EQUILIBRATION TIMESCALES FOR ICE FLOW ON GEMINA LINGULA INDICATE ENHANCED FLOW AT LOW TEMPERATURES. M.R. Koutnik[1], D.P. Winebrenner[2,1], E.D. Waddington[1], A.V. Pathare[3], and S. Byrne[4]. [1]Dept. of Earth and Space Sciences, University of Washington, Seattle, WA 98195 USA, mkoutnik@u.washington.edu; [2]Applied Physics Laboratory, University of Washington, Seattle, WA 98185 USA, dpw@apl.washington.edu; [3]Planetary Science Institute, 1700 E. Fort Lowell Rd., Ste. 106, Tucson, AZ 857194; [4]Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721.

Introduction: On Earth and Mars, ice masses experience temporal changes in precipitation, temperature, and radiation, i.e., climate. In response to a change in climate, ice masses adjust in length and thickness. When mass exchange at the surface is equilibrated by ice flow, the response toward a new equilibrium has a characteristic timescale, which depends on surface mass flux rates and on near-basal ice temperature and other rheological factors [1].

The shape of an ice mass near equilibrium has a generic, predictable shape (again, as a function of ice temperature, rheology and surface mass flux distribution). Topography between troughs. over a wide area on Gemina Lingula (GL) in the Martian North Polar Layered Deposits (NPLD), has precisely the shape of such an ice mass [2]. Moreover, stratigraphy within GL, as observed with orbital sounding radar, further supports a scenario of significant ice flow in the past, at a time when locations now occupied by troughs were filled with ice [3].

The time available to establish near-equilibrium topography on GL (starting from some prior, unknown state) is bounded above by independent estimates of the age of the NPLD. We have shown previously that computed equilibration timescales for pure water ice (Ih), at plausible current temperatures at the base of the NPLD, and for a range of plausible surface mass fluxes, easily exceed the age of the solar system [4]. For flow of pure ice to shape GL in less than 5 MY (a popular estimate for the age of the NPLD [5]) would require basal temperatures of about 250 K [4]. Such high temperatures seem highly implausible given current understanding of Martian polar surface temperatures [6] and heat fluxes from the Martian interior [5].

Here we show that with ice-flow enhancement at values comparable to those observed in Taylor Glacier, East Antarctica [7], equilibration timescales for an ice mass like GL can be less than a few million years for basal temperatures that are only modestly warmer than today. This suggests to us that ice-flow enhancement likely had a role in facilitating flow at least across GL. Although flow enhancement (i.e., softening of the ice rheology compared to pure ice) in Taylor Glacier appears to be associated with a debris-rich basal layer at roughly 256 K, enhancement on Mars, if any, may be associated with other impurities at lower temperatures, as we discuss below.

Theory of Equilibration Timescales: The relationship between shear strain rate and shear stress for ice (i.e., the ice flow law) is found empirically to be:

$$\dot{\varepsilon}_{xz} = EA(\theta)\tau_{xz}^{n} \qquad (1)$$

where $\dot{\varepsilon}_{xz}$ is the simple-shear strain rate along a horizontal plane, E is the dimensionless ice-flow enhancement factor, θ is the near-basal ice temperature (because strain is greatest near the bed), τ_{xz} is the shear stress along a horizontal plane, the flow-law exponent, n, is found empirically for glacial flow on Earth [12] and more recently for past flow on GL [2] to be 3, and $A(\theta)$ is the temperature-dependent softness parameter for ice Ih (cf. [1], pg. 86) and follows an Arrhenius relationship:

$$A(\theta) = A_0 \exp\left(\frac{-Q}{R_0\theta}\right) \qquad (2)$$

where Q is the activation energy for dislocation creep (~60 kJ/mol for temperatures below 263K), A_0 is the temperature-independent ice softness parameter (A_0 ~ $4\text{x}10^{-4}\,kPa^{-3}s^{-1}$ for $n=3$), and R_0 is the universal gas constant.

