VISCOELASTIC DEFORMATION OF FREEZING CRYOMAGMA RESERVOIRS ON EUROPA.

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Introduction: Liquid water reservoirs within Europa's ice crust, if they exist, could represent the most accessible liquid water bodies in the solar system. Understanding the behavior of these potential bodies is therefore key for the exploration of ocean worlds and the search for habitability and life beyond Earth. Europa is the target of NASA's upcoming Europa Clipper mission [1], and one target of ESA's JUICE mission [2]. To anticipate the arrival of these spacecrafts, it is important to address the question of whether or not liquid water could reach Europa's surface, and to know where would be the source of the flows.

Previous studies demonstrated that freezing cryoreservoirs might trigger eruptions through overpessurization of the liquid cavity as the liquid phase transitions to the less-dense solid phase. However, these studies neglect viscoelastic deformation of the icy cavity that might accommodate the inner overpressure. In Lesage et al., [3], we modeled the freezing of cryomagma reservoirs in Europa's ice shell and calculated the associated overpressure, as well as the freezing time required to trigger eruptions. In this study, we improve our first cryomagma reservoir freezing model in order to take into account the viscoelastic deformation of ice in response to the freezing overpressure. This can increase the time required for eruption, the potential erupted volume, or even prevent an eruption if the deformation is great enough.

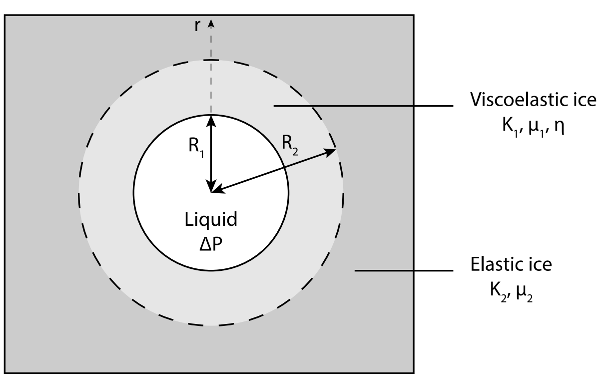

Figure 1: Cryomagma reservoir surrounded by viscoelastic and elastic ice. Adapted from Dragoni and Magnanensi [4].

Methods: We model a cryomagma reservoir as a spherical or ellipsoid cavity located in Europa's lithosphere (assumed to be the upper 10 km) filled with briny cryomagma. We use the analytical approach of Dragoni and Magnanensi [4] which we adapt for freezing-induced pressurization –and eruption– of cryomagma reservoirs in Europa's ice shell. In this model, cryomagma reservoirs are surrounded by a viscoelastic ice shell, embedded itself in elastic ice as illustrated in Fig. 1.

This approach is more realistic than a purely elastic icy lithosphere because it takes into account viscous relaxation. In our model, heat transfer between the liquid cryomagma at melting temperature and the surrounding colder ice locally lowers the ice viscosity around the reservoir.

Ice rheology. The key physical parameter used in this study to determine the ice rheology is the Maxwell time $\tau_M = \eta/E$ with η the ice viscosity (calculated with a Newtonian law [5]) and E its Young modulus. The Maxwell time has to be compared to the time scale on which the stress is applied on ice, which is the freezing time scale in our case. We use the freezing times τ_c calculated under the non-deformable reservoir wall approximation by Lesage et al. [3] as a first order estimate. Finally, $\tau_M > \tau_c$ means the ice behaves elastically at the freezing time scale, whereas $\tau_M < \tau_c$ indicates a viscoelastic behavior of the ice at this time scale.

We also calculate the ice shell thickness to better model the ice rheology. For the deepest reservoirs, located in warm ice, the ice is fully viscoelastic, so there is no elastic ice layer, which we take into account in our model.

Numerical approach. The cryomagma freezing rate and the associated overpressure are calculated as proposed by Lesage et al. [3]. The reservoir wall deformation caused by freezing overpressure is calculated using the analytical solution from Dragoni and Magnanensi [4]. As pressure and deformation are functions of each-other, they cannot be decoupled. Hence, we use an iterative process to take into account the feedback between pressure and deformation. This algorithm converges to a realistic critical freezing time after which the reservoir can trigger an eruption, or diverges if the deformation is great enough to completely accommodate the freezing overpressure, i.e. if the reservoir cannot erupt.

