

Brine Volume Fraction as a Habitability Metric for Europa's Ice Shell

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Key Points:

- Brine pockets in Europa's ice shell may not be geochemically prohibitive to life as we know it, and as such 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 *nutrient-open*, *nutrient-closed*, and *relict* habitats are stable. Whereas *nutrient-closed* habitats could exist wherever brine is stable, *nutrient-open* habitats are confined to meter-scale regions near the ice-ocean interface 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 geochemical 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 ocean-sourced 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 the global sub-ice ocean represents Europa’s 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 character-

istics have been relatively limited (e.g., Kargel et al., 2000; Marion et al., 2003; J. Deming & Eicken, 2007).

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 J. W. Deming and Young (2017) for a thorough review). Examples of these strategies include the generation of extracellular polymeric substances (EPS), which protect 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 microbial growth in sea ice. Microalgae, for example, tend to concentrate within the more permeable sea ice base that can be replenished by oceanic material (Arrigo et al., 2014; Arrigo, 2014; Meiners & Michel, 2017; Arrigo, 2017). The observation that microalgae concentrate in the region of the ice furthest

78 from their energy source (sunlight), emphasizes that access to ocean-supplied nutrients
79 is important for sustaining in-ice habitats. During the polar winter (i.e., in the absence
80 of sunlight), bacteria and archaea that inhabit sea ice are likely similarly dependent on
81 oceanic nutrients (Junge et al., 2004; Cowie et al., 2011; Collins et al., 2010); however,
82 these prokaryotes are relatively less studied than algae and thus the factors that control
83 their growth are less understood (Bowman, 2015; Campbell et al., 2022). These stud-
84 ies of sea ice habitats motivate our decision to consider access to oceanic-nutrients as a
85 factor governing the habitability of Europa’s ice shell (Duarte et al., 2022).

86 Although sunlight is not expected to serve as an energy source to support life at
87 Europa (i.e. organisms inhabiting the ice shell and/or ocean are likely not phototrophic),
88 radiolytically generated oxidants at the surface may represent an analogous energy source
89 for chemotrophic organisms (Chyba, 2000). The oxidant flux from Europa’s surface to
90 the ocean is poorly constrained and could be punctuated or continuous depending on
91 the transport mechanism (e.g., brine drainage from chaos terrain or complete overturn-
92 ing of the ice shell) (Hesse et al., 2022; Vance et al., 2016). Estimates assuming the ice
93 shell fully overturns on timescales equal to the age of the surface suggest Europa’s ocean
94 could be more oxygenated than Earth’s ocean (Hand et al., 2007; Greenberg, 2010). For
95 this work, we assume that the oxidant flux will govern the amount of sustainable biomass
96 in Europa’s subsurface, similar to how irradiance limits the extent of algae blooms in sea
97 ice (Hancke et al., 2018). , and that the oxidant flux is such that some non-zero biomass
98 can be maintained at Europa, but that access to oceanic nutrients will govern whether
99 this biomass can be sustained within the ice shell.

100 In our study of potential European sub-millimeter-scale brine pocket habitats (see
101 Text S1), we first model and evaluate a series of traditional habitability metrics related
102 to geochemical properties of the brine: water activity, ionic strength, and salinity (Sec-
103 tions 2 and 3). We introduce brine volume fraction as a novel habitability metric, and
104 argue that because of its role in governing the permeability of ice, it can serve as a proxy
105 for access to oceanic nutrients (Section 4). Finally, we use brine volume fraction as a hab-
106 itability metric to define three classes of potential habitats: *nutrient-open*, *nutrient-closed*,
107 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 here in units of ppt (g/kg solution). Hypersaline environments on Earth have been the subject of significant study in constraining the limits of life (see Text S3). High salinity can impede the functioning of proteins by causing them to precipitate, whereas the high osmotic stress resulting from a high salinity differential between the cell interior and exterior can cause potential dehydration and reduction of the cell volume (Ewert & Deming, 2013; Thomas & Dieckmann, 2002; Ralph et al., 2007). Laboratory studies of hypersaline solutions have demonstrated microbial growth can occur up to the saturation point; however, these limits are composition dependent (Stevens & Cockell, 2020). Despite apparent salinity-based limits for growth, microbial communities have been found to inhabit hypersaline lakes which approach or exceed these conditions (see Text S3).

