

“FRECKLES”, “SPOTS” AND DOMES ON EUROPA AND CERES: SURFACE FEATURES DRIVEN BY SUBSURFACE CRYOVOLCANIC DIKING AND SURFACE RESPONSE?

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Introduction: Many planetary bodies in our solar system show evidence of volcanism, mostly with silicate-based magma. Volcanism has also been postulated to occur in icy bodies, but with a warm, potentially salty, water-ice mixture as the magma, referred to as “cryovolcanism” [e.g. 1, 2]. The question remains of whether or not the magma ever extruded to the surface, leaving raised morphology and salt deposits behind, such as the pits and domes (“freckles”) on Europa and the Ahuna Mons dome on Ceres (Fig. 1). The Dawn spacecraft has imaged several features on the surface of Ceres that suggest cryovolcanic activity [3-6]. Previous studies suggest over-pressurization could have driven fluids from a subsurface reservoir on Ceres [7,8]. These processes may also occur on icy moons such as Europa and Enceladus [e.g. 1,9]. Here, we build on our prior models [10] of how a pressure increase in a cryovolcanic chamber in

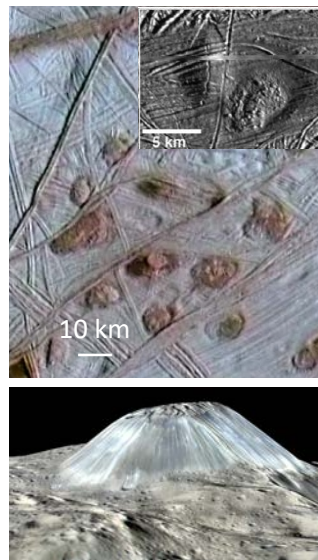


Figure 1. a. Pits and domes (“freckles”) on Europa) b. Ahuna Mons, Ceres [NASA]

subsurfaces could drive dike-like fractures towards the surface, enabling the formation of bright deposits and/or deformation of the surface. On Earth’s seafloor we observe this type of activity through hydrothermal vents releasing fluids heated by the magma beneath and seismic data and modeling that indicate dikes driven from the magma chamber [e.g. 11].

Methods: We model dike propagation using a finite element program, FRANC2d [12] that calculates displacements and stresses, given: a specific body geometry, imposed loads, material parameters, and boundary conditions. FRANC2d then determines the fracture direction and distance of propagation using the calculated stress results. First, we assume a cooling and freezing magmatic lens pressurized at a level, P_{int} (see Fig. 2 showing model set-up). The internal pressure causes

stress on the chamber perimeter and based on where the maximum stress occurs and that is greater than the strength of the ice + overburden, a fracture can initiate. Hydrostatic pressure acts outward within the dike as it propagates to the surface and so changes with depth as: $P_d = P_l - \rho_m g h$ where P_d is the dike pressure, P_l is the pressure at the base of the dike, ρ_m is the cryomagma density, and h is the distance the fluid has traveled above the chamber. $P_l = P_{freeze} + P_{lit}$, where P_{freeze} is the pressure due to the magma freezing and expanding and P_{lit} is the lithostatic load = $\rho_c g D$ where ρ_c is the density of the crust above the chamber, g is gravity, D is the chamber depth. These parameters vary for each body modeled and are specified in the Results section.

