Glacier-Linked Eskers on Mars: Environments of Recent Wet-Based Glaciation From Numerical Models

Conference or Workshop Item

GLACIER-LINKED ESKERS ON MARS: ENVIRONMENTS OF RECENT WET-BASED GLACIATION FROM NUMERICAL MODELS. F. E. G. Butcher[1], N. S. Arnold[2], M. R. Balme[1], C. Gallagher[3,4], S. J. Conway[5], A. Hagermann[1], and S. R. Lewis[1], [1]School of Physical Sciences, Open University, Milton Keynes, UK (frances.butcher@open.ac.uk), [2]Scott Polar Research Institute, University of Cambridge, Cambridge, UK, [3]UCD School of Geography, University College Dublin, Dublin 4, Ireland, [4]UCD Earth Institute, University College Dublin, Dublin 4, Ireland, [5]CNRS, UMR 6112 Laboratoire de Planétologie et Géodynamique, Université de Nantes, France.

Introduction: We recently identified an esker emerging from a putative debris-covered glacier (viscous flow feature; VFF) in the Tempe Terra region of Mars' northern mid-latitudes [1]. Eskers are ridges of sediment deposited by meltwater in conduits within glacial ice. This newly-identified VFF-linked esker indicates that its parent glacier underwent basal melting ~110 Myr ago, at a similar time to the formation of the only other known VFF-linked esker, in the Phlegra Montes region, ~150 Myr ago [2]. The parent VFF of these eskers both occupy tectonic rifts/graben [1-2].

Evidence for past melting of VFF remains extremely rare. The VFF-linked eskers likely represent transient, localized melting [2], but their existence challenges the assumption that mid-latitude VFF have been ubiquitously cold-based since their formation [3]. Therefore, we explored the environmental conditions required for basal melting of VFF on Mars, considering the effect of strain heating for the first time. We test whether locally-elevated geothermal heat flux associated with the similar tectonic rift/graben settings of the two VFF-linked eskers could have permitted glacial melting despite cold late Amazonian climates [1-2].

Methods: Using a 1D model of heat flow through glacial ice, we explored the environmental conditions required for basal melting of VFF on Mars [1]. We calculated the temperature at the glacier bed by comparing possible rates of geothermal and viscous strain heating of the basal ice with the rate of heat loss to the ice surface (Fig 1)[1]. Assuming a linear vertical temperature profile through the ice, we derived the temperature of the basal ice from:

$$dT = H\,Q/k_T \qquad (1)$$

where dT is the difference between the mean annual surface temperature (varied between 190-230 K) and the temperature of the basal ice (K), H is ice thickness (varied between 500-1500 m), k_T is thermal conductivity of the ice (assumed to be 2.5 $Wm^{-1}K^{-1}$ [4]), and Q is basal heating (Wm^{-2}), equal to geothermal heat flux (varied between 20-100 mWm^{-2}) plus internal strain heating [1].

Our initial experiments considered only geothermal heating as a heat input to the basal ice (Fig 1a). In subsequent experiments (Fig 1b-c), we incorporated strain heating as an additional heat input to the basal ice [1].

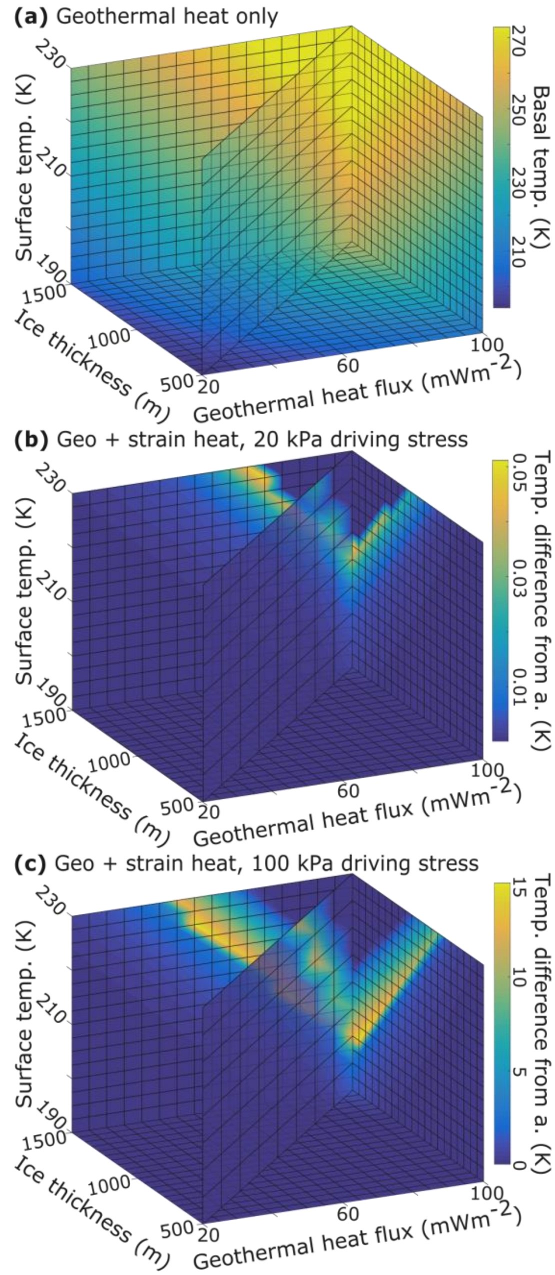

***Fig 1**. 3D projections of: **(a)** calculated basal temperatures for geothermal heat only, **(b)** and **(c)** temperature changes relative to (a) induced by strain heating for driving stresses of 20 kPa and 100 kPa, respectively. Top right corner is at 273 K, so no change occurs here. Adapted from [1].*

