

A VOLUME FLUX APPROACH TO CRYOLAVA DOME EMPLACEMENT ON EUROPA.

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Introduction: We previously modeled a subset of domes on Europa with morphologies consistent with emplacement by viscous extrusions of cryolava [1]. These models assumed instantaneous emplacement of a fixed volume of fluid onto the surface, followed by relaxation to form domes [1]. However, this approach only allowed for the investigation of late-stage eruptive processes far from the vent and provided little insight into how cryolavas arrived at the surface. Consideration of dome emplacement as cryolavas erupt at the surface is therefore pertinent. A volume flux approach, in which lava erupts from the vent at a constant rate, was successfully applied to the formation of steep-sided volcanic domes on Venus [2]. These domes are believed to have formed in the same manner as candidate cryolava domes on Europa [1,3]. In order to gain a more complete understanding of the potential for the emplacement of Europa domes via extrusive volcanism, we have applied this new volume flux approach to the formation of putative cryovolcanic domes on Europa. Assuming as in [1] that european cryolavas are briny, aqueous solutions which may or may not contain some ice crystal fraction, we present the results of this modeling and explore theories for the formation of low-albedo moats that surround some domes (Fig. 1).

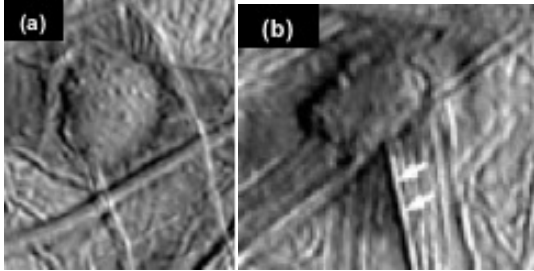


Figure 1. Candidate cryolava domes with low-albedo moats. Domes are 5-6 km wide.

Approach: An alternative method for inferring bulk cryolava rheology, which incorporates the lava emplacement stage, is presented here. This method was employed in [2] for dome emplacement on Venus. An innovative perturbation solution to the generalized form of the Boussinesq equation for fluid flow in a cylindrical geometry is presented in [4]. The continuity equation describing radial expansion of a Newtonian fluid with an unbounded (free) upper surface is:

$$\frac{\partial h}{\partial t} - \frac{g}{3\nu} \frac{1}{r} \frac{\partial}{\partial r} \left(r h^3 \frac{\partial h}{\partial r} \right) = 0 \quad (1)$$

[4] found a similarity solution to (1) by transforming this equation to an ordinary differential equation when

a constant volumetric flowrate, Q , at the origin is given. This similarity solution is found by perturbation by defining a parameter $\varepsilon = 1/(n+1)$ [2,4]. The new independent variable, x , and dependent variable P , that transform (1) to an ordinary differential equation are defined as:

$$x = \left(\frac{r^2}{4t} \right) \left[\varepsilon \Phi \left(\frac{Q}{4\pi\varepsilon} \right)^{1-\varepsilon} \right]^{-1} \quad \text{and} \quad (2)$$

$$P(x; \varepsilon) = 4\pi\varepsilon h^4 / Q$$

where $\varepsilon = 1/4$ and $\Phi = 1.2$ for European cryolavas when a Newtonian rheology is assumed [2-4]. Following the approach from [4], flow thickness, h , as a function of time is described by:

$$h = h_o \left(P \frac{Q}{4\pi\varepsilon} \right)^\varepsilon \quad (3)$$

Results: Fig. 2 shows the solution of a radially spreading, Newtonian fluid with a bulk kinematic viscosity, $\nu = 10^5 \text{ m}^2/\text{s}$ (equivalent to a bulk dynamic viscosity, $\mu = 10^8 \text{ Pa s}$) [1]. Here, the overall “shape” of the flow surface and the aspect ratio at $t = 40$ days is very similar to the dimensions of the domes in Fig. 1 [1, 3]. Note that the bulk kinematic viscosity reported above includes the contribution from the brittle cryolava crust [1, 5-6]. The initial viscosity of the erupted cryolava may be up to 4 orders of magnitude lower than this value [1-2, 5-7], perhaps as low as $10^1 \text{ m}^2/\text{s}$. In a next iteration of this work, we will explore the effects on dome formation while varying ν and Q at the vent. We will also place bounds on plausible cryolava compositions that would be commensurate with the reported viscosity values.

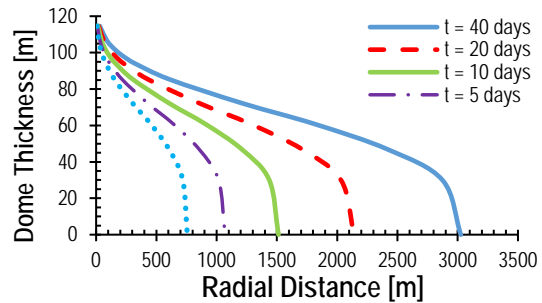


Figure 2. Axially symmetric Newtonian fluid flow profiles at five times when $Q = 550 \text{ m}^3/\text{s}$ at the vent

Moat Formation: Several putative cryolava domes are surrounded by low-albedo moats (Fig. 1). A number of theories have been set forth for their formation [e.g., 3, 8]. Notwithstanding, as these moats are associated with putative cryolava domes, it is also possible

that they were emplaced due to processes associated with extrusive cryovolcanism. Cryolava coextrusion and lithospheric flexure have thus been explored as plausible mechanisms for moat formation.

