A VOLUME FLUX APPROACH TO EUROPA CRYOLAVA DOME FORMATION AND IMPLICATIONS FOR THE THERMAL EVOLUTION OF CRUSTAL FLUID RESERVOIRS. Lynnae C. Quick[1], Sarah A. Fagents[2], Karla A. Nuñez[3], Ross A. Beyer[4,5], Chloe B. Beddingfield[4,5], Louise M. Prockter[6], [1]NASA Goddard Space Flight Center, Greenbelt, MD 20771, Lynnae.C.Quick@nasa.gov, [2]The University of Hawai'i at Mānoa, Honolulu, HI 96822, [3]University of Maryland College Park, College Park, MD 20742, [4]The SETI Institute, Mountain View, CA 94043, [5]NASA Ames Research Center, Mountain View, CA 94035, [6]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723.

Introduction: Previously, we modeled a subset of domes on Europa with morphologies consistent with emplacement by viscous cryolavas (Fig. 1) [1]. However, that 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 onto Europa's surface, and the conditions in subsurface fluid reservoirs that would facilitate these eruptions, 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 better gauge the potential for dome formation on Europa via effusive eruptive events, we have applied this new approach to the formation of putative cryolava domes on Europa.

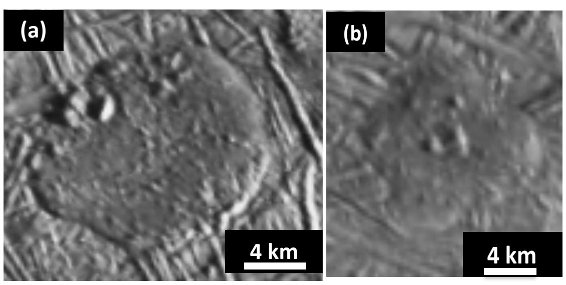

Figure 1. Candidate cryolava domes. (a) DEMs reveal that this kidney-bean shaped dome has a central depression ~ 50 m deep. (b) The petal-shaped outline of this dome is consistent with the formation of flow lobes.

Approach: An alternative method to [1] for inferring bulk cryolava rheology, which incorporates the fluid emplacement stage, is presented here. 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:

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

[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:

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

where ε = ¼ and Φ = 1.2 for Europan 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:

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

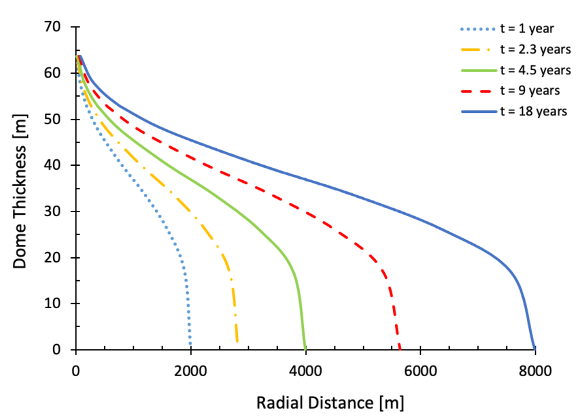

Figure 2. Axially symmetric Newtonian fluid flow profiles at five times when Q = 13 m³/s at the vent.

Results: Fig. 2 shows the solution of a radially spreading, Newtonian fluid with a bulk kinematic viscosity, ν = 4 x 10^5 m^2/s. Here, the overall "shape" of the flow surface, and its aspect ratio at t = 18 years, are very similar to the dimensions of the dome in Fig. 1a. Our modeling does not consider the dome's central depression, which was likely formed by drawback of fluid into the subsurface after the dome was emplaced. Note that the bulk kinematic viscosity reported above includes the contribution from the brittle cryolava crust [1, 5-6]. Thus, the initial viscosity of the erupted cryolava may be up to 5 orders of magnitude lower than this value [5-7], perhaps as low as 10^3 m^2/s. These viscosity values suggest that Europan cryolavas are briny slurries composed of a mixture of water, salts and ice crystals, consistent with previous studies [1,3]. In a next iteration of this work, we will explore the effects on dome emplacement of varying ν and Q at the vent.

Crustal Fluid Reservoirs: Excess pressures caused by the gradual freezing of crustal fluid reservoirs may lead

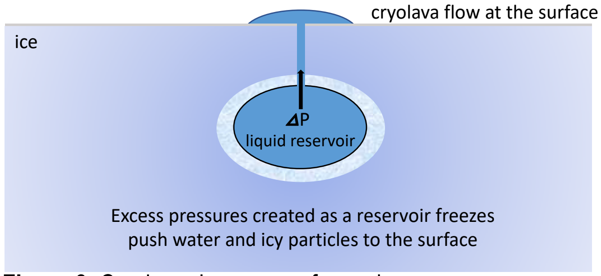

Figure 3. Cryolava domes may form when excess pressures created by the gradual freezing of crustal fluid reservoirs push viscous fluid to Europa's surface. Figure after [3].

to stress conditions that promote fracturing in Europa's ice shell; fluids may then be transported to the surface in these fractures (Fig. 3) [3, 8]. However, the successful transfer of cryolava to Europa's surface will also be dependent upon the thermal state of the reservoir from which it originates. Thus, exploring the thermal evolution of fluid reservoirs in Europa's crust allows reasonable constraints to be placed on the longevity of cryovolcanic eruptions at the surface, and the maximum volume of fluid that can be driven to the surface during each eruptive event [9].The temperature, T, as a function of time, t, for spherical fluid reservoirs, embedded in Europa's ice shell may be expressed as:

$$T = T_{cold} + (T_o - T_{cold})\left(e^{-3t\kappa_{ice}/r^2}\right) \quad (4)$$

