DYNAMICS OF EUROPAN VOLCANISM: CONSTRAINTS FROM HEAT TRANSFER AND PHASE EQUILIBRIA. Lynnae C. Quick[1,2] and Bruce D. Marsh[1]. [1]Dept. of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, MD, [2]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, lquick5@jhu.edu

Introduction: Europa has a relatively young surface (~ 60 Myr on average) [1] which may be due, in part, to cryovolcanic processes. Current models of both effusive and explosive cryovolcanism on Europa may be expanded and enhanced by linking the potential for cryovolcanic processes at the surface to cryomagmatic processes in Europa's interior. We seek to place constraints on the occurrence, style, and longevity of cryovolcanism at Europa's surface by modeling specific styles of cryomagma transport within the Europan lithosphere.

The success of cryomagma transfer through the Europan lithosphere depends critically on the rate of cryomagma transfer relative to the rate of cryomagma solidification, and the rate of solidification is strongly dependent upon the size of the pressure-temperature region that exists between the liquidus and solidus of the cryomagma. The size of this pressure-temperature region is, in turn, set by cryomagma composition. The final ascent distance of cryomagmas through the Europan lithosphere is thus governed by initial melt volume, rate of ascent, overall ascent distance, and the mechanism of ascent (i.e. diapiric, elastic crack propagation or pipe flow) [2]. Moreover, initial cryomagma temperature and composition are critical in determining the budget of expendable energy before complete solidification. Using these factors as constraints and employing terrestrial magmatic processes as a baseline, we explore conditions under which cryomagma transfer in Europa's interior may lead to cryovolcanism at the surface.

Solidification of the Cryomagma Ocean: To assess the dynamic state of solidification of Europa's ocean, we present two simple calculations where the ocean is represented as undergoing Stefan-style solidification involving an infinite liquid half space that freezes over a specific time interval. This freezing is measured by the temporal progression of a solidification front, *S(t)* [3,4] (Fig. 1). The solidification front can be viewed as a plane over which the boundary of the liquid retreats while the boundary of the solid advances, allowing solidification of the cryomagma ocean to occur contemporaneously with the formation of the icy lithosphere. Our initial model assumes no internal heating and solves for the time of solidification of the entire ocean, while the second model explores the interplay of steady-state lithospheric thickness and the magnitude of internal heating due to tidal dissipation.

Time of Solidification: Assuming that the cryomagma ocean solidifies to a single, pure compound and that there is no internal heating, the time of solidification, *t*, is given by:

$$t = \frac{[S(t)]^2}{4\kappa b^2} \quad (1)$$

where $\kappa = 6.4 \times 10^{-6}$ is the thermal diffusivity of water ice at 100 K according to [5], $b = 0.68$ is an empirical constant, determined by taking into account the specific heat at constant pressure of the cryomagma melt, the difference in temperature between the solidification plane and liquid half space, and the latent heat of melting of ice at 273 K [4]. Additionally, we assume that solidification has advanced over the entire depth of Europa's cryomagma ocean and as such take *S(t)* = 100 km [6].

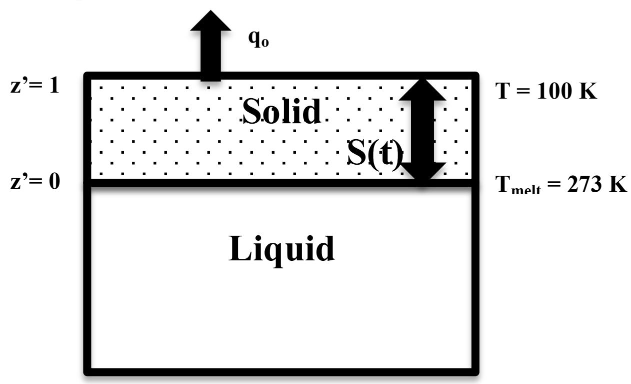

Fig. 1. Geometry for solidification of an infinite half-space of cryomelt. The solidification front, S(t), has a single, constant temperature, T = 100 K, while the boundary between the lithosphere and cryomagma ocean, represented here as a solid and a liquid layer, respectively, is at a temperature, T_{melt} = 273 K.

Thickness of the Icy Lithosphere: Next, we assume that the Europan lithosphere is in a steady-state Stefan conductive regime where outward heat loss is replaced by heating from below due to tidal effects. That is, assuming that the total global heat flux out of the icy shell is solely furnished by tidal dissipation, the thickness of the icy shell, *d*, is given by:

$$d = \frac{k_c \Delta T 4\pi r^2}{q_0} \quad (2)$$

where k_c = 5.4 W/m·K is a representative thermal conductivity of water ice over a range of lithospheric temperatures [5], ΔT = 173 K is the difference in temperature between the icy lithosphere and the cryomagma ocean [7], $r \cong 1569$ km is the radius of Europa, and q_o

$\cong 1\text{x}10^{12}$ W is a representative amount of tidal energy dissipated into Europa's icy shell by Jupiter [8,9].

