

## MARTIAN MORAINES AND ICE FLOW MODELS: A PATH TO CONSTRAINING AMAZONIAN OBLIQUITY? Reid A. Parsons<sup>1</sup> <sup>1</sup>Earth and Geographic Sciences, Fitchburg State University, U.S.A.

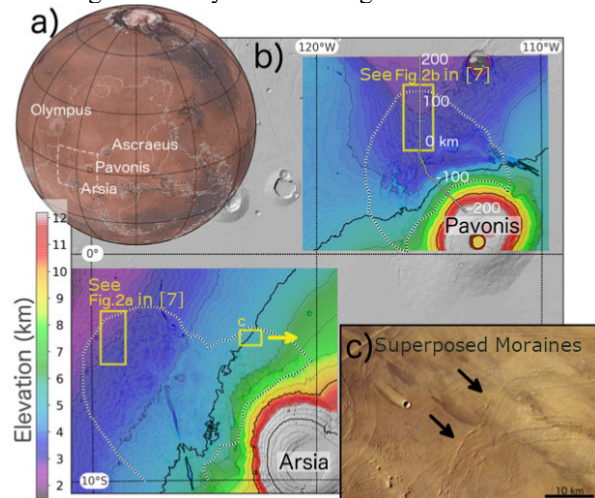
**Introduction:** The accumulation, flow and ablation of volatiles on the Martian surface has resulted in the deposition of moraine-like features in a variety of environments. From CO<sub>2</sub> glaciers at high latitudes likely formed during periods of low obliquity [1] to the extensive equatorial fan-shaped deposits (FSDs) found on the flanks of the Tharsis volcanic edifices (Figure 1a,b,c) which likely formed during high obliquity [2]. In addition, present-day debris-mantled water ice deposits are scattered throughout mid-latitudes and border steep slopes in craters (concentric crater fill) mesas, and massifs (lobate debris aprons). These current and former deposits are likely the result of episodic obliquity-driven volatile redistribution which consisted of multiple episodes of ice accumulation based on ice lobe superposition [3], topographic shape [4, 5], moraine superposition [1, 6, 7] and variation in down-glacier surface boulder concentration [8].

This study focuses on the formation of moraines in the equatorial FSDs using a thermomechanical ice sheet model assuming cold-based glacial conditions as a first step toward extracting more detailed climate information from martian moraines found on the Tharsis Montes (Fig. 1a).

**Moraine formation during advance or retreat?:** The most recent crater density measurements for the Arsia, Pavonis, and Ascraeus FSDs give best-fit ages of 210, 125, and 220 Myr, respectively [9]. Kadish et al. (2014) [9] separated the outer ridged unit of the Arsia FSD into three concentric regions and found a progressive increase in age with distance away from the Arsia edifice. The authors argued that such a relationship would be expected for a thick, slowly retreating ice sheet which deposits moraines during retreat. The remnant ice sheet would shield the interior of the FSD from all but the largest impacts.

The ridged units in the Martian FSDs are assumed to be deposited during glacial recession based on their similarity to terrestrial analogs in the Dry Valleys of Antarctica [10] and Iceland [11, 12]. Although the crater density measurements made by Kadish et al. (2014)[9] appear to support this hypothesis, they do not rule out a scenario in which ridges are deposited during glacial advance. If moraines are deposited at the ice margin during advance, then subsequent burial of the ridge by the overriding ice sheet would shield the ridge from further impacts until obliquity changes gradually allowed the ice to sublimate back into the atmosphere. Thus, the crater density observations provide a surface exposure age estimate (time since ice sheet removal) and do not necessarily represent the age of ridges which may have formed before or during ice sheet advance.

Superposition of remnant ice (smooth unit) on ridges (Fig. 10 of [6]) and intersecting ridge sequences (Fig. 1c) provide geomorphic evidence for episodes of glacial advance following times of retreat within the Pavonis and Arsia FSDs. These features suggest several episodes of retreat and advance may have taken place [6] and also show that ridges can remain preserved even after being overrun by an advancing ice sheet.



**Figure 1:** MOLA Topography of the Arsia and Pavonis FSDs (colored regions) in (b) with the FSDs outlined with black/white dotted line. Distances shown along line in the Pavonis FSD give the model flowline. (c) HRSC image from the Arsia FSD showing intersecting moraines.

**Moraine-forming mechanisms:** In order to deposit a moraine, the ice margin needs to be roughly stationary while ice flow continues to advect ice and englacial/supraglacial debris to the ice margin. The location of the ice margin is a sensitive function of the aerial extent and rates of ablation and accumulation but is stationary when the total mass accumulated over the ice sheet is equal to the mass ablated (steady state).

Given the number of ridges and their close spacing in the FSDs, it is likely that the ridges are not the product of intermittent times of steady-state, but are instead formed by an ice sheet responding to cyclic obliquity changes during times of advance or retreat. Some possibilities include:

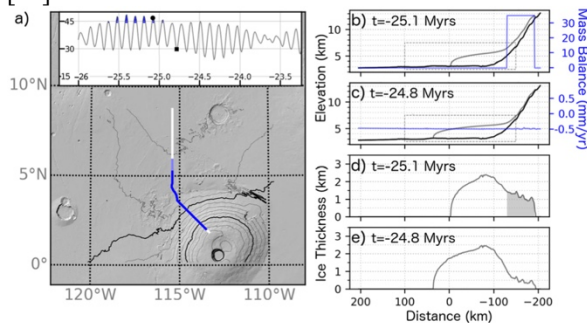
- (1) During times of glacial retreat, the ice margin might be temporarily held fixed by enhanced ice flow during relatively warm periods (during low obliquity) allowing sediment to accumulate in a single location.
- (2) During glacial advance, the margin of the ice deposit may be slowed during times of high obliquity (cooler ice temperatures) which could allow even a low sublimation rate to maintain a temporarily fixed ice margin

position—allowing debris to accumulate and a ridge to form.

