EVIDENCE FOR ICE FLOW AND SUBSEQUENT, RAPID TROUGH FORMATION ON THE MARTIAN NORTH POLAR LAYERED DEPOSITS.

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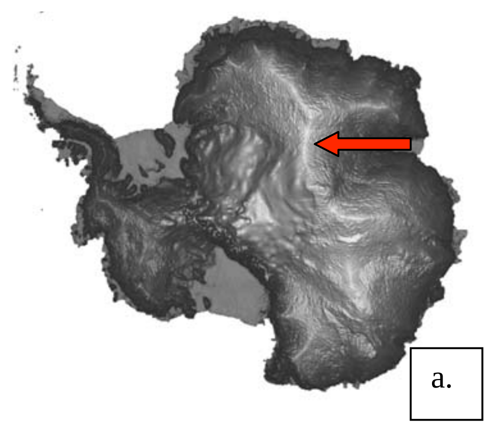
Introduction: How ice flow and mass exchange have shaped the Martian north polar layered deposits (NPLD) is a fundamental, open question. This question can be addressed quantitatively by solving an ice flow inverse problem to interpret topographic and stratigraphic data from the NPLD. Solution of a flow inverse problem estimates ice cap parameters and climatic forcing by incorporating observed characteristics into an ice-flow model. This stands in contrast to the solution of a forward model, which uses an ice-flow model to predict ice cap characteristics using specified parameters and forcing.

We focus here on inferences from the Mars Orbiter Laser Altimeter (MOLA) digital elevation model (DEM) on the lobe of NPLD that bounds Chasma Boreale to the south, to which we refer as Titania Lobe (cf. [1]). We examine topography exclusively outside the prominent troughs that incise the lobe, i..e, inter-trough topography. We consider possible ice flow paths along gradients of a surface defined by the inter-trough topography and interpolation across the tops of the troughs.

We find that surface topography on a broad swath of such paths conforms, with high accuracy, to the topography that would be expected for a flowing ice mass. However, the ice flow model that reproduces inter-trough topography would also require ice to fill and flow in the spaces where troughs currently incise the ice cap, i.e., in spaces that are today occupied by the Martian atmosphere. We therefore infer that the troughs must post-date the deposition of the inter-trough material and its modification by flow.

Furthermore, the ice-flow model implies accumulation near the ridge of the lobe and ablation near the base, without the concentration of ablation in present-day trough locations that seems necessary to explain the latter. Thus we infer a fundamental shift in dominant mechanisms, or at least components, of mass balance on the lobe. Finally, because trough-formation has apparently altered the inter-trough topography very little, we infer that the process of trough formation must be rapid in comparison to the (still unknown) time-scale of ice flow since troughs began to form.

Methods: Ice divides are boundaries separating regions of flow in different directions. Their locations, or their absence, are key features on any ice cap. Surface slopes tend to be low and slowly varying along terrestrial ice divides, and divides tend to be lines with low curvature in map view. Experience with terrestrial ice caps shows that divides are revealed effectively by shading digital elevation data to emphasize regions that are simultaneously high in elevation and low in slope [2,3] (Figure 1a). Such shading of the MOLA DEM of the NPLD reveals an apparent ice divide along the ridgeline of Titania Lobe (Figure 1b).



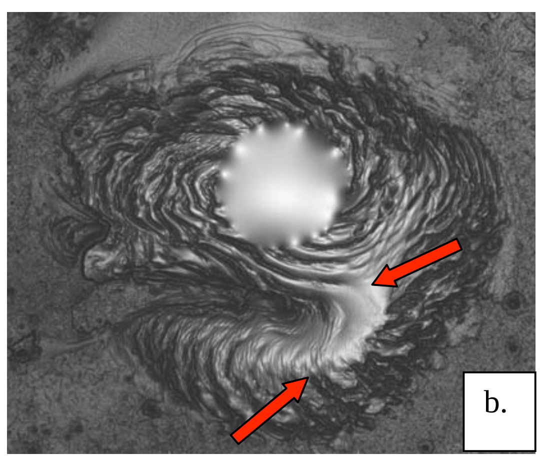


Figure 1. (a) Digital elevation data from the ERS-1 radar altimeter for Antarctica[2], shaded to highlight areas that are both high in elevation and low in slope. Arrow indicates one ice divide among several visible. (b) MOLA digital elevation data for the NPLD shaded identically to those in part a. An apparent ice divide on Titania Lobe is indicated by arrows.

