THERMAL AND CHEMICAL EVOLUTION OF SMALL, SHALLOW WATER BODIES ON EUROPA.

C.J. Chivers[1], J.J. Buffo[2], and B.E. Schmidt[1], [1]Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA 30332 (cchivers@gatech.edu), [2]Thayer School of Engineering, Dartmouth College, Hanover, NH 03755

Introduction: The young surface of Europa's ice shell is dotted with elliptically shaped features ~10 km in dimeter, 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 through the pressurization of the remaining liquid as it solidifies. 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 salt [8]. Only one study has been completed to understand their longevity, but considered only pure water sills in a relatively thin brittle shell, predicting a ~31 – 800 kyr $(1 \times 10^{12} - 2.5 \times 10^{13}$ 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"

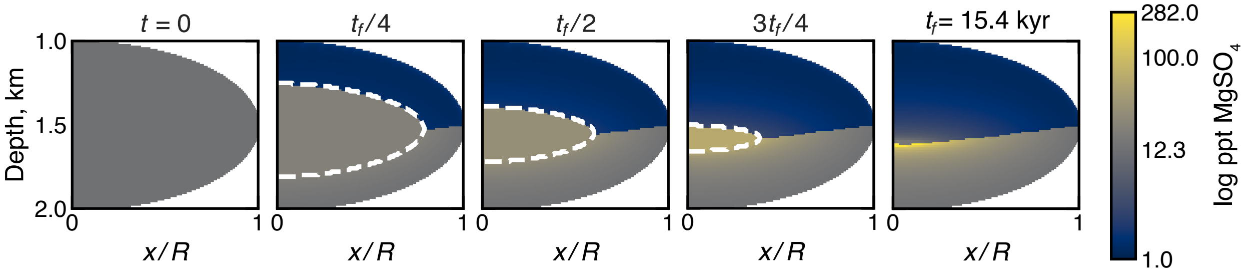

Figure 1. Snapshots of the chemical evolution of a 1 km thick sill with an initial 12.3 ppt $MgSO_4$ emplaced 1 km beneath the equator in a thick shell scenario until it reaches its solidification time (t_f). Radius R is given by the radius-depth relationship from [5], $R = 2.4d$. White dashed lines denotes the liquidus contour. These snapshots illustrate how salt is entrained differently at the roof and floor, creating zones of highly saline ices at the floor.

with a 10 km thick brittle portion overlying the ocean, and a "thick shell" with a 5 km thick brittle 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 what is needed to create the observed topographic relief of ~10^2 m [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 $MgSO_4$ 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 ($5.8 \times 10^{10} - 2.5 \times 10^{12}$ s) while those with an initial 12.3 ppt $MgSO_4$ will solidify within ~1.9 – 108 kyr ($6 \times 10^{10} - 3.4 \times 10^{12}$ 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 salt in the initial water is entrained into the ice (Figures 1-2). Different entrainment regimes create chemical zones in the ice and these zones tracks the thermal and chemical evolution of the sill as it freezes. Brine rejection processes from the top-down freezing at the roof creates relatively fresh ices (< 12 ppt) while the ices freezing at the floor entrain salt at the liquid salinity, creating highly saline ices. During freezing, salts may precipitate up to ~50% of the initial salt mass and create layers of salt precipitates equivalent of a few meters thick. These fingerprints of the chemical and thermal evolution of shallow water may be detectable through the reflection or attenuation of an ice-penetrating radar like REASON onboard Europa Clipper.

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 near-surface above the sill. We predict a maximum ~0.6 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 ~0.5 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 ~110,000 years. This suggests that if lenticulae, or other geologic features, are indeed formed this way, they may be younger than previously thought. However, evidence for saline liquid water should be readily accounted for in multiple instruments onboard the Europa Clipper, including REASON and E-THEMIS.

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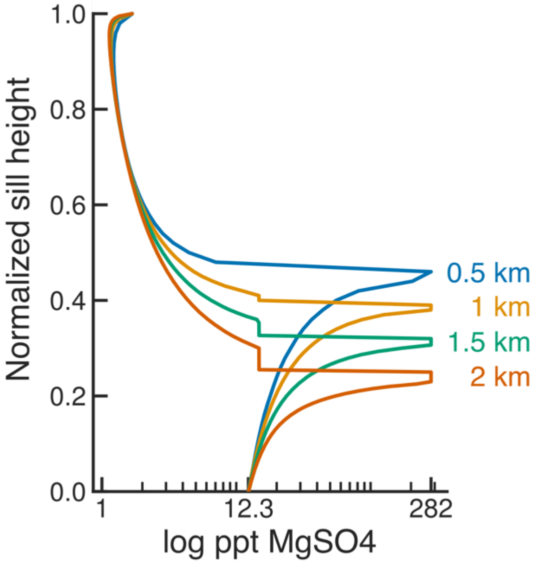

Figure 2. Cross-sectional profiles of entrained $MgSO_4$ through the center of various thickness sills (labeled and colored) below the equator in a thick shell with normalized sill height from the floor of the initial liquid. The roof displays the sea ice-like "C"-shaped profile while the floor tracks the evolution of the liquid salinity.