The Habitability of Brine Pockets in Europa's Ice Shell

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Key Points:

- Brine pockets in Europa's ice shell are not geochemically prohibitive to life as we know it, suggesting they could be potential habitats
- Brine volume fraction, as a proxy for nutrient transport and recycling, may be a critical factor for the habitability of Europa's ice shell
- Ice shell habitats sustained by drainage of brine and recharge by ocean water (brine convection) can exist where the ice shell is freezing

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Abstract

Brine systems in Europa's ice shell have been hypothesized as potential habitats that could be more accessible than the sub-ice ocean. We model the distribution of sub-millimeter-scale brine pockets in Europa's ice shell. Through examination of three habitability metrics (water activity, ionic strength, salinity), we determine that brine pockets are likely not geochemically prohibitive to life as we know it for the chloride and sulfate-dominated ocean compositions considered here. Brine volume fraction is introduced as a novel habitability metric to serve as a proxy for nutrient transport and recycling—because of its role in governing permeability—and used to define regions where *active*, *dormant*, and *relict* habitats are stable. Whereas *dormant* habitats could exist wherever brine is stable (bottom ∼20% of a thermally conductive ice layer), *active* habitats are confined to meter-scale regions near ice-water interfaces where freezing is occurring. This classification scheme can help guide future life-detection missions to ocean worlds.

Plain Language Summary

Pockets of salty liquid water (brines) could exist in the ice shell of Jupiter's moon Europa. Because brines would be stable over long timescales within these pockets, they represent places that could be inhabited by microorganisms. We model where sub-millimeter-scale brine pockets might exist in Europa's ice shell and then study the properties of the brine using a geochemistry model. Our results demonstrate that the conditions of the brine do not fall beyond the limits of where life can exist on Earth, indicating that brine pockets may be suitable habitats in Europa's ice shell. We also model the amount of brine in the ice shell to see if organisms inhabiting these brine pockets could have access to nutrients via their transport along brine networks in the ice. By considering these factors, we classify potential brine habitats in Europa's ice shell.

1 Introduction

Jupiter's icy moon Europa is a high-priority target for exploration in the search for habitable worlds beyond Earth. Although Europa's global sub-ice ocean represents the most compelling potential habitat, habitable niches could extend from the ocean into the ice shell interior. Brine systems within Europa's ice shell have been hypothesized to represent potential habitats; however studies focused on their distribution and characteristics have been relatively limited (e.g., Kargel et al., 2000; Marion et al., 2003).

The distribution of brine in Europa's ice shell is governed by the shell's thermal profile as well as the composition and concentration of impurities within the ice (Wolfenbarger, Fox-Powell, et al., 2022). In Europa's ice shell, impurities are either incorporated through freezing of oceanic material at the base of the ice shell (e.g., Buffo et al., 2020; Allu Peddinti & McNamara, 2015; Wolfenbarger, Buffo, et al., 2022) or through geologic processes that transport surface impurities into the subsurface (e.g., Kattenhorn & Prockter, 2014).

Although impurities in an ice shell allow liquid water to be thermodynamically stable at temperatures below the pure ice pressure melting temperature (as brine), the presence of liquid water alone does not make an environment habitable. Chemical properties of the brine can be unfavorable—and even preventative—to supporting life, particularly conditions of low water activity (Stevenson et al., 2015), high ionic strength (Fox-Powell et al., 2016), and high salinity (Oren, 2011).

Organisms that inhabit analogous environments on Earth have developed strategies to endure the geochemical extremes that come with the reductions in temperature and increases in salinity associated with brine in equilibrium with ice (see Deming and Young (2017) for a thorough review). Examples of these strategies include the generation of extracellular polymeric substances (EPS), which protects cells from damage by encroaching ice crystals and increasing brine salinity (Liu et al., 2013; Aslam et al., 2012; Ewert & Deming, 2013; Krembs et al., 2002), and the accumulation of ions and/or synthesis of compatible solutes, which restores osmotic balance across the cell membrane (Thomas & Dieckmann, 2002; Ewert & Deming, 2013). Importantly, these strategies come at a cost to the organisms that employ them, requiring access to a supply of energy and nutrients, particularly those strategies that involve the synthesis of organic compounds (Oren, 2011; Aslam et al., 2012).

The significance of nutrient accessibility in governing the distribution of habitats in ice-brine environments is particularly pronounced in sea ice. Access to ocean-supplied nutrients is one of the key factors governing microalgae growth in sea ice. As such, microalgae tend to concentrate within the more permeable sea ice base that can be replenished by oceanic material (Arrigo, 2014; Meiners & Michel, 2017; Arrigo, 2017). The observation that microalgae concentrate in the region of the ice furthest from their energy source (sunlight), emphasizes that access to ocean-supplied nutrients is important for sustaining in-ice habitats and motivates our decision to consider this as a factor govern-

ing the habitability of Europa's ice shell (Greenberg, 2010; Hand et al., 2007; Hesse et al., 2022).

