ARE THERE STABLE BRINE LAYERS BENEATH EUROPA'S CHAOS TERRAIN?

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Introduction: Geologic activity in Europa's ice shell over the last 100 Myr is represented by a number of surface features. Among the most intriguing are the young chaotic terrains, regions where blocks of pre-existing terrain sit within a low-albedo hummocky matrix material. At present, their formation mechanism is unknown, though many hypotheses have been proposed [1-4]. "Shallow water" models propose that chaos is formed by the presence of liquid water at shallow depths (~1-5 km) below the surface, emplaced either through injection [4] or *in situ* melting [2]. Recent work on the distribution and morphology of potentially related, but smaller, features called lenticulae has bolstered this hypothesis [5,6]. These "shallow water" models are enticing as they both provide explanations for chaos morphology and suggest there may exist relatively accessible reservoirs to understand Europa's ocean and habitability.

Recent work [7] on the longevity and evolution of small sills (~1-10 km^3) suggests that they will freeze within ~10^5 yr. The authors found that a Europan ocean dominated by $MgSO_4$, which has a relatively small melt-depression effect, will extend the lifetime upward of ~10% relative to freshwater and leave a record of its evolution, even for a small initial concentration of 12.3 ppt (~1 wt%).

NaCl is the other plausible dominant salt on Europa [8] and recent terrestrial observational evidence [9] points to its presence on the surface, which may be reflective of the ocean composition. Crucially, NaCl may further extend the lifetime of small sills due to its larger melt-depression effect. Furthermore, putative melt lenses [2] beneath chaos terrain, are orders of magnitude larger than small sills (~2×10^4–6×10^4 km^3). Together, this suggests that if shallow water is responsible for chaos and lenticulae, it may persist to present day.

Methods: We update and extend the model presented in [7] by parameterizing mushy layer theory – which describes the entrainment and rejection of NaCl in/from forming ice – for Europa-relevant conditions as well as included the assumed geometry and formation conditions for melt lenses. For the small sills, we use all the same assumptions for initial conditions as in [7] excluding emplacement beneath the pole (50 K surface temperature) scenarios and begin with an initial 35 ppt NaCl brine filling the sill.

Entrainment and Rejection of NaCl: The parameterization of the mushy layer theory uses constitutive equations derived by [10,11]. For NaCl at Europa relevant conditions, we simulate ice formation using the SOFTBALL model [11,12] assuming an initial fluid concentration of 35, 100, and 200 ppt then fit the constitutive equations (relating NaCl entrainment rate to local thermal gradient) to these results. SOFTBALL solutions become unstable as the reservoir concentration approaches the eutectic, thus we linearly extrapolate the constitutive equations from 200 ppt to 232 ppt.

Melt Lens Geometry and Formation: All previous results assumed that small sills formed by injection through a fracture to the near subsurface, but as the melt lens is assumed to follow the eutectic melt model from [2] it requires different conditions. For these simulations, we assume that the melt lens forms by the *in situ* melting of a 5 km brittle ice shell via an impinging warm plume from a lower, warmer

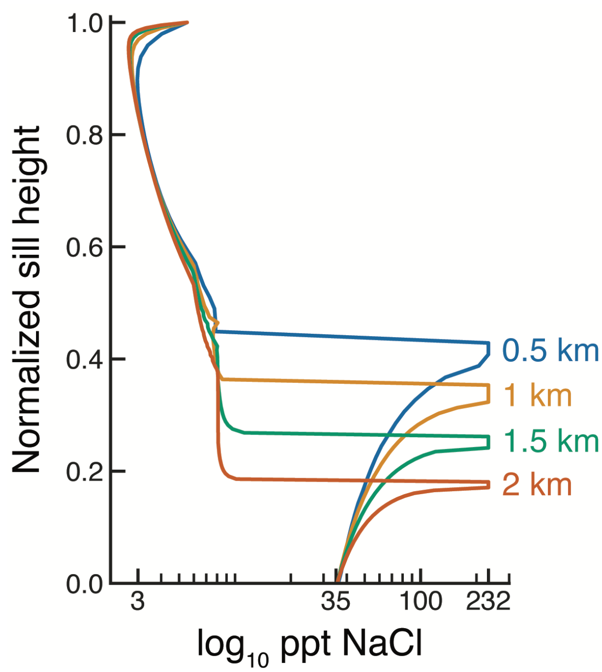

Figure 1. Cross-sectional profiles of entrained NaCl through the center of sills emplaced 1 km below the equator (110 K surface temperature) in a thick shell (5 km brittle ice) of various thicknesses (colors and labels). The chemical zoning at the roof and the floor are indicative of the different freezing conditions at these interfaces and their evolution.

convecting ice layer [2]. To simulate this formation scenario, we make several assumptions: the plume is stable after melting and providing minimal heat during solidification; the plume minimally warms the base of the melt lens at the initial melting temperature (dependent on salinity); and the plume head shape is a smoothed step function with the coldest temperature at the far-field domain boundary at 260 K. Based on [2] we assume that the melt lens has a flat roof, 3 km from the surface, with sloped exteriors based on *Galileo* observations of circumferential fractures surrounding large chaos. The salinity of the melt lens is determined by the salinity of the ice shell, derived using the constitutive equations from [8,9].

