RHEOLOGY OF LAVA FLOWS ON EUROPA AND THE EMERGENCE OF CRYOVOLCANIC DOMES.
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Introduction: There is ample evidence that Europa is currently geologically active [1-4]. Crater counts suggest that the surface is no more than 90 Myr old [5], and cryovolcanism may have played a role in resurfacing the satellite in recent geological times [6-10]. Europa's surface exhibits many putative cryovolcanic features [1,7-12], and previous investigations have suggested that a number of domes imaged by the Galileo spacecraft may be volcanic in origin [1,9] (Fig.1). Consequently, several Europa domes have been modeled as viscous effusions of cryolava [9,13]. However, previous models for the formation of silicic domes on the terrestrial planets contain fundamental shortcomings. Many of these shortcomings have been alleviated in our new modeling approach, which warrants a re-assessment of the possibility of cryovolcanic domes on Europa.

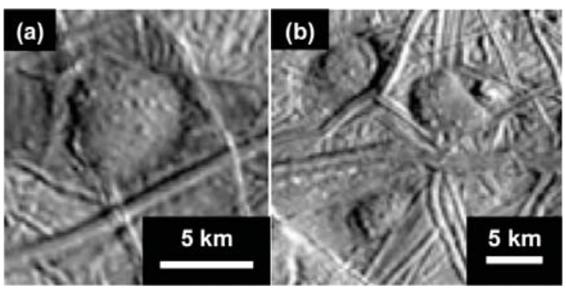

Figure 1. Some domes on Europa may have been emplaced as viscous effusions of cryolava onto the surface. The models presented here help constrain such cryovolcanic extrusions.

New Modeling Approach: We have investigated the emplacement of cryovolcanic domes on Europa, exploring the effect of boundary conditions on the solution of the Boussinesq equation for pressure driven fluid flow in a cylindrical geometry. The continuity equation describing radial expansion of a Newtonian fluid with an unbounded (free) upper surface and a time-dependent viscosity is:

$$\frac{\partial h}{\partial \theta} - \frac{g}{3\nu_o}\frac{1}{r}\frac{\partial}{\partial r}\left(r h^3 \frac{\partial h}{\partial r}\right) = 0 \qquad (1)$$

[14] found a similarity solution to the general form of (1) for a constant fluid volume with constant viscosity. This solution has been previously applied to the emplacement of putative volcanic domes on Venus and Europa [9, 15-16]. Here we offer an alternative similarity solution to (1) that eliminates the singularity at $t = 0$ inherent to the solution in [14] and allows for the investigation of associated plausible boundary conditions. This model also addresses the issue of time dependent changes in lava viscosity due to cooling. The similarity solution for flow thickness, h, is:

$$h(r,t) = \frac{4V}{3\pi r_o^2 (1+\theta/\tau)^{1/4}} \left[1 - \frac{1}{\left(\theta/\tau + 1\right)^{1/4}} \frac{r^2}{r_o^2} \right]^{1/3} \qquad (2)$$

where θ is a time transformation constant of the form:

$$\theta(t) = \nu_o \int \frac{dt}{\nu(t)} \qquad (3)$$

The time constant that eliminates the singularity at $t = 0$ is $\tau = (3/4)^5 (\pi/V)^3 \nu_o r_o^8/g$. A variety of forms can be chosen for the time-dependent kinematic viscosity $\nu(t)$. One plausible form is a cryolava viscosity that increases exponentially with time as it cools [17], $\nu(t) = \nu_o e^{t/\Gamma}$. Fig. 2 shows the solution of a radially spreading, Newtonian fluid with $\nu_o = 10^7$ m^2/s (equivalent to 10^{10} Pa-s for cryolava density of 10^3 kg/m^3) at four times. Here, the overall "shape" of the flow surface, as well as the aspect ratio at the final time, is very similar to the dimensions of the domes in Fig. 1 [9] when $\tau = 2.95 \times 10^6$ sec (34 days), and $\Gamma = 7$ months. The total relaxation time is ~ 3 years, which is well within the range of emplacement times for icy lavas predicted by conductive and radiative cooling [9,18].

