ICE MELTING ABOVE A CONVECTING, CRYSTALLIZING MAGMATIC SILL ON MARS. Dave Mercier and Robert P. Lowell, 4044 Derring Hall (0420), Department of Geosciences, Virginia Tech, Blacksburg, VA 24061, rlowell@vt.edu, dave.mercier@vt.edu.

Introduction: The formation of Martian fluvial features such as valley networks, and outflow channels could be caused by hydrothermal processes linked to magmatic or volcanic activity [1]. Hydrothermal fluid may be derived from ice melted near an igneous intrusion emplaced in the crust [2,3]. As a result of heat transfer from the intrusion the melt would begin to convect, creating a hydrothermal system which would foster additional ice melting [4]. The fluxing of hydrothermal fluid at the Martian surface may provide a formation mechanism for fluvial features. Moreover, magma-ice-water interactions, especially those from subglacial eruptions, on Earth show that these interactions may result in the formation of textural features such as such as lava pillows, hyaloclastites, and volcanic glass [5], [6]. Head and Wilson [7] review magma-ice-water interactions on Mars.

Background: Some fundamental questions concerning magma-ice-water processes relate to the volume of ice that can be melted from a magmatic intrusion and the nature of the resulting textural and alteration products. Estimates of the volume of ice melt have been derived from a calorimetric viewpoint by considering conductive heat transfer [5,6,8], or by considering heat transfer from bottom boundary maintained at constant temperature [4]. Here we consider ice melt above a vigorously convecting, crystallizing magmatic sill of finite thickness. Two end-member scenarios in which (a) crystals are suspended within the magma (b) crystals settle rapidly to the sill floor are depicted in Figure 1. Only the crystals suspended model is discussed here.

Methodology and Results: The methodology for this work stems from Huppert and Sparks [9] and Liu and Lowell [10], who consider heat transfer from a vigorously convecting, well-mixed magma sill of thickness D and mean temperature $T_m(t)$, where t is the time. In this case the rate of heat loss from the top of the sill is given by the classical relationship between the dimensionless Nusselt number Nu and the dimensionless Rayleigh number $Nu = (\lambda\Delta T/D)Ra^{1/3}$, where λ is the thermal conductivity of magma, $\Delta T = T_m(t)-T_s$ and Ra is given by

$$Ra = (\alpha_m g \Delta T D^3)/(a_m \nu_m) \quad (1)$$

where α_m is the coefficient of thermal expansion of the magma, g is the acceleration due to gravity, a_m is the thermal diffusivity of the magma, ν_m is the kinematic viscosity of the magma, and T_s is the solidus temperature of the magma, respectively .

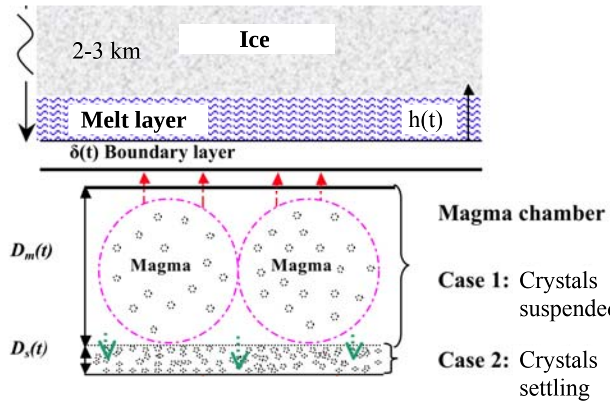

Figure 1: Schematic of a crystallizing, convecting sill emplaced beneath a layer of ice. Convective heat transfer from the sill results in melting of overlying ice. Two crystallization scenarios are shown: (1) Crystals remain suspended in magma or (2) Crystals settle to the floor of the sill.

The Nu ~$Ra^{1/3}$ relationship lead to an expression for the heat flux $F_m(t)$ from the sill given by

$$F_m(t) = \rho_m c_m J (T_m(t) - T_s)^{4/3} \quad (2)$$

where ρ_m is the density of the magma, c_m is the specific heat capacity of the magma, and $J = 0.1(\alpha_m g a_m^2/\nu_m)^{1/3}$, This heat flux is transferred conductively to the overlying ice. A simple heat balance expression relates equation (2) to the rate of change in the heat content of the magma, which leads to the equation

$$dT_m/dt = -(J/D)(T_m-T_s)^{4/3} / [1-L_m c_m^{-1} \chi_m'(T_m)] \quad (3)$$

where χ_m' is the derivative of the crystal content equation, discussed below and L_m is the latent heat of the melt. To complete the solution to equation (3) we use the expression for crystal content as a function of temperature from [9]

$$\chi(T_m(t)) = (7200 / T_m(t)) \quad (4)$$

and the kinematic viscosity as a function of crystal content

$$\nu_m = \nu_{m0}(1-1.67\,\chi)^{-2.5} \quad (5)$$

Equation (5) shows that the viscosity approaches ∞ as crystal content approaches 60%. At this point, convection in the magma sill ceases.