We identify likely flow lines (if ice flow has, in fact, occurred) by following the surface gradient on a surface derived from the inter-trough topography by interpolating across the tops of the troughs and smoothing the result. Specifically, we remove troughs by excluding parts of the surface with slope larger than 0.015 radians, as well as the lower-slope areas at the bottoms of troughs. We then interpolate linearly across gaps in the resulting surface (Figure 2a). and smooth the result on scales up to that of typical trough widths (roughly 40 km). Elevation contours on the smoothed surface closely match those of the original MOLA data for locations on the inter-trough surface (Figure 2b). Figure 2c shows 51 gradient paths on the interpolated, smoothed surface overlain on a shaded-relief presentation of the MOLA-observed topography.

Of the 51 paths, 40 climb toward the divide shown in Figure 1b with smoothly, monotonically decreasing separations that appear highly analogous to similar paths on terrestrial ice sheets. Those paths cover a broad swath of the lobe starting on the chasma side of the tip and including all of the terrain where inter-trough topography spans a wide range of elevations. The remaining 11 paths are those nearest to 0 degrees longitude, where inter-trough topography extends down only to about -3900 m elevation on the MOLA datum (1200 m above the planum beneath Titania Lobe). Separations between these flow paths widen and narrow several times as they climb toward the divide, and are particularly variable at locations of troughs in the actual topography.

Surface topography is more sensitive to ice dynamics than to the spatial distribution of surface mass balance [4], and thus yields information only on the gross pattern of accumulation and ablation. We therefore assume, along each flow line, an ice flow model with uniform, steady-state accumulation from the divide to an equilibrium-line location (to be determined), and uniform, steady-state ablation from that location to the cap edge [4]. We assume the ice-flow law to be a power-law with exponent n, which we take as a parameter. We combine these elements with assumed constant-elevation basal topography (based on MOLA observations surrounding the cap).

The topographies computed from this model cannot reproduce the short-scale topography between troughs, which is presumably due to more complex patterns of mass balance than can be diagnosed from topographic data alone. We therefore fit the model to inter-trough topography in a least-squares sense, doing so along each flow line independently. Each fit yields an independent estimate of the flow-law parameter, n, and the equilibrium-line location on that flow line.

