**THE NORTHERN SPIRAL TROUGHS OF MARS AS CYCLIC STEPS: A THEORETICAL FRAMEWORK FOR CALCULATING AVERAGE MIGRATION AND ACCUMULATION RATES.** I. B. Smith, J. W. Holt, 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:** The spiral troughs on Mars' North Polar Layered Deposits (NPLD) contain a rich, detailed stratigraphic record of surface processes in Mars' recent polar history. SHARAD radar data near the center of the NPLD revealed that the troughs have migrated more than 50 km towards the north during the accumulation of the uppermost ~ 600 m of NPLD [1]. It was proposed that katabatic winds are the primary driver of this migration process [1, 2]. Here we test that hypothesis by integrating observations of current surface winds, quantitative radar stratigraphy, and mesoscale model results into a model of trough migration based on cyclic steps. We find that wind transport of ice and vapor may be able to account for the observed amount of spiral trough migration. Although this does not require an assumed accumulation rate, the average rates of migration estimated from this analysis compare favorably with rates derived by assuming constant accumulation during trough development [1].

**Model:** Surface morphology in and around the spiral troughs indicates a complex system of erosion and deposition. Features such as albedo, surface slopes, terrain (banded vs. layered), and radar reflectors are all asymmetric across the spiral troughs. This observation suggests that either non-uniform deposition or post-deposition transport of material is important during trough evolution.

In terrestrial and submarine environments on Earth, features that resemble the spiral troughs in morphology and stratigraphy have been well characterized. Material transport is responsible for the asymmetries in these systems which belong to a class of features termed cyclic steps [3]. Furthermore, this has been validated in flume experiments and numerical models intended to replicate cyclic steps. The experiments reproduced stratigraphy and morphology qualitatively similar to those associated with the spiral troughs (Fig. 1) [3]. We therefore interpret the spiral troughs as a depositional form of cyclic steps and apply the cyclic step model, modified for Martian atmospheric conditions, to constrain flow parameters of the katabatic winds on the NPLD. Using this technique, we are able to calculate average migration rates of the troughs and deposition rates of the NPLD since trough onset.

**Constraints:** SHARAD radar stratigraphy associated with spiral troughs has provided both a ratio of lateral trough migration to NPLD accumulation and estimates of the required mass transport [1]. THEMIS VIS and other optical imagery provide observations of

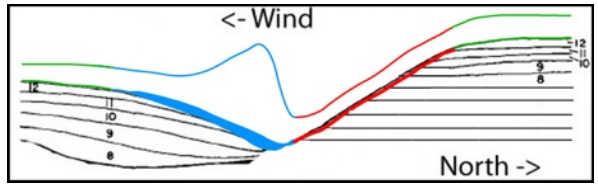


***Figure 1:*** *Cartoon depicting single hydraulic jump in cyclic step model. Flow is right to left. Green indicates no change in topography, red: erosion and supercritical (thin) flow; blue: deposition and subcritical (thick) flow after a hydraulic jump.*

active aeolian processes. From these observations we extract flow parameters required for Froude number calculations. Two physical constraints are necessary for the model: Froude numbers as predicted by cyclic step theory and conservation of flux across a boundary. Existing mesoscale models [4] provide the final constraints necessary to complete the calculations of total mass moved during a katabatic wind storm.

**Observations:** More than 9000 THEMIS VIS images covering the NPLD north of 82° have been examined. Of those images, approximately 250 capture katabatic winds acting on the spiral troughs and fall within solar longitude ($L_s$) range of 36-98, the majority after $L_s$ 76. Images capture thick, linear clouds that we interpret as hydraulic jumps near the bottom of, and parallel to, the troughs. Several images also show linear vortices of entrained ice particles that enter a trough perpendicular to its length, descending from its higher side. Beyond the hydraulic jump, and along the lower slope, the thick clouds become turbulent and flow downstream. Sequential observations provide constraints on the duration of active winds.

**Analysis:** The cyclic step model describes and predicts the observed flow (Fig. 2), which alternates between supercritical, shallow flow and subcritical, thick flow [3]. The process repeats in a series of steps. The Froude number (Equation 1) is a dimensionless number defined as the ratio of characteristic velocity to gravitational wave velocity. It is a measure of the thickness of a flow in comparison to the topography

(1) $$Frd = \frac{U}{\sqrt{gHr}}$$

(2) $$r = (\rho_i - \rho_{ia})C + (\rho_{ia} - \rho_a)(1 - C)$$

(3) $$f_1 = H_1 \times U_1 \times C_1 = f_2 = H_2 \times U_2 \times C_2$$

over which it flows. Supercritical flow is defined as having a densimetric Froude number greater than 1, while subcritical flow has a Froude number less than one. In the cyclic step model they are associated with erosion and deposition, respectively.

