THERMAL AND CHEMICAL EVOLUTION OF SMALL, SHALLOW WATER BODIES ON EUROPA.
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Introduction: The young surface of Europa’s ice shell is dotted with elliptically shaped features ~10 km in diameter, collectively called lenticulae. Lenticulae appear as depressions called pits, uplifts called domes, disruptions called small (or micro-) chaos, or a combination of dome and chaos morphology that may represent distinct stages in the evolution after one formation event [1]. Although that formation mechanism is not well constrained, recent work on mapping the distribution, clustering, and geometry of lenticulae suggests they are most consistent with bodies of liquid water, or sills, [2,3] emplaced at shallow depths (~1-3 km) below the surface, so-called “shallow water” models [4-6].

Shallow water models propose that water is delivered via the in situ melting of ice [6,7] or injected through dikes from the ocean (or other large water body) [4,5]. In either case, the observed surface morphology is formed as the remaining liquid pressurizes during the solidification process. These hypotheses hinge on the longevity of the liquid in the shallow subsurface and, accordingly, the rate at which the water pressurizes to deform the overlying ice. Lenticulae are often low albedo and reddish in color which indicates the presence of high concentrations of salt [8]. Only one study has been completed to understand their longevity, but considers only pure water sills in a relatively thin brittle shell, predicting a ~31 – 800 kyr (1 × 10¹² – 2.5 × 10¹³ s) liquid lifetime [4]. The presence of salts in the water will depress the freezing temperature and likely prolong the liquid lifetime, but creates a much more dynamic and complex freezing process.

In sea ice on earth, a process analogous to fractional crystallization during solidification in magmatic systems occurs: as the ocean water freezes top-down, the ice is unable to incorporate all impurities into the crystalline lattice. While some of the impurities are trapped in the ice, the majority are rejected into the interstitial liquids, which eventually leads to the drainage of highly saline brine into the ocean [9-11]. In the case of water bodies in Europa’s ice shell, the saline brines are rejected into a closed system, which continually increases the concentration of salt in the remaining liquid reservoir. This process may provide a rich chemical gradient that offers a plausible habitable niche as it does on earth.

The possibility of liquid water near the surface is enticing for future remote and in situ exploration, as it may provide a plausible habitable niche and a way to assess the potential habitability of Europa’s ocean. Here, we present a multiphase, two-dimensional, finite difference model that describes the thermal and chemical evolution of small bodies of liquid water after they are emplaced in the ice shell of Europa. We present results from a number of different simulations, and discuss their implications for NASA’s planned remote sensing mission to Europa, Europa Clipper.

Numerical Model: The two-dimensional model is a stand-alone code built in Python, fully described in [12]. It was designed to accurately simulate the two-phase thermal diffusion of the ice-water/brine system. Using sea ice as an analog environment for the roof of the sill and terrestrial magma chambers for the floor, a conservative parameterization of salt entrainment and rejection is implemented using constitutive equations derived in [11] relating the bulk salinity in the ice to the thermochemical formation environment.

We tested liquid water sills in various thermal structures of the shell, depths of emplacement, sill thickness, initial salinity, and latitude of emplacement. Estimates on shell thickness vary, but we test two possibilities: a “thin shell” with a 10 km thick brittle portion overlying the ocean, and a “thick shell” with a 5 km thick brittle

![Figure 1](image-url) Figure 1. Cross-sectional profiles of entrained MgSO₄ through the center of various thickness sills (labeled) below the equator in a thick shell (blue in Figure 2b) with normalized sill height from the floor of the initial liquid. The roof displays the sea ice-like “C” shaped profile while the floor tracks the evolution of the liquid salinity. Solid salt layer (Figure 2) excluded.
portion overlying a warmer, possibly convecting ice layer [13,14]. Depths (1-3 km below surface) and thicknesses (0.5 – 2 km) are based on that needed to create the observed topographic relief [4-6]. The radius of each sill is 2.4 times the depth of emplacement [5]. The best constraints on the composition of the salt present in the ocean suggest MgSO₄ dominates and varies in concentration from ~12.3 ppt to a saturated 282 ppt [13]. Finally, latitude of emplacement are the warmest (equator, ~100 K) and coldest (pole, ~50 K) surface temperatures to bound the solidification times [16].

**Thermal and chemical evolution:** We find that under various conditions, pure liquid water in the shallow subsurface will solidify within ~1.9 – 79.3 kyr (5.8 × 10¹⁰ – 2.5 × 10¹² s) while those with an initial 12.3 ppt MgSO₄ will solidify within ~1.9 – 108 kyr (6 × 10¹⁰ – 3.4 × 10¹² s). Higher initial salinities (e.g., 100 ppt) can increase the solidification time by ~50% depending on the shell structure, sill thickness, emplacement depth, and latitude. Regardless of geometry, salinity, or other factors, our results show that freezing of these water bodies is an order of magnitude faster than [5], owed to our more accurate treatment of phase change.

The majority of the initial salt mass of the liquid is entrained into the ice in every simulation (Figure 1). Once the liquid reaches saturation concentration (282 ppt), we assume that solid salt “precipitates” out of solution. In this case, up to ~50% of the initial salt mass can be precipitated out of solution from a sill starting with 12.3 ppt MgSO₄. If the solid precipitate is spread across the initial diameter of the sill, this can create layers of solid salt in the ice up to ~7 m thick (Figure 2)

As we assume that all extra heat at the surface is lost instantaneously, our model predicts a lower bound for the temperature anomaly at the surface above the sill. We predict a maximum 0.63 K temperature anomaly above a 750 m thick pure water sill at 1 km depth below the equator in a thin shell. In a thick shell, we predict that maximum anomaly is only 0.54 K for the same sill geometry, emplacement depth, and latitude. Below 2 km depth for any scenario, the thermal anomaly is likely not detectable by the E-THEMIS infrared spectrometer onboard Europa Clipper [17].

**Conclusions:** Our results illustrate that small bodies of water emplaced in the shallow subsurface of Europa’s ice shell are geologically transient and last less than ~100,000 years. This suggests that if lenticulae, or other geologic features, are indeed formed this way, they are even younger than previously thought. However, evidence for saline liquid water should be readily accounted for in multiple instruments onboard the Europa Clipper, including REASON (Figures 1 and 2) and E-THEMIS.

**References:**

![Figure 2](https://example.com/f2.jpg)

**Figure 2.** Thickness of the layer of solid salt precipitated out of solution during freezing for an initially 12.3 ppt MgSO₄ liquid water sill of various initial thicknesses, depths (labeled) in a thick shell, at the (a) pole and the (b) equator.