[10] where T_{cold}, the temperature at which cryomagma freezes in the reservoir, is taken here to be the eutectic temperature of the cryovolcanic fluid, T_o = 273 K and r are the reservoir's initial temperature and radius, respectively, and κ_{ice} is the thermal diffusivity of the solid phase. The total cooling time of the reservoir may be approximated as: $t_{total} = r^2/4\lambda^2\kappa_{fluid}$ [1] where κ_{fluid} = 1.3 x 10^{-7} m^2/s is the thermal diffusivity of the cryomagma, commensurate with [3]. If it is then assumed that only a fraction of the reservoir, $r_{part} = 2\lambda\sqrt{\kappa_{fluid}t}$, is crystallized at all other times, t, a general relationship between % crystallinity and t is: $\%_{\text{reservoir crystallized}} = (r_{part}/r)$ x 100%. Here we have assumed that the fluid in the reservoir is an NaCl-rich solution, so that T_{cold} is its 252 K eutectic temperature, λ = 0.244 and $\kappa_{ice} \cong$ 1.3 x 10^{-6} m^2/s in (4) .

The dome in Fig. 1a has a volume of ~ 1.3 x 10^{10} m^3 [11]. The cryolava that formed this dome may have originated in a reserovir with r = 1.4 km, commensurate with proposed reservoir volumes on Europa and Earth [9, 12]. Fig. 4 shows temperature as a function of time for such a reservoir. It is clear that T > 252 K for 7 x 10^4 years. Fig. 5 shows that at this time, the reservoir has reached ~ 18% crystallinity. Although this value is much less than the 55% crystallinity threshold beyond which magmas are precluded from erupting [1, 13], Figs. 4 & 5 show that for the scenario envisioned here, eruptions would occur at Europa's surface for a maximum period of 7 x 10^4 years. After this time, the reservoir's temperature would rapidly approach the eutectic temperature of the NaCl-rich fluid. Given the relatively short timescales required for cryolava domes to form (Fig. 2), this suggests that effusive eruptions at Europa's surface halt long before subsurface reservoirs completely freeze, so that the release of excess pressure in crustal reservoirs is the deciding factor on how long eruptions continue at the surface. This pressure release would occur over much shorter timescales than are implied by the thermal arguments presented here and will be investigated in a next iteration of this model.

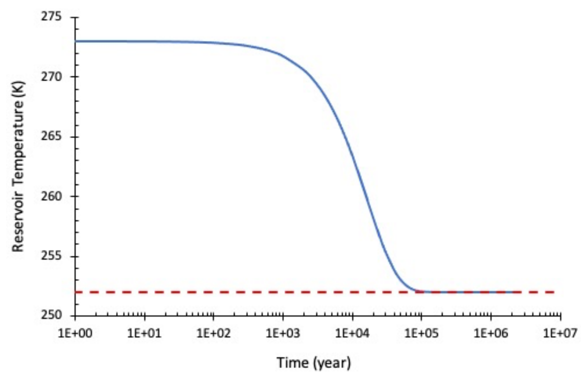

Figure 4. Temperature as a function of time for a spherical reservoir when r = 1.4 km. T = 273 K for the first 300 years and T > 252 K for 7 x 10^4 years (indicated by red stippled line)

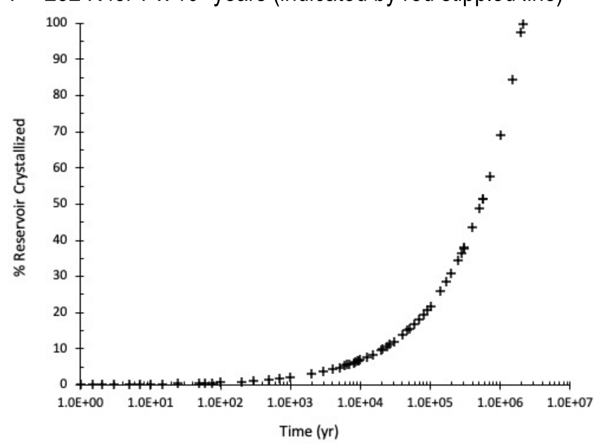

Figure 5. Gradual freezing of the reservoir as a function of time. After 7 x 10^4 years, the reservoir reaches 18% crystallinity and the fluid within becomes too viscous to erupt.

References: [1] Quick, L. C. et al. (2017) *Icarus*, *284*, 477-488. [2] Quick, L. C. et al. (2016) *JVGR 319*, 93-105. [3] Fagents, S. A. (2003) *JGR, 32,* E12. [4] D. K. Babu & Van Genuchten, M. T. (1980) *J. Hydrol., 48*, 269-280. [5] Schenk, P. M. (1991) *JGR, 96,* 1887-1906. [6] Lorenz, R. D. (1996) *P&SS, 9*, 1021-1028. [7] Stofan, E. R. et al. (2000) *JGR,105*, 26,757-26,771. [8] Manga, M. & Wang. C-Y. (2007) *GRL, 34*, L07202. [9] Lesage, E., et al. (2020) *Icarus, 335,* 113369. [10] Marsh, B. D. (1984) *JGR, 89,* 8245-8251. [11] Nuñez, K.A., et al. (2019) *50th LPSC*, Abstract #3264. [12] Townsend, M. & Huber, C. (2020) *Geology, 48,* 431-435. [13] Marsh, B. D. (1981) *Contrib. Mineral Petrol., 78*, 85-98.