VALLEY GLACIERS ON MARS: CALCULATION OF FLOW RATE AND THICKNESS.

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Introduction: On Mars, ice masses 10 m to 100 m thick, on slopes of about 20 to 30 degrees, have strain rates in the range necessary to produce glacier-like flows (GLF) in tens of thousands years or more [1,2]. Here, I demonstrate how to calculate strain rates in a manner more applicable to valley GLF such as in Dao Vallis (Figure 1), which are typically on slopes of about 1 degree and thick enough for flow rates to be significantly affected by geothermal heating.

Physics: Strain rates can be calculated using Glen's Law, **(1)** $\varepsilon = A\tau^n$, where ε is strain rate, A is a variable that relates viscosity to temperature, τ is sheer stress, and n is a variable related to the deformation rheology of ice (n = 3 is recommended) [3]. Terrestrial based laboratory and field data indicate that A decreases near-exponentially with temperature [3]. However, because temperatures on Mars are well below those found on Earth, values of A must be extrapolated from the terrestrial temperature regime data. For pure ice, A is: **(2)** $A = 0.6e\text{-}2\exp(-(7{,}800/T))$, where T is temperature [4].

Geothermal heat (Q) significantly increases glacier surface velocities because temperature and shear stress increases with depth. With geothermal heat, viscosity is lowest where the shear stress is greatest, inducing higher strain rates. The geothermal profile can be calculated by: **(3)** $T(z) = T(s) + Qz/k$, where T(z) is temperature at depth z , T(s) is the average surface temperature, and k is the thermal conductivity [3]. Yearly average mid-latitude temperature for Mars can be taken as 180 K, and geothermal heat flux is unknown but .030 Wm^{-2} is considered reasonable [5]. Thermal conductivity of pure ice is derived from: **(4)** $k = 9.828 \exp(-5.7e\text{-}3T)$, which yields 3.3 W/mK at 192 K [3].

The thickness (h) of a valley GLF can be estimated by: **(5)** $h = \tau / (F\rho g \sin\alpha)$, where F is a shape factor related to glacier width to thickness ratio, ρ is density (916 kg m^{-3} for pure ice), g is gravitational acceleration (3.7 ms^{-2} for Mars), and α the surface slope [3,5]. Surface slope can be determined from MOLA data and I calculate an average value of 1.27 degrees for a 24-km long section of the valley GLF in Figure 1. For terrestrial valley glaciers, the basal shear stresses are usually between 50 and 150 kPa, and the shape factor is usually between 0.5 (thickest and narrowest) and 0.9 (thinnest and widest). For comparison, the shape factor of terrestrial ice sheets where the width to thickness ratio approaches infinity, is usually taken as 1. Assuming pure ice, a basal shear stress of 100 kPa, and a shape factor of 0.5, a thickness of 2,700 m is derived from **(5)** for the valley GLF in Figure 1. The geothermal profile can now be calculated (Figure 2a).

However, obliquity cycles cause the average surface temperatures at mid-latitudes to fluctuate. I assume an average surface temperature oscillation with an amplitude of 15 K and a period of 129,000 years [5]. The effect on the geothermal profile through time is: **(6)** $T(z) = T(g) + T(o)\exp(-z/z^*)\sin((2\pi t/P) - (z/z^*))$, where T(g) is the geothermal profile from equation **(3)**, T(o) is the half amplitude (7.5 K), P is period of oscillation, t = P/4, and z* is derived from: **(7)** $z^* = (\kappa P/\pi)^{-1/2}$, where κ (thermal diffusivity) is equal to $k/\rho c$, where c (specific heat capacity) is given by: **(8)** $c = 152.5 + 7.122T$, or 1,520 J/kgK at 192 K [3]. The effect of obliquity on the geothermal profile can now be calculated (Figure 2a)

Shear stress is given by, **(9)** $\tau = F\rho g z \sin\alpha$. Finally, integrating strain rates from **(1)** gives surface velocities near 2 mm/yr for the valley GLF in Figure 1 (Figure 2b). This velocity is comparable to those of Antarctic ice sheets on very low gradients.

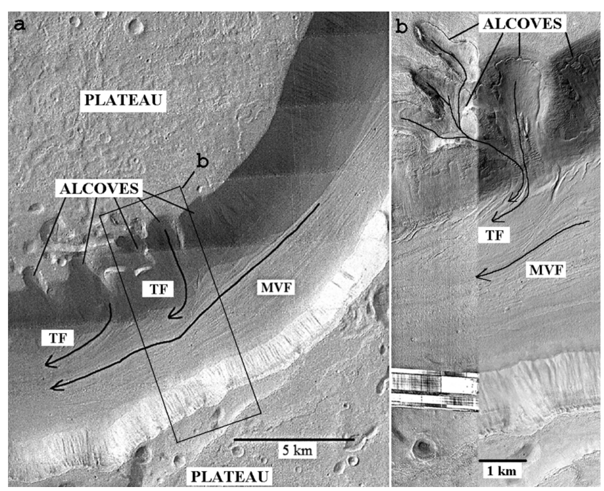

Figure 1: Main-valley glacier-like flow (MVF) with tributaries (TF). Arrows are probable flow directions. Dao Vallis, 36°S 269°W. North top, lighting upper left. a) THEMIS 20020807. b) M09-05715/M03-04950.

