

Where Ice Flows on Mars; Where Ice does not seem to flow; Why the Difference?

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Introduction: Ice has been detected on Mars in many places, from the polar caps, to mid-latitudes. In many of the non-polar locations there exists strong evidence for glacial flow (e.g. lobate debris aprons (LDAs) [1,2], Fig. 1 and CO₂ glaciers residing in Mars' southern polar layered deposits [3], among other suspected locations). Most, if not all of these features exhibit primary and secondary features visible from the surface that are tell-tale signs of flow: convex-up axial profiles, arcuate contours, lobate toes, extended lineations - or flow lines, even crevasses and moraines for CO₂ glaciers. Questions remain about whether these features are flowing today or if they are in a flow hiatus, but there seems to be little question that they flowed to reach their current state.

This raises the possibility of flow for the polar layered deposits (PLD). Since the >2000 m thick deposits were first observed by robotic missions [4,5], speculation about the flow status of the north and south PLD have persisted. Several predictions regarding flow have been made about the composition of the PLD, and CO₂ ice was ruled out because the PLD are too thick and too old to have retained their current shape [5-7].

Other interpretations, consistent with a primarily water-ice PLD, predicted that the surface spiral troughs

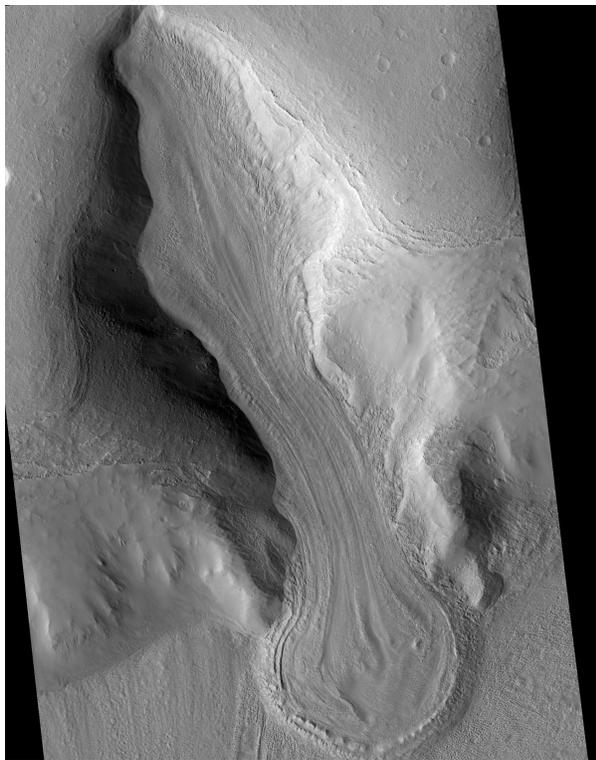


Figure 1: Evidence for past or current glacial flow on a Martian LDA. HiRISE image ESP_019358_2225.

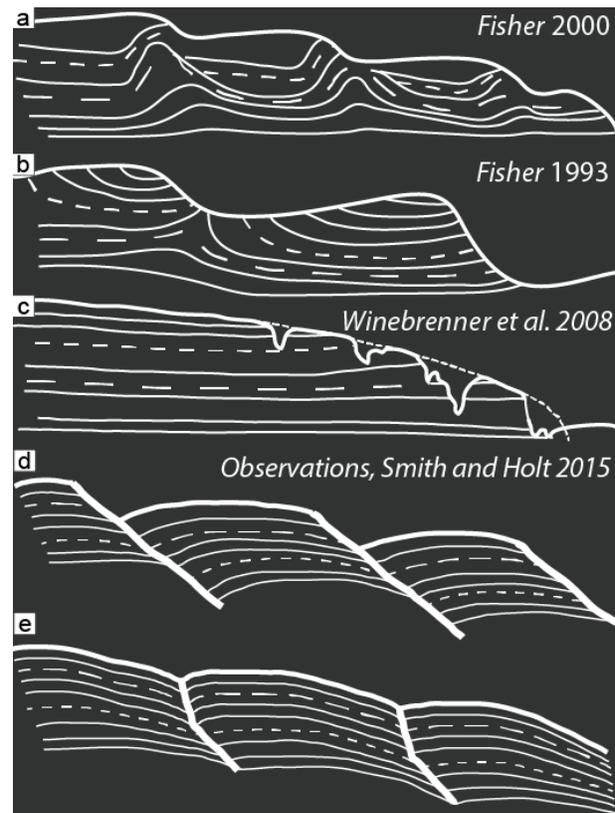


Figure 2: Stratigraphic predictions that involve flow compared to interpreted stratigraphy. a) and b) Stratigraphy used to explain the persistence of spiral troughs while the north PLD undergoes flow [11,12]. c) Predicted stratigraphy of a flowing ice sheet with spiral troughs later cut into the surface [9]. d) and e) Interpreted stratigraphy near the spiral troughs. The troughs have persisted for extended durations, and their stratigraphy is incompatible with any flow hypothesis [13, 14]).

should either close due to topographic relaxation [8], have formed after flow stopped [9] (Fig. 2c), formed during and because of flow [10], or are representative of a current flow state [11,12] (Figs. 2a and 2b). Each of these predictions has been met with observational evidence that contradicts those interpretations [13,14] (Figs 2d and 2e). [8-10] are inconsistent with long-lived spiral troughs that grow over time, and specific predictions made by [11 and 12] about the internal stratigraphy of the NPLD supporting spiral troughs were not confirmed.

