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1 Accumulation Processes of Trace Metals into Arctic Sea Ice: Distribution of Fe, Mn 2 and Cd Associated with Ice Structure

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11

12

13 *Abstract*

14 Biogeochemical cycling of trace metals in sea ice is important to the productivity of the
15 Arctic Ocean. Unfortunately, the processes by which trace metals accumulate into sea ice are
16 poorly understood. To gain a clearer understanding of the mechanisms behind trace metal
17 accumulation, dissolved (D, <0.2 µm), and labile particulate (LP = Total Dissolvable - Dissolved)
18 iron (Fe), manganese (Mn), and cadmium (Cd) concentrations were compared to the structure
19 observed in sea ice. Samples were pre-concentrated via solid-phase extraction on NOBIAS

20 Chelate PA-1 resin and analyzed on a Graphite Furnace Atomic Absorption Spectrometer. Using
21 photographic analysis for the percentage of pore microstructure and $\delta^{18}\text{O}$ analysis, sea ice
22 structure was determined to be snow ice, granular ice (frazil ice), mixed ice (granular and
23 columnar ice) and columnar ice. Salinity and nutrients were low, indicating brine drainage and
24 multi-year ice. High trace metal concentrations in snow ice indicated meteoric snow was a
25 source of trace metals to sea ice. High concentrations of LPFe in granular ice indicated
26 entrainment of suspended particulate trace metals by frazil ice during the formation of the
27 granular ice structure. Whereas the high concentrations of DFe and DMn in granular ice may
28 have been due to reduction from LPFe and LPMn after particle entrainment, indicating chemical
29 transformation processes. Low dissolved and labile particulate trace metal concentrations in
30 mixed and columnar ice indicated a release due to brine drainage. Our study clearly indicates
31 that the differences observed in trace metals among sea ice structures, showed that sea ice
32 formation, chemical reduction and brine release were the processes driving trace metal
33 accumulation and release in the Arctic sea ice.

34 Key Words: Sea ice structure; Trace metals; Dissolved; Labile Particulate

35

36 *Introduction*

37 The Arctic Ocean is characterized by a persistent layer of perennial (multi-year) sea ice
38 during the summer. Multi-year ice is a buffer for solar radiation and a source of both freshwater
39 and trace metals into the Arctic Ocean (Eicken et al., 1995; Tovar-Sanchez et al., 2010). In
40 recent years the Arctic has seen an increase in atmospheric temperatures by 1.6°C , over double

41 the global average rate for mean temperatures (Overland et al., 2017). During the spring and
42 autumn seasons, the Pacific and Canadian regions have shown the greatest increases in
43 temperature (Przybylak, 2007). Relating this to Arctic sea ice extent, a decreasing trend of -
44 13.2% per decade was observed when compared to the sea ice extent averages of 1981 - 2010
45 (Perovich et al., 2017). In regard to multi-year ice, a decrease of $7 \times 10^6 \text{ km}^2$ to $3.5 \times 10^6 \text{ km}^2$
46 was observed from 1980 - 2017 (Comiso et al., 2017). Decreases in sea ice extent may point to a
47 regime shift from multi-year ice towards annual (first-year) ice. The presence of thick, multi-
48 year ice dampens wave energy, creating calm waters (Ackley and Sullivan, 1994; Squire and
49 Moore, 1980). The thinner first-year ice is highly influenced by turbulent waves and strong
50 winds. These dynamic conditions can allow for sea ice to collide and thicken through rafting or
51 ridging events (Squire and Moore, 1980; Toyota et al., 2004).

52 Sea ice initially forms when seawater is supercooled (-1.86°C) creating thermohaline
53 mixing by the convection of heat from the warmer water at depth to the now cooler surface
54 water. With the aid of wind and wave energy frazil ice will form (Eicken, 2003). Frazil ice crystals
55 (3 to 4 mm) form under rough conditions (strong winds or rough currents) at the water's
56 surface, within the water column, or along shelf areas (Kempema et al., 1989; Maykut, 1985;
57 Weeks and Ackley, 1986). As frazil ice float to the surface they create a slush layer that can
58 reduce thermohaline mixing and wind stress (Eicken, 2003; Maykut, 1985). Continual freezing
59 and ice condensing forms grease ice that can solidify up to 10 cm depth (granular ice; Maykut,
60 1985) creating calm conditions under the ice. As seawater congeals downward in calm
61 conditions it forms vertically elongated, prismatic crystal structures known as columnar ice
62 (Eicken et al., 1995; Maykut, 1985). The composition of sea ice is a complex, porous matrix. As

63 sea ice forms, salts concentrate into interstitial dense liquid brine. Some of this brine is released
64 from the ice to ultimately form dense bottom water (Weingartner et al., 1998), while some can
65 be trapped in ice pockets (brine channels) until ice permeability increases (Golden et al., 1998).
66 As brine is retained in sea ice, it can affect the sea ice's nutrient and trace metal composition
67 (Lannuzel et al., 2008; van der Merwe et al., 2011). The rapid decline of multi-year ice in the
68 Arctic may affect the biogeochemical cycling of trace metals, hindering the supply of these
69 metals to the underlying seawater.

70 Within the polar oceans, sea ice is a source of trace metals to the underlying seawaters
71 (Grotti et al., 2005; Sedwick and DiTullio, 1997). The Ross Sea concentrations of particulate
72 ($>0.4\text{ }\mu\text{m}$) and dissolved ($<0.4\text{ }\mu\text{m}$) metals in sea ice were enriched up to two orders of
73 magnitude when compared to the underlying seawater (Grotti et al., 2005). As sea ice melts, it
74 can supply trace metals to the underlying surface seawaters. Aguilar-Isla et al. (2008) found
75 that melting sea ice in the outer Bering Sea shelf provided additional DFe to ice-edge
76 phytoplankton that may have increased their biomass and utilization of available nitrate. A
77 study done by Evans and Nishioka (2018) observed drift sea ice from the Chukchi Sea was
78 dominated by the labile particulate (LP = difference between the total dissolvable; TD,
79 unfiltered sample; and dissolved; D, $<0.22\text{ }\mu\text{m}$ filtered sample) fraction of iron (Fe), manganese
80 (Mn) and cadmium (Cd) when compared to Chukchi surface seawater. It is possible that the
81 consistent flushing of seawater, or brine drainage released the available dissolved metals in the
82 drift sea ice. The migration of sea ice in the Arctic Ocean allows sea ice to transport
83 incorporated materials (such as trace metals, nutrients and sediments) from areas of formation
84 (e.g. shelf seas) to areas of melting (e.g. open ocean, basins; Darby, 2003; Eicken et al., 2005).

85 This gives sea ice the potential to circulate trace metals biogeochemically, increasing its
86 importance as a source in the Arctic Ocean (Grotti et al., 2005; Lannuzel et al., 2008). To add to
87 the body of knowledge for the biogeochemistry of trace metals in polar sea ice, the goal of this
88 study was to observe the mechanisms behind accumulation and release of trace metals from
89 Arctic sea ice.

90 Observations of ice structure can allow for the detection of the formation process of sea
91 ice. It is possible that, as sea ice forms, it may incorporate trace metals into the ice. Trace
92 metals may also accumulate into ice after it is established. The processes by which trace metals
93 are retained or released from the ice are varied and not clear. In seawater, Fe, Mn and Cd
94 exhibit different chemical sensitivity and behavioral (i.e. oxidation-reduction reactions)
95 properties. Manganese displays a scavenging-type distribution where it has interactions with
96 particles and shelf sediments. Cadmium is an example of a nutrient-type distribution. This metal
97 is influenced by biological processes (i.e. phosphate cycle) and organic particulate matter. Iron
98 shows more of a scavenging-type distribution and can also display nutrient-type behavior
99 (Bruland et al., 1994; Bruland and Lohan, 2006). Comparisons of Fe and Mn yield different
100 reduction potentials (Landing and Bruland, 1987; Saager et al., 1989) which may influence the
101 concentrations of their size fractions (Evans and Nishioka, 2018). Relating the concentrations of
102 trace metals that display different actions in sea ice structure, from an Arctic core sample, may
103 aid in revealing mechanisms behind trace metal accumulation.

104 *Materials and Methods*

105 *Materials Cleaning Procedure*

106 High-density polyethylene (HDPE) jars, HDPE buckets, and low-density polyethylene
107 (LDPE) bottles (HDPE, LDPE, Nalgene Company, Limited), Teflon (bottles and tubing), filters
108 (0.22 µm, Durapore, Millipore Ltd.), and other plastics were cleaned using the methods outlined
109 in previous studies (Nishioka et al., 2001; Takeda and Obata, 1995) for trace metal clean
110 sampling and analysis of sea ice. Ceramic knives used during the cleaning (planing) step for sea
111 ice were cleaned in an onshore clean room by the following procedure: knives were placed in
112 5% Extran® (alkaline and phosphate-free liquid, Merck) for one day, rinsed with reverse osmosis
113 (RO) water then placed in ultrapure hydrochloric acid (0.1 M HCl, Tamapure-AA-10, Tama
114 Chemical Ltd.) for one day. The knives were rinsed with Milli-Q water (Millipore Ltd.) and air
115 dried on a laminar flow clean bench before use.

116 An acrylic ice holder (Fig. 1) was used in the ice planing step to keep the ice core sample
117 stable during planing. The ice holder was cleaned by a 5 % Extran® bath for one day, rinsed with
118 RO water and air dried. Ice samples were prepared by planing in a 137 L freezer (cold tub,
119 Panasonic; Fig. 1) located in a dust free clean room. The cold tub was covered with clean plastic,
120 allowing it to maintain the preset temperature (-20°C). 24 hrs before ice planing, the cold tub
121 was turned on and all planing materials (ceramic knives, gloves, collection buckets, etc.) were
122 double bagged and placed in the cold tub as the tub cooled down to -20°C. For each subsequent
123 sample that was planed, the cold tub was cleaned of previous ice waste generated during
124 planing and air dried in the clean room.

125 *Sea Ice Sampling*

126 Sea ice was collected from the Beaufort Sea on August 2013 at ice station 76°56'N,
127 138°38'W during the JIOS cruise aboard the *CCGS Louis S. St-Laurent* (Fig. 2). Sea ice was
128 sampled with a 9 cm diameter corer and the core length was immediately measured with a
129 tape measure (Fig. 3a). The core sample was then cut in half (50 cm and 53 cm respectively),
130 individually placed in coolers and transported to an onboard cold room (-15°C) before being
131 transported to an onshore cold room (-15°C). The sample was held for 4 years before analysis.

132 *Milli-Q Ice Contamination Test*

133 The corer used to collect the sea ice was made of metal. Unfortunately, this process can
134 contaminate the outer layers of the sea ice sample for trace metal analysis. To account for this
135 contamination, sea ice is usually cleaned through planing a couple of centimeters off the outer
136 ice layers with acid cleaned ceramic knives. The cleaned inner core of the ice is then analyzed
137 for trace metals. To determine the amount of contamination contributed by ice planing
138 materials (ceramic knives, plastics and collection buckets), the coring process and the planing
139 procedure, a contamination test was performed on Milli-Q ice. All samples were handled with
140 clean plastic gloves and plastic wrap. In an onshore class 100 clean room, two Milli-Q ice
141 samples were prepared by freezing Milli-Q water in acid cleaned 500 mL HDPE bottles (tops cut
142 off). The resulting ice formed as a cylinder (Milli-Q ice). One day before planing, one of the Milli-
143 Q ice samples was removed from the 500 mL bottle and wrapped in aluminum foil (Foil ice). It
144 was placed in the cold tub to mimic contamination resulting from the coring process during
145 sample collection. The other Milli-Q ice was left untouched in the freezer before the planing
146 step (Milli-Q Clean ice). Each Milli-Q ice was planed separately.

147 Before ice planing, the ice holder was wrapped in clean plastic and placed in the cold
148 tub (-20°C). For the Foil ice, the aluminum foil was removed before planing. For the Milli-Q
149 Clean ice, the ice sample was removed from the bottle and immediately planed to minimize
150 handling. For each ice sample two layers (1 cm each) was planed using acid cleaned ceramic
151 knifes. A new, clean knife was used to plane each side as evenly as possible. All ice pieces that
152 were in contact with the planing materials were collected into acid cleaned 325 mL HDPE jars.
153 The planed ice core was collected in acid cleaned HDPE buckets and all samples were melted at
154 room temperature in a dust free clean room. Melted samples were immediately acidified by
155 ultrapure HCl (final concentration 0.05 M with <pH 2.0, Tamapure-AA-10) and pre-concentrated
156 via NOBIAS Chelate PA-1 resin (NOBIAS, 150 mg, Hitachi High-Technologies Co.) before analysis
157 on a graphite furnace atomic adsorption spectrophotometer (GFAAS, Hitachi High-Technologies
158 Co.). The Milli-Q ice contamination test results are shown in Figure 4 (pre-concentration factor
159 ranging from 4.6 - 8.7 times, avg. 7.5 times). Planing 2 cm of ice off the outer core sample was
160 sufficient for trace metal analysis as the ice planing materials and procedure did not contribute
161 contamination to the ice sample.

162 *Sea Ice Planing and Preparation*

163 When the sea ice core sample was planed, a blank sample (Milli-Q water) was frozen
164 (Milli-Q blank) in a 325 mL LDPE jar and set in the cold tub. The Milli-Q blank was used to check
165 that the planing conditions were clear of contamination. The planing of sea ice followed the
166 methods outlined above. Once 2 cm of the outer ice core was planed, the sample was visually
167 observed and separated based on sea ice structure. Pictures of each section were taken with a
168 digital camera to aid with the sea ice structure determination. Pictures were transformed to

169 black and white and overlaid with a filter to detect the outline of the pore microstructure
170 captured in the pictures (GNU Image Manipulation Program, GIMP). The % white area in the
171 transformed pictures, the area that represents the outline of the pore microstructure
172 (hereafter porosity %), was calculated using R analysis package (R Core Team 2013; Ooms,
173 2018; Mouselimis, 2018). This analysis allowed for an objective discrimination between
174 granular and columnar ice, and the identification of mixed (granular plus columnar) ice. All
175 planed samples, and the Milli-Q blank, were placed in acid clean HDPE buckets and melted at
176 room temperature in a clean room.

177 Immediately after melting, samples were separated for trace metal analysis, salinity,
178 $\delta^{18}\text{O}$, and nutrients. Nutrient samples were re-frozen immediately after melting and stored
179 before analysis. To prepare for trace metal analysis, a portion of the meltwater was separated
180 into acid cleaned 125 mL LDPE bottles for total dissolvable samples and immediately acidified
181 with ultrapure HCl (final concentration 0.05 M with <pH 2.0, Tamapure-AA-10). Another portion
182 of meltwater (dissolved) was immediately filtered by 0.22 μm Durapore filters (Milipore) with a
183 peristaltic pump (Cole-Parmer Instrument Company), Teflon micro-tubing and a Teflon filter
184 holder into acid cleaned 125 mL LDPE bottles. The filtrate was immediately acidified with
185 ultrapure HCl (final concentration 0.05 M with <pH 2.0, Tamapure-AA-10). All samples were
186 held for 3 weeks in a clean room before analysis.

187 *Analytical Methods*

188 *NOBIAS Pre-Concentration Method*

189 Chemicals used during the pre-concentration process held a chemical grade of reagent,
190 pure or ultrapure and were prepared with Milli-Q water. The NOBIAS Chelate PA-1 chelating
191 resin has a high affinity for trace metals and the ability to separate alkali- and alkaline-earth
192 metals from sea ice and seawater (Evans and Nishioka, 2018; Minami et al., 2015; Sohrin and
193 Bruland, 2011). The cleaning, setup and methods for the NOBIAS pre-concentration are detailed
194 in Evans and Nishioka (2018). Briefly, a 3.36 M acetic acid-ammonium acetate ($\text{HAcO-NH}_4\text{AcO}$)
195 buffer was made from glacial acetic acid (Optima, Fisher Chemical), 20% NH_4OH (ultrapure,
196 Temapure-AA-10) and Milli-Q water. A portion of this buffer was diluted to 0.05 M HAcO-
197 NH_4AcO and purified twice via NOBIAS before use.

198 Pre-concentration for both total dissolvable and dissolved sea ice and ice blank samples
199 with the NOBIAS resin were modified from the methods detailed in Evans and Nishioka (2018).
200 The resin column was initially cleaned by loading 1 M ultrapure HNO_3 (Temapure-AA-100, Tama
201 Chemical Ltd.) at 1 mL/min. and then conditioned with Milli-Q water and 0.05 M $\text{HAcO-NH}_4\text{AcO}$
202 (both at 3 mL/min.). During the conditioning step, 1.8 mL of 3.6 M $\text{HAcO-NH}_4\text{AcO}$ was added to
203 30 mL of sample. The sample's pH was adjusted to $\text{pH } 6 \pm 0.1$ with 20% NH_4OH then loaded
204 onto the resin column (3 mL/min.). The 0.05 M $\text{HAcO-NH}_4\text{AcO}$ (3 mL/min.) buffer followed the
205 sample to flush out any interferences (i.e. salts) and the column was disconnected from the
206 manifold. The eluent was back-eluted by an acid cleaned hand syringe with 10 mL of 1 M
207 ultrapure HNO_3 into an acid clean polyethylene collection tube. To calculate the original trace
208 metal concentration in the meltwater, both the initial and final weights of the eluent and
209 sample bottles were determined. If multiple samples were pre-concentrated, the procedure
210 would begin at the initial cleaning step (1 M HNO_3 at 1 mL/min.).

211 All pre-concentrated samples were analyzed on a GFAAS. Single element standards were
212 made from diluting 1000 ppm individual standards (Wako Chemical Ltd.) of Fe, Mn and Cd in 1
213 M ultrapure HNO₃. The pre-concentration detection limit (DL) was calculated with pre-
214 concentrated Milli-Q procedural blanks by multiplying their standard deviation by three (n = 6).
215 For each metal the detection limit yielded: 2.0 nM Fe, 0.4 nM Mn and 0.05 nM Cd. After pre-
216 concentration and analysis with GFAAS, ice core sample data was compared to the pre-
217 concentrated DL. Comparison with the pre-concentrated DL allowed for accurate detection of
218 the lowest concentrations of elements (Fe, Mn or Cd) within a sample. Pre-concentrated ice
219 core sample data that was above the DL was calculated with the concentration factor (range 2.3
220 - 3.0 times) and presented within this study. Validation of the NOBIAS pre-concentration
221 method was done with NASS-6 reference seawater materials (National Research Council of
222 Canada). Measured values (n = 8) showed 9.5 ± 1.3 nM Fe, 11.2 ± 1.4 nM Mn and 0.3 ± 0.1 nM
223 Cd that was similar to the National Council of Canada's certified values (8.9 ± 0.8 nM Fe, 9.6 ±
224 0.9 nM Mn, and 0.3 ± 0.02 nM Cd).

225 *Analysis of Salinity, δ¹⁸O, and Nutrients*

226 For salinity measurements, a portion of the sea ice meltwater was measured for
227 chloride ions using a chloride analyzer (Model SAT-500, Towa Electronic Industry, repeatability:
228 <0.5%). A lab standard regression curve (paired salinity and chloride; AUTOSAL 8400B
229 salinometer, Ocean Scientific International Ltd.) was used to determine the salinity of the
230 meltwater from the measured chloride values. Oxygen isotopes for sea ice were determined by
231 an isotope water analyzer (Picarro, Inc.) with an analytical precision of ± 0.3%. For the nutrient
232 analysis a portion of sea ice meltwater that was frozen was re-melted at room temperature in

233 an onshore class 100 clean room. Samples were analyzed on a continuous flow system
234 autoanalyzer (QuAArto, BL TEC, Inc.). Standard solutions were made in Milli-Q water to match
235 the low salinity of the sea ice samples.

236 *Results*

237 *Physical and Chemical Properties in Sea Ice*

238 Immediately after the ice sample was collected, the sea ice core length was measured to
239 103 cm and photographed (Fig. 3a). The sea ice structure was determined by visual inspection
240 using the terms defined by Petrich and Eicken (2010). Usually thick (5 mm) and thin (0.5 mm)
241 ice sections illuminated by polarized light are used to observe the crystallographic structure
242 (textural variability, boundary layers, etc; Toyota et al., 2004) of sea ice. These sections are cut
243 with a metal saw, contaminating the ice samples for trace metal analysis. To avoid adding
244 contamination during the ice structure analysis, visual observations, photographic image
245 analysis and porosity % analysis were performed on planed ice samples in this study.

246 The ice structures of the planed ice core were analyzed in six sections: 0 - 24 cm, 24 - 41
247 cm, 41 - 58 cm, 58 - 75 cm, 75 - 91 cm and 91 - 103 cm (Fig. 3b). Each section was homogenized
248 before separation for salinity, $\delta^{18}\text{O}$, nutrients and trace metal analysis. Sections were large to
249 account for the volume necessary for the NOBIAS pre-concentration before trace metal
250 analysis. The 0 - 24 cm section showed snow/slush-like ice that was in the transition of turning
251 more solid. The porosity % (Fig. 3c) of this section show 1.9, indicating highly porous ice. A
252 piece of solid ice (below 9 cm; Fig. 3b) may represent snow that was melted and re-frozen,
253 hinting at multi-year ice. Sections 24 - 75 cm showed ice with disconnected pore microstructure

254 that was more apparent than in the 0 - 24 cm section. The porosity % for each section (0.7%,
255 1.3%, and 0.6%, respectively, Fig. 3c) were lower than seen from 0 - 24 cm. From 75 - 91 cm the
256 porosity % (0.5) was similar to the 58 - 75 cm section, but it lacked obvious pore microstructure.
257 Instead the structure represented solid ice intermixed with ice that had disconnected pore
258 microstructures. From 91 - 103 cm solid ice (porosity 0.04%) was observed.

259 Sea ice salinity was observed to be low (1.3 to 2.1, Fig. 5a). In first-year ice, typical
260 salinity profiles exhibit a C-type profile (Cox and Weeks, 1988) with salinities around 5 - 15
261 (Eicken et al., 1995). As sea ice ages and thickens, desalination processes decrease the salinity
262 to below 4 characterizing multi-year ice (Cox and Weeks, 1974; Eicken et al., 1995). Therefore,
263 the observed salinity for this study indicates multi-year ice. It is possible that brine may have
264 been artificially released during the coring process, lowering salinity, nutrient and trace metal
265 concentrations within the ice core sample. After coring an adjacent ice core was tested for
266 salinity. High salinity values would indicate that brine was present in the adjacent sea ice core
267 after coring. If brine was released in the sea ice, before coring, salinity values would be low in
268 the adjacent ice core. The concentrations from the adjacent ice core matched the
269 concentrations within the ice core sample after a 3 year holding period. Therefore, the brine
270 was released from the sea ice sampling site before coring. Nutrient concentrations in the ice
271 core were below the DL ($0.02 \mu\text{mol/L}$ $\text{NO}_3 + \text{NO}_2$, $0.02 \mu\text{mol/L}$ PO_4 , and $0.1 \mu\text{mol/L}$ SiO_2). It is
272 possible that the nutrients, along with the salinity, were released from the sea ice during
273 desalination before coring. Measured $\delta^{18}\text{O}$ values are shown in figure 5b and were used to
274 identify source water to sea ice. As seawater freezes to form sea ice, it induces the
275 fractionation of oxygen isotopes (Toyota et al., 2004; Ukita et al., 2000). This allows for the

276 comparison of $\delta^{18}\text{O}$ with sea ice to determine the water source (freshwater or seawater).
277 During the JIOS cruise, an average surface seawater (<50 m) $\delta^{18}\text{O}$ value for the area near the
278 sampling site was observed at -3.38‰ (Yamamoto-Kawai personal comm.). It is possible that
279 sea ice melt, Pacific origin water and river water mixed with the surface seawater, to decrease
280 the $\delta^{18}\text{O}$ value (Yamamoto-Kawai et al., 2008). A freshwater sample was collected from snow-
281 like ice observed on the surface of the ice sample. The $\delta^{18}\text{O}$ was observed to be -4.1‰ (Surface;
282 Fig. 5b), indicating a meteoric snow source. Although there was a strong freshwater influence
283 on the seawater in this study, the seawater $\delta^{18}\text{O}$ values was higher than that for the surface
284 snow value allowing for the distinction between freshwater and seawater sources during sea
285 ice formation. The sea ice section from 0 - 24 cm had a $\delta^{18}\text{O}$ value of -2.6‰. This section may
286 represent a mixture of both freshwater and seawater sources. Sea ice sections from 24 - 103 cm
287 had $\delta^{18}\text{O}$ values ranging from -1.2 to -0.8‰. This indicates that these sections were sourced
288 from seawater (see discussion). The ice structure was then determined by comparing the $\delta^{18}\text{O}$
289 values with the picture analysis and porosity % analysis from each section. Snow ice was
290 dominate for section 0 - 24 cm, granular ice for section 24 - 75 cm, mixed ice for section 75 - 91
291 cm and columnar ice for section 91 - 103 cm. The ice structures determined from these
292 analyses will be used for the remainder of this study.

293 *Trace Metals*

294 *Dissolved Metals in Sea Ice*

295 Sea ice concentrations for DFe ranged from 1.1 to 4.8 nM (Fig. 6a). Snow ice (3.1 nM)
296 and granular ice (3.6 ± 0.8 nM, $n = 3$) showed higher concentrations when compared to mixed

297 ice (1.1 nM) and columnar ice (1.3 nM). Dissolved Mn in sea ice ranged from 1.4 to 11.0 nM
298 (Fig. 6c). The snow and granular ice showed higher concentrations (5.5 nM and 8.5 ± 3.5 nM,
299 respectively) than mixed (1.5 nM) and columnar (1.4 nM) ice. Dissolved Cd in sea ice was low
300 and ranged from <DL to 0.2 nM (Fig. 6e). Dissolved Cd was only observed in snow (0.1 nM) and
301 granular (0.1 ± 0.06 nM) ice. Within this sea ice sample the snow and granular ice structures
302 held the highest trace metal concentrations.

303 *Labile Particulate Metals in Sea Ice*

304 Concentrations of labile particulate metals seemed to be dependent on the trace metal.
305 LPFe in sea ice ranged from 2.2 to 475.6 nM (Fig. 6b). The snow (92.3 nM) and granular ($232.9 \pm$
306 172 nM, $n = 3$) ice had higher LPFe concentrations when compared to the mixed (7.6 nM) and
307 columnar (2.2 nM) ice. Labile particulate Mn was low in sea ice and ranged from <DL to 0.5 nM
308 (Fig. 6d). Labile particulate Mn was detected in snow (0.5 nM), granular (0.1 nM) and mixed
309 (0.08 nM) ice. Labile particulate Cd was also low in sea ice ranging from <DL to 0.08 nM (Fig. 6f)
310 and only detected in granular ice (0.03 ± 0.03 nM, $n = 3$). The LP fraction for trace metals were
311 high in the snow and granular ice structures as observed with the D fraction. For both fractions,
312 concentrations of trace metals were dependent on the metal.

313 *Discussion*

314 *Sea Ice Stratigraphy and Formation Processes*

315 Sea ice formation processes are reflected in the ice structures that are created and
316 manifested in distinct vertical sections of an ice core. In the snow ice section, the observed $\delta^{18}\text{O}$
317 showed a mixture of freshwater (meteoric snow) and seawater (Fig. 5b). Snow ice formation

318 may have occurred through a flood-freeze cycle (Ackley et al., 1990). Generally meteoric snow
319 will collect and accumulate onto the surface of sea ice. As more snow is added, the weight can
320 compress sea ice below the water's surface. Snow ice can then form as accumulated meteoric
321 snow mixes with incoming seawater (Fritsen et al., 1998; Hudier et al., 1995). At the bottom
322 part of the snow ice section, slush-like ice was observed (Fig. 3b, above 24 cm). Slush ice is
323 created by seawater mixing with snow, further indicating that the flood-freeze cycle process
324 may have occurred.

325 A large portion of the sea ice sample was composed of granular ice (Fig. 3c). Granular ice
326 has two genetic classifications: snow-granular and frazil-granular that can be identified through
327 grain (via thick, 5 mm, or thin, 0.5 mm, sections) and $\delta^{18}\text{O}$ analysis (Toyota et al., 2004; Ukita et
328 al., 2000). Since it was not possible to make trace metal clean thick or thin sections for grain
329 analysis to classify ice stratigraphy, $\delta^{18}\text{O}$ was used to differentiate between the two genetic
330 classifications. Frazil-granular ice usually has higher $\delta^{18}\text{O}$ values (seawater) than observed for
331 snow-granular ice (freshwater). The $\delta^{18}\text{O}$ in granular ice for this study yielded high values (-0.8
332 to -1.1‰) due to isotopic fractionation from a seawater source (Fig. 5b; Lange et al., 1990;
333 Toyota et al., 2004; Ukita et al., 2000). Therefore, the granular ice section was composed of
334 frazil ice. The mixed ice section (75 - 91 cm) yielded similar porosity % (0.5) values as observed
335 in the granular ice. The photo analysis of the thick section indicated that this structure was not
336 fully granular ice but a mixture of granular and columnar ice (Fig. 3b,c). Mixed ice may be an
337 indication, along with frazil ice, of dynamic growth processes (Toyota et al., 2007). Mixed ice
338 can form during rough currents and high winds which can allow for: 1) the formation of new
339 frazil ice over established/deformed ice regardless of ice texture, 2) the overlapping of ice

340 sheets, and 3) frazil ice formation in between floe gaps caused by rafting/ridging event (Hopkins
341 et al., 1999; Lange and Eicken, 1991; Lange et al., 1989). The observed columnar ice within this
342 sample was created through the congelation of seawater in calm conditions (Toyota et al.,
343 2004). This is supported by observations of the ice structure from photo analysis (Fig. 3b), and
344 low porosity % value (Fig. 3c). It should be noted that sea ice within a single ice floe is
345 heterogeneous allowing for the ice stratigraphy within a floe to be variable. The heterogeneity
346 of sea ice may be due to different wind conditions during ice growth (Eicken and Lange, 1989).
347 Therefore, the use of one ice core sample represents only a subset of the trace metal
348 accumulation and release mechanisms that may affect the composition of Arctic sea ice.

349 *Source and Accumulation Processes of Trace Metals into Sea Ice*

350 Ice structure explains the formation processes utilized by sea ice. Comparing ice
351 structure to trace metal concentrations within a single core sample allows the determination of
352 trace metal sources. In addition, the determination of possible mechanisms behind trace metal
353 accumulation in, and release from, sea ice become clearer. In this study the snow ice showed
354 high concentrations of dissolved for all metals and high concentrations of labile particulate for
355 Fe and Mn (Fig. 6). This indicates that one mechanism for trace metal accumulation into sea ice
356 may be snow ice formation through the flood-freeze cycle (Ackley et al., 1990).

357 Polar snow is mostly composed of water (99.99%), with less than 1% composed of
358 particulate dust and sea salt aerosols (Barrie, 1986; Planchon et al., 2004). The amount of
359 contaminates within Arctic snow can fluctuate depending on anthropogenic activities from
360 Eurasia and North America, with higher particulate dust available in winter than in summer

361 (Krachler et al., 2005). Trace metals, bound to particulate dust, are then deposited onto sea ice
362 during snow fall. As snow ice forms, these trace metals can become trapped within the ice
363 crystals. Increases in Arctic temperatures have increased water vapor which, along with
364 increased anthropogenic emission, has yielded higher precipitation in the Arctic Ocean (Tovar-
365 Sanchez et al., 2010). Therefore, the high concentrations of LPFe observed in this study may be
366 due to meteoric snow. Lannuzel et al. (2007) observed TDFe and DFe in snow ice from the
367 Antarctic region, indicating that atmospheric deposition was a minor source of trace metals to
368 the snow ice fraction of sea ice when compared to seawater influences. The range of DFe (3.1
369 nM, Fig. 6a) from snow ice in this study was comparable to that of Antarctic snow (1.0 - 6.5
370 nM). Total dissolvable Fe from snow ice in this study (92.3 nM Fig. 6b) was observed to be
371 higher than in Antarctic snow (1.8 - 23.7 nM). This indicates that atmospheric deposition may
372 be a source of trace metals to Arctic sea ice. Snow ice from the sub-polar marginal Sea of
373 Okhotsk was also observed as comparable concentrations of DFe (3.7 ± 1.3 nM DFe) with that
374 of snow ice from this study. Although the comparison for the different size fraction of Fe
375 concentrations were variable depending on location, the trace metal trend further supports
376 meteoric snow as a source of trace metals to snow ice. Another possible mechanism for trace
377 metal accumulation from meteoric snow may be the influence of snow meltwater during snow
378 ice formation (Granskog and Kaartokallio, 2004; Marsay et al. 2018). In the current study,
379 results from the $\delta^{18}\text{O}$ analysis yielded the snow ice section source water as a mixture of both
380 freshwater and seawater (Fig. 5b). Although the percent contribution from the two water
381 sources was not quantified; it is possible that meteoric snow was a source of trace metals to
382 snow ice.

383 The concentration of trace metals was higher in granular ice than observed in snow ice,
384 indicating another mechanism for trace metal accumulation into Arctic sea ice. As discussed
385 above, the granular ice structure was composed of frazil ice indicating that the high
386 concentrations of LPFe (Fig. 6b) may be explained by particle entrainment. In the Arctic Ocean,
387 frazil ice can form in shallow (<50 m) shelf areas (Dethleff et al., 1998; Eicken et al., 2005;
388 Reimnitz et al., 1994). Turbulence in the water column, due to fall storms, can re-suspend shelf
389 sediments and smaller particles in the water column. Frazil ice can interlock with these
390 suspended particles through suspension freezing and rise together to the water surface
391 (Campbell and Collin, 1958; Nürnberg et al., 1994; Osterkamp and Gosink, 1984; Reimnitz et al.,
392 1992). As frazil ice thickens (from slush ice to floe ice), particles are entrained into the granular
393 ice structure (Dethleff, 2005). Ito et al. (2017) used Acoustic Doppler Current Profiler
394 backscatter data to observe the entrainment of sediments by frazil ice. They found that at a
395 wind speed of 15 - 19 m s⁻¹ and a current speed of 1.0 - 1.5 m s⁻¹ sediments were re-suspended
396 into the water column where they interlocked with the frazil ice. Through this process, trace
397 metal bound sediments and smaller particles are also scavenged by frazil ice and finally
398 entrained into granular ice (Hölemann et al., 1997; Ito et al., 2017; Lannuzel et al., 2010, 2017),
399 increasing the concentrations of sediment/particle associated metals in the sea ice. Lannuzel et
400 al. (2007) reported that the Fe concentrations in sea ice, made from seawater, were also due to
401 sediment entrainment. Sea ice formed in the southeastern Chukchi and western Beaufort shelf
402 areas is characteristically sediment-laden (Eicken et al., 2005). This sea ice can follow the
403 Beaufort Gyre moving westward further into the Arctic Ocean. Sea ice collected for this study
404 may have formed in the shelf areas of the Beaufort Sea. As the sea ice aged and travelled

405 following the Beaufort Gyre flow, trace metals may have been added during ridging events or
406 frazil formation in the leads between floes (Lange et al., 1989; Lange and Eicken, 1991; Toyota
407 et al., 2004). Based on the visual observations of sea ice melt in the lab, sediments were not
408 detected in this sample. Labile particulate Fe showed a trend of higher concentrations in
409 granular ice (232.9 ± 172 nM) when compared to mixed and columnar ice (7.6 nM and 2.2 nM
410 respectively; Fig. 6). Particulates derived from fine-grained sediment or organic matter origins
411 (Dethleff, 2005; Kempema et al., 1989; Nürnberg et al., 1994) maybe influential to trace metals.
412 Comparing the trace metal concentrations from snow ice to granular ice yields higher
413 concentrations in the granular ice (with the exception of LPMn; Fig. 6). In addition, the sea ice
414 sourced from seawater in the current study's ice sample yielded more volume than observed
415 for the snow sourced ice. It is possible that a sediment source from a seawater medium is more
416 influential than from atmospheric deposition (Granskog and Kaartokallio, 2004). Thus, particle
417 scavenging during the dynamic growth processes used to form frazil ice allowed trace metals to
418 entrain and accumulate into the granular structure of sea ice.

419 The process of trace metal accumulation by particle entrainment is further supported by
420 the concentrations of dissolved and labile particulate Cd observed in granular ice (Fig. 6e,f).
421 Cadmium is associated with clay materials (Pardue et al., 1992) and with Fe/Mn oxides in oxic
422 sediments (Guo et al., 1997). As sediments entrain into sea ice, fine silts or clays are effectively
423 retained in the ice crystals (Nürnberg et al., 1994). It is possible that the observed
424 concentrations of Cd in granular ice further indicates the presence of fine particles, possibly
425 sourced from sediments, in this ice structure. Dissolved and labile particulate metal
426 concentrations in granular ice were also observed to be vertically heterogeneous (Fig. 6). The

427 dynamic environment where frazil ice forms and its non-uniformity (such as shelf seas), have
428 yielded patchy sediment-laden ice within Arctic sea ice (Eicken et al., 2005; Garrison et al.,
429 1983). Patchy entrainment of sediments into sea ice can then translate to heterogeneous
430 concentrations of trace metals observed in sea ice (Evans and Nishioka, 2018). Based on the
431 observations from this and previous studies (Campbell and Collin, 1958; Dethleff, 2005;
432 Hölemann et al., 1997; Ito et al., 2017; Lannuzel et al., 2007, 2010, 2017; Nürnberg et al., 1994;
433 Reimnitz et al., 1992), the accumulation of trace metals into granular ice may be due to frazil ice
434 formation and particle entrainment.

435 *Release Processes of Trace Metals from Sea Ice*

436 Mixed and columnar ice structures in Arctic sea ice yielded trace metal concentrations
437 that were low or below the detection limit (Fig. 6). This indicates a trace metal release
438 mechanism resulting from brine drainage. In the early stages of sea ice formation during fall,
439 most of the seawater salts are released from the ice crystal lattice. In sea ice around 0.05 m
440 thickness, bulk salinity is about 25. As sea ice thickens (1.5 m) the percent bulk salinity can
441 decrease to 5 (Kovacs, 1996). The interstitial salts remaining in the sea ice will concentrate into
442 liquid brine (Kingery and Goodnow, 1963; Untersteiner, 1968). Brine drainage occurs when
443 dense brine convects through permeable ice from cold (top of the ice) to warm (bottom of the
444 ice; Jardon et al., 2013) temperatures. As the ice strives for thermodynamic equilibrium, the
445 movement of brine widens brine channels (Petrich and Eicken, 2010) through the ice lattice
446 increasing the potential for fluid percolation. Relating the ability of brine drainage with sea ice
447 structure, the columnar structure maybe more efficient in releasing brine when compared to
448 the granular structure (Lannuzel et al., 2007). Columnar ice structure can form more slowly

449 (approximately factor of 2) than granular ice structure (Eicken and Lange, 1989; Weeks and
450 Ackley, 1986). The formation of different ice structures dictates the orientation of brine
451 channels (Spindler, 1994; Weissenberger et al., 1992). In granular ice the branching of brine
452 channels retains the liquid brine until they widen. In the columnar ice structure brine channels
453 have a laminar orientation (Petrich and Eicken, 2010). This can allow brine to be rejected more
454 efficiently (Janssens et al., 2016; Weissenberger and Grossmann, 1998). In sea ice, nutrients
455 have a decreasing linear trend with bulk salinity (Thomas et al., 2010). Therefore, the presence
456 of brine can be detected by its salinity and nutrient concentrations. In this study, the nutrient
457 concentrations analyzed in sea ice were below the detection limit. This indicates that brine,
458 along with the trace metals, was released from the sea ice. Brine has been shown to retain high
459 concentrations of trace metals. In the Antarctic region, concentrations of TDFe and DFe from
460 brine sack-holes were two orders of magnitude higher than the surrounding seawater (Lannuzel
461 et al., 2007). When compared to sea ice, brine concentrations of DFe were elevated (van der
462 Merwe et al., 2011). Dissolved trace metals in brine can thus be influenced by brine release,
463 decreasing their concentrations within sea ice (Lannuzel et al., 2007; van der Merwe et al.,
464 2011). In contrast, PFe concentrations in Antarctic brine have been observed to be low. This
465 indicates that PFe may bind to the brine channel walls or organic matter (Lannuzel et al., 2010).
466 A robust community of phytoplankton and bacteria has been observed in the brine channels of
467 the sea ice interior (Ackley et al., 1979; Horner et al., 1992) and at the sea ice-seawater
468 interface (Spindler, 1994). Ice algae and bacteria create exopolymeric (i.e. exopolysaccharides)
469 gel like substances. They are composed of uronic acids and sulphates allowing them to act as
470 organic ligands for both dissolved and labile particulate fractions within sea ice (Krembs et al.,

471 2002; Lannuzel et al., 2015). Trace metals can bind to these ligands, increasing the dissolved
472 concentrations, and bind to brine channels walls (Lannuzel et al., 2007, 2015). Phytoplankton
473 were not observed in this ice sample, but they may have been present in the brine allowing for
474 some of the dissolved metals to bind to the channel walls before collection. Regardless of the
475 sorption properties of brine channel walls, the decreasing trend for the trace metals indicates
476 that the release of liquid brine can drive trace metal concentrations in the mixed and columnar
477 ice structures.

478 *Chemical Transformation of Trace Metals in Sea Ice*

479 The concentrations of trace metal size fractions were variable within sea ice. For
480 example, high concentrations of LPFe, DMn and DCd were observed in the granular ice
481 structure (Fig. 6). The presence of high LPFe in granular ice indicated that suspended particles,
482 possibly from sediments, was a major source of LPFe. During turbulent conditions Fe(III) and
483 Fe(II) are released into the overlying water column as sediments are re-suspended (Lohan and
484 Bruland, 2008). Once in the oxic environment Fe(II) is quickly oxidized (Landing and Bruland,
485 1987) creating particulate Fe oxides. This reaction was estimated to occur within hours in the
486 bottom waters of the Bering Sea (Lohan and Bruland, 2008). As water temperatures cool (-
487 1.86°C) and turbulent conditions persist, this newly available pool of Fe oxides along with re-
488 suspended sediments containing Fe can accumulate as a result of suspension freezing by frazil
489 ice (Ito et al., 2017).

490 Granular ice also showed high concentrations of DFe and low concentrations of LPMn
491 (Fig. 6b,c,d). As discussed above, particle entrainment allowed for the accumulation of LPFe

492 into granular ice. Due to their similar behaviors, LPMn concentrations should mimic LPFe, but
493 LPMn concentrations were observed to be low (Fig. 6d). Therefore, the resulting high DMn
494 observed in granular ice can be explained by chemical transformation. The concentration of
495 oxygen in sea ice is low, where brine is supersaturated in oxygen (Glud et al., 2002; Rysgaard
496 and Glud, 2004). Oxygen concentrations in sea ice can further decrease due to organic matter
497 decomposition from bacteria (Rysgaard et al., 2008) or from limited access to wind generated
498 waves (Ackley and Sullivan, 1994; Huang et al., 2017). The nutrient concentrations within the
499 sea ice sample were low (<DL), therefore, brine release had a greater influence on the oxygen
500 concentration. As sediments are re-suspended during turbulent conditions, both Fe and Mn
501 oxides are released into the water column. The oxides are then entrained into frazil ice through
502 suspension freezing. Manganese has a higher reduction potential than Fe (Froelich et al., 1979;
503 Hatta et al., 2013) allowing elevated concentrations of DMn to be represented in the ice
504 structure. Sea ice and snow also have the potential to allow for the photochemical
505 transformation of Mn (LPMn to Mn²⁺) within its matrixes (Granskog and Kaartokallio, 2004).
506 Another indication for the chemical transformation to dissolved metals in sea ice is its effect on
507 DCd concentrations in granular ice (Fig. 6e,f). At the sediment-water column interface and in
508 surface sediments, Cd is adsorbed onto the surfaces of Fe and Mn oxides. Therefore, the
509 increase in DCd concentrations observed in this sea ice sample is mainly due to release from Fe
510 and Mn oxides during the reduction process (Yu et al., 2000; Huang et al., 2017). This process
511 may also occur in the suboxic areas of sea ice, making chemical transformations another
512 mechanism that can control the concentrations of DMn and DCd.

513 *Summary*

514 In the Arctic Ocean, sea ice is an important player in the biogeochemical cycling of trace
515 metals. However, the processes by which trace metals accumulate into sea ice are not well
516 known. Comparing sea ice structure to trace metal concentrations gives a clearer
517 understanding of these processes. To determine the structure of sea ice, photographic images,
518 porosity % and $\delta^{18}\text{O}$ analyses were used. The structures observed in sea ice, from top to
519 bottom, are as follows: snow ice, granular ice, mixed ice and columnar ice. Analysis of the sized
520 fractionated (D, and LP) trace metals (Fe, Mn and Cd) showed that their concentrations differed
521 depending on ice structure. The sea ice used in this study had low salinity indicating a multi-
522 year ice sample. In addition, brine was determined to be released from the sea ice as both
523 nutrients and salinity were observed to be low. Low trace metal concentrations in mixed and
524 columnar ice were also determined to be due to the brine release process. The concentration of
525 Fe, Mn and Cd differed among sea ice structures, indicating that accumulation processes for
526 trace metals are reliant on sea ice formation processes. The observed differences within trace
527 metal size fraction concentrations indicated that there are additional controls through external
528 sources: meteoric snow, particle entrainment, and reductive processes.

529 Figure 7a represents a schematic of the possible accumulation and release processes,
530 and Figure 7b represents the chemical transformation process observed for Mn oxides in
531 granular ice. As Fe and Mn oxides have similar behaviors, Figure 7b will hold true for Fe oxides
532 as well. High concentrations in snow ice indicated that snow ice formation, through the mixing
533 of meteoric snow and seawater, can add atmospheric trace metals. High and heterogeneous
534 concentrations of LPFe in granular ice indicate particle (possible hydroxide and clay particles)
535 entrainment by frazil ice scavenging. During frazil ice formation, sea ice can entrain suspended

536 trace metal bound particles (Fe and Mn) that are reflected in granular ice. Once LPFe and LPMn
537 (oxides) accumulates into sea ice, it can undergo reduction to release DFe, DMn and (adsorbed)
538 DCd in granular ice. This chemical transformation process within sea ice can increase the
539 bioavailability of trace metals. Low trace metal concentrations observed in mixed and columnar
540 ice show that these structures are unable to retain metals following brine drainage. The
541 differences observed in trace metals within sea ice structure show that sea ice formation,
542 chemical reduction, and brine release were the processes behind trace metal accumulation and
543 release in this Arctic sea ice.

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809 *Figure Captions*

810 **Figure 1.** Picture and schematic of cold tub used during the ice core planing step. Cold tub was
811 cooled to -20°C by cooling coils located inside the tub's chamber. The temperature inside the
812 chamber remained consistent below a temperature limit line. Above this line the temperatures
813 significantly increased. a) Picture of cold tub, b) cooling coils, c) pre-set temperature limit line,
814 and d) ice planing step.

815 **Figure 2.** Location of sea ice sampling site. Sea ice concentration on August 24, 2013 (24 hr
816 average) from ECMWF metadata. Black dot - Location of the ice station where sea ice was
817 collected.

818 **Figure 3.** Photo and schematic of ice core structure. a) Photo of ice core taken after collection
819 from coring with the depth representing the length of the core, b) photos taken after planing (2
820 cm), c) transformed planed photo to black and white, with a filter overlaid, to represent the
821 outline of the micropores (porosity %), d) schematic of observed sea ice structure. 0 - 24 cm
822 snow ice, 24 - 75 cm granular ice, 75 - 91 cm mixed ice and 91 - 103 cm columnar ice.

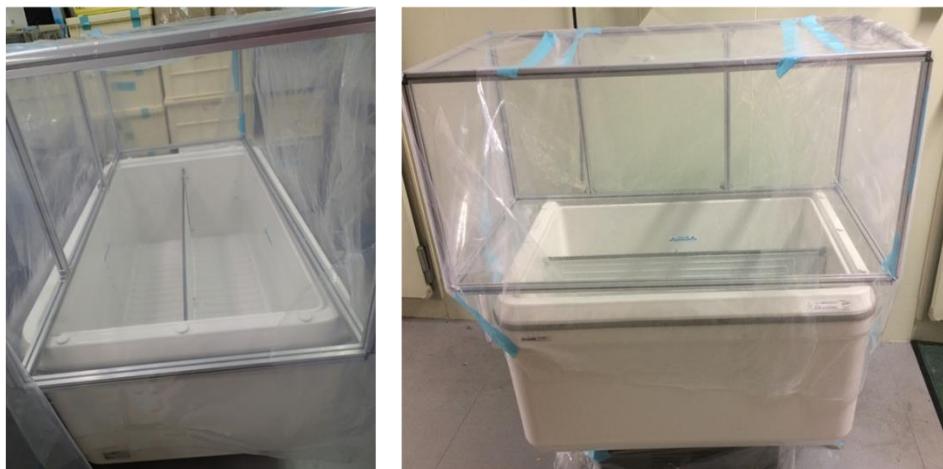
823 **Figure 4.** Milli-Q Ice Contamination Test. Concentrations of a) Fe, b) Mn, and c) Cd in Milli-Q ice
824 without foil (Milli-Q Clean Ice) and Milli-Q ice wrapped in aluminum foil (Foil Ice). Samples were
825 planed up to 2 cm and each layer (Layer 1 – Outer 1 cm of ice, Layer 2 – Inner 1 cm of Ice, Core
826 – Cleaned ice) was pre-concentrated with the NOBIAS resin. Presented values were above the
827 pre-concentrated DL and then calculated with the pre-concentration factor (4.5 - 8.6 times).
828 The pre-concentration factor was determined by the sample weights before pre-concentration
829 and the eluent weights after pre-concentration.

830 **Figure 5.** Salinity and $\delta^{18}\text{O}$ for each ice structure. a) Salinity, b) $\delta^{18}\text{O}$, dotted line represents $\delta^{18}\text{O}$
831 values from the surrounding surface seawater (<50 m; Yamamoto-Kawai personal comm.).

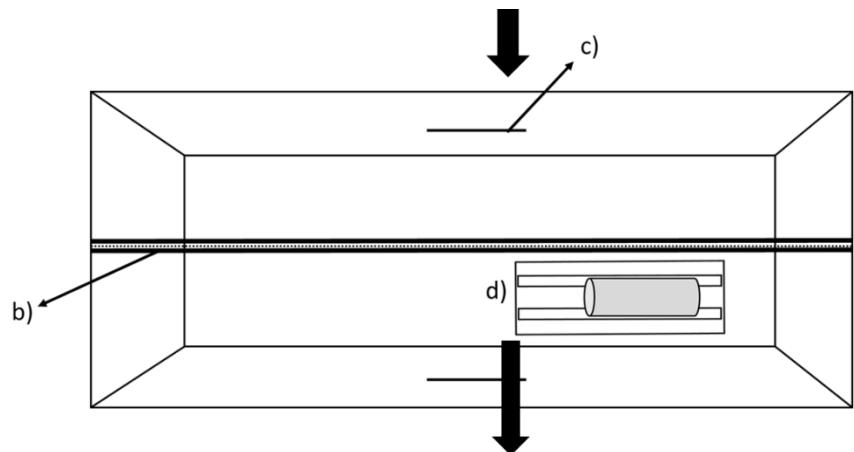
832 **Figure 6.** Concentrations of dissolved and labile particulate metals for snow ice, granular ice,
833 mixed ice and columnar ice. The ice core depth is represented on the y-axis. Error bars are SD
834 from GFAAS measurement data. a) DFe, b) LPFe, c) DMn, d) LPMn, e) DCd, f) LPCd.

835 **Figure 7.** a) Schematic of trace metal accumulation and release processes in multi-year Arctic
836 sea ice, and b) schematic of chemical reduction process for multi-year Arctic sea ice.

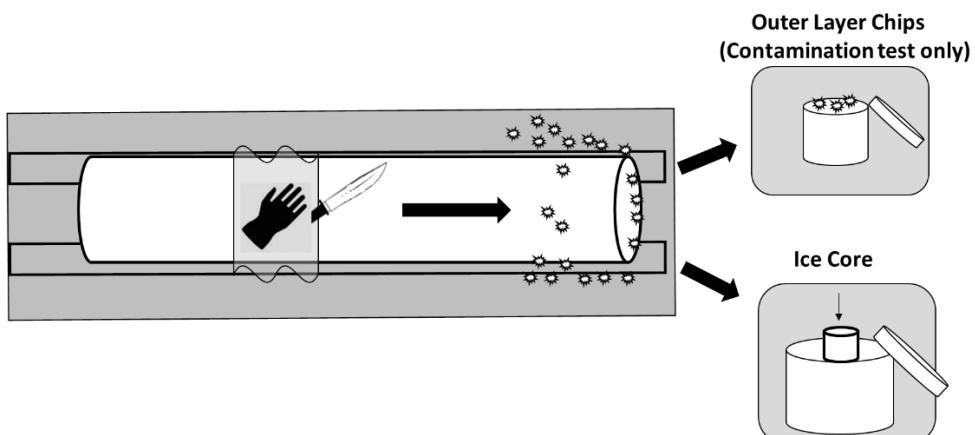
a)



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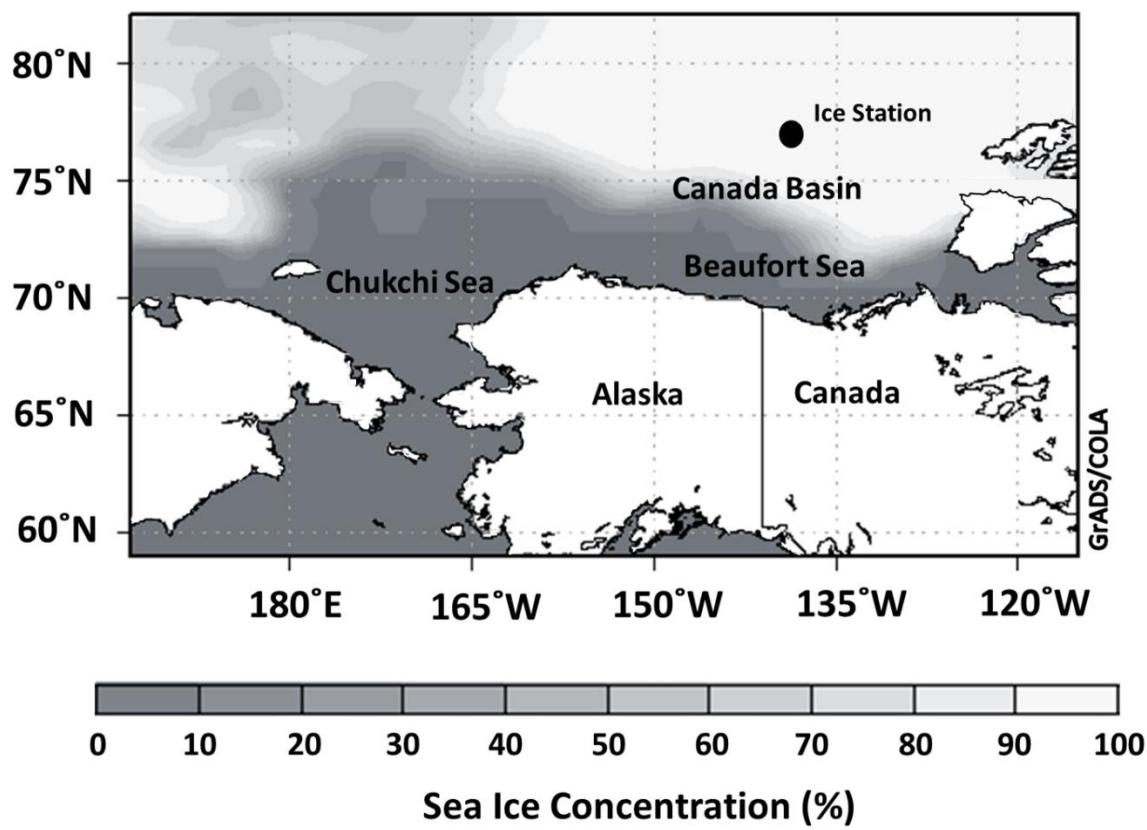
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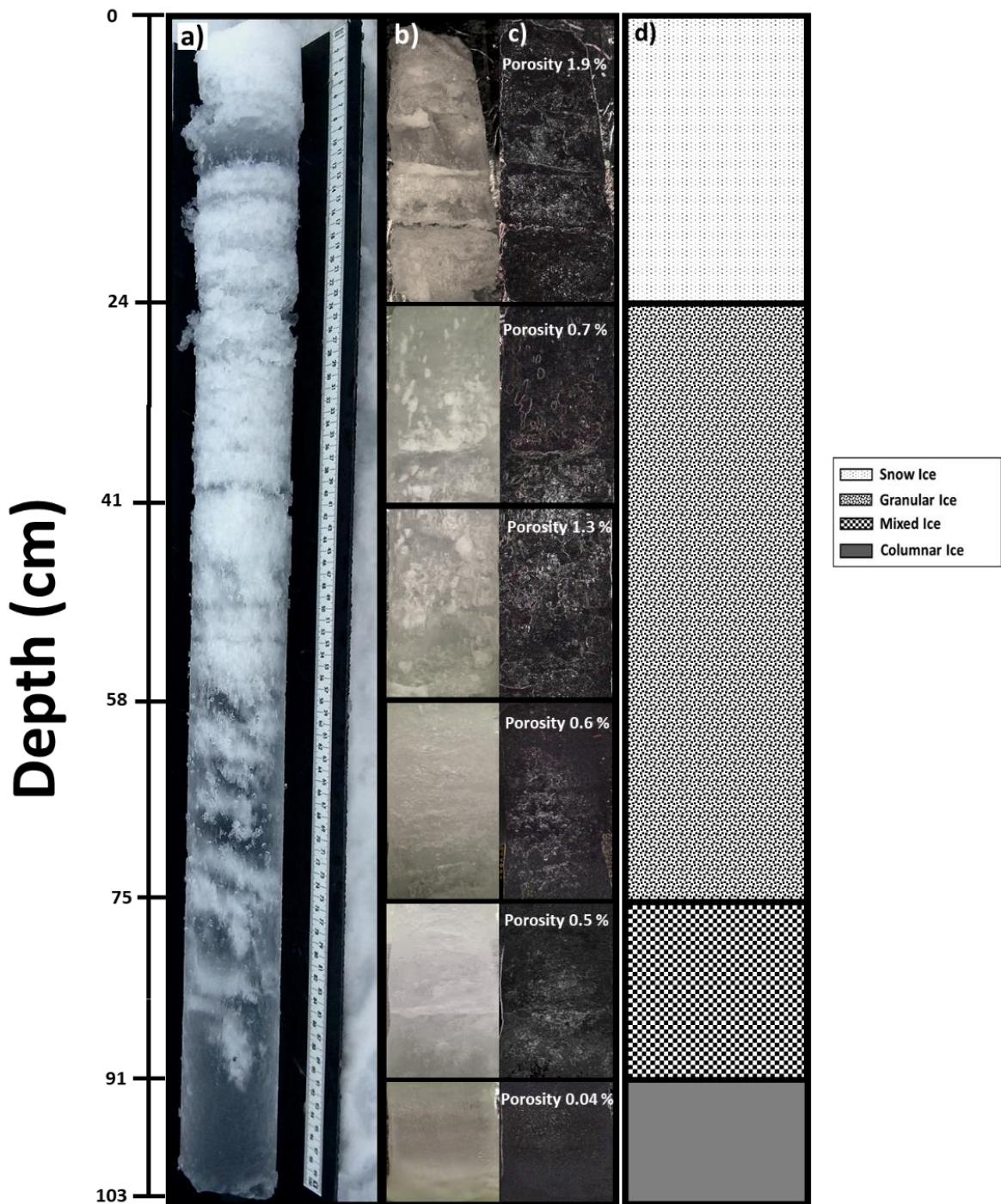
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840 Figure 1

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843 Figure 2
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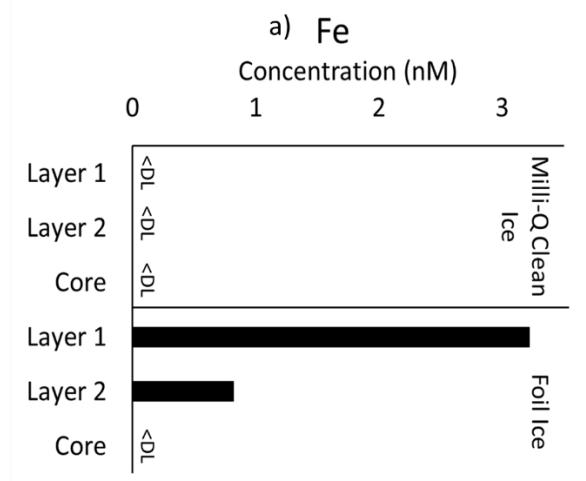


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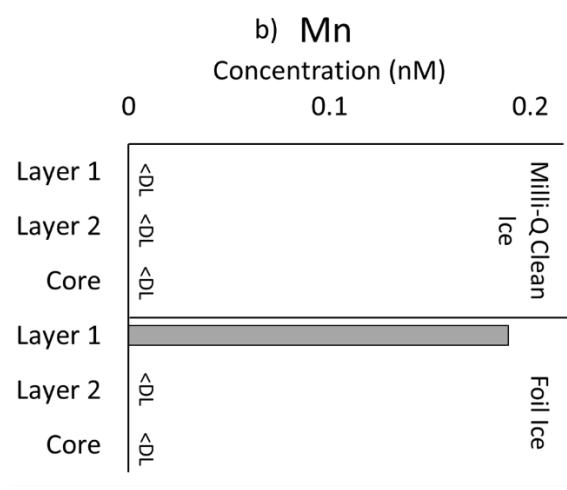
849 Figure 3

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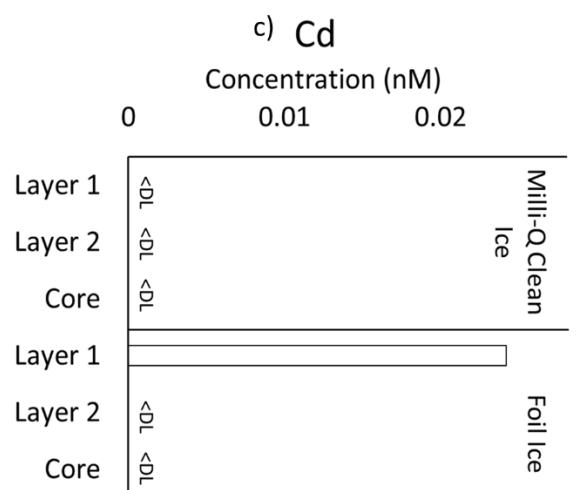
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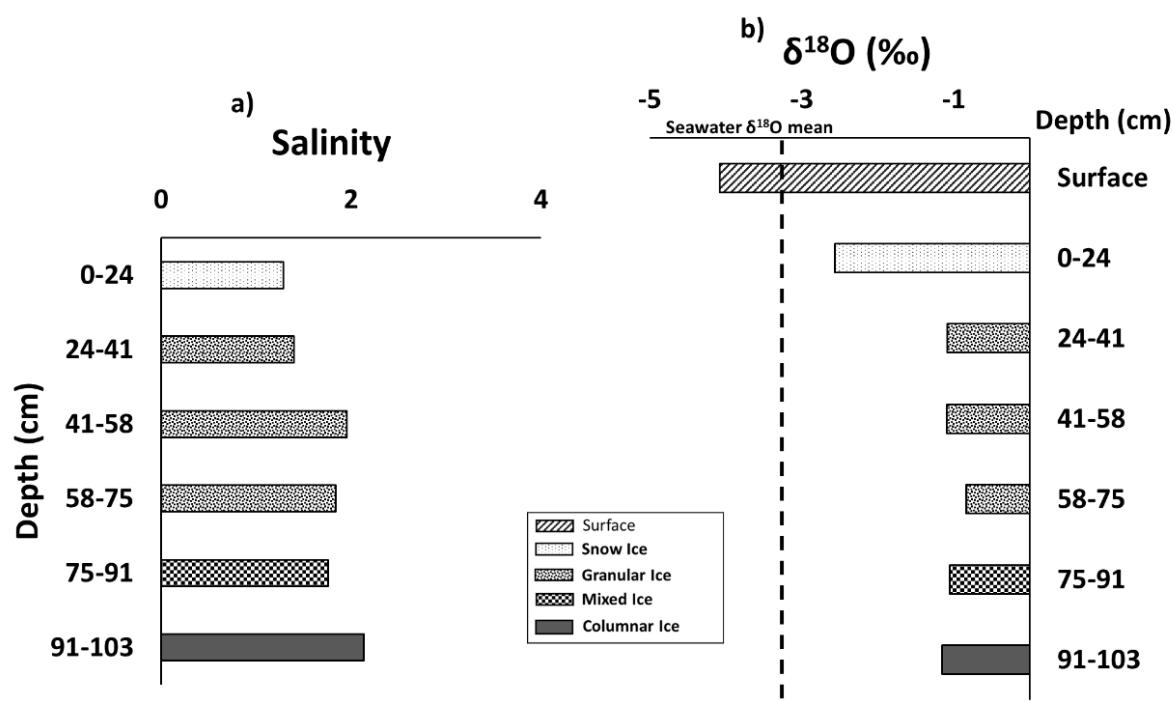
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854 Figure 4.



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857 Figure 5.

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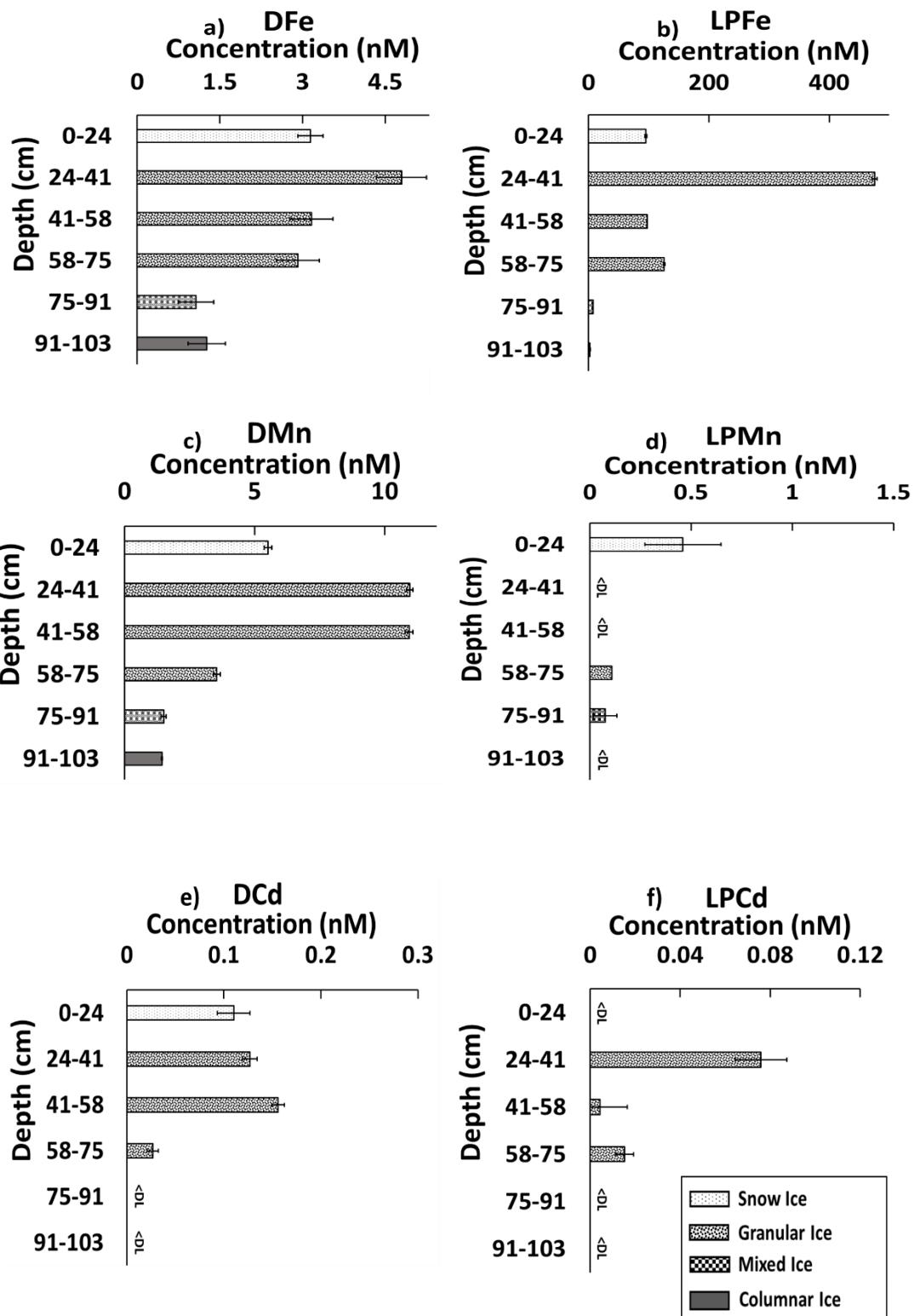
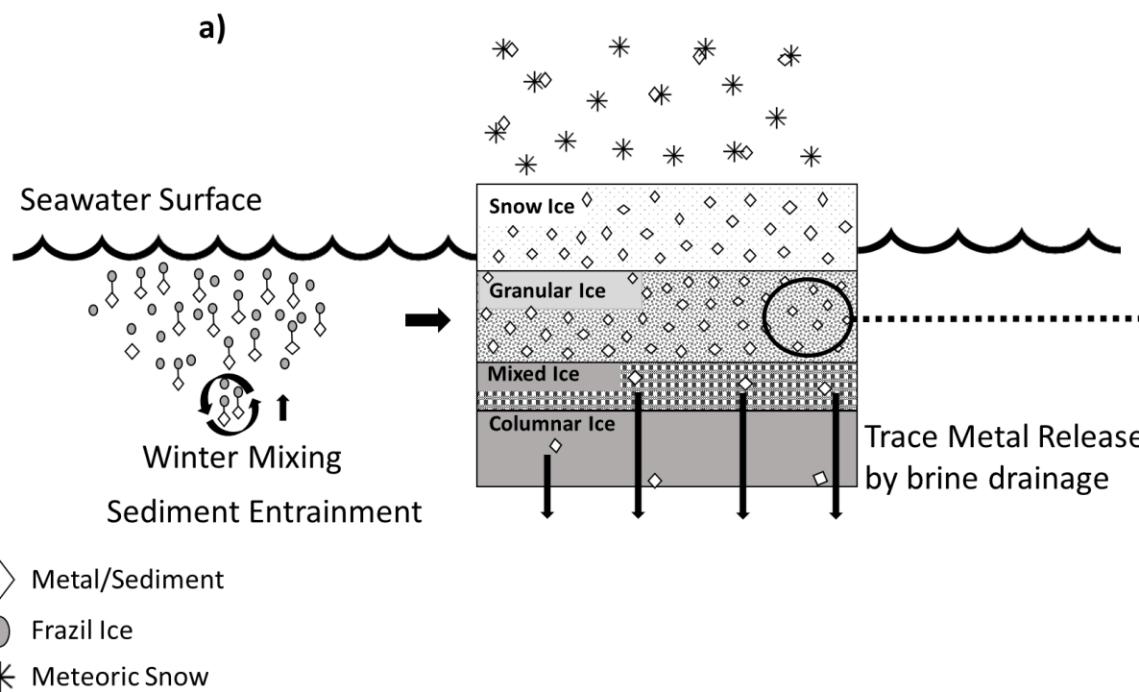


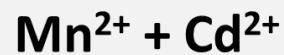
Figure 6



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b)

Granular Ice – Suboxic Area



866

867 Figure 7

868