DRAINAGE OF MOATS SURROUNDING LAVA DEPOSITS SUPERPOSED ON MARTIAN ICE SHEETS. J. J. Fastook[1] and J. W. Head[2], [1] University of Maine, Orono, ME, 04469, USA, fastook@maine.edu, [2] Brown University, Providence, RI, 02912, USA, James_Head@Brown.edu

Introduction: The "icy-highlands" hypothesis **[1,2]** proposes that water ice deposited at higher elevations in an adiabatic atmosphere where temperature declines with height rather than latitude can serve as a reservoir for the release of liquid water, potentially creating landforms such as valley networks **[3-7]** open- and closed-basin lakes **[8-10]**, and phyllosilicates **[11,12]**. One mechanism to release liquid water from the icy-highlands reservoirs is the increased volcanism that occurred in the late Noachian and early Hesperian **[13-15]**.

In **[16]** we investigated how a superposed lava deposit would affect the flow properties of the underlying ice, as lava slabs of various thicknesses melted their way into an ice deposit (see **[17]**, Figure 4 for a schematic of the lava deposition process). This involved three competing effects: 1) the added driving stress due to the weight of the lava, 2) the softer ice during the transient warming of the ice column, and 3) the reduced driving stress due to the thinning of the ice column by the top-down melting. We found that roughly 4.5 times the thickness of the lava slab was melted from the ice over a period of tens to hundreds of years, and that there were two peaks of ice motion acceleration, a short-duration peak (tens of years) immediately on deposition of the lava, and a second longer-duration peak (hundreds of years) as the warming temperature wave reaches the bed. **Figure 1** shows a typical example for a 90 m lava slab melting into a 500 m thick layer of ice, with a first-peak acceleration of 5.2 (an increase from 0.035 m/yr to 1.8 m/yr) and a second-peak acceleration of 4.3 (increasing to 0.15).

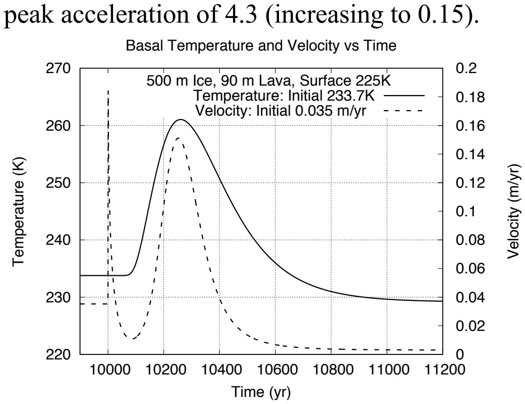

Figure 1: Basal temperatures and velocities for 500 m ice, 90 m lava with surface temperature 225K.

As the lava initially melts into the ice it occupies almost the entire melted volume, so considerable water must be spilled out onto the ice sheet surface, where it can either run off or be refrozen onto the surface. As the slab sinks to the point where its top surface is below the level of the ice surface, the more dense liquid water occupies less volume than the ice that was melted, and so spillage will eventually stop. Nonetheless, the "moat" created by the lava slab will be almost completely full of water.

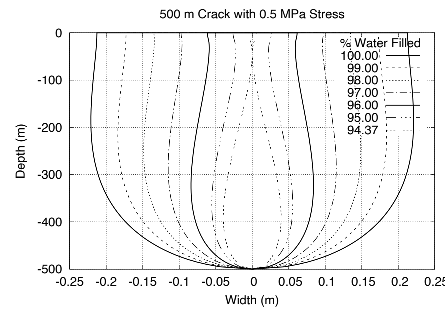

Figure 2: 500 m crack with 0.5 MPa extending stress for various percentages of water filling, pinching closed for ~94%.

Model: It has been demonstrated that a water-filled crevasse can penetrate into an ice mass **[18]** potentially providing an avenue for water to drain directly to the bed as has been observed as supra-glacial lakes in Greenland drain catastrophically though crevasse-initiated moulins **[19]**. Weertman's solution for an elastic crevasse of a specified depth requires the elongating longitudinal stress and the percentage of the crevasse depth filled with water. **Figure 2** shows a 500 m crevasse with a longitudinal stress of 0.5 MPa for various water filling percentages. Note that as the percentage filled decreases, the crevasse narrows and ultimately pinches off at a depth of 45 m for ~94% water filled.

White [20] provides us with a method for calculating the flow velocity, and hence the flux, within a circular pipe of specified length and diameter, draining a larger basin with a specified depth of water. Pressure at the top of the basin is atmospheric and at the bottom of the pipe is equal to the ice overburden pressure. From this we can estimate the amount of time that it takes to drain a moat of specified dimensions (the moat volume of course being dependent on the lateral size of the lava slab).

