WAS MARTIAN ICE WARMER IN THE PAST? M. R. Koutnik[1], E.D. Waddington[1], D.P. Winebrenner[1,2], and T.A. Neumann[3] [1]University of Washington, Department of Earth and Space Sciences, Box 351310, Seattle, WA 98195 (mkoutnik@ess.washington.edu), [2]Applied Physics Laboratory, 1013 NE 40th Street, Seattle, WA 98105, [3]University of Vermont, Department of Geology, Burlington, VT 05405.

Introduction: An ice mass that has experienced steady-state ice flow has a characteristic surface shape. A wide range of pairs of ice temperature and mass-balance rate (accumulation and ablation) can create identical surface shapes; if the mass-balance rate is higher, then the ice temperature must also be warmer. It takes time for any ice mass to achieve a steady-state shape. Warmer temperatures and higher mass-balance rates allow the ice mass to respond faster.

Winebrenner et al. [1] found that the Gemina Lingula portion of the Martian North Polar Layered Deposits (NPLD) has a shape characteristic of a flowing steady-state ice mass. Assuming a mass-balance pattern comprising a zone of uniform accumulation and a zone of uniform ablation (separated at the equilibrium line), they fit a rate-independent model to the inter-trough Mars Orbiter Laser Altimeter (MOLA) topography and reconstructed the characteristic shape shown in Figure 1. Using simple ice dynamics, we can calculate a range of possible mass-balance rates and response time-scales [e.g. 2, 3] associated with a plausible range of ice temperatures to create this geometry. By putting upper bounds on the response time, we put lower bounds on the past ice temperature and mass-balance rate.

We find that the conditions on present-day Mars are inconsistent with the present-day shape of Gemina Lingula. We also find that Gemina Lingula ice had to be warmer in the past to develop its present-day surface shape in a physically reasonable interval of time.

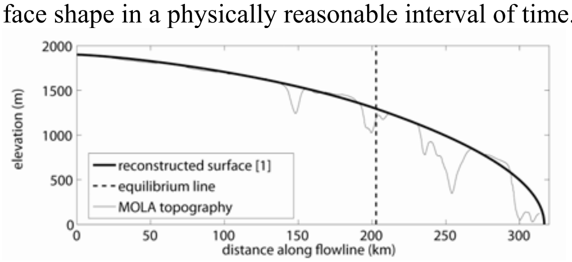

Figure 1. Reconstructed ice surface from Winebrenner et al. [1] along a flowline across Gemini Lingula, NPLD, compared to the MOLA topography. The equilibrium line separates accumulation and ablation zones.

Ice Dynamics: We assume a simple, dimensional representation of a steady-state ice surface [e.g. 4, p. 243]. The average horizontal ice velocity is given by

$$\bar{u} = \frac{2A(T)}{(n+2)}(\rho g \alpha)^n h^{h+1} \tag{1}$$

where n is the flow-law exponent, ρ is density, g is gravity, α is the surface slope, h is the ice thickness, and the softness parameter, A, is a function of temperature, T, following an Arrhenius relationship [e.g. 4]. Since the accumulation rate and ablation rate are both unknown, we use an idealized model that assumes all ablation occurs by calving at the edge (the surface profile is only a function of the accumulation rate). Using Equation 1 in the continuity equation, $cx = h\bar{u}$, where c is the accumulation rate and x is the distance along the flowline, gives a differential equation with the solution [e.g. 4, pg. 243],

$$H^{2+\frac{2}{n}} = K\left(L^{1+1/n}\right) \tag{2}$$

$$K = \frac{2(n+2)^{1/n}}{\rho g}\left(\frac{c}{2A(T)}\right)^{1/n} \tag{3}$$

for $h = H$ at $x = 0$, where H is the maximum ice thickness and L is the flowline length. For any given ice temperature, maximum ice thickness, and length, we can estimate the accumulation rate from Equation 2.

Volume Response Time: The response time is an e-folding time. Nye [2] showed how the response of ice masses to small perturbations can be determined using linearized kinematic wave theory. From this solution for a spatially uniform step-change in mass balance from $b_0(x)$ to $b_0(x) + b_1$, Jóhannesson et al. [3] show that the response time to approach the new total ice volume (the volume response time) is:

$$\tau_V = -\frac{H_{0\max}}{b_0(l_0)} \tag{4}$$

where $H_{0\ \max}$ is the maximum ice thickness in the datum state and $b_0(l_0)$ is the mass balance (ablation) at the terminus in the datum state.

Present-day Mars: We explore possible combinations of accumulation rate, ablation rate, and ice temperature that correspond to the geometry in Figure 1 [1] and the mass-balance pattern inferred by Winebrenner et al. [1], with a ratio of accumulation rate to ablation rate of 0.52. The ice temperature is assumed to vary linearly with depth with a heat flux of 0.025 W/m^2; the ice temperature is warmer when the surface temperature is higher. In Figure 2, the horizontal axis shows “ice temperature at depth”, which we take to be the value near the base, where most of the ice deformation occurs.