Although sunlight is not expected to serve as an energy source to support life at Europa, radiolytically generated oxidants at the surface may represent an analogous energy source (Chyba, 2000). The oxidant flux from Europa's surface to the ocean is poorly constrained and could be punctuated or continuous depending on the transport mechanism (e.g., brine drainage from chaotic terrain or complete overturning of the ice shell) (Hesse et al., 2022; Vance et al., 2016). Estimates assuming the ice shell fully overturns on timescales equal to the age of the surface suggest Europa's ocean could be more oxygenated than Earth's ocean (Hand et al., 2007; Greenberg, 2010). The oxidant flux will govern the amount of sustainable biomass in Europa's subsurface, similar to how irradiance limits the extent of algae blooms in sea ice (Hancke et al., 2018). For this work we assume the oxidant flux is such that some non-zero biomass can be maintained at Europa, but that access to oceanic nutrients will govern whether this biomass can be sustained within the ice shell.

In our study of potential Europan sub-millimeter-scale brine pocket habitats (see Text S1), we first model and evaluate a series of traditional habitability metrics related to geochemical properties of the brine: water activity, ionic strength, and salinity (Sections 2 and 3). We introduce brine volume fraction as a novel habitability metric, and argue that because of its role in governing the permeability of ice, it can serve as a proxy for access to oceanic nutrients (Section 4). Finally, we use brine volume fraction as a habitability metric to define three classes of potential habitats: *active*, *dormant*, and *relict*, and identify where they might exist in Europa's ice shell (Sections 5 and 6).

2 Traditional Habitability Metrics

Through modeling the brine volume fraction in Europa's ice shell, we can constrain the amount of thermodynamically stable water in equilibrium with ice for a given bulk salinity and composition (Wolfenbarger, Fox-Powell, et al., 2022). However, to examine the potential for brine systems to serve as an in-ice habitat for life as we know it, it is necessary to evaluate certain characteristics and chemical properties of the brine. We select three habitability metrics to consider in our evaluation: water activity, ionic strength, and salinity (see Text S2 for a discussion of chaotropicity). These habitability metrics

can be extracted directly from the aqueous geochemistry program FREZCHEM (Marion & Kargel, 2007).

Salinity quantifies total concentration of aqueous species in the brine, expressed in units of ppt (g/kg solution). In sea ice, high brine salinity has been observed to impede the functioning of proteins as well as cause dehydration by increasing osmotic pressure (Ewert & Deming, 2013). However, other studies have shown that high salinity NaCl brines are thermodynamically moderate habitats for certain species of halophiles and could even correspond to their optimum environmental growth conditions (Lee et al., 2018). Hypersaline sulfate lakes in British Columbia, Canada were found to host an abundance of anaerobes and extremophiles, suggesting these organisms can not only endure such high salinity environments but are capable of growth and reproduction (Pontefract et al., 2017). These studies suggest that microbial growth can occur at any salinity, providing other environmental conditions are within permissible biological limits.

Ionic strength represents a molality-weighted quantification of solution charge density, expressed in units of mol/kg H_2O in FREZCHEM. An ionic strength above 10 mol/L has been argued to challenge the habitability of otherwise biologically permissible brines due to its perturbing effect on biological molecules (Fox-Powell et al., 2016). A later study found biological growth was permissible in an $MgSO_4$ brine system at an ionic strength of 12.1 mol/L, suggesting ionic strength limits are likely dependent on the composition of the brine as well as the evolutionary adaptations of particular strains (Fox-Powell & Cockell, 2018). Additional experiments are needed to better elucidate the complex interplay between ionic strength and water activity.

Water activity represents the thermodynamic availability of water in an environment for metabolic processes (Grant, 2004; Stevenson et al., 2015; Fox-Powell et al., 2016), expressed as the ratio of the vapor pressure of solution to the vapor pressure of pure water (Grant, 2004) (pure water has a water activity of 1). A majority of microbes cannot multiply below a water activity of 0.9; however, extremophilic species across the three domains of life (e.g., Bacteria, Archaea, and Eukarya) are capable of reproducing at water activities as low as ∼0.6 (Stevenson et al., 2015). In FREZCHEM, water activity is calculated using the Pitzer equations, as described in Marion and Kargel (2007). Where brine is in equilibrium with ice, water activity is equivalent to the ratio of water vapor

pressure of ice to the water vapor pressure of pure liquid water, and as such is solely a

function of temperature and not the composition or concentration of solutes (Koop, 2002).