As magmatic heat is transferred to the overlying ice layer, melting occurs. We equate the heat flux $F_m(t)$

from equation (2) to the heat conducted into the ice. Assuming the initial temperature of the overlying ice layer is T_0, and assuming a linear gradient across the layer, we write

$$F_m(t) = \lambda^*(T_i(t) - T_0)/h(t) \qquad (6)$$

where λ^* is the thermal conductivity of the overlying medium, $T_i(t)$ is the temperature at the interface $z = 0$ between the sill and the overlying layer, and $h(t)$ is the thickness of the melt layer. To determine $h(t)$ we again construct a heat balance in which the rate of heat flow into the layer is equal to the rate of change of the heat content within the layer. That is

$$H_s(dh(t)/dt) = F_m(t) \qquad (7)$$

where $H_s = \rho_{ice}\,[c_{ice}\,(T_{ice}-T_0)+L_{ice}]$ is the heat required to raise a unit volume of ice to its melting temperature T_{ice} and to melt it [5],[6], [9], [10]. We use the density of ice $\rho_{ice} = 916.7$ kg/m^3, its specific heat, $c_{ice} = 2108$ J/kg K, T_{ice}= 0°C, the melting temperature of ice, and its latent heat of fusion $L_{ice} = 3.34 \times 10^5$ J/kg. Substituting equations (2) and (3) into equation (7) and integrating we obtain an explicit expression for thickness of ice that can melt in terms of the sill thickness D. The result is

$$h(t))/D = H_s^{-1}\{\rho_m c_m[T_m(0)-T_m]+\rho_m L_m \chi_m(T_m)\} \qquad (8)$$

where $T_m(0)$ is the initial temperature of the melt.

The maximum value of $h(t)/D$ is found in this case by setting $\chi_m = 60\%$, corresponding to $T_m = 1091$°C (equation (4)). Then with $\rho_m = 2700$ kg/m^3, $c_m = 1400$ J/kg-°C, $L_m = 4.2 \times 10^5$ J/kg, $T_m(0) = 1200$ °C, and assuming ice is initially at its melting point, we find (see Figure 2)

$$h_{icemax}/D \approx 3.5 \qquad (9)$$

Discussion and Conclusions. Equation (9) shows that during the convective stage of magma crystallization and cooling with crystals suspended, the thickness of ice melted is approximately 3.5 times the thickness of the sill. This result can also be applied to ice melt in a layer of permafrost, provided heating of the melt ice mixture is neglected. In this case only a fraction ϕ of the latent heat, corresponding to the crustal porosity is used. The ratio $h(t)/D$ would then be $3.5/\phi$, but the actual amount of ice melted would be the same. To obtain a better estimate of the amount of ice melted in a permafrost layer, one would need to account for the heating of the rock-melt mixture during magma crystallization.

Noting that melting of ice in a permafrost layer might lower the effective melting temperature of the ice/rock mixture, the result in equation (8) can also be used to estimate the thickness of melted rock above the intruded sill [9]. Using values for a silicic rock: ($\rho_r = 2500$ kg/m^3, $c_r = 1400$ J/kg °C, $T_r(0) = 0$ °C, $T_r = 800$ °C, $L_r = 3 \times 10^5$ J/kg), $h_{rockmax}/D \approx 0.3$ (Figure 2).

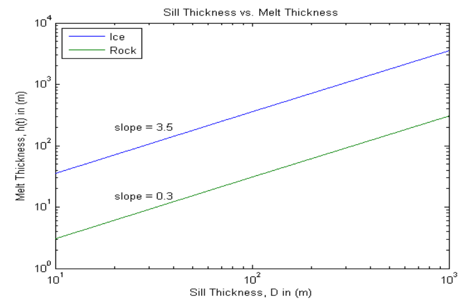

Figure 2. Max thickness ice melt to max thickness rock melt, as a function of sill thickness D.

We also compare the amount of ice melt determined here with that determined by conduction from a large igneous dike [2] and by conduction from a intruded sill [8]. In the case of a large dike thermal conduction modeling showed that ~ 6.5 km^3 of ice was melted/km of dike length above dike whose volume was 350 km^3/km of dike; the melt was formed over an approximately 8 Ma period of dike cooling [2]. In contrast, Wilson and Head [8] estimated that a maximum thickness of 14.5 m if ice would be melted for each m of sill thickness assuming the sill cooled to 0°C. The estimate derived here lies between these, but we only consider the thickness of ice melt during the magma convection phase. More ice would melt upon further conductive cooling, but at a much slower rate as the heat flux from the sill decays with time.

The results presented here represent a first stage in the investigation of a sill emplaced beneath a layer of ice. Future work will consider the amount of ice and rock that can be melted from a layer of permafrost of varying porosity and composition, the role of convection in the melt layer, and the likely sequence of alteration products developed. We will also consider the case in which crystals settle rapidly to the floor of the sill. In this case, the convective lifetime of the sill will be prolonged [10], allowing for more ice to be melted.

References: [1] Gulick, V. (1998), *JGR*, *103*, 19365-19387; [2] McKenzie, D. and F. Nimmo (1999), *Nature*, *397*, 231 – 233; [3] Craft, K. L., et al. (2011), *LPSC Abs.* 2334; [4] Ogawa, Y., et al. (2003), *J. Geophys. Res., 108, No. E4,* doi: 10.1029/2002JE001886; [5] Gudmundsson, M. T. (1997), *Nature*, *389,*954-957; [6] Gudmundsson, M. T. (2003) *Geophys. Monogr., 140,* 61-72, doi: 10.1029/140GM04; [7] Head and Wilson (2002) *Geol. Soc. Spec. Pub. 202*, p.27-57; [8] Wilson and Head, *ibid.*, p. 5-26; [9] Huppert, H. E. and Sparks, R. S. J. (1988), *J. Petrol. 29,* 599-624. [10] Liu, L. and Lowell, R. P. (2009), *J. Geophys. Res., 114*, B02102.