INFLUENCE OF DEBRIS COVER ON GLACIER-SURFACE EVOLUTION. M.R. Koutnik[1], A.V. Pathare[2], C. Todd[3], and E.D. Waddington[1] [1]University of Washington, Earth and Space Sciences, Seattle, WA 98195 (mkoutnik@uw.edu), [2]Planetary Science Institute (pathare@psi.edu), [3]Pacific Lutheran University, Tacoma, WA.

Introduction: We propose to advance upon previous work by studying the effects of debris cover on terrestrial glaciers in order to ascertain how to best apply terrestrial flow models to debris-covered Martian Lobate Debris Aprons (LDAs). We will follow the approach of Vacco et al. (2010; [1]) to incorporate the effects of debris cover into existing ice-flow models that we have already developed (e.g., [2], [3]). Our modeling will simulate internal deformation of ice due to gravitational driving stress subject to a physically based surface mass-exchange pattern (i.e., ablation and accumulation) that accounts for the effects of debris cover, and we will consider rock avalanches, spatial variations in debris, and evolution of debris cover.

For different problems, ice-flow models have been developed with different physical complexity, numerical approximations, and computational sophistication. A basis of an ice-surface evolution model is mass conservation (e.g. [4]),

$$\frac{\partial h(x)}{\partial t} = -\frac{1}{W(x)}\left(\frac{\partial q(x)}{\partial x}\right) + \dot{b}(x) \tag{1}$$

where along-flow gradients in the volumetric flux of ice $q(x)$, in a flowband with surface profile, $S(x)$, bedrock profile, $B(x)$, and width, $W(x)$, must balance the rate of surface accumulation or ablation, $\dot{b}(x)$; ice thickness $h = S-B$. If applicable, inclusion of glacier width variations is considered a "flowband" model; if width is constant this is a "flowline" model. The surface calculation we use is a dynamic calculation because it incorporates the constitutive relation for strain rate. One constitutive relation, called Glen's flow law, describes ice flow by a non-linear relationship between strain rate and deviatoric stress, where deformation occurs primarily by dislocation creep. The flow-law exponent, n, is typically assumed to have a value of 3. However, under different temperature and stress conditions, and for different ice-grain sizes, deformation of ice may be influenced by, or even controlled by, processes other than dislocation creep. The mechanisms of dislocation creep, grain-boundary-sliding-limited creep, and basal-slip-limited creep, can have unique flow-law exponents n, ice-grain-size exponents p, and activation energies for creep Q (e.g., [5]). Assumptions for different flow-parameter values can be tested using ice-flow models.

For this work we will develop a model that calculates glacier ice-surface evolution (including supraglacial debris) and handles the protective influence of debris cover on ablation. We will use this model to **(1)** calculate the sensitivity of a generic glacier, **(2)** evaluate the past decades evolution of the thinning Nisqually Glacier and the thickening Emmons Glacier on Mt. Rainier, and then **(3)** test evolution hypotheses for select Martian LDAs.

In our **ice-dynamic calculation**, the depth-averaged horizontal velocity in our flowline model comes from the Shallow Ice Approximation (SIA, [4]). The SIA is a simplifying assumption that applies in cases where the ice thickness is much smaller than the characteristic horizontal length scales over which thickness or stress change significantly. If the characteristic horizontal length scale is the lateral extent of the glacier, then derivatives of velocities and stresses with respect to x (horizontal axis) are generally much smaller than derivatives with respect to z (vertical axis). For Glen's flow law, the SIA depth-averaged horizontal velocity can be written as:

$$\bar{u}(x) = \frac{2\tilde{A}(x)}{n+2}(\rho g)^n \left|\frac{dS}{dx}\right|^{n-1}\left(-\frac{dS}{dx}\right)H^{n+1}(x) \tag{2}$$

where ρ is density, g is gravitational acceleration, $S(x)$ is ice-surface elevation, $H(x)$ is ice thickness, and $\tilde{A}(x)$ is an effective isothermal softness parameter.

In the **supraglacial debris calculation**, following [1], debris is advected along the ice surface and also moved downslope by mass wasting. This is calculated as a mass diffusion:

$$\frac{\partial h_{debris}}{\partial t} = \kappa\frac{\partial^2 S_{debris}}{\partial x^2} - \frac{\partial}{\partial x}\left(h_{debris}u_{ice}(S_{ice})\right) + D \tag{3}$$

Where h_{debris} is the thickness of supraglacial debris (meters), S_{debris} is the supraglacial debris surface elevation, S_{ice} is the ice-surface elevation, $u_{ice}(S_{ice})$ is the ice-surface velocity, κ is the mass diffusivity of debris (m^2/yr), and D is the mass source of debris (m/yr). In this treatment of debris conservation and evolution, a mass diffusivity must be prescribed. Vacco et al. [1] pointed out that this process has not been well-studied, so they showed that their calculations were not affected by diffusivities an order of magnitude larger or smaller than their best estimate; we can perform a similar sensitivity test. If the debris cover is thick enough, it will introduce an additional overburden stress. We will modify the SIA model to account for the sediment and ice load, incorporating the debris-layer thickness and density.