Although these three parameters are intimately linked, they can vary with composition. As we will demonstrate, brines at identical salinities can exhibit drastically different water activities and ionic strengths if they differ in their major ionic composition. Exploring the implications of brine composition for habitability thus necessitates considering all three independently.

3 Evaluation of Habitability Metrics in Europa's Ice Shell

In our evaluation of habitability metrics for Europa's ice shell, we assume the analog endmember ocean compositions of Wolfenbarger, Fox-Powell, et al. (2022). In their model they considered only impurities sourced from the ocean and adopted two endmember ocean compositions: (i) a chloride-dominated composition, analogous to terrestrial seawater, and (ii) a sulfate-dominated composition, analogous to the modeled Europa K1a ocean of Zolotov and Shock (2001). We similarly adopt their linear temperature profile, with a surface temperature of -173.15 °C (100 K) and a basal temperature of 0 °C (273.15 K). Figure 1 presents the water activity, ionic strength, and salinity extracted from FREZCHEM v15.1 for the analog endmember ocean compositions, as well as two binary endmember compositions (NaCl, $MgSO_4$) for reference. By examining these habitability metrics as a function of brine volume fraction, in addition to temperature, we can study the influence of composition on the characteristics of habitats where the same amount of water is present.
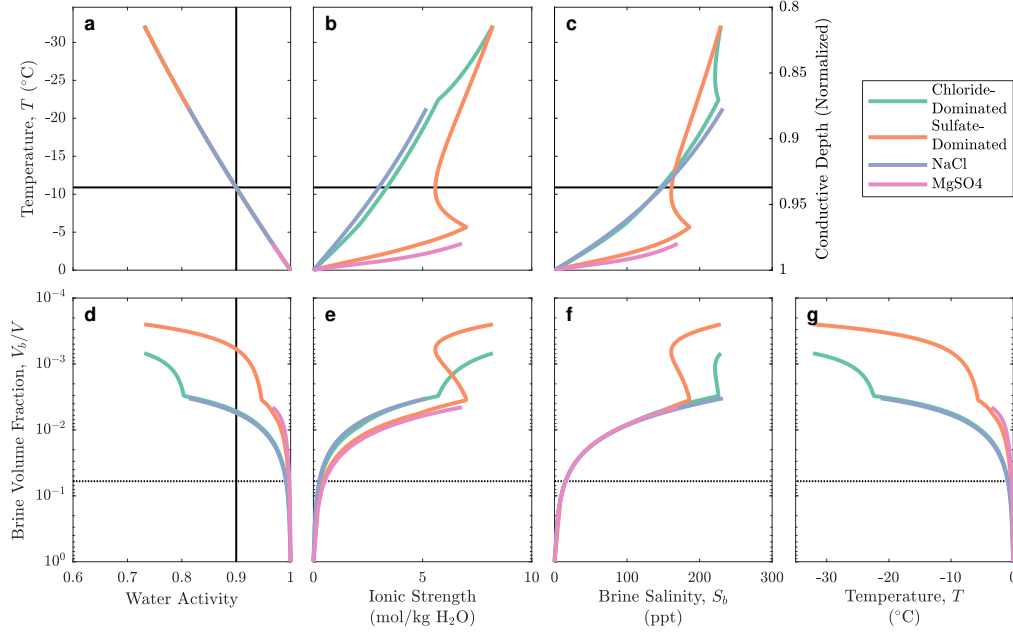
Figure 1. Habitability metrics for the bottom 20% of a thermally conductive Europan ice shell assuming binary (NaCl, $MgSO_4$) and analog endmember (chloride-dominated, sulfate-dominated) ocean compositions and a fixed pressure of 1 atm. For **a** – **c**, curves are defined from infinite dilution to the eutectic for each composition. For **d** – **g**, brine volume fraction is calculated using the model of Wolfenbarger, Fox-Powell, et al. (2022), assuming a bulk ice salinity of 1 ppt (see Text S3). The solid black lines depict a water activity of 0.9 (**a** and **d**) and the temperature at which the water activity equals 0.9 (**a** – **c**). The dotted black line in **d** – **g** corresponds to a brine volume fraction equal to 0.06.

Figure 1a illustrates that for brine in equilibrium with ice, the water activity is a function of temperature alone (Koop, 2002). However, because the composition of solutes governs the eutectic temperature, this determines the minimum water activity where brine is in equilibrium with ice. At the ice-ocean interface, the maximum water activity is governed by the ocean salinity. Importantly, for the endmember compositions assumed here, the water activity does not fall below the current empirical limit of approximately 0.6 (Fig. 1a). Extrapolating the curve in Fig. 1a suggests that water activity could fall below 0.6 for an ice shell composition where the eutectic temperature is below −50.6 °C (222.5 K), in agreement with Marion (2002). In the absence of low-eutectic impurities (e.g., sulfuric acid, perchlorates, or ammonia), it is unlikely water activity will be the limiting factor governing the habitability of in-ice brine systems.

