Supporting Information for "The Habitability of Brine Pockets in Europa's Ice Shell"

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Introduction The supplementary materials include text to provide background for certain assumptions (Text S1 on the scale of brine pockets in Europa's ice shell, Text S2 on neglecting chaotropicity, Text S3 on stable bulk ice salinity, and Text S4 on calculation of mushy layer thickness using FREZCHEM) as well as two figures which serve as additional support for our conclusions (Figure S1 for the maximum vertical extent of *active* potential habitats in Europa's ice shell and Figure S2 for constraints on the vertical extent of *active* potential habitats in Europa's ice shell from mushy layer theory).

Text S1. The Scale of Brine Pockets in Europa's Ice Shell

We expect the incorporation of oceanic material in the ice shell to produce sub-millimeter-scale pockets, where the scale will decrease with temperature as brine volume fraction decreases. The scale of these brine pockets at the ice-ocean interface is likely controlled by the plate spacing of columnar crystals which form at the ice-ocean interface and entrap brine (Maus, 2020). Sea ice brine pockets are typically millimeter-scale; however, the slower growth velocities expected for Europa's ice shell will influence the microstructural interface morphology (Wolfenbarger, Buffo, et al., 2022). Extrapolation of relationships modeling plate spacing as a function of ice growth velocity suggests the scale could approach one centimeter, assuming the lower bound estimates of ice shell growth velocities at Europa (Maus, 2020; Wolfenbarger, Buffo, et al., 2022). The plate spacing associated with the J-9 Ross Ice Shelf core, an ice core which could sample growth conditions approaching those expected at Europa (Wolfenbarger, Buffo, et al., 2022), was approximately 5 mm (Maus, 2020).

Text S2. Neglecting Chaotropicity

While chaotropicity (a measure of the *destabilizing* nature of a solute to macromolecules) is known to stress cells and limit the habitability of brine systems (Hallsworth et al., 2003, 2007; Fox-Powell et al., 2016), we do not consider its role as a habitability metric here for the following reasons: (i) it is an experimentally-derived quantity that cannot currently be modeled (Cray et al., 2013), (ii) organisms have been found inhabiting highly chaotropic environments on Earth, challenging existing limits (Yakimov et al., 2015; Cubillos et al., 2019), and (iii) certain organisms synthesize and/or accumulate chaotropes in response to low temperatures to support growth (Chin et al., 2010). We note that for both of our analog endmember compositions for Europa's ocean/ice shell, the brine becomes progressively more chlorine-rich as freezing progresses. This suggests the brine could become more chaotropic as temperature decreases and kosmotropic solutes (a measure of the *stabilizing* nature of a solute to macromolecules), like sulfate salts, precipitate out of solution; however, this also depends on the specific composition of associated cations. For example, NaCl brines are mildly kosmotropic whereas $MgCl_2$ brines are highly chaotropic (Lee et al., 2018; Hallsworth et al., 2007).

Text S3. Stable Bulk Ice Salinity

For simulating the brine volume fraction in Fig. 1d – f, we adopt 1 ppt as a representative stable bulk ice salinity. This bulk ice salinity would imply an ocean salinity of 14.9 ppt, using the equilibrium solute distribution coefficient of 0.067 ($k_{eq} = S_{ice}/S_{ocean}$) derived by Wolfenbarger, Buffo, et al. (2022). We note that this ocean salinity is on the order of that predicted by Zolotov and Shock (2001) for Europa's ocean (12.1 ppt) and compatible with the range of possible ocean salinities derived from *Galileo* magnetometer data (Wolfenbarger, Buffo, et al., 2022).

Text S4. Calculation of the Equilibrium Mushy Layer Thickness using FREZCHEM

To calculate the equilibrium mushy layer thickness for our analog endmember compositions we follow the approach of Buffo, Schmidt, Huber, and Meyer (2021). Instead of adopting their parameterizations for brine density and salinity, we use relationships derived from FREZCHEM v15.1. For a 10 km ice shell subject to a percolation threshold of $\phi_c = 0.06$, our estimate for mushy layer thickness for the Cl-dominated composition is slightly lower than that obtained from the approach of Buffo et al. (2021) (1.66 m vs 2.06 m, respectively). We note that there is a verified (but minor) bug in the code used to generate the figures in Buffo et al. (2021) that causes the equilibrium mushy layer thickness to be slightly underestimated (approximately 1 m vs. 2.73 m for a 10 km Europan ice shell, 34 ppt ocean, and surface temperature of 100 K). We use a corrected implementation of their code where the bug is fixed. Figure S2 presents a comparison of our equilibrium mushy layer thicknesses to that predicted by the approach of Buffo et al. (2021) (a), including a comparison of modeled freezing temperature (b) and difference in brine density relative to that of the ocean (c). The brine density difference shown in Fig. S2c suggest that the density contrast predicted by the parameterization of Buffo et al. (2021) could be an underestimate, which would produce a larger equilibrium mushy layer thickness than we obtained here. Although the equilibrium mushy layer thickness is almost a factor of two difference between the two assumed analog endmember compositions, these estimates are on the order of meters for a range of possible ocean salinities. This analysis supports our conclusion that *active* potential habitats in a conductive ice shell are likely only meters thick, regardless of the assumed ocean salinity and composition.