Discussion: The above calculations assume pure ice, which is probably unrealistic for many GLF because they are likely comprised mostly of ice-rich mantling [6,7,8]. Ice-rich mantling on flat surfaces such as plateaus probably contains only dust and other particles that settled on the surface of the mantling. Ice will be ablated and deposited in cycles tied to obliquity, with sublimation lag being concentrated on the surface through periods of ablation, which may increase the dust and debris fraction of mantling with each cycle [9,8,4]. The topography where valley and slope GLF are located (Figure 1) and the flow itself will increase the debris fraction further. This is because debris can fall on to GLF surfaces from nearby slopes through mass movement processes, and material may be eroded and plucked from the ground by the base of GLF. Because it is not yet possible to ascertain the fraction of dust and debris in GLF, calculated flow rates are rough approximations.

The thickness and flow rate history of long-lived valley GLF may be somewhat self governing. Most deformation occurs in the lower portion of valley GLF because temperatures and shear stresses increase with depth (Figure 2). After a period of mantling, flow and ablation will thin valley GLF. Because maximum temperature and shear stress within valley GLF decrease inversely with thickness, flow rates will decrease as GLF thin, reducing the rate of thinning caused by flow. The ablation rate will be unaffected by thickness, but will decrease as sublimation lag thickens [9]. Conversely, during a period of mantling, flow rates will increase as valley GLF thicken. These two effects may have acted to preserve and to regulate the flow rates of valley GLF on Mars through many orbital cycles by inducing cycles of flow and stagnation.

References: [1] Turtle E. et al. (2001) *LPS XXXII,* Abstract #2044. [2] Milliken R. E. et al. (2002) *LPS XXXIII,* Abstract #1870. [3] Paterson W. S. B. (2001) *The Physics of Glaciers*. [4] Arfstrom J. D. (in prep.). [5] Mellon M. T. and Phillips R. J. (2001) *JGR,* 106, E10, 23165-26179. [6] Mustard J. F. et al. (2001) *Nature*, 412, 411-413. [7] Christensen, P. R. (2003) *Nature*, 422, 45-47. [8] Arfstrom J. D. and Hartmann W. K. (submitted) *Icarus.* [9] Richardson M. I. et al. (2003) *LPS XXXIV,* Abstract #1281.

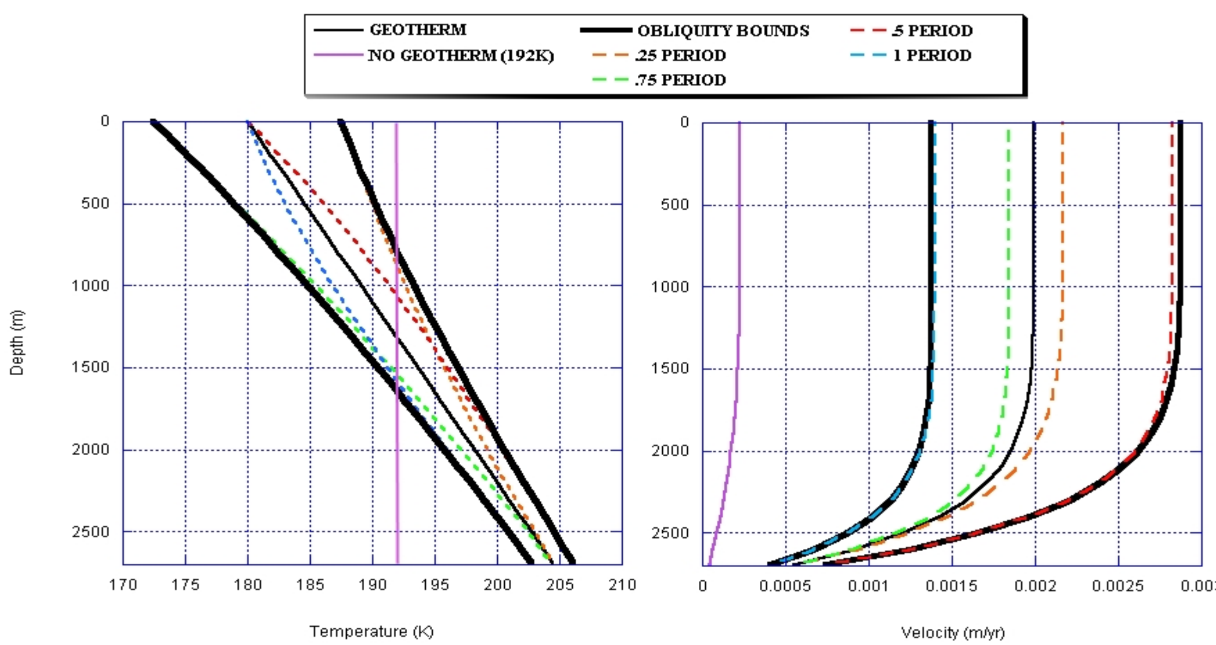

Figure 2a: Geothermal profiles of pure ice on Mars. "Geotherm" is profile for average surface T of 180 K. "Obliquity Bounds" indicate range of 15 K/129,000 year oscillation. Dashed lines are 1/4 periods of the oscillation. Vertical line is average of "Geotherm".

Figure 2b: Velocities of a 2,700-m thick glacier (pure ice) on a 1.27 degree slope on Mars with T profiles indicated in 2a. Surface velocities are read at zero depth. Note pronounced increase in velocities for geotherm vs. no geotherm, and effect of oscillations.