Ionic strength represents a molality-weighted quantification of solution charge density, expressed in units of mol/kg H₂O 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 MgSO₄ 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, especially at subzero conditions.

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),

140 expressed as the ratio of the vapor pressure of solution to the vapor pressure of pure wa-
141 ter (Grant, 2004) (pure water has a water activity of 1). A majority of microbes can-
142 not multiply below a water activity of 0.9; however, extremophilic species across the three
143 domains of life (Bacteria, Archaea, and Eukarya) are capable of reproducing at water
144 activities as low as ~ 0.6 (Stevenson et al., 2015). In FREZCHEM, water activity is cal-
145 culated using the Pitzer equations, as described in Marion and Kargel (2007). Where
146 brine is in equilibrium with ice, water activity is equivalent to the ratio of water vapor
147 pressure of ice to the water vapor pressure of pure liquid water, and as such is solely a
148 function of temperature and not the composition or concentration of solutes (Koop, 2002).

149 Although these three parameters are intimately linked (see Figure 15.5 in J. Dem-
150 ings and Eicken (2007)), they can vary with composition. As we will demonstrate, brines
151 at identical salinities can exhibit drastically different water activities and ionic strengths
152 if they differ in their major ionic composition. Exploring the implications of brine com-
153 position for habitability thus necessitates considering all three parameters independently.

154 **3 Evaluation of Habitability Metrics in Europa’s Ice Shell**

155 In our evaluation of habitability metrics for Europa’s ice shell, we assume the ana-
156 log endmember ocean compositions of Wolfenbarger, Fox-Powell, et al. (2022). In their
157 model they considered only impurities sourced from the ocean and adopted two endmem-
158 ber ocean compositions: (i) a chloride-dominated composition, analogous to terrestrial
159 seawater, and (ii) a sulfate-dominated composition, analogous to the modeled Europa
160 K1a ocean of Zolotov and Shock (2001). We similarly adopt their linear temperature pro-
161 file, with a surface temperature of -173.15 °C (100 K) and a basal temperature of 0 °C
162 (273.15 K), and assume a fixed pressure of 1 atm to represent an ice shell of arbitrary
163 thickness. Note that neglecting the influence of overburden pressure affects the vertical
164 brine extent (i.e., fraction of total conductive ice layer thickness where brine is thermo-
165 dynamically stable) by less than 1% (Wolfenbarger, Fox-Powell, et al., 2022).

166 Figure 1 presents the water activity, ionic strength, and salinity extracted from FREZCHEM
167 v15.1 for the analog endmember ocean compositions, as well as two binary endmember
168 compositions (NaCl, MgSO₄) for reference. By examining these habitability metrics as
169 a function of brine volume fraction, in addition to temperature, we can study the influ-

170 ence of composition on the characteristics of habitats where the same amount of water
 171 is present.

