MAPPING AND MODELING OF CANDIDATE CRYOVOLCANIC DOMES ON EUROPA. Kierra A. Wilk[1,2], Lynnae C. Quick[1], Emily S. Martin[3], Sarah A. Fagents[4], Chloe B. Beddingfield[5], Ross A. Beyer[6], [1]NASA Goddard Space Flight Center, [2]Brown University (kierra_wilk@brown.edu), [3]National Air and Space Museum, Smithsonian Institution, [4]University of Hawaii, [5]John Hopkins University – Applied Physics Lab, [6]SETI Institute

Introduction: The Galileo spacecraft's Solid State Imager revealed that Jupiter's moon Europa has a young surface with diverse features, including pits, spots, and domes [1,2]. A variety of mechanisms have been proposed for the formation of Europa's domical uplifts [2,3], including diapirism [1,4,5] and cryovolcanic emplacement [5–8]. Owing to their circular or lobate shape and relatively smooth surfaces which are distinct from the background terrain, a subset of Europa's domes are considered to be cryovolcanic in origin [6–8].

The morphology and emplacement of putative cryolava domes have been the focus of several studies. Thirty-eight candidate cryolava domes in the Conamara region were included in a preliminary cryolava dome database [9]; a third of these domes were later modeled using a volume flux approach that considered dome formation as cryolava was erupted onto Europa's surface at a constant rate [6]. That modeling approach resulted in fluid viscosities of dome-forming cryolavas that are up to five orders of magnitude less than previous studies [7]. We significantly expanded the cryolava dome database to include 186 candidate cryolava domes and modeled the formation of these cryolava domes to enhance our understanding of the rheology of Europa's cryolavas and better constrain the rates of surface-subsurface exchange of potentially habitable subsurface reservoirs in perhaps youthful areas on Europa's surface.

Methods: We used mosaics and digital elevation models (DEM) derived from Galileo's E6, E14, E15, and E17 flybys of Europa to identify and map candidate cryovolcanic domes. We note the geologic and morphologic context of the domes, including whether they intersect or are intersected by a double ridge, sit in a depression, contain a depression, or appear to contain one or more flow lobes at the limit of image resolution.

Three topographic profiles for each candidate feature were obtained using the 3D Analyst tool in ArcGIS. A significant number of the candidate cryolava domes are positioned within regional topographic lows or sloped terrains, and as such we implement a background subtraction for each topographic profile to obtain relative dome heights. We report the mean diameter and mean maximum height of each feature from the three background subtracted profiles (Fig. 2), which are then used as inputs to model the emplacement of the candidate cryolava domes.

The formation of cryolava domes has previously been described using the generalized form of the Boussinesq equation for the radial expansion of a fluid in a cylindrical geometry [10], with the dimensionalized form expressed as:

$$\frac{\partial h}{\partial t} - \frac{g}{3\nu_0}\frac{1}{r}\frac{\partial}{\partial r}\left(rh^3\frac{\partial h}{\partial r}\right) = 0 \qquad (1)$$

where g is Europa's gravity, ν_0 is the bulk kinematic viscosity of the cryolava, t is time, r is the radial distance of the dome-forming cryolava from the vent, and h is the cryolavas flow height. Note that bulk dynamic viscosity, μ, can be found by multiplying ν_0 by the assumed density for a briny cryolava (ρ = 1200 kg/m^3) and the fluid viscosity at the time of eruption, which does not include contributions from the insulating surface crust, may be up to ~5 orders of magnitude lower than the bulk dynamic viscosity [11]. The cryolava flow thickness and distance of the flow from the vent as a function of time during dome formation is described by:

$$h(r,t) = \left(\frac{P(x)r_0h_0^3}{2\varepsilon}\right)^{\frac{1}{4}} \qquad (2)$$

$$r(t) = \sqrt{\frac{xtg\Phi}{3\nu_0}\left(2r_0h_0^3\right)^{\frac{3}{4}}} \qquad (3)$$

where x and $P(x)$ transform (1) to an ordinary differential equation and ε = ¼ and Φ = 1.2 for Europa's cryolavas when assuming a Newtonian rheology. Terrestrial lava domes can take anywhere from several months to several decades to form, and previous studies have suggested that Europa's cryolava domes may take as little as one month and as long as 50 years to be emplaced [6,7]. In this work we consider a minimum emplacement time of one month and a maximum emplacement time is constrained by the conductive cooling time (i.e., solidification time) of the cryolava dome.

Results: We mapped 186 candidate cryolava domes (Fig. 1). Of these, 63 contain either a large central depression or contain multiple lobate flow fronts.

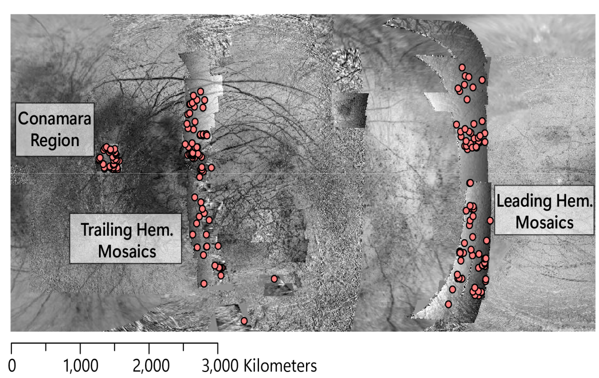

Figure 1: Locations of the 186 candidate cryolava features considered in this study.

