MELTING A MARTIAN VISCOUS FLOW FEATURE: A MODERN-CLIMATE, DUST-BLANKETED GLACIER MODEL.

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Introduction: Berman [1] and Hubbard et al. [2] presented compelling evidence for glacial flow of a landform in a crater east of Hellas, Mars (Fig. 1). This feature also exhibits evidence for meltwater channels and possible moulins (Fig. 2). Though uncommon on this type of Martian landform, the indications of melting are reasonably compelling here. We show that a blanket of insulating dust could allow melting under the present climate if the dust was thick (then blown away to reveal the ice), its thermal conductivity was low, and Martian heat flow was high. This 'climate change minimalist' model differs from the dusty snowpack model of melting [3] because ordinary geothermal heat, not warm air and sunlight, drives melting. Water could accumulate at the bed at high elevation, then flow onto and erode the ice surface. If needed conditions are lacking, the observations and inferred melting require a modified, warmer recent climate.

Thermal Model Parameterization: Finite element modeling was used to explore the thermal conditions of an idealized ice body similar to that shown in Fig. 1 to assess whether the modern Martian climate could produce melting under a thick insulating dust blanket. Model simulations cover a range of plausible parameter space. Thermal conductivity was defined for three materials, including (1) basalt crust, (2) a pure ice surface deposit, and (3) a porous, fine-grained dust blanket. The conductivities are well established for ice and basalt [4]. On Mars, where water infiltration and weathering are apt to have been nil and the atmosphere thin over the last few million years, unconsolidated airfall dust would be very fine grained (~1-5 μm) and have low grain-to-grain contact areas, high porosity, and exceeding low thermal conductivity. These deposits cannot have thermal conductivity, k, lower than that of Martian air. We assume k (expressed in MKS units) comparable to or lower than those of loess [5] and fine basaltic ash [6] and use the following parameterization:

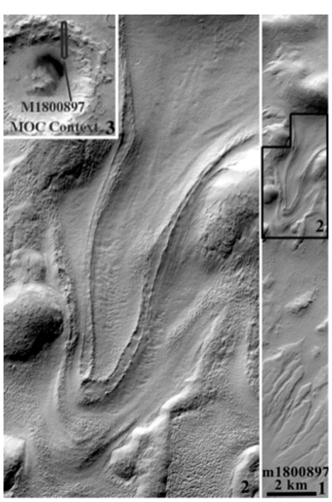

Fig. 1 (left). MOC image of glacier-like flow feature set in an impact crater east of Hellas, Mars.

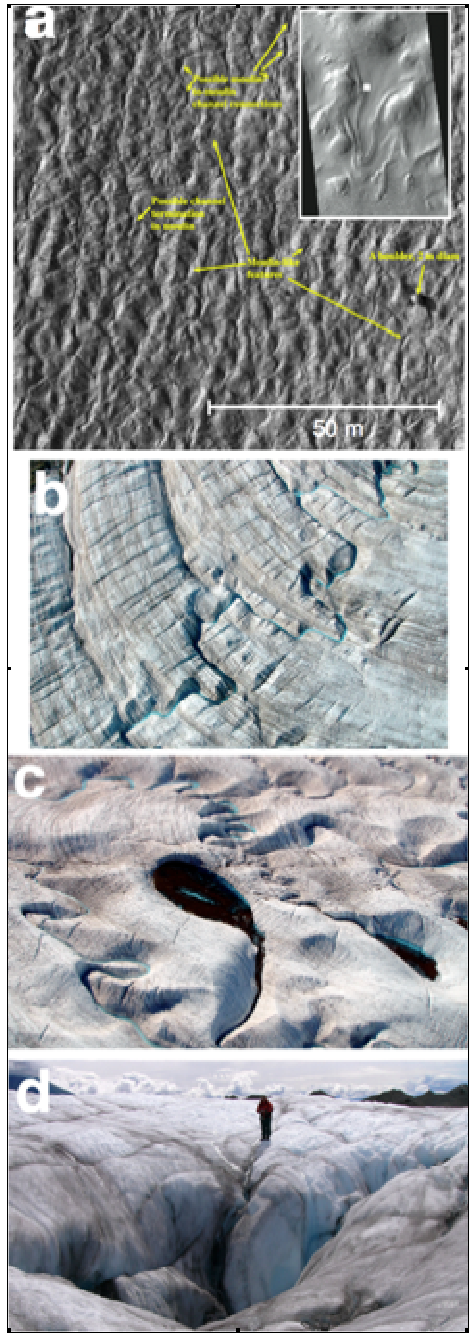

Fig. 2 (right). a: HiRISE image of sinuous to reticulate troughs on the feature shown in Fig 1. Some terminate in small depressions, per-haps moulins. b-d: Analogs on Root/Kennicott Glaciers, Alaska. Photos by Kargel

$$k = AT^B,$$

where T is absolute temperature, and A and B are empirical values given in Table 1 for two dry soils. The higher value is for fine, dry intermediate composition ash [6], composed of 70% glass, 15% scoria fragments, and 15% minerals such as quartz and feldspar. The lower value is 1/3 that of the higher and is intended to represent extremely porous, completely unconsolidated, unweathered airfall dust deposits on Mars. For the rock thermal conductivity we use log k = 1.50 - 0.35 log T. For ice, we use log k = 2.7154 - 0.97520 log T.