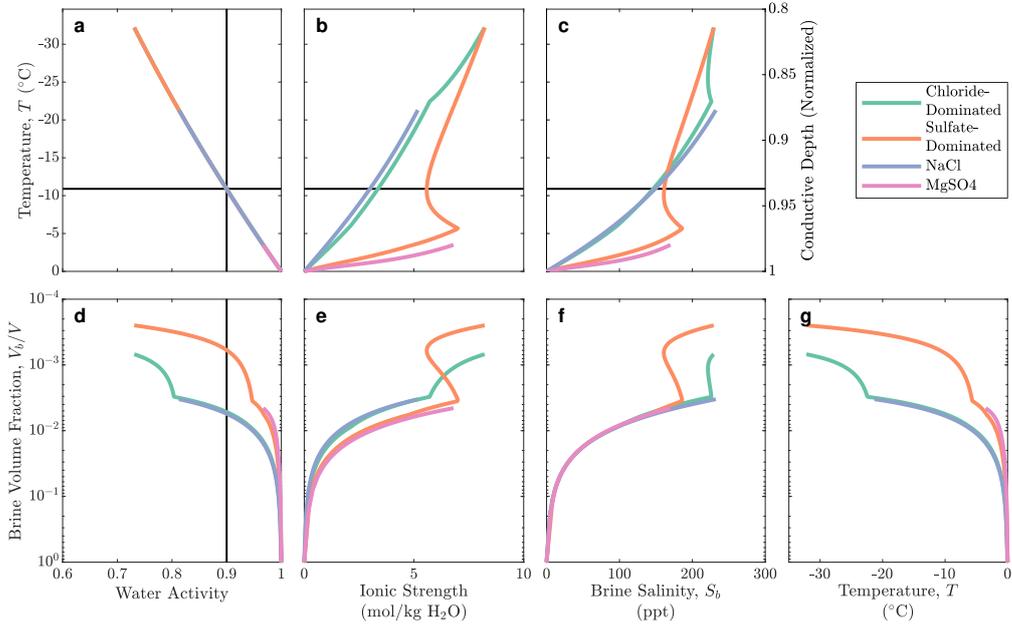


Figure 1. Habitability metrics for brine in the bottom 20% of a thermally conductive European ice shell assuming binary (NaCl, MgSO₄) and analog endmember (chloride-dominated, sulfate-dominated) ocean compositions and a fixed pressure of 1 atm. For **d – g**, brine volume fraction is calculated using the model of Wolfenbarger, Fox-Powell, et al. (2022), assuming a bulk ice salinity of 1 ppt (see Text S4). 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**). Although we assume a linear temperature profile here, because the habitability metrics in **a – c** and **g** are represented as a function of temperature, they could represent any location in the ice shell where these temperatures are relevant. Similarly, although we assume a fixed pressure of 1 atm, accounting for the influence of overburden pressure would shift the curves in **a – c** upwards and **g** to the left (i.e., to lower temperatures).

172 Figure 1a illustrates that for brine in equilibrium with ice, the water activity is a
 173 function of temperature alone (Koop, 2002). However, because the composition of so-
 174 lutes governs the eutectic temperature, this determines the minimum water activity where
 175 brine is in equilibrium with ice. At the ice-ocean interface, the maximum water activ-
 176 ity is governed by the ocean salinity. Importantly, for the endmember compositions as-
 177 sumed here, the water activity does not fall below the current empirical limit of approx-

178 imately 0.6 (Fig. 1a). Extrapolating the curve in Fig. 1a suggests that water activity
179 could fall below 0.6 for an ice shell composition where the eutectic temperature is be-
180 low $-50.6\text{ }^{\circ}\text{C}$ (222.5 K), in agreement with Marion (2002). In the absence of low-eutectic
181 impurities (e.g., sulfuric acid, perchlorates, or ammonia), it is unlikely water activity will
182 be the limiting factor governing the habitability of in-ice brine systems.

183 Figure 1b shows that ionic strength increases as temperature decreases, although
184 following precipitation of meridianiite at $T = -5.7\text{ }^{\circ}\text{C}$ (267.45 K) in the sulfate-dominated
185 case, the ionic strength decreases due to the sink of divalent ions, whereas the ionic strength
186 increases in the chloride-dominated after precipitation of hydrohalite at $T = -22.5\text{ }^{\circ}\text{C}$
187 (250.65 K) due to a sink of monovalent ions. For both analog endmember compositions
188 the ionic strength does not exceed the empirical limit of 10 mol/L.

189 Although water activity has been used as a measure of salinity (see Marion (2002),
190 Marion et al. (2003), and Tosca et al. (2008)), Fig. 1c shows that brine salinity does not
191 increase monotonically as water activity decreases for brine in equilibrium with ice. The
192 precipitation of minerals as the solution freezes causes the salinity to decrease under con-
193 tinued cooling as minerals serve as a sink for dissolved ions. The brine salinity for each
194 analog endmember composition closely follows the salinity of the related binary endmem-
195 ber composition up to the eutectic temperature of the binary composition. As such, the
196 sulfate-dominated composition has a higher salinity than the chloride-dominated com-
197 position at higher temperatures and a lower salinity at lower temperatures. At the eu-
198 tectic, $T_{eut} = -32.2\text{ }^{\circ}\text{C}$ (240.95 K), these two cases share the same salinity.

