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P21E-3388: Brinicles and the fates of trapped salts in the ices of ocean worlds

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Abstract

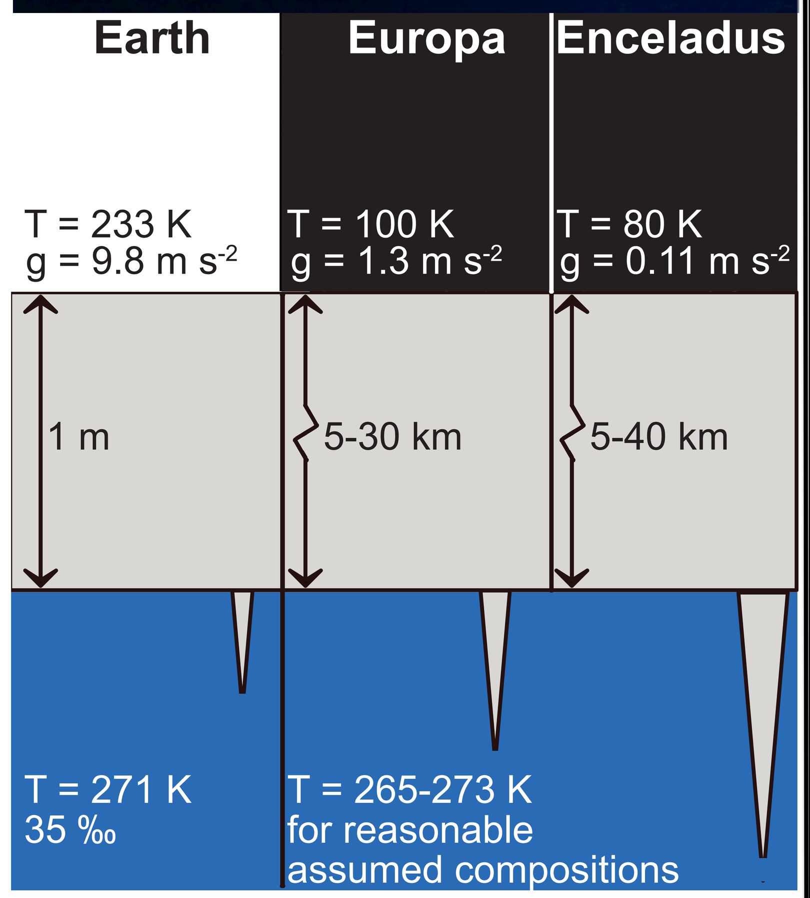
Brinicles are self-assembling tubular ice membrane structures, centimeters to meters in length, formed by the downward migration of supercooled brine rejected from ice sheets, and found beneath sea ice in the polar regions of Earth. They provide a plausible setting for geochemical gradients amenable to life at the ice-ocean interface, in some ways analogous to hydrothermal vents at the seafloor-ocean interface. Their occurrence in icy ocean worlds like Europa and Enceladus remains hypothetical.

The context of brinicles on Earth includes influences from oceanic flow, which will differ in other worlds, and surficial inputs from the atmosphere that do not exist in oceans with kilometers-thick global coverings of ice formed from the underlying ocean. Thus, it is difficult to project the likely occurrence and role of brinicles based on field observations of their earthly analogues. We discuss brinicles as they are currently understood, including their electrochemical properties in connection with potential habitats at the ice-ocean interface on Europa and Enceladus. We employ a fluid mechanical model (Cardoso and Cartwright, 2017) to assess the properties of brinicles on other worlds and consider their longevity relative to potential brine outflows from the overlying ice. We demonstrate how brinicles may grow by thermal diffusion, and provide simple scaling for their growth and outflow rates.

The specifics of the composition and dynamics of both the ice and the ocean in these worlds remain poorly constrained. We demonstrate through calculations using FREZCHEM that sulfate likely fractionates out of accreting ice in Europa and Enceladus, and thus that an exogenous origin of sulfate observed on Europa's surface need not preclude additional endogenous sulfate in Europa's ocean.

