Thermal and chemical evolution of shallow liquid water on Europa

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Background & motivation

- Chaos and lenticulae on Europa may be best explained by the presence of liquid water in the shallow subsurface, e.g. [1-3]

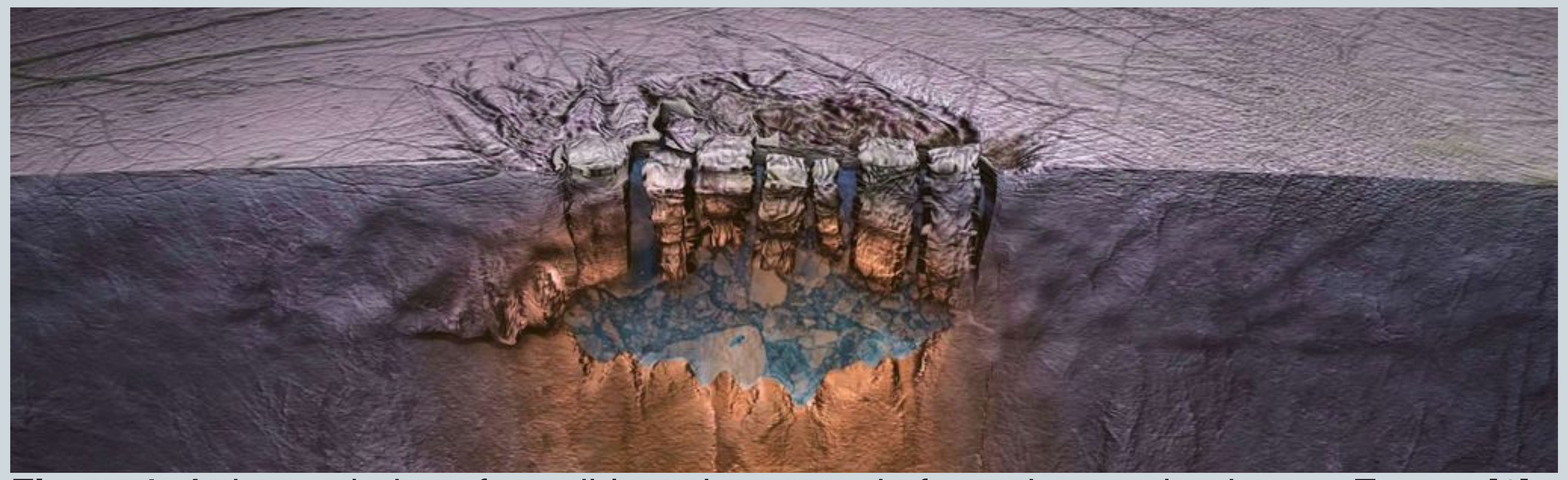


Figure 1. Artist rendering of possible a chaos terrain formation mechanism on Europa [1]. This model assumes a similar hypothesis and studies its thermal and chemical evolution (Image credit: NASA)

- Evidence suggests hydrated salt impurities within the putative subsurface ocean [4], on the surface [5] and within the shell [6]
- Current models (e.g. [7]) of shallow liquid bodies do not account for plausible chemistries such as magnesium sulfate ($MgSO_4$) or sodium chloride (NaCl) that would affect their thermal and dynamical evolution
- Future missions will target features indicative of shallow water for possible biosignatures as potential habitable niches
- We present results from numerical modeling of shallow liquid water to understand their evolution and history

Model description

- We model the system as a two-dimensional, two-phase conduction problem with temperature-dependent thermal conductivity governed by the equation

$$\rho \bar{C}_p \frac{\partial T}{\partial t} = \nabla \cdot \bar{k} \nabla T - \rho_i L_f \frac{\partial \phi}{\partial t} + Q$$

temperature; pure ice density; volumetric liquid fraction [8]; volume averaged heat capacity; heat sources & sinks; volume averaged thermal conductivity; latent heat of fusion

- Salinity is included as a way to modify the thermal properties and track its evolution in the system
- As liquid water freezes top-down, the amount of salt entrained in the ice depends on the thermal gradient, described in [6] with two constitutive equations with composition- and concentration-dependent constants a, b, c, d

$$S_{\text{ent}} = \begin{cases} a + b\nabla T \\ a + b\frac{c+\nabla T}{1+\nabla T}\left[1 - \exp\left(\frac{-d}{\nabla T}\right)\right] \end{cases}$$

- The remaining salt is rejected back and evenly mixes into the remaining liquid, eventually saturating the liquid solution
- Ice formation at the bottom entrains impurities at the liquid concentration because the colder, denser brine is gravitationally stable there

Model setup

- An elliptically shaped intrusion of ocean-derived liquid water, or sill, with a particular composition (pure, $MgSO_4$, NaCl) and concentration is emplaced at some depth in a conductive shell in thermal equilibrium
- We explore two potential thermal structures of the ice shell