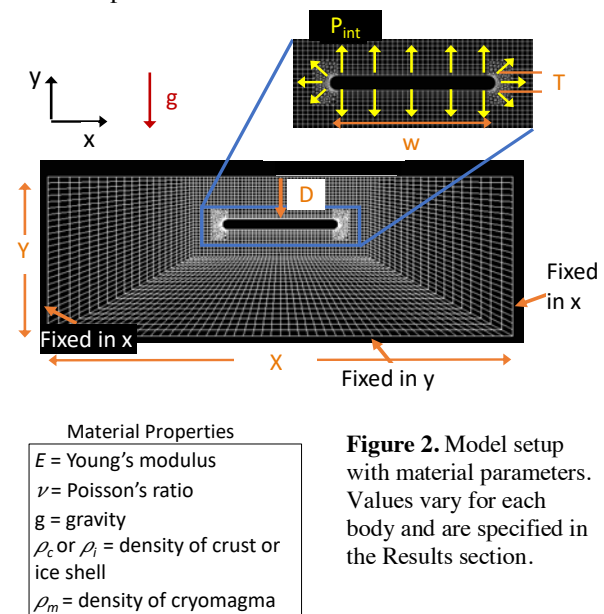


Figure 2. Model setup with material parameters. Values vary for each body and are specified in the Results section.

Effects of fractures containing water or refrozen liquid are shown to affect surface response [9]. The response of the surface above the chamber to over pressurization in the subsurface and subsequent dike propagation and thermal evolution are calculated using models of subsidence [13]. This study also investigates temperature profiles above the chamber, as the chamber cool, and considers if convection is occurring within the chamber.

Results: Fracturing and surface response for Ceres and Europa under various initial conditions are shown below. Fig. 3a shows results of the σ_l stress field during the freezing and over-pressurization of a pure

waterchamber at Europa (1 km deep, 5 km wide) with 11% freezing that allows fracturing and provides enough P_{int} to drive fluid to the surface. Fig. 1 shows the locations that fracture initiation is most likely to occur along the edge of the chamber (highest tensile stress). Material parameters are: $E = 5e9$ Pa, $\nu = 0.3$, $\rho_c = 900$ kg/m³, $g = 1.31$ m/s², $\rho_m = 1200$ kg/m³ (brine). Fig. 3b shows the fracture at propagation completion. Fig. 4 shows that surface uplift would be < 50 m.

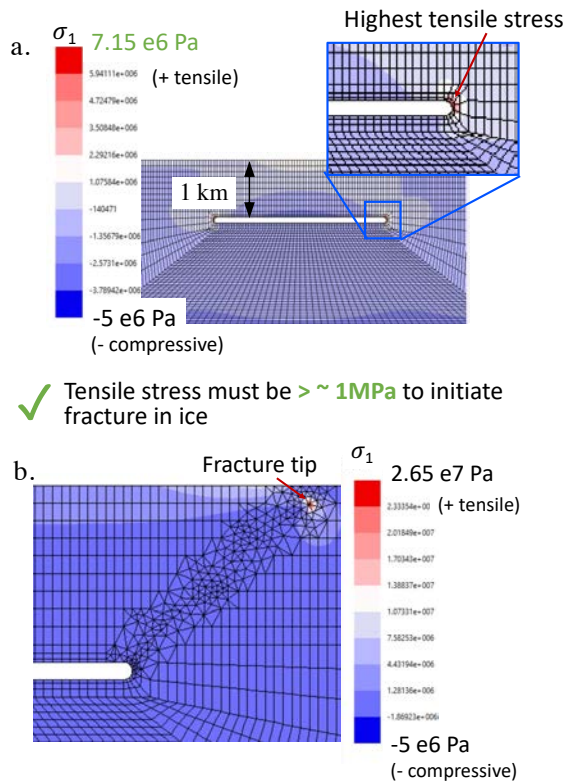


Figure 3. a. σ_1 stress field around pressurized cryomagma chamber for Europa. Bright blue = compressional stress, with gradients to red denoting increasing tensile stress **b.** Dike propagation from chamber to surface. Fracture initiated at points on chamber of highest tensile stress shown in a.