We suggest that, like hydrothermal vents on Earth, brinicles in icy ocean worlds constitute ideal places where ecosystems of organisms might be found.

Brinicles under sea ice near McMurdo station in Antarctica. Images courtesy of Rob Robbins



Brinicle sizes in ocean worlds

Radius and flow rate of a cylindrical fluid jet from a 1D analytical solution to the Navier-Stokes equation (Cardoso & Cartwright, 2017)

$$\frac{8\mu_i}{\Delta\rho g\pi R_C^4}Q_i = R'^4\left[1+4\frac{\mu_i}{\mu_e}\left(ln\frac{1}{R'}-\frac{1}{2}\right)+\frac{1}{\Delta\rho_i g}\frac{dP}{dz}\left(\frac{\mu_i}{\mu_e}\left(2-\frac{1}{R'^2}\right)-1\right)\right] \quad (1)$$

R'	radius of the tube growing
R_C	radius of external recirculation in the environment
$\Delta\rho_i = 150$ kg m^{-3}	density difference between brine and external fluid
$\mu_i/\mu_e = 1$	internal and external fluid viscosities
$dP/dz = 0$	longitudinal pressure gradient

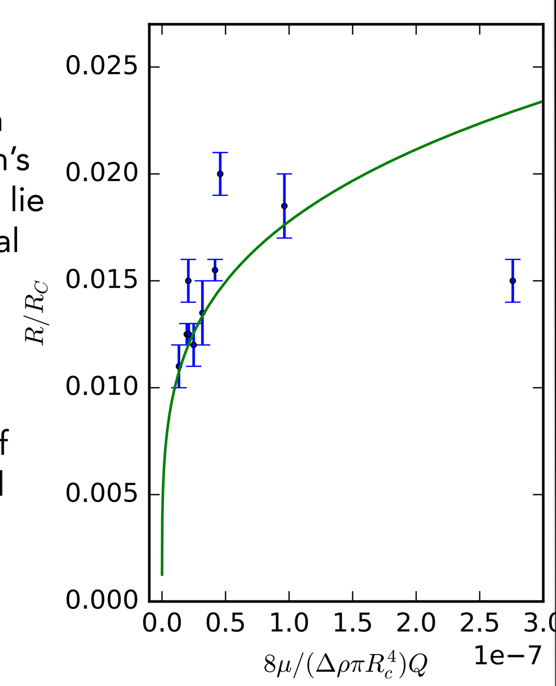
Volumetric flow rate determines diameter of brinicle tube

Inner flow affected only by the presence of the wall
outside fluid is effectively solid, Poiseuille flow applies

This contrasts with mineral chemical gardens where the tube wall behaves as a liquid

Wall thickness grows with ice thermal diffusivity D as $\sqrt{(D\,t)}$

Right: Variation of tube radius R' with flow rate Q. Martin's (1974) data mostly lie within experimental error along the Poiseuille flow solution, which is contained within Eq. 1 in the limit of large external fluid viscosity.



