IMPLICATIONS FOR CURRENT AND PAST ATMOSPHERIC CONDITIONS OF MARS FROM RADAR STRATIGRAPHIC STUDIES OF SPIRAL TROUGHS IN THE NORTH POLAR LAYERED DEPOSITS.

I. B. Smith[1], J. W. Holt[1], [1]University of Texas Institute for Geophysics, Jackson School of Geosciences, University of Texas, Austin, TX 78758 isaac@ig.utexas.edu; jack@ig.utexas.edu

Introduction: Recent observations made by the Shallow Radar (SHARAD) onboard Mars Reconnaissance Orbiter have provided stratigraphic evidence for migration of the spiral troughs that cover the North Polar Layered Deposits (NPLD) [1]. Internal radar reflectors were used to demonstrate that the spiral troughs formed during two distinct periods separated by hundreds of meters of ice accumulation and have migrated northward and upward during a period of net deposition (Figure 1). This constructional origin was as hypothesized by Alan Howard in 1982 [2] based on Viking imagery, in contrast to many later studies that asserted the troughs were incised into existing stratigraphy.

Smith and Holt [1] argued that after a long period of trough non-existence in the NPLD, wind, combined with atmospheric deposition of new material was one of the primary agents of trough initiation and evolution, eventually causing increased amplitudes and migration. They also proposed that a punctuated change in climate, combined with favorable topographic relief, made conditions suitable for troughs to develop before each onset. Once the troughs initiated, winds transported material transversely across the troughs during times of deposition, causing the upwind and uphill migration, identified by stratigraphic discontinuities called trough migration paths (TMPs) and a varying thickness of radar reflectors. The troughs quickly grew to a steady state in amplitude and have maintained a constant wavelength.

Here we extend those observations [1] and offer new insights into the conditions responsible for trough initiation. Additionally, we discuss the role of wind in material transport and provide a new metric for constraining flow parameters by comparing the troughs to terrestrial analogues that are better understood through both physical and numerical models. We attempt to introduce both the temporal and spatial constraints that will likely provide new constraints for meso-scale and higher-resolution models related to climate within the last several million years. We see this as an important step in understanding the history of ice and climate on Mars.

Methods: The bulk of this work is conducted by interpreting radar data collected by SHARAD. SHARAD operates at frequencies between 15 and 25 MHz and is capable of observing reflections beneath the NPLD surface with resolution of approximately 10 m in water ice, the primary component of the NPLD [3]. Reflectors are traced within individual radargrams and across multiple radargrams in order to create isochrone maps of former surfaces of the NPLD. Mapping of reflectors is undertaken in the original time-delay data, before any depth conversion, using Schlumberger's GeoFrame seismic interpretation software. Software generated in-house converts the time-based interpretations to depth and spatially locates the point of first reflection and subsequent subsurface reflectors. ArcGIS is then used to create maps and generate ancillary data.

Trough Initiation: At least two trough initiation surfaces (TIS) can be observed by radar data within the uppermost 500m of the NPLD. The older TIS is approximately 1500 m above the base of the NPLD and overlies about three fourths of the entire deposit. On that surface the majority of spiral troughs formed. The second and younger TIS is stratigraphically higher than that of the first and covers a distinct region of the NPLD from 25° to 100° east and south of 85° north (Figure 2). No older troughs appear in this region.

