STRATIGRAPHIC IMPLICATIONS OF THE RELAXATION OF TROUGHS AND SCARPS WITHIN THE MARTIAN NORTH POLAR LAYERED DEPOSITS. A. V. Pathare[1] and D. A. Paige[2], [1]California Institute of Technology (avp@gps.caltech.edu), [2]University of California, Los Angeles (dap@mars.ucla.edu)

Introduction: Previously [1], we showed that the viscous relaxation of subsurface water ice in the North Polar Layered Deposits (NPLD) provides a much better fit than does surface sublimation to the key morphological observations of NPLD troughs and scarps. These include: the lack of latitudinal dependence of either the maximum surface slope or total depth of NPLD troughs; the correlation of maximum surface slope to total depth of NPLD scarps; the equatorward-facing/poleward-facing (EWF/PWF) slope asymmetry of opposing NPLD trough walls; and the presence of extremely steep NPLD scarps well above the angle of repose. Here, we argue that the stratigraphy of North PLD troughs and scarps is also more consistent with relaxation .

Trough Evolution: The results of both our sublimation modeling and relaxation simulations indicate that NPLD troughs are relatively young features [1]. For if NPLD troughs predate the last high obliquity epoch (5 Ma < t < 10 Ma), then neither EWF nor PWF walls experience a significant long-term sublimation advantage, which means that the observed trough slope asymmetry cannot be sustained by preferential sublimation of EWF walls. Moreover, trough closure relaxation times (to a depth of less than d = 200 m) at high obliquities are much shorter than at present, due to increased subsurface temperatures. Thus we conclude that most North PLD troughs have probably formed within the last 5 Myr—most likely during the transitional period from high to low mean obliquity that Martian orbit models consistently place at $t \sim 4$ Ma [2,3].

The central question is: what mechanism has governed the subsequent evolution of North PLD troughs? More specifically, does the NPLD trough asymmetry somehow result from preferential sublimation of EWF walls during the last few Myr—despite the greatly reduced sublimation rates at lower obliquities? Or is the slope asymmetry produced by differential relaxation of EWF and PWF trough walls that arises from insolation-driven thermal variations? The strong morphological correlation of trough depth and slope, which is difficult to explain in terms of sublimation, is consistent with the predicted relaxation history of North PLD troughs [1]. Additional support for the relaxation hypothesis is provided by the observed stratigraphy of NPLD troughs.

Trough Stratigraphy: Fig. 1a shows a high-resolution MOC observation of a typical North PLD trough (the location of which is outlined in the wide-angle context image of Fig. 1b). PLD troughs have been divided [4] into three main stratigraphic units: (1) Layered Terrain, expressed upon EWF trough slopes; (2) Banded Terrain, located on PWF trough walls; and (3) Smooth Terrain, which spans the regions between the troughs.

The EWF Layered Terrain are comprised of clearly delineated fine-scale laminae, most of which are relatively dark in appearance. The continued visibility of these layers implies active resurfacing by not only water ice sublimation but also eolian erosion—otherwise, a sublimation dust lag would be expected to form [5,6]. The wider layers of the intermediate-toned PWF Banded Terrain are much more irregular, and have been interpreted as representing the eroded "feather edges" of ice or dust layers deposited on PWF trough walls [4]. These two stratigraphic units provide the basis for the standard model of trough evolution in which water ice sublimed from the EWF Layered Terrain recondenses upon the PWF Banded Terrain, resulting in the poleward migration of the trough [4].

However, we argue that the relative thinness of the Banded Terrain actually indicates that deposition within troughs is insignificant. The diffuse Banded Terrain often appear to be translucent, exposing underlying fine-scale layers upon PWF trough walls that are continuous with their EWF Layered Terrain counterparts [4]. But deposition of a millimeter-thick layer should be more than sufficient to alter surface albedo and obscure the trough wall [7]. If we conservatively assume that the average thickness of the Banded Terrain is a full meter, then given that most present-day NPLD troughs likely formed about 4 Ma, the implied net deposition rate is only 0.25 microns per year—or about three orders of magnitude less than the MAWD-derived net NPLD sublimation rate of 0.19 mm/yr [1].