Cryolava Coextrusion. In terrestrial volcanic systems, magma ascending in dikes and conduits often takes the form of two-component flow, in which melt of differing viscosities travel side by side to the surface [9-12]. As these magmas ascend, viscous segregation causes the low-viscosity component to migrate to the high-shear regions adjacent to dike walls. This configuration is dynamically stable [9-10, 13-14] and allows the low-viscosity component to lubricate the flow of its high viscosity counterpart. On Europa, coextrusion is likely to take the form of a two component cryomagma in which a briny, low-viscosity melt migrates to the walls of a fracture, encapsulating a viscous, crystal-liquid slurry in the center of the flow where shear is negligible. A detailed, analytical treatment of two-component effusive flow was undertaken by [12]. Following this method, the volume flux of cryomagma transported during two-component Newtonian flow in a cylindrical conduit was derived:

$$Q_{wall} = \frac{G\pi}{2\mu_{wall}} \left[\frac{da^3}{3} - \frac{a^4}{4} \right] \quad (4)$$

$$Q_{core} = \frac{G\pi}{2\mu_{core}} \left[a^2 \left(\frac{d^2}{16} - \frac{a^2}{4} \right) \cdot \frac{d^4}{64} + \frac{d(2a-d)^2(a+d)}{6} \right]$$

$$+ \frac{G\pi}{2\mu_{wall}} \left[\frac{a^4}{4} + \frac{ad^3}{8} - \frac{a^2d^2}{8} - \frac{a^3d}{2} \right]$$

$G = [g(\rho_i - \rho_f) - \Delta P/H]$ is the pressure gradient due to both the hydrostatic overburden, and the excess pressure that would allow melt to be driven from a crustal fluid reservoir at depth H [3]. a is the thickness of the low-viscosity lubricating layer (i.e., the shear layer) in a conduit of width d . Fig. 3 shows Q_{wall} and Q_{core} as a function of a for cryomagmas when $H = 5$ km and $d = 6$ m. Here, $\mu_{wall} = 20$ Pa s, $\mu_{core} = 4 \times 10^4$ Pa s and $\Delta P = 4 \times 10^6$ Pa. For a briny solution ascending in an icy crust, $\rho_i = 917$ kg/m³ and $\rho_f = 1400$ kg/m³. For $a < d/3$, $Q_{core} > Q_{wall}$, and the high viscosity melt component is rapidly erupted onto the surface (Fig 3). This initial eruption stage could therefore provide the cryolavas necessary for dome formation at the surface. As a approaches $d/3$, the two-component flow configuration breaks down and Q_{core} approaches 0 (Fig. 3). The high viscosity cryomagma becomes depleted in the conduit, leaving only the low-viscosity component available for later eruptions. This low viscosity component may subsequently erupt to form a moat. The fluidity of the cryolava involved in this later eruption stage would enable it to travel farther from the vent than its high-viscosity counterpart, while the moat's low albedo may be a tell-tale sign of its briny composition.

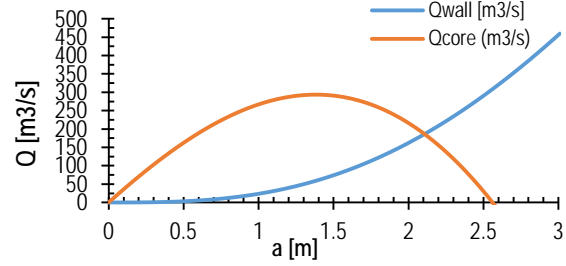


Figure 3. Volume flux of co-extruding cryomagmas as a function of shear-layer thickness. Here $G = 172$ Pa/m.

Lithospheric Flexure. Flexure has been observed along fractures on Europa, and ridges, which sit atop the elastic lithosphere [15], weigh it down, producing secondary uplifts, or forebulges. Galileo imagery revealed clear cases of crustal warping near ridges, which follow the expected flexure geometry for a loaded lithosphere. By comparing the observed distance of the forebulges with theory, lithospheric thicknesses of 0.2 to 2 km were estimated [16-18]. Extrusion of dome material onto Europa's surface would also place a load on the elastic lithosphere, warping the ice shell and causing secondary uplift around domes. In the next iteration of this study, dome margins will be studied to look for signs of uplift. If a relationship is found to exist between candidate cryolava domes and lithospheric flexure, it would reinforce a possible cryovolcanic origin for these domes and suggest that moats surrounding these domes are not solely a result of material extrusions, but that they may also form when the weight of erupted cryolava causes the crust to sag into mushy fluid layers beneath.

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