Internal Structure of a Glacier on Mars Revealed by Gully Incision

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INTERNAL STRUCTURE OF A GLACIER ON MARS REVEALED BY GULLY INCISION.

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Introduction: We present observations of internal flow structures within a viscous flow feature (VFF; 51.24°W, 42.53°S) interpreted as a debris-covered glacier in Nereidum Montes, Mars (Figures 1–2). The structures (Figure 2B) are exposed in the wall of a gully that is incised through the VFF, parallel to its flow-direction. They are located near to the glacier terminus and appear to connect the glacier bed (or basal ice) to arcuate flow-transverse foliations on its surface (Figure 2A). Such flow-related foliations are common on the surfaces of VFF in Mars' mid-latitudes [e.g., 1], but their relation to VFF-internal structures and ice flow is poorly understood. The internal structures we observe, and their relationships to surface foliations, are reminiscent of up-glacier dipping structures observed near to the termini of glaciers on Earth [e.g., 2, 3]. We combine image and 3D analyses of the VFF-internal structures with 3D numerical modelling to explore their implications for glacial flow, stress regime, and debris transport.

Methods: We use a 1 m/pixel digital elevation model (DEM) derived from 25 cm/pixel High Resolution Imaging Science Experiment (HiRISE) stereo-pair images, along with a false-color (merged IRB) HiRISE image. We measured the dip and strike of the VFF-internal structures using the qgSurf plugin for QGIS, and validated these measurements via a manual dip-and-strike extraction method in ArcGIS 10.7 software. We also input the DEM (and an inferred glacier bed topography derived from it) into ice flow simulations using the Ice Sheet System Model [4], assuming no basal sliding and present-day mean annual surface temperature (210K).

Results and Discussion: The bed of the VFF dips ~12° towards the SW. VFF-internal structures associated with surface foliations dip up-glacier (~NE) at ~20° from the bed (~8° above horizontal). This is inconsistent with formation of the structures by passive bed-parallel ice-accumulation layering without modification by ice flow. The up-glacier-dipping structures and associated surface foliations are spectrally 'redder' than adjacent portions of the VFF, which appear 'bluer' (Figure 2B). This could result from differences in debris concentration and/or surficial dust trapping (e.g. due to roughness variations arising from differences in debris concentration) between the internal structures and the bulk VFF [e.g. 5].

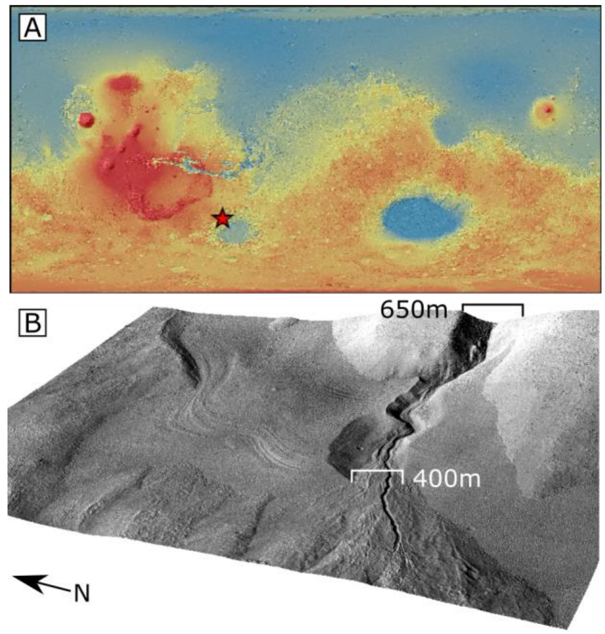

***Figure 1: (A)** Colorized Mars Orbiter Laser Altimeter Elevation map of Mars showing the study location (red star). **(B)** Oblique view of HiRISE image ESP_051036_1370 showing a viscous flow feature interpreted as a debris-covered glacier in Nereidum Montes. The flow is incised by a gully channel that sources at an erosional alcove in the hillslope above the glacier headwall, and terminates in a depositional fan beyond the glacier terminus.*

In contrast to the up-glacier-dipping structures associated with the surface foliations near to the terminus, VFF-internal layers up-glacier of this zone are approximately bed-parallel. This suggests that these layers record passive ice accumulation with little or no influence of post- depositional deformation. Thus, it seems likely that the up-glacier-dipping structures associated with the surface foliations result from locally-induced stresses. There are no visible VFF-internal structures associated with the crevasse field near to the VFF headwall (Figure 2A).