Undulations: The bright Smooth Terrain, which corresponds to the water ice surface of the North Permanent Cap (NPC), gradually transitions into the Layered Terrain (Fig. 1a), which is why the NPC is widely presumed to simply represent the uppermost layer of the North PLD [8]. Although the Smooth Terrain often appears to be featureless in summertime images (Fig. 1b), springtime observations such as Fig. 1c that highlight topography (due to the ubiquity of the seasonal CO_2 frost cap) reveal the presence of gentle wave-like undulations [4]. These shallow undulations typically have a vertical amplitude of 10-100 m, and are most prominent parallel to the equatorward (i.e., southern) edge of North PLD troughs [6].

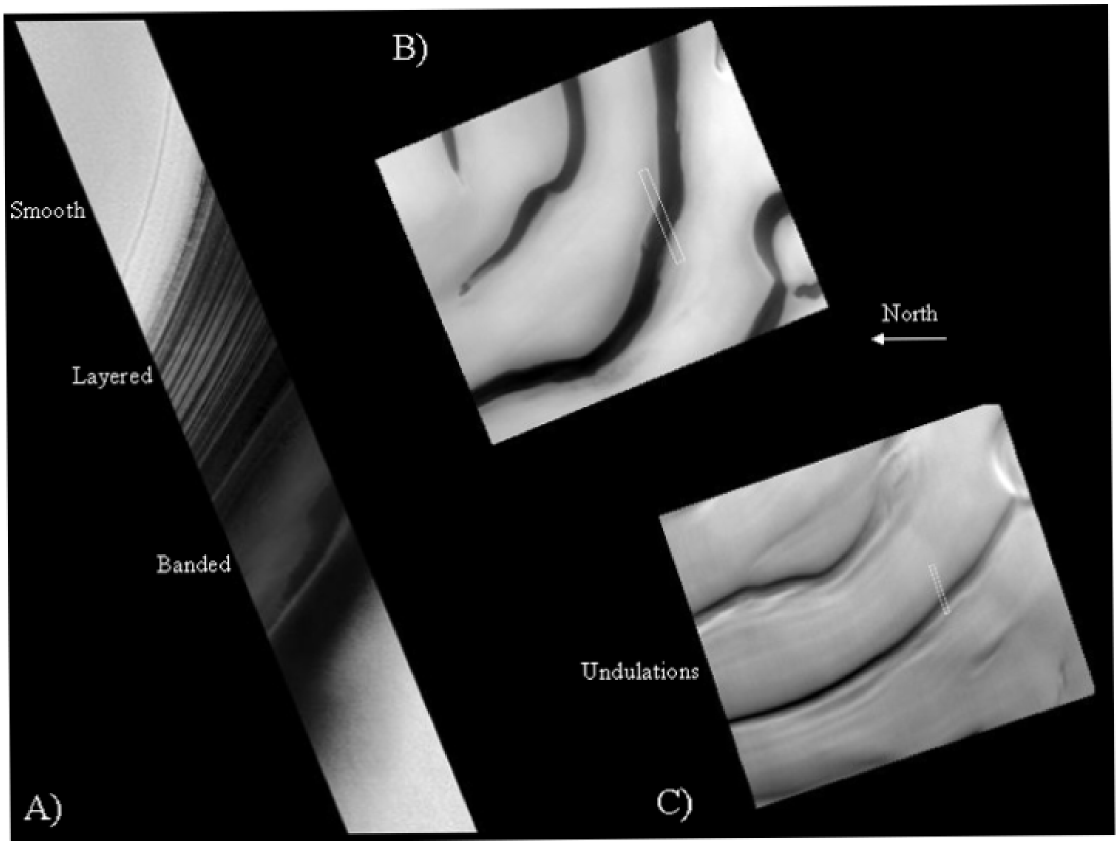

Figure 1 North PLD Trough Stratigraphy. MOC images (a) E01-01092: 87.0°N, 264.4°W, resolution = 13.0 m/pixel, size = 3.34 × 36.3 km, L_s = 118°; (b) E01-01093: 87.4°N, 265.8°W, resolution = 274 m/pixel, size = 133 × 113 km, L_s = 118°; (c) M18-00805: 86.7°N, 282.4°W, resolution = 272 m/pixel, size = 133 × 114 km, L_s = 35°. Context for part (a) shown in part (b).