172   Figure 1b shows that ionic strength increases as temperature decreases, although

173   following precipitation of meridianiite at $T = -5.7$ °C (267.45 K) in the sulfate-dominated

174   case, the ionic strength decreases due to the sink of divalent ions, whereas the ionic strength

175   increases in the chloride-dominated after precipitation of hydrohalite at $T = -22.5$ °C

176   (250.65 K) due to a sink of monovalent ions. For both analog endmember compositions

177   the ionic strength does not exceed the empirical limit of 10 mol/L.

178   Although water activity is often used as a measure of salinity (see Marion (2002),

179   Marion et al. (2003), and Tosca et al. (2008)), Fig. 1c shows that brine salinity does not

180   increase monotonically as water activity decreases for brine in equilibrium with ice. The

181   precipitation of minerals as the solution freezes causes the salinity to decrease under con-

182   tinued cooling as minerals serve as a sink for dissolved ions. The brine salinity for each

183   analog endmember composition closely follows the salinity of the related binary endmem-

184   ber composition up to the eutectic temperature of the binary composition. As such, the

185   sulfate-dominated composition has a higher salinity than the chloride-dominated com-

186   position at higher temperatures and a lower salinity at lower temperatures. At the eu-

187   tectic, $T_{eut} = -32.2$ °C (240.95 K), these two cases share the same salinity.

188   For both compositions, the habitability metrics in Fig. 1 suggest that these brine

189   systems are not inherently prohibitive to life as we know it, although we note that mi-

190   crobial growth in ice on Earth has not been observed below -20 °C, possibly due to the

191   onset of vitrification (glass transition) (Clarke, 2014). Although not geochemically pro-

192   hibitive to life as we know it, these brines are certainly not considered favorable to most

193   life on Earth, and in general become more extreme as temperatures decrease. Even for

194   a water activity higher than 0.9, which is considered a lower bound water activity for

195   most microbes on Earth (Stevenson et al., 2015), the brine salinity and ionic strength

196   are consistent with those expected of hypersaline environments. Organisms that inhabit

197   analogous environments on Earth are classified as halophiles and/or psychrophiles, char-

198   acterized by growth and reproduction in environments of high salt concentrations (specif-

199   ically NaCl) and low temperatures, respectively. These results suggest that brine salin-

200   ity and ionic strength—and not water activity—may represent the driving environmen-

201   tal stressors for organisms inhabiting Europan brine habitats.

202   It has been argued previously that characterizing potential habitats using metrics

203   such as those in Fig. 1 alone may not give proper consideration to complex interactions

between these metrics and that certain limits may be organism-specific and/or salt-specific, particularly when these metrics do not fall outside the thermodynamic limits (Stevens & Cockell, 2020). Additionally, the occurrence of multiple extremes can conspire to either limit or enhance growth, depending on the conditions (Kaye & Baross, 2004). For example, below a water activity of 0.9, the sulfate-dominated case exhibits a significantly higher ionic strength than the chloride-dominated case across the temperature range, until very near the eutectic. If ionic strength can interact with water activity to restrict growth, brine habitats formed from the sulfate analog endmember may present greater challenges to habitability (Fox-Powell et al., 2016). If we examine what factors govern the distribution of potential habitats within Earth analog environments, brine volume fraction itself becomes a compelling metric for consideration.

4 Brine Volume Fraction as a Habitability Metric

Fundamentally, brine volume fraction represents a quantification of the potentially habitable space in ice (Thomas et al., 2017). Studies of in-ice habitats seem to indicate that increased brine volume fraction is favorable to organisms. For example, the net effect of EPS on sea ice microstructure is to increase the brine volume fraction (Krembs et al., 2011). Ice-binding proteins, glycoproteins, and/or polysaccharides increase the tortuosity of the ice, which in turn retains salt and thus increases the brine volume fraction (Krembs et al., 2011; Ewert & Deming, 2011). Studies of natural saline ice that include both brine volume fraction and cell density profiles illustrate a correlation between these two quantities (Uhlig et al., 2018; Buffo et al., 2022), although further dedicated studies are needed.

Because the brine volume fraction of ice represents the governing variable in permeability models for columnar sea ice (Petrich et al., 2006; Golden et al., 2007), it also represents an important control on nutrient transport (Meiners & Michel, 2017). Even in glacial ice, where the brine volume fraction can be orders of magnitude lower than sea ice, nutrient transport through liquid veins at grain boundaries is essential for supporting the metabolic activity of in-ice organisms (Price, 2000, 2007). Access to such nutrients is essential for organisms to grow, reproduce, and survive.