Preliminary modelling experiments which assume a frozen glacier bed (i.e. no basal sliding) suggest that the up-glacier-dipping internal structures occur at the onset of a compressional regime as ice flow slowed towards the VFF terminus. Model results also show

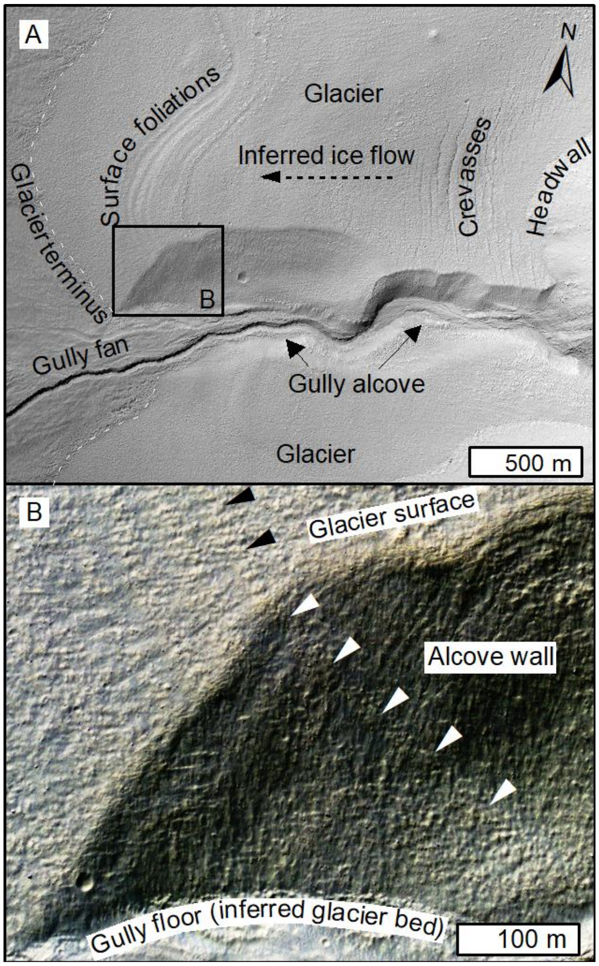

Figure 2: (A) *HiRISE image ESP_015947_1370 of the gully incision through the viscous flow feature shown in Figure 1 (white dotted line is glacier terminus), and transverse to foliations on its surface. Black box is extent of* ***(B),*** *HiRISE merged IRB image ESP_051036_1370 showing the color signature of the VFF-internal structures (e.g. white arrows), and associated surface foliations (black arrows).*

that the up-glacier crevasse field occurs in a region of flow extension.

Up-glacier-dipping structures are common near to the margins of glaciers on Earth. In cold-based glaciers, they have been attributed to folding of ice approaching zones of enhanced ice rigidity near the glacier margin [3]. Ice ablation (e.g. by sublimation) can behead fold crests, leaving linear structures which intersect the glacier surface [3]. Where multiple folds coexist, the outermost typically comprises basal ice with a component of subglacial debris entrained in the presence of interfacial films of liquid water at sub-freezing temperatures [3, 6]. In polythermal glaciers, debris-rich up-glacier-dipping thrust faults can form where sliding wet-based ice converges with cold-based ice [2].

Conclusions: We propose that the up-glacier-dipping VFF-internal structures observed in Nereidum Montes represent englacial shear zones (folds or thrusts), formed under a compressional ice flow regime [e.g., 2]. They could represent transport pathways for englacial and subglacial material to the VFF surface. The vast majority of extant mid-latitude viscous flow features on Mars are thought to have been perennially cold-based [cf. 7–8]; thus we favor the hypothesis that the up-glacier-dipping VFF-internal structures are folds formed under a cold-based thermal regime, and that the fold crests have been removed by ice sublimation [3]. Under this mechanism, the outermost surface foliation, and its corresponding VFF-internal structure, is the most likely to contain subglacial debris.

Implications for Exploration of Subglacial Environments on Mars: The beds of glaciers on Mars are of astrobiological interest due to the availability of water ice and the shelter they could provide to microbes from the harsh radiation environment at Mars' surface [9]. However, current limitations in drilling technology prevent direct exploration of VFF interiors and beds. Our new evidence that surficial debris near to VFF termini could contain a component of englacial and/or subglacial materials suggests that it may be possible to sample those materials without access to the subsurface. This could reduce the potential cost and complexity of future missions that aim to explore englacial and subglacial environments on Mars.

Future Work: Future modelling experiments will explore the possible influences of a range of stress conditions, ice rheologies, mean annual surface temperatures, and perhaps even wet-based glacier sliding, upon the formation of the VFF-internal structures.

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