Brinicle compositions in ocean worlds

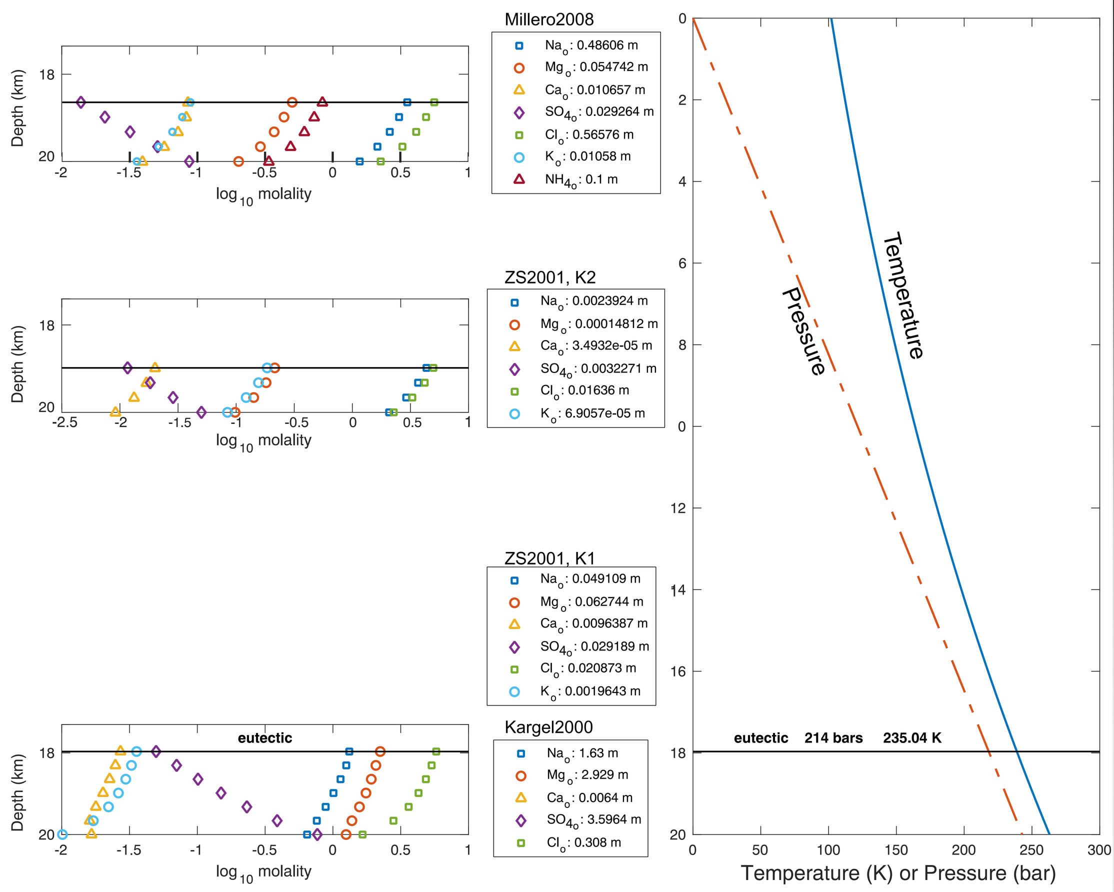
Brinicles are due to the expulsion of brine pockets in ice.
The magnitude of such expulsions in icy ocean worlds may create structures that persist over geologically significant time scales.
Determining their possible existence on other worlds requires understanding the detailed workings of icy lithospheres: generation and transport of fluids, and role of salts.

The compositions and dynamics of ice and ocean in ocean worlds have few constraints
Europa's ocean composition is mainly either SO_4^{-2} or Cl^- based on:

- chemical modeling (Zolotov and Kargel 2009)
- infrared reflectance spectra of the surface (McCord et al. 1998, Brown and Hand 2013)

Inferences from surface composition may be misleading:

- Under slow equilibrium freezing at the ice-ocean interface, sulfates leave accreting ice (Marion et al. 2005).
- If Europa's surface SO_4 is exogenous (Brown & Hand 2013) this need not preclude a sulfate-dominated ocean.



