al. (2010), *PSS*, 58. [3] Seu, R. et al. (2007) *JGR*, 112. [4] Putzig N. E. et al. (2009) *Icarus*, 204. [5] Brothers, T.C. et al. (2010), *LPSC 41*, Abs. 2590 [6] Phillips, R.J. et al. (2008) *Science*, 320, 1182. [7] Grima, C. (2009), *GRL*, 36. [8] Nunes, D.C. and Phillips, R.J., (2006) *JGR*,111 [9] Fisher, D.A. (2000), *Icarus*, 144, 289-294. [10] Pathare, A. and D. Paige (2005), *Icarus*, 174. [11] Winebrenner et al. (2008), *Icarus*, 195. [12] Karlsson, N.B. et al. (2011) *GRL* 38. [13] Carr, M.H. and Schaber, G.G. (1977), *JGR* 82. [14] Squyres, S.W. (1979), *JGR* 84. [15] Holt, J.W. et al. (2008), *Science* 322. [16] Laskar, J. et al. (2002), *Icarus* 170. [17] Kocurek, G. et al. (2011), *5th Mars Polar Conf.* [18] Smith, I.B. & Holt, J.W. (2010) *Nature* 465. [19] Howard et al. (1982) *Icarus* 50. [20] Steel, L.E. & Holt, J.W., *43rd LPSC*. [21] Holt, J.W. et al. (2010), *Nature* 465. [22] Smith, I.B. et al. (2011), *43rd LPSC*. [23] Levrard et al., (2007), *JGR*, 112. [24] Tanaka K. L. et al. 008) *Icarus*, 196. [25] Cowan, T.C. & Holt, J.W., *43rd LPSC.*