The conditions on present-day Mars are inconsistent with the present-day shape of Gemina Lingula. The surface temperature is too cold, and the mass-exchange rates are too high to develop the topography shown in Figure 1. We show this in Figure 2 by plotting all pairs of accumulation rate, ablation rate, and ice temperature that correspond to this geometry and mass-balance pattern [1]. We estimate the accumulation rate from Equation 2 and find the ablation rate from the accumulation/ablation rate ratio. The ablation rate is used with the maximum ice thickness to calculate a volume response time using Equation 4.

For a surface temperature of 170 K, the corresponding accumulation rate is 5×10^{-6} mm/yr, and the volume response time is ~200 Byr. For an ablation rate of 0.2 mm/yr [e.g. 5], the corresponding surface temperature is ~230 K (ice temperature at depth is ~247 K), and the volume response time is 6 Myr.

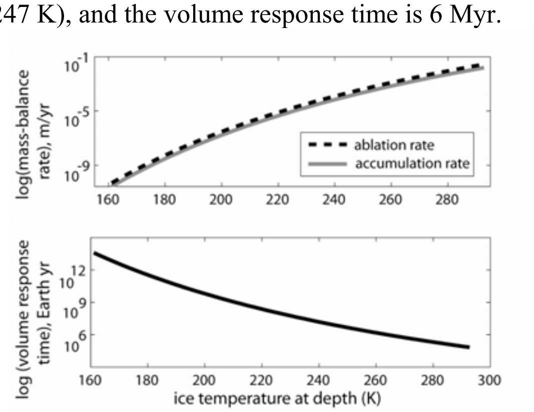

Figure 2. The accumulation and ablation rate, and the volume response time for a range of ice temperatures associated with the geometry shown in Figure 1. Time is in Earth years.

Ice Thickness and Length: Using Equation 2, the ice thickness is expressed in terms of the flowline length [4]. We estimate the maximum ice thickness and length for the North and South PLD domes, Gemina Lingula, the Greenland Ice Sheet, and Arctic Ice Caps. In Figure 3 we find the ice temperature that best fits the estimated points and is also associated with an accumulation rate that generates a volume response time of 100 Myr for Gemina Lingula. We pick 100 Myr based on the age of the SPLD [6], though the actual response time could be higher or lower.

This analysis is another way to show that present-day ice temperature and mass-balance do not match the ice thickness and length of the present-day Gemina Lingula or the PLD. For Gemina Lingula to develop its present-day shape in less than 100 Myr, the ice temperature had to be ~230 K.

Discussion: We use a very simple ice-flow model with few required parameters. All of the results shown here use a flow-law exponent $n = 3$, associated with dislocation creep. We will test the sensitivity of our results to higher and lower flow-law exponents, though we anticipate that this will not significantly change our results.

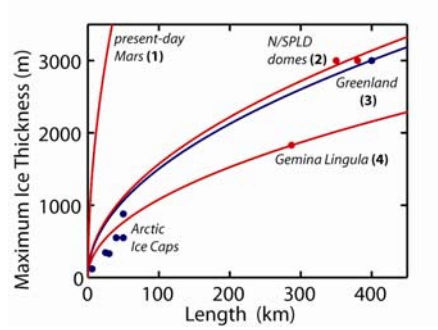

Figure 3. Maximum ice thickness compared to length for Terrestrial (blue) and Martian (red) ice masses. Points are estimated values for existing ice masses and curves are from our model assuming an ice temperature at depth (T) and accumulation rate (b). (1) T = 170 K; b = 0.5 mm/yr. (2) T = 213 K; b = 0.01 mm/yr. (3) T = 260 K; b = 0.1 m/yr. (4) T = 231 K; b = 0.01 mm/yr. The accumulation rates for (2) and (4) correspond to a volume response time of 100 Myr.

Conclusions: Winebrenner et al. [1] found that an ice-flow model can replicate the inter-trough topography across Gemina Lingula, within twenty meters. The consistency of this result across Gemina Lingula makes a strong case for an era of near-steady ice flow in the past. Many pairs of ice temperature and mass-balance rate can be associated with their reconstructed topography. By requiring that the volume response time to form this topography is physically reasonable, we can constrain the possible range of ice temperatures when the topography was formed. For Gemina Lingula to respond in less than 100 Myr, the ice temperature at depth would need to be at least 230 K. Faster response times require even warmer ice temperatures.

The present-day ice temperature and mass-balance rates are inconsistent with an ice mass shaped like the present-day Gemina Lingula. The ice temperature at depth across Gemina Lingula, and possibly across other parts of the N/SPLD, must have been warmer in the past to form the topography we see today.

References: [1] Winebrenner D.P. et al. (In Press), *Icarus*. [2] Nye J.F. (1960) *Proc. Roy. Soc. Lond.,* 256(1287)*,* 559-584. [3] Jóhannesson et al. (1989) *J. Glaciology* 35(121), 355-369. [4] Paterson W.S.B. (1994) *The Physics of Glaciers*. 4th Ed. [5] Pathare, A.V., D.A. Paige (2005) *Icarus* 174, 419-443. [6] Koutnik et al. (2002), *JGR* 107(E11), 5100-5112. [7] Holt et al. (2007), *Eos Trans. AGU*, 88(52), Fall Meet. Suppl., Abstract P24A-08.