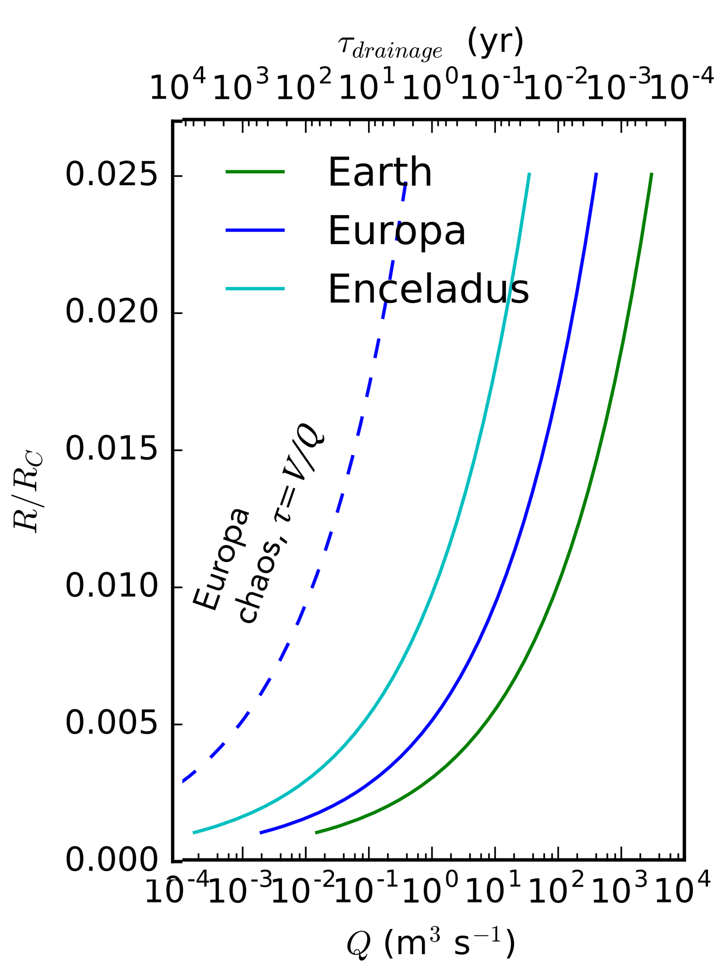
Composition of equilibrium brines computed with FREZCHEM after Marion et al. (2005; from Vance et al., in press)

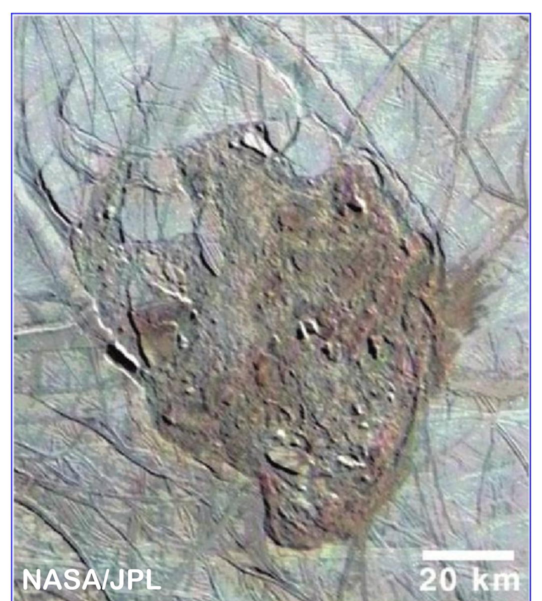
How much salt is in the ice?