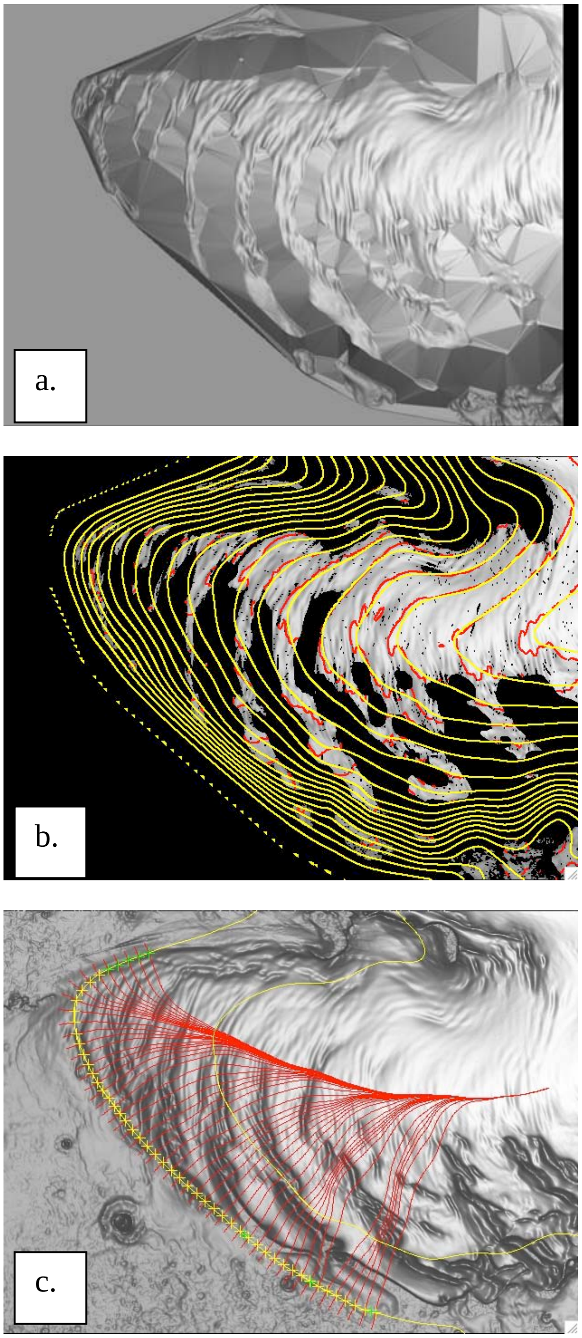


Figure 2. (a) DEM of our study area on Titania Lobe after exclusion of points where slope exceeds 0.015 radians (which excludes troughs) and low-slope areas at the bottoms of troughs, followed by linear interpolation across the tops of the troughs. Compare this surface with the corresponding region in Figure 1b. (b) Elevation contours (at 300 m intervals) of the interpolated and smoothed surface, in yellow, compared with corresponding contours of the MOLA DEM, in red, on inter-trough topography (only). (c) 51 gradient paths on the interpolated, smoothed surface shown overlain on the MOLA-observed topography, shaded as in Figure 1b. These paths are spaced at 12-km intervals (marked by +'s) along the elevation contour 200 m that is above the surrounding planum i.e., -4900 m. The higher elevation contour is 1200 m above the planum (i.e., -3900 m).

Results: Of the 40 paths that converge monotonically toward the divide, the ice-flow model fits the observed inter-trough topography to within an rms difference of 10-26 m, over elevation ranges of 1600-1800 m, in 39 cases. (The remaining case, in which the difference is 32 m rms, is the path most closely neighboring the irregular paths.) Figure 3 shows two representative examples.

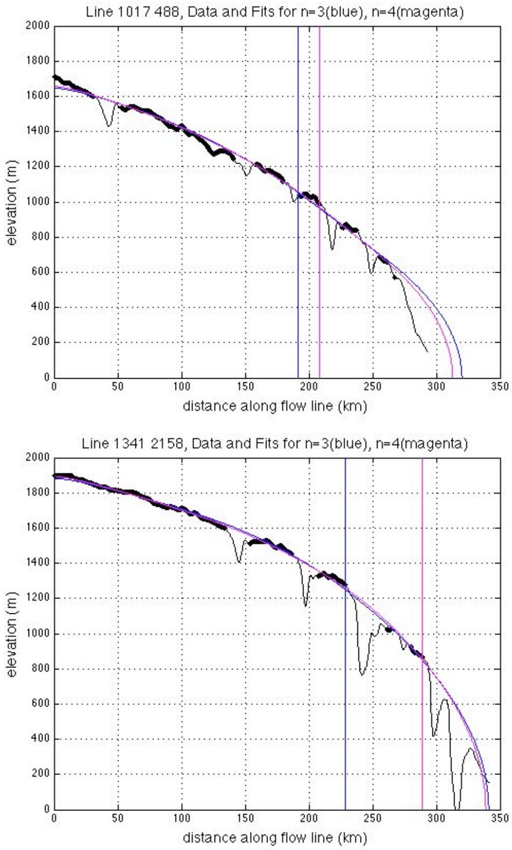


Figure 3. (a) Plots of MOLA-observed elevations as a function of pathlength along a gradient path near the tip of Titania Lobe (thin black line), inter-trough topography (thick black line), and fits of the ice-flow for flow-law exponents 3 (blue) and 4 (magenta). Elevations are in meters above -5100 m, which we take to be the elevation of the base of Titania Lobe. Vertical lines in corresponding colors mark the estimates of equilibrium line position. The rms differences between inter-trough topography and model fits in this case are 22m for n=4 and 26m for n=3. (b) Corresponding plots for a gradient path on the flank of the planum side of Titania Lobe. The rms differences in this case are 12m for n=4 and 15m for n=3.

Most significantly, the model fits on each of the 40 independent profiles yield consistent estimates of the flow-law exponent, *n*, in a range of 3-4. Estimates of equilibrium positions are the least well-determined by model fits (i.e., the solution of the inverse problem yields the least resolution of this parameter), but the inferred positions are nonetheless roughly mutually consistent (Figure 4).