On Earth, nutrient availability has been used to identify three distinct groupings of metabolic activity in microbial communities (Price & Sowers, 2004), where a "growth"

metabolism implies unlimited access to nutrients, a "maintenance" metabolism implies nutrient levels are too low for growth, and a "survival" metabolism implies nutrient levels can only support repairing damage (Price, 2009). We similarly define three classes of potential habitats using brine volume fraction as a proxy for nutrient accessibility: (i) *active* potential habitats characterized by "growth", (ii) *dormant* potential habitats, characterized by "maintenance" and "survival", and (iii) *relict* potential habitats, characterized by an absence of viable microorganisms.

5 Classification of Brine Pocket Habitats

In our model of Europa's ice shell, we assume that the ice shell retains the columnar crystal structure originating from directional freezing of the ocean (Fig. 3d). This assumption is validated by studies of the microstructure of sea ice which suggest that in the absence of warming, ice can retain its original grain boundaries (Zotikov et al., 1980; Maus, 2020). Because the ice forms with a columnar texture, it is subject to a percolation threshold at some critical porosity, ϕ_c (Maus et al., 2021). Where the brine volume fraction is higher than this critical porosity, convective overturning of brine can occur within the ice and transport oceanic material, including nutrients, into the icy interior (Meiners & Michel, 2017). To define the region where nutrient replenishment can operate efficiently and support *active* potential habitats, we adopt $\phi_c = 0.06$—the effective critical porosity derived by Wolfenbarger, Fox-Powell, et al. (2022) from the J-9 Ross Ice Shelf core, an ice core which could represent growth conditions approaching those expected at Europa (Wolfenbarger, Buffo, et al., 2022).

Nutrient transport could still operate at brine volume fractions below this critical porosity—albeit less efficiently—since the ice is not completely impermeable. Measurements of the dihedral angles for ice binary systems have shown that, in general, values are below 60°, indicating that melt is not confined to triple junctions and is mobile along ice grain boundaries (McCarthy et al., 2019). This indicates that ice should be permeable even at very low brine volume fractions and would suggest nutrient transport could be permissible at temperatures down to the eutectic. This property has been used previously to justify the transport of oxidants through Europa's ice shell via porosity waves (Hesse et al., 2022). We designate the region of the ice shell where the brine volume fraction is less than 0.06 but water is still stable as *dormant* potential habitats. Here, metabolic

activity is still possible, but organisms are nutrient-limited and thus have limited potential to grow and reproduce.

In contrast, given that by our definition the entire ice shell was once innately active, we designate the region of the ice shell where the brine volume fraction is zero as *relict* potential habitats. Where liquid water is no longer stable within the ice shell, we consider organisms that were once inhabiting the interstices of ice crystals to be in a non-viable state (i.e., unable to metabolize). However, premelting (the formation of quasi-liquid layers, see Slater and Michaelides (2019) for a review), and/or supercooling (see Toner et al. (2014) and Primm et al. (2017)) could extend the vertical extent of *dormant* potential habitats to temperatures below the eutectic. EPS, if present, could depress the eutectic temperature by inhibiting salt and ice crystallization (Izutsu et al., 1995). Rohde and Price (2007) demonstrated that diffusion of nutrients through the ice crystal structure itself could occur; however, the absence of liquid water could prevent uptake of those nutrients by a cell membrane, assuming the membrane is intact and still fluid enough to enable transport (Clarke, 2014).

6 Potential Habitats in Europa's Ice Shell

Figure 2 shows the brine volume fraction, V_b/V, for Europa's ice shell, adapted from Wolfenbarger, Fox-Powell, et al. (2022). Only the portion of the ice shell where brine is thermodynamically stable for the assumed temperature profile is shown (bottom $\sim 20\%$ of the ice shell). We truncate the salinity domain to 100 ppt since the brine volume fraction model is not valid for ocean salinities greater than this (Wolfenbarger, Fox-Powell, et al., 2022).

