

# EVIDENCE FOR INTERNAL DEFORMATION AND FLOW IN THE NORTHERN POLAR CAP OF MARS. S.

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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 extensive lateral layers of ice and dust found throughout the polar cap. The polar layered deposits were first identified in Mariner 9 images [1, 2] and later studied in detail with the Viking orbiters [e. g. 3, 4, 5, 6, 7] and with the Mars Orbiter Camera (MOC) onboard the Mars Global Surveyor (MGS) [e. g., 8, 9, 10, 11]. These layers 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 cap can help to interpret the climate record.

It is well-documented that terrestrial ice of sufficient thickness can flow [e.g., 12, 13, 14]; if the martian 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 unknown due to the unknown proportion of dust in the polar layered deposits within 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 cap.

**Predictions:** What kind of evidence should we be looking for to determine where, when, and how much the ice flows? Ice flows through a combination of creep (internal dislocations within and/or between ice crystals) and basal sliding. The rate of creep is a function of shear stress and is greatest near the base of glaciers. The addition of dust can alter the rate of creep [20, 21, 22, 23, 24, 25]. When creep is insufficient to accommodate stress, the ice can undergo brittle failure or fracture [13, 14, 26, 27]. Basal sliding may occur if pressure melting permits a thin layer of water to form at the bed of wet-based glaciers. The combination of creep and basal sliding allows for accelerated ice flow. In extremely cold environments, ice temperatures may lie below the pressure-melting point. Such cold-based glaciers move slowly and only by creep. Cold-based glaciers are common in Antarctica today and geologic evidence for former cold-based glaciers on Mars has been previously documented [28, 29].

Extensional zones within the ice 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 fracture; the ductile material will flow into 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 detached 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, the bed topography, and whether the ice is located beneath an accumulation zone or an ablation zone. For a simple ice sheet, the interior regions most commonly experience extension while the marginal regions undergo compression (Figure 1) [23].

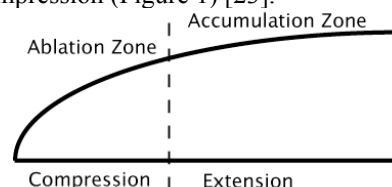


Figure 1. Location of extension and compression within a simple ice sheet. After Figure 7-1 in [23].

This simple model of ice cap dynamics (Figure 1) offers a framework for assessment of evidence for flow. We should look for evidence of flow in the north polar cap by searching for deformation in layers near the cap base. The troughs cutting deepest into the cap are located at the cap margins; based on terrestrial experience [23], we expect any deformation present will be due to compression.

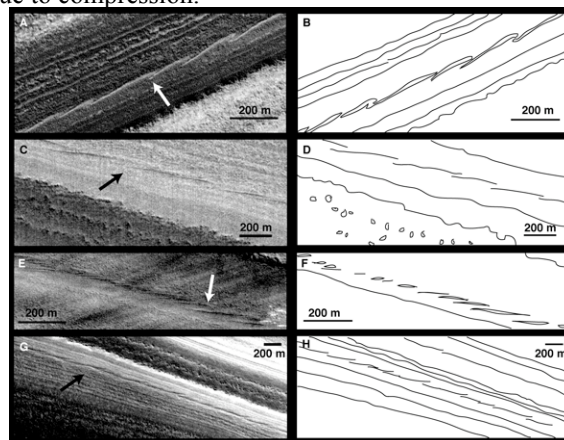


Figure 2: Examples of proposed thrust faulting in the north polar layered deposits. Arrows point to the layers with the fault-like features. A) Subframe of R01-00641. B) Sketch of R01-00641. C) Subframe of M18-00948. D) Sketch of M18-00948. E) Subframe of FHA-01515. F) Sketch of FHA-01515. G) Subframe of E18-01329. H) Sketch of E18-01329.

**Observations:** Previous examinations of high resolution images located around the cap have found possible but not conclusive evidence of layer deformation [8, 22]. In fact, the upper 300 m of layered deposits appears to be continuous and undeformed around the cap [11]. This implies that the upper sequence of layers has not experienced stress conditions required for brittle fracture, although they may have thinned due to

flow. We therefore turn our attention to layers towards the base of the polar cap where maximum shear stress should be manifested and deformation is likely [23].