Strain heating has not been included as a potential heat source in previous martian studies [e.g. 4]. We calculated volumetric strain heating (P, Wm^{-3}) according to:

$$P = 2 A_T \sigma_{xz}^4 \qquad (2)\ [5]$$

where A_T is the temperature-dependent flow rate factor for clean ice ($s^{-1}Pa^{-3}$)[6] and σ_{xz} is shear stress (Pa). We simulated a range of basal driving (shear) stress conditions (20-100 kPa; calculated as $\rho\ g\ h\ tan\ \alpha$, where ρ is ice density, g is gravity, h is depth within the VFF, and α is ice surface slope) by varying ice surface slope (~0.1-3.5°) with ice thickness.

To estimate basal temperature for each scenario, we calculated basal temperature using equation (1). This informed estimations of A_T [from 6, p. 75], which we then inserted into equation (2) to calculate P in the lowest 10% of the ice thickness. We integrated P over this depth to obtain basal strain heating (Wm^{-2}). Adding strain heat to the geothermal heat, we extracted new basal temperature (eqn. 2) and A_T values, iterating until basal temperatures stabilized or reached 273 K [1].

We aimed to constrain a first-order estimate of the most conservative environmental scenario required for basal melting. Hence, we assumed that neither debris-cover (which reduces heat loss to the glacier surface, warming basal ice), nor impurities (e.g. salts, which lower the melting point of ice) were present. There remains considerable uncertainty over the effect of impurities upon the rheology of ice on both Earth and Mars [e.g. 7]; hence, we applied the value of A_T for clean terrestrial ice [6]. See [1] for the effect of variations in A_T upon our results.

Results and Discussion: Assuming that geothermal heat is the only source of heat to the basal ice (Fig 1a), warm surface temperatures (>215 K), thick ice (>1100 m), and high geothermal heat flux (80 mWm^{-2}) are required to induce temperatures approaching 273K. These conditions seem unlikely for late Amazonian Mars [e.g. 8].

Experiments incorporating strain heating for the first time showed a greatly expanded range of environmental conditions over which basal melting of VFF could occur (Fig 1b-c). Basal temperatures approach 273 K for mean annual surface temperatures >205 K, ice thicknesses >900 m, or geothermal heat fluxes >50 mWm^{-2}, given local driving stresses of 100 kPa (Fig 1c). Within our experiments, strain heating provided up to 14.5K of additional basal warming (Fig 1c), significantly reducing magnitude of the requisite geothermal heat flux anomaly above the modelled global average of 23-27 mWm^{-2} [8]. Morphologically 'fresh' fault scarps proximal to VFF-linked esker in Tempe Terra indicate very recent tectonism, and potentially elevated geothermal heat flux [1].

The contribution of strain heating to warming of basal ice (Fig 1b-c) increases non-linearly with temperature (A_T increases by 3 orders of magnitude between 220-270 K) and driving stress (raised to fourth power in eqn. 2). While average driving stresses calculated for bulk VFF on Mars (~20-35 kPa) [9] are low compared to typical terrestrial glaciers (~50-200 kPa) [6], it is highly likely that localized variations in ice thickness and surface slope induce large local-scale deviations from these average driving stresses. Thus, the potential influence of strain heating upon VFF melting should not be ignored. The VFF-linked esker in Tempe Terra is located in an area of potentially strong convergence of ice flow from the steep walls of the tectonic rift in which it is located, which could be particularly conducive to strain heating [1].

Conclusions: We have derived first-order estimates of the environmental conditions required for basal melting of putative debris-covered glaciers (VFF), and hence formation of rare VFF-linked eskers, on Mars during the late Amazonian [1]. We find that, in combination with locally elevated geothermal heat flux, strain heating was potentially of great importance for initiating basal melting [1]. For an assumed basal driving stress of 100 kPa (as could occur in areas of locally thick ice and/or steep slopes), we estimate that basal melting would have been possible under mean annual temperatures >205 K, geothermal heat fluxes >50 mWm^{-2}, and ice thicknesses >900 m [1]. We find these conditions to be plausible given the geomorphic evidence [1]. We are now using the high-order 3D JPL/University of California Ice Sheet System Model [10] to explore in more detail the roles of strain and geothermal heating in VFF-linked esker formation.

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References: [1] Butcher F. E. G. et al. (2017) *JGR Planets, 122*, https://doi.org/10.1002/2017JE005434. [2] Gallagher C. and Balme M. R. (2015) *Earth Planet. Sci. Lett., 431*, 96-109. [3] Marchant D. R. and Head J. W. (2007) *Icarus, 192*, 187-222. [4] Cassanelli J. P. et al. (2015) *Planet. Space. Sci., 108*, 54-65. [5] Lüthi M. P. et al. (2015) *The Cryosphere, 9(1)*, 245-253. [6] Cuffey K. M., and Paterson W. S. B. (2010) *The Physics of Glaciers (4th ed.)*, Oxford: Elsevier Science. [7] Parsons R. A. et al. (2011) *Icarus, 214(1)*, 246-257. [8] Plesa A. –C. et al. (2016) *JGR Planets, 121*, 2386-2403. [9] Karlsson N. B. et al. (2015) *Geophys. Res. Lett., 42*, 2627-2633. [10] Larour E. et al. (2012) *JGR. Earth Surf., 117(F1)*, F01022.