199 For both compositions, the habitability metrics in Fig. 1 suggest that these brine
200 systems are not inherently prohibitive to life as we know it, although we note that mi-
201 crobial growth in ice on Earth has not been observed below $-20\text{ }^{\circ}\text{C}$ (see Text S5), pos-
202 sibly due to the process of vitrification (glass transition) (Clarke, 2014). Although not
203 geochemically prohibitive to life as we know it, these brines are certainly not considered
204 favorable to most life on Earth, and in general become more extreme as temperatures
205 decrease. Even for a water activity higher than 0.9, which is considered a lower bound
206 water activity for most microbes on Earth (Stevenson et al., 2015), the brine salinity and
207 ionic strength are consistent with those expected of hypersaline environments. Organ-
208 isms that inhabit analogous environments on Earth are classified as halophiles and/or
209 psychrophiles, characterized by growth and reproduction in environments of high salt

210 concentrations (specifically NaCl) and low temperatures, respectively. These results sug-
211 gest that brine salinity and ionic strength—and not water activity—may represent the
212 driving environmental stressors for organisms inhabiting European brine habitats.

213 It has been argued previously that characterizing potential habitats using metrics
214 such as those in Fig. 1 alone may not give proper consideration to complex interactions
215 between these metrics and that certain limits may be organism-specific and/or salt-specific,
216 particularly when these metrics do not fall outside the thermodynamic limits (Stevens
217 & Cockell, 2020). Additionally, the occurrence of multiple extremes can conspire to ei-
218 ther limit or enhance growth, depending on the conditions (Kaye & Baross, 2004). For
219 example, below a water activity of 0.9, the sulfate-dominated case exhibits a significantly
220 higher ionic strength than the chloride-dominated case across the temperature range, un-
221 til very near the eutectic. If ionic strength can interact with water activity to restrict
222 growth, brine habitats formed from the sulfate analog endmember may present greater
223 challenges to habitability (Fox-Powell et al., 2016). If we examine what factors govern
224 the distribution of potential habitats within Earth analog environments, brine volume
225 fraction itself becomes a compelling metric for consideration.

226 **4 Brine Volume Fraction as a Habitability Metric**

227 Fundamentally, brine volume fraction represents a quantification of the potentially
228 habitable space in ice (Thomas et al., 2017). In fact, a study of artificial sea ice revealed
229 that 95% of cells trapped within the ice were contained within brine inclusions (Junge
230 et al., 2001). Retaining brine represents an important survival strategy for organisms
231 inhabiting ice, as evidenced by studies of EPS (Krembs et al., 2011; Ewert & Deming,
232 2011). For example, the net effect of EPS on sea ice is to increase the brine volume frac-
233 tion (Krembs et al., 2011). Ice-binding proteins, glycoproteins, and/or polysaccharides
234 increase the tortuosity of the ice, which in turn retains salt and thus increases the brine
235 volume fraction (Krembs et al., 2011; Ewert & Deming, 2011). Studies of natural saline
236 ice that include both brine volume fraction and cell density profiles illustrate a corre-
237 lation between these two quantities (Uhlig et al., 2018; Buffo et al., 2022), although fur-
238 ther dedicated studies are needed.

239 Because the brine volume fraction of ice represents the governing variable in per-
240 meability models for columnar sea ice (Petrich et al., 2006; Golden et al., 2007), it also

241 represents an important control on nutrient transport (Meiners & Michel, 2017). Even
 242 in glacial ice, where the brine volume fraction can be orders of magnitude lower than sea
 243 ice, nutrient transport through liquid veins at grain boundaries is essential for support-
 244 ing the metabolic activity of in-ice organisms (Price, 2000, 2007). Access to such nutri-
 245 ents is essential for organisms to grow, reproduce, and survive. On Earth, nutrient avail-
 246 ability has been used to identify three distinct groupings of metabolic activity in micro-
 247 bial communities (Price & Sowers, 2004), where a “growth” metabolism implies unlim-
 248 ited access to nutrients, a “maintenance” metabolism implies nutrient levels are too low
 249 for growth, and a “survival” metabolism implies nutrient levels can only support repair-
 250 ing damage (Price, 2009). Inspired by these groupings based on nutrient accessibility,
 251 we define three classes of potential habitats: (i) *nutrient-open* potential habitats char-
 252 acterized by “growth”, (ii) *nutrient-closed* potential habitats, characterized by “main-
 253 tenance” and “survival”, and (iii) *relict* potential habitats, characterized by an absence
 254 of viable microorganisms.