An examination of the highest-resolution MOC narrow angle images around the polar cap reveals several layers with characteristics consistent with brittle deformation. Three images located in the same trough near  $83^{\circ}$  N and  $94^{\circ}$  E contain a layer that appears to have been folded and locally faulted and overthrust (Figure 2a, b, c, d, e, f). The layer, located towards the base of the trough at an elevation of about  $-3750$  m, is  $\sim 1$  m thick (the shallow slope of the trough makes it appear thicker in the images). Individual segments of the layer range from  $\sim 90$  m to  $\sim 260$  m in length, averaging  $\sim 160$  m. The edges of most segments are rotated away from the neighboring segments, oriented at an angle to the layer plane; this is consistent with motion along a fault due to shear stress. An additional image located at  $83.3^{\circ}$  N and  $98.3^{\circ}$  E (Figure 2g, h) in a neighboring trough also has a layer with brittle deformation features. The segments in this layer average  $\sim 120$  m length and are also rotated away from the layer plane. An unusual layer is observed in the bottom of a trough located at  $84.8^{\circ}$  N,  $124.1^{\circ}$  E (Figure 3); this layer may contain a fault. Unfortunately, only a small portion of this layer is exposed in the image. Nevertheless, there is evidence for thinning of the upper layer, topography on the basal contact, stratigraphic differences across the structure, and an apparent fault-like ramping. Initial examination of the geometry of these fault-like features indicates that they are oriented so the hanging wall is moving towards the margin of the cap; this is consistent with compression experienced at the margin of a flowing sheet of ice [23].

It is important to determine whether these features are consistent with compression or extension. The deformed layer in Figure 1b in particular appears to contain several segments that have not quite broken apart but are connected and may be folded. This is similar to layer deformation in a compressive stress regime where the layer is folded to such an extreme that portions of the folds undergo faulting and low-angle overfaulting. Therefore, we interpret this layer as a compressive feature. The presence of this layer combined with the probable faulted layer in Fig. 3 indicates that compressive forces were at one time present in these troughs.

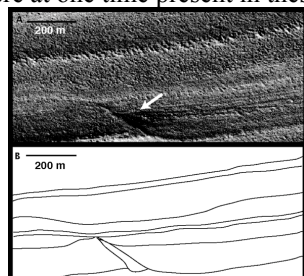


Figure 3: Deformation in the north polar layered deposits. A) Subframe of M00-00163. B) Sketch of M00-00163. Image has been rotated so the top of the trough is up.

**Discussion:** Did the entire cap experience flow, or did this occur only in selected lobes of the cap? The locations of images containing evidence of compression (Figure 4) indicates that at least the region of the cap near  $\sim 100^{\circ}$  E experienced flow.

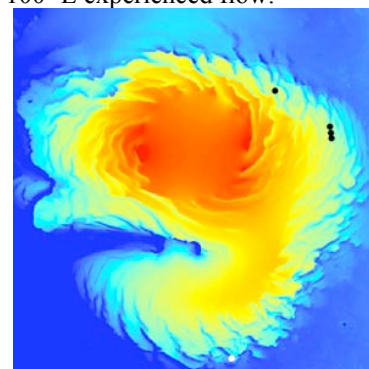


Figure 4. Locations of images displaying deformed layers (black circles) identified in this analysis and ridges interpreted as indications of cap retreat (white circles)[5, 30].

Howard et al [5] found features at the edge of the cap at  $\sim 10^{\circ}$  E that have been interpreted to be marginal deposits left by advance and retreat of the cap, either by erosion or by glacial flow [30]. The location of these features is not near the location of a majority of the images identified in this analysis (Figure 4). Thus, there may be additional deformed layers elsewhere around the cap. The areal extent of regions that experienced flow is being further documented through a more extensive search for deformational features at the margins of the cap. Efforts to use the geometry of the extensional features to constrain the stress regime of cap as it underwent flow are in progress.

**References:** [1] Soderblom L., et al. (1973) *JGR* 78, 4197-4210. [2] Cutts J. (1973) *JGR* 78, 4231-4249. [3] Kieffer H. et al. (1976) *Science* 194, 1341-1344. [4] Blasius K., et al. (1982) *Icarus* 50, 140-160. [5] Howard A., et al. (1982) *Icarus*, 50, 161-215. [6] Thomas P. et. al. in *Mars* [ed. by H. Kieffer et al] pp.767-795. Univ. of Arizona Press, Tuscon. [7] Squyres S. W. (1977) *Icarus* 40, 244-261. [8] Malin M., Edgett K. (2001) *JGR*, 106, 23429-23570. [9] Kolb E., Tanaka K. (2001) *Icarus* 154, 22-39. [10] Laskar J., et al. (2002) *Nature* 419, 375-377. [11] Milkovich S., Head J. (2005) *JGR in press*. [12] Hambrey M., Milnes A., (1975) *Ann of Glaciology* 14, 383-393. [13] Patterson W. (1994) [14] Benn, Evans, (1998) [15] Clifford, S. (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. (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*. [28] Head, Marchant (2003) *Geology*, 31, 641-644. [29] Milkovich, S., Head, (2003) *J. 6th Mars abstr* 3149 [30] Clifford, et al (2000) *Icarus* 144, 210-242.