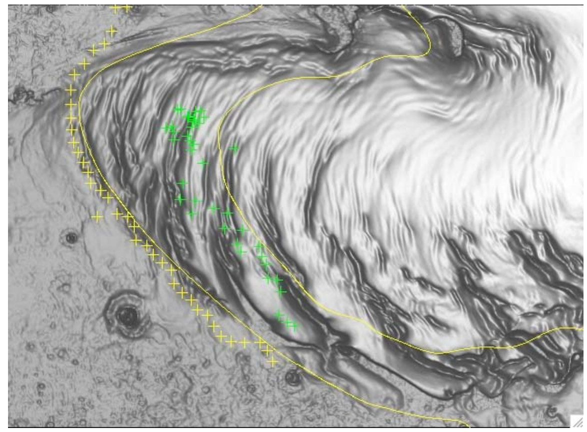


Figure 4. Positions of inferred equilibrium line positions (green +'s) and terminus positions along ice-flow paths at the time when inter-trough topography was formed (yellow +'s), for model fits with n=4.

This consistency in independent fits on 40 separate profiles is strong evidence that the ice-flow model captures the essential physics responsible for the observed topography. By contrast, paths on parts of Titania Lobe where little inter-trough topography apparently remains do not fit our model well, as shown in Figure 5. Not only are rms differences much larger in this case, but surface and model topographies differ qualitatively (except at the highest elevations).

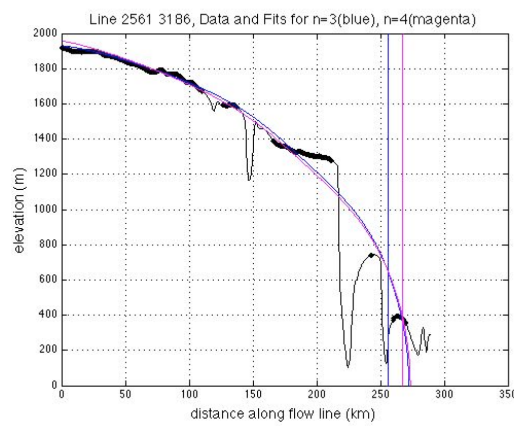


Figure 5. Plots analogous to those in Figure 3 for a irregular gradient path near 0 degrees longitude (cf. Figure 2c) on which inter-trough topography is confined to elevations above 1200m. The rms differences between models and data in this case are 44m for n=3 and 52m for n=4. The fits we obtain for paths yet closer to 0 degrees longitude are considerably poorer than this one.

Interpretation: We conclude that present-day inter-trough topography is highly consistent with steady-state ice flow in a previous era which acted to equilibrate mass accumulation at elevations largely above the present-day troughs with ablation at lower elevations, and that this flow occurred at a time when ice filled the present trough locations. We know of no other physical mechanism that could produce the inter-trough topography except for quite particular patterns of mass deposition or ablation, which would seem to be highly fortuitous. If, however, the physics in our model is responsible for the inter-trough topography, we cannot escape the conclusion that the troughs were filled with flowing ice at the time the inter-trough topography was formed, and thus that the troughs must post-date the inter-trough topography. This in turn requires a significant change in the distribution and perhaps magnitude of surface mass balances on Titania Lobe. Moreover, the ice-flow model fits inter-trough with high fidelity even down to low elevations in many cases (cf. Figure 3). This seems to indicate that troughs have incised the prior surface so rapidly, compared to the time-scale of ice flow at the time of trough formation, that subsequent flow has had insufficient time (because flow is slow, or time has been short, or both) to deform inter-trough topography significantly.

We cannot infer, at this stage, any absolute timing for the change in mass balance regime or the age of the inter-trough surface.

Future Work: The observation of stratigraphy (e.g., radar stratigraphy from MARSIS or SHARAD) could provide a strong test of the consistency of our interpretation. Our model can also be used with inter-trough topography on the main dome of the NPLD, and could be compared with recent stratigraphic work there [5].

References: [1] Pathare, A. V., and D. A. Paige 2005, *Icarus* **174**, 419-443. [2] Bamber, J.L. 2004. In: *Spatial modeling of the terrestrial environment* (eds. R.J. Kelly, N. Drake, S. Barr), John Wiley. [3] Ekholm, S. et al. 1998. *Geophys. Res. Lett.* **25**, 3623-3626. [4] Paterson, W.S.B., 1994, *The Physics of Glaciers*, 3rd ed., Elsevier Science Inc., Tarrytown, N.Y. [5] Milkovich, S.M., and J.W. Head. 2005. *JGR* **110**, E01005.