Cryomagma Transfer Through the Europan Lithosphere: The potential for cryovolcanism at Europa's surface is crucially dependent upon the ability of "warm" cryomagmas to traverse the lithosphere and arrive at the surface prior to immobilization, which occurs as a direct result of solidification. The (dimensionless) temperature $T'(=T/T_o)$ of a well mixed spherical diapir of melt ascending through cool lithosphere as a function of ascent distance $z'(=z/z_o)$ is given by:

$$T' = \frac{T}{T_o} = \left\{ \left(\frac{J}{b}\right)^2 \cos\left(\frac{\pi z'}{2}\right) + \left(\frac{J}{b}\right) \sin\left(\frac{\pi z'}{2}\right) + \frac{1}{e^{Jt}} \right\} \times \left\{ \left(\frac{J}{b}\right)^2 + \frac{1}{1} \right\}^{-1} \quad (3)$$

where T_o is the initial temperature of the cryomagma prior to mobilization, a is diapir radius, $J = 3Nu\kappa/a^2$, $b = \pi t/2z'$ and t is time [2]. Nu is the Nusselt Number, which is a ratio relating the total amount of heat transferred by various mechanisms to the amount of heat that is transferred solely by conduction. Here, the dimensionless ascent distance, z', goes from 0 to 1, where $z'=0$ is located at the boundary between the base of Europa's ice shell and its cryomagma ocean and $z'=1$ corresponds to the Europan surface (Fig. 1). We have explored cryomagma temperature as a function of z' for cryomelts where J/b ranges from 0.25 to 20, corresponding to variations in diapir radius and cryomelt ascent velocity. By assuming that the base of Europa's lithosphere is in a convective regime, the Europan geotherm, i.e. the temperature of the lithospheric wall rock as a function of depth through the lithosphere, may be approximated by:

$$T' = \frac{T_m(t)}{T_o} = \cos\left[\left(\frac{\pi}{2}\right) z'\right] \quad (4)$$

where $T_m(t)$ represents the variation of temperature within the lithosphere as a function of time [2] and z' is once again allowed to vary from 0 to 1. From these values, we may obtain ascent velocity, v, of the cryomagma as a function of z' [2] using:

$$Nu = 0.46\sqrt{\frac{vz}{\kappa}} \quad (5)$$

Effects of Melt Chemistry: If the cryomagma ocean is pure water and ascent begins from the base of the lithosphere, then the initial cryomagma temperature is, by definition, 273K, and solidification begins immediately upon ascent. On the other hand, if the cryomagma contains significant amounts of $MgSO_4$, Na_2SO_4, and/or NaCl [10,11], it will possess a well-defined liquidus and solidus that provides a thermal corridor of buffer to forestall complete solidification and immobility. Yet, since the probable amount of these solutes is relatively small, on the order of ~10 wt% [10], the spread in the liquidus-solidus may be quite small (~ 20 K), and as such will limit the ascent distance for any given ascent rate and cryomagma volume.

Results: According to Equation (1), in the absence of impurities and any internal heating, Europa's liquid water ocean will have solidified in about 30 Myr. However, from the known presence of a liquid layer inside Europa today, we may infer that the cryomagma ocean most likely contains substances such as $MgSO_4$, Na_2SO_4 and NaCl [10,11], which may have served to depress the freezing point of the ocean over the lifetime of the solar system. These compounds may also be incorporated into various eutectic mixtures of H_2O and hence may play key roles in subsurface cryomagmatic processes, as well as in recent cryovolcanic activity at the surface.

Equation (2) suggests that the steady state thickness of the icy lithosphere is ~30 km per terawatt of dissipative heating. If heating is doubled, the shell thickness decreases by a factor of 2, etc. This finding illustrates the possibility that even in the presence of an advancing solidification front, the thickness of the Europan lithosphere has most likely fluctuated over time as a function of the amount of tidal dissipation imparted to the icy satellite [12]. These models illustrate that both lithospheric thickness and cryomagma composition place major constraints on the ability of cryomelts to successfully traverse the Europan lithosphere.

From equations (3)-(5) we may obtain cryomagma ascent velocities and temperature variations of cryomelts as they travel through the lithosphere, and the radii of potential diapirs within which the cryomelts are transported. In the next iteration of this model, we will incorporate these parameters into a tradeoff diagram from which we will deduce conditions under which cryomelts may reach Europa's surface, thereby allowing cryovolcanism to ensue.

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