In the context of trough migration, the undulations are theorized to be "scars" representing the former positions of trough floors undergoing poleward retreat [4]. The main difficulty with this theory is that the troughs are currently substantially deeper than the undulations; hence, some mechanism must have increased the depth of the troughs while preserving the shallowness of the undulations, which given their proximity seems unlikely [6]. Alternatively, the undulations were formerly much deeper and have subsequently experienced massive infill. But the rate of trough deposition implied by the thin PWF Banded Terrain layers is much too low to raise deep trough floors by several hundred meters on Myr time scales.

However, our finite element simulations of North PLD troughs demonstrate that viscous relaxation can produce such rapid trough floor uplift, particularly at high obliquities [1]. Furthermore, our modeling indicates that troughs that have attained "closure" (defined for convenience as the time when d < 200 m) still retain a distinct V-shape which is similar in appearance to the gentle trough-like morphology of undulations [6].

Therefore, we propose that undulations within the Smooth Terrain represent relict paleo-troughs that have experienced closure via viscous relaxation. Similarly, the slope asymmetry of present-day North PLD troughs is concordant with differential flow rates resulting from intra-trough thermal variations, which could either result from the expected slope dependence of surface temperature or from the generally lower albedo of EWF Layered Terrain relative to PWF Banded Terrain [1]. Thus we conclude that viscous relaxation is the resurfacing mechanism most consistent with both the stratigraphy and topography of NPLD troughs.

Scarp Evolution: Much like troughs, North PLD scarps exhibit a strong correlation between maximum slope and total depth, which is consistent with the predicted depth dependence of viscous relaxation. Our finite element modeling also indicates that the initial slope sensitivity of viscous relaxation can account for the presence of numerous extremely steep PLD scarps