As the moat drains the percentage filled declines and the crack narrows, ultimately pinching off as shown in **Figure 2**. A narrower crack passes a smaller flux, so the rate at which the moat drains decreases with time. **Figure 3** shows both water level and percentage filled as a 100 X 100 m wide 90 m deep moat drains over a period of 30 days through a crack to the base of the 500 m thick ice. Finally **Figure 4** shows the evolution of the crack shape as the percentage filled declines until the crack pinches off at the base of the moat.

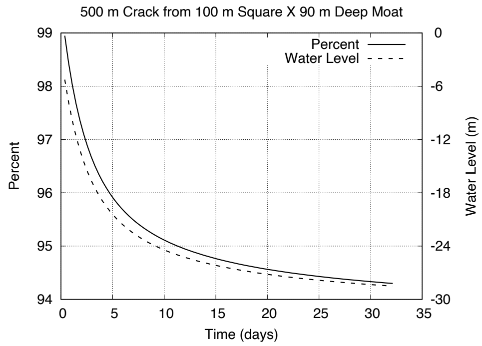

Figure 3: Percent filled and water level within 90 m deep moat as it drains over 30 days, stopping when the crack pinches off at the base of the 90 m deep moat.

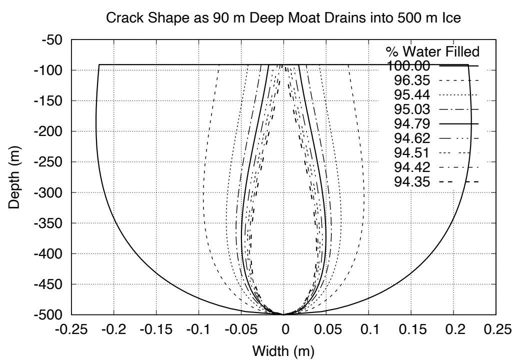

Figure 4: Crack shape below the 90 m deep moat as it drains, stopping when it pinches off at ~94% water filled.

While by no means an exhaustive search of the parameter space, this analysis demonstrates that the moats produced as a lava slab melts into an ice sheet can deliver much of their water to the base where enhanced sliding can then occur without the need to bring the basal temperature to the melting point. Because the ice is cold, this water would rapidly refreeze over a period of days to months, depending on the rate and duration of the draining event. In **Figure 1**, the two acceleration peaks were caused by increased overburden and a transient temperature wave reaching the bed. The case where liquid water at the bed lubricates and allows sliding would produce a transient acceleration even greater than that produced by the warming of the ice column. Our case of a 100 X 100 wide 90 m deep moat (that which would be produced by a 20 m thick lava flow) is of course at the low end of the size we might expect for superposed lava. A larger area flow with a larger moat would of course take proportionally longer to drain, however, for a larger moat there is more likelihood of multiple cracks forming. Additionally, the crack shape predicted by the Weertman formulation **[18]** is for the elastic response (i.e. short term), and ice also has a viscous (i.e. creep) response, which Weertman states is not qualitatively different in form, although perhaps larger in scale. Hence our estimate of draining times may be longer than would occur if a full viscoelastic solution were used. Importantly, such a solution should still pinch off at some depth as the percentage filled decreases, leaving the moat incompletely drained.

Conclusions: The volume of meltwater produced depends on the areal extent and thickness of the imposed lava slab and will be roughly 4.5 times the lava slab volume. Spilled water (that deposited on the surface of the ice sheet) will be roughly equal to the volume of the lava. Whether it runs off the ice sheet without refreezing depends on the ice surface slope (which may be topographically controlled) and proximity of the lava to the ice sheet margin (where slopes are generally steeper). As the slab melts further into the ice, the moat will remain full until a crevasse penetrates to the ice sheet bed (this can happen quickly, potentially in a matter of days), at which point roughly half of the moat volume will drain to the bed before the decreasing filled percentage drops to 94% and the crevasse pinches off, terminating the draining. With water lubricating the base of the ice sheet, enhanced sliding can occur and will persist until all that water is refrozen onto the bed, a process that can take weeks to months. A freezing bed will incorporate considerable debris into the basal ice producing wet-based erosional features as well as enhancing morainal features, both lateral and terminal. This acceleration, combined with the two transients from increased overburden and thermal wave reaching the bed, may further fracture the ice surface, enhancing crevasse generation and allowing further water to reach the bed, a positive feedback mechanism. Decoupling the bed simultaneously increases ice velocity while lowering surface slope, which may lead to further ponding of spilled water on the ice surface. We are currently comparing these predictions to observations of features in the southern uplands to assess the implications.

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