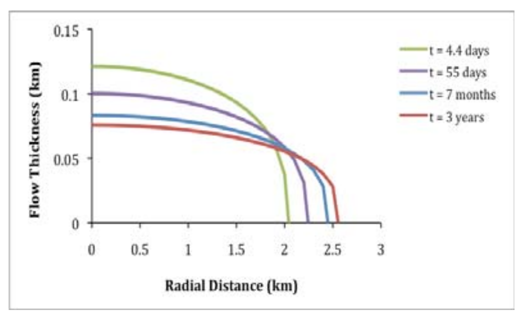

Figure 2. Axially symmetric Newtonian fluid flow profiles obtained from (2).

Skin Strength: Owing to water's very low vapor pressure (~600 Pa), cryolava erupted into Europa's low-pressure environment will boil violently until an approximately 0.5 m thick icy carapace forms; flows can then be maintained beneath this insulating layer [19]. For cryolava erupting at temperatures near 273 K, the latent heat of vaporization is approximately 7 times larger than the latent heat of fusion [19-20]. As a con-

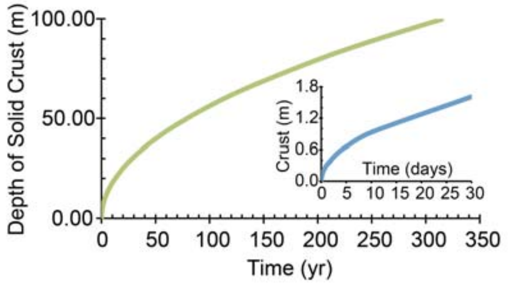

Figure 3. Growth rate of cryolava surface crust. **Inset.** A solid icy carapace 0.5 m thick will take ~ 3 days to grow.

sequence, appreciable quantities of ice will be produced for any given amount of lava that is boiled off, and conductive cooling will dominate [18, 20]. The growth of the icy crust atop the flow can therefore be modeled after [21]. Figure 3 shows an example of icy carapace growth as a function of time on a cooling cryolava at Europa's surface conditions.

If cryolavas on Europa are briny solutions [12, 22-23], their eutectic temperatures could be as low as 193 K [24], and they may supercool 5-15° below their eutectics before crystallization commences [25]. The profiles in Fig. 4 show that after 3 years, approximately 85% of a ~ 75 m thick flow would still be ductile, and hence able to relax and advance. The depth at which the glass transition temperature is reached in the flow can also be used as a gauge to determine the extent of crustal growth [17, 26]. From Fig. 4 it is clear that the ~ 136 K glass transition temperature for water [27] is only reached down to shallow depths of ~ 3.6 m within the flow. Hence the vast majority of the flow would still be mobile.

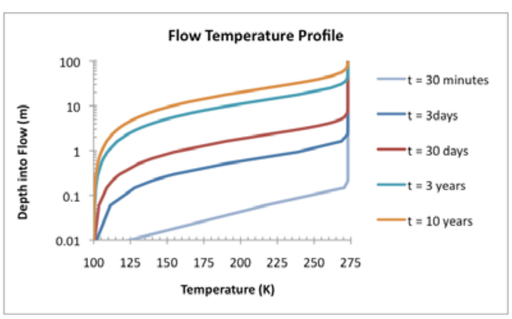

Fig. 4. For an ~75 m thick dome that comes to a final, relaxed shape after 3 years (Fig. 2), only the top 10 m of the flow falls below 193 K, and only the top 3.6 m is below water's glass transition temperature (i.e., 136 K). Hence, the flow will still be mobile.

Nevertheless, crustal strength will have some effect on bulk lava viscosity by providing a resistive pressure and slowing the flow of the fluid lava in the interior. The hydrostatic pressure of cryolava may initially be large enough to entrain the icy crust, thereby ensuring continued dome relaxation [9, 19]. A similar scenario has been suggested for silicate lavas [28]. When taking into account the effect of the crust for terrestrial silicate lavas and cryolavas, the effective viscosity can be up to four orders of magnitude higher than the actual viscosity of the fluid [17-18, 29]. Therefore, the actual initial kinematic viscosity for the dome modeled in Fig. 2 may be significantly below 10^7 m^2/s.

If, based on their morphology, we assume that the domes in Fig. 1 are volcanic extrusions of cryolava, the projected kinematic viscosities for Europan lavas range from 10^{-5} – 10^8 m^2/s [9, 22]. The next step of this work will be to apply these models to other putative cryovolcanic domes imaged by Galileo to constrain the range of emplacement times and eruption rates for this particular style of cryovolcanism.

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