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Evidence for ice flow prior to trough formation in the martian north polar layered deposits

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Abstract

The relative importance of surface mass fluxes and ice flow in shaping the north polar layered deposits (NPLD), now or in the past, remains a fundamental and open question. Motivated by observation of an apparent ice divide on Gemina Lingula (also known as Titania Lobe), we propose a two-stage evolution leading to the present-day topography on that lobe of the NPLD. Ice flow approximately balances surface mass fluxes in the first stage, but in the second stage ice flow has minimal influence and topography is modified predominantly by the formation of troughs. We focus here on evidence for the first stage, by testing the fit of topography between troughs to an ice-flow model. We find that independent model fits on distinct flow paths closely match inter-trough topography, uniformly over a broad region on Gemina Lingula, with mutually consistent and physically reasonable fitting parameters. However, our model requires ice to occupy and flow in spaces where troughs currently incise the ice. We therefore infer that the troughs (and the distribution of mass balance that caused them) post-date deposition of the inter-trough material and its modification by flow. Because trough formation has apparently altered inter-trough topography very little, we infer that trough formation must have been rapid in comparison to the (still unknown) time-scale of flow since troughs began to form. We view the evidence for past flow as strong, but we do not think that topographic evidence alone can be conclusive. Observations of englacial stratigraphy using orbital sounding radars will yield conclusive tests of our inferred mechanism for the formation of inter-trough topography.

Keywords: Mars, polar caps; Geophysics; Ices

1. Introduction

The north polar layered deposits (NPLD) are the largest surface reservoir of martian water ice that actively exchanges with the atmosphere. Their nearly complete lack of impact craters suggests that their surface is geologically young, or has been recently and extensively modified (Herkenhoff and Plaut, 2000). Alternating bright and dark layers can be seen along the walls of arcuate troughs that cut through the NPLD. This layered structure likely reflects deposition during orbitally-driven climate changes (Touma and Wisdom, 1993; Laskar et al., 2002; Levrard et al., 2007), which may have been modified subsequently, both within and between troughs. Hence, understanding the mechanics and evolution of the NPLD is necessary to decipher any evolution of martian climate recorded in the layers.

It is generally assumed that topography and layering of the NPLD are governed by two processes: ice deposition and loss at the surface (mass balance), and ice flow. However, the relative importance of these processes in shaping the NPLD, now or in the past, remains a fundamental and open question.

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To set a framework in which to discuss this question, we introduce two characteristic time scales. The first is the time required to build up an ice sheet through accumulation alone at some characteristic accumulation rate, or equivalently, to remove it by ablation alone at some characteristic ablation rate. The second is the time for material to move a characteristic distance, such as the length of the ice mass, by flow at some characteristic speed. The ratio of these two characteristic times gives a nondimensional number F, which we call a *flow number*. In Appendix A, we use conservation laws for mass and momentum together with a temperature-dependent constitutive relation for ice to derive expressions for both of these characteristic time scales and for F in terms of characteristic values of accumulation rate, temperature, and ice-mass dimensions. When $F \ll 1$, mass exchange with the atmosphere alone controls surface topography, and the ice mass is stagnant. When F is of order unity, both surface mass exchange and ice flow influence the surface shape, and the ice mass can be in a near-equilibrium state. When $F \gg 1$, ice flow alone controls surface-elevation changes, and surface mass exchanges are negligible. On Earth, surging glaciers (Kamb et al., 1985) fall in this regime. However, most terrestrial ice masses are in a near-equilibrium regime with F of order unity.

Some researchers have modeled the NPLD as a near-equilibrium regime with F of order unity. Budd et al. (1986) first modeled the NPLD as a large-scale, steady-state flow system. Zuber et al. (1998) and Zwally et al. (2000) interpreted Mars Orbiter Laser Altimeter (MOLA) data from the NPLD as supporting that view. Fisher (1993, 2000) developed a model to explain more detailed NPLD topography by incorporating flow with an alternating pattern of accumulation and sublimation resulting from local radiative effects of troughs (i.e., "accublation"). Fisher et al. (2002) found evidence in the directionality of NPLD surface texture for flow in the directions expected from large-scale topography. Modeling by Hvidberg (2003) and by Pathare and Paige (2005) also supports a role for ice flow in shaping the NPLD, especially near troughs. Nye (2000) even considered martian ice caps shaped entirely by flow in the absence of surface mass fluxes ($F \gg 1$).