255 5 Classification of Brine Pocket Habitats

256 In our model of Europa’s ice shell, we assume that the ice shell retains the colum-
 257 nar crystal structure originating from directional freezing of the ocean (Fig. 3d). This
 258 simplifying assumption is validated by studies of the microstructure of sea ice which sug-
 259 gest that in the absence of warming, ice can retain its original grain boundaries (Zotikov
 260 et al., 1980; Maus, 2020). Because the ice forms with a columnar texture, it is subject
 261 to a percolation threshold at some critical porosity, ϕ_c (Maus et al., 2021). Where the
 262 brine volume fraction is higher than this critical porosity, convective overturning of brine
 263 can occur within the ice and transport oceanic material, including nutrients, into the icy
 264 interior (Meiners & Michel, 2017). To define the region where nutrient replenishment can
 265 operate efficiently and support *nutrient-open* potential habitats, we adopt $\phi_c = 0.06$.
 266 This value corresponds to the effective critical porosity derived by Wolfenbarger, Fox-
 267 Powell, et al. (2022) from ice which formed at the base of the Ross Ice Shelf (Zotikov et
 268 al., 1980), under growth conditions that could approach those expected at Europa (Wolfenbarger,
 269 Buffo, et al., 2022).

270 Nutrient transport could still operate at brine volume fractions below this effec-
 271 tive critical porosity—albeit less efficiently—since the ice may not be completely imper-
 272 meable. Measurements of the dihedral angles for partially molten ice binary systems have

273 shown that, in general, values are below 60° , indicating that melt is not confined to triple
 274 junctions and should be mobile along ice grain boundaries (McCarthy et al., 2019). These
 275 measurements suggest that ice in textural equilibrium should be permeable even at very
 276 low brine volume fractions and nutrient transport could be permissible at temperatures
 277 down to the eutectic. This property has been used previously to justify the transport
 278 of oxidants through Europa’s ice shell via porosity waves (Hesse et al., 2022); however,
 279 we note that sea ice does not possess an equilibrium texture (e.g., Junge et al., 2001, 2004;
 280 Moore et al., 1994). We thus designate the region of the ice shell where the brine vol-
 281 ume fraction is less than 0.06 but water is still stable as *nutrient-closed* potential habi-
 282 tats. Here, metabolic activity is still possible, but organisms are nutrient-limited and thus
 283 have limited potential to grow and reproduce.

284 In contrast, given that by our definition the entire ice shell was once innately *nutrient-*
 285 *open* (i.e., froze from an ocean and thus evolved from a brine volume fraction of unity
 286 to zero), we designate the region of the ice shell where the brine volume fraction is zero
 287 as *relict* potential habitats. Where liquid water is no longer stable within the ice shell,
 288 we consider organisms that were once inhabiting the interstices of ice crystals to be in
 289 a nonviable state (i.e., unable to metabolize). However, premelting (the formation of quasi-
 290 liquid layers, see Slater and Michaelides (2019) for a review), and/or supercooling (see
 291 Toner et al. (2014) and Primm et al. (2017)) could extend the vertical extent of *nutrient-*
 292 *closed* potential habitats to temperatures below the eutectic. EPS, if present, could de-
 293 press the eutectic temperature by inhibiting salt and ice crystallization (Izutsu et al., 1995).
 294 Rohde and Price (2007) demonstrated that diffusion of nutrients through the ice crys-
 295 tal structure itself could occur; however, the absence of liquid water could prevent up-
 296 take of those nutrients by a cell membrane, assuming the membrane is intact and still
 297 fluid enough to enable transport (Clarke, 2014).