While we mapped these candidate cryovolcanic domes, we do not model them as their central depressions suggests that there may have been a partial draining of the cryolava back into the vent and the additional flow lobes suggests that these domes may have been formed by multiple episodes of cryovolcanic eruptions. Modeling the formation of these features is therefore reserved for future studies. The mean radius of the remaining 123 cryovolcanic domes is 3476 ± 1653 m, with a mean maximum height of 144 ± 93 m. There are 4 domes that are intersected by a double ridge, 28 domes intersect double ridges, and 6 domes sit in a depression.

Depending on the size of the candidate cryolava dome, the lower limit eruption viscosities of the modeled domes range from $10^1 – 10^3$ Pa s and the upper limit eruption viscosities range from $10^3 – 10^7$ Pa s when considering the conductive cooling time to be commensurate with the maximum emplacement time of the domes. The maximum emplacement time for these domes ranges from $10^8 – 10^9$ s (years to decades), with some of the largest candidate features (>300 m in height) having emplacement times upwards of 10^{10} s (hundreds of years). Figure 2 shows the topographic and modeled profiles of two candidate cryolava domes. Dome 3726rA" (referenced as dome #4 in [6,7]) has a mean maximum height of 143 m and a mean radius of 3280 m. The modeled emplacement time of this feature ranges from $2.5 \times 10^6 – 4 \times 10^9$ s (1 month – 126 years) with an eruption viscosity of $1.4 \times 10^3 – 2.3 \times 10^6$ Pa s. Dome 4379rD, which was not included in previous analyses in [4-5], has a mean maximum height of 145 m and a mean radius of 2603 m. The modeled emplacement time of this dome ranges from $2.5 \times 10^6 – 4.1 \times 10^9$ s (1 month – 129 years) with an eruption viscosity of $2.4 \times 10^3 – 3.8 \times 10^6$ Pa s.

Discussion: The height of Dome 3726rA" was previously reported as 70 m [7] and 88 [6], while we report a maximum height of 143 m. Differences in reported heights may be due to using different transects for the topographic profiles and/or DEMs. Additionally our modeling utilizes the mean maximum height of each dome rather than the mean height as considered in [6]. We have done this as the mean height considerably underestimates dome height. As such, using mean dome height in our models has the potential to underestimate the viscosity by up to two orders of magnitude. The emplacement time of Dome 3726rA" is consistent with previous studies [6], although we find that the viscosity of the erupted cryolava may be up to an order of magnitude higher when the conductive cooling time is considered to be equal to the domes emplacement time.

The range of potential eruption viscosities is consistent with dome forming cryolavas on Europa having a basaltic to andesitic like rheology at the onset of eruption, suggesting that the cryomagma may be composed of a thick brine containing icy particulates. Variations in eruption viscosity are consistent with compositional or thermal differences in cryolava source regions. By investigating spatial variations in cryolava eruption viscosities, we can better understand the thermal evolution and potential heterogeneities in heat flux within Europa's interior. Higher resolution images of Europa's surface, which will be provided by the Europa Imaging System (EIS) on Europa Clipper [12], will allow for the identification of new or additional candidate cryolava domes, and potential locations of active resurfacing on the icy moon. Subsurface cryomagma reservoirs may also represent near-surface habitable environments. By studying Europa's candidate cryolava domes, we gain valuable insights into the compositional states of these potentially habitable abodes and current geological activity rates on this enigmatic moon.

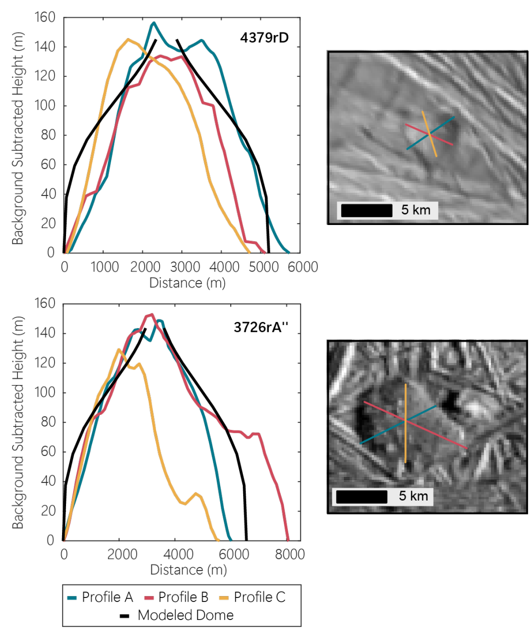

Figure 2: Observational and modeled profile of Domes 3726rA" and 4379rD.

References: [1]Pappalardo, R. T. et al. (1999) *JGR.*, *104*, 24015–24055. [2] Collins, G. and Ninmo, F. in: Pappalardo, R.T. et al., *Europa*, (2009). [3] Daubar, I. J. et al. (2024) *Space Sci Rev*, *220*, 18. [4] Rathbun, J. A. et al. (1998) *GRL*, *25*, 4157–4160. [5] Pappalardo, R. T. and Barr, A. C. (2004) *GRL*, *31*, 2003GL019202. [6] Quick, L. C. et al. (2022) *Icarus*, *387*, 115185. [7] Fagents, S. A. (2003) *JGR.*, *108*. [8] Quick, L. C. et al. (2017) *Icarus*, *284*, 477–488. [9] Núñez, K. A. et al. *LPSC* (2019), Abstract #3264. [10] Huppert, H. E. (1982) *J.Fluid Mech.*, *121*, 43. [11] Schenk, P. M. (1991) *JGR.*, *96*, 1887–1906. [12] Turtle, E. P. et al. (2024) *Space Sci Rev*, *220*, 91.