Results: In the context of the freezing of a cryomagma reservoir of given depth, volume, and geometry, we demonstrated that Europa's icy lithosphere ca be separated in two distinct layers: (i) The outermost part of the lithosphere, where, far from any reservoir, the Maxwell time of the ice τ_M is greater than the reservoir freezing time τ_c, mostly behaves as an elastic material at the freezing time scale. This part of the lithosphere deforms slightly, slowly enough for the reservoir to be pressurized by freezing. It is possible to trigger an eruption by freezing a reservoir stored in this part of the lithosphere.

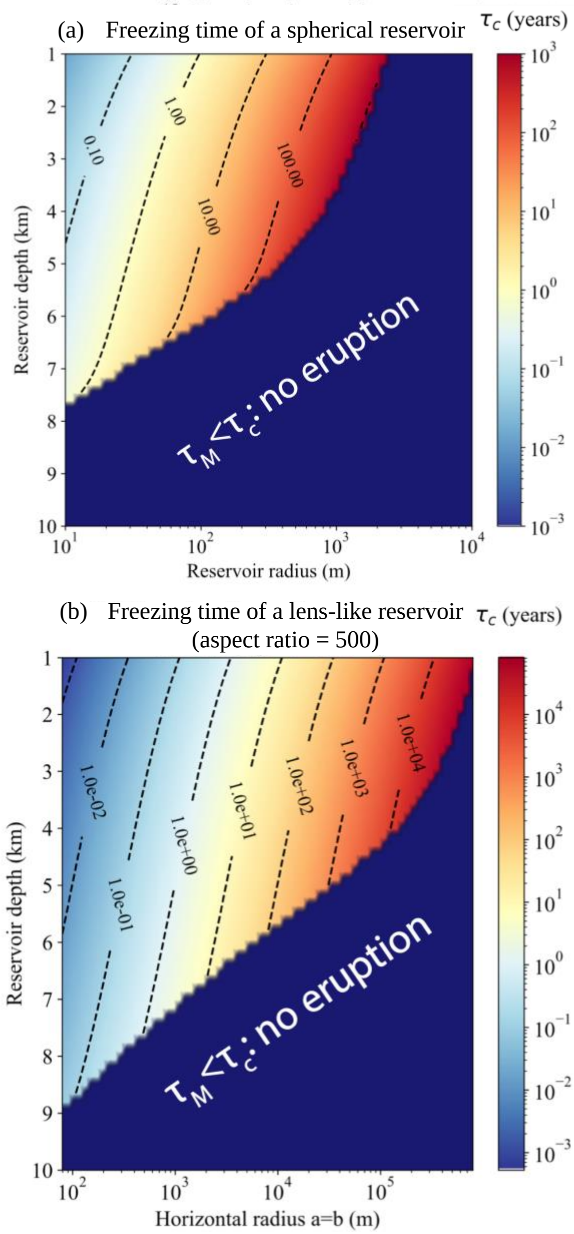

Figure 2: Freezing time of (a) spherical reservoirs and (b) elongated, lens-like reservoirs with horizontal radii 500 times greater than their vertical extent.

(ii) The inner part of the lithosphere, where $\tau_M < \tau_c$, behaves as a viscous material at the freezing time scale. It deforms easily and accommodates completely the freezing overpressure. It is not possible to trigger an eruption from a reservoir stored in this part of the lithosphere. The transition depth between these two regimes depends on the reservoir freezing time and thus its radius, shape, and depth. This is illustrated in Fig. 2, which also shows the freezing times obtained from our model for reservoirs able to erupt.

Another important result of this study is that the non-deformable wall approximation used in Lesage et al. [3] is valid if $\tau_M > \tau_c$. This may simplify further modelling of cryovolcanic eruptions on icy satellites.

This study [6] may have implications for future exploration of Europa as we refine the maximum depth of active cryoreservoir and propose a relationship between their characteristics (radius, depth, geometry, cryomagma composition) and the eruption they may produce (freezing time, erupted volume). Our results can also be useful to the ongoing development of probes aiming to reach subsurface water on Europa.

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