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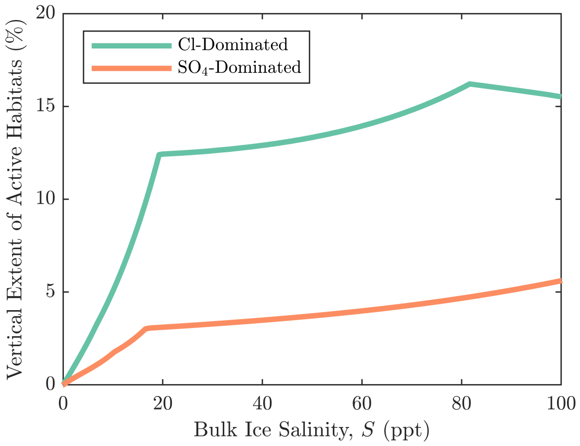

Figure S1. Maximum vertical extent of *active* potential habitats in Europa's ice shell derived from Fig. 2, expressed as a percentage of the total conductive ice shell thickness. The bulk ice salinity is assumed equal to the underlying ocean salinity to obtain an estimate corresponding to the maximum. Note that we calculate the percentage using temperature as a proxy for ice shell depth and thickness, where temperature at the ice-ocean interface is determined by the ocean salinity. Although this estimate assumes a fixed pressure of 1 atm, introducing a pressure-dependence affects the results by less than 1% for a range of possible ice shell thicknesses (Wolfenbarger, Fox-Powell, et al., 2022).

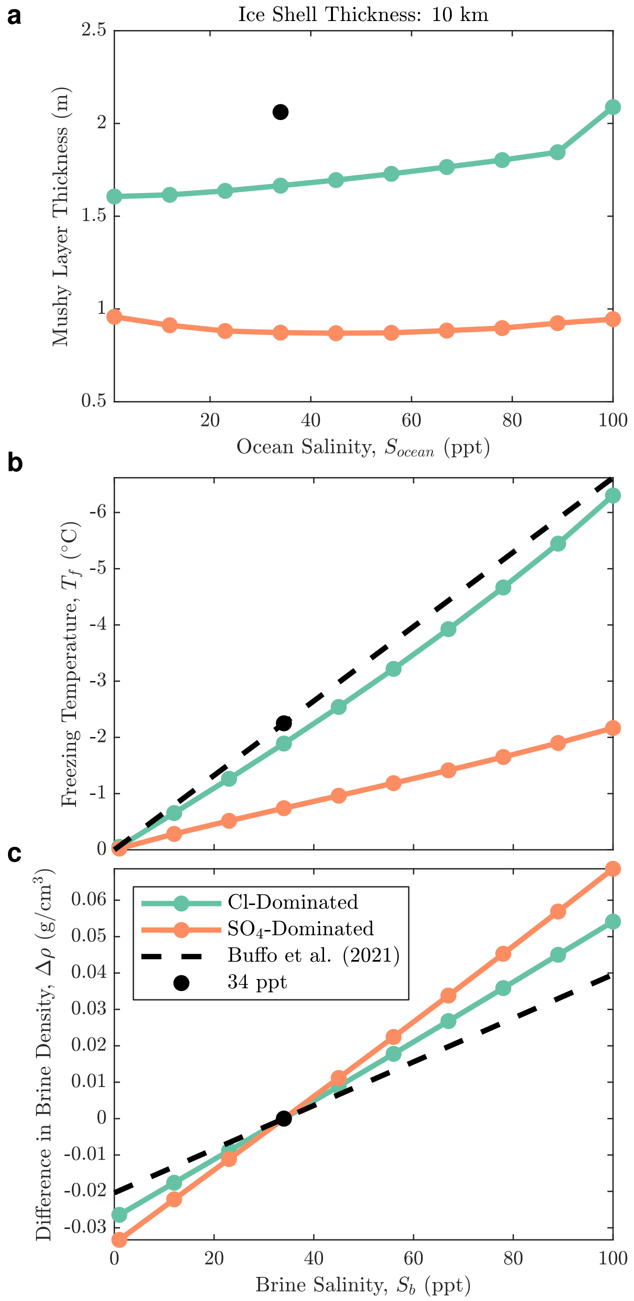

Figure S2. Constraints on the vertical extent of *active* potential habitats in a 10 km thermally conductive Europan ice shell from mushy layer theory, assuming $\phi_c = 0.06$. Mushy layer thickness (a) as a function of ocean salinity and brine properties (b,c) as a function of brine salinity for our two analog endmember compositions. The black dots represent values for an ocean salinity of 34 ppt derived using the approach of Buffo et al. (2021) (but changing $\phi_c = 0.05$ to $\phi_c = 0.06$) and the black dashed lines represent their parameterizations of brine properties. Note that the difference in brine density is expressed relative to an ocean salinity of 34 ppt to be directly comparable to Buffo et al. (2021).