ICE-COVERED VOLCANIC WATER FLOWS ON GANYMEDE, M. Lee Allison, Dept. of Geology & Geography, and Stephen M. Clifford, Dept. of Physics & Astronomy, Univ. of Massachusetts, Amherst, MA 01003

The most geologically reasonable model for the origin of grooved terrain on Ganymede involves flooding of a planetary graben system by water or water-ice magmas that rose to the surface along normal faults in the rift zones (1,2). To investigate this process further, we have examined the thermal evolution of a water flow on Ganymede's surface. The model is a variation of earlier work on ice-covered water flows (3,4,5). It is based on the simplifying assumptions that laminar flow and a concomitant solid ice cover are achieved relatively soon after eruption; and that the amount of energy lost to the substratum is negligible.

The two primary sources of heat at the ice surface are the fraction of solar radiation absorbed within the ice ($(1-f)q_i$, where $q_i = I(1-A)$),and the conductive heat flux from the underlying water flow ($q_c = k\ (273.15 - T)/x$). These heat inputs are balanced by radiative cooling ($4\sigma T^4$) and by the heat lost through sublimation of the ice cover ($L_s\ dm_u/dt$). Thus, the total surface heat balance is given by the equation: $(1-f)q_i + q_c = 4\sigma T^4 + L_s\ dm_u/dt$ (1)

where f, the fraction of incident solar radiation which is transmitted through the ice, is given by:

$$f = \exp(-Kx). \quad (2)$$

K, the bulk extinction coefficient (=.01 cm^{-1}), was selected on the basis of several studies on the optical properties of terrestrial sea and glacial ice (6,7). The variation of f with depth is illustrated in Fig. 2.

The equilibrium surface temperature required to solve the surface energy balance in Equation 1 was found using Newton's method. In the same matter as (5) this temperature was then used to determine the conductive heat loss (q_c) from the underlying water flow. Consideration of the heat balance at the base of the ice layer shows that q_c equals the sum of the fraction of the solar flux absorbed in the water (fq_i) and the latent heat released by freezing ($L_f\ dm_i/dt$) as the ice cover thickens with time. More simply:

$$q_c = fq_i + L_f\ dm_i/dt \quad (3)$$

The increase in ice thickness dx which occurs in the time interval dt was calculated by noting that $dm_i/dt = \rho\ dx/dt$. Equation 3 was then solved for dx, yielding:

$$dx = dt(q_c - fq_i)/L_f \quad (4)$$

where we have assumed $\rho = 1\ g\ cm^{-3}$. With each time step the series of calculations (Equations 1-4) were repeated based on the increase in ice thickness determined in the previous time step. The net effect of the increase in ice thickness is to reduce both the conductive heat loss from the water (q_c) and the fraction of solar radiation absorbed in the water (f).

During the first few minutes following the eruption of the water-magma, the surface temperature of the ice cover drops from 273 K to ~ 170 K, eventually cooling to below 150 K on a timescale of several tens of days (Fig. 3). These surface temperatures assume a magma flow which is sufficiently deep that a portion remains unfrozen beneath its protective ice cover over the given time period. The rate of increase in ice cover thickness is illustrated in Figure 4. During the first hour, the ice cover thickens to more than 10 cm - after which the growth rate begins to slow significantly. A 5 m thick water flow would take about 75-80 days to freeze to its base.

The above results appear to be independent of reasonable changes in the assumed value of the bulk extinction coefficient or the albedo of the ice surface. The most sensitive parameter is the thermal conductivity of the ice cover; for example, decreasing it to .006 from our assumed value of .013 cal $cm^{-1}\ s^{-1}\ K^{-1}$ means that a 5 m thick flow would take more than twice as long to freeze to its base.

Our results suggest that water, under a protective and thickening ice cover, can exist on the surface of Ganymede for significant periods of time. Given a rate of discharge for water volcanism on Ganymede (per kilometer length of active fissure) similar to that of average terrestrial basalt flows, a 5 m thick flow erupting from a 100 km long fissure could flood an area of 17 km^2 in a single day - and more than 1200 km^2 in the time required to freeze the flow to its base. Based on these calculations, we conclude that it would not be difficult for a series of water flows to fill Ganymede's planetary rift system and create the high albedo grooved terrain in a geologically reasonable interval of time.