Our proposed classification indicates that $\sim 80\%$ of the ice shell corresponds to *relict* potential habitats, since brine is not thermodynamically stable for temperatures below the eutectic of $T = -32.2 \, °C$ (240.95 K). To establish where *active* and *dormant* potential habitats could be stable, we must identify where the brine volume fraction exceeds our effective critical porosity of 0.06.
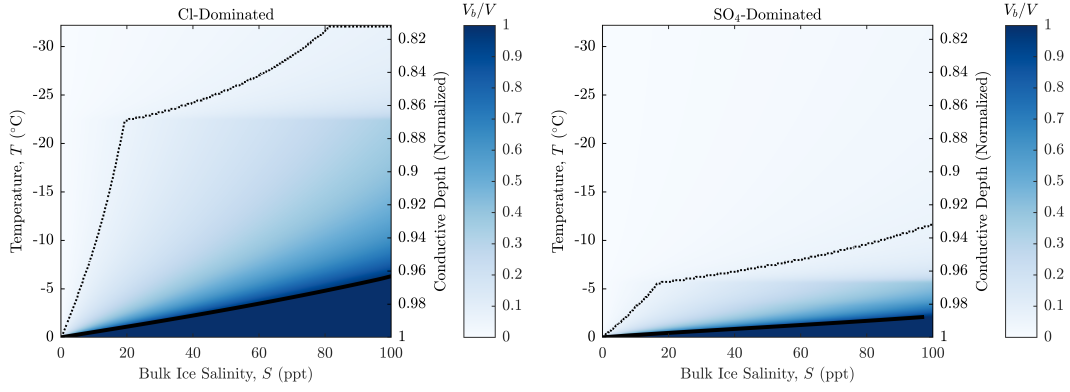
Figure 2. Brine volume fraction for Europa's ice shell assuming analog endmember compositions for the ocean and a fixed pressure of 1 atm, adapted from Wolfenbarger, Fox-Powell, et al. (2022). The solid black curve represents the brine salinity as a function of temperature (or equivalently the freezing temperature as a function of ocean salinity). The thin dotted curve corresponds to the lowest temperature where the brine volume fraction is greater than 0.06 for a given bulk ice salinity.

6.1 Maximum Vertical Extent of *Active* Potential Habitats

The black dotted curves in Fig. 2 represent the lowest temperature where the brine volume fraction is greater than the effective critical porosity of 0.06 for a given bulk ice salinity, and thus define the upper boundary where *active* potential habitats are stable in a conductive ice shell. The solid black curves in Fig. 2 represent the freezing temperature as a function of ocean salinity (i.e., the temperature at the ice-ocean interface), and thus define the lower boundary of the vertical region where *active* potential habitats within the ice are stable. Defining this curve as the lower boundary ensures the bulk salinity of the ice shell does not exceed that of the underlying ocean.

Consequently this represents the extreme case where bulk ice shell salinity is equal to the underlying ocean salinity and thus represents a maximum estimate for the vertical extent of *active* potential habitats (Fig. S1). For both compositions considered, the maximum vertical extent of *active* potential habitats increases with salinity. The chloride-dominated ice shell is capable of supporting a much larger vertical extent of *active* potential habitats, due to having a higher volume fraction of brine stable for a given bulk ice salinity and temperature than the sulfate-dominated ice shell.

6.2 Limitations on the Vertical Extent of *Active* Habitats due to Brine Drainage

An important consequence of designating *active* habitats as locations where the brine volume fraction exceeds a percolation threshold is that they are only stable if brine is actively draining. For Europa's ice shell, this corresponds to locations of active freezing (i.e., where the ice shell is in the processes of desalinating). In other words, the brine volume fraction in a conductive ice shell which is in thermal equilibrium will not exceed the percolation threshold and thus cannot support *active* habitats. It is possible that portions of an otherwise thermally equilibrated ice shell could locally have brine volume fractions exceeding the percolation threshold—such as hypothesized perched lakes/sills (Chivers et al., 2021) or fractures (Buffo et al., 2020).

Recall that the region bounded by the curves in Fig. 2 specifically represents the case where the bulk ice shell salinity is equivalent to the underlying ocean salinity. Practically, this assumption is nonphysical because the ice will be in a state of progressive desalination due to the unstable brine density gradient in the region where *active* habitats are present. Ultimately, this process will limit the stable bulk ice shell salinity to a fraction of the underlying ocean salinity (Wolfenbarger, Buffo, et al., 2022; Wolfenbarger, Fox-Powell, et al., 2022). Thus, the true vertical distribution of *active* habitats in a conductive ice shell is governed by the fraction that is in an active state of desalination, where brine convection is occurring within the ice. We can constrain the thickness of this layer using mushy layer theory.

Mushy layer theory has only recently been applied to the ice shells of ocean worlds (Buffo et al., 2020; Buffo, Meyer, & Parkinson, 2021; Buffo, Schmidt, et al., 2021). Assuming a composition consistent with 34 ppt seawater, Buffo, Schmidt, et al. (2021) found equilibrium mushy layer thicknesses are unlikely to exceed meters thick for an ice shell subject to a percolation threshold of $\phi_c = 0.05$. Relative to their assumed composition of 34 ppt seawater, we would expect our chloride-dominated *active* layer to be the same thickness and our sulfate-dominated *active* layer to be thinner (see Text S4).

