EVIDENCE FOR INTERNAL DEFORMATION AND FLOW IN THE NORTHERN POLAR CAP OF MARS: PART 1, BACKGROUND.

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Introduction: Within the northern residual polar cap of Mars are dark lanes or troughs; on the walls of these exposures are layered deposits. These deposits consist of laterally extensive layers of ice and dust and are found throughout the polar cap. They were first identified in Mariner 9 images [1, 2] and later studied in detail with Viking orbiter data [e. g. 3, 4, 5, 6, 7] and with the Mars Orbiter Camera (MOC) data from the Mars Global Surveyor (MGS) [e. g., 8, 9, 10, 11]. The polar layered deposits are thought to contain the record of recent climate change and polar history [e.g., 5, 7, 10, 11]. An understanding of the processes at work shaping the polar cap can help to interpret this climate record.

It is well-documented that terrestrial ice sheets of sufficient thickness can flow [e.g., 12, 13, 14]; if the martian northern polar cap is thick enough and the geothermal gradient at the base of the cap is high enough, it should flow as well [15, 16, 17, 18, 19, 20]. However, the strength of the cap material is not known due to the unknown proportion of dust in the polar layered deposits internal to the cap; the presence of dust can strengthen or weaken the cap material, depending on the amount of dust [21, 22]. The presence of layers deformed by flow would provide insight into the strength and behavior of the northern cap as well as the conditions and style of deformation.

In this abstract, we review the current efforts to model flow of the northern cap and outline predictions of the resulting geomorphology of the polar layered deposits. In a companion abstract, we examine the evidence for deformation and flow of the polar layered deposits.

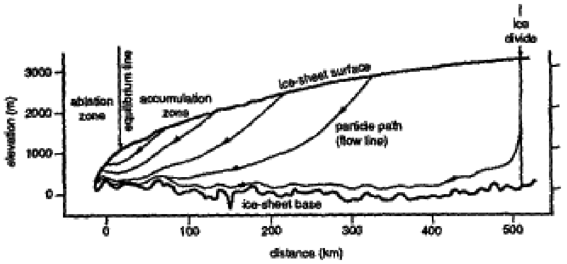

Figure 1. Behavior of material in a simple domed ice cap. Developed from an actual cross section of Greenland. From [16].

Ice Flow Models: In a simple symmetric terrestrial ice cap in temporal steady state, accumulation of ice in the center of the cap and ablation of ice at the edges are constant. Mass balance requires that ice flows from the accumulation zone to the ablation zone. Ice and other material deposited in the accumulation zone moves downward and is thinned by compression and shear flow (Figure 1). Thus, layers internal to the ice cap (for instance, dust or tephra) also get thinner and experience more shear as they get closer to the ice bed. In addition, the ice towards the very base of an ice sheet must flow over the ground surface that underlies the ice sheet; the topographic relief of this surface may distort the layers [summarized in 16].

A major difference between the simple ice cap described above and the martian north polar cap is the presence of spiraling troughs cutting into the martian cap, exposing layers of ice and dust. The walls of these troughs are much darker than the ice-covered polar flats between troughs, which has led to the theory that ablation in the form of sublimation occurs on the equator-facing slopes while deposition occurs on the bright flat areas [4, 5, 7, 16, 17]. This process may cause the troughs to migrate poleward in a conveyor-like fashion [7, 16, 17, 18]. Thus, the troughs may be moving inward on top of the ice which is moving outward [16].