This disagreement between model and observations, expounded upon in [15] has led to a general consensus that the polar ice flows more slowly than other processes acting on the NPLD. This is an acceptable inter-

pretation for the NPLD, but the SPLD surface age is 10-100 times older than the NPLD, and potentially much older yet. Slopes there are quite steep, and a maximum thickness of > 3 km should supply enough driving stress to induce flow. Even very slow processes should exhibit evidence over that long time. Yet, no evidence, either in the stratigraphy or from surface observations has been consistent with flow predictions.

One sticking point is that glaciological formulae do not allow for interpretations that the PLD do not flow at all, so perhaps something in the structure itself prevents measurable flow.

To answer this question [16] conducted rheological experiments on impurity-laden ice, at ~5%, similar to the bulk composition of the NPLD [17]. The conclusion was that, “small particle fractions and small particle sizes have a negligible effect on ice flow behavior.” In other words, impurities, such as dust, don’t slow down flow at moderate concentrations.

New interpretation: Here I posit that the polar layered deposits do not act as a single, generic ice sheet (Figs. 3a and 3b). Instead, they act as a stack of ice sheets, where each layer is separated by a boundary of dust, and all layers flow individually (Fig 3c). The dust acts as a barrier to flow and sliding, so the viscosity of the cold ice can only be expressed through lateral expansion, much like the marshmallow in Fig 4. Unlike the marshmallow, the PLD layers are on the order of 1 m thick and 1,000,000 m in breadth. Thus, marginal bulging should be minimal.

Along with a more rigorous explanation of this hypothesis, I plan to present simple laboratory experiments demonstrating the multi-layer, stacked flow hypothesis. I will demonstrate that the layers themselves flow but do not deform the entire ice sheet, as previously predicted. This allows for the PLD to retain their steep slopes and prevents many of the normally observed flow features to form.

This interpretation comes with some predictions. First, the lowermost layers experience more pressure than higher layers and should be warmer and less viscous because of the geothermal gradient. Thus, deformation at the margins of the lower levels should be greater than that at the top. I will test these scenarios using SHARAD analysis and present them at LPSC.

The major component of this hypothesis is that the dust layers hinder flow. Thus, constraining the friction coefficient, viscosity, tensile strength and compressibility of the dust layers becomes an important next step for testing the stacked, multi-layer flow scenario.

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References: [1] Holt, *et al.*, (2008) *Science* 322, 1235–1238. [2] Plaut, *et al.*, (2009) *GRL* 36, L02203. [3] Smith, *et al.*, (2016) *6th Intern. Conf. Mars Sci. and Exp.* #6072. [4] Sharp, (1974) *J. Glaciology* 13, 173–185. [5] Clark and Mullin, (1976) *Icarus* 27, 215–228. [6] Durham *et al.*, (1999). *GRL* 26, 3493–3496.

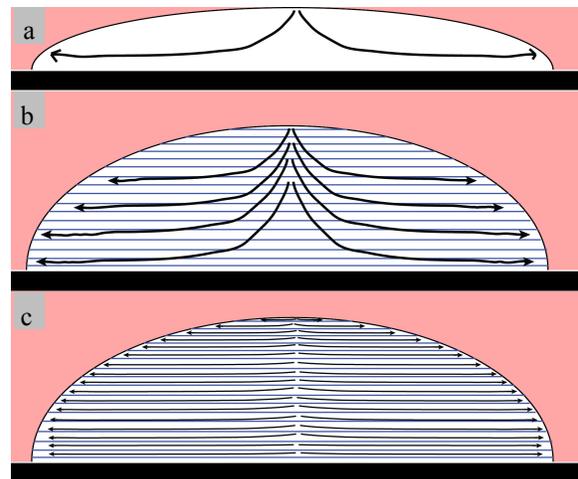


Figure 3: Flow scenarios for various ice sheets. a) Generic ice sheet. Flow spreads from center outwards. b) Long-time interpretation of the NPLD. The volume of ice flows as in (a), and the layers do not play a major role. Stratigraphy like in Fig 2a should occur when spiral troughs are present. c) Flow interpretation that includes a multi-layer, stacked composite ice sheet. Each layer flows, as would a thicker ice sheet, but communication between layers is not allowed. Very little vertical deformation can occur. Thus lateral expansion is the only form that flow can take.



Figure 4: Smore analog to individual layers in the PLD. The viscous fluid here is compressible, but vertical flow and slipping are not allowed, so lateral expansion occurs. At NPLD scales, ~1 m thickness to 1,000,000 m breadth, only minor bulging at the margins will take place.

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