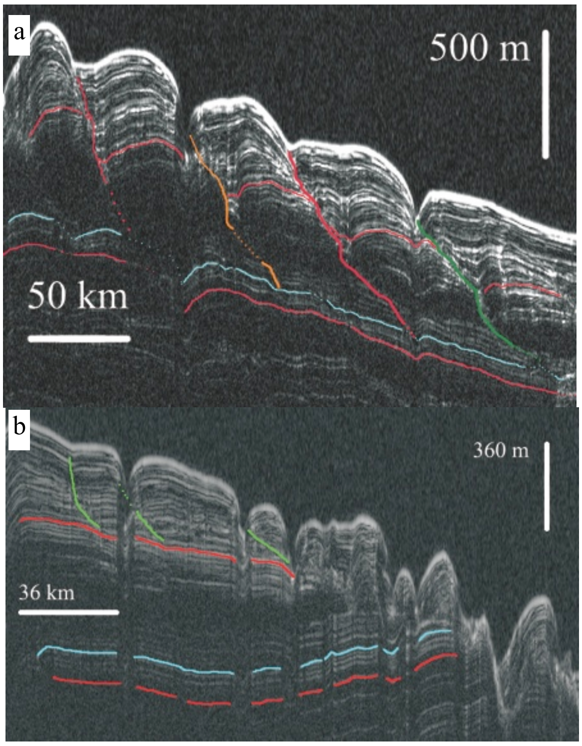

Figure 1: Interpreted radargrams demonstrating trough initiation surface and TMP. (a) radargram 519201, red line in Figure 2. TMP from oldest troughs reach blue and colored reflectors. (b) Radargram 761602, black line in Figure 2. Younger troughs do not reach the blue and red reflectors below and instead are only within the top ~360 m.

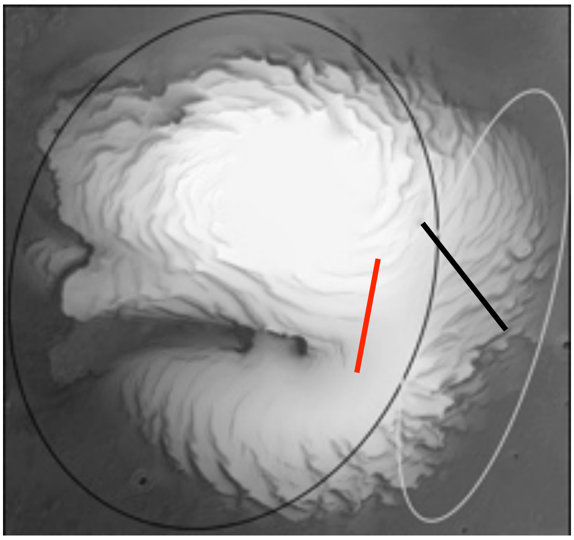

Figure 2: Map of NPLD showing older (black oval) and younger (white oval) troughs. Colored lines indicate location of radargrams in Figure 1.

Radar mapping at the interface of pre-trough and post-initiation deposits reveals that for both generations of troughs, initiation occurs at a change from steep to shallow slope. The underlying layers at the slope change end abruptly rather than diminish with distance, indicating that erosion created the scarp. This former surface morphology provides the initial conditions needed to form troughs from the combination of deposition and katabatic winds affected by surface slope.

These erosional surfaces are not limited to exactly where a trough began, but instead cover a large portion of the NPLD and indicate that there was widespread, non-uniform loss of NPLD material. Two possibilities for this mass loss are sublimation due to insolation and wind scouring, although more evidence for the former can be found in literature [4, 5]. Alternating periods of erosion and deposition as observed by SHARAD are predicted to result from large changes in obliquity and insolation at the Martian north pole [5], suggesting that the timing of trough initiation may be related to orbital forcing.

Previous erosion events had not produced troughs; therefore the Martian atmosphere probably changed in a way that permitted trough formation, and/or topography evolved so that the necessary winds were produced. Some possible candidates for atmospheric factors may include atmospheric density, temperature gradients, boundary layer thickness, or depth of flow in katabatic winds.

Once the troughs had initiated they maintained approximately the same wavelength as can be measured today, and the amplitude, upon reaching a steady state, has not continued to grow. Alternate hypotheses of small wavelength bedforms growing larger is not supported. Visibly exposed contacts of pre-trough material and material that existed during trough evolution do not show small-scale bedforms, sfurthering this interpretation.

Froude Supercritical Flow: Features on Earth have similar stratigraphic structures and surface morphologies to those associated with the spiral troughs on Mars. It has been shown that these bedforms migrate upstream towards the source of fluid and sediment. Taki and Parker [6, 7] demonstrate that under a broad range of conditions, a flow and bed will evolve into a series of spatially periodic steps, called cyclic steps. The bed must be erodible, and copious sediment must be available for transport to create the steps. Once formed, the cyclic steps are stable and maintain a very large wavelength-to-height ratio and constant wavelength while migrating upstream. Figure 3 shows both radar stratigraphy of the NPLD and seismic stratigraphy of a sediment wave, or cyclic step system, in a marine environment.