298 **6 Potential Habitats in Europa’s Ice Shell**

299 Figure 2 shows the brine volume fraction, V_b/V , for Europa’s ice shell considering
 300 a range of bulk salinities up to 100 ppt, adapted from Wolfenbarger, Fox-Powell, et al.
 301 (2022) (see Section 3 for model assumptions). Our proposed classification indicates that
 302 $\sim 80\%$ of the ice shell corresponds to *relict* potential habitats, since brine is not ther-
 303 modynamically stable for temperatures below the shared eutectic of $T = -32.2^\circ\text{C}$ (240.95
 304 K). To establish where *nutrient-open* and *nutrient-closed* potential habitats could be sta-

305 ble, we must identify where the brine volume fraction exceeds our effective critical poros-
 306 ity of 0.06.

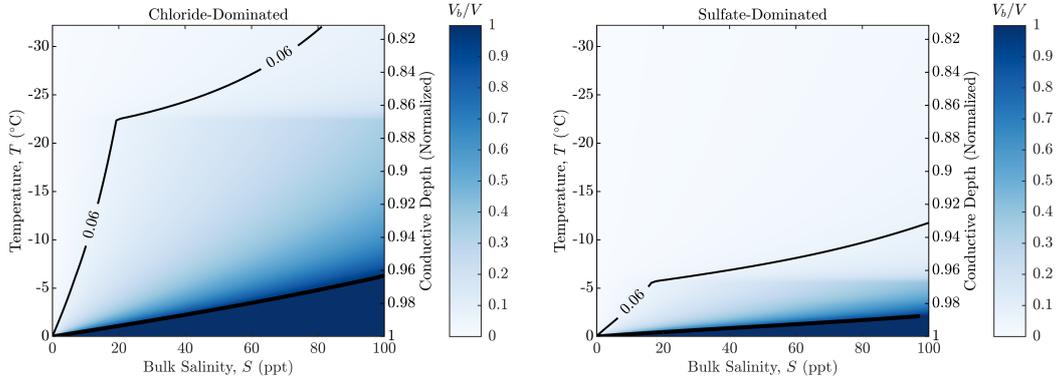


Figure 2. Brine volume fraction for Europa’s ice shell assuming analog endmember compositions for the ocean and an ice shell of arbitrary thickness (assuming a fixed pressure of 1 atm), adapted from Wolfenbarger, Fox-Powell, et al. (2022). The 0.06 contour depicts the temperature and bulk salinity where the brine volume fraction equals our effective critical porosity. The thick black curve represents the freezing temperature as a function of ocean salinity (i.e., the temperature at the ice-ocean interface). Note that because the domain is truncated to a bulk salinity of 100 ppt, this curve does not represent the brine salinity for the full temperature range, which is shown in Fig. 1c.

307 **6.1 Maximum Vertical Extent of *Nutrient-Open* Potential Habitats**

308 The contours in Fig. 2 represent the lowest temperature where the brine volume
 309 fraction is greater than the effective critical porosity of 0.06 for a given bulk ice salin-
 310 ity, and thus define the upper boundary where *nutrient-open* potential habitats are sta-
 311 ble in a conductive ice shell. The thick black curves in Fig. 2 represent the freezing tem-
 312 perature as a function of ocean salinity (i.e., the temperature at the ice-ocean interface),
 313 and thus define the lower boundary of the vertical region where *nutrient-open* potential
 314 habitats within the ice are stable. Defining this curve as the lower boundary ensures that
 315 the bulk salinity of the ice shell does not exceed that of the underlying ocean.

316 Consequently the region bounded by the two curves in Fig. 2 represents the ex-
 317 treme case where bulk ice shell salinity is equal to the underlying ocean salinity and thus
 318 represents a maximum estimate for the vertical extent of *nutrient-open* potential habi-

319 tats (Fig. S1). For both compositions considered, the maximum vertical extent of *nutrient-*
320 *open* potential habitats generally increases with salinity. The chloride-dominated ice shell
321 is capable of supporting a much larger vertical extent of *nutrient-open* potential habi-
322 tats, due to having a higher volume fraction of brine stable for a given bulk ice salinity
323 and temperature than the sulfate-dominated ice shell.