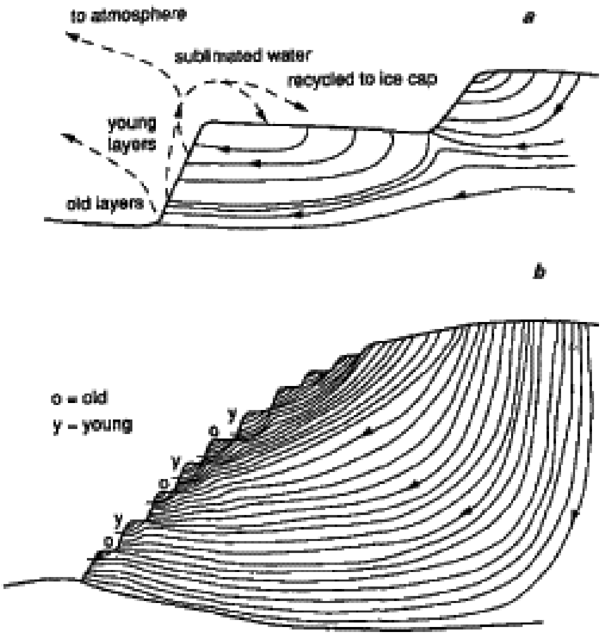

Figure 2. Fisher's model of cap flow. A) Proposed particle paths through migrating scarps. As the scarp migrates, some sublimated water vapor moves to the polar flats between troughs. Some layers have originated near troughs farther north and moved down from flow. B) Schematic cross section through the cap. A given trough wall is fed by ice laid down on the polar flat immediately above it and by ice from higher up the cap. This results in a temporal discontinuity in the layers exposed in any given trough wall. The troughs lower in elevation tend to have more layers originating from the interior of the cap. From [16].

The behavior of internal layers in such a cap is quite complex and open to several interpretations. Fisher [16] calculated the behavior of internal layers in an ice sheet with idealized trough topography assuming that the ice thickness was much thicker than the trough depth, in effect, that the trough system only involved the very uppermost section of ice cap (Figure 2). In this model, the uppermost layers in the trough walls are young layers formed from material recycled from the retreat of the trough wall; as material is removed from the trough wall, a portion is redeposited on the nearby polar flat and a new layer is formed. The troughs at the lower elevation and outer margin of the cap contain older layers which are from material deposited towards the center of the cap which has flowed out, similar to the behavior of a simple ice sheet. In effect, there is a simple ice sheet with internal layers underlying a complex ice sheet with trough topography; layers from the simple sheet are exposed at the edges of the cap and at depth. A discontinuity is expected between layers from different source regions.

Fisher [17] expanded on this theory, adding the prediction that the upper layers formed by local recycling of polar volatiles will be more disorganized and non-homogenous than the older, deeper layers. Waves in the layers are expected at depth due to the presence of the troughs; the wavelength and amplitude of these waves are a function of the rate of trough migration compared to the rate of outward ice flow.

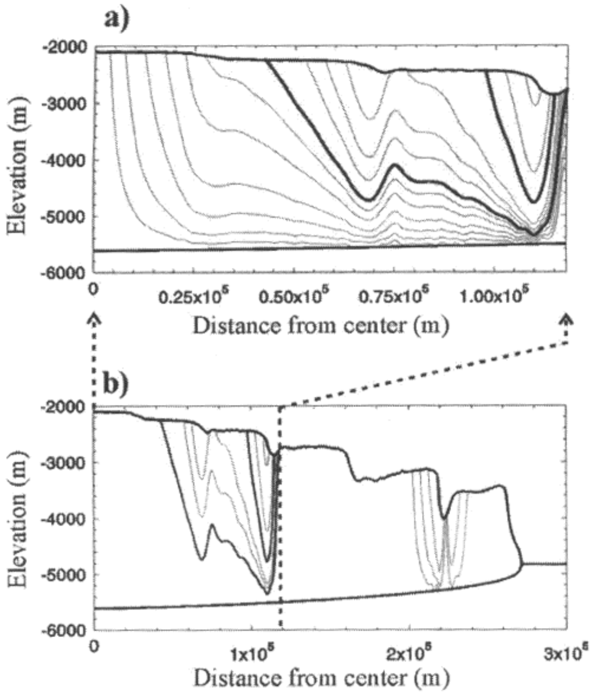

Figure 3. Hvidberg's model of cap flow. Particle paths along a topographic profile of the cap. A) An enlargement of a part of the flow line, and B) the full flow line. The presence of troughs on the surface affects the motion of the cap material all the way to the base; thus, the troughs divide the cap into discrete dynamic units. From [19].

Modeling work by Hvidberg [19] leads to another model of flow in the cap (Figure 3). Hvidberg [19] used a finite element ice flow model to calculate flow rates and trajectories assuming pure ice in the northern cap using the topographic profile of the cap measured by MOLA. She found that rather than allowing ice to flow below the trough system, the troughs separate the cap into distinct units. In this model, there is no flow between the major troughs. This is due to the fact that ice exposed in the pole-facing slopes of the troughs will either not flow at all or flow slowly towards the pole. Indeed, flow alone should smooth the troughs in less than 10^6 years; this implies that other forces such as sublimation or erosion by katabatic winds are actively keeping the troughs open.