Several important processes are at work in this case. First, a relatively high-density fluid must flow over a sloped surface. The dimensionless quantity $U(gL)^{-1/2}$ is called the Froude number, where U is the velocity of flow, g is the acceleration of gravity, and L a characteristic length. If the flow is swift and thin, then the Froude number will be supercritical (>1) [7]. This Froude number is not stable over the entire length of the bed, but instead it breaks into

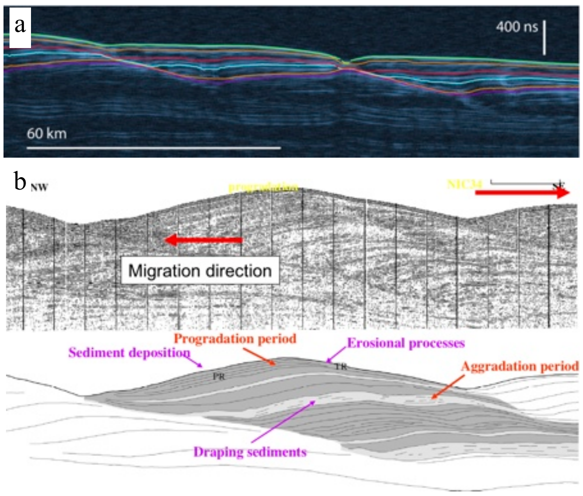

Figure 3: Similar stratigraphies across NPLD spiral troughs and submarine sediment waves on Earth. (a) Mapped horizons on SHARAD observation 519201. 400 ns is approximately 350 m in water ice. (b) Seismic section spanning sediment waves. (Lower two panels courtesy Gary Parker.)

steps, or "hydraulic jumps." These can be described as a change in hydraulic pressure from high to low in the direction of flow. This results in a dramatic change in flow depth. Figure 4 shows two types of hydraulic jumps, one on Mars and another in a ter-

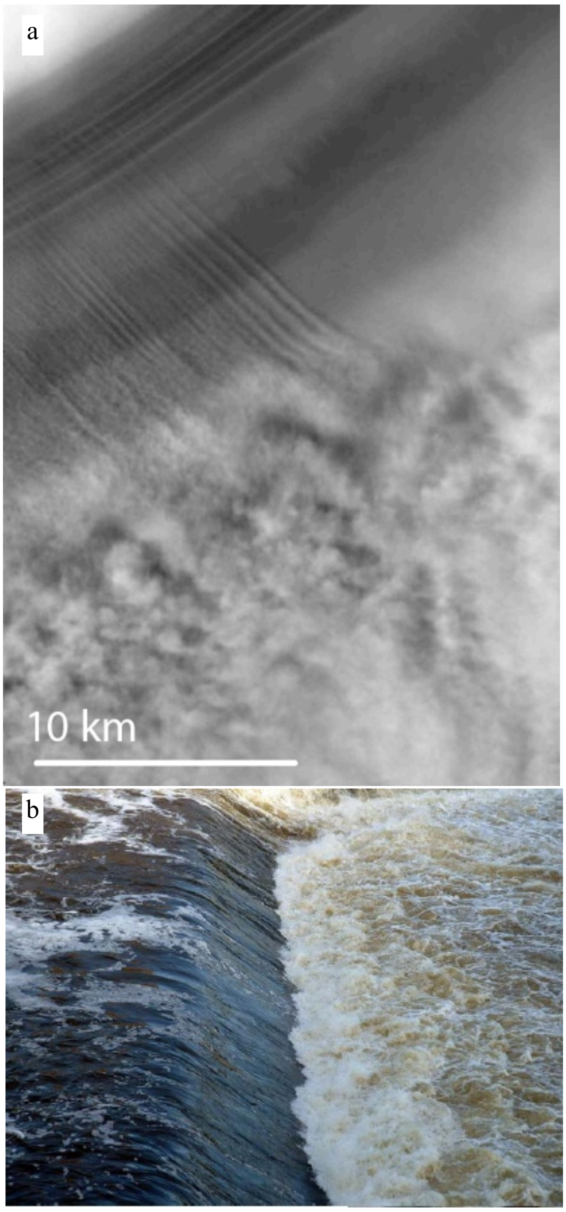

Figure 4: Examples of hydraulic jumps (a) crossing a trough on the NPLD and (b) in a river. Left (upslope) side in both has supercritical Froude number (place of erosion) while right (downslope) side has subcritical Froude number (zone of deposition).

restrial river. In both cases thin laminar flow moves from high to low, until the slope breaks and flow velocity decreases.