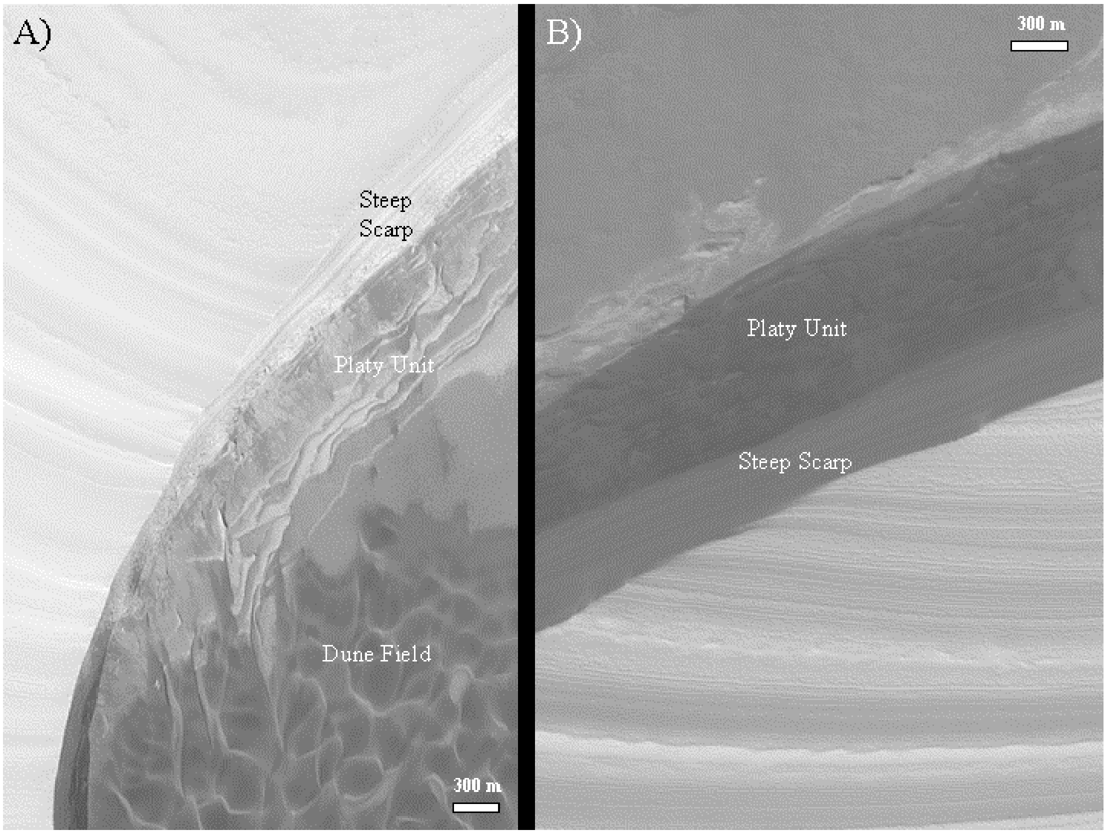

Figure 2 North PLD Scarp Stratigraphy. Portions of MOC NA images (a) E01-01773: 83.6°N, 242.0°W, resolution = 4.9 m/pixel; and (b) E02-01503: 85.4°N, 173.6°W, resolution = 3.2 m/pixel.

with surface slopes much greater than $\alpha = 40°$ [9]. An alternative mechanism for oversteepening of scarps is eolian erosion of a basal layer [4,6]. The validity of these theories can be assessed by examining the stratigraphy of steep North PLD scarps, two of which are shown in the high-resolution MOC images of Fig. 2.

Scarp Stratigraphy has been divided [4,9] into three main units: (1) the Steep Scarp itself, which is often arcuate in shape and like EWF trough walls is comprised of finely Layered Terrain; (2) the Platy Unit located at the base of the scarp, which appears to consist of irregularly jumbled layers; and (3) nearby Dune Fields, which are often located in the vicinity of PLD scarps, whence they are most likely derived. One widespread interpretation of Fig. 2a is that the apparent formation of dunes from the Platy Unit leads to "creation of steep scarps as the sand is removed and the upper unit is undermined" [10].

However, we have two major objections to this conclusion. First of all, it is difficult to envision how scarp slopes so much greater than the angle of repose ($\alpha >> 35°$) can be stable in the presence of extensive eolian erosion [6]. Secondly, the basal undermining hypothesis requires that the lower unit is less resistant to erosion than the overlying scarp; yet as seen in Fig. 2b, Platy Units generally extend outward by as much as a km from the base of the upper layers [9]. Thus Platy Units are clearly *more* resistant to erosion than the layered terrain of the Steep Scarps, which appear to have undergone extensive lateral retreat, most likely due to sublimation of water ice.

Basal Conditions: The presence of the basal Platy Units may also explain why the Steep Scarps appear to remain frozen at their base, which is an essential requirement for the long-term steepening predicted by our finite element scarp simulations [1]. For if the Platy Units are significantly rougher than the overlying scarps (as consistent with their apparent corrugation: Fig. 2a), then lateral advance of the scarp via basal sliding will be inhibited, particularly at the low subsurface temperatures characteristic of the NPLD. Of course, collapse of the overlying scarps may still occur, but the lack of observed taluses—either upon the Platy Units or just off the NPLD—at the $\alpha \sim 35°$ angle of repose for unconsolidated material suggests that such collapse has not occurred. (Indeed, the presence of dramatically steeper slopes is consistent with the $\alpha > 60°$ angle of repose measured for snow avalanches composed of fresh crystalline water ice.)

Therefore, we propose that viscous relaxation is the most likely mechanism of steep scarp formation, as our finite element simulations yield maximum surface slopes well above the angle of repose for a variety of initial conditions [1]. Since subsurface flow also best explains the correlation of PLD scarp slope with depth, we conclude that viscous relaxation is consistent with both the stratigraphy and topography of NPLD scarps.

