MODELS OF MARTIAN HYDROTHERMAL CIRCULATION AND ICE MELT WITH IMPLICATIONS FOR SURFACE FEATURE FORMATION.
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Introduction: In analogy with hydrothermal processes on Earth's seafloor, Martian hydrothermal systems may provide a mechanism for transporting water, chemicals, and energy to the surface, and hence could help form Martian surface morphology and may provide environments for biological processes. Evidence of water on Mars includes hydrothermal salt deposits and mineral hydrates discovered by the rovers Spirit and Opportunity at the plateau, Home Plate [1] and subsurface ice indicated by radar observations of the Mars Reconnaissance Orbiter [2]. A magma driven hydrothermal system is one possible formation mechanism for surface features that could cause groundwater release as a result of induced fluid circulation and possible ice melt.

Here we build on previous magma driven hydrothermal modeling [3],[4],[5],[6] and investigate the amount of fluid provided to the surface by melted overlying ice layers. The effects of crystallization within a magmatic sill on the heat transferred to overlying ice and melt layers are also considered. The resulting fluid flow rates are then compared to model estimates for fluid flow rates required to form surface features on Mars to determine which features may be formed by a hydrothermal system.

Background: Craft et al. [6] investigated magma driven hydrothermal systems by first applying the boundary layer theory, as described by Cheng and Minkowycz [7], to obtain heat and fluid fluxes near a dike intrusion (Figure 1). The steady-state boundary layer model provides upper estimates for the heat and fluid mass flux as the cooling of the magma intrusion over its lifetime is not considered. Results indicated that fluid flow rates are only marginally adequate for forming small features including gullies and stepped fans.

Additional fluid flow may occur if an ice layer overlying the hydrothermal system melts and/or subsurface hydrates dissociate. Here we investigate ice melt on Mars by modeling both dike and sill driven hydrothermal systems with overlying permafrost layers. Figure 1a shows the dike driven system while Figure 1b depicts the sill driven system.

Dike driven hydrothermal system: A layer of ice or permafrost about 2-3 km thick located above a hydrothermal system would gradually melt as heat from the magma intrusion transfers to the adjacent fluid-filled porous medium, which then transfers heat to the ice above. Figure 1 depicts the system. Once the melt water layer reaches a certain thickness, convection occurs within and controls the rate of heat transfer

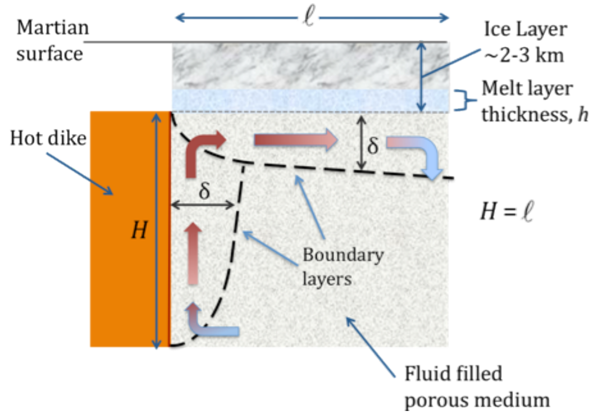

Figure 1: Model of a permafrost layer overlying a dike driven hydrothermal system. Heat from the dike induces circulation that transfers a constant heat flux to the ice. Over time, a melt layer forms and convection begins when the Rayleigh number exceeds the critical value.

to the remaining overlying ice. Craft et al. [8] and Craft et al. [6] describe the calculations to determine the time convection begins and the melt layer thickness over the lifetime of the system. If the ice layer melts through, the melt water will contribute to the volume of water released at the surface, helping to form the surface features observed on Mars. Additionally, the melt layer may contribute to destabilizing the crust and could result in flow of rock-meltwater mixture and/or subsidence of the surface. Over the lifetime of both a 10 m wide, 10 km tall dike with a high $K=10^{-10}$ m^2 and a 1 km tall, 10 m wide dike with $K=10^{-11}$ m^2 both with μ and α_f parameters at high temperature values, about 1 km of ice will melt. For all other system parameter combinations where the steady-state boundary layer theory is applicable, the maximum ice thickness of 2-3 km will melt over the lifetime of the hydrothermal system. Using this model it is possible to explore the dike emplacement conditions required to form different geomorphic features on Mars.