Variations in Froude number determine a specific type of flow, and the morphology of the bed provides constraints on them. In fact, only a few specific scenarios are allowed if hydraulic jumps exist between cyclic steps, and with this knowledge we will be able to reduce the uncertainty in velocity, suspension of sediment, and depth of katabatic flow over the NPLD. Additionally, both physical and numerical models exist that help describe these parameters. Only slight modifications to density, gravitational constant, and sediment concentration are required to model the flows on Mars, a project we are just beginning to undertake.

Stratigraphy Near Troughs: Stratigraphic mapping is the key tool to understanding the morphologic evolution of sedimentary systems. Exposures of layers at outcrops have, until recently, been our only guides to understanding subsurface geometry near troughs. Quantifying the 3-dimensional stratigraphy, especially layer thickness variations over large areas, has been elusive until now.

Generally, the layers in the NPLD are sub-horizontal and continuous in the lowermost 1500 m of imaged deposits. Discontinuities, TMP, dominate the uppermost 500 m of section between spiral troughs. These discontinuities are associated with trough migration and are shown to be bounding surfaces where ice-rich material on-laps formerly-eroded, south-facing slopes of spiral troughs (Figure 3a; [1]).

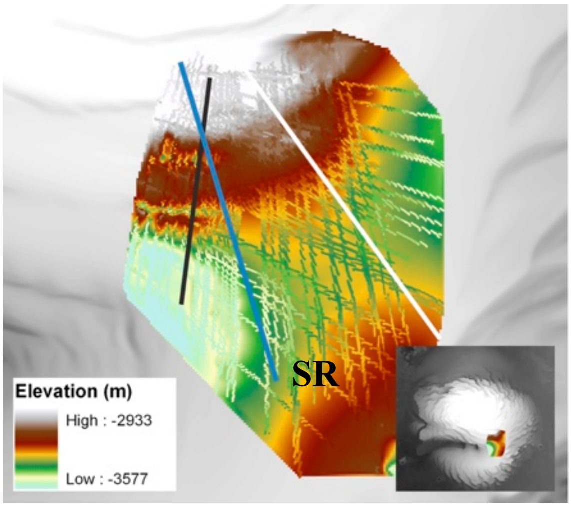

Figure 5: Basemap and data locations. 80 SHARAD orbits overlay a gridded interpolation of a paleo-surface. Elevations are referenced to the MOLA-defined aeroid. Black line is orbit track of observation 519201, Figure 3a. White line is location of Figure 6's profile. Inset: Planum Boreum with gridded surface for location.

Proposed processes of trough migration are few, including: solar-induced ablation, atmospheric deposition, and aeolian transport. By investigating subsurface stratigraphy we can begin to constrain the role and relative importance of each process for future studies.

In a preliminary study, 80 SHARAD observations (Figures 3 and 5) in a region between 15° and 55° E and 82° and 86° N were used to reconstruct paleo-surfaces within the NPLD. A total of 6 reflector horizons, all within the uppermost 500 m and including the present surface, were interpreted (Figure 3a). The extracted time-delay data were then geospatially referenced and interpolated to create slope and isopach maps as described above.

Once the six horizons were mapped, profiles oriented approximately perpendicular to the spiral troughs, following current wind direction, were selected to investigate accumulation patterns. The spacecraft orbit is fixed, so creating this grid allows for more flexibility in choosing useful profiles. An area of 30,000 km^2, covering two main-lobe troughs and the Saddle Region (SR) between the Main Lobe and Gemina Lingula, was mapped (Figure 5).