324 **6.2 Limitations on the Vertical Extent of *Nutrient-Open* Habitats due** 325 **to Brine Drainage**

326 An important consequence of designating *nutrient-open* habitats as locations where
327 the brine volume fraction exceeds a percolation threshold is that they are only stable if
328 brine is actively draining. For Europa's ice shell, this corresponds to locations of active
329 freezing (i.e., where the ice shell is in the processes of desalinating). Recall that the re-
330 gion bounded by the curves in Fig. 2 specifically represents the case where the bulk ice
331 shell salinity is equivalent to the underlying ocean salinity. Practically, this assumption
332 is not realistic because the ice will be in a state of progressive desalination due to the
333 unstable brine density gradient in the region where *nutrient-open* habitats are present.
334 Ultimately, this process will limit the stable bulk ice shell salinity to a fraction of the un-
335 derlying ocean salinity (Wolfenbarger, Buffo, et al., 2022; Wolfenbarger, Fox-Powell, et
336 al., 2022). Thus, the true vertical distribution of *nutrient-open* habitats in a conductive
337 ice shell is governed by the fraction that is in an active state of desalination, where brine
338 convection is occurring within the ice (i.e., the equilibrium mushy layer of Buffo et al.
339 (2021)).

340 Estimates of equilibrium mushy layer thickness applied to Europa, assuming a range
341 of ice shell thicknesses and ocean salinities (see Buffo et al. (2021) and Text S6/Fig. S2,
342 respectively), imply that *nutrient-open* habitats in Europa's ice shell are likely at most
343 only meters thick when accounting for the role of brine drainage in governing the sta-
344 ble bulk ice shell salinity. As such the majority of the ice shell where brine is thermo-
345 dynamically stable will likely be characterized by *nutrient-closed* habitats. We note that
346 the model of Buffo et al. (2021) represents the case of natural convection. Forced con-
347 vection, driven by tides or sub-ice currents (see Soderlund et al. (2020) for a review), might
348 increase the vertical extent of *nutrient-open* habitats, similar to sea ice on Earth (Arrigo
349 & Thomas, 2004).

6.3 Extensions on the Vertical Extent of *Nutrient-Open* Habitats

Recall that our classification scheme assumes that brine convection represents the only mechanism of nutrient transport that could support *nutrient-open* 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 *nutrient-closed* habitats could be reclassified as *nutrient-open* habitats. Hypothesized exchange processes that could transport oceanic nutrients include ocean-injection of sills via fracturing (Michaut & Manga, 2014), diapirism (R. T. Pappalardo & Barr, 2004), 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 that 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 *nutrient-open* or *nutrient-closed* potential habitats. To rigorously quantify the distribution of potential *nutrient-open* 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 *Nutrient-Closed* and *Relict* Potential Habitats for Biosignatures

Although *nutrient-open* habitats are compelling targets in the search for life beyond Earth, *nutrient-closed* 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 *nutrient-closed* 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 *nutrient-closed* and *relict* potential habitats at Europa is ancient glacial ice on Earth. Glacial ice samples (some

381 estimated to be up to 8 Myr old) have been discovered to harbor both viable and non-
382 viable microorganisms, frozen into the ice at the time of formation (Christner et al., 2003;
383 Ma et al., 1999; Knowlton et al., 2013; Bidle et al., 2007). Although neither environment
384 discussed here is a perfect analog for potential habitats at Europa, organisms are clearly
385 capable of prolonged survival in environments analogous to brine pockets in an ice shell
386 (Bradley et al., 2019). Beyond survival, the ubiquity of ancient biologic material in ter-
387 restrial ice bodes well for biosignature preservation in *relict* potential habitats at Europa
388 (Castello et al., 2005).

389 7 Conclusions

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

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

405 We found that $\sim 80\%$ of a conductive European ice shell is characterized by *relict*
406 potential habitats, $\sim 20\%$ is characterized by *nutrient-closed* potential habitats, and *nutrient-*
407 *open* potential habitats are confined to a few meters of an ice-ocean interface, where the
408 ice shell is actively freezing (Fig. 3). Extending our results to an ice shell where solid
409 state convection is occurring, we argue that a convective ice layer—shown by Kalousová
410 et al. (2017) to be on the order of half the total ice shell thickness—could represent the
411 most extensive potential habitat in Europa’s ice shell, where efficiency of nutrient ex-

412 change will govern whether brine pockets are *nutrient-open* or *nutrient-closed* potential
413 habitats.