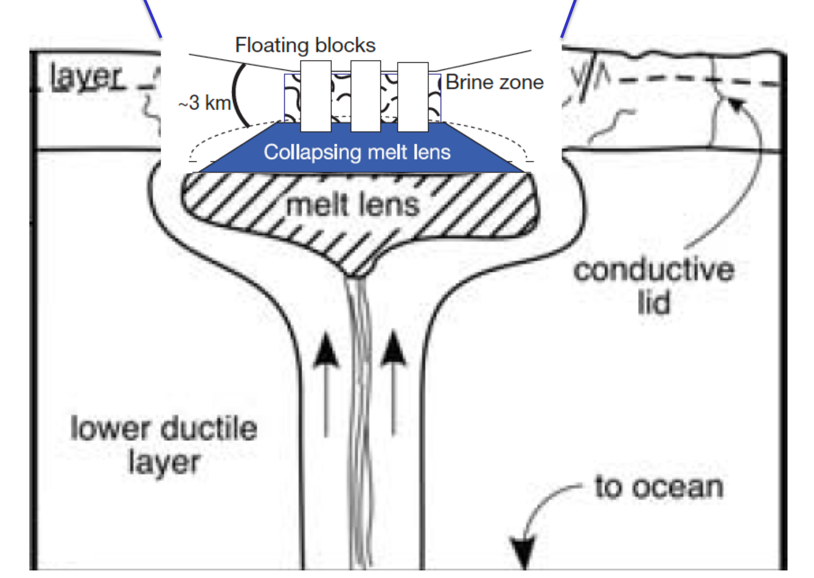
Needed to assess the feasibility of near-surface brine lakes, long-lived brinicles
Upper limits
Rapid freezing of sea ice is predicted trap up to 0.1wt% salt
→ That's 10^{18} kg of salt for a 25 km-thick ice shell (Buffo et al. 2018)
Over >10kyr, such high concentrations seem difficult to sustain against return
Lower limits
Ions substitute into the ice matrix and interstices
Partition coefficient k = Cs/Cl<1.
For alkali chlorides (e.g., NaCl), k=2.7 ppt (Gross et al. 1977)
For a 3.4wt% NaCl ocean (~seawater), that's 0.01wt% salt in the ice

How long could brinicles persist?

Right: Outflow rates predicted by Eq. 1. Dashed line shows corresponding timescales to empty a cylindrical briny melt lens with R=10 km and depth D=100 m, the entire volume of the chaos feature (V=πR^2D) delivered to the ocean through a brinicle







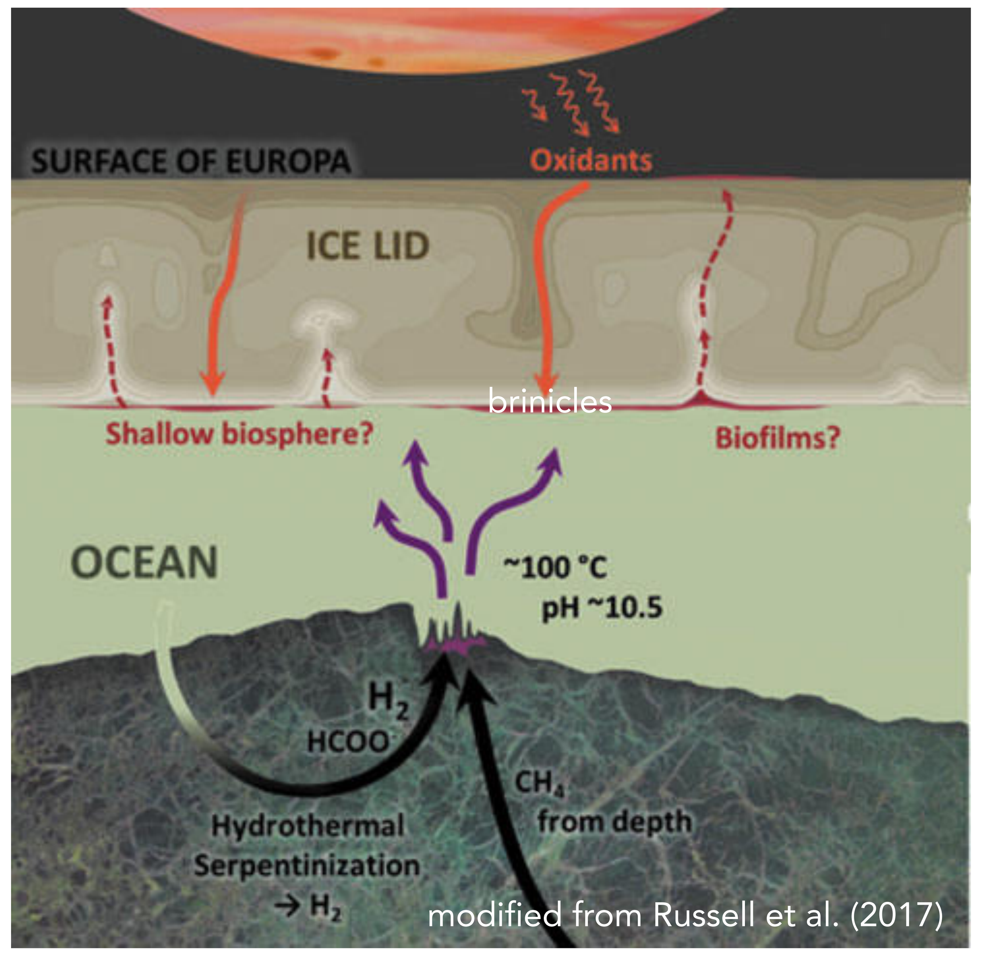
Near surface brine lakes on Europa are gravitationally unstable, and should reenter the ocean on 10kyr timescales (Kalousova et al. 2014)
(Oversimplified) schematic: composite from Schmidt et al. (2011) and Sotin et al. (2002)

