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1 **Holocene shifts in sub-surface water circulation of the North-East Atlantic inferred**
2 **from Nd isotopic composition in cold-water corals**

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13

14 **Abstract:**

15 Variations of the Sub-Polar Gyre (SPG) and the Sub-Tropical Gyre (STG) circulation during
16 the Holocene are believed to be related to regional and global climate over this time period.
17 To improve our understanding of these phenomena we provide new constraints on variations
18 in surface circulation patterns using neodymium isotopes (ϵNd) on precisely U-Th dated coral
19 fragments of *L. pertusa*. The fragments were retrieved from two sediment cores taken from
20 cold-water coral (CWC) mounds at ~ 127-134 m water depth in the Mingulay Reef Complex
21 located on the Western British continental shelf. The results have been combined with ϵNd
22 analyzed on seawater samples from two stations located on the continental shelf and margin
23 in order to establish whether ϵNd is a reliable proxy of the ocean circulation variations and

24 notably of the relative contribution of water originating from the SPG and STG. ϵNd values in
25 CWCs from the Mingulay Reef Complex range from -14.5 ± 0.4 to -11.8 ± 0.3 , highlighting two
26 major variations. Unradiogenic ϵNd values (-14.5 ± 0.4) indicate a higher contribution of water
27 from the SPG around 2.8 ka. Conversely, more radiogenic values at 3.4 ka (-11.8 ± 0.3) point
28 to a declining SPG strength, accompanied by stronger northward penetration of STG water
29 along the western European margin transported by the Shelf Edge Current (SEC) and/or
30 cooler and fresher waters from the interior Seas. The eastward extension of the SPG at 2.8 ka
31 is associated with lower ^{14}C reservoir age (200 yrs) compared to periods associated with a
32 higher contribution of STG waters. This indicates that ^{14}C reservoir ages are mainly a function
33 of vertical mixing of the sub-surface of the ocean. As stronger vertical ventilation is not
34 associated with a higher proportion of local radiogenic surface water, we hypothesize it could
35 represent vertical ventilation in the North-Eastern Atlantic. Active SPG is associated with a
36 better ventilation of the water masses within the SPG and warmer climatic conditions in
37 Northern Europe and in the Eastern Norwegian Sea linked to an intensification of the surface
38 limb of the AMOC.

39

40 **Key words:** Nd isotopic composition; cold-water corals; NE Atlantic; Sub-Polar Gyre

41

42 1. Introduction

43 The Atlantic Meridional Overturning Circulation (AMOC) transports warm saline surface
44 water masses northwards and deeper cool waters southwards (Hansen and Østerhus, 2000;
45 Read, 2001). The upper layer of the AMOC, the North Atlantic Current (NAC), loses much of
46 its heat to the atmosphere on its way northwards, impacting the climate over Europe (Hall and
47 Bryden, 1982). Whereas variability of the lower branch of the AMOC is relatively well
48 established during the Holocene, at least for the Iceland-Scotland Overflow Water (ISOW)

49 and the Labrador Sea Water (LSW) (e.g. Hillaire-Marcel et al., 2001; Hoogakker et al., 2011;
50 Thornalley et al., 2013; Mjell et al., 2015), the variations of the upper layer of the AMOC are
51 not yet well established. This is due to the complex spatial and temporal variability of the
52 classical Sea Surface Temperature (SST) and Sea Surface Salinity (SSS) proxies used to track
53 past changes of the AMOC that are strongly influenced by an orbitally-induced insolation
54 trend and the final disintegration of the residual Laurentide ice sheet during the early
55 Holocene, which induces a pronounced provincialism in the surface physical property records
56 of the North Atlantic (e.g. de Vernal and Hillaire-Marcel, 2006; Renssen et al., 2009).

57 It has been suggested that during modern times variations in the shape and position of the
58 subpolar gyre (SPG) (Fig. 1) play a major role in the redistribution of fresh melt-water and in
59 pole-ward heat transport at surface and intermediate depths and subsequently have an impact
60 on the AMOC strength and the properties of waters entering the Nordic Seas (e.g. Häkkinen et
61 al., 2013). The NAC follows the boundary between the North Atlantic subpolar gyre (SPG)
62 and the subtropical gyre (STG), and its position, intensity and composition have been
63 modulated by SPG variations over recent decades (Håttun et al., 2005; Berx and Payne, 2017;
64 Zunino et al., 2017). Foukal & Lozier (2018), by using a combination of empirical orthogonal
65 functions and direct calculations of the size and strength of the SPG, have proposed that the
66 SPG dynamics may not control the magnitude of the STG waters flowing into the North east
67 Atlantic, