

1 **Geometry of Freezing Impacts Ice Composition: Implications for Icy Satellites**

2 **J. J. Buffo<sup>1</sup>, C. R. Meyer<sup>1</sup>, C. J. Chivers<sup>2,3</sup>, C. C. Walker<sup>3</sup>, C. Huber<sup>4</sup> and B. E. Schmidt<sup>5</sup>**

3 1 – Dartmouth College, 2 – Georgia Institute of Technology, 3 – Woods Hole Oceanographic Institution, 4 – Brown  
4 University, 5 – Cornell University

5  
6 **Key Points**

- 7 • When a brine freezes the direction of solidification affects the structure and composition  
8 of the resulting ice  
9 • Ice formation at sill floors and fracture walls provide a mechanism for heterogeneous and  
10 amplified impurity entrainment in planetary ice shells  
11 • Cryoconcentration of impurities in freezing intrashell hydrological features can impact ice  
12 shell material properties, geophysics, and habitability

13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47

48 **Abstract**

49 Non-ice impurities within the ice shells of ocean worlds (e.g., Europa, Enceladus, Titan) are  
50 believed to play a fundamental role in their geophysics and habitability and may become a surface  
51 expression of subsurface ocean properties. Heterogeneous entrainment and distribution of  
52 impurities within planetary ice shells have been proposed as mechanisms that can drive ice shell  
53 overturn, generate diverse geological features, and facilitate ocean-surface material transport  
54 critical for maintaining a habitable subsurface ocean. However, current models of ice shell  
55 composition suggest that impurity rejection at the ice-ocean interface of thick contemporary ice  
56 shells will be exceptionally efficient, resulting in relatively pure, homogeneous ice. As such,  
57 additional mechanisms capable of facilitating enhanced and heterogeneous impurity entrainment  
58 are needed to reconcile the observed physicochemical diversity of planetary ice shells. Here we  
59 investigate the potential for hydrologic features within planetary ice shells (sills and basal  
60 fractures), and the unique freezing geometries they promote, to provide such a mechanism. By  
61 simulating the two-dimensional thermal and physicochemical evolution of these hydrological  
62 features as they solidify, we demonstrate that bottom-up solidification at sill floors and horizontal  
63 solidification at fracture walls generate distinct ice compositions and provide mechanisms for both  
64 enhanced and heterogeneous impurity entrainment. We compare our results with magmatic and  
65 metallurgic analogs that exhibit similar micro- and macroscale chemical zonation patterns during  
66 solidification. Our results suggest variations in ice-ocean/brine interface geometry could play a  
67 fundamental role in introducing compositional heterogeneities into planetary ice shells and  
68 cryoconcentrating impurities in (re)frozen hydrologic features.

69

70 **Plain Language Summary**

71 The ice shells of ocean worlds are not pure water ice but contain significant amounts of salts and  
72 other ocean-derived impurities. These impurities are believed to play an important role in  
73 governing the material properties, evolution, and habitability of planetary ices. Furthermore,  
74 linking observations of impurity distributions on ice shell surfaces to interior properties and  
75 processes (e.g., ocean composition) is a fundamental pillar in our understanding of ice-ocean  
76 worlds. That said, material entrainment at the ice-ocean interfaces of thick ice shells will be  
77 inefficient, leading to relatively pure ice, and necessitating an explanation for how the  
78 compositional heterogeneities observed in ice shells are introduced. Here we explore a possible  
79 solution: the freezing of water bodies within ice shells that have solidification interfaces which  
80 propagate vertically upward (sill floors) and horizontally (fracture walls). We find that these  
81 solidification geometries facilitate enhanced and heterogeneous impurity entrainment. Our results  
82 suggest the solidification of saline water bodies within ice shells could play a key role in explaining  
83 the compositional diversity observed on ice-ocean world surfaces and that constraining the  
84 dynamics that govern these ice-brine systems will be critical in linking spacecraft measurements  
85 of planetary ice compositions to the properties of subsurface water reservoirs.

86

87

88

89

90

91

92

93

## 94 1. Introduction

95 Many high-priority ice-ocean worlds in our solar system possess geologically rich surfaces  
96 indicative of ongoing geophysical activity within their ice shells and potential ocean-surface  
97 interactions (e.g., fractures [*Craft et al.*, 2016; *Figueredo and Greeley*, 2004; *Nimmo and Schenk*,  
98 2006; *Walker et al.*, 2014], plumes [*Matson et al.*, 2007; *Sparks et al.*, 2016; *Waite et al.*, 2006],  
99 chaos terrain [*Greenberg et al.*, 1999; *Schmidt et al.*, 2011], dilational bands [*Carr et al.*, 1998;  
100 *Fagents et al.*, 2000; *Howell and Pappalardo*, 2018; *Manga and Sinton*, 2004], cryohydrologic  
101 features [*Chivers et al.*, 2021; *Kalousová et al.*, 2014; *Manga and Michaut*, 2017; *Michaut and*  
102 *Manga*, 2014; *Quick et al.*, 2019]). Ongoing activity and associated material transport (e.g., [*Allu*  
103 *Peddinti and McNamara*, 2015; *Postberg et al.*, 2011]) have important implications for the  
104 geophysics [*Buffo et al.*, 2021b], habitability [*Vance et al.*, 2016; *Vance et al.*, 2020], and remote  
105 observation [*Culha et al.*, 2020; *Kalousova et al.*, 2017; *Schroeder et al.*, 2016; *Trumbo et al.*,  
106 2019] of ice-ocean worlds and suggests planetary ice shells exhibit a wide array of  
107 spatiotemporally variable activity levels and geodynamic processes. Advection and diffusion of  
108 energy and mass (e.g., heat, salt, and other ocean-derived material) will govern the dynamic  
109 evolution of planetary ice shells and any intrashell hydrologic/geophysical structures contained  
110 therein (e.g., lenses, dikes, sills, fractures, convection-conduction boundaries, compositional  
111 heterogeneities) [*Buffo et al.*, 2021b]. The thermochemical properties of planetary ice shells will  
112 influence a myriad of important material/environmental characteristics, including but not limited  
113 to phase structure [*Buffo et al.*, 2021a; *Buffo*, 2019; *Buffo et al.*, 2021b], rheology [*Durham et al.*,  
114 2005; *McCarthy et al.*, 2011], dielectric properties [*Kalousova et al.*, 2017; *Moore*, 2000;  
115 *Schroeder et al.*, 2016], density [*Barr and McKinnon*, 2007; *Han and Showman*, 2005; *Kalousová*  
116 *et al.*, 2018; *Pappalardo and Barr*, 2004], water activity [*Buffo et al.*, 2022; *Fox-Powell et al.*,  
117 2016; *Hallsworth et al.*, 2007], and melting point [*McCarthy et al.*, 2013; *McCarthy et al.*, 2011;  
118 *Toner et al.*, 2014]. The transport of ocean-derived reductants and surface-derived oxidants across  
119 ice shells (via fractures, plumes, subduction/subsumption, or solid-state convection) has been  
120 suggested as a mechanism that could facilitate disequibrated ocean chemistries and support redox  
121 driven metabolism [*Allu Peddinti and McNamara*, 2015; *Vance et al.*, 2016; *Vance et al.*, 2020].  
122 Our current and near future understanding of icy world interiors is fundamentally dependent on  
123 remote sensing measurements and our ability to relate these observations to internal dynamics and  
124 properties (e.g., inferring ocean composition/habitability, determining instrument detection limits,  
125 quantifying putative biosignature expression) [*Bryson et al.*, 2020; *Gleeson et al.*, 2012; *Kalousova*  
126 *et al.*, 2017; *Schmidt*, 2020; *Schmidt and Buffo*, 2017; *Schroeder et al.*, 2016].

127 A crucial, yet underconstrained feature broadly impacting nearly all characteristics,  
128 properties, and dynamics of planetary ice shells is their physicochemical heterogeneity [*Buffo et*  
129 *al.*, 2020; *Buffo et al.*, 2021b; *Vance et al.*, 2020]. Numerous numerical models and theoretical  
130 studies implement vertical or lateral variations in ice shell porosity, chemistry, liquid fraction, and  
131 material properties to generate results consistent with several observed and inferred icy world  
132 geophysical processes (e.g., subduction/subsumption [*Johnson et al.*, 2017], solid state convection  
133 [*Han and Showman*, 2005], diapirism [*Pappalardo and Barr*, 2004], eutectic melting and the  
134 generation of perched hydrological features [*Schmidt et al.*, 2011], ocean-surface material  
135 transport [*Hesse et al.*, 2019; *Vance et al.*, 2020], liquid water stability [*Chivers et al.*, 2021],  
136 tectonic feature generation [*Howell and Pappalardo*, 2018]). Numerous studies have analogized  
137 the crucial role impurities play in terrestrial geophysics [*Buffo et al.*, 2020; *Buffo*, 2019; *Buffo et*  
138 *al.*, 2021b; *Stiefel et al.*, 2005] and the stratigraphies of many planetary ice shells are thought to  
139 mirror that of Earth's lithosphere-mantle system (i.e., a brittle ice lithosphere overriding a ductile

140 ice mantle) [Nimmo and Pappalardo, 2016; Sotin and Tobie, 2004]. Other studies highlight the  
141 profound importance of planetary ice shell composition and phase structure to the performance  
142 and efficacy of mission instruments (e.g., ice penetrating radar) and the interpretation of their data  
143 products [Kalousova et al., 2017; Moore, 2000; Schroeder et al., 2016]. Consequently, authors  
144 have long emphasized the important role impurities and physicochemical heterogeneities likely  
145 play in the dynamics, evolution, and habitability of ice-ocean worlds. For example, in their  
146 commentary on Buffo et al. [2020], Vance et al. [2020] discuss at length the specific role of salts  
147 and other ocean-derived impurities in governing icy world surface geology, the geophysics of  
148 planetary ice shells composed of both ice Ih and high pressure ices, ocean world habitability, life  
149 detection, and spacecraft observation interpretation. Nevertheless, we are only beginning to place  
150 physically realistic constraints on the impurity content and physicochemical heterogeneity of  
151 planetary ices and ice shells [Buffo et al., 2020; Buffo et al., 2021b; Hammond et al., 2018].

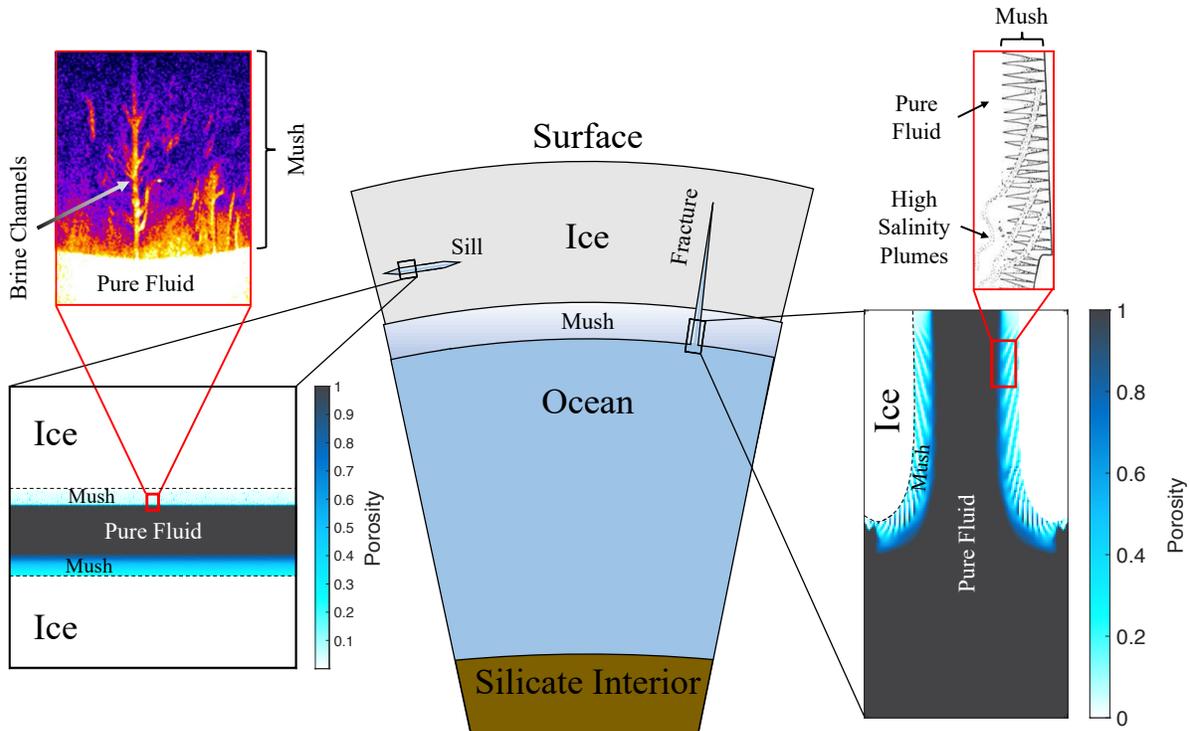
152 A fundamental component in accurately simulating ocean- or brine-derived planetary ices  
153 is the ability to simulate the complex multiphase dynamics that occur at ice-ocean/brine interfaces  
154 [Feltham et al., 2006; Hunke et al., 2011]. Typically characterized by porous brine-saturated ice,  
155 these dynamic interfacial layers play a disproportionate role in governing heat and material  
156 transport between ice and liquid reservoirs, as the interstitial hydrology, thermodynamics, and  
157 geochemistry of these complex regions ultimately dictate the level of impurity entrainment in, and  
158 thus physicochemical composition of, the adjacent ice [Buffo et al., 2020; Buffo, 2019; Buffo et  
159 al., 2021b; Feltham et al., 2006; Hunke et al., 2011]. This has been observed in both laboratory  
160 settings and naturally occurring ice-ocean/brine systems (e.g., sea ice, hypersaline lake ice)  
161 [Cottier et al., 1999; Cox and Weeks, 1974; Eicken, 1992; Nakawo and Sinha, 1981; Worster and  
162 Rees Jones, 2015]. The physics of multiphase reactive transport theory have been shown to  
163 successfully capture the dynamics and evolution of ice-ocean and ice-brine systems and are a staple  
164 of the most accurate high-resolution sea ice models (e.g., [Parkinson, 2019; Parkinson et al.,  
165 2020b; Wells et al., 2019]). Accordingly, state of the art planetary ice models have adopted and  
166 integrated the physics of multiphase reactive transport theory, to varying degrees of complexity,  
167 into their architectures. Buffo et al. [2020] and Hammond et al. [2018] independently designed  
168 one-dimensional reactive transport models to simulate the first order physicochemical composition  
169 of the ice shells of Europa and Triton, respectively. Other studies (e.g., [Kalousova and Sotin,  
170 2020; Kalousova et al., 2018; Kalousova et al., 2014; 2016; Sotin et al., 2002]) have designed  
171 and/or employed one- and two-dimensional multiphase transport models to simulate the generation  
172 and flow of meltwater in icy satellite shells, however these models do not include impurities (e.g.  
173 salts). To our knowledge, there are currently only two models that simulate two-dimensional  
174 multiphase reactive transport processes in planetary ices, those of Buffo et al. [2021b] and Hesse  
175 et al. [2019], who simulate the 2D physicochemical evolution of solidifying planetary ice shells  
176 and oxidant delivery through Europa's ice shell via porosity waves, respectively. These two studies  
177 provide the first steps in realizing the likely complex, dynamic, and heterogenous nature of  
178 geophysically active planetary ice shells. Currently, however, both investigations have only  
179 explored simplified planar ice geometries subject to unidirectional temperature gradients (cold  
180 upper boundary, warm lower boundary), limiting our understanding to relatively idealized  
181 systems.

182 The need to reconcile multiphase reactive transport processes at ice-ocean/brine interfaces  
183 with the potentially complex geometry of geophysical structures within the ice shells of ocean  
184 worlds is exemplified by Chivers et al. [2021] who simulate the two-dimensional physical and  
185 thermochemical evolution of solidifying perched water lenses within Europa's ice shell. As the

186 lenses freeze inward, they entrain salt heterogeneously, leaving behind a chemically complex  
187 structure that will have distinct and gradated material properties (melting point, dielectric  
188 signatures, density, rheology, etc.). This is due to variations in the thermal gradients experienced  
189 by different portions of the chamber’s walls (larger thermal gradients entrain more salt) as well as  
190 the geometry of the system. *Chivers et al.* [2021] assume no interstitial brine drainage, and thus  
191 one hundred percent retention of salt, for chamber walls that are solidifying upward – consistent  
192 with the physics that govern the retention of buoyant melt in the multiphase roofs of terrestrial  
193 magma chambers [*Huppert*, 1990; *Worster et al.*, 1990]. While *Chivers et al.* [2021] have  
194 parameterized salt entrainment as a function of thermal gradient, and therefore do not simulate  
195 fluid transport explicitly, they highlight the immense importance geometry and heterogeneous  
196 structure within planetary ice shells will likely play in their geochemical and geophysical  
197 evolution. Moreover, their study emphasizes the need to constrain the dynamics of multiphase  
198 interfacial layers in thermally and geometrically complex ice-ocean/brine systems, as such  
199 environments could be associated with several high-priority geophysical features within planetary  
200 ice shells (e.g., lenses, sills, dikes, fracture walls, the ice-ocean interface) [*Buffo et al.*, 2021b]  
201 (Figure 1). Given the significant impact solidification geometry has on the interfacial multiphase  
202 reactive transport processes, resulting physicochemical structure, and material properties of  
203 analogous magmatic and metallurgic systems (e.g., chemical zonation in magmatic dikes, A- and  
204 V-segregate formation in alloy ingots) [*Campbell*, 2003; *Chistyakova and Latypov*, 2009;  
205 *Chistyakova and Latypov*, 2010; *Fowler*, 1987; *Li et al.*, 2014; *Mehrabian et al.*, 1970; *Steeffel et al.*,  
206 2005; *Worster et al.*, 1990], it stands to reason that comparable heterogeneities could  
207 significantly impact the composition, material properties, and ultimately dynamics of ocean/brine-  
208 derived planetary ices. This has fundamental implications for the geophysics, geology, habitability,  
209 and remote investigation of ice-ocean worlds.

210 Here we extend the work of *Buffo et al.* [2021b] and present novel two-dimensional  
211 multiphase reactive transport simulations of two unique endmember geometries that may be  
212 present in the ice shells of ice-ocean worlds (sills and fractures). Additionally, we explore two  
213 distinct ocean chemistries (35 ppt [g/kg] sodium chloride (NaCl) and 35 ppt [g/kg] magnesium  
214 sulfate (MgSO<sub>4</sub>)) and investigate model results over four orders of magnitude (simulation grid  
215 spacing ranging from  $7.8125 \times 10^{-3}$  m to 7.8125 m). The first geometry considers the bidirectional  
216 (top-down and bottom-up) solidification of an isolated sill intruded into the shallow ice shell of  
217 Europa (Figure 1). This allows us to validate the assumption of *Chivers et al.* [2021] – that bottom-  
218 up solidification will result in complete retention of interstitial brine due to a lack of the  
219 gravitational instability that drives ice desalination (via brine drainage) during top-down  
220 solidification – by explicitly simulating the multiphase evolution of the system. Additionally, we  
221 compare the resulting vertical bulk salinity profiles and solidification times predicted using our  
222 model to those of *Chivers et al.* [2021] to constrain the predicted longevity of perched water  
223 features in Europa’s shallow ice shell and the compositional fingerprint left by solidified intrusive  
224 features. The former provides an important constraint for astrobiological investigations and  
225 planetary protection protocols [*Schmidt*, 2020; *Schmidt and Buffo*, 2017]. The latter offers insight  
226 for interpreting ice penetrating radar measurements that depend on the physicochemical and  
227 dielectric properties of the ice shell [*Kalousova et al.*, 2017], such as those planned for Europa  
228 Clipper’s REASON instrument and JUICE’s RIME instrument [*Schroeder et al.*, 2016]. The  
229 second geometry we explore is the horizontal (edge to center) solidification of fluid filled basal  
230 fractures that extend upward into Europa’s ice shell from the ice-ocean interface (Figure 1). We  
231 produce two-dimensional spatiotemporal maps of the physicochemical evolution of these

232 solidifying fractures, compare their structural and compositional trends to magmatic and metal  
 233 alloy analogs, and identify quantitative relationships between material entrainment and interfacial  
 234 thermal gradients in this geometric configuration. We highlight the critical role interface geometry  
 235 likely plays in the dynamics and properties of ice-ocean/brine systems, address the applicability  
 236 and limitations of leveraging petrologic and metallurgic analogs to explain the dynamics of  
 237 cryohydrologic systems, briefly describe collaborative opportunities between modelers and  
 238 experimentalists that would target outstanding questions related to multiphase ice-ocean/brine  
 239 systems, and discuss specific implications our results have for the geophysics, habitability,  
 240 geology, observation, and ocean-surface material transport capabilities of planetary ice shells.  
 241



242  
 243 **Figure 1** – Hydrological features and multiphase interfaces in planetary ice shells. **Center)**  
 244 Schematic representation of a typical ice Ih planetary ice shell and hydrological features that may  
 245 populate its interior (fractures, sills). Modified from [Buffo *et al.*, 2021a]. **Left)** The multiphase  
 246 interfaces that will likely characterize the roofs and floors of intruded/isolated water bodies within  
 247 planetary ice shells. Bottom – Simulated porosity plot of a solidifying sill (Section 3.1); note the  
 248 multiphase ‘Mush’ regions above and below the fluid filled center of the sill (domain is 1000 m  
 249 by 1000 m, grid resolution = 7.8125 m). Top – Brine channels imaged in laboratory grown sea ice  
 250 (modified from [Worster and Rees Jones, 2015]), demonstrating the fine scale structure associated  
 251 with reactive transport (desalination) processes in top-down ice-ocean/brine solidification  
 252 interfaces (image width is 3.7 cm). **Right)** The multiphase structure and dynamics of laterally  
 253 freezing interfaces. Bottom – Simulated porosity plot of a basal fracture (Section 3.2); note the  
 254 heterogenous mushy layers at the fracture sidewalls and sloped brine channels within the ‘Mush’  
 255 zone (domain is 1 m by 2 m). Top – Diagram depicting the formation of inclined channels in a  
 256 laterally growing ice-brine mushy layer by dissolution of the solid ice crystal matrix by high  
 257 salinity plumes (modified from [Campbell, 2003]), a process similar to that of A-segregate  
 258 formation in metal alloys, See Figure 9).

259  
260  
261  
262  
263  
264  
265  
266  
267  
268  
269  
270  
271  
272  
273  
274  
275  
276  
277  
278  
279  
280  
281  
282  
283  
284  
285  
286  
287  
288  
289  
290  
291  
292  
293  
294  
295  
296  
297  
298  
299  
300

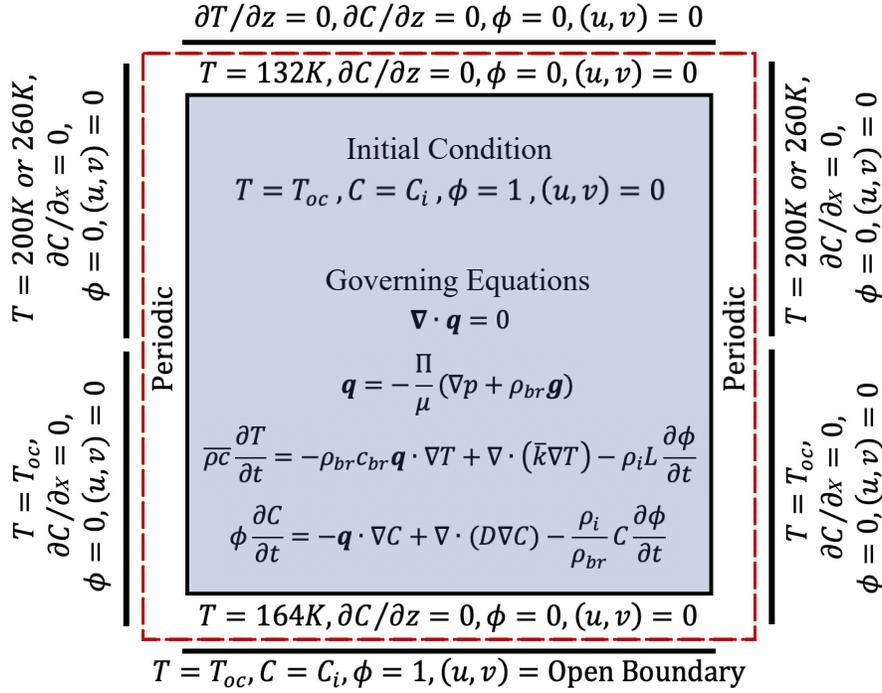
## 2. Methods

To simulate the sill and fracture solidification scenarios described above we implement the two-dimensional multiphase reactive transport model SOFTBALL, first described in *Parkinson et al.* [2020b]. Capable of tracking the fluid dynamic, thermochemical, and phase evolution of binary alloy systems, SOFTBALL has been used by numerous studies to investigate the dynamics and properties of both terrestrial and planetary ices [*Buffo et al.*, 2021b; *Parkinson*, 2019; *Parkinson et al.*, 2020b; *Wells et al.*, 2019]. Here, we build on the work of *Buffo et al.* [2021b], who simulate the planar top-down solidification of planetary ice shells, to include more complex geometries and variable ocean chemistries.

In all simulations we begin with a static (fluid velocity = 0) completely fluid filled domain at a homogeneous temperature and salinity (Figure 2). Multidirectional solidification geometries (sills and basal fractures) are produced by prescribing undercooling to select boundaries (Figure 2). In the case of isolated sills these undercoolings are constant (Dirichlet) boundary conditions at the upper and lower boundaries, representative of a 1 km thick sill emplaced 1 km below the surface in a 5 km thick conductive ice lithosphere overlying a convective ice mantle (akin to the thermal environment implemented by *Chivers et al.* [2021]). Assuming a surface temperature of 100K, a brittle lithosphere to ductile mantle transition temperature of 260K, and a linear conductive thermal profile this results in sill roof temperatures of 132K and sill floor temperatures of 164K. During sill simulations we implement periodic boundary conditions at the horizontal edges of the domain. In the case of basal fractures, we implement constant (Dirichlet) undercoolings over the top halves of the horizontal boundaries (simulating the background ice-ocean interface across the domain's equatorial center). These undercoolings range from 200-260K to simulate fractures within a brittle ice lithosphere and a ductile mantle. The top boundary is set as a no flux (Neumann) no flow boundary condition for all transportable fields (mass, momentum, energy), while the bottom boundary is free to interact with an ambient underlying ocean.

To simulate variable ocean chemistries three key parameters were modified from those used by *Buffo et al.* [2021b]; the solutal contraction coefficient ( $\beta$ ) describing how ocean/brine density changes with salt concentration, the eutectic concentration of the ocean ( $C_e$ ) describing the concentration at which precipitation of solid salt/salt hydrates will occur, and the linear liquidus slope coefficient ( $m$ ) describing the impact of salt on freezing point depression. In Table 1 we list the values we implement for these variables for both a NaCl ocean and a MgSO<sub>4</sub> ocean. All other variables utilized by SOFTBALL are the same as those used by *Buffo et al.* [2021b] (Table 1). We highlight the system of conservation equations solved by SOFTBALL in Figure 2 (mass, momentum, energy, and salt – closed using a salinity dependent linear phase relationship), but point the reader to *Parkinson et al.* [2020b] and *Buffo et al.* [2021b] for complete descriptions of SOFTBALL's functionality.

Lastly, to investigate the effects of simulation resolution on the resultant properties and structure of the solidified features, we ran simulations at several resolutions ranging from meter-scale fractures (grid resolution =  $7.8125 \times 10^{-3}$  m) to kilometer-scale fractures (grid resolution = 7.8125 m). A summary of all our simulations can be found in Table 2.



301  
 302 **Figure 2** – Governing equations, initial conditions, and boundary conditions during sill and  
 303 fracture solidification simulations. Governing equations ensure conservation of mass, momentum  
 304 (Darcy’s Law), energy, and salt and are closed using a salinity dependent linear phase relationship  
 305 to describe the liquidus and eutectic points of the system [Buffo *et al.*, 2021b; Parkinson *et al.*,  
 306 2020b] (variables:  $T, C, \phi, u, v$ ). Initial conditions describe a static fluid filled domain at ambient  
 307 ocean temperature and salinity. Boundary conditions inside the red dashed line are those used  
 308 during sill simulations, while those outside the red dashed line are those used during basal fracture  
 309 simulations. (All variables, their definitions, and their values, if applicable, can be found in Table  
 310 1. Variables with overbars are volume averaged quantities (i.e.,  $\bar{k} = k_{br} \phi + k_i (1 - \phi)$ ), where  
 311 the subscripts  $i$  and  $br$  refer to ice and brine phases, respectively, and  $\phi$  is porosity).  
 312

Variable	Definition	Value (35 ppt NaCl)	Value (35 ppt MgSO <sub>4</sub> )
$\beta$	Solutal contraction coefficient	7.7E-4 kg ppt <sup>-1</sup>	8.3E-4 kg ppt <sup>-1</sup>
$c$	Specific heat	$c_{br} \phi + c_i (1 - \phi)$	$c_{br} \phi + c_i (1 - \phi)$
$c_{br}$	Specific heat of the ocean	3985 J kg <sup>-1</sup> K <sup>-1</sup>	3985 J kg <sup>-1</sup> K <sup>-1</sup>
$c_i$	Specific heat of ice	2000 J kg <sup>-1</sup> K <sup>-1</sup>	2000 J kg <sup>-1</sup> K <sup>-1</sup>
$C$	Brine concentration	Calculated	Calculated
$C_e$	Eutectic concentration	230 ppt	175 ppt
$C_i$	Ocean concentration	35 ppt	35 ppt
$D$	Salt diffusion coefficient	2E-9 m <sup>2</sup> s <sup>-1</sup>	2E-9 m <sup>2</sup> s <sup>-1</sup>
$g$	Gravity	1.32 m s <sup>-2</sup>	1.32 m s <sup>-2</sup>
$k$	Thermal conductivity	$k_{br} \phi + k_i (1 - \phi)$	$k_{br} \phi + k_i (1 - \phi)$
$k_{br}$	Ocean thermal conductivity	0.6 W m <sup>-1</sup> K <sup>-1</sup>	0.6 W m <sup>-1</sup> K <sup>-1</sup>
$k_i$	Ice thermal conductivity	2.0 W m <sup>-1</sup> K <sup>-1</sup>	2.0 W m <sup>-1</sup> K <sup>-1</sup>
$L$	Latent heat of fusion	334774 J kg <sup>-1</sup>	334774 J kg <sup>-1</sup>
$m$	Linear liquidus slope	0.0913 K ppt <sup>-1</sup>	0.0228 K ppt <sup>-1</sup>
$\mu$	Dynamic viscosity	1.88E-3 Pa s	1.88E-3 Pa s

$p$	Dynamic pressure	Calculated	Calculated
$\phi$	Porosity	Calculated	Calculated
$\Pi$	Permeability	See [Buffo et al., 2021b]	See [Buffo et al., 2021b]
$q$	Darcy velocity	(u,v) m s <sup>-1</sup>	(u,v) m s <sup>-1</sup>
$\rho$	Density	$\rho_{br}\phi + \rho_i(1 - \phi)$	$\rho_{br}\phi + \rho_i(1 - \phi)$
$\rho_{br}$	Brine density	1000+1000 $\beta C$ kg m <sup>-3</sup>	1000+1000 $\beta C$ kg m <sup>-3</sup>
$\rho_i$	Ice density	917 kg m <sup>-3</sup>	917 kg m <sup>-3</sup>
$t$	Time	Independent variable	Independent variable
$T$	Temperature	Calculated	Calculated
$T_{oc}$	Ocean Temperature	273.15- $mC_i$ +0.01 K	273.15- $mC_i$ +0.01 K
$u$	Horizontal Darcy velocity	Calculated	Calculated
$v$	Vertical Darcy velocity	Calculated	Calculated
$x$	Horizontal spatial coordinate	Independent variable	Independent variable
$z$	Vertical spatial coordinate	Independent variable	Independent variable

313 **Table 1** – Variables and values used throughout the manuscript.

314

Run Type	Undercooling (K)	Ocean Chemistry	Domain Size (m)	Resolution (m)
Sill	Top: 132, Bottom: 164	NaCl	1000 x 1000	3.90625
Sill	Top: 132, Bottom: 164	MgSO <sub>4</sub>	1000 x 1000	3.90625
Fracture	200	NaCl	1 x 2	7.8125E-3
Fracture	200	NaCl	10 x 40	7.8125E-2
Fracture	200	NaCl	100 x 400	7.8125E-1
Fracture	200	NaCl	500 x 2000	7.8125
Fracture	200	MgSO <sub>4</sub>	1 x 2	7.8125E-3
Fracture	200	MgSO <sub>4</sub>	10 x 40	7.8125E-2
Fracture	200	MgSO <sub>4</sub>	100 x 400	7.8125E-1
Fracture	200	MgSO <sub>4</sub>	500 x 2000	7.8125
Fracture	260	NaCl	500 x 2000	7.8125

315 **Table 2** – Environmental conditions and model domain architecture for all the simulations carried  
316 out during this investigation.

317

### 318 3. Results

319

#### 319 3.1 Sills

320

321

322

323

324

325

326

327

328

329

330

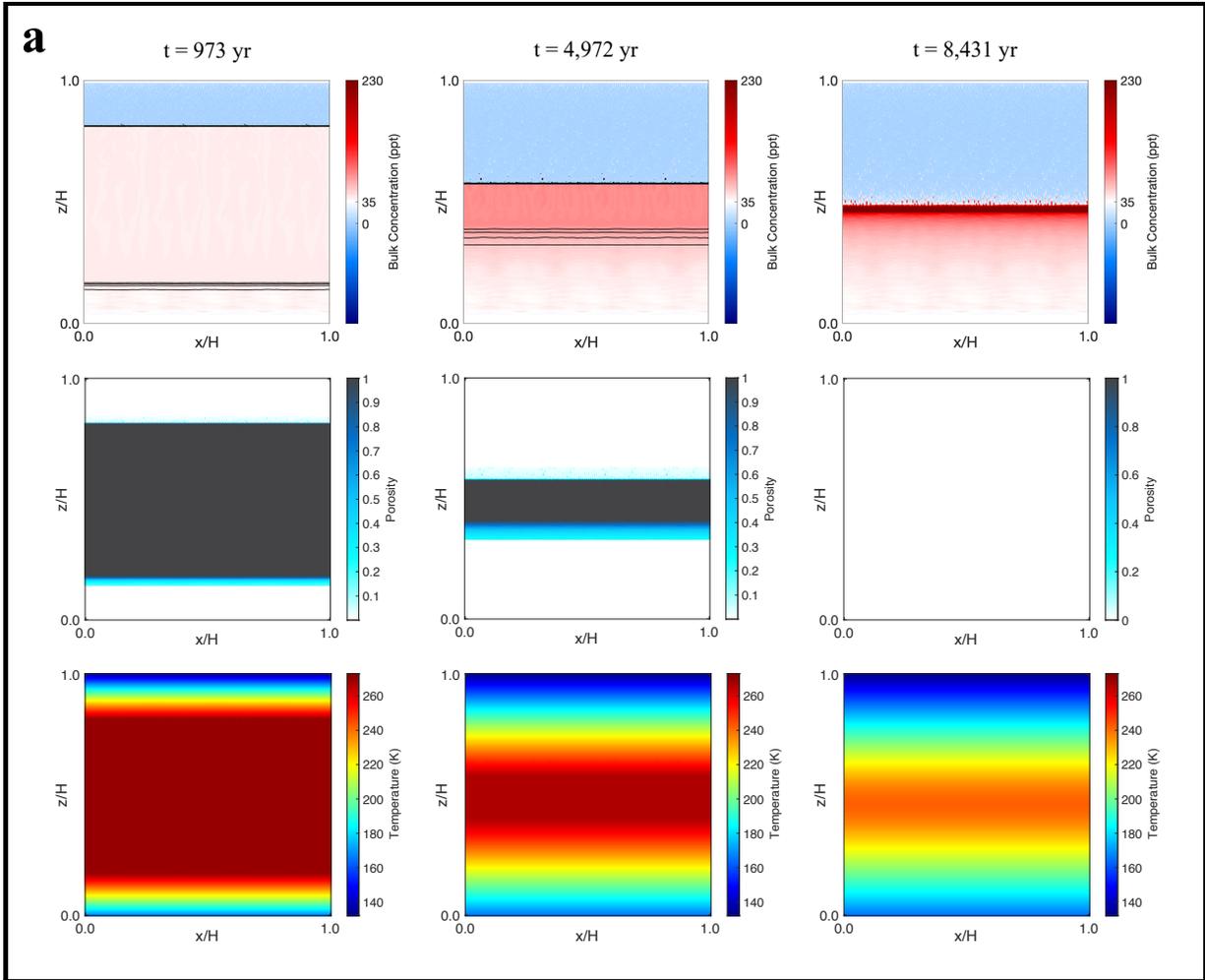
331

332

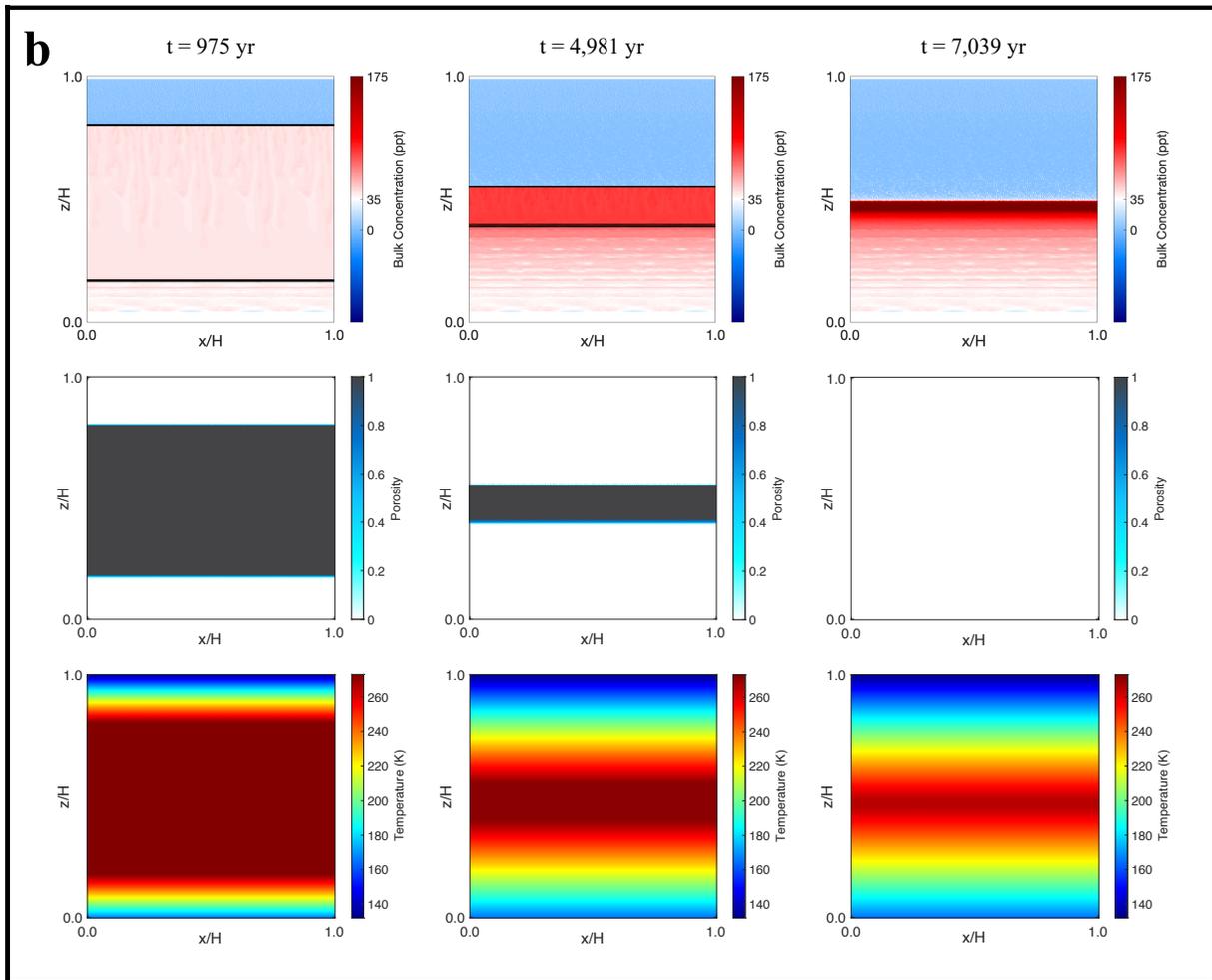
333

Isolated brine-filled sills and other perched water features (e.g., dikes, lenses, laccoliths) may be commonplace in the shells of icy satellites and could have significant geological and astrobiological implications [Chivers et al., 2021; Manga and Michaut, 2017; Michaut and Manga, 2014; Schmidt et al., 2011; Walker and Schmidt, 2015]. Near surface (<5 km deep) water features could be the progenitors of geologically young, depressed/disrupted surface terrain (e.g., chaos [Postberg et al., 2011], lenticulae [Chivers et al., 2021; Manga and Sinton, 2004; Michaut and Manga, 2014]) and any shallow water reservoirs (especially those potentially interacting with the surface) are of immense astrobiological interest in the lens of both planetary exploration and planetary protection [Council, 2012; Schmidt and Buffo, 2017]. The intrusive nature of these features facilitates the generation of multidirectional freezing fronts along their boundaries and, if they are isolated from the underlying ocean, the potential for unique geochemical processes (e.g., concentration, saturation). In the case of isolated sills, top-down freezing will occur from the roof, bottom-up freezing will occur from the floor, and the residual brine will become increasingly saline until it reaches its saturation limit and begins to precipitate a eutectic mixture of ice and solid salt

334 hydrates. Here we simulate the thermal and physicochemical evolution (from initial intrusion to  
 335 complete solidification) of 1 km thick sills emplaced 1 km below the surface in a 5 km thick brittle  
 336 ice lithosphere whose initial chemical composition is 35 ppt NaCl (Figure 3a) and 35 ppt MgSO<sub>4</sub>  
 337 (Figure 3b). The grid resolution of both simulations is 3.90625 m.  
 338



339



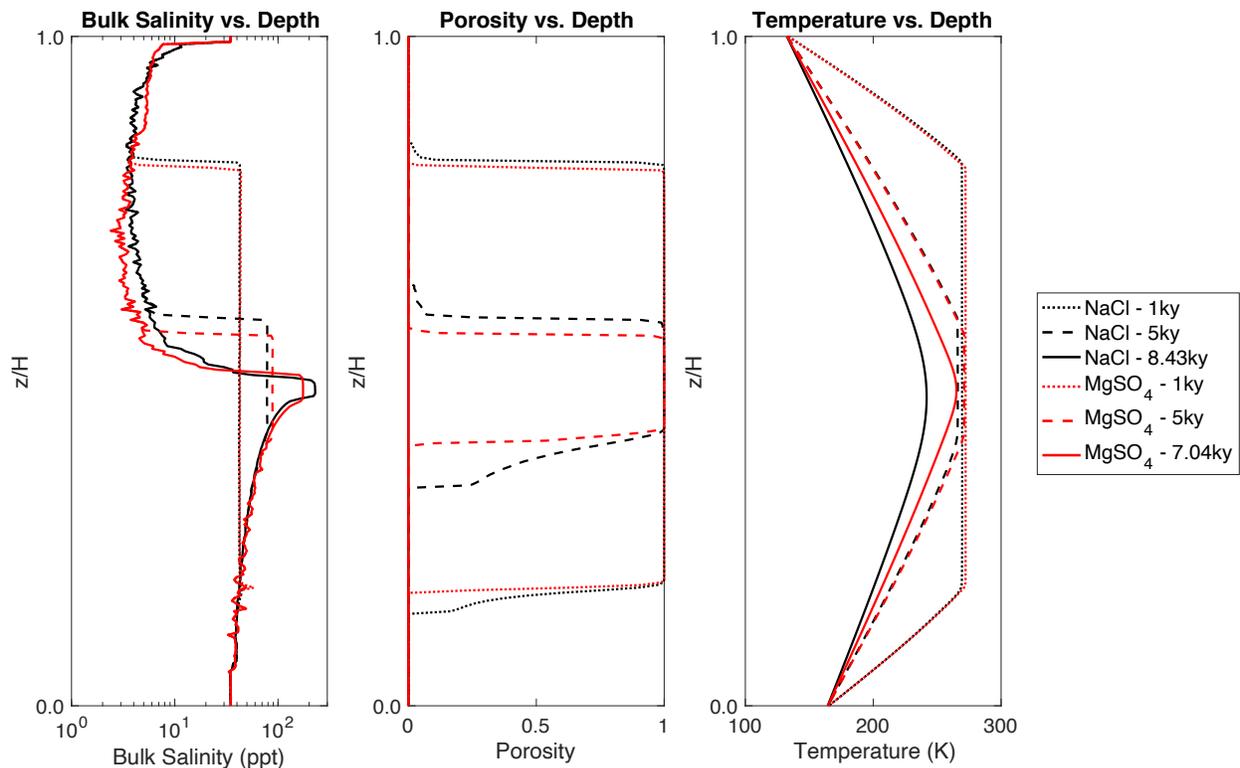
340  
 341 **Figure 3** – The thermal and physicochemical evolution of isolated saline sills in a brittle ice shell  
 342 lithosphere. **a)** The spatiotemporal evolution of a 1 km thick 35 ppt NaCl sill subject to the  
 343 undercooling boundary conditions presented in Figure 2. Rows: Top – bulk salinity (black contours  
 344 demarcate porosities ranging from 0.15 to 0.95 in increments of 0.2); Middle – porosity; Bottom  
 345 – temperature. Columns: temporal snapshots of the simulation. The third column represents the  
 346 completely solidified sill ( $H = 1000$  m). Note the thicker mushy layer at the sill floor compared to  
 347 the sill roof, the dichotomy of salt retention at the sill floor and salt rejection at the sill roof, and  
 348 the cryoconcentration of the residual brine as the simulation progresses. **b)** The spatiotemporal  
 349 evolution of a 1km thick 35 ppt  $MgSO_4$  sill subject to the undercooling boundary conditions  
 350 presented in Figure 2. Rows and columns same as in panel (a) ( $H = 1000$  m). Note the significantly  
 351 thinner mushy layers compared to the NaCl simulation, a result of the reduced freezing point  
 352 depression effects of  $MgSO_4$ . Detailed movies of the bulk salinity, porosity, and fluid dynamic  
 353 evolution of the NaCl and  $MgSO_4$  sills can be found in Supplementary Movies M1-M6.  
 354

355  
 356 Horizontally averaged vertical profiles of bulk salinity, porosity, and temperature can be  
 357 seen in Figure 4. As the sills solidify salt is rejected from the roof of the chamber, salinating the  
 358 residual brine. Conversely, all of the interstitial brine is retained in the basal multiphase  
 359 solidification front, corroborating the work of *Chivers et al.* [2021], who predicted complete  
 360 retention of salts in the solidifying floors of perched water lenses. This mechanism of complete  
 retention is exemplified by the increasing bulk salinity values as the basal freezing front propagates

361 upward from the initial sill floor, entraining higher concentrations of salt in the newly formed ice  
362 as the sill thins and increases in salinity. Upon complete solidification, both sills are left with a  
363 sheet of ice-salt mixture near the eutectic concentration of the respective ocean composition (230  
364 ppt for NaCl and 175 ppt for MgSO<sub>4</sub>). The thickness of this layer in the NaCl simulation is 15.6  
365 m and that of the MgSO<sub>4</sub> simulation is 31.2 m (these thicknesses are for regions that possess bulk  
366 salinities within 1% of the eutectic concentration). *Chivers et al.* [2021] predicted that solidifying  
367 perched lenses of equivalent thickness (1 km) placed 1 km deep in a 5 km thick brittle ice  
368 lithosphere would produce *pure* salt lags ~1 m thick. Translating our eutectic layers into equivalent  
369 pure salt layers would produce thicknesses of 1.71-2.08 m.

370 Solidification times are represented by the rightmost columns of Figure 2a & 2b – 8,431  
371 years for the NaCl sill and 7,039 years for the MgSO<sub>4</sub> sill. The longer solidification time for the  
372 NaCl sill is to be expected as NaCl depresses the freezing point of water more significantly than  
373 does MgSO<sub>4</sub>. The multiphase solidification fronts at both the roof and floor of the NaCl sill are  
374 thicker than those of the MgSO<sub>4</sub> sill. This agrees with previous numerical and theoretical results  
375 [*Buffo et al.*, 2021a; *Buffo et al.*, 2020; *Buffo et al.*, 2021b] that predict thinner multiphase regions  
376 for solutions whose eutectic temperatures are closer to the freezing point of pure water (i.e., solutes  
377 with less freezing point depression potential). In both the NaCl and MgSO<sub>4</sub> simulations, the  
378 multiphase layer at the sill floor is thicker than the multiphase layer at the sill roof, consistent with  
379 the lack of brine expulsion and multiphase layer trends in the roofs and floors of magmatic analogs  
380 [*Worster et al.*, 1990]. For an extended discussion of the multiphase evolution of sill roofs/floors  
381 and the influence of reservoir chemistry and thermal driving on their thicknesses and propagation  
382 rates see the Supplementary Material (Section S1 and Figures S1-S2).

383 The thermal profiles within the ice are very close to linear – suggesting conduction  
384 dominated heat transport in the surrounding ice – while the temperature of the residual brine is  
385 homogeneous – suggesting the fluid is well mixed (consistent with the assumption of *Chivers et*  
386 *al.* [2021]) – and decreases with time due to the salination of the brine and associated freezing  
387 point depression. Heterogeneities in bulk salinity in the lower portion of the solidified sills (e.g.,  
388 horizontal variations in Figure 3a-b, oscillations in the bulk salinity profile of the MgSO<sub>4</sub> sill –  
389 Figure 4) are likely the result of downwelling saline plumes interacting with the basal solidification  
390 front (See Supplementary Movies M1, M3, M4, and M5). In reality, turbulence and convective  
391 mixing in the residual brine would likely dissipate these plumes before their impingement upon  
392 the sill floor (except perhaps near the end of the sill's solidification, when the residual brine  
393 reservoir is relatively thin) resulting in a more homogenous distribution of salt in the basally  
394 formed ice. The amplified plume stability is a result of implementing a finite permeability in the  
395 free fluid, which significantly optimizes computation time. The benefits and drawbacks of this  
396 approach are discussed at length in *Buffo et al.* [2021b], however given the general thermochemical  
397 homogeneity of the residual brine (Figure 4) we are confident that significant free fluid mixing is  
398 occurring and that our results are minimally affected by this optimization. The full spatiotemporal  
399 evolution of both sills can be found in Supplementary Movies M1-M6.



400  
 401 **Figure 4** – Vertical profiles of bulk salinity, porosity, and temperature during sill solidification ( $H$   
 402 = 1000 m). **Left)** Horizontally averaged vertical bulk salinity profiles of the NaCl and  $\text{MgSO}_4$  sills  
 403 depicted in the first rows of Figure 3a and 3b. Eutectic ice+hydrate mixtures can be seen as plateaus  
 404 in the NaCl – 8.43ky and  $\text{MgSO}_4$  – 7.04ky profiles at 230 ppt and 175 ppt, respectively. **Center)**  
 405 Horizontally averaged vertical porosity profiles of the NaCl and  $\text{MgSO}_4$  sills depicted in the  
 406 second rows of Figure 3a and 3b. The vertical extents of the multiphase ice-brine interfacial layers  
 407 can be seen thickening with time, consistent with contemporary theoretical and numerical  
 408 predictions [Buffo *et al.*, 2021a; Buffo *et al.*, 2021b]. **Right)** Horizontally averaged vertical  
 409 temperature profiles of the NaCl and  $\text{MgSO}_4$  sills depicted in the third rows of Figure 3a and 3b.  
 410 Temperatures within solid and mushy regions ( $\phi < 1$ ) are representative of linear conductive  
 411 thermal profiles, while the residual brines in the center of the sills ( $\phi = 1$ ) are well mixed and are  
 412 at their salinity dependent freezing points.

413  
 414 **3.2 Fractures**

415 A second type of hydrological feature that may be present in the ice shells of ocean worlds  
 416 is fluid filled basal fractures. The same tidal heating that promotes the longevity of subsurface  
 417 oceans on worlds like Europa and Enceladus also exerts cyclic stresses on the overlying ice shell.  
 418 This combination of tensional, compressional, and rotational stresses has been suggested as a  
 419 process capable of generating several of the fractural and other geological features seen across the  
 420 surfaces of icy moons in the solar system (e.g., the tiger stripe fractures of Enceladus [Nimmo,  
 421 2020; Rudolph and Manga, 2009], ridges [Dombard *et al.*, 2013; Head *et al.*, 1997; Hoppa *et al.*,  
 422 1999; Manga and Sinton, 2004], dilational bands [Howell and Pappalardo, 2018; Prockter *et al.*,  
 423 2002], lenticulae [Craft *et al.*, 2016; Fagents *et al.*, 2000; Manga and Michaut, 2017], fractures  
 424 [Dombard *et al.*, 2013; Helfenstein and Parmentier, 1983; Nathan *et al.*, 2019; Rudolph and

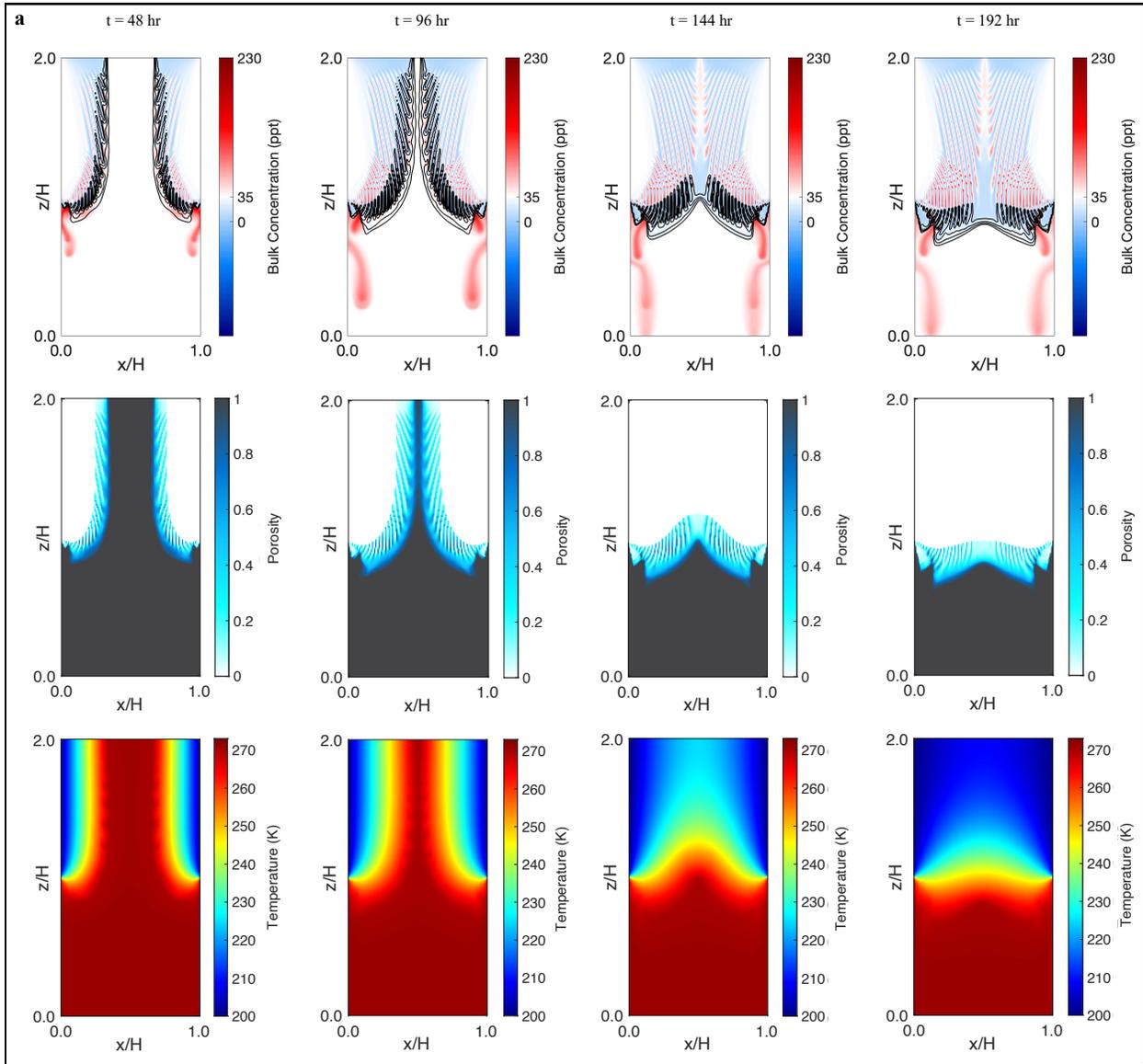
425 *Manga, 2009; Walker et al., 2014; Walker et al., 2021*], strike slip faults [*Hoppa et al., 2000;*  
426 *Hoppa et al., 1999; Kalousová et al., 2016; Nimmo and Gaidos, 2002*], sill/lens/dike evolution  
427 [*Chivers et al., 2021; Craft et al., 2016; Manga and Michaut, 2017; Michaut and Manga, 2014*],  
428 and chaos formation on Europa [*Walker and Schmidt, 2015*], global scale fractures across less  
429 geologically modified icy worlds [Ganymede, Charon, Iapetus] [*Nathan et al., 2019*]).  
430 Additionally, the solidification of the underlying ocean during initial ice shell formation or  
431 periodic/regional thickening will generate significant internal pressure, due to the density  
432 difference between ice and water, that could lead to fracture generation [*Berton et al., 2020; Manga*  
433 *and Wang, 2007*]. If these fractures are connected to a fluid reservoir (either the underlying ocean  
434 or a perched water body within the shell) they are prone to infiltration by the fluid, upon which  
435 heat loss to the cold fracture walls should induce freezing of the injected brine. Given the  
436 significantly different geometry compared to top-down or bottom-up solidification and the  
437 indelible role interstitial fluid flow plays in resultant ice characteristics, this begs the question;  
438 what are the physicochemical characteristics of ocean/brine-derived ices that have grown along  
439 vertical fracture walls? To investigate the properties and evolution of ice grown in this geometric  
440 configuration we simulate the solidification of basal fractures filled with 35 ppt NaCl and MgSO<sub>4</sub>  
441 ocean water (a similar total salt content to Earth's ocean) at four different grid resolutions  
442 (7.8125E-3 m, 7.8125E-2 m, 7.8125E-1 m, and 7.8125 m).

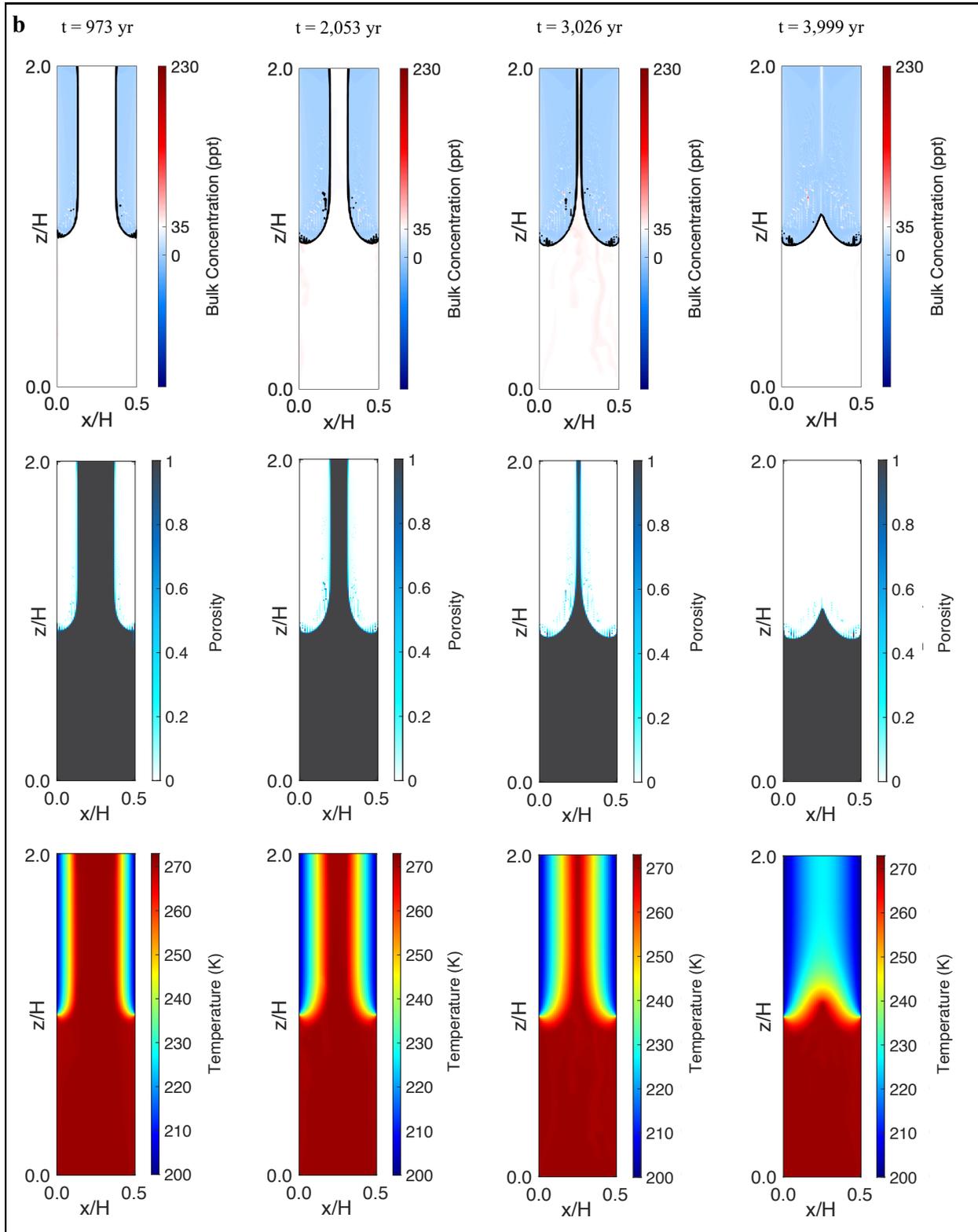
### 443 **3.2.1 Solidification Evolution**

444 Temporal snapshots of the thermal and physicochemical evolution of NaCl ocean filled  
445 fractures simulated grid resolutions of 7.8125E-3 m and 7.8125 m (domain size: 1 meter by 2 m,  
446 and domain size: 500 meters by 2000 meters) can be seen in Figure 5a & 5b, respectively. As the  
447 fractures solidify inward salt is rejected from the forming ice and is transported downward into the  
448 underlying ocean via cold, dense, high salinity plumes that percolate through the sidewall mushy  
449 layer. These plumes are evident in both the high-resolution (Figure 5a) and low-resolution (Figure  
450 5b) simulations, although they are much more prominent in the high-resolution simulation due to  
451 higher thermal gradients and more rapid ice formation (and thus brine rejection).

452 The most striking features produced during these simulations are the diagonally shaped  
453 brine channels that form along the fracture walls (See the porosity plots of Figure 5a). These high  
454 porosity, high salinity regions characterize the multiphase solidification interface and are  
455 responsible for transporting brine away from the propagating freezing front, akin to brine channels  
456 in sea ice [*Wells et al., 2019; Worster and Rees Jones, 2015*]. The unique geometry of the problem  
457 (a horizontally propagating freezing front) results in a distinct 'V-shaped' pattern of high salinity  
458 regions as the channels solidify. This phenomenon is common in the solidification of  
459 multicomponent systems (e.g., metal alloys, aqueous solutions) and is referred to as A-segregation  
460 [*Bédard et al., 1992; Campbell, 2003; Li et al., 2014*]. The negative buoyancy of melt in ice-brine  
461 systems means the formation of macrosegregates occurs in the inverse direction – that is, A-  
462 segregation dynamics produce V-shaped rather than A-shaped channels. Given the widespread  
463 occurrence of analogous macrosegregation patterns in other systems, we believe that these features  
464 are realistic byproducts of a horizontal ice-brine solidification geometry and not the result of any  
465 numerical effects (e.g., numerical dispersion). While the lower resolution simulation (Figure 5b)  
466 does not exhibit channelization patterns, the continuum approach implemented by SOFTBALL  
467 guarantees that ice properties affected by brine drainage dynamics (e.g., bulk salinity) are still  
468 properly captured even when channels are not explicitly resolved (e.g., [*Buffo et al., 2021b*]).

469  
470





472  
473  
474  
475

**Figure 5** – The thermal and physicochemical evolution of resolidifying basal fractures. **a)** A 1 m by 1 m 35 ppt NaCl ocean filled fracture ( $H = 1$  m), highlighting the macrosegregation (formation of brine channels and ultimately inverted A-segregates) that occurs during the solidification of

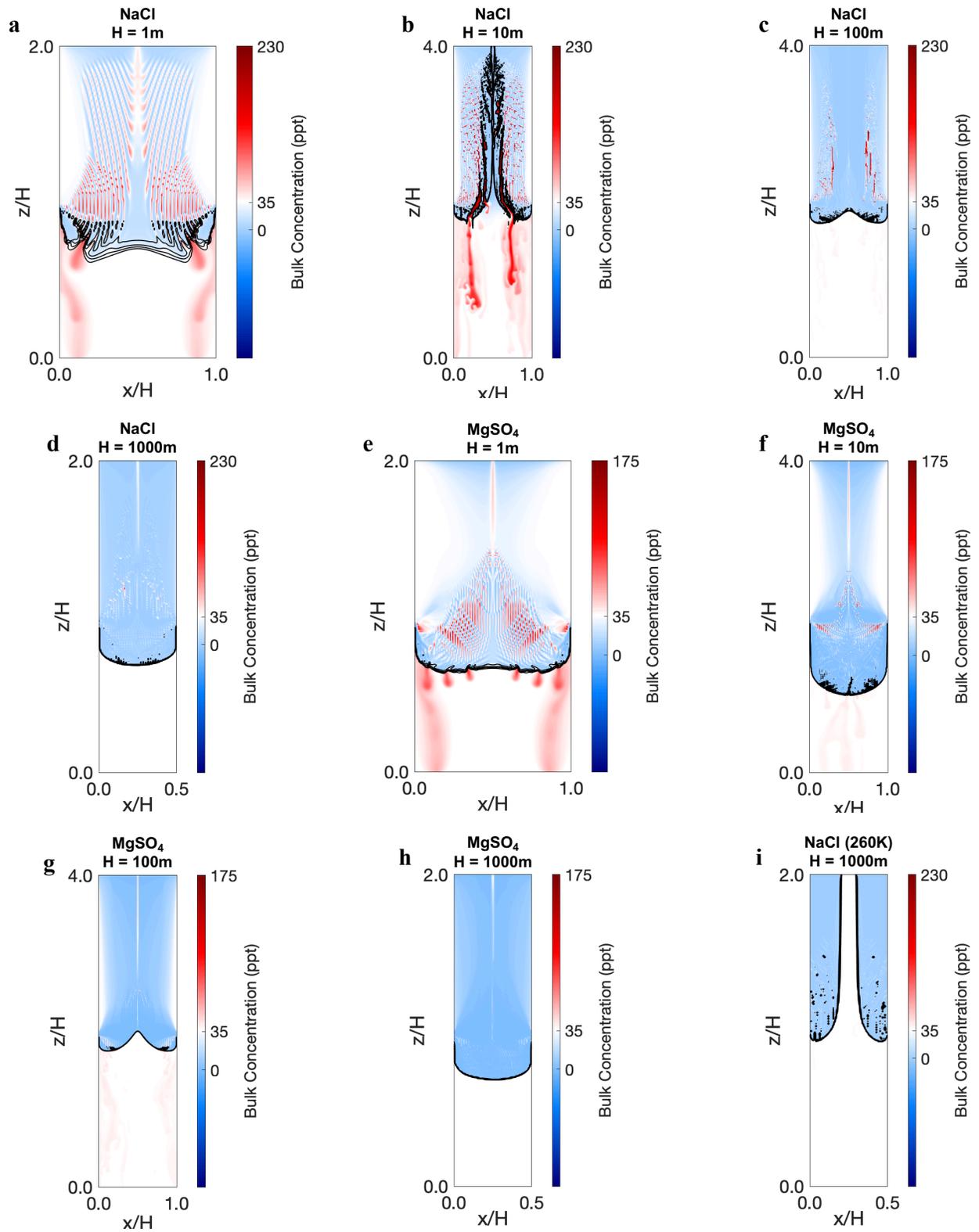
476 brines. Note that the downwelling high salinity plumes do not flow out into the central portions of  
477 the fracture, but percolate downward through or at the boundary of the mushy layers that  
478 characterize the fracture walls (see Supplementary Movie M9 for exemplification of these  
479 dynamics via streamlines). Rows: Top – bulk salinity (black lines are porosity contours – 0.15 to  
480 0.95 in increments of 0.2); Middle – porosity; Bottom – temperature. Columns: temporal snapshots  
481 of the simulation. **b)** A 500 m by 1000 m 35 ppt NaCl ocean filled fracture ( $H = 1000$  m). While  
482 the coarser simulation does not explicitly resolve the macrosegregation textures seen in panel (a)  
483 the model’s continuum approach guarantees that salt entrainment and associated chemical zonation  
484 patterns are still accurately captured (e.g., [Buffo *et al.*, 2021b]). Rows and columns same as in  
485 panel (a). Detailed movies of the bulk salinity, porosity, and fluid dynamic evolution of all the  
486 NaCl and MgSO<sub>4</sub> ocean filled fractures described in Table 2 can be found in Supplementary  
487 Movies M7-M33.

488

### 489 **3.2.2 Resultant Bulk Salinity Profiles**

490 As the fractures solidify the level of salt entrained in the newly formed ice is likely  
491 governed by the rate at which the fractures freeze (equivalently, the thermal gradient at the  
492 solidification interface). This logic is consistent with previous studies of ice formed in top-down  
493 solidification geometries under both Earth [Griewank and Notz, 2013; Hunke *et al.*, 2011] and  
494 planetary [Buffo *et al.*, 2020; Zolotov and Kargel, 2009] conditions (e.g., sea ice, planetary ice  
495 shell formation) and the results of our sill solidification simulations (Section 3.1). In Figure 6, we  
496 plot the ultimate bulk salinity profiles of all fracture scenarios described in Table 2. In general,  
497 bulk salinities are highest near the distal edges of the fractures (where thermal gradients are the  
498 highest) and decrease towards the fracture centers, except for regions of high salinity that occupy  
499 the very centers of the solidified fractures where residual brine/salt has been trapped. The NaCl  
500 (Figure 6a-d) and MgSO<sub>4</sub> (Figure 6e-h) ocean filled fractures share many characteristics, including  
501 general bulk salinity trends, preserved brine channel structures, and more efficient salt rejection as  
502 thermal gradients decrease. The thinner mushy layers of the MgSO<sub>4</sub> systems are likely responsible  
503 for the enhanced salt entrainment at the distal edges of the fractures when compared to NaCl  
504 systems of the same scale (e.g., thicker regions of white near the outer portions of the fractures).  
505 The simulation subject to warmer sidewalls (Figure 6i – sidewalls at 260K) efficiently rejects salts  
506 from the ice due to the low thermal gradients at the solidification interface, however there are  
507 regions of residual liquid fraction in the ice (‘freckles’ seen in Figure 6i). This is because 260K is  
508 above the eutectic point of the NaCl system, meaning that regions with even small amplifications  
509 in bulk salinity (e.g., relict brine channels) can remain in a liquid state in the relatively temperate  
510 ice.

511



512  
 513  
 514  
 515

**Figure 6** – Bulk salinity profiles of solidified fractures. These plots show the final frame of the nine fracture simulations described in Table 2. **a)** 1 m by 1 m 35 ppt NaCl ocean filled fracture. **b)** 10 m by 20 m 35 ppt NaCl ocean filled fracture. **c)** 100 m by 200 m 35 ppt NaCl ocean filled

516 fracture. **d)** 500 m by 1000 m 35 ppt NaCl ocean filled fracture. **e)** 1 m by 1 m 35 ppt MgSO<sub>4</sub>  
517 ocean filled fracture. **f)** 10 m by 20 m 35 ppt MgSO<sub>4</sub> ocean filled fracture. **g)** 100 m by 200 m 35  
518 ppt MgSO<sub>4</sub> ocean filled fracture. **h)** 500 m by 1000 m 35 ppt MgSO<sub>4</sub> ocean filled fracture. **i)** 500  
519 m by 1000 m 35 ppt NaCl ocean filled fracture with 260K sidewall undercooling. Simulations  
520 where the sidewalls did not freeze together by the end of the simulation, panel (b) and (i), were  
521 due to instabilities that effected the convergence of the model (in the case of panel (b)) and long  
522 run times due to lower sidewall undercooling (in the case of panel (i)). Detailed movies of all  
523 fracture solidification simulations can be found in Supplementary Movies M7-M33.

524

525 To quantitatively investigate the impacts of a horizontal freezing geometry on the level and  
526 spatial heterogeneity of salt entrainment in basal fractures, we sample two distinct types of  
527 horizontal bulk salinity profiles. The first consists of horizontal profiles along the topmost domain  
528 elements of all fracture simulations. We select this profile to isolate the effects of horizontal  
529 solidification geometry on salt entrainment rates from the impacts of heterogeneous fluid  
530 composition and dynamics along the vertical length of the fracture. That is, the topmost layer of  
531 the domain is uncontaminated by any downwelling brine from higher in the ice (which we will  
532 show significantly impacts salt entrainment) and thus represents a ‘control’ signal to investigate  
533 the effects of horizontal solidification on the amount of salt entrained in the ice. The most useful  
534 comparison to be made (both across simulations and with previous studies of salt entrainment –  
535 e.g. [Buffo *et al.*, 2021b]) is the relationship between bulk salinity of the newly formed ice and the  
536 interfacial thermal gradient at the time of solidification, as this is more agnostic than comparisons  
537 with depth or distance, which depend on the specific environmental parameters of the system. This  
538 comparison is relatively straightforward as thermal gradients within the ice are well represented  
539 by linear conductive profiles (e.g., Figure 4 and Figure 5). In Figure 7 we plot the relationship  
540 between ice bulk salinity and interfacial thermal gradient for the topmost cells of all fracture  
541 simulations shown in Figure 6.

542

543 To contextualize our simulated fracture bulk salinities with those predicted to occur in top-  
544 down solidification geometries and determine if bulk salinity-thermal gradient relationships are  
545 consistent across freezing geometries we compare our results to those of Buffo *et al.* [2021b], who  
546 leveraged the work of Buffo *et al.* [2020] to analytically derive a functional relationship between  
547 bulk salinity and interfacial thermal gradient in top-down solidification scenarios:

548

$$C \left( \frac{\partial T}{\partial x} \right) = a + \left( \frac{-b \left( \frac{\partial T}{\partial x} - c \right)}{-d - f \frac{\partial T}{\partial x}} \right) \left( 1 + h \exp \left( \frac{-j}{\partial T / \partial x} \right) \right) \quad (1)$$

549

550 where  $C$  is bulk salinity in [ppt],  $T$  is temperature in [K],  $x$  is distance in [m] and  $a, b, c, d, f, g, h$   
551 and  $j$  are constant coefficients that account for variations in the composition and concentration of  
552 the ocean/brine being frozen and the dynamics of brine convection in the mushy layer [Buffo *et*  
553 *al.*, 2020; Buffo *et al.*, 2021b]. In Figure 7 we plot the relationship between bulk salinity and  
554 interfacial thermal gradient derived by Buffo *et al.* [2021b] for the top-down solidification of a  
555 planetary ice shell from a 35 ppt saline ocean (liquidus slope ( $m$ ) of 0.048 K ppt<sup>-1</sup>, and solutal  
556 contraction coefficient ( $\beta$ ) of 5.836E-4 kg ppt<sup>-1</sup>):

557

558 
$$c \left( \frac{\partial T}{\partial x} \right) = 7.864 + \left( \frac{-2576 \left( \frac{\partial T}{\partial x} - 5.148 \right)}{-2067 - 869.2 \frac{\partial T}{\partial x}} \right) \left( 1 + 10.93 \exp \left( \frac{-27.2}{\partial T / \partial x} \right) \right) \quad (2)$$

559  
 560 To determine if a comparable functional relationship can describe our simulated refrozen fracture  
 561 bulk salinities, thus capturing the underlying multiphase physics of the analytical top-down  
 562 solution while accounting for the additional effects of a horizontal freezing geometry, we seek a  
 563 bulk salinity-thermal gradient relationship that varies minimally from that of the top-down  
 564 solidification configuration (Equation 2). Accordingly, we fit our simulation results to a simple  
 565 log-linear translation of the bulk salinity-thermal gradient relationship described by Equation 2:  
 566

567 
$$c' \left( \frac{\partial T}{\partial x} \right) = c \left( \exp(a) \frac{\partial T}{\partial x} \right) - b \quad (3)$$

568  
 569 where  $a$  and  $b$  are constant coefficients that account for the geometric effects of horizontal  
 570 solidification. In Figure 7 we plot a Levenberg-Marquardt algorithm best fit of Equation 3 to the  
 571 fracture bulk salinities simulated during this work:  
 572

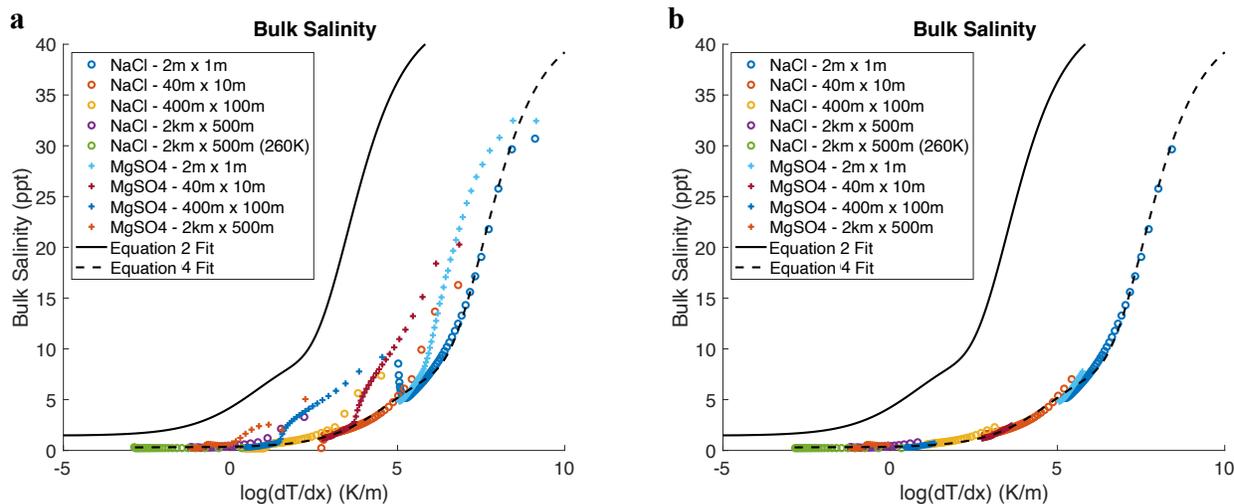
573 
$$c' \left( \frac{\partial T}{\partial x} \right) = c \left( \exp(4.05) \frac{\partial T}{\partial x} \right) - 1.153 \quad (4)$$

574  
 575 The bulk salinities produced by the horizontal solidification of fractures are less than those  
 576 produced during top-down solidification scenarios under comparable thermal forcing. This is  
 577 likely caused by more efficient brine drainage in the multiphase fracture walls than in horizontal  
 578 mushy layers beneath vertically growing ice, which must overcome a Rayleigh-Taylor instability  
 579 for convective brine drainage to occur [*Griewank and Notz, 2013; Notz and Worster, 2009*]. We  
 580 discuss the geophysical implications of this variance in salt entrainment in Section 4.2. Equation  
 581 4 captures the relationship between interfacial thermal gradients and resultant ice bulk salinity for  
 582 both the NaCl and MgSO<sub>4</sub> oceans, which can likely also be attributed to the system not needing to  
 583 overcome a critical Rayleigh number for brine drainage to occur in the mushy layers of the fracture  
 584 walls. This, again, contrasts with horizontal mushy layers beneath vertically growing ice, where  
 585 variable ocean composition impacts mushy layer thickness, onset and behavior of Rayleigh-Taylor  
 586 convection within the mushy layer, and ultimately the rate of salt entrainment in the ice (e.g.,  
 587 differences in the bulk salinity profiles of our simulated sills (Figure 4) and *Buffo et al. [2020]*).

588 As thermal gradients decrease so does salt entrainment, less the amplifications at the  
 589 centers of the fractures caused by interactions with the opposite fracture wall. In all of the  
 590 simulations there are three distinct regimes: 1) at high thermal gradients, prior to the growth of a  
 591 mushy layer that is greater than one discretization cell thick, there are amplified levels of salt  
 592 entrainment due to a lack of resolution (this is supported by the fact that MgSO<sub>4</sub> simulations, with  
 593 their thinner mushy layers, spend a longer time in this regime); 2) once a mushy layer greater than  
 594 one cell thick is established and the fracture is freezing inward, but hasn't begun interacting with  
 595 the other fracture wall, convective overturn (gravity drainage driven desalination) in the mushy  
 596 layer occurs and governs the resultant salt entrainment in the forming ice; and 3) at the end of  
 597 solidification an amplified level of salt entrainment at the center of the fracture occurs due to  
 598 reduced fluid flow in the narrowing fracture and any residual brine is trapped. One notable  
 599 exception is the simulation of the 100 m by 200 m 35 ppt NaCl ocean filled fracture, which

600 generated freshwater plumes during rapid brine drainage events that buoyantly rose and filled the  
 601 fracture center, resulting in a significantly freshened bulk salinity profile within the central region  
 602 of the fracture and a dearth of the typical Regime 3 spike (See Figure 4c and Supplementary  
 603 Movies M13-M15).

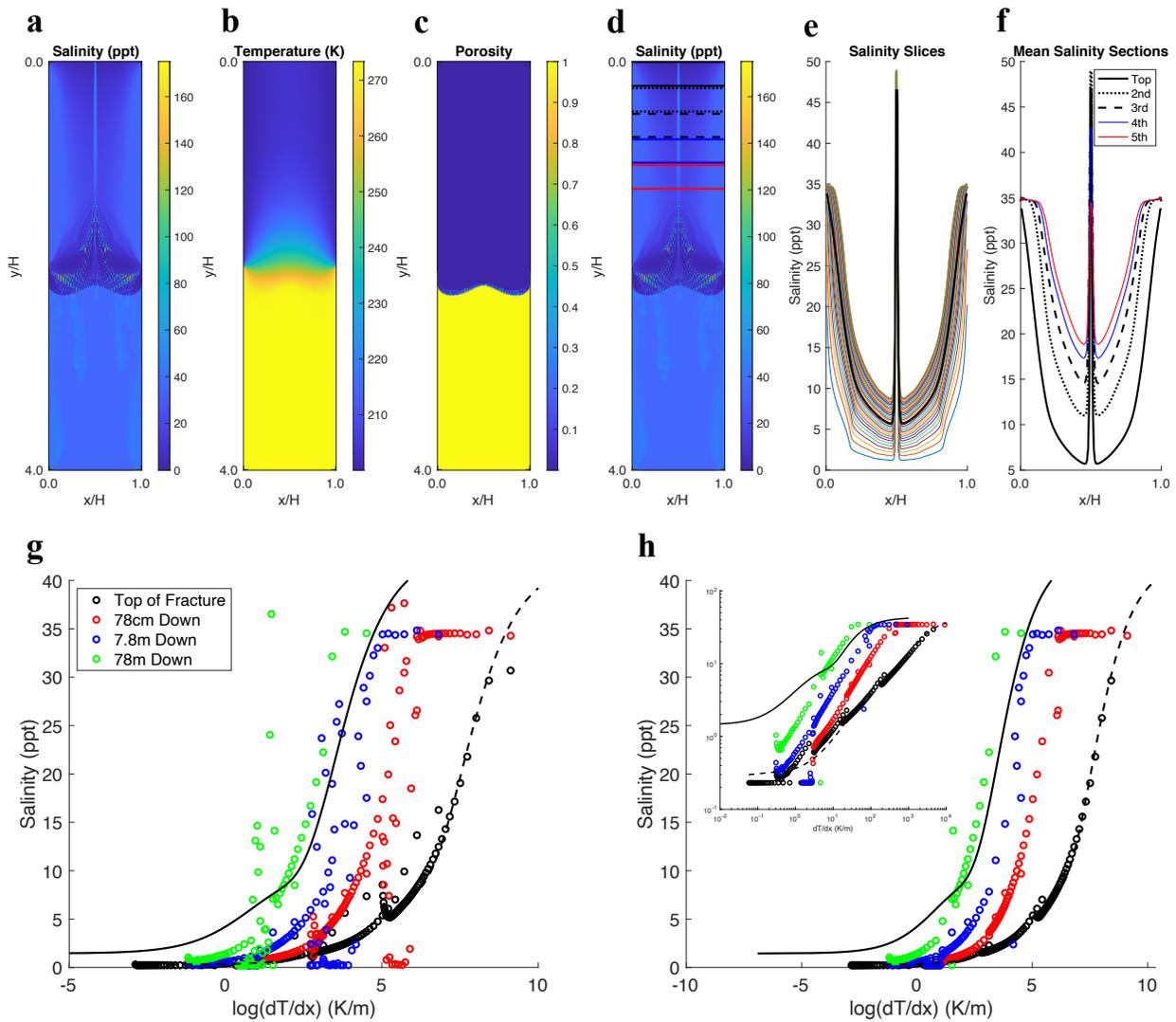
604 Regime 1 is not physically realistic and is the result of not resolving the mushy layer (i.e.,  
 605 finite discretization leads to a one-dimension mushy layer that does not support vorticity to  
 606 drive/resolve convection). Similar anomalous amplifications in ice bulk salinity were observed by  
 607 *Buffo et al.* [2021b] when simulating the top down solidification of planetary ice shells (their  
 608 Figure 3d-f). The final phase of fracture solidification – when the two fracture walls begin to  
 609 interact and ultimately freeze together – is a classic example of a non-isolated system. That is, the  
 610 resulting spatial heterogeneity is due to dynamic interactions between the fracture walls and not a  
 611 result of horizontal freezing alone. In Figure 7b we plot only the second regime, excluding bulk  
 612 salinities generated by thin (1 cell thick) mushy layers as well as the central portions of the  
 613 fractures with amplified salinities. With the influence of horizontal solidification isolated (Figure  
 614 7b), the translated relationship of *Buffo et al.* [2021b] (Equation 4, dashed line of Figure 7) fits the  
 615 simulated bulk salinities exceptionally well.  
 616



617 **Figure 7** – The impact of ice-ocean/brine interfacial thermal gradient on impurity entrapment in  
 618 solidifying basal fractures. **a)** The relationship between the interfacial thermal gradient at the time  
 619 of ice formation and the amount of salt retained in the ice. This plot includes all the raw data  
 620 extracted from the top discretized row of the domain for all the fracture simulations outlined in  
 621 Table 1 except the central amplifications/depletions (Regime 3 outlined in the text). The solid  
 622 black line is the relationship between salt entrapment and thermal gradient for top-down  
 623 solidification geometries derived by *Buffo et al.* [2021b] (Equation 2). The dashed black line is the  
 624 best fit log-linear translation of this line to the current data (Equation 4). **b)** This plot contains the  
 625 same data and fit lines as panel (a) but data points that were acquired when the interfacial mushy  
 626 layer was less than one discretization cell thick (Regime 1) have been removed.  
 627

628  
 629 In addition to horizontal trends in bulk salinity driven by variable thermal gradients, there  
 630 are vertical variations in the bulk salinity profiles of the solidified fractures. Figure 8a-c show the  
 631 two-dimensional bulk salinity (a), temperature (b), and porosity (c) profiles of a 10 m by 20 m  
 632 solidified basal fracture initially filled with a 35 ppt MgSO<sub>4</sub> ocean. Figure 8d-f highlight five  
 633 distinct vertical regions within the fracture where we investigate the mean horizontal bulk salinity

634 profile (d), shows the fine scale vertical variations in horizontal bulk salinity of the upper region  
 635 (e), and plots the mean horizontal bulk salinity profiles of the five regions (f). In the plots of  
 636 horizontal bulk salinity (Figure 8e & 8f), the bulk salinity of the solidified fracture increases with  
 637 depth; that is, ice formed in deeper portions of the fracture retains more salt than ice subject to the  
 638 same thermal gradients (i.e., ice at the same distance from the domain's distal edges) in higher  
 639 portions of the fracture. We discuss physical mechanisms that could cause this vertical trend to  
 640 occur in Section 4.2. This amplification of bulk salinity with depth occurs across all ocean  
 641 chemistries and simulation resolutions. In Figure 8g-h we plot the bulk salinity versus thermal  
 642 gradient for various depths within 35 ppt NaCl ocean filled fractures (Figure 8g is raw data while  
 643 Figure 8h removes the data from Regime 1 and 3 discussed above). We include an inset in Figure  
 644 8h of the same data plotted in log-log space to highlight an interesting near-linear relationship  
 645 between  $\log(\partial T/\partial x)$  and  $\log(C)$ . Again, it is evident that lower portions of the fracture will retain  
 646 more salt than higher regions subject to the same thermal forcing. The implications of this  
 647 vertically heterogeneous salt retention on icy world geophysics and ocean-surface transport are  
 648 discussed in depth in Section 4.  
 649



650

651 **Figure 8** – Heterogeneous spatial distributions of salt retention within solidified basal fractures.  
652 **a)** The bulk salinity distribution in a 10 m by 20 m ( $H = 10$  m) solidified basal fracture that was  
653 initially filled with a 35 ppt  $MgSO_4$  ocean (200K sidewall undercooling). **b)** The temperature  
654 profile of the basal fracture depicted in panel (a). **c)** The porosity profile of the basal fracture  
655 depicted in panel (a). **d)** This plot is identical to panel (a) but highlights the five discrete regions  
656 where we explore vertical trends in salt retention (See panels (e) and (f)). **e)** Horizontal bulk  
657 salinity profiles of the top 32 discretized rows of the simulated domain (space between the top two  
658 solid black lines of panel (d)). Colored lines – the top row of the simulation domain is the blue line  
659 with the lowest bulk salinity and each consecutive row has a higher bulk salinity. The black solid  
660 line is the vertically averaged horizontal bulk salinity profile of the top 32 rows of the simulation  
661 domain. **f)** Vertically averaged horizontal bulk salinity profiles of the regions depicted in panel  
662 (d). Note the increasing bulk salinity of the ice with depth. **g)** The relationship between interfacial  
663 thermal gradient and salt entrainment for different depths within solidified basal fractures. This  
664 plot includes data from all NaCl fracture simulations listed in Table 2. The solid and dashed black  
665 lines are the fit lines described by Equations 2 and 4, respectively. **h)** This plot contains the same  
666 data as panel (g), but, like Figure 6b, data points generated in regions where the interfacial mushy  
667 layer was only one discretization cell thick (Regime 1) or interacting with the opposite fracture  
668 wall (Regime 3) have been removed. Inset – The same plot in log-log space.

## 670 4. Discussion

### 671 4.1 Sills

672 The bidirectional solidification of sills in Section 3.1 highlighted the role of gravitational  
673 instability-driven convection in the interfacial mushy layer of forming ice as the principal  
674 mechanism of ice desalination in ice-ocean/brine systems. This is epitomized by the complete  
675 retention of salt in ice formed via bottom-up solidification – i.e., the floors of the sills – contrasted  
676 with the efficient expulsion of brine from sill ceilings forming via top-down solidification. This  
677 process of salt retention is facilitated by the gravitational *stability* of the interstitial brine in the  
678 basal mushy layer, precluding convective overturn and desalination. Furthermore, a large Lewis  
679 number ( $\gg 1$ ) for all systems considered here means there is no appreciable diffusion of salt out  
680 of the interfacial mushy layers as the ice growth rate due to thermal diffusion will outpace  
681 molecular diffusion (this rationale was previously highlighted by *Chivers et al.* [2021]). The  
682 ultimate chemical signature of a solidified intruded sill will be characterized by three zones: 1) a  
683 relatively fresh upper region that has formed via top-down solidification, where decreasing salt  
684 retention occurs with decreasing thermal gradient (increasing depth) and increased salt retention  
685 occurs near the central portion of the sill as the residual fluid concentrates; 2) a high salinity lower  
686 region formed via bottom-up solidification, where salt retention will reflect the sill chemistry at  
687 the time of ice formation; and 3) a central portion of the sill containing a eutectic mixture of ice  
688 and salt hydrates resulting from the residual fluid saturating (Figure 3 & 4).

689 The properties and dynamics highlighted here (e.g., perfect salt retention in the sill floor,  
690 trends in the resultant chemical profiles of solidified isolated water bodies, a high salinity eutectic  
691 layer at the sill center) are in excellent agreement with the predictions of *Chivers et al.* [2021] who  
692 simulated the two-dimensional thermochemical evolution of perched saline lenses in Europa’s ice  
693 shell using the salt entrainment parameterizations of [*Buffo et al., 2020*] (See Figure 7 & 8 of  
694 *Chivers et al.* [2021] in comparison to our Figure 3 & 4). Our predictions for the freeze out times  
695 of 1 km thick sills intruded 1 km deep in a 5 km thick brittle European lithosphere (8,431 years for  
696 35 ppt NaCl filled sills and 7,039 years for 35 ppt  $MgSO_4$  filled sills) are consistent with *Chivers*

697 *et al.* [2021]’s simulations of 1 km thick lenses intruded 1 km below the surface in a 5 km thick  
698 conductive lithosphere (8,400-15,400 years depending on whether they are located at the pole or  
699 equator). The reduced solidification times in our study can be accounted for by the fact that *Chivers*  
700 *et al.* [2021] simulated a larger domain and included heat loss to the surrounding ice, whereas our  
701 simulations did not account for this insulative warming (boundaries of the domain were held at  
702 constant low temperature) and thus will overpredict the rate of heat loss from the intruded sill.  
703 Additionally, the quantity of residual salt associated with the saturated liquid at the final stage of  
704 solidification is consistent across both investigations (~1 m pure salt for *Chivers et al.* [2021] and  
705 1.71-2.08 m of pure salt in the current study – calculated from our simulated eutectic ice-salt layer  
706 thicknesses of 15.6-31.2 m). The quantitative and qualitative consistencies between *Chivers et al.*  
707 [2021] and our present work gives credence to both investigations, suggesting the  
708 parameterizations implemented by *Chivers et al.* [2021] are representative of the multidimensional  
709 reactive transport physics explicitly captured by SOFTBALL, and demonstrating that SOFTBALL  
710 accurately simulates the complex thermal and physicochemical evolution of ice-ocean/brine  
711 systems, including our concomitant investigation of fracture solidification.

712 There are several important geophysical and astrobiological implications related to the  
713 chemically heterogeneous solidification of perched water features within planetary ice shells.  
714 Fundamentally, chemical heterogeneities in planetary ice shells will likely be associated with  
715 collocated gradients in other material properties (e.g., strength, rheology, melting point, density,  
716 reactivity) [*Durham et al.*, 2005; *Han and Showman*, 2005; *McCarthy et al.*, 2011; *Pappalardo*  
717 *and Barr*, 2004; *Toner et al.*, 2014]. Given the variety of ice shell dynamics hypothesized to be  
718 driven or amplified by heterogeneities within the ice (e.g., thermocompositional solid state  
719 convection, subduction/subsumption, eutectic melting, ocean-surface interaction, brittle lid  
720 dynamics, multiphase reactive transport processes), understanding cryohydrologic processes that  
721 can produce such heterogeneities is imperative in expanding our understanding of ice-ocean world  
722 systems [*Buffo et al.*, 2020; *Buffo et al.*, 2021b; *Vance et al.*, 2020]. The ability to predict the  
723 chemical evolution of hydrologic features within the ice shells of ocean worlds is also integral in  
724 assessing the habitability and biosignature preservation capabilities of planetary ices [*Arnold et*  
725 *al.*, 2019; *Schmidt*, 2020; *Schmidt and Buffo*, 2017; *Vance et al.*, 2016; *Vance et al.*, 2018]. Beyond  
726 identifying the location and longevity of aqueous environments within planetary ice shells that  
727 may act as habitable niches, assessing the evolution of biologically relevant water properties such  
728 as salinity, water activity, and chao-/kosmotropicity that impact life and its function will be  
729 fundamental in quantifying the spatiotemporal habitability of ocean worlds [*Buffo et al.*, 2022;  
730 *Cosciotti et al.*, 2019; *Fox-Powell and Cockell*, 2018; *Hallsworth et al.*, 2007; *Pontefract et al.*,  
731 2019]. Moreover, if the evolving reservoir chemistry of perched water bodies is recorded in the  
732 compositional stratigraphy of their resolidified floors, they could provide an observable means of  
733 reconstructing the geochemical evolution and habitability of liquids within the shell long after they  
734 have frozen solid.

735

## 736 4.2 Fractures

737 The two-dimensional reactive transport simulations of horizontally freezing ice-  
738 ocean/brine interfaces conducted here are, to our knowledge, the first of their kind. While other  
739 works have simulated the multidimensional solidification of water bodies (e.g., [*Buffo et al.*, 2020;  
740 *Chivers et al.*, 2021; *Hesse and Castillo-Rogez*, 2019]) these studies implement parameterizations  
741 for material entrainment rather than explicitly simulating the multiphase dynamics of the  
742 interfacial ice-brine mushy zone. With the goal of investigating the dynamics of hydrological

743 feature sidewall freezing (e.g., vertical fractures, dikes, the sidewalls of liquid reservoirs such as  
744 lenses), our results exhibit several novel characteristics and behaviors that suggest the geometry  
745 of solidification fronts will have significant impacts on the ice's structural, thermochemical, and  
746 material properties. These properties have direct implications for the geochemistry and geophysics  
747 of planetary ices and the dynamics associated with nonplanar and nonvertical solidification fronts  
748 may provide physical mechanisms for introducing amplified and heterogeneous material loads into  
749 planetary ice shells.

750 The most fundamental observation in our simulations of horizontal solidification is the  
751 presence of diagonally oriented brine channels that populate the interfacial mushy layer during  
752 growth and ultimately solidify as high salinity macrosegregates (e.g., the high-resolution  
753 simulations of Figure 5a). The occurrence of brine channels is to be expected as the gravitational  
754 instability of brine in the growing mushy layer leads to the convective downwelling of brine away  
755 from the propagating interface (akin to the physical process of gravity drainage desalination  
756 observed in the planar mushy layer interfaces of sea ice [*Griewank and Notz, 2013; Notz and*  
757 *Worster, 2009*] and the ceilings of the sills simulated in Section 3.1). Here we suggest that the  
758 diagonal orientation of the channels is also to be expected based on analogy to the formation of A-  
759 segregates during the solidification of multicomponent metal alloys.

760 During the cooling and solidification of multicomponent metal alloy castings for industrial  
761 or engineering use there will always occur some amount of macrosegregation – localized ionic or  
762 molecular enrichments that depart from a uniform distribution of chemical elements in the alloy  
763 brought about by the multiphase reactive transport dynamics associated with solution solidification  
764 [*Campbell, 2003*]. As multicomponent alloys cool (e.g., ingot castings) they begin to fractionally  
765 crystallize, solidifying in a columnar fashion from the casting walls and rejecting solutes that  
766 cannot be incorporated into the growing crystal lattice (e.g., carbon, sulfur, and phosphorous in  
767 the case of steel) into the interdendritic spaces of the forming mushy layer (Figure 9b) [*Campbell,*  
768 *2003*]. In metal alloy systems the solute-rich melt is less dense than the background liquid, driving  
769 the buoyant ascension of plumes through the interfacial mushy zone. The depressed melting point  
770 of the solute rich melt leads to the dissolution of channels/chimneys upon its ascension and the  
771 ultimate formation of A-channel segregates once the ingot completely solidifies (Figure 9b & 9c).  
772 The physics governing the formation of A-segregates in metal alloy systems is identical, but  
773 inverted, to those driving the V-shaped amplifications of salt in the frozen fracture simulations. As  
774 salt is rejected from forming ice crystals it produces a negatively buoyant brine in the pore space  
775 of the interfacial mushy layer. Gravity drainage drives downward convection of the brine, where  
776 it dissolves paths through existing dendritic ice structures and leads to the formation of high  
777 salinity brine channels (Figure 9b). Ultimately, these channels are frozen into the ice of the  
778 solidified fracture, introducing heterogeneities in ice structure and chemistry compared to the  
779 surrounding 'country' ice in which the fracture was emplaced (Figure 9c). Concomitant  
780 heterogeneities in the ice's material properties (e.g., ice strength, rheology, melting point) could  
781 make fractures susceptible to reactivation long after they have solidified (e.g., via tidal stresses,  
782 tidal heating, or eutectic melting) and constitutes a likely widespread geological process capable  
783 of introducing variable composition, structure, and material properties into planetary ice shells.

784 While we do not explicitly model free floating crystal formation in our ice-brine system  
785 simulations, a common process observed in both magmatic and metallurgic analog systems (e.g.,  
786 Figure 9b), we do observe freshwater melt plumes pooling at the fracture tips during some model  
787 runs (e.g., Supplementary Movie M13). Such buoyantly rising masses of freshwater have the  
788 potential to form frazil/platelet ice crystals via the ice pump mechanism (depressurization

789 crystallization) – potentially infilling fractures with an inverted snowfall of ice crystals (akin to  
790 marine/frazil ice accretion on Earth [Craven *et al.*, 2009; Fricker *et al.*, 2001; Galton-Fenzi *et al.*,  
791 2012; Holland *et al.*, 2009; Khazendar and Jenkins, 2003; Khazendar *et al.*, 2009; Lawrence *et*  
792 *al.*, 2020; McGuinness *et al.*, 2009; Smedsrud and Jenkins, 2004]) and leading to an analogous  
793 region of segregation (in this case exceptionally fresh ice [Wolfenbarger *et al.*, 2018; Wolfenbarger  
794 *et al.*, 2019]) at the fracture tip. SOFTBALL does not currently account for the pressure dependent  
795 freezing point depression of the ocean.

796 On a larger scale there are two important compositional trends that occur during fracture  
797 freezing, one horizontal and one vertical. As the fractures freeze inward and the thermal gradients  
798 driving continued solidification decrease the rate of salt entrainment decreases. This result is  
799 consistent with previous studies of top-down solidification (e.g., [Buffo *et al.*, 2020; Buffo *et al.*,  
800 2021b; Griewank and Notz, 2013]) as well as chemical zonation patterns observed in solidifying  
801 mafic dikes, metal alloys, and aqueous salt solutions [Chistyakova and Latypov, 2009; Chistyakova  
802 and Latypov, 2010; Hebditch and Hunt, 1974; Huppert, 1990; Leitch, 1985] (Figure 9a and 9d) –  
803 terrestrial analogs of these fracture systems. Furthermore, the functional relationships between  
804 thermal gradient and material entrainment rate are consistent with previous investigations [Buffo  
805 *et al.*, 2021b], only requiring simple translations in logarithmic-linear space to account for the  
806 geometric effects on resultant ice salinity (Section 3.2.2) – suggesting the physics of multiphase  
807 reactive transport still dominate the evolution of the system. In isolating the effects of horizontal  
808 solidification on salt retention (that is, focusing on the uppermost portion of the fracture that is  
809 unmodified by infalling brine) we have shown that brine is more readily expelled from the mushy  
810 layer and results in lower salt retention than would be expected for ice formed via top-down  
811 solidification subject to the same thermal gradient. This is due to the unconditional density  
812 instability that initiates downward convection of the brine in the sidewall mushy layer (a  
813 fundamental restriction that governs the initiation and continuation of convective overturn in  
814 mushy layers grown by top-down solidification [Griewank and Notz, 2013; Notz and Worster,  
815 2009]). The horizontal chemical gradation within the solidified fractures will result in associated  
816 spatial variations in ice material properties that could result in the strengthening or weakening of  
817 these regions depending on the impurity load and composition [Assur, 1958; Durham *et al.*, 2005;  
818 McCarthy *et al.*, 2011] – making them either susceptible or resilient to reactivation via both  
819 mechanical and thermal processes (e.g., tidal stress, melting).

820 In addition to horizontal chemical gradients within the refrozen fractures there exist distinct  
821 vertical trends in salt entrainment. Highlighted in Section 3.2.2, lower portions of the resolidified  
822 fractures retain higher levels of salt than upper portions of the fractures that have been subject to  
823 the same thermal gradient (e.g., Figure 8g-h). We believe this is caused by the downward  
824 percolation of high salinity brine through the mushy layer from the upper reaches of the fracture  
825 as the lower walls continue to freeze inward. That is, unlike the upper portions of the fracture's  
826 mushy layers, which are refreshed by upwelling ocean water present in the central liquid region of  
827 the fracture (see the velocity vectors and streamlines of Supplementary Movies M9, M12, M15,  
828 M18, M21, M24, M27, and M30) resulting in relatively fresh ice, the lower portions of the mushy  
829 layers are flushed with brine that is continually concentrating (due to continued freezing -  
830 cryoconcentration) as it percolates downward through the multiphase walls of the fracture,  
831 producing increasingly saltier ice. These lower reaches of the fracture receive minimal to no  
832 freshening via circulation of upwelling ocean water through the interior of the fracture, evidenced  
833 by the lack of streamlines entering the sidewall mushy layers in Supplementary Movies M9, M12,  
834 M15, M18, M21, M24, M27, and M30. This is a novel result for cryohydrologic systems that, to

835 our knowledge, has not been investigated in naturally occurring analog systems on Earth (e.g.,  
836 measurement of chemical zonation in sea ice leads or congelation ice growth in ice shelf basal  
837 fractures), however similar zonation patterns *have* been observed in laterally solidifying aqueous  
838 solutions in the laboratory [Leitch, 1987]. While lateral chemical zonation in magmatic dikes has  
839 been observed (Figure 9a), variable zonation in the vertical direction (i.e., the amplification of  
840 solute retention with depth as observed in our ice-brine simulations) has not been measured or  
841 reported in the literature. It is important to note that this does not preclude such vertical zonation  
842 in magmatic systems and searching for examples of such vertical zonation could potentially be a  
843 fruitful analog investigation.

844 The analog system that exhibits the strongest similarity to our ice-brine systems (and is the  
845 most well studied) is the solidification of metal alloys. In addition to the presence of A-segregates,  
846 whose governing physics mimic and explain the formation of the V-shaped salinity amplifications  
847 observed in our resolidified basal fractures (Figure 9b-c), and the occurrence of lateral variations  
848 in solute retention driven by variable thermal gradients, metal alloy castings exhibit vertical  
849 variations in solute distribution driven by the ongoing concentration of melt as it buoyantly  
850 percolates through the actively propagating mushy layer (e.g., Figure 9b-c) [Hebditch and Hunt,  
851 1974; Huppert, 1990]. In the case of confined metal alloy castings this results in the formation of  
852 A-segregates as channels are dissolved and ultimately crystallize in the mushy dendritic zone as  
853 well as larger regions of positive and negative segregation driven by solute and crystal buoyancy,  
854 respectively (Figure 9b-d) [Campbell, 2003; Hebditch and Hunt, 1974; Huppert, 1990]. These  
855 features have been empirically observed in the laboratory and successfully simulated using two-  
856 dimensional multiphase reactive transport models akin to the one implemented in our current  
857 investigation (Figure 9d) [Li *et al.*, 2014].

858 Governed by the same multiphase reactive transport dynamics as binary metal alloys, the  
859 horizontally solidifying ice-brine systems explored in this work exhibit strikingly similar  
860 physicochemical characteristics (e.g., the formation of inverted A-segregates) and zonation trends  
861 (both lateral and vertical) to their magmatic and metallurgic analogs. The consistency between the  
862 ultimate physicochemical profiles of these systems, as well as the fundamental nature of the  
863 physics driving their evolution, suggests that chemical zonation, macrosegregation, and  
864 physicochemical heterogeneities introduced by variations in solidification geometry likely play a  
865 significant role in dictating the material properties and characteristics of ocean- and brine-derived  
866 ices formed at ‘nontraditional’ interfaces (geometries other than top-down planar solidification).

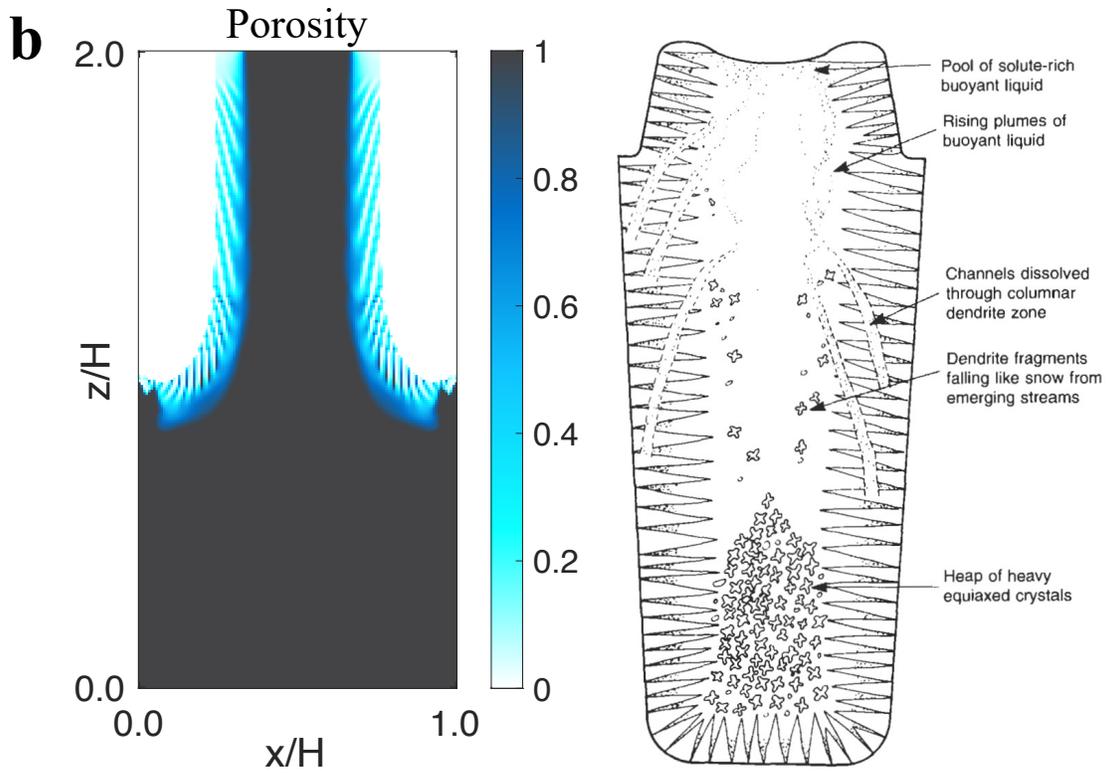
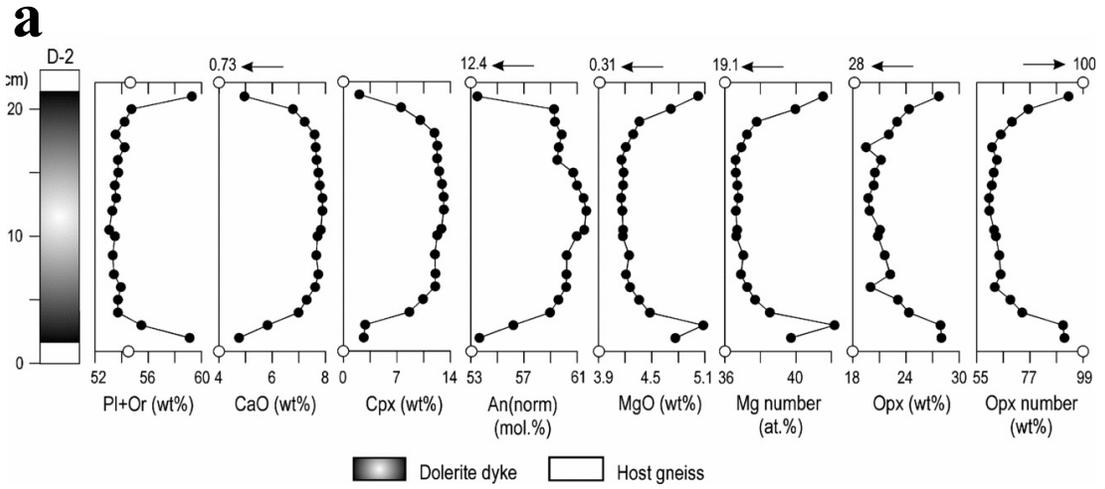
867 The potential for resolidifying hydrological features (lenses, fractures, dikes, etc.) to  
868 provide a mechanism that can introduce both lateral and vertical physicochemical heterogeneities  
869 into planetary ice shells has far reaching implications. We have demonstrated that the multiphase  
870 physics governing metallurgical and petrological solidification processes produce chemical  
871 zonation patterns and physicochemical heterogeneities that are mirrored by those observed in our  
872 simulations of planetary relevant ice-brine environments. In the former analog systems, the  
873 resulting macrosegregation and impurity distribution dictate characteristics of the resultant solids  
874 that influence global terrestrial geology and geophysics (e.g., magmatic differentiation) and are  
875 imperative to the strength, integrity, and durability of widely used industrially cast metals (e.g.,  
876 building materials, tools, mechanical components) [Campbell, 2003; Li *et al.*, 2014; Turcotte and  
877 Schubert, 2014]. Similarly, segregation and solute distribution in ice-brine systems will influence  
878 the strength, rheology, dielectrics, melting point, permeability, and other material properties of  
879 planetary ices relevant to global ice shell geophysics (e.g., solid state convection, eutectic melting,  
880 fracture propagation/activity), transport capabilities (e.g., ocean-surface redox cycling,

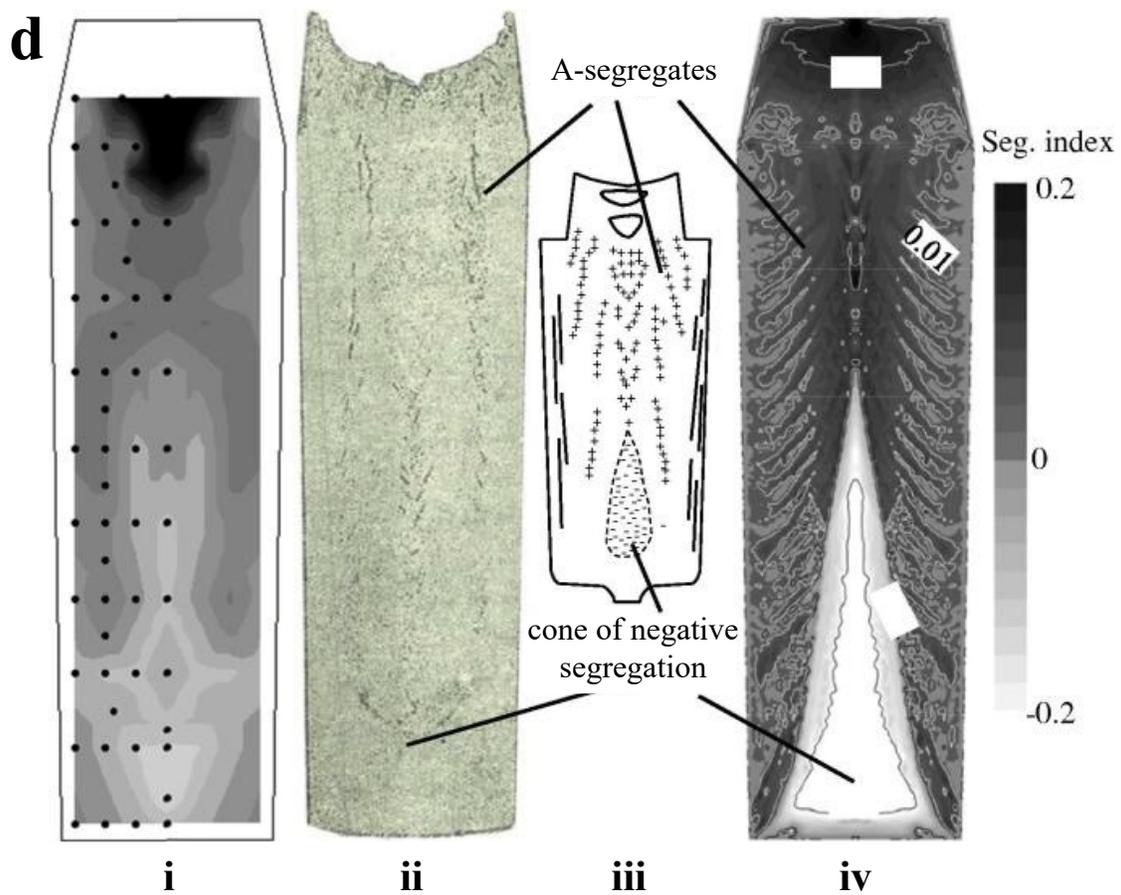
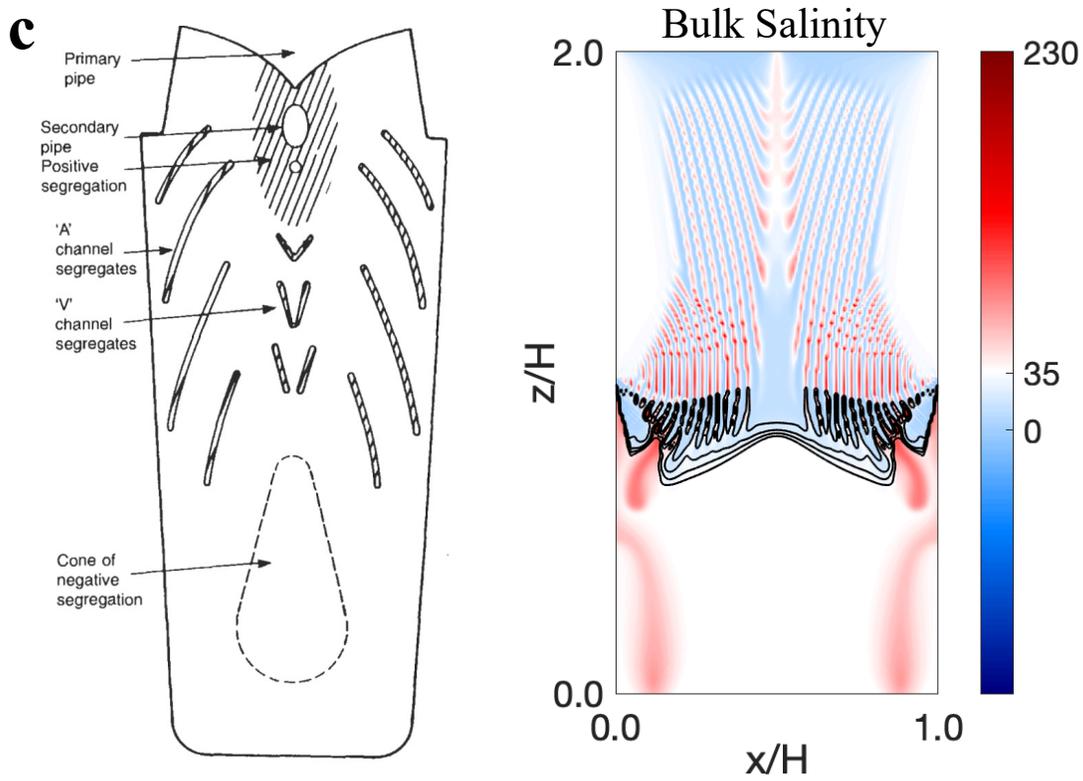
881 biosignature expression, brine mobilization), and observation via spacecraft (e.g., ice penetrating  
882 radar measurements). This is particularly pertinent to geologically active ice-ocean worlds such as  
883 Europa and Enceladus, that may possess contemporary near surface liquids [Chivers *et al.*, 2021;  
884 Manga and Michaut, 2017; Michaut and Manga, 2014; Schmidt *et al.*, 2011; Walker *et al.*, 2014]  
885 and active fractures that could be hydraulically connected to subsurface multiphase or liquid  
886 reservoirs [Boury *et al.*, 2021; Postberg *et al.*, 2009; Postberg *et al.*, 2011].

887 A particularly exciting result is the enhanced solute entrainment in lower portions of basal  
888 fractures due to the extended residence time of highly concentrated brine in the vertically elongated  
889 sidewall mushy layer as it percolates downward toward the ocean. This suggests that hydrologic  
890 and geophysical phenomenon capable of facilitating ice-brine interfaces whose normal vectors are  
891 not aligned with local gravity (fractures, dikes, sills, lenses) have the potential to retain more  
892 impurities than do planar interfaces formed via top-down solidification (e.g., [Huppert, 1990]).  
893 Furthermore, the degree to which impurity entrainment is amplified in these off-axis  
894 (nontraditional) interfaces is directly related to the vertical extent, or residence time of the  
895 downward percolating brine in, the mushy layer. Similarly, we hypothesize that the further the  
896 solidification interface deviates from the traditional top-down orientation (normal vector parallel  
897 to gravity – 0° deviation), the higher the level of potential impurity entrainment. This is consistent  
898 with the amplification of impurity entrainment in fractures with a normal vector perpendicular to  
899 gravity (90° deviation) and epitomized by the complete retention of impurities in the floors of  
900 lenses, whose normal vector is antiparallel to gravity (180° deviation). This is additionally  
901 supported by empirical observations of chemical zonation patterns in mushy layers grown at  
902 variable geometries [Bédard *et al.*, 1992; Hebditch and Hunt, 1974; Huppert, 1990; Leitch, 1987;  
903 Stephen *et al.*, 1987]. We note the specification of ‘potential’ impurity entrainment, as we have  
904 also shown that for shallow fractures (~meters to tens of meters) the increase in efficiency of  
905 gravity drainage due to the horizontal freezing geometry results in *lower* impurity retention than  
906 in ice formed via top-down solidification subject to the same thermal forcing. Accordingly, we  
907 emphasize the additional complexities and competing dynamics introduced by nonstandard  
908 interface geometries. Nevertheless, given the putative efficiency of solute rejection at the  
909 contemporary ice-ocean interfaces of moons like Europa and Enceladus (due to low thermal  
910 gradients [Wolfenbarger *et al.*, 2019]) and the associated difficulty of introducing compositional  
911 heterogeneities into their overlying ice shells, the identification of a plausible geophysical  
912 mechanism that does just that is certainly significant. The mechanism’s consistency with multiple  
913 macrosegregation and chemical zonation phenomena in terrestrial analog systems (magmatic,  
914 petrologic, metallurgic) provides a bolstered validation of the process at work and demonstrates  
915 the widespread occurrence and influence of reactive transport processes (e.g., [Steefel *et al.*,  
916 2005]), giving further credence to the idea that it will likely be a prevalent process on icy worlds  
917 and have a substantial impact on the geophysical and biogeochemical evolution of planetary ice-  
918 ocean and ice-brine systems (e.g., fracture reactivation/propagation, material entrainment and  
919 transport across ice shells, ice shell hydrology, etc. [Buffo *et al.*, 2021b; Vance *et al.*, 2020]).

920 In the case of highly evolved fluids (e.g., brine that has been cryoconcentrated as it  
921 percolates through fracture walls or the last residual fluid in isolated sills) there is the potential for  
922 unique geochemical precipitates to occur. As brines reach their saturation or eutectic points the  
923 formation of a variety of salt hydrates will ensue (dependent on the brine’s composition and local  
924 thermal environment), introducing additional novel phases into the ice shells of ocean worlds  
925 [Durham *et al.*, 2005; McCarthy *et al.*, 2007]. Both the sill and fracture geometries investigated  
926 here provide physical mechanisms that could facilitate cryoconcentration and precipitation of

927 unique salt hydrates. While these phases would likely comprise only a small volumetric fraction  
928 of the ice shell, concentrated in regions associated with solidified/saturated hydrologic features,  
929 they would constitute unique cryopetrologic features containing deposits rich in non-ice  
930 geochemical species. Here we draw a potential analog to terrestrial pegmatites, the crystallization  
931 product of late-stage volatile-rich granitic magma [Troch *et al.*, 2021]. These intrusive pockets,  
932 dikes, and sills contain significant chemical zonation as well as some of the rarest Earth elements  
933 due to their unique enrichment in incompatible trace elements and late-stage solidification  
934 [Thomas *et al.*, 2006; Troch *et al.*, 2021]. In the ice-brine system, high salinity fluids may be  
935 additionally enriched in other impurities that cannot be incorporated into ice lattices, perhaps most  
936 notably organic or inorganic biosignatures. This concentrative effect could make such features  
937 lucrative targets for life detection missions that must contend with instrument sensitivity (detection  
938 limit) restrictions [JPL, 2017; Schmidt, 2020; Schmidt and Buffo, 2017]. Moreover, salt hydrates  
939 have been shown as a viable preservation medium for biosignatures, protecting them from  
940 radiation and oxidation [Hays *et al.*, 2017; Perl *et al.*, 2021; Pontefract *et al.*, 2019].  
941





944 **Figure 9** – Macrosegregation and chemical zonation trends in magmatic and metallurgic analog  
945 systems. **a)** Chemical zonation trends in a solidified dolerite dike [Chistyakova and Latypov,  
946 2009]. Several components show edge to center depletion trends (normal fractionation) that mimic  
947 the salinity profiles of our simulated basal fractures (e.g., Figure 8e-f), while other component  
948 concentrations increase towards the center of the dike exhibiting ‘reverse fractionation’ trends.  
949 Such reverse fractionation trends, which do not follow from predicted liquidus phase equilibria,  
950 could add additional complexities to the resolidified systems and may have analogous counterparts  
951 in ice-brine systems (e.g., if certain ions could be preferentially incorporated into ice crystal lattices  
952 – clathrates). **b)** A depiction of the multiphase processes leading to A-segregate formation and  
953 chemical zonation during the solidification of metal alloy ingots (right, H = 1 m). The channels  
954 dissolving through the dendritic zone are akin to the brine channels formed in the mushy layer of  
955 basal fracture sidewalls (left). **c)** Impurity distribution patterns within a completely solidified metal  
956 alloy ingot (left). Note the structural similarities (e.g., diagonal geometry, distribution) between  
957 the A-segregates and the solidified brine channels of our simulated solidified basal fracture (right,  
958 H = 1 m). (right panel of 8b and left panel of 8c modified from [Campbell, 2003]) **d)** From Left to  
959 Right: **i)** Segregation map of a cast ingot, from [Li et al., 2014], with black dots showing the  
960 location of drill samples. **ii)** Sulphur print of the same ingot. **iii)** Qualitative representation of the  
961 expected segregation pattern. **iv)** Numerical modelling prediction of segregation patterns in the  
962 same solidified ingot [Li et al., 2014]. The consistency between the macrosegregation and  
963 chemical zonation patterns of their model and our results (e.g., channel and segregate formation,  
964 edge to center and vertical trends in impurity entrainment), coupled with the validation of their  
965 model against empirical measurements of cast ingot segregation and zonation patterns gives  
966 credence to our predictions of geometry-induced chemical heterogeneity, both fine scale channel  
967 formation and macroscale zonation, in solidifying ice-brine systems.

### 968 4.3 Applicability and Limitation of Analog Systems

969 The petrological, magmatic, and metallurgical processes highlighted in Section 4.1 and  
970 Section 4.2 suggest that comparable macrosegregation and multiphase reactive transport dynamics  
971 could be commonplace in planetary ices and have significant implications for the geophysics and  
972 habitability of ice-ocean worlds. However, it is important to assess the limitations of such  
973 comparisons and remain diligent in vetting the translation of system properties and/or dynamics  
974 lest we overprescribe such process similarities or overlook differences between high and low  
975 temperature multiphase systems. While the fundamental physics governing the solidification of  
976 metals, rocks, and aqueous solutions are the same there exist unquities within each system that  
977 may differentiate their resultant dynamics, evolution, and material properties. As such, it is  
978 important to interpret and synthesize the implications of these analogisms for ice-ocean worlds  
979 with a critical acumen, armed with a knowledge of how ice-brine systems differ from their  
980 magmatic and metallurgic counterparts and how this may influence their multiphase evolution.  
981 Several publications have addressed the unique properties and behaviors of planetary ice-brine  
982 systems as well as the utility and limitations of utilizing terrestrial analog and numerical modeling  
983 approaches to improve our understanding of these exciting aqueous systems. Buffo et al. [2021b]  
984 specifically address the applicability and limitations of SOFTBALL, the model implemented in  
985 this investigation, and discuss precautionous approaches to extending our contemporary state of  
986 knowledge regarding Earth-based ice-ocean/brine analogs to planetary environments. Other  
987 considerations are included in Vance et al. [2020], whose commentary of Buffo et al. [2020]  
988 highlighted the utility and limitations of terrestrial ice-ocean/brine and geophysical (e.g.,  
989

990 magmatic, tectonic) analogs as well as contemporary multiphase reactive transport models and  
991 explored avenues and potential hurdles for future research, and *Schmidt* [2020], who provides a  
992 detailed discussion of the important links between geophysical processes, habitability, and  
993 biomarker production/preservation on ice-ocean worlds in the Jovian system.

994 Ultimately, laboratory investigations of bottom-up and lateral ice formation using our  
995 simulated ocean chemistries would be valuable benchmarks – similar to the investigations  
996 performed by *Leitch* [1987] for the aqueous sodium nitrate (NaNO<sub>3</sub>) system and *Bédard et al.*  
997 [1992] for the aqueous ammonium chloride (NH<sub>4</sub>Cl) system. These studies could be conducted in  
998 a manner akin to those of metal ingot characterization, wherein two-dimensional salinity profiles  
999 of an ‘ice ingot’ frozen via a controlled directional solidification would be measured – targeting  
1000 thermal forcing such as bidirectional undercooling and vertical sidewall undercooling. The ability  
1001 to control initial solution chemistry and thermal forcing in the lab would provide a method to  
1002 investigate specific relationships between brine chemistry, thermal forcing, interface slope and  
1003 resultant material entrainment. Furthermore, such experiments could either confirm or refute the  
1004 formation of the inverted A-segregates and chemical zonation patterns predicted by our model.  
1005 These type of laboratory measurements will be imperative to determining the validity of our use  
1006 of metallurgic and magmatic analogs and will be crucial for quantifying and improving the  
1007 accuracy of multiphase reactive transport models such as SOFTBALL. Given the importance of  
1008 ice shell properties and dynamics to our understanding of multiple high-priority ice-ocean worlds,  
1009 including Earth, these results and their byproducts will provide ground truthing resources for a  
1010 significant portion of the planetary science and cryosphere communities. This is particularly true  
1011 given the need to support and interpret the data from multiple upcoming missions to ocean worlds  
1012 (JUICE, Dragonfly, Europa Clipper). As such, any targeted collaborative and cross-disciplinary  
1013 efforts between the experimental and modeling communities to address these, and other similar,  
1014 outstanding cryohydrologic questions/goals (e.g., permeability-porosity relationships in  
1015 ocean/brine-derived ices [*Buffo et al.*, 2021b]) would be incredibly timely and pertinent to both  
1016 planetary and Earth science research.

#### 1017 1018 **4.4 Future Outlooks**

1019 As the era of ocean world exploration accelerates (e.g., via missions such as Europa  
1020 Clipper, JUICE, and Dragonfly) classification and quantification of ice-ocean world special  
1021 regions will play a fundamental role in both planetary exploration (e.g., target identification) and  
1022 planetary protection (e.g., contamination avoidance). Additionally, modeling techniques such as  
1023 those presented here will be an indispensable tool for interpreting and synthesizing upcoming  
1024 spacecraft observations of planetary ice shells. The ability to link the chemical fingerprints left by  
1025 hydrological processes within ice shells to the thermophysical evolution of their progenitor fluid  
1026 reservoirs will provide a powerful tool when paired with observational data such as ice penetrating  
1027 radargrams. The significant dependence of ice penetrating radar on the dielectric properties of the  
1028 substrate it is travelling through and the influence of both salts and brines on the dielectric  
1029 properties of ice may provide a means to identify high salinity and/or aqueous environments within  
1030 planetary ice shells and potentially characterize the nature (e.g., chemistry, habitability) and  
1031 history of these environments. Finally, the versatility and adaptability of the SOFTBALL code will  
1032 enable its ongoing application to our evolving understanding of ice-ocean world environments.  
1033 The current investigation as well as other contemporary works [*Buffo et al.*, 2021b] have  
1034 demonstrated the model’s ability to accommodate new ocean/brine chemistries, planetary scales  
1035 and environmental conditions, and more complex geometries and its adaptive architecture is

1036 primed to integrate additional system conditions and physics (e.g., geochemistry,  
1037 biogeochemistry).

1038

## 1039 **5 Conclusion**

1040 The chemically and geologically rich surfaces of many ice-ocean worlds in our solar  
1041 system indicate that their ice shells are likely still active and that a host of putative geophysical  
1042 processes could facilitate ocean-surface material transport essential for subsurface ocean  
1043 habitability, driving geophysical processes, placing constraints on interior compositions, and the  
1044 remote sensing of biosignatures. Given the difficulty of establishing fractures or conduits that  
1045 penetrate the entire thickness of planetary ice shells – promoting direct ocean-surface exchange  
1046 [Rudolph and Manga, 2009; Walker et al., 2021] – the prevailing material transport theories invoke  
1047 the notion that ocean materials will be entrained at the base of the ice shell via imperfect rejection  
1048 at a multiphase ice-ocean interface [Allu Peddinti and McNamara, 2015; Buffo et al., 2020; Buffo  
1049 et al., 2021b]. These theories are supported by analogous observations of salt entrainment in  
1050 terrestrial sea ice and congelation ice growth beneath ice shelves [Cox and Weeks, 1974; Eicken,  
1051 1992; Notz et al., 2005; Tison and Verbeke, 2001; Zotikov et al., 1980]. However, contemporary  
1052 modeling and theoretical work has shown that the relatively shallow thermal gradients present at  
1053 the base of planetary ice shells are such that only minimal levels of non-ice impurities will be  
1054 entrained [Buffo et al., 2020; Buffo et al., 2021b; Hammond et al., 2018; Wolfenbarger et al., 2018;  
1055 Wolfenbarger et al., 2019]. This is problematic for the ocean-surface transport rates needed to  
1056 facilitate a chemically disequilibrated ocean favorable for metabolic reactions as well as several  
1057 ice shell geophysical processes that may be driven by physicochemical heterogeneities within the  
1058 ice [Buffo et al., 2021b; Vance et al., 2016; Vance et al., 2020]. Accordingly, an additional  
1059 mechanism beyond entrainment at a planar ice-ocean interface must be responsible for the  
1060 incorporation and/or distribution of the observed chemical heterogeneities within planetary ice  
1061 shells.

1062 In the current study we demonstrated the potential for hypothesized hydrologic features  
1063 within planetary ice shells (sills and basal fractures), which generate complex ice-ocean/brine  
1064 interface geometries, to produce ice with higher levels of ocean/brine-derived impurities. We've  
1065 shown that amplification of impurity entrainment is due to increased residence time of  
1066 cryoconcentrated brine in the multiphase ice-brine interfacial layers that characterize the distal  
1067 liquid-ice boundaries of these hydrologic features. The resolidifying walls of basal fractures retain  
1068 vertically and horizontally heterogeneous levels of salt, as more concentrated brine from higher  
1069 reaches of the fracture sidewall percolate through the interfacial mushy layer as it continues to  
1070 freeze. The end member of this geometric effect is bottom-up freezing, such as what occurs at the  
1071 floor of a lens or sill perched within the ice shell. In this case, no impurities are rejected from the  
1072 ice as the freezing front propagates, retaining an exceptional chemical fingerprint of the parent  
1073 fluid from whence the ice formed. *This geometrically influenced material entrainment*  
1074 *amplification provides a potential solution to the problem of introducing chemical, and possibly*  
1075 *biological, heterogeneities into planetary ice shells that would otherwise struggle to do so.*

1076 The multiphase dynamics and resultant physicochemical trends exhibited by the ice-  
1077 ocean/brine systems explored in this work closely mirror those of analogous magmatic, petrologic,  
1078 and metallurgic systems on Earth – at both the small and large scale. The formation of diagonal  
1079 brine channels and salt-rich macrosegregation patterns during fracture wall solidification is  
1080 consistent with A-segregate formation in metal alloys and the horizontal and vertical bulk salinity  
1081 trends of solidified fractures and sills mirror the chemical zonation patterns of solidified magmatic

1082 dikes, magma chambers, and multicomponent metal alloy castings. The broad and multiscale  
1083 agreement between the properties of these disparate multiphase systems demonstrates the  
1084 importance of multiphase reactive transport processes in governing the evolution of multiple  
1085 planetary geophysical systems and lends credence to our results.

1086 Given the potential prevalence of diverse, multiphase, brine-rich environments in planetary  
1087 ice shells (e.g., [Vance *et al.*, 2020]) and the significant impact heterogeneous reactive transport  
1088 processes have on the material properties and dynamic evolution of the terrestrial cryosphere, as  
1089 well as petrologic, magmatic, and metallurgical analog systems, it stands to reason that inclusion  
1090 of these physics in predictive models of ice-ocean worlds will move our understanding of these  
1091 systems forward. Multiphase reactive transport models have revolutionized our conception of  
1092 terrestrial geophysics and biogeochemistry, and their extension to icy worlds has already provided  
1093 us with novel insights into the physicochemical structure and evolution of planetary ice shells  
1094 [Buffo *et al.*, 2020; Buffo *et al.*, 2021b; Chivers *et al.*, 2021; Hammond *et al.*, 2018; Hesse *et al.*,  
1095 2019; Kalousova *et al.*, 2018; Kalousova *et al.*, 2014; 2016; Vance *et al.*, 2020]. Coupling this  
1096 knowledge with our current findings, that the multiphase solidification of geometrically complex  
1097 ocean/brine filled hydrological features within planetary ice shells:

- 1098
- 1099 1) Provides a physical mechanism for amplified entrainment of ocean/brine-derived  
1100 impurities into forming ice, particularly when compared to the low entrainment rates of a  
1101 slowly solidifying or equilibrated planar ice-ocean interface.
  - 1102 2) Provides a physical mechanism for heterogeneous entrainment of ocean/brine-derived  
1103 impurities into forming ice – a process lauded as integral for multiple ice shell geophysical  
1104 processes and ocean-surface material transport.
  - 1105 3) Provides a physical mechanism for the cryoconcentration of non-ice impurities (e.g., salts,  
1106 organics, etc.) that could introduce novel and localized deposits of salt hydrates and/or  
1107 other eutectic mixtures (regions with fundamentally unique material properties) and  
1108 facilitate the localization/concentration of astrobiologically relevant materials (e.g.,  
1109 nutrients, biosignatures) – processes important for ice shell geophysics, habitability, and  
1110 biosignature expression.

1111

1112 suggests that planetary ice shells will be characterized by heterogeneous geologically,  
1113 thermophysically, geochemically, and potentially biologically complex and dynamic  
1114 environments. Given the astrobiological potential of diverse ocean worlds [Des Marais *et al.*,  
1115 2008; Hendrix *et al.*, 2019], and the fundamental role ice shell processes likely play in governing  
1116 the geophysical evolution, habitability, and future exploration of these bodies (e.g., site selection,  
1117 instrument detection limits, planetary protection, measurement interpretation) [Buffo *et al.*, 2020;  
1118 Buffo *et al.*, 2021b; Kalousova *et al.*, 2017; Schroeder *et al.*, 2016; Vance *et al.*, 2016; Vance *et al.*  
1119 *et al.*, 2020], it is imperative that our conception of planetary ice shells reflects this complexity and  
1120 that future investigations – numerical, experimental, and analog – target the quantitative constraint  
1121 and holistic understanding of multiphase ice-ocean/brine processes.

## 1122

### 1123 **6 Data Availability**

1124 SOFTBALL and its associated documentation can be found in Parkinson *et al.* [2020a]  
1125 and Parkinson *et al.* [2020b]. All model input files used in this manuscript can be found in the  
1126 repository directory “mushy-layer/examples/lenses-fractures” [Parkinson *et al.*, 2020a].

1127

1128  
1129  
1130  
1131  
1132  
1133  
1134  
1135  
1136  
1137  
1138  
1139  
1140  
1141  
1142  
1143  
1144  
1145  
1146  
1147  
1148  
1149  
1150  
1151  
1152  
1153  
1154  
1155  
1156  
1157  
1158  
1159  
1160  
1161  
1162  
1163  
1164  
1165  
1166  
1167  
1168  
1169  
1170  
1171  
1172  
1173

**7 Acknowledgements**

The authors sincerely thank Dr. Jamie Parkinson, designer of SOFTBALL, for his continued support in our adaption and implementation of the model. Jacob Buffo and Colin Meyer were supported by the NASA Solar System Workings grant 80NSSC21K1804 and the NASA Established Program to Stimulate Competitive Research grant 80NSSC21M0329.

1174 **References**

- 1175 Allu Peddinti, D., and A. K. McNamara (2015), Material transport across Europa's ice shell,  
1176 *Geophysical Research Letters*, 42(11), 4288-4293, doi:10.1002/2015GL063950.
- 1177 Arnold, N. S., S. J. Conway, F. E. G. Butcher, and M. R. Balme (2019), Modeled Subglacial Water  
1178 Flow Routing Supports Localized Intrusive Heating as a Possible Cause of Basal Melting  
1179 of Mars' South Polar Ice Cap, *Journal of Geophysical Research-Planets*, 124(8), 2101-  
1180 2116, doi:10.1029/2019je006061.
- 1181 Assur, A. (1958), Composition of sea ice and its tensile strength, *Arctic sea ice*, 598, 106-138.
- 1182 Barr, A. C., and W. B. McKinnon (2007), Convection in ice I shells and mantles with self-  
1183 consistent grain size, *Journal of Geophysical Research: Planets*, 112(E2),  
1184 doi:10.1029/2006JE002781.
- 1185 Bédard, J. H., R. C. Kerr, and M. A. Hallworth (1992), Porous sidewall and sloping floor  
1186 crystallization experiments using a reactive mush: implications for the self-channelization  
1187 of residual melts in cumulates, *Earth and planetary science letters*, 111(2-4), 319-329.
- 1188 Berton, M., E. Nathan, H. Karani, T. Girona, C. Huber, P. G. Williard, and J. Head (2020),  
1189 Experimental investigations on the effects of dissolved gases on the freezing dynamics of  
1190 ocean worlds, *Journal of Geophysical Research: Planets*, 125(8), e2020JE006528.
- 1191 Boury, S., C. Meyer, G. Vasil, and A. Wells (2021), Convection in a mushy layer along a vertical  
1192 heated wall, *Journal of Fluid Mechanics*, 926.
- 1193 Bryson, F. E., M. Nassif, P. A. Szot, C. J. Chivers, N. Daniel, B. E. Wiley, T. Plattner, A. Hanna,  
1194 Y. Tomar, and S. Rapoport (2020), Vertical Entry Robot for Navigating Europa (VERNE)  
1195 Mission and System Design, in *ASCEND 2020*, edited, p. 4061.
- 1196 Buffo, J., et al. (2022), The Bioburden and Ionic Composition of Hypersaline Lake Ices: Novel  
1197 Habitats on Earth and Their Astrobiological Implications, *Astrobiology*.
- 1198 Buffo, J., B. Schmidt, C. Huber, and C. Meyer (2021a), Characterizing the Ice-Ocean Interface of  
1199 Icy Worlds: A Theoretical Approach, *Icarus*.
- 1200 Buffo, J., B. Schmidt, C. Huber, and C. Walker (2020), Entrainment and dynamics of ocean-  
1201 derived impurities within Europa's ice shell, *JGR: Planets*.
- 1202 Buffo, J. J. (2019), Multiphase reactive transport in planetary ices, Georgia Institute of  
1203 Technology.
- 1204 Buffo, J. J., C. R. Meyer, J. R. Parkinson, and B. E. Schmidt (2021b), Dynamics of a solidifying  
1205 icy satellite shell, *JGR: Planets*.
- 1206 Campbell, J. (2003), *Castings*, Elsevier.
- 1207 Carr, M. H., et al. (1998), Evidence for a subsurface ocean on Europa, *Nature*, 391(6665), 363-  
1208 365, doi:10.1038/34857.
- 1209 Chistyakova, S., and R. Latypov (2009), Fine-scale chemical zonation in small mafic dykes, Kestiö  
1210 Island, SW Finland, *Geological Magazine*, 146(4), 485-496.
- 1211 Chistyakova, S., and R. Latypov (2010), On the development of internal chemical zonation in  
1212 small mafic dykes, *Geological Magazine*, 147(1), 1-12, doi:10.1017/S0016756809990343.
- 1213 Chivers, C., J. Buffo, and B. Schmidt (2021), Thermal and Chemical Evolution of Small, Shallow  
1214 Water Bodies on Europa, *JGR: Planets*(2326), 1047.
- 1215 Cosciotti, B., A. Balbi, A. Ceccarelli, C. Fagliarone, E. Mattei, S. E. Lauro, F. Di Paolo, E.  
1216 Pettinelli, and D. Billi (2019), Survivability of Anhydrobiotic Cyanobacteria in Salty Ice:  
1217 Implications for the Habitability of Icy Worlds, *Life (Basel)*, 9(4), 86,  
1218 doi:10.3390/life9040086.

1219 Cottier, F., H. Eicken, and P. Wadhams (1999), Linkages between salinity and brine channel  
1220 distribution in young sea ice, *Journal of Geophysical Research-Oceans*, 104(C7), 15859-  
1221 15871, doi:Doi 10.1029/1999jc900128.

1222 Council, N. R. (2012), *Assessment of Planetary Protection Requirements for Spacecraft Missions  
1223 to Icy Solar System Bodies*, National Academies Press.

1224 Cox, G. F., and W. F. Weeks (1974), Salinity variations in sea ice, *Journal of Glaciology*, 13(67),  
1225 109-120.

1226 Craft, K. L., G. W. Patterson, R. P. Lowell, and L. Germanovich (2016), Fracturing and flow:  
1227 Investigations on the formation of shallow water sills on Europa, *Icarus*, 274, 297-313,  
1228 doi:10.1016/j.icarus.2016.01.023.

1229 Craven, M., I. Allison, H. A. Fricker, and R. Warner (2009), Properties of a marine ice layer under  
1230 the Amery Ice Shelf, East Antarctica, *Journal of Glaciology*, 55(192), 717-728, doi:Doi  
1231 10.3189/002214309789470941.

1232 Culha, C., D. M. Schroeder, T. M. Jordan, and M. S. Haynes (2020), Assessing the detectability  
1233 of Europa's eutectic zone using radar sounding, *Icarus*, 339, 113578.

1234 Des Marais, D. J., et al. (2008), The NASA Astrobiology Roadmap, *Astrobiology*, 8(4), 715-730,  
1235 doi:10.1089/ast.2008.0819.

1236 Dombard, A. J., G. W. Patterson, A. P. Lederer, and L. M. Prockter (2013), Flanking fractures and  
1237 the formation of double ridges on Europa, *Icarus*, 223(1), 74-81,  
1238 doi:10.1016/j.icarus.2012.11.021.

1239 Durham, W. B., L. A. Stern, T. Kubo, and S. H. Kirby (2005), Flow strength of highly hydrated  
1240 Mg-and Na-sulfate hydrate salts, pure and in mixtures with water ice, with application to  
1241 Europa, *Journal of Geophysical Research: Planets*, 110(E12).

1242 Eicken, H. (1992), Salinity Profiles of Antarctic Sea Ice - Field Data and Model Results, *Journal  
1243 of Geophysical Research-Oceans*, 97(C10), 15545-15557, doi:Doi 10.1029/92jc01588.

1244 Fagents, S. A., R. Greeley, R. J. Sullivan, R. T. Pappalardo, L. M. Prockter, and G. S. Team (2000),  
1245 Cryomagmatic mechanisms for the formation of Rhadamanthys linea, triple band margins,  
1246 and other low-albedo features on Europa, *Icarus*, 144(1), 54-88, doi:DOI  
1247 10.1006/icar.1999.6254.

1248 Feltham, D. L., N. Untersteiner, J. S. Wettlaufer, and M. G. Worster (2006), Sea ice is a mushy  
1249 layer, *Geophysical Research Letters*, 33(14), doi:Artn L14501  
1250 10.1029/2006gl026290.

1251 Figueredo, P. H., and R. Greeley (2004), Resurfacing history of Europa from pole-to-pole  
1252 geological mapping, *Icarus*, 167(2), 287-+, doi:10.1016/j.icarus.2003.09.016.

1253 Fowler, A. (1987), Theories of mushy zones: applications to alloy solidification, magma transport,  
1254 frost heave and igneous intrusions, in *Structure and Dynamics of Partially Solidified  
1255 Systems*, edited, pp. 159-199, Springer.

1256 Fox-Powell, M. G., and C. S. Cockell (2018), Building a Geochemical View of Microbial Salt  
1257 Tolerance: Halophilic Adaptation of *Marinococcus* in a Natural Magnesium Sulfate Brine,  
1258 *Front Microbiol*, 9, 739, doi:10.3389/fmicb.2018.00739.

1259 Fox-Powell, M. G., J. E. Hallsworth, C. R. Cousins, and C. S. Cockell (2016), Ionic Strength Is a  
1260 Barrier to the Habitability of Mars, *Astrobiology*, 16(6), 427-442,  
1261 doi:10.1089/ast.2015.1432.

1262 Fricker, H. A., S. Popov, I. Allison, and N. Young (2001), Distribution of marine ice beneath the  
1263 Amery Ice Shelf, *Geophysical Research Letters*, 28(11), 2241-2244, doi:Doi  
1264 10.1029/2000gl012461.

1265 Galton-Fenzi, B., J. Hunter, R. Coleman, S. Marsland, and R. Warner (2012), Modeling the basal  
1266 melting and marine ice accretion of the Amery Ice Shelf, *Journal of Geophysical Research:*  
1267 *Oceans*, 117(C9).

1268 Gleeson, D. F., R. T. Pappalardo, M. S. Anderson, S. E. Grasby, R. E. Mielke, K. E. Wright, and  
1269 A. S. Templeton (2012), Biosignature Detection at an Arctic Analog to Europa,  
1270 *Astrobiology*, 12(2), 135-150, doi:10.1089/ast.2010.0579.

1271 Greenberg, R., G. V. Hoppa, B. R. Tufts, P. Geissler, and J. Riley (1999), Chaos on Europa, *Icarus*,  
1272 141(2), 263-286, doi:DOI 10.1006/icar.1999.6187.

1273 Griewank, P. J., and D. Notz (2013), Insights into brine dynamics and sea ice desalination from a  
1274 1-D model study of gravity drainage, *Journal of Geophysical Research: Oceans*, 118(7),  
1275 3370-3386.

1276 Hallsworth, J. E., et al. (2007), Limits of life in MgCl<sub>2</sub>-containing environments: chaotropy  
1277 defines the window, *Environ Microbiol*, 9(3), 801-813, doi:10.1111/j.1462-  
1278 2920.2006.01212.x.

1279 Hammond, N. P., E. Parmentier, and A. C. Barr (2018), Compaction and Melt Transport in  
1280 Ammonia-Rich Ice Shells: Implications for the Evolution of Triton, *Journal of*  
1281 *Geophysical Research: Planets*, 123(12), 3105-3118.

1282 Han, L., and A. P. Showman (2005), Thermo-compositional convection in Europa's icy shell with  
1283 salinity, *Geophysical research letters*, 32(20).

1284 Hays, L. E., H. V. Graham, D. J. Des Marais, E. M. Hausrath, B. Horgan, T. M. McCollom, M. N.  
1285 Parenteau, S. L. Potter-McIntyre, A. J. Williams, and K. L. Lynch (2017), Biosignature  
1286 preservation and detection in Mars analog environments, *Astrobiology*, 17(4), 363-400.