Brinicles as inverted chemical gardens

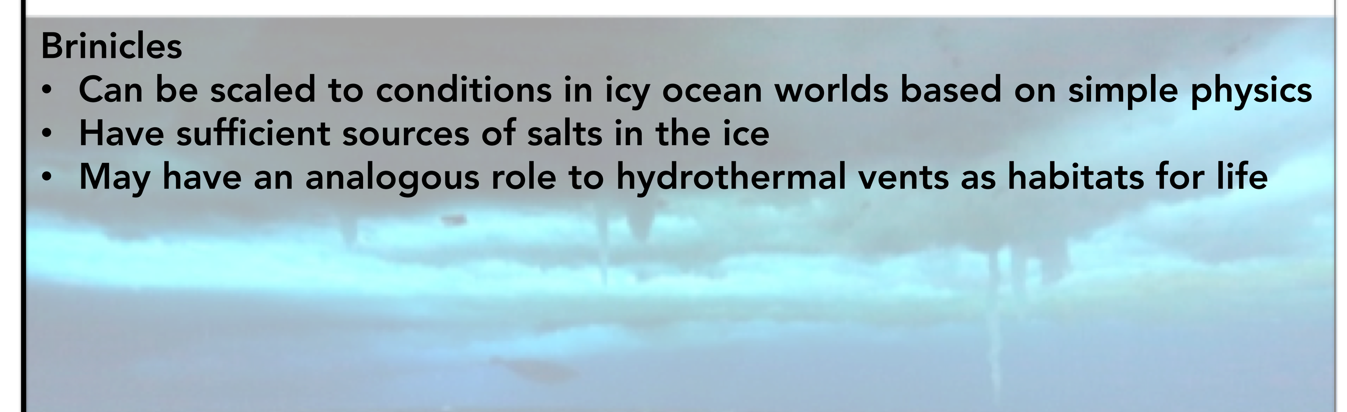
Brinicles provide a possible setting for geochemical gradients amenable to life at the ice-ocean interface, analogous to hydrothermal vents at the seafloor.

This especially relevant if the ocean is reducing, in which case down-welling oxidants delivered through brinicles would be the best source of energy for life.

This scenario fits with the biosphere described by Russell et al. (2017)



In the above scenario, serpentinization is abundant on Europa, facilitating life's origin and continuance.
Brinicles could be the means for supporting the most verdant part of Europa's hypothetical biosphere by serving as the conduit for oxygen-rich fluids from above.



Brinicles

- Can be scaled to conditions in icy ocean worlds based on simple physics
- Have sufficient sources of salts in the ice
- May have an analogous role to hydrothermal vents as habitats for life

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