Small NaCl Sill Evolution: Our results suggest that small sills with an initial 35 ppt NaCl will freeze within ~139 kyr (4.38×10^{12} s). This is up to 79% and 59% slower than fresh water and 12.3 ppt $MgSO_4$ sills for the same sill geometry and shell thicknesses [7].

The majority of the initial dissolved NaCl is entrained into the ice (Figure 1) and the distribution is qualitatively similar to the profiles of $MgSO_4$ sills [7] including the distinct chemical zoning. The differences between their vertical distributions are representative of the distinct chemical dynamics of NaCl and $MgSO_4$. For instance, the floor and roof freezing directions meet closer to the floor of the sill in NaCl sills than in $MgSO_4$ sills due to the greater melt depression effect of NaCl. Finally, NaCl sills may precipitate salt during the freezing process. Our results suggest that they could precipitate ~50% of their initial salt mass, leading to layers of ice and precipitated NaCl hydrates (e.g., hydrohalite) within the ice shell equivalent of up to ~10 m thick.

Melt Lens Evolution: In our simplified scenario, a freshwater melt lens will freeze within ~175 kyr (similar to the prediction made by [2]) making them the longest lasting shallow water bodies tested. However, the thermal and chemical evolution of melt lenses are highly distinct from that of smaller reservoirs. While the freshwater scenario will completely freeze, both NaCl and $MgSO_4$ scenarios will almost completely stall their freezing after ~180 kyr leaving a quasi-stable volume of brine for ~100 kyr (Figure 2). This distinctive evolution is in part owed to the unidirectional (top-down) freezing, the warm ice plume at the base, and the composition-dependent salination during freezing. The greater melt depression effect of NaCl results in a greater volume of quasi-stable brine (~255 km^3) than $MgSO_4$ (~130 km^3). Neither the $MgSO_4$ nor the NaCl melt lenses tested reach the eutectic concentration (Figure 2) and thus they precipitate no salt in our 350 kyr simulations

Conclusions: All together, our results demonstrate that the formation mechanism, composition, and shell structure are crucially important to the evolution and fate of shallow water. If chaos (and lenticulae) formation is more ancient than currently thought (suggesting a relatively inactive ice shell), then saline shallow water will leave behind a record of its presence. Alternatively, if large chaos features are among the youngest features on Europa's surface and form by melt lens formation and collapse then we suggest that missions to Europa such as NASA's Europa Clipper or ESA's JUICE will find evidence for contemporaneous brine layers beneath chaos features. Furthermore, such layers may be a realistic target to sample a potentially habitable environment for future penetration missions.

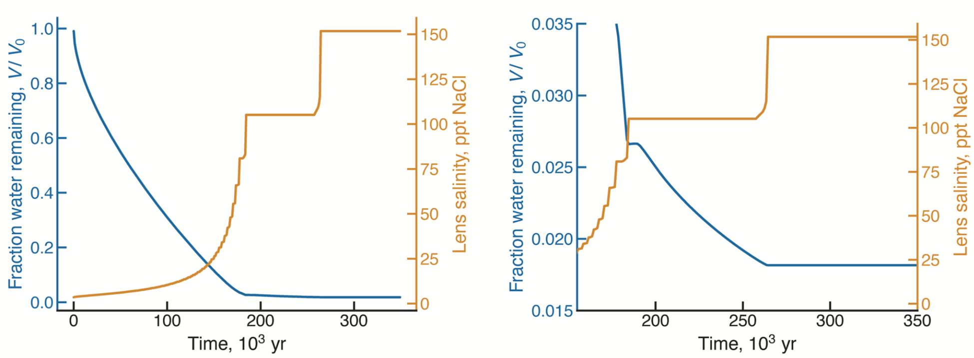

Figure 2. Timeseries of NaCl melt lens bulk evolution including the fraction of remaining brine (blue line) and the bulk salinity of the lens (orange). Right plot zooms into the last 150 kyr of evolution to highlight the stable brine layer after ~260 kyr of freezing.

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