MODELLING CATASTROPHIC FLOODS ON THE SURFACE OF MARS. A. S. Bargery, L. Wilson and K. L. Mitchell, Environmental Science Department, Lancaster University, Lancaster LA1 4YQ, UK. (*a.bargery@lancaster.ac.uk*).

Summary: We explore the issues governing the flow, evaporation, freezing and sublimation of water released onto the surface of Mars. The consequences of the rheological changes caused by ice crystal growth in water are discussed and an attempt is made to predict the relationship between water volume flux and the maximum run-out distance.

Introduction: The release of large amounts of groundwater at high volume fluxes is generally accepted to have provided the massive erosive power that produced outflow channels on Mars [1, 2], especially valleys associated with fracture systems such as the Athabasca [3] and Mangala [4] Valles. Studies into the fluid dynamics of flows on Mars are important to estimate how far a water could travel before it developed a significant ice cover and eventually froze completely and came to a standstill. A model for an ice-water flood would also help to estimate the erosive power of the flood so as to identify features that a flood could possibly have created. This is particularly relevant because one interpretation of the plates and ridges seen within the channel margins of Athabasca and Marte Valles (Fig. 1) is that they are ice deposits from floods [3, 5]. Models have been developed for water flow under martian atmospheric pressure by Wallace and Sagan [6] and under vacuum conditions on Ganymede by Allison and Clifford [7]. These models have tended to concentrate on the thermodynamics, whereas our recent work has focussed on the fluid dynamics [8]. Here we consider the fluid mechanics of an ice-water flow after ice crystal nucleation has started, focussing on the resulting changes in flow rheology.

Consequences of ice formation: A critical issue is that water flows on planetary surfaces will essentially always be fully turbulent when first released if they have depths greater than the order of one meter. The ambient temperature on Mars is below the freezing point of water almost everywhere on the planet at all times, and so virtually any water released will cool eventually to the triple point temperature at which it will begin to freeze. Once it reaches this temperature, ice crystals will form in the flow as a result of evaporation of vapour from the surface, a process controlled by the water vapour pressure and the atmospheric conditions as modelled in detail by Wallace and Sagan [6]. As long as the flow is well stirred and an ice raft does not form, the water temperature will remain buffered at the triple point temperature. As ice crystals are formed in a such a flow, the turbulent velocity will initially exceed the buoyant vertical velocity of the ice crystals, so that the crystals will be entrained within the flow and will not immediately segregate to the top of the flow to form incipient ice rafts. As the ice crystal content increases, the bulk viscosity of the flow increases and the fluid becomes non-Newtonian, developing a finite yield strength.

In our model we adopt the simplest form of non-Newtonian fluid, the Bingham plastic, characterised by two dimensionless numbers, the Reynolds number Re and the Hedstrom number He defined by

$$Re = (4\ d\ v\ \rho)/\eta \qquad (1)$$

and

$$He = [(16\ d^2\ y\ \rho)/\eta^2] \qquad (2),$$

where d is the flow depth, v is the flow speed, y is the yield strength and η is the viscosity. Simple expressions for y and η as a function of the volume fraction φ of the flow which consists of ice crystals are

$$\log_{10}(y) = -4 + (200/9)\ \varphi^2 \qquad (3)$$

and

$$\eta = \eta_0\ [1 - (5/3)\ \varphi]^{-2.5} \qquad (4),$$

where η_0 is the viscosity of the water at the triple point temperature. The requirement that the flow remains turbulent is that the Reynolds number Re must remain greater than a crtitcal value Re_{crit} that is itself an increasing function of the Hedstrom number He. A function that fits the experimental data quoted by Malin [9] is

$$\log_{10}(Re_{crit}) = 3.3781 + 0.0034048\ \log_{10}(He) - 0.03405\ \log_{10}(He)^2 + 0.010877\ \log_{10}(He)^3 \qquad (5).$$

If Re decreases to a value close to Re_{crit}, the turbulence will begin to be damped out. The vertical velocity of the ice crystals will begins to exceed the typical turbulent velocity and the ice crystals will begin to float to the surface of the water and aggregate to eventually form an ice raft. As soon as a continuous ice surface is formed, that surface will cool below the triple point temperature and heat will be conducted through the growing thickness of the ice layer. Further ice crystal formation in the water beneath will take place, and we anticipate that crystals will separate from the bulk of the fluid in such a way as to maintain the volume fraction at a value that just allows the motion of the fluid to remain turbulent.

The process of formation of a continuous ice cover may be complex. At first, a central ice raft is likely to be sheared between stationary ice levees on either side or internally disrupted into a pattern similar to that seen in Figure 1. At this stage, there are likely to be gaps through which vapor can still escape. Eventually, the upper surface may become completely frozen.

The timescales for these processes are ultimately controlled by the heat loss rate from the surface of the flow, in turn controlled by the water evaporation rate. In an atmosphere, this rate corresponds to a mass flux per unit area of [6]

$$\mathrm{d}m/\mathrm{d}t = \acute{\alpha}(P_v - P_a)\,(M/2\pi GT)]^{1/2} \qquad (6),$$

where P_v is the temperature-dependent saturation vapor pressure of the ice or water, P_a is the atmospheric pressure, M is the molecular weight of water, G is the universal gas constant, T is the absolute temperature, and $\acute{\alpha}$ is the coefficient of evaporation. The value of $\acute{\alpha}$ must be determined empirically, and has been given as 0.94 [6]. Equation (6) is only valid if $P_v > P_a$. When $P_v < P_a$, the escape of the vapor is governed by diffusion rather than effusion and other considerations apply [6].

Once a continuous layer of ice forms on the surface of the flow, the temperature of the ice surface will cool below the triple point temperature, probably quite rapidly, to the ambient temperature. The rate of loss of mass by sublimation from the surface will decrease as the temperature decreases [10]. Heat transfer to the surface from the interior also becomes less efficient because heat is now being conducted through the solid ice layer. The rate of cooling of the flow decreases as the thickness of the ice raft increases, although the temperature gradient increases across the ice. The time taken to freeze all of the flow can now be calculated using the changing heat flux from the ice surface, making an allowance for the variation of thermal conductivity of the ice with temperature.

Possibilities for future work: The model described above deals with water flowing in an environment at temperatures well below the triple point, with an upper surface exposed to the atmosphere and provides a mechanism for estimating the maximum travel distance. Once the flow regime is determined, the corresponding fluid mechanical equations could then be used to show the 2-D velocity profile at each point. Additional applications of our model are to the release of groundwater during subglacial eruptions, to cryopshere fracture [1], and to investigating possible mechanisms of rapid flooding [10, 11] of the northern lowlands.

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Figure 1: MOC NA image SP1-21905, courtesy of MSSS/NASA, in Athabasca Valles centered at 5.7 N, 209.0 W, oriented with north up. The jigsaw-like plates have been interpreted as being due to platy lava flows [5] or ice-raft bearing water floods [3].