Predictions: What kind of evidence should we be looking for to determine where, when, and how much the ice flows, in order to test these different models? Ice flows by creep, or movement within or between individual ice crystals. The rate of ice creep is a function of shear stress and is affected by impurities such as the presence of dust within the ice [20, 21, 22, 23, 24, 25]. Most creep occurs in the lower region of an ice cap or glacier where the shear stress is greatest. When the ice cannot creep fast enough to allow the ice cap or glacier to adjust its shape under stress, the ice can undergo brittle failure or fracture [13, 14, 26, 27].

Extensional zones within the ice can cause individual layers to thin (in the case of a ductile layer) or fracture (in the case of a brittle layer). A brittle layer surrounded by ductile layers will break apart, and the surrounding ductile material will flow around and into the gaps to form boudinage structures.

Compression zones within the ice can cause fold-and-thrust features similar to those found at compressive plate boundaries on the Earth [27]. Folded ductile ice can also be detatched from the underlying substrate along a bedding plane known as a décollement. The folded ice can be further deformed by overthrusting reverse faults.

The state of stress (compressional vs extensional) at the base of an ice sheet depends on whether the ice is accelerating or decelerating. This in turn depends on the thickness of the ice, the basal temperature of the ice, and whether the ice is located beneath an accumulation zone or an ablation zone. For a simple domical ice sheet, the interior regions experience extension while the marginal regions undergo compression (Figure 4) [23].

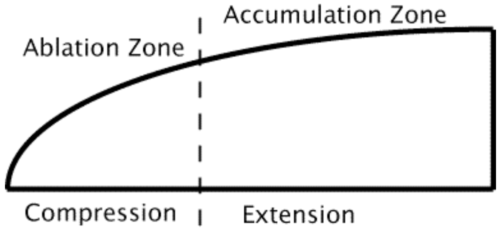

Figure 4. Location of extension and compression within a simple ice sheet. After Figure 7-1 in [23].

This simple model of ice cap dynamics (Figure 4) offers a framework for assessment of evidence for flow. We should look for evidence of flow in the northern polar cap by searching for deformation in layers near the base of the cap. The troughs which cut the deepest into the cap are located towards the cap margins; based on terrestrial experience [23], we expect that any deformation present will be due to compression.

References: [1] Soderblom L., et al. (1973) *JGR 78,* 4197-4210. [2] Cutts J. A. (1973) *JGR 78,* 4231-4249. [3] Kieffer H. H. et al, (1976) *Science 194,* 1341-1344. [4] Blasius K. R., et al. (1982) *Icarus 50,* 140-160. [5] Howard A. D., et al. (1982) *Icarus, 50,* 161-215. [6] Thomas P. C. et. al. in *Mars* [ed.by H. H. Kieffer et al] pp.767-795. Univ. of Arizona Press, Tuscon. [7] Squyres S. W. (1977) *Icarus 40,* 244-261. [8] Malin M. C., Edgett K. S. (2001) *JGR 106,* 23429-23570. [9] Kolb E. J., Tanaka K. L (2001) *Icarus 154,* 22-39. [10] Laskar J., et al. (2002) *Nature 419,* 375-377. [11] Milkovich S. M., Head J. W. (2004) submitted to *JGR.* [12] Hambrey M. J., Milnes A. G., (1975) *Ann of Glaciology 14,* 383-393. [13] Patterson W. S. (1994) [14] Benn and Evans (1998) [15] Clifford S. M. (1987) *JGR, 92,* 9135-9152. [16] Fisher D. (1993) *Icarus, 105,* 501-511. [17] Fisher D. (2000) *Icarus, 144,* 289-294. [18] Fisher D. et al, (2002) *Icarus, 159,* 39-52. [19] Hvidberg, C. (2003) *Ann. Of Glaciology.* [20] Greve, R. et al (2003) *Planet. Space Sci., 51,* 193-204. [21] Greve R., Mahjan R. A. (2003) *3rd Intl. Mars Polar Sci Conf.,* #8003. [22] Hofstadter, Murray B. (1990) *Icarus, 84,* 352-361. [23] Bennett M., Glasser, N. (1996) *Glacial Geology: Ice Sheets and Landforms* [24] Durham, W. et al (1992) *JGR 106,* 20883-20891. [25] Goldsby, D., Rohlstedl (2001) *JGR 106,* 11017-11030. [26] Suppe, J. (1985) *Principles of Structural Geology.* [27] Ramsay (1967) *Folding and Fracturing of Rocks.*