1287 Head, J., R. Pappalardo, R. Greeley, R. Sullivan, C. Pilcher, G. Schubert, W. Moore, M. Carr, J.  
1288 Moore, and M. Belton (1997), Evidence for recent solid-state convection on Europa: The  
1289 nature of pits, domes, spots, and ridges, paper presented at Bulletin of the American  
1290 Astronomical Society.

1291 Hebditch, D., and J. Hunt (1974), Observations of ingot macrosegregation on model systems,  
1292 *Metallurgical transactions*, 5(7), 1557-1564.

1293 Helfenstein, P., and E. M. Parmentier (1983), Patterns of Fracture and Tidal Stresses on Europa,  
1294 *Icarus*, 53(3), 415-430, doi:Doi 10.1016/0019-1035(83)90206-3.

1295 Hendrix, A. R., et al. (2019), The NASA Roadmap to Ocean Worlds, *Astrobiology*, 19(1), 1-27,  
1296 doi:10.1089/ast.2018.1955.

1297 Hesse, M., J. Jordan, S. Vance, and C. McCarthy (2019), Oxidant Transport Through Europa's Ice  
1298 Shell by Porosity Waves, paper presented at Lunar and Planetary Science Conference.

1299 Hesse, M. A., and J. C. Castillo-Rogez (2019), Thermal Evolution of the Impact-Induced  
1300 Cryomagma Chamber Beneath Occator Crater on Ceres, *Geophysical Research Letters*,  
1301 46(3), 1213-1221, doi:10.1029/2018gl080327.

1302 Holland, P. R., H. F. J. Corr, D. G. Vaughan, A. Jenkins, and P. Skvarca (2009), Marine ice in  
1303 Larsen Ice Shelf, *Geophysical Research Letters*, 36(11), doi:Artn L11604  
1304 10.1029/2009gl038162.

1305 Hoppa, G., R. Greenberg, B. R. Tufts, P. Geissler, C. Phillips, and M. Milazzo (2000), Distribution  
1306 of strike-slip faults on Europa, *Journal of Geophysical Research: Planets*, 105(E9), 22617-  
1307 22627.

1308 Hoppa, G., B. R. Tufts, R. Greenberg, and P. Geissler (1999), Strike-slip faults on Europa: Global  
1309 shear patterns driven by tidal stress, *Icarus*, 141(2), 287-298, doi:DOI  
1310 10.1006/icar.1999.6185.

1311 Howell, S. M., and R. T. Pappalardo (2018), Band Formation and Ocean-Surface Interaction on  
1312 Europa and Ganymede, *Geophysical Research Letters*, 45(10), 4701-4709.

1313 Hunke, E. C., D. Notz, A. K. Turner, and M. Vancoppenolle (2011), The multiphase physics of  
1314 sea ice: a review for model developers, *Cryosphere*, 5(4), 989-1009, doi:10.5194/tc-5-989-  
1315 2011.

1316 Huppert, H. E. (1990), The fluid mechanics of solidification, *Journal of Fluid Mechanics*, 212,  
1317 209-240.

1318 Johnson, B. C., R. Y. Sheppard, A. C. Pascuzzo, E. A. Fisher, and S. E. Wiggins (2017), Porosity  
1319 and Salt Content Determine if Subduction Can Occur in Europa's Ice Shell, *Journal of*  
1320 *Geophysical Research-Planets*, 122(12), 2765-2778, doi:10.1002/2017je005370.

1321 JPL (2017), Report of the Europa Lander Science Definition Team.

1322 Kalousova, K., D. M. Schroeder, and K. M. Soderlund (2017), Radar attenuation in Europa's ice  
1323 shell: Obstacles and opportunities for constraining the shell thickness and its thermal  
1324 structure, *Journal of Geophysical Research-Planets*, 122(3), 524-545,  
1325 doi:10.1002/2016je005110.

1326 Kalousová, K., and C. Sotin (2020), Dynamics of Titan's high-pressure ice layer, *Earth and*  
1327 *Planetary Science Letters*, 545, 116416.

1328 Kalousová, K., C. Sotin, G. Choblet, G. Tobie, and O. Grasset (2018), Two-phase convection in  
1329 Ganymede's high-pressure ice layer—Implications for its geological evolution, *Icarus*,  
1330 299, 133-147.

1331 Kalousová, K., O. Souček, G. Tobie, G. Choblet, and O. Čadek (2014), Ice melting and downward  
1332 transport of meltwater by two-phase flow in Europa's ice shell, *Journal of Geophysical*  
1333 *Research: Planets*, 119(3), 532-549.

1334 Kalousová, K., O. Souček, G. Tobie, G. Choblet, and O. Čadek (2016), Water generation and  
1335 transport below Europa's strike-slip faults, *Journal of Geophysical Research: Planets*,  
1336 121(12), 2444-2462.

1337 Khazendar, A., and A. Jenkins (2003), A model of marine ice formation within Antarctic ice shelf  
1338 rifts, *Journal of Geophysical Research-Oceans*, 108(C7), doi:Artn 3235  
1339 10.1029/2002jc001673.

1340 Khazendar, A., E. Rignot, and E. Larour (2009), Roles of marine ice, rheology, and fracture in the  
1341 flow and stability of the Brunt/Stancomb-Wills Ice Shelf, *Journal of Geophysical*  
1342 *Research: Earth Surface*, 114(F4).

1343 Lawrence, J., B. Schmidt, P. Washam, C. L. Hulbe, H. J. Horgan, C. Stevens, G. B. Dunbar, M.  
1344 R. Meister, B. Hurwitz, and E. Quartini (2020), ROV Icefin at Ross Ice Shelf Grounding  
1345 Zone: 5 km of ice, ocean, seafloor, and crevasse exploration, paper presented at AGU Fall  
1346 Meeting Abstracts.

1347 Leitch, A. (1987), Various aqueous solutions crystallizing from the side, in *Structure and*  
1348 *Dynamics of Partially Solidified Systems*, edited, pp. 37-57, Springer.

1349 Leitch, A. M. (1985), Laboratory models of magma chambers evolving due to side-wall  
1350 crystallization.

1351 Li, J., M. Wu, A. Ludwig, and A. Kharicha (2014), Simulation of macrosegregation in a 2.45-ton  
1352 steel ingot using a three-phase mixed columnar-equiaxed model, *International journal of*  
1353 *heat and mass transfer*, 72, 668-679.

1354 Manga, M., and C. Michaut (2017), Formation of lenticulae on Europa by saucer-shaped sills,  
1355 *Icarus*, 286, 261-269, doi:10.1016/j.icarus.2016.10.009.

1356 Manga, M., and A. Sinton (2004), Formation of bands and ridges on Europa by cyclic deformation:  
1357       Insights from analogue wax experiments, *Journal of Geophysical Research-Planets*,  
1358       109(E9), doi:Artn E09001  
1359       10.1029/2004je002249.

1360 Manga, M., and C. Y. Wang (2007), Pressurized oceans and the eruption of liquid water on Europa  
1361       and Enceladus, *Geophysical Research Letters*, 34(7), doi:Artn L07202  
1362       10.1029/2007gl029297.

1363 Matson, D. L., J. C. Castillo, J. Lunine, and T. V. Johnson (2007), Enceladus' plume:  
1364       Compositional evidence for a hot interior, *Icarus*, 187(2), 569-573,  
1365       doi:10.1016/j.icarus.2006.10.016.

1366 McCarthy, C., J. R. Blackford, and C. E. Jeffree (2013), Low-temperature-SEM study of dihedral  
1367       angles in the ice-I/sulfuric acid partially molten system, *J Microsc*, 249(2), 150-157,  
1368       doi:10.1111/jmi.12003.

1369 McCarthy, C., R. F. Cooper, D. L. Goldsby, W. B. Durham, and S. H. Kirby (2011), Transient and  
1370       steady state creep response of ice I and magnesium sulfate hydrate eutectic aggregates,  
1371       *Journal of Geophysical Research-Planets*, 116(E4), doi:Artn E04007  
1372       10.1029/2010je003689.

1373 McCarthy, C., R. F. Cooper, S. H. Kirby, K. D. Rieck, and L. A. Stern (2007), Solidification and  
1374       microstructures of binary ice-I/hydrate eutectic aggregates, *American Mineralogist*,  
1375       92(10), 1550-1560, doi:10.2138/am.2007.2435.

1376 McGuinness, M. J., M. J. M. Williams, P. J. Langhorne, C. Purdie, and J. Crook (2009), Frazil  
1377       deposition under growing sea ice, *Journal of Geophysical Research-Oceans*, 114(C7),  
1378       doi:Artn C07014  
1379       10.1029/2007je004414.

1380 Mehrabian, R., M. Keane, and M. Flemings (1970), Interdendritic fluid flow and  
1381       macrosegregation; influence of gravity, *Metallurgical and Materials Transactions B*, 1(5),  
1382       1209-1220.

1383 Michaut, C., and M. Manga (2014), Domes, pits, and small chaos on Europa produced by water  
1384       sills, *Journal of Geophysical Research: Planets*, 119(3), 550-573.

1385 Moore, J. C. (2000), Models of radar absorption in European ice, *Icarus*, 147(1), 292-300, doi:DOI  
1386       10.1006/icar.2000.6425.

1387 Nakawo, M., and N. K. Sinha (1981), Growth rate and salinity profile of first-year sea ice in the  
1388       high Arctic, *Journal of Glaciology*, 27(96), 315-330.

1389 Nathan, E., M. Berton, T. Girona, H. Karani, C. Huber, J. Head III, and P. Williard (2019), The  
1390       Freezing and Fracture of Icy Satellites: Experimental Analog and Stress Analysis,  
1391       *AGUFM*, 2019, P53D-3489.

1392 Nimmo, F. (2020), Solving the puzzle of Enceladus's active south pole, *Proc Natl Acad Sci U S A*,  
1393       117(28), 16107-16108, doi:10.1073/pnas.2011055117.

1394 Nimmo, F., and E. Gaidos (2002), Strike-slip motion and double ridge formation on Europa,  
1395       *Journal of Geophysical Research: Planets*, 107(E4), 5-1-5-8.

1396 Nimmo, F., and R. T. Pappalardo (2016), Ocean worlds in the outer solar system, *Journal of*  
1397       *Geophysical Research-Planets*, 121(8), 1378-1399, doi:10.1002/2016je005081.

1398 Nimmo, F., and P. Schenk (2006), Normal faulting on Europa: implications for ice shell properties,  
1399       *Journal of Structural Geology*, 28(12), 2194-2203, doi:10.1016/j.jsg.2005.08.009.

1400 Notz, D., J. S. Wettlaufer, and M. G. Worster (2005), A non-destructive method for measuring the  
1401 salinity and solid fraction of growing sea ice in situ, *Journal of Glaciology*, 51(172), 159-  
1402 166, doi:Doi 10.3189/172756505781829548.

1403 Notz, D., and M. G. Worster (2009), Desalination processes of sea ice revisited, *Journal of*  
1404 *Geophysical Research-Oceans*, 114(C5), doi:Artn C05006  
1405 10.1029/2008jc004885.

1406 Pappalardo, R. T., and A. C. Barr (2004), The origin of domes on Europa: The role of thermally  
1407 induced compositional diapirism, *Geophysical Research Letters*, 31(1), doi:Artn L01701  
1408 10.1029/2003gl019202.

1409 Parkinson, J. R. (2019), Nonlinear convection in sea ice and other mushy layers, 258 pp, University  
1410 of Oxford.

1411 Parkinson, J. R., D. F. Martin, and J. Buffo (2020a), jrgparkinson/mushy-layer: Code and input  
1412 files for Europa simulations, edited, GitHub, doi:10.5281/zenodo.4118457.

1413 Parkinson, J. R., D. F. Martin, A. J. Wells, and R. F. Katz (2020b), Modelling binary alloy  
1414 solidification with adaptive mesh refinement, *Journal of Computational Physics: X*, 5,  
1415 100043.

1416 Perl, S., S. Adeli, C. Basu, B. K. Baxter, J. Bowman, E. Boyd, M. Cable, A. J. Celestian, C. S.  
1417 Cockell, and F. A. Corsetti (2021), Salty Environments: The importance of evaporites and  
1418 brine environments as habitats and preservers of biosignatures, *Bulletin of the American*  
1419 *Astronomical Society*, 53(4), 240.

1420 Pontefract, A., C. E. Carr, and M. R. Osburn (2019), The Role of Ionic Composition and  
1421 Concentration on Biosignature Preservation: Lessons from the “Spotted” Lakes of British  
1422 Columbia, paper presented at 2019 Astrobiology Science Conference, AGU.

1423 Postberg, F., S. Kempf, J. Schmidt, N. Brilliantov, A. Beinsen, B. Abel, U. Buck, and R. Srama  
1424 (2009), Sodium salts in E-ring ice grains from an ocean below the surface of Enceladus,  
1425 *Nature*, 459(7250), 1098-1101, doi:10.1038/nature08046.

1426 Postberg, F., J. Schmidt, J. Hillier, S. Kempf, and R. Srama (2011), A salt-water reservoir as the  
1427 source of a compositionally stratified plume on Enceladus, *Nature*, 474(7353), 620-622,  
1428 doi:10.1038/nature10175.

1429 Prockter, L. M., J. W. Head, R. T. Pappalardo, R. J. Sullivan, A. E. Clifton, B. Giese, R. Wagner,  
1430 and G. Neukum (2002), Morphology of European bands at high resolution: A mid-ocean  
1431 ridge-type rift mechanism, *Journal of Geophysical Research: Planets*, 107(E5).

1432 Quick, L. C., D. L. Buczkowski, O. Ruesch, J. E. C. Scully, J. Castillo-Rogez, C. A. Raymond, P.  
1433 M. Schenk, H. G. Sizemor, and M. V. Sykes (2019), A Possible Brine Reservoir Beneath  
1434 Occator Crater: Thermal and Compositional Evolution and Formation of the Cerealia  
1435 Dome and Vinalia Faculae, *Icarus*, 320, 119-135, doi:10.1016/j.icarus.2018.07.016.

1436 Rudolph, M. L., and M. Manga (2009), Fracture penetration in planetary ice shells, *Icarus*, 199(2),  
1437 536-541, doi:10.1016/j.icarus.2008.10.010.

1438 Schmidt, B. (2020), The Astrobiology of Europa and the Jovian System, *Planetary Astrobiology*,  
1439 185.

1440 Schmidt, B. E., D. D. Blankenship, G. W. Patterson, and P. M. Schenk (2011), Active formation  
1441 of 'chaos terrain' over shallow subsurface water on Europa, *Nature*, 479(7374), 502-505,  
1442 doi:10.1038/nature10608.

1443 Schmidt, B. E., and J. Buffo (2017), Biomarker Production and Preservation on Europa, paper  
1444 presented at European Planetary Science Congress.

1445 Schroeder, D. M., A. Romero-Wolf, L. Carrer, C. Grima, B. A. Campbell, W. Kofman, L.  
1446 Bruzzone, and D. D. Blankenship (2016), Assessing the potential for passive radio  
1447 sounding of Europa and Ganymede with RIME and REASON, *Planetary and Space*  
1448 *Science*, 134, 52-60, doi:10.1016/j.pss.2016.10.007.

1449 Smedsrud, L. H., and A. Jenkins (2004), Frazil ice formation in an ice shelf water plume, *Journal*  
1450 *of Geophysical Research-Oceans*, 109(C3), doi:Artn C03025  
1451 10.1029/2003jc001851.

1452 Sotin, C., J. W. Head, and G. Tobie (2002), Europa: Tidal heating of upwelling thermal plumes  
1453 and the origin of lenticulae and chaos melting, *Geophysical Research Letters*, 29(8), 74-  
1454 71-74-74, doi:Artn 1233  
1455 10.1029/2001gl013844.

1456 Sotin, C., and G. Tobie (2004), Internal structure and dynamics of the large icy satellites, *Comptes*  
1457 *Rendus Physique*, 5(7), 769-780, doi:10.1016/j.crhy.2004.08.001.

1458 Sparks, W. B., K. P. Hand, M. A. McGrath, E. Bergeron, M. Cracraft, and S. E. Deustua (2016),  
1459 Probing for Evidence of Plumes on Europa with Hst/Stis, *Astrophysical Journal*, 829(2),  
1460 121, doi:Artn 121  
1461 10.3847/0004-637x/829/2/121.

1462 Steefel, C. I., D. J. DePaolo, and P. C. Lichtner (2005), Reactive transport modeling: An essential  
1463 tool and a new research approach for the Earth sciences, *Earth and Planetary Science*  
1464 *Letters*, 240(3-4), 539-558, doi:10.1016/j.epsl.2005.09.017.

1465 Stephen, R., J. Sparks, and H. E. Huppert (1987), Laboratory Experiments with Aqueous Solutions  
1466 Modelling Magma Chamber Processes. I. Discussion of Their Validity and Geological  
1467 Application, in *Origins of Igneous Layering*, edited, pp. 527-538, Springer.

1468 Thomas, R., J. D. Webster, and P. Davidson (2006), Understanding pegmatite formation: the melt  
1469 and fluid inclusion approach, *Melt inclusions in plutonic rocks*, 36, 189-210.

1470 Tison, J.-L., and V. Verbeke (2001), Chlorinity/salinity distribution patterns in experimental  
1471 granular sea ice, *Annals of Glaciology*, 33, 13-20.

1472 Toner, J. D., D. C. Catling, and B. Light (2014), The formation of supercooled brines, viscous  
1473 liquids, and low-temperature perchlorate glasses in aqueous solutions relevant to Mars,  
1474 *Icarus*, 233, 36-47, doi:10.1016/j.icarus.2014.01.018.

1475 Troch, J., C. Huber, and O. Bachmann (2021), The physical and chemical evolution of magmatic  
1476 fluids in near-solidus silicic magma reservoirs: Implications for the formation of  
1477 pegmatites, *Goldschmidt2021• Virtual• 4-9 July*.

1478 Trumbo, S. K., M. E. Brown, and K. P. Hand (2019), Sodium chloride on the surface of Europa,  
1479 *Sci Adv*, 5(6), eaaw7123, doi:10.1126/sciadv.aaw7123.

1480 Turcotte, D., and G. Schubert (2014), *Geodynamics*, Cambridge University Press.

1481 Vance, S. D., K. P. Hand, and R. T. Pappalardo (2016), Geophysical controls of chemical  
1482 disequilibria in Europa, *Geophysical Research Letters*, 43(10), 4871-4879,  
1483 doi:10.1002/2016gl068547.

1484 Vance, S. D., B. Journaux, M. Hesse, and G. Steinbrügge (2020), The Salty Secrets of Icy Ocean  
1485 Worlds, *Journal of Geophysical Research: Planets*, e2020JE006736.

1486 Vance, S. D., M. P. Panning, S. Stähler, F. Cammarano, B. G. Bills, G. Tobie, S. Kamata, S. Kedar,  
1487 C. Sotin, and W. T. Pike (2018), Geophysical investigations of habitability in ice-covered  
1488 ocean worlds, *Journal of Geophysical Research: Planets*, 123(1), 180-205.

1489 Waite, J. H., Jr., et al. (2006), Cassini ion and neutral mass spectrometer: Enceladus plume  
1490 composition and structure, *Science*, 311(5766), 1419-1422, doi:10.1126/science.1121290.

1491 Walker, C., and B. Schmidt (2015), Ice collapse over trapped water bodies on Enceladus and  
1492 Europa, *Geophysical Research Letters*, 42(3), 712-719.

1493 Walker, C., B. Schmidt, and J. Bassis (2014), Breaking the ice: On the application of fracture  
1494 system mechanics and fragmentation theory to the chaos regions of Europa, *LPI(1777)*,  
1495 2659.

1496 Walker, C. C., J. N. Bassis, and B. E. Schmidt (2021), Propagation of Vertical Fractures through  
1497 Planetary Ice Shells: The Role of Basal Fractures at the Ice–Ocean Interface and Proximal  
1498 Cracks, *The Planetary Science Journal*, 2(4), 135.

1499 Wells, A. J., J. R. Hitchen, and J. R. G. Parkinson (2019), Mushy-layer growth and convection,  
1500 with application to sea ice, *Philos Trans A Math Phys Eng Sci*, 377(2146), 20180165,  
1501 doi:10.1098/rsta.2018.0165.

1502 Wolfenbarger, N., D. Blankenship, K. Soderlund, D. Young, and C. Grima (2018), Leveraging  
1503 Terrestrial Marine Ice Cores to Constrain the Composition of Ice on Europa, *LPI*  
1504 *Contributions*, 2100.

1505 Wolfenbarger, N., K. Soderlund, and D. Blankenship (2019), Revisiting the Salt Distribution  
1506 Coefficient for Icy Ocean Worlds, *LPI Contributions*, 2168.

1507 Worster, M. G., H. E. Huppert, and R. S. J. Sparks (1990), Convection and Crystallization in  
1508 Magma Cooled from Above, *Earth and Planetary Science Letters*, 101(1), 78-89, doi:Doi  
1509 10.1016/0012-821x(90)90126-I.

1510 Worster, M. G., and D. W. Rees Jones (2015), Sea-ice thermodynamics and brine drainage, *Philos*  
1511 *Trans A Math Phys Eng Sci*, 373(2045), 20140166, doi:10.1098/rsta.2014.0166.

1512 Zolotov, M. Y., and J. Kargel (2009), *On the chemical composition of Europa's icy shell, ocean,*  
1513 *and underlying rocks*, University of Arizona Press Tucson, AZ.

1514 Zotikov, I. A., V. S. Zagorodnov, and J. V. Raikovsky (1980), Core Drilling through the Ross Ice  
1515 Shelf (Antarctica) Confirmed Basal Freezing, *Science*, 207(4438), 1463-1464, doi:DOI  
1516 10.1126/science.207.4438.1463.

1517