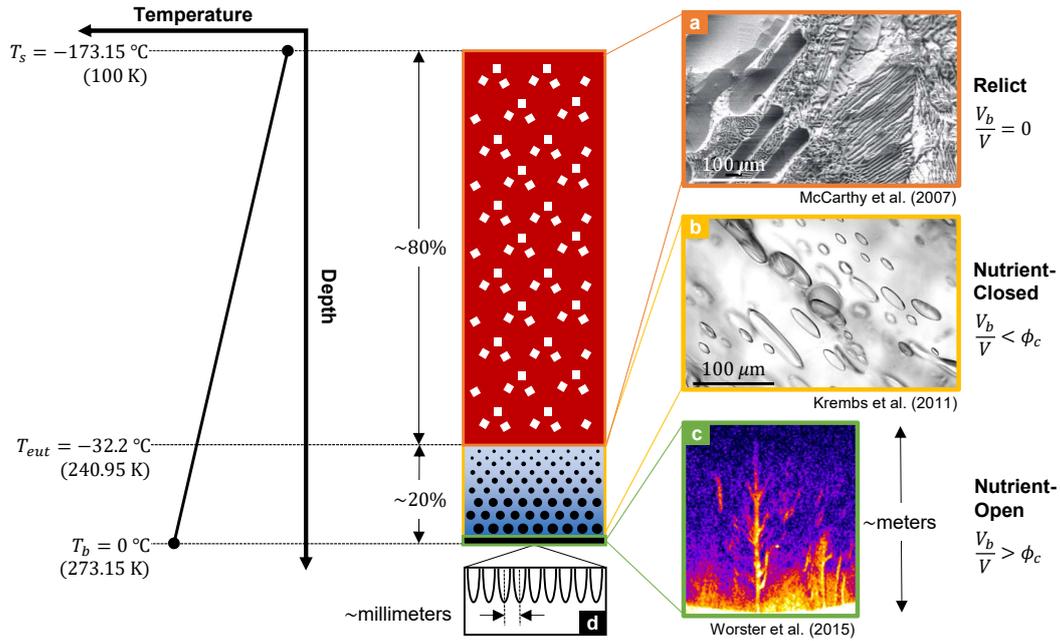


Figure 3. Classification of potential habitats in Europa’s ice shell based on brine volume fraction, V_b/V , for the thermal profile assumed in this work. For brine volume fractions greater than the effective critical porosity, ϕ_c , convective overturning of brine can occur within the ice and transport oceanic material, including nutrients, into the interior to support *nutrient-open* potential habitats. At lower brine volume fractions, metabolic activity is still possible; however, organisms inhabiting these *nutrient-closed* 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 that 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 ($\phi_c = 0.06$).

414 Identifying where *nutrient-open*, *nutrient-closed*, and *relict* potential habitats could
415 exist in Europa’s ice shell can guide future life-detection missions, such as a Europa Lan-
416 der (R. Pappalardo et al., 2013). Our study demonstrates that *relict* potential habitats
417 represent the most accessible targets for future missions to sample biosignatures at Eu-
418 ropa. For missions where the goal is to detect potentially viable microorganisms *in situ*,
419 a cryobot would be necessary to access depths where *nutrient-closed* potential habitats
420 are stable (Zimmerman et al., 2001). Notably, this would not require penetrating the full
421 ice shell thickness to access the ice-ocean interface. However, for the impurity compo-
422 sitions and thermal profile considered here, accessing these depths for a 10 km ice shell
423 would require penetrating ~ 8 km of ice—almost double the thickest ice on Earth (Fretwell
424 et al., 2013). In the case of a convective ice shell, descending through half the total ice
425 shell thickness could be sufficient to reach *nutrient-closed* potential habitats (Kalousová
426 et al., 2017). Beyond Europa, this classification scheme could be invaluable for guiding
427 future life-detection missions to other icy ocean worlds such as Enceladus or Titan.

428 **Open Research**

429 The code base used to generate Figures 1, 2 and S2 is preserved at nwolfenb (2022)
430 and licensed under the GNU General Public License v3.0.

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