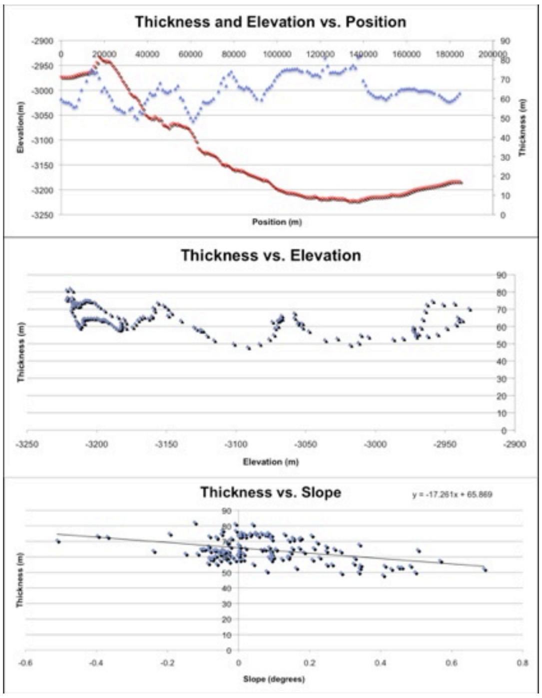

Figure 6: An example of package thickness (blue) plotted against local position, elevation, and surface slope along with elevation profile (red; location indicated by blue line in Fig. 2). Negative slopes indicate pole-facing surfaces and positive slopes indicate equator-facing surfaces. Elevation varies by ~ 500 m with no systematic change in thickness. Surface slope and deposit thickness are correlated.

Observations: Deposits near the spiral troughs showed wide variation in thickness. Longitudinal variation is also observed; the westernmost profiles, those directly north of Chasma Boreale, had more variation than those farther east and north of the SR where regional topography is much less variable.

Plots of thickness show no systematic change with elevation (Figure 6b). However, thickness plotted against slope illustrates a clear relationship: positive, south-facing slopes are anti-correlated with thickness while negative, north-facing slopes have increasingly thicker packages (Figure 6c).

We interpret these data to demonstrate that katabatic winds entrain material from an upwind slope and transport it to a downwind slope across a trough. This interpretation accounts for the layer thickness variation, agrees well with previous interpretations based on optical images from earlier missions [7], and supports the concept of cyclic steps.

Modeling Applications: With the observations of relative trough initiation timing for multiple generations and internal trough stratigraphy, combined with the concept of supercritical flow causing hydraulic jumps and cyclic steps, new constraints can be applied to atmospheric models of all scales, especially those concerning the NPLD. Primarily we can contribute to an understanding of katabatic winds and topographic feedbacks in ice accumulation patterns.

The cyclic step interpretation of spiral troughs makes further predictions on the observed wavelengths and amplitudes and sediment supply from atmospheric deposition with the specific locations of erosion and deposition at a trough. With the context of large-scale deposition and erosion events, possibly tied to orbital forcing of insolation, trough stratigraphy should help us better understand the long-term evolution of Mars climate as recorded in the NPLD.

Summary: Early in NPLD history, spiral troughs did not exist. Something changed to allow the formation of the troughs. After extensive, cap-wide mass loss, the first troughs began to form. The major change may have been atmospheric, climatic, topographic, orbital forcing, or some combination. The observed onset of two generations of spiral troughs immediately post-dating erosional events may suggest one of those mechanisms.

Once formed, the troughs were acted upon by accelerating winds that removed material from the upwind slopes (Froude number >1) and carried the material to the downwind or north-facing slope across a hydraulic jump. Plots of thickness vs. slope demonstrate that accumulation has not been uniform across a trough and support the wind transport model. Interior trough slope played a major role in accumulation.

The timing of transport relative to deposition is still in question. There are two possibilities: either sediment (ice) was deposited uniformly and later preferentially remobilized, or winds moved accumulating ice during deposition. Both possibilities give rise to trough migration. Continuing studies will attempt to differentiate between the two.

References: [1] Smith, I.B. & Holt, J.W. (2010) *Nature* 465, 450-453. [2] Howard A. D. (1982) *Icarus*, 50, 161-215. [3] Grima C. et al., (2009) *GRL, 36,* L03203. [4] Head, J.W., et al., (2003) *Nature* 426, 797-802. [5] Laskar, J. et al., (2004) *Icarus* 170, 343-364. [6] Taki, K. & Parker, G., (2005) *JHR* 43, 488. [7] Kostic, S. & Parker, G., (2010) *JHR* 44:5, 631-653.[8] Howard A. D. (2000) *Icarus*, 144, 267-288.