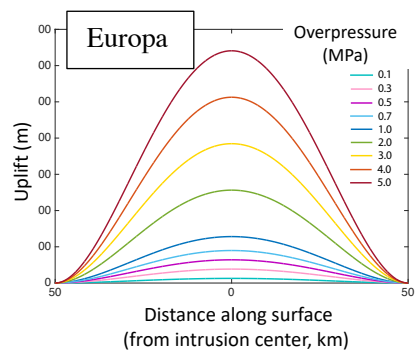


Figure 4. Europa surface uplift due to freezing

Fig. 5 shows a similar chamber for Ceres of 10 km x 100 km at 40 km depth. Material parameters are: $E = 5e9$ Pa, $\nu = 0.36$, $\rho_c = 1300$ kg/m³ (Carbonate), $g = 0.28$ m/s², $\rho_m = 1050$ kg/m³ [14]. Tensile stress occurs for a

chamber pressurized at $P_{\text{int}} = 1\%$ over lithostatic load and the fracture is able to propagate to the surface.

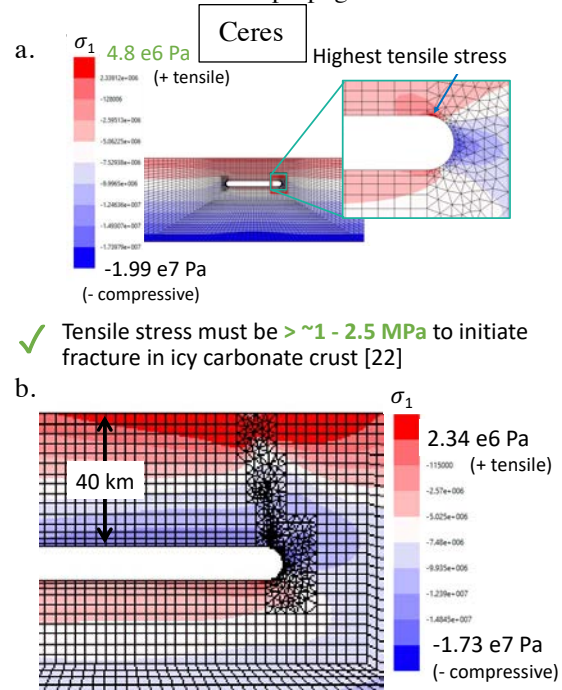


Figure 5. a. σ_1 stress field around pressurized cryomagma chamber for Ceres. Bright blue = compressional stress, with gradients to red denoting increasing tensile stress **b.** Dike propagation from chamber to surface. Fracture initiated at points on chamber of highest tensile stress shown in a.

Discussion: These results lend further credence to the feasibility that cryovolcanism could indeed occur on icy bodies including Europa and Ceres. Given the initial conditions specified, results indicate only low volumes of freezing, relative to the chamber size, are required to provide enough pressure for a fracture to reach the surface. The models also provide indication of the path the fractures take and show they differ fairly significantly. Questions then arise as to why this is the case and what parameters most control the propagation direction. We will explore this behavior and will investigate the possibility of multiple dikes driven from a single chamber and resulting fracturing behavior. With multiple dikes, we will compare the locations of the dike tips that reach the surface to the general spacing of the centers of the pits and domes observed on Europa.

References: [1] Fagents 2003, *JGR*, 108, 5139; [2] Kargel 1991, *Icarus*, 94, 368; [3] Buczkowski et al. (2016) *Science*, 353, aaf4332; [4] Buczkowski et al. (2018) *Icarus*, 316, 128; [5] Ruesch et al. (2016) *Science*, 353, aaf4286; [6] Krohn et al. (2016) *GRL* 43, 11,994; [7] Neveu & Desch (2015), *GRL*, 42, 10,197; [8] Quick et al. (2018) 49th LPSC, Abs #2921. [9] Walker & Schmidt (2018), 49th LPSC, Abs #1302; [10] Craft et al. (2018), AGU, #P21E-3394; [11] Germanovich et al. (2011), *JGR*, 16(B5); [12] Wawrzynek and Ingraffea (1987), *Theoret. App. Frac. Mech.*, 8; [13] Walker et al. (2012), *JGR*, 117. [14] Bejan (1995), Wiley, 639. [14] Castillo-Rogez et al. (2018), *Meteor. & Planet. Sci.*, 53(9), 1820.