For example, typical gullies on Mars are on the order of meters to tens of meters wide, ~ 10 m deep, and hundreds of meters to a few kilometers long [9], [10]. A dike on this scale, 5 km long and 1 km wide with a surrounding medium porosity of 10%, is calculated to form a 1 km thick layer of melt that adds 0.5 km^3 of water to the fluid flow to the surface. To form gullies in recent Martian conditions, Heldmann et al. [10] estimate that a flow rate of about 1 km^3/yr is required. A dike 10 km tall, 5 km long with K = 10^{-10} m^2 can produce 0.73 km^3/yr for high temperature parameter values. Adding the 0.5 km^3 from ice melt provides adequate fluid flow to form a gully. However, one consideration is that K = 10^{-10} m^2 is a very high permeability that may not be reasonable for the Martain crust.

For deltas on Mars, the feeder channels range from 10s of km to around 100 km in length and 100 to 2000 m in width [11]. With K = 10^{-10} m^2, fluid flow using high temperature parameter values for 100 km long and 10 km tall dikes will occur at a rate of 15 km^3/yr, respectively. According to and Moore et al. [12] and Jerolmack et al. [13], deltas require 300 to 900 km^3 respectively. At the calculated fluid flow rates, a delta can form in 20 to 60 years. The dike must therefore be about 25 to 45 m wide to provide heat over this lifetime.

For large valleys such as Ma'adim Vallis, high fluid volumes are required. Maximum dike lengths observed on Mars are on the order of 1000 km, and if a maximum width of 1000 m (a set of multiple narrow dikes) is assumed, the lifetime will be on the order of 30,000 years. Using high temperature parameter values with a 1000 km long dike of 1 km or 10 km height and K = 10^{-10} m^2, fluid flow rates are 50 or 150 km^3/yr, respectively. Cabrol [14] estimates 10^3 to 10^4 km^3 while Irwin [15] estimates 10^5 km^3 of fluid is required to form the valley. The maximum lifetime needed for the lower 50 km^3/yr rate and larger 10^5 km^3 volume is 2000 years. This is well below the maximum quasi steady state dike lifetime.

Sill driven hydrothermal system: It is also possible for an ice layer to be melted from beneath by a sill (Figure 2). The models investigated here improve upon previous studies of sill driven hydrothermal systems by considering heat transfer through both conduction and convection. Liu and Lowell [16] model a terrestrial ocean ridge, sill driven, hydrothermal system and predict that a 100 m thick sill with an area of 10^6 m^2 cooling with suspended crystals releases an average of 10^8 W over 10 years. An analogus sill system on Mars would provide a heat flux, Q_s = 100 W/m^2, to the base of the ice layer. Heat released per unit area of a melting ice layer, Q_{ice}, is expressed as:

$$Q_{ice} = \phi \rho_{ice} L h(\tau) \qquad (1)$$

where Φ is porosity, ρ_{ice} is the density of ice, L is the latent heat, and h is the melt layer thickness at time τ. Setting $Q_{ice} = Q_s \tau$ with $\Phi = 0.1$, ρ_{ice} = 916 kg/m^3, L = 3.33 x 10^5 J/kg and τ = 10 yrs, forms a melt layer ~ 1 km thick. For the sill area of 1 km^2 and 1 km melt layer over 10 years gives a very low fluid flow rate of 0.1 km^3/yr. The Rayleigh number exceeds the critical value for higher permeabilities at this melt layer thickness and convects vigorously. Within the melt layer, a temperature gradient exists that can indicate the rock types that will form as the heat and water alters them. Future work will investigate the rock alteration and also the crystals settling case.

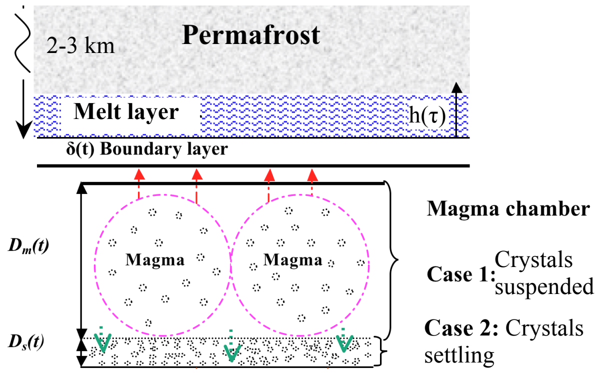

Figure 2: A sill driven hydrothermal system model that takes into consideration sill cooling by conducation and convection. Two types of crystallization are investigated: (1) Crystals remain suspended in magma or (2) Crystals settle out of magma.

Summary: Hydrothermal processes may play essential roles in the transfer of heat and fluid to the Martian surface. The dike and sill driven models investigated here provide a more complete picture of magma driven hydrothermal systems as mechanisms for melting overlying permafrost layers and possibly forming surface morphology. According to estimates for fluid volume required for certain features, if the surrounding medium has a high permeability, gullies, deltas and the valley Ma'adim Vallis could be formed by a magma driven hydrothermal system.

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