**(3)** Renewed ice accumulation at the head of a sublimating ice deposit during high obliquity may produce a kinematic (velocity) wave which may collect surface debris and deposit a ridge upon reaching the ice margin.

These processes may work in concert or independently to produce ridges of varying sizes depending on the dominant process at a given point in time. Furthermore, this list is not exhaustive but represents the most likely mechanisms based on our assumption of cold-based glacial conditions.

**PISM Ice Sheet Model:** In order to investigate the process(es) responsible for depositing ridges at Pavonis Mons an open-source thermomechanical parallel ice sheet model (PISM) was employed [13]. The model inputs assume ice accumulates at a rate of 35 mm/yr in an accumulation zone corresponding with precipitation in GCM results [6] when a critical obliquity of  $45^\circ$  is reached or exceeded. Ice ablation occurs at a rate associated with a protective lag cover 0.5 m in thickness [14].

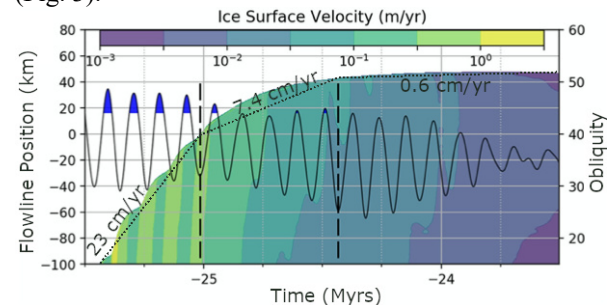


**Figure 2:** Model snapshots at 25.1 and 24.8 Mya illustrating ice mass balance assumptions. (a) MOLA hillshade contour (1 km interval) with model flowline (white line), ice extents (blue lines), and obliquity history in the inset showing episodic accumulation at obliquity  $> 45^\circ$  (blue peaks). Circle illustrates accumulation at  $t = -25.1$  Myrs with associated elevation and ice thickness profiles shown in b, d (accumulation in shaded region), respectively. Box symbol in inset is associated with panels c, e showing ablation.

The model utilizes the well-constrained obliquity history over the last 26 Myrs [15] as a proxy for past obliquity changes. The influence of time-varying surface temperature and ice accumulation on the location, shape, and flow velocity of the ice margin is determined and the influence of a basal heat flux, strain heating, and climate forcings on the ice temperature are accounted for in PISM and provide insight into the timescale and process(es) responsible for ridge formation.

**Results:** In regard to the deposition of ridges, the model provides some insights: **1)** During retreat of the ice margin, ice flow has essentially ceased (Fig. 3) preventing

the advection of debris necessary to form a moraine. **2)** During glacial advance, repetitive pulses of accumulation every 120 kyrs produce kinematic waves which could episodically advect surface debris to the ice margin to create a series of ridges (Fig. 3). **3)** During advance, obliquity-driven surface temperature changes are conducted to the base of the ice sheet, causing slight flow velocity changes which could potentially result in deposition of small ridges **4)** The 0.2 to 4 cm/yr ice margin velocity estimates derived from ridge spacing measurements (assuming deposition occurs every 120 kyrs) agrees well with the simulated ice margin velocity during glacial advance at a flowline position of 0 km (Fig. 3).



**Figure 3:** Model output showing the ice sheet extent (left y-axis) over time (x-axis) with colors corresponding to the ice surface velocity. Fastest surface velocities occur after accumulation events at high obliquity (sinusoidal line, right axis) – potentially advecting large volumes of surface debris to the ice margin. Vertical dashed lines separate chunks of time used for calculating the average velocity of the ice margin as it advances.

Based on these results we hypothesize that ridge deposition occurs during glacial advance when ice flow velocities are high relative to times of retreat. The ridges would subsequently be over-run by advancing ice, but would remain preserved. This new interpretation suggests that the formation of individual ridges takes place over a shorter timescale ( $\sim 120$  kyrs) than previously proposed and provides an opportunity to use ridge sequences to develop a chronology of ice accumulation events which are likely associated with high obliquity oscillations.

**References:** [1] Kreslavsky, M.A. & J.W. Head (2011), *Icarus*, 216(1), 111–115. [2] Forget, F. et al. (2006) *Science*, 311, 368–371. [3] Pierce, T. & D. Crown (2003) *Icarus*, 163(1), 46–65. [4] Parsons, R.A. & J. Holt (2016) *JGR-Planets*, 121. [5] Grindrod, P., and S. Fawcett (2011), *GRL*, 38(L19201). [6] Shean, D.E. et al. (2005) *JGR*, 110(E05001). [7] Parsons, R.A. et al. (2020) *PEPS*, 7:13. [8] Levy, J. et al. (in press) *PNAS*. [9] S. Kadish et al. (2014) *PSS* 91, 52–59. [10] Head, J.W. & Marchant, D.R. (2003) *Geology*, 31(7). [11] Lucchitta, B. (1981) *Icarus*, 45, 264–303. [12] Williams, R. (1978) *In Geol. Soc. Am.*, volume 10, 517. [13] Winkelmann, R. et al. (2011) *The Cryosphere*, 5, 715–726. [14] Chevrier, V. et al. (2008) *Icarus*, 196(2), 459–476. [15] Laskar, J. et al. (2004) *Icarus* 170, 343–364.