**TWO-DIMENSIONAL NUMERICAL ICE FLOW MODELING OF AN EMPIRICALLY RECONSTRUCTED MARTIAN GLACIER-LIKE FORM.** S. Brough\(^1\), B. Hubbard\(^1\) and A. Hubbard\(^1,2\),

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**Introduction:** Landforms of glacial origin have been identified and described across large areas of Mars’ mid-latitudes. Based on data from the Shallow Radar (SHARAD) on board the Mars Reconnaissance Orbiter (MRO), the composition of these ice-rich landforms is consistent with relatively pure water ice [1–2], and their surface morphologies indicative of viscous flow of that ice. Collectively these landforms have become known as viscous flow features (VFFs) [3] and are hypothesized to have formed during past periods of high obliquity-induced glaciation [4].

Although recent evidence suggests that these ice-rich landforms represent a substantial store of water, equivalent to a ~1 - 2.5 m-thick global layer [5], there is also a large body of evidence suggesting that VFFs are the relict remains of larger ice masses that have receded since a last martian glacial maximum (‘LMGM’[6]). The superposed nature of some VFFs has led to the suggestion of recurrent glacial phases, with at least one ‘local’ glacial phase advancing over an earlier ‘regional’ glaciation [7–8]. Despite these inferred changes – and their subsequent implications for the reconstruction of past martian climate – several fundamental planetary and glaciological issues remain; for example debate still persists regarding the spatial and temporal nature of formation, current and former extent, and dynamic evolution of VFFs [see 9].

Here we present initial results from a two-dimensional (2D) numerical model of ice flow for an empirically reconstructed GLF [10] – a distinctive subtype of VFFs, similar in planform appearance to valley or debris-covered glaciers on Earth – in eastern Hellas Planitia, Mars (~38.65°S and 113.16°E).

**Methods:** GLF reconstruction: The numerical model boundary conditions require the bed and surface geometry of the GLF’s former extent to be known. Therefore, we reconstructed the GLF’s former three-dimensional extent (Fig. 1 [10]) using the perfect-plasticity approximation for ice flow [11], tuned to martian conditions (e.g. gravity \(\text{g} = 3.71 \text{ ms}^{-1}\)). We produced three reconstruction scenarios by amending the yield strength parameter to Shallow Radar (SHARAD)-validated ice thickness measurements on Mars [12]. Our reconstructions comprised of a mean yield strength (22 kPa), bracketed by a lower (12 kPa) and upper (38 kPa) boundary scenario. The bed and surface values were subsequently extracted every 100 m along a central flowline and used as input into the numerical model (Fig. 1d [10]).

**Numerical model:** Our approach uses a two-dimensional model of ice flow which is based on a finite-difference first-order solution of the ice-flow equations [13], thereby including includes the effects of longitudinal or deviatoric stress. Although this scheme is much more elaborate than the often used driving stress approximation, these stresses have been shown to be important in valley-glacier modelling, where tensile and compressive stresses can be induced by local changes in gradients at the glacier surface and bed, and by spatial variability in basal and lateral friction [14].

The boundary conditions required for such models are glacier geometry, ice viscosity and the basal sliding distribution. As the distribution of basal sliding is seldom understood in martian ice masses, and little evidence of basal sliding is preserved in the geomorphic record, we set the effect of basal sliding to zero (i.e. ice is below the pressure melting point). The ice viscosity is based on Glen’s flow law and requires the definition of the flow-law exponent (\(n\)), which we set to the generally used value 3 [15], and rate factor \((A \mu^{-1} \text{ bar}^{-1})\), which is strongly dependent on ice temperature and water content (below).

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![Fig. 1: (a)-(c) Ice thickness of reconstructed GLF. (d) 100 m ice surface elevation along central flowline [10].](https://example.com/fig1.png)
**Experiment aims and design:** Our aims are two-fold: (i) to investigate whether our empirically-reconstructed ice bed and surface are sufficiently accurate to be modeled using realistic martian parameter values; and (ii) if (i) is successful, to investigate the long-term temperature requirement to yield surface ice flow rates consistent with those recently reconstructed from boulder trails observed at a GLF in Prontonilus Mensae [16], for our study GLF.

We apply a 2D higher-order, plane-strain numerical model to the central flowline under steady-state conditions varying the rate factor parameter, A, according to a range of temperatures from $0 - 100 \, ^\circ C$.

**Results and conclusions:** The model converges for all reconstruction scenarios and temperatures, yielding a range of 2D stress and strain configurations for our reconstructed GLF (e.g. Fig. 2). Output from all model experiments reveals a similar pattern of englacial stress distribution (Fig. 2). Close to the headwall a region of positive-tensile $T_{xx}$ indicates extensional flow – though not enough to initiate localized crevassing, whereas across its terminus, the GLF experiences a region of negative $T_{xx}$ concurrent with compressive flow. The magnitude of longitudinal stress gradients is $\sim 5-28 \, \%$ of the observed basal shear stress distribution, which is relatively uniform with mean values of 12.5, 21.6 and 36.5 kPa for each of our lower, mean and upper reconstruction scenarios, respectively (e.g. Fig. 2).

The mean annual surface velocity across the three reconstruction scenarios show a similar pattern, with motion recorded at temperatures ranging from $0 \, ^\circ C - \sim -60 - -70 \, ^\circ C$ (Fig. 3). Below this value, motion is negligible ($<10^{-5} \, m \, a^{-1}$) and may also be influenced by rounding uncertainty in the numerical model. This envelope of temperatures is not unrealistic and also overlaps with other VFF modeling studies [9].

In order to simulate flow rates to 7.5 mm a$^{-1}$, comparable for other martian GLFs [16], the model experiments reveal a mean temperature perturbation for the GLF of between $\sim -7.5$ (12 kPa) and $-27 \, ^\circ C$ (38 kPa), with a best-estimate of $\sim -15.5 \, ^\circ C$ for the 22 kPa reconstruction scenario (Fig. 3).

![Mean velocity vs temperature for our three reconstruction scenarios.](image)

**Fig. 3:** Mean velocity vs temperature for our three reconstruction scenarios. The grey box indicates the range of surface velocities identified by [16]. The thin horizontal and vertical dashed black lines represent the best estimate flow speed of 7.5 mm a$^{-1}$, and the corresponding temperature required to meet this velocity for each of the three reconstruction scenarios, respectively.

**References:**