These results (see Buffo, Schmidt, et al. (2021) and Fig. S2) imply that *active* habitats in Europa's ice shell are likely only meters thick when accounting for the role of brine drainage in governing the stable bulk ice shell salinity. As such the majority of the ice shell where brine is thermodynamically stable will likely be characterized by *dormant*

habitats. We note that the model of Buffo, Schmidt, et al. (2021) represents the case of natural convection. Forced convection, driven by tides or sub-ice currents (see (Soderlund et al., 2020) for a review), might increase the vertical extent of *active* habitats, similar to sea ice on Earth (Arrigo & Thomas, 2004).

6.3 Extensions on the Vertical Extent of *Active* Habitats

Recall that our classification scheme assumes that brine convection represents the only mechanism of nutrient transport that could support *active* habitats. If other transport processes are found to be capable of supplying a sufficient flux of nutrients to support growth and reproduction of organisms trapped in the ice, many of the regions classified as *dormant* habitats could be reclassified as *active* habitats. Hypothesized exchange processes that could transport oceanic nutrients include ocean-injection of sills via fracturing (Michaut & Manga, 2014), diapirism (Barr & McKinnon, 2007), and ice shell solid-state convection (Allu Peddinti & McNamara, 2015).

Although our analysis excludes the potential existence of a convective ice layer, extrapolation of our results suggest this layer could represent the most extensive potential habitat. Numerical simulations of ice shell convection have shown that temperatures in the convective ice layer thickness can exceed the eutectic temperatures considered here (Kalousová et al., 2017). The efficiency of nutrient exchange will govern whether these are *active* or *dormant* potential habitats. To rigorously quantify the distribution of potential *active* habitats in a convective layer requires the following: (i) a convection model which incorporates two-phase flow, (ii) a permeability-porosity relationship compatible with the expected ice texture (grain size, shape, etc.), and (iii) a parameterization of bulk ice thermophysical properties based on brine volume fraction.

6.4 Significance of *Dormant* and *Relict* Potential Habitats for Biosignatures

Although *active* habitats are compelling targets in the search for life beyond Earth, *dormant* and *relict* habitats represent more extensive, more accessible, and more feasible targets for biosignature detection. On Earth, viable microorganisms have been found in brine inclusions in halite evaporites that are older than the estimated age of Europa's surface (Jaakkola et al., 2016; Bierhaus et al., 2009). Because brine inclusions would not

be thermodynamically stable anywhere below the eutectic temperature, this is a more relevant analog for *dormant* potential habitats within the ice shell interior, where brine inclusions are trapped in the ice, than *relict* potential habitats, like salt deposits at the surface. Another analog relevant to *dormant* and *relict* potential habitats at Europa is ancient glacial ice on Earth. Glacial ice samples (some estimated to be up to 8 Myr old) have been discovered to harbor both viable and nonviable microorganisms, frozen into the ice at the time of formation (Christner et al., 2003; Ma et al., 1999; Knowlton et al., 2013; Bidle et al., 2007). Although neither environment discussed here is a perfect analog for potential habitats at Europa, organisms are clearly capable of prolonged survival in environments analogous to brine pockets in an ice shell (Bradley et al., 2019). Beyond survival, the ubiquity of ancient biologic material in terrestrial ice bodes well for biosignature preservation in *relict* potential habitats at Europa (Castello et al., 2005).

7 Conclusions

Three habitability metrics (water activity, ionic strength, and brine salinity) were chosen to evaluate ice shell brine pockets as potential habitats for two ocean analog end-member compositions. It was found that for ice shell impurities considered here, brine pockets were not geochemically prohibitive to life as we know it. This suggests that anywhere water is detected within Europa's ice shell could represent a potential habitat. Note that our study ignores the potential contribution of low eutectic impurities that could be generated at the surface (e.g., sulfuric acid and perchlorates) (Ligier et al., 2016), which would reduce the water activity and thus habitability of cold, low-brine volume fraction environments.

Motivated by examination of analog habitats, we argue that brine volume fraction should be used as a habitability metric to classify potential habitats within Europa's ice shell because it serves as a measure of potentially habitable space and governs the efficiency of nutrient transport (Thomas et al., 2017; Meiners & Michel, 2017). Using brine volume fraction as a proxy for nutrient transport, we defined three classes of potential in-ice brine habitats: (i) *active*, (ii) *dormant*, and (iii) *relict*.