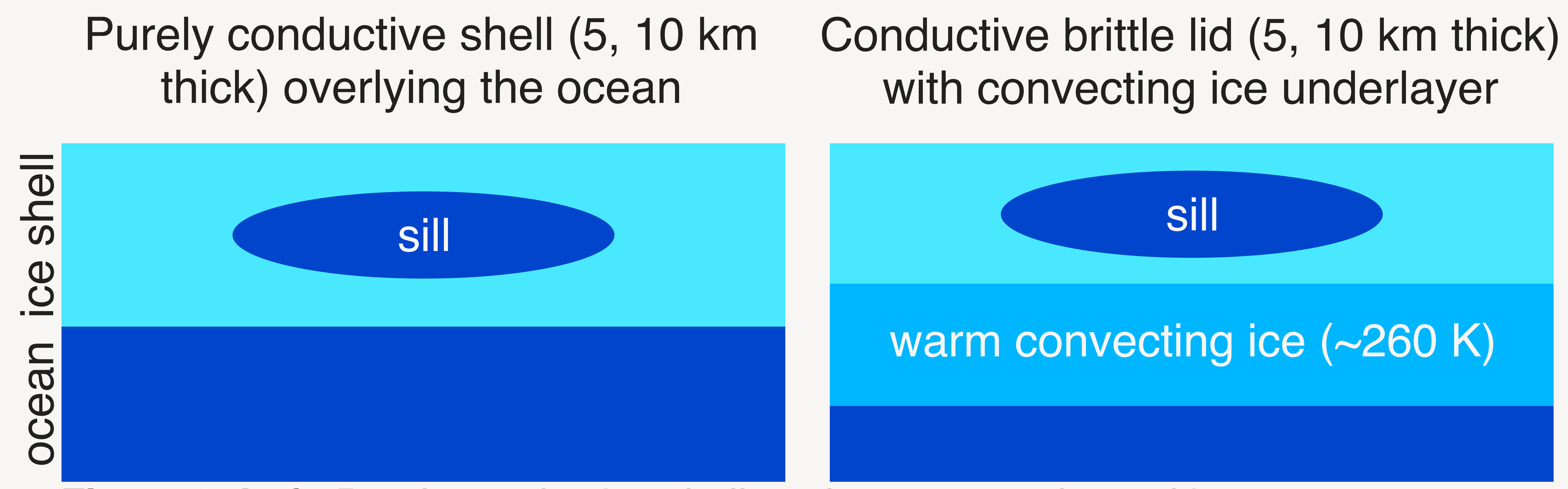
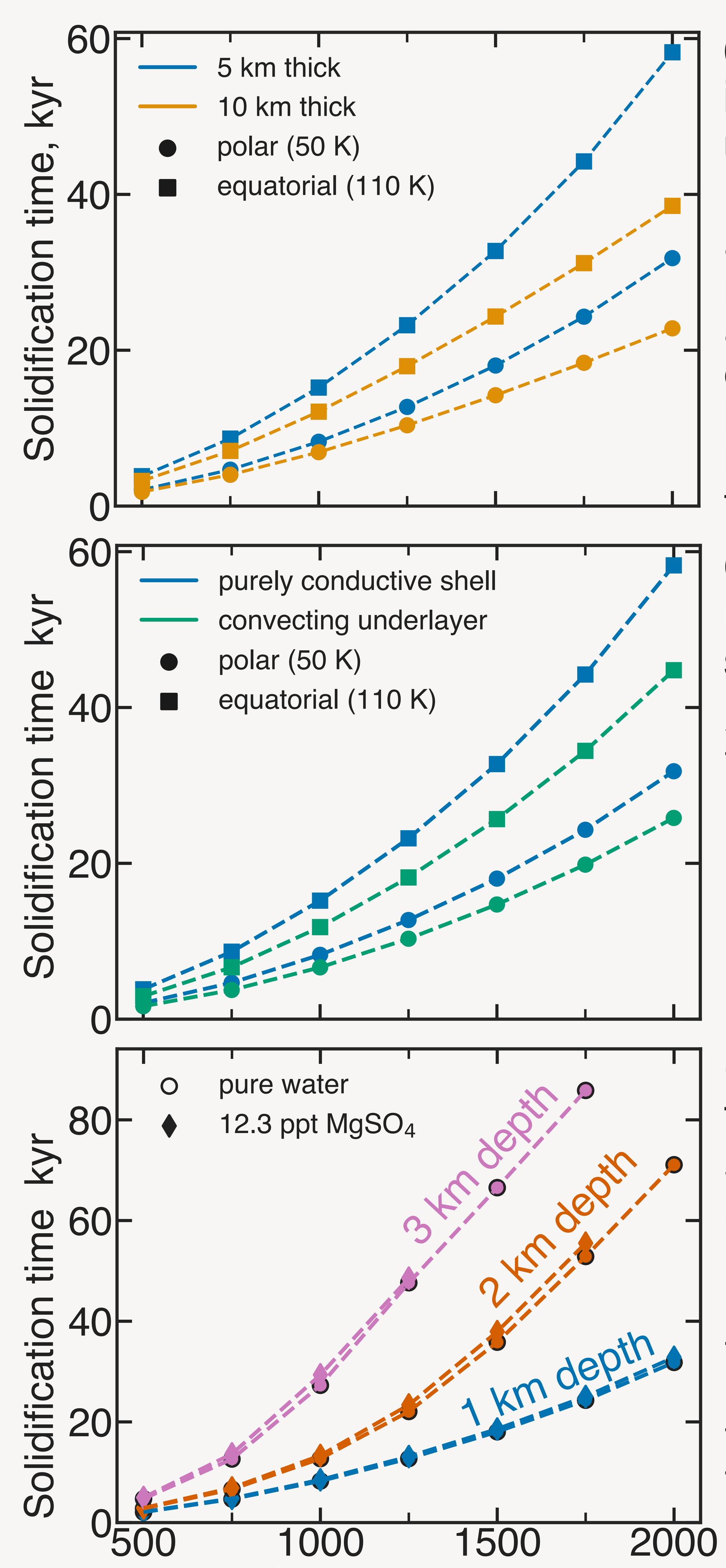