Recent NPLD Evolution: Almost all models of recent NPLD evolution presume that the EWF Layered Terrain (Fig. 1a) is actively sublimating, since its unobscured fine-scale layering clearly indicates a lack of present-day accumulation [4], and because the slope dependence of sublimation favors EWF trough walls at the current obliquity [1]. However, the relative importance of sublimation and condensation upon other units is more contentious.

The uniformitarian evolutionary hypothesis assumes that water ice sublimed from EWF Layered Terrain continually condenses upon both opposing PWF Banded Terrain and adjacent flat-lying Smooth Terrain, a pattern that results in the steady poleward migration of the trough [4]. The evidence for deposition upon the Banded Terrain mainly consists of that unit's characteristically wide and diffuse layers [4]—although as discussed above, the magnitude of such deposition is limited by the apparent thinness of these bands. As for the Smooth Terrain, analogy with terrestrial glaciers suggests that the bright whitish hue of this unit is indicative of accumulation, in contrast to the ablation implied by the darker Layered Terrain [11].

However, this simple albedo-based argument is stratigraphically inconsistent. For even though the PWF Banded Terrain is more favored for condensation than the flat-lying Smooth Terrain, the Banded Terrain generally has an albedo intermediate between that of the dark Layered Terrain and the bright Smooth Terrain (Fig. 1a). In other words, if the Smooth Terrain has a high albedo because it is accumulating fresh water ice, then why isn't the Banded Terrain at least as bright?

Therefore, we argue that the inter-trough Smooth Terrain is undergoing net sublimation, along with the EWF Layered Terrain. Moreover, the obliquity dependence of sublimation suggests that the PWF Banded Terrain may also be ablating. For example, our sublimation modeling predicts that the $\theta = 26.2°$ summertime sublimation rate from a nominal $\alpha_\varepsilon = -3.1°$ NPLD surface (corresponding to the mean slope of PWF trough walls) is $E_{net} = 0.43$ mm/yr, which is slightly *greater* than the present obliquity ($\theta = 25.2°$) $E_{net} = 0.42$ mm/yr calculated for a nominal $\alpha_\varepsilon = 5.4°$ NPLD surface (characteristic of the mean slope of EWF trough walls). These results imply that opposing trough walls are in different sublimation/condensation regimes for a relatively narrow obliquity window (the actual width of which depends upon the uncertain orbital modulation of wintertime H_2O recondensation). Hence we suspect that the diffuse bands observed upon PWF trough walls result from deposition at lower obliquities, and that over the probable 3-5 Myr lifetimes of North PLD troughs, the PWF Banded Terrain undergoes net sublimation.

Consequently, we suggest that long-term deposition of H_2O does not occur anywhere in the vicinity of troughs. Instead, we propose that net condensation of water ice is restricted to the very center of the North PLD (where troughs are absent) via the "vacuum effect" associated with repeated H_2O recondensation within the retreating seasonal CO_2 cap. However, this scenario of widespread ablation throughout the outer NPLD and focused accumulation within the inner NPLD raises long-term stability concerns, since the MAWD-derived average North PLD sublimation rate of $E_{net} = 0.19$ mm/yr is fast enough to transfer a $Z = 1$ km thick layer from the outer to the inner NPLD in a little over 5 Myr. Thus in order to prevent massive thickening near the pole, some process must be redistributing material back to the margins.

Our modeling implies that glacial flow is the most likely mechanism of maintaining mass balance within the North PLD. For not only do our sublimation calculations indicate that the NPLD is divided into ablation and accumulation zones (much like terrestrial glaciers), but our finite element relaxation modeling clearly demonstrates that the PLD consist of deformable ice—which is a fundamental prerequisite for glacial flow. Therefore, we conclude that flow processes not only control the relaxation history of mid-sized features such as troughs and scarps, but also govern the large-scale evolution of the entire North PLD.

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