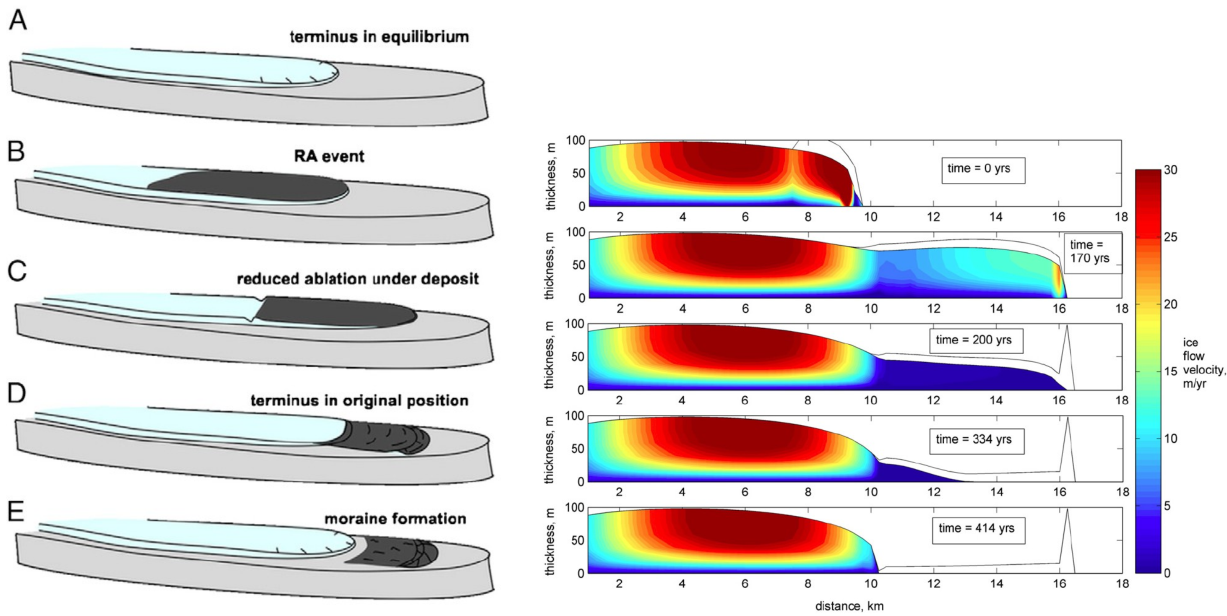

Figure 1: *(left from Reznichenko et al., 2011; [6])* Schematic showing evolution of a glacier after a rock avalanche. *(right from Vacco et al., 2010; [1])* Model results for a glacier with a 2-km long and 35-cm thick rock avalanche at the terminus. Cartoon panels B-E roughly correspond to the model snapshots. Modeled debris layer shown with a thin black line in right panels, and is vertically exaggerated by 200 times.

To treat the **insulating effects of debris**, we apply the melt-rate parameterization [1]:

$$\dot{m}_{debris} = \dot{m} \exp\left(-\frac{h_{debris}}{H^*_{debris}}\right) \quad (4)$$

where $\dot{m}_{debris}$ is the ablation rate with debris cover, $\dot{m}$ is the ablation rate of bare glacier ice, h_{debris} is the thickness of supraglacial debris, and H^*_{debris} is the thickness at which insulation of ice is effective ('e-folding thickness' of the debris). H^*_{debris} is usually assumed to be ~0.1 meters because even a thin layer of debris typically insulates underlying glacier ice [6]. However, if site-specific information is available another value could be used: one of the main objectives of our field experiments will be to provide a better constraint on the effective insulating thickness.

We will parameterize terrestrial ablation via the commonly-used Positive Degree Day (PDD) approach, which assumes that the ablation rate is proportional to the number of days above 0°C (positive degree days) and utilizes measured temperature and precipitation fields. Running this model requires standard inputs of the glacier geometry (bed topography, ice thickness), the ice softness, and the calculated surface mass exchange (accumulation and ablation), but also requires information about debris-cover thickness and the thickness at which debris insulates underlying glacier ice. Since there is no single terrestrial glacier that is a perfect analogue to Martian ice masses, we will design new model experiments relating to LDA evolution by first exploring the sensitivity of a generic terrestrial glacier, and then modeling two glaciers on Mt. Rainier, Washington that are the locations of our new field studies. Mt. Rainier is an interesting target for process-based analogue studies because many glaciers flanking the volcano are debris-covered, there is a 40+ year observation record, and we will conduct new studies on Emmons Glacier (which has some of the most positive thickness change) and on Nisqually Glacier (which has some of the most negative thickness change).

Figure 1 illustrates the type of calculations we propose for new model scenarios relevant to our study. We will consider the effects of a rock avalanche at different locations along the glacier, as well as uniform and non-uniform debris cover that either insulates or promotes ablation. We will also parameterize the formation of a debris cover as a function of total surface ablation. We will present our preliminary results at the conference.

References: [1] Vacco et al. (2010), *EPSL* 294, 123-130. [2] Koutnik et al. (2009), *Icarus* 204, 458-470. [3] Koutnik and Waddington (2012), *J. Glaciology* 58, 1008-1020. [4] Cuffey and Paterson (2010), *The Physics of Glaciers*. [5] Goldsby and Kohlstedt (1997), *J. Geophys. Res.* 106, 11017-11030. [6] Reznichenko et al. (2011), *Geomorpology* 132, 327-3.