The quantities in equations 1 and 2 can be related to the topography and spatial distribution of surface mass fluxes on an ice mass by means of a model in which ice flow moves mass to equilibrate surface accumulation and ablation in differing locations, with the driving stress for ice flow at a given point set by the surface slope at that point. This was the approach taken by Paterson [13], and which we adapted for use on Gemina Lingula [2], under the assumption of a very simple distribution of surface accumulation and ablation, namely a constant accumulation rate, c, along a flow line from an ice divide down (in elevation) to an equilibrium line location, then a constant ablation rate, $a>0$, from the equilibrium line down to the terminus. Within this model, the maximum ice thickness, H, is related to the length of the flow line, L, according to:

$$\left(\frac{H^2}{L}\right)^{1+\frac{1}{n}} = \frac{2(n+2)^{1/n}}{\rho g}\left[\frac{c}{2EA(\theta)}\right]^{\frac{1}{n}}\left(\frac{a}{c+a}\right)^{\frac{1}{n}} \qquad (3)$$

where ρ is the density of the ice and g is the acceleration due to gravity (3.72 ms^{-2} at the surface of Mars). This equation can be rearranged to show the relationship between the terminal ablation rate, a, and the ice rheological factor including both flow enhancement and temperature, $EA(\theta)$:

$$a = \left(\frac{H^2}{L}\right)^{n+1} \frac{(\rho g)^n}{2^{n-1}(n+2)} EA(\theta)\left(\frac{1+c/a}{c/a}\right) \quad (4)$$

Finally, the response of ice masses to small perturbations can be estimated using linearized kinematic wave theory. From this fundamental theory, Johannesson et al. [14] showed that the e-folding time for an ice mass to evolve from an initial to a new steady-state, following a change in climate, i.e., the equilibration timescale, is approximately:

$$T_V = \frac{H}{a}. \quad (5)$$

Equations 4 and 5, together with specific values for *H, L, c/a* and *n* provide a basis for computing either the equilibration timescale, T_V or terminal ablation rate, a.

Results for Gemina Lingula: For *H, L, c/a,* and *n*, we use values from a representative model fit on Gemina Lingula from [2], specifically H=2 km, L=317 km, c/a=0.56, and n=3.

Figure 1 shows T_V and a as functions of the near-basal ice temperature (over a range from 180 - 260 K) and of the ice-flow enhancement factor (over a range from 1-100). In Antarctica and in Greenland the enhancement factor typically has a value of 1-3 at temperatures down to about 260k [1], though it has been estimated to have a value of over 50 at Taylor Glacier, East Antarctica at a basal temperature near 256 K[7]. Timescales with no enhancement (i.e., pure ice with isotropic crystal fabric) are long compared to the estimated age of the NPLD, whereas an enhancement factor of 50 and temperature of 220K yields timescales on the order of 1 MY.

Discussion: Prospective components of dust in Martian ice such as perchlorate [8] and hydrogen peroxide [9] could lower eutectic temperatures and soften ice at temperatures well below 273 K, similar to softening observed in ice doped with sulfuric acid [10]. Chemically active dust is also observed in terrestrial ice sheets to be associated with changes in ice crystal fabrics that effectively soften ice [1,11]. The acid and dust concentrations necessary for softening are small compared with the upper bound on impurity concentration inferred from radar observations [5]. Thus there are plausible mechanisms for softening by impurities in Martian ice which are consistent with evidence for past ice flow and timescale arguments on GL.

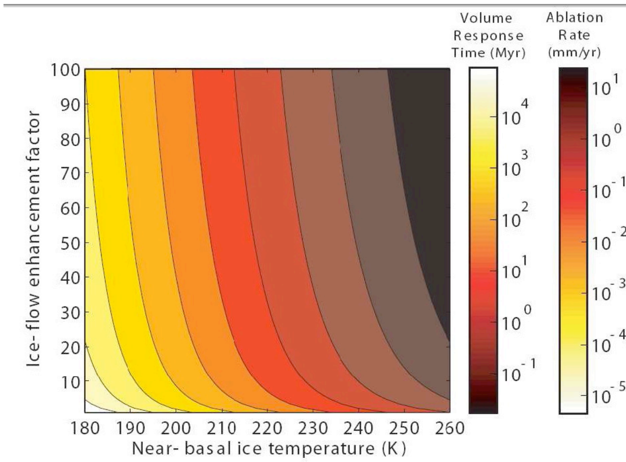

Figure 1. Contours of equilibration timescale and terminal ablation rate for pairs of near-basal temperature and ice flow enhancement factor. For H=1 km, multiply these values by 0.5. For H=3 km, multiply these values by 1.5.

We suggest that evidence for flow enhancement at low temperatures in GL may motivate consideration of whether such enhancement is limited to the NPLD, or may occur also in a range of prospective Martian ice flow scenarios, including past mid-latitude glaciation and present-day lobate debris aprons.

Our results motivate future work to further understand the actual role impurities may have in softening ice at low temperatures. We think that this can be best understood by new experimental work on ice rheology and recrystallization in perchlorate- or peroxide-laden dusty water ice.

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