Acknowledgement: This work was supported in part by NASA Grant NSG 7405.

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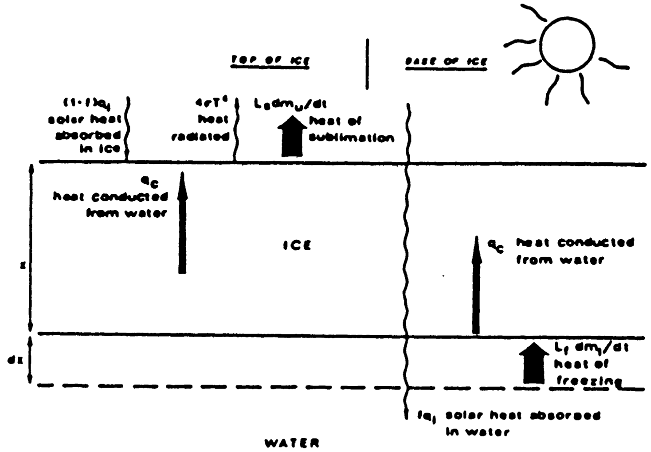

Fig. 1. Energy balance of thickening ice layer over water.

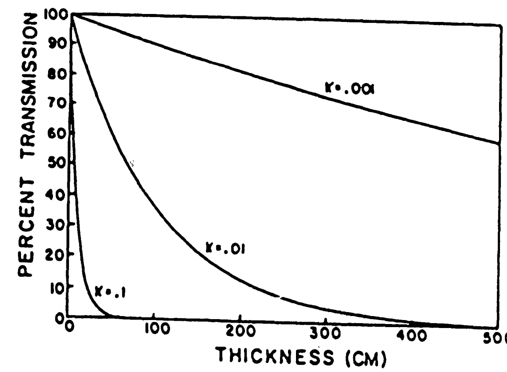

Fig. 2. Percentage of solar radiation penetrating pure ice with different values of the extinction coefficient, K.

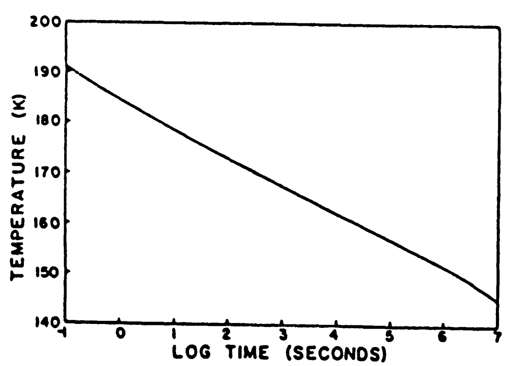

Fig. 3. Surface temperature of ice as a function of time after eruption.

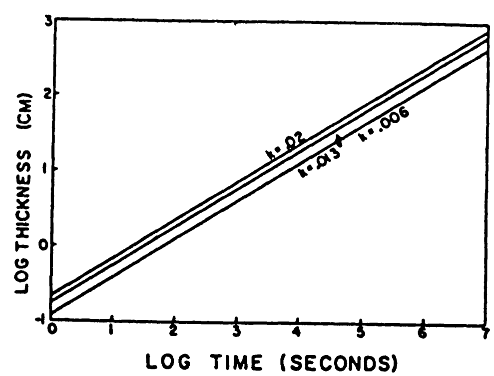

Fig. 4. Thickness of ice layer as a function of time after eruption for different values of thermal conductivity, k. The calculated value of k is .013. Extreme values of .02 and .006 represent significant amounts of material other than H_2O in the flows.

Table 1. Definition of symbols

f	fraction of q_i absorbed in water
q_i	solar heat absorbed at or below ice surface
q_c	heat conducted to surface
L_f	latent heat of freezing
L_s	latent heat of sublimation
k	thermal conductivity
K	bulk extinction coefficient
dt	incremental time change
x	ice thickness
dx	increase in ice thickness
σ	Stefan-Boltzmann constant
dm_l/dt	mass gain at ice base - freezing
dm_u/dt	mass loss at ice top - sublimation
T	surface temperature of ice
A	mean surface bond albedo
I	solar insolation