$Fr_d$ is the densimetric Froude number used for two-phase flow; U is the horizontal velocity; g the gravitational acceleration; H the flow depth, and C is the volumetric concentration. $\rho_a$, $\rho_i$, and $\rho_{ia}$ are estimated densities of air, ice, and icy-air respectively. Equation 3 is the conservation of flux across a hydraulic jump.

Using these equations with values listed in Table 1, an instantaneous flux can be calculated. An estimate of duration for an event may be derived from one or multiple VIS images. Most events are captured in only one image; however, in one series of 18 images from Mars Year 29, an event lasted longer than 200 hours.

Using the calculated flux and estimated duration of 20 hours, the total two-dimensional mass moved across the hydraulic jump is 12.94 m^2. Very little mass transfers between adjacent troughs, as can be demonstrated by SHARAD radargrams [5], so we assume all the material flux is deposited on the pole-facing slope, acquired from material carried from the ~ 22 km equator-facing slope. This amounts to ~ 3.75 mm of erosion, and 47.7 mm of scarp retreat (migration) using a nominal slope of 4.5°. Alternately, during a 1 hour storm the trough will migrate about 2.4 mm.

| | Supercritical$_1$ | Subcritical$_2$ |
|---|---|---|
| Fr | 1.4 | 0.55 |
| U (m/sec) | 12 | 6 |
| g ($m^2$/sec) | 3.698 | 3.698 |
| H (m/sec) | 275 | 424 |
| C | $4.813x10^{-7}$ | $6.24x10^{-7}$ |
| Flux ($m^2$/sec) | $1.59x10^{-3}$ | $1.59X10^{-3}$ |

***Table 1:*** *Estimated values used for Equations 1 and 3. Constraints obtained from the following: Fr: cyclic step model, U: models of katabatic winds on the NPLD [4], $H_1$: distance between vortices in Fig. 2, $H_2$ Belanger equation, C: calculated from Eqn. 1.*

**Implications:** The preponderance of events captured between Ls 76 and 98 and the lack of confirmed events during other times of the year suggest that the poleward migration of troughs occurs during the late spring and first few days of summer. From radar analysis, it is known that the older troughs have migrated more than 50 km [1]. Estimating 2.4 mm of migration per hour, approximately $2.1x10^7$ hours of wind are required to account for the total migration.

Given the duration and frequency of events observed in THEMIS observations, we estimate the total migration undergone by a trough in one Mars year to be as much as 476 mm but closer to 48 mm on average. This is in agreement with rates of 20 to 75 mm/yr as described in [1].

Based on the best available constraints, average rates, and estimated age of the NPLD (~4 Myr), we find that katabatic storms may have been sufficient to account for the 50+ km of observed trough migration. SHARAD revealed that migration rates are not constant throughout time, and the current regime is one of reduced migration [1], suggesting that migration rates may have been greater (and hence, winds may have been stronger) during earlier times.

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**References:** [1] Smith, I.B. & Holt, J.W. (2010) *Nature* 465, 450-453. [2] Howard A. D. (1982) *Icarus*, 50, 161-215. [3] Kostic, S. et al., (2010) *Journal of Hydro-enviro Ress* 3, 167–172. [4] Spiga, A. et al. (2011) *Icarus*, 212, 504-519. [5] Smith, I.B. et al, (2011) *LPSC* XLII, Abst #2742.

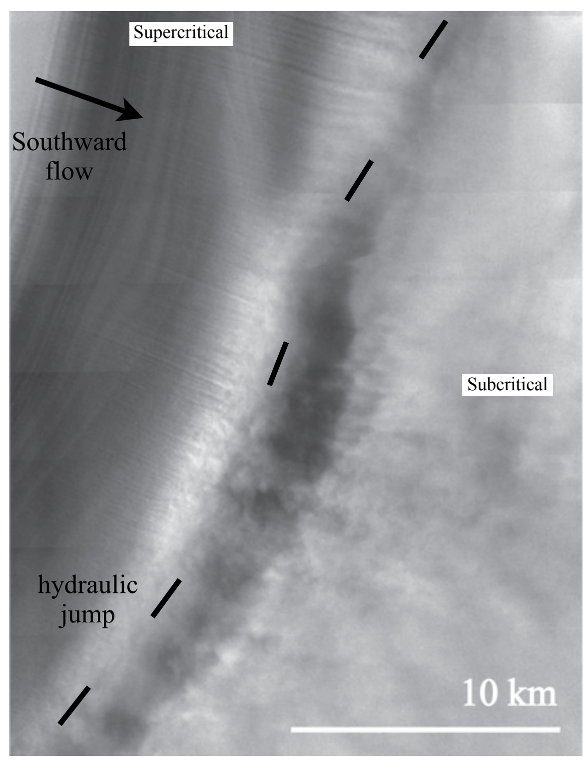


***Figure 2:*** *Portion of THEMIS image V12295001. Katabatic wind event captured with vortices and hydraulic jump where flow thickens by factor of ~ 1.5.*