Table 1. Dust thermal conductivities, $k = AT^B$

	Low k	High k
A	0.00107	0.0032
B	0.716	0.716

We take two values of dust thickness, 120 m and 200 m. The thicker value was chosen to allow melting.

Heat flow values are 0.015 and 0.030 W/m^2. The high value was calculated as the modern Mars global mean heat flow scaled from Earth's using mass and surface area scaling [7-8]. The lower value stems from heat flows assessed from tectonic approaches to the problem [e.g., 9], with further allowance for global cooling. These values carry different assumptions.

The surface boundary condition is set as temperature T = 154K + 71K*cos (α+θ), where latitude θ = –39º S Lat, and the slope α is defined as negative for southerly slopes and positive for northerly slopes.

Thermal Model Results and Discussion: Figure 3 shows results for one thermal model that optimizes all parameters to achieve a desired melting outcome; parts of the ice mass attain the melting point. Since heat emanates from below, and since pressure melting pertains, the meltwater is generated at the base, where it can pool, infiltrate, or flow along the base or could be transferred to the ice surface [10] (beneath the dust) along crevasses. Suboptimal parameterizations allow warming, and consequent ice softening (so as to enable solid-state flow), but not melting or sliding.

120-200 m of dust could be deposited in ~2-40 Ma for accumulation rates of ~10-100 μm/Mars year. Areas of thin ice and thick dust may be most prone to melt, whereas thicker ice may deform glacially at temperatures below the melting point of ice. Basally melted domains might slide and erode their beds; thin ice with thin dust cover might be inactive, neither melting nor flowing much. Topographic loops of this landform might be produced either by flow of a rheologically layered material, or by differential insulation.

It is not assured that dust would accumulate to such a thick layer, or if it does, that the thermal conductivity would remain very low. Self compaction, crushing of grain contact points, chemical weathering, or pore infilling by ice or salts could increase grain contact area

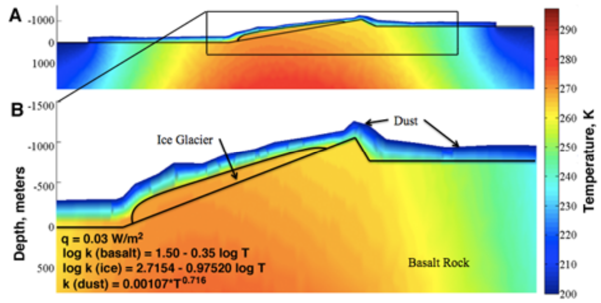

Fig. 3. Model simulation with the parameters optimized to achieve melting temperatures at a small part of the base of the dust-covered glacier. In this simulation the crater has a thermal conductivity like that of basalt rock; the glacier is ice; ~200m of dust has a "low-k" conductivity from Table 1.

and thermal conductivity and thus reduce the thermal gradient within the dust blanket. Heat flow could be at the lower end of the range considered. If the ice flows excessively, the insulating dust blanket will thin. Furthermore, geothermal melting can produce only a small amount of liquid each year; storage and sudden release is also needed [10]. Many plausible situations may prevent the dust from achieving the needed effect, in which case a warm climate excursion may be needed.

For this model to explain the observations without a warm climate, the model parameters must be just right. Thick insulating dust is required, but also needed is subsequent removal of most of the dust blanket to expose and "freeze in" (preserve) the melt features. The removal seems not difficult, beause the eolian environment of Mars is dynamic; where dust accumulates, wind can also remove dust. 200 m is a lot of dust, but the presence of sand dunes in the crater indicates a definite contribution of eolian deposits. Regardless of whether melting occurs, any thick cover of dust or sand causes a warm anomaly in the subsurface, enough perhaps to affect glacier flow and hydrothermal flow.

The necessary physical conditions for basal melting to occur by this mechanism are plausible but probably uncommon across much of Mars' surface in the absence of climatic amelioration. Ancient glaciers with thick, rapidly deposited impact ejecta airfall deposits and Tharsis glaciers with thick volcanic ashfalls may be susceptible to basal melting by this mechanism.

References: [1] Berman, D.C. et al., 2009, *Icarus* 200, 77-95. [2] Hubbard, B. et al., 2010, *Icarus* (in press). [3] Clow, G.D., 1987, *Icarus* 72, 95-127. [4] Ross, R.G. & J.S. Kargel, 1998, *Solar System Ices*. [5] Johnson, J.B. & R.D. Lorenz, 2000, Geophys. Res. Lett. 27, 2769-2772. [6] Sawada, S., 1977, *Temperature Dependence of Thermal Conductivity of Frozen Soil*, Kirami Technical College, Kirami, Hokkaido, Japan, Research Report, v. 9(1), kitir.lib.kitami-it.ac.jp/dspace/bitstream/10213/352/1/9-1-14.pdf. [7] Kargel, J.S. & J.S. Lewis, 1993, *Icarus* 105, 1-25. [8] Kargel, J.S., *Mars: A Warmer, Wetter Planet*, Praxis-Springer (Publ.). [9] Ruiz, J., et al. 2009, *Icarus* 203, 49-57. [10] Copland, L. et al., 2003, J. Glaciol. 49, 337-348.