Figure 2. Left. Purely conductive shell on the ocean at the melting temperature. **Right.** Conductive shell lies above a convecting underlayer at ~260 K.

Solidification times

Figure 3. Times for liquid in sills of varying thickness with radii = 2.4 × depth [6] and at two latitudes to completely freeze.



(a) Pure water sills at 1 km depth in a 5 or 10 km thick purely conductive shells

Pure water sills at the pole (50 K surface temperature), in either shell thickness, will solidify 50- 60% faster than at the equator (110 K). The 10 km thick shell causes a 20-40% faster solidification time due to the shallower temperature gradient across the sill in a thick shell.

(b) Pure water sills at 1 km depth in shells with different thermal structures

A convecting underlayer (~260 K at the bottom) assumes an overall cooler brittle lid (5 km thick), causing the liquid to freeze ~20% faster at the poles and ~30% faster at the equator.

(c) Salinity effect on polar sills in a thin (5 km), purely conductive shell

Comparing pure and saline (12.3 ppt MgSO4) at various depths (labeled). Saline intrusions affect deeper and thicker sills more strongly. In deeper sills, this is likely due to the shallower temperature gradient at the solidification front that entrains less salt, thus making the remaining water more saline more quickly.

Salinity profiles after solidification

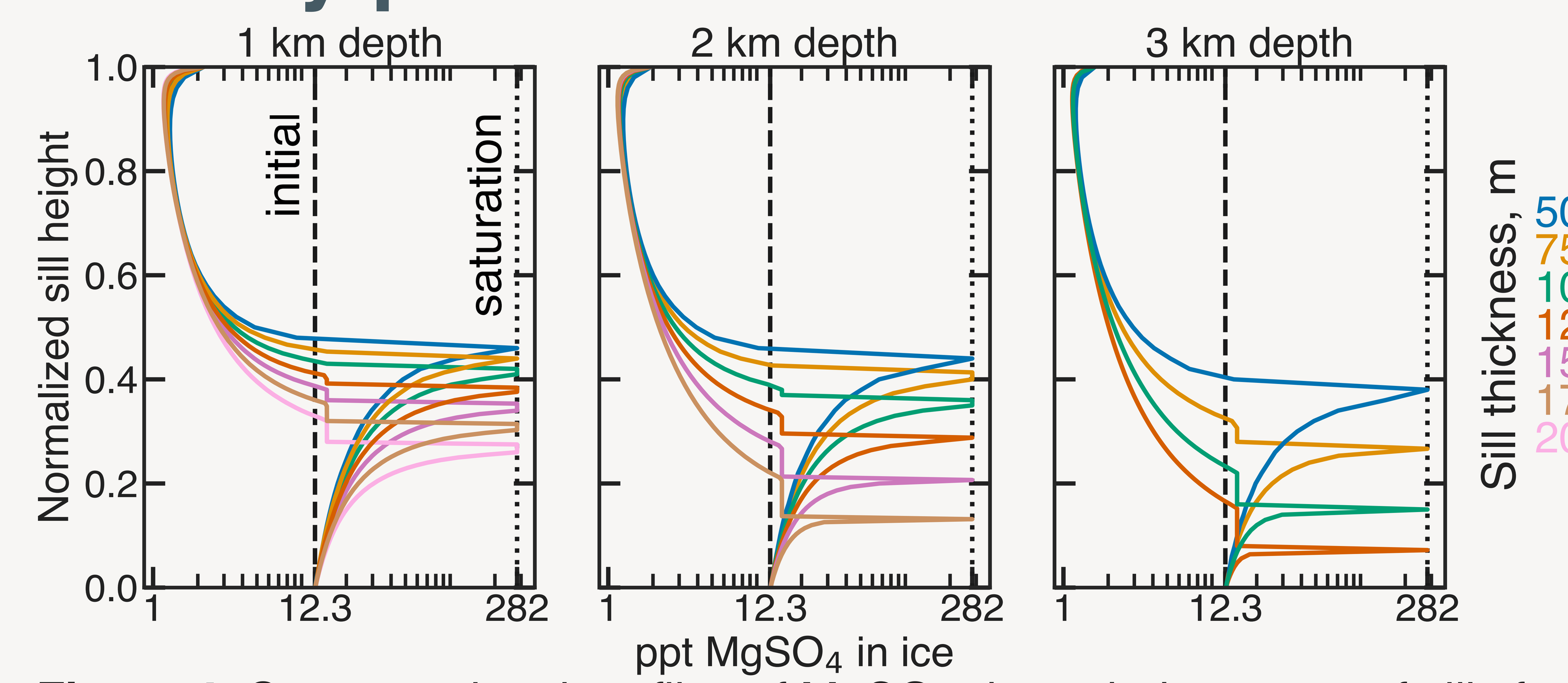
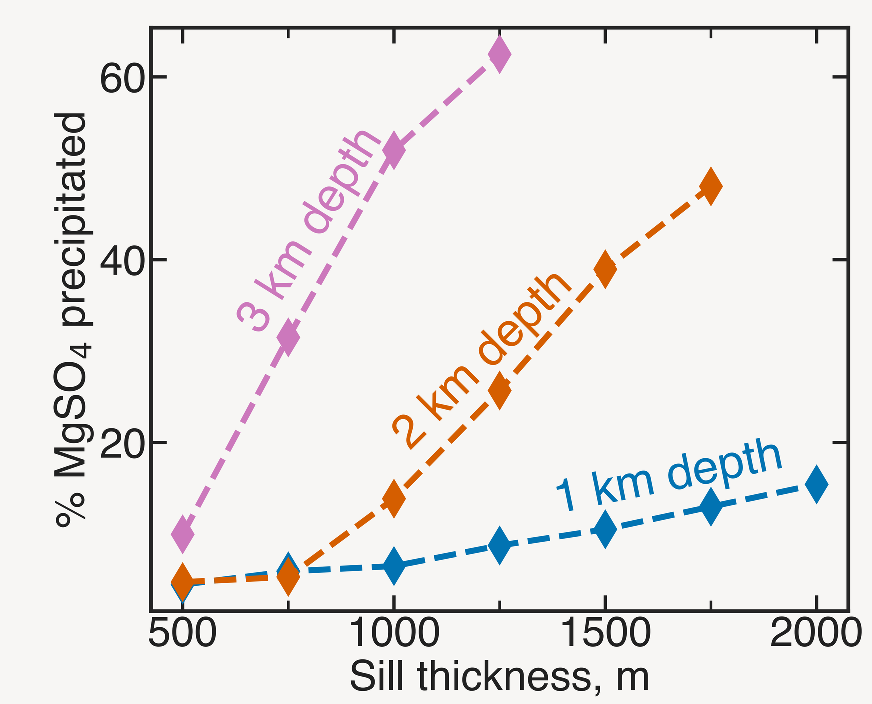


Figure 4. Cross-sectional profiles of MgSO4 through the center of sills from Figure 3c at various depths (labeled) and sill thicknesses (color). Top-down "C" profile is characteristic of entrained salt in sea ice profiles on Earth [9, 10]. The increase from initial salinity at the bottom reflects the gravitational stability of the brine and reflects the liquid salinity history. Sudden stability of concentration in thicker, deeper sills is because they reach saturation more quickly due to less entrained salt from lower temperature gradients.

Precipitated salt

12.3 ppt MgSO4 sills in a thin (5 km) purely conductive shell

Figure 5. Percent of initial salt mass that has precipitated out of solution after the liquid became saturated from brine drainage at the top for sills from Figure 3c. The deepest and thickest solidify the slowest and precipitate the most amount of salt.



Conclusions

- Solidification occurs an order of magnitude faster than previous models [7] indicate, suggesting lenticulae and chaos may be even younger than previously assumed
- Ocean derived liquids with 12.3 ppt magnesium sulfate only increase the lifetime by <10%
- Up to ~60% initial $MgSO_4$ by mass may be precipitated out of solution due to oversaturation

Future work

- Simulate *in situ* melting scenarios (e.g. [1]) and impurities within the shell
- Implement sodium chloride as another plausible impurity

References

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