We found that $\sim 80\%$ of a conductive Europan ice shell is characterized by *relict* potential habitats, $\sim 20\%$ is characterized by *dormant* potential habitats, and *active* potential habitats are confined to a few meters of an ice-ocean interface, where the ice

shell is actively freezing (Fig. 3). Extending our results to an ice shell where solid state

convection is occurring, we argue that a convective ice layer—shown by Kalousová et al.

(2017) to be on the order of half the total ice shell thickness—could represent the most

extensive potential habitat in Europa's ice shell, where efficiency of nutrient exchange

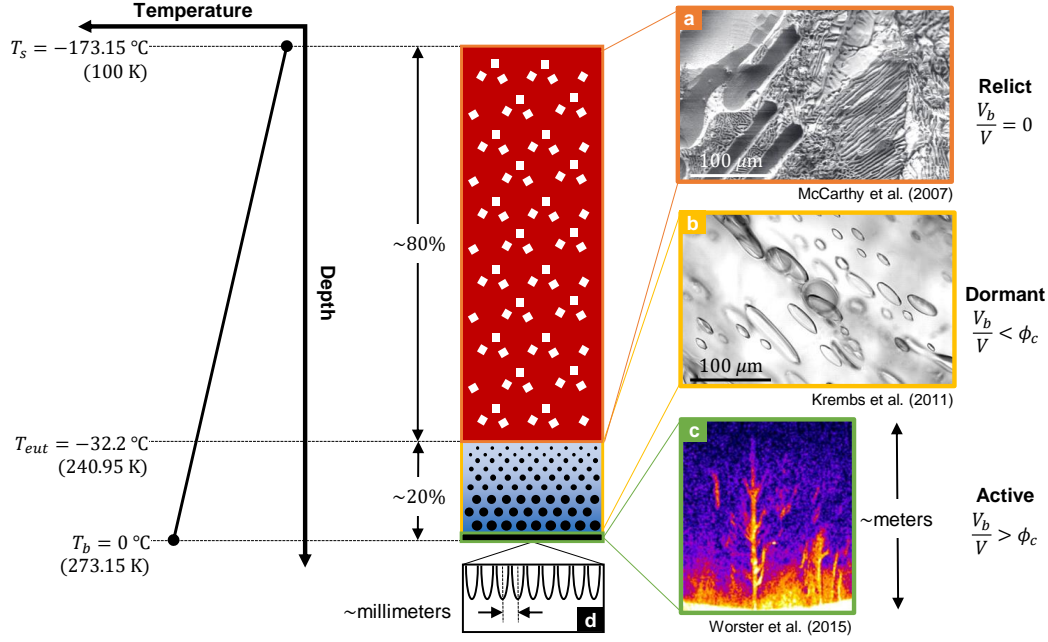will govern whether brine pockets are *active* or *dormant* potential habitats.

Figure 3. Classification of potential habitats in Europa's ice shell based on brine volume fraction, V_b/V, for the thermal profile assumed in this work. For brine volume fractions greater than the critical porosity, ϕ_c, convective overturning of brine can occur within the ice and transport oceanic material, including nutrients, into the interior to support *active* potential habitats. At brine volume fractions lower than this, metabolic activity is still possible; however, organisms inhabiting these *dormant* habitats are nutrient-limited and thus have limited potential to grow and reproduce. Viable organisms are unlikely to be found in *relict* habitats but terrestrial analogs suggest biosignature preservation may still be possible. **a** − **c** are images from laboratory experiments that are representative of the small-scale characteristics of these potential habitats, where **a** depicts meridianiite crystals (light) in ice (dark) with a eutectic bulk composition adapted from McCarthy et al. (2007), **b** depicts brine pockets in an artificial sea ice sample adapted from Krembs et al. (2011), and **c** depicts brine channels in the lower portion of a mushy layer adapted from Worster and Rees Jones (2015). **d** is a sketch representing the microstructural interface morphology assumed in this work compatible with the existence of a percolation threshold ($\phi_c = 0.06$).

Identifying where *active*, *dormant*, and *relict* potential habitats could exist in Europa's ice shell can guide future life-detection missions, such as a Europa Lander (Pappalardo et al., 2013). Our study demonstrates that *relict* potential habitats represent the most accessible targets for future missions to sample biosignatures at Europa. For missions

where the goal is to detect potentially viable microorganisms *in situ*, a cryobot would

be necessary to access depths where *dormant* potential habitats are stable (Zimmerman

et al., 2001). Notably, this would not require penetrating the full ice shell thickness to

access the ice-ocean interface. In the case of a convective ice shell, descending through

half the total ice shell thickness could be sufficient to reach *dormant* potential habitats

(Kalousová et al., 2017). Beyond Europa, this classification scheme could be invaluable

for guiding future life-detection missions to other icy ocean worlds such as Enceladus or

Titan.

Open Research

Acknowledgments

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