However, modeled ice flow speeds on Mars are generally very slow, even during high obliquity and during NPLD formation, so surface mass balance can easily dominate flow in producing the modeled shape (Greve et al., 2004; Greve and Mahajan, 2005). Ivanov and Muhleman (2000), in fact, argue that the observed NPLD topography can be explained by sublimation alone. Fishbaugh and Hvidberg (2006) conclude that internal layers in the upper portion of the NPLD show no evidence of flow, i.e., that the NPLD are currently in a stagnant regime with $F \ll 1$.

Thus there is presently no consensus on the roles of surface mass fluxes and ice flow in shaping the NPLD as a whole. This suggests investigation of new alternatives, including a search for parts of the NPLD on which effects of relatively recent processes may be most evident. Our investigation is motivated by an examination of MOLA data shaded to emphasize regions that are simultaneously high in elevation and low in slope

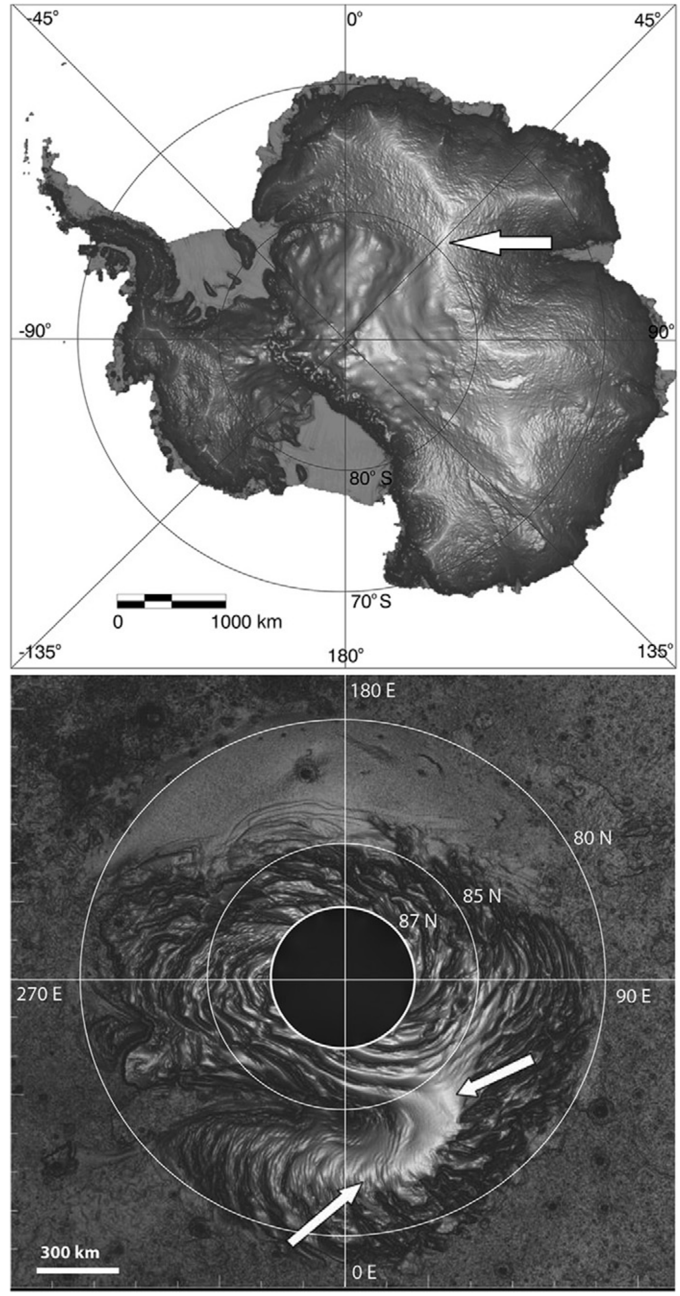

Fig. 1. (a) Digital elevation data for Antarctica, shaded to highlight areas that are both high in elevation and low in slope (Bamber, 2004). The arrow indicates one ice divide among several visible. (b) Digital elevation data from the MOLA laser altimeter for the NPLD. Here we use the 512-point-per-degree DEM, which does not include data for locations poleward of 87° N (Smith et al., 2003). Shading in this presentation is identical to that in (a). Arrows indicate a contiguous topographic feature that appears similar to ice divides on Earth.

(Bamber, 2004; Ekholm et al., 1998). On Earth, such shading effectively highlights ice divides, which are boundaries separating regions of flow in different directions. The locations, or absence, of ice divides are key features on any ice cap. Surface slopes on terrestrial ice divides tend to be low and slowly varying, and divides tend to be lines with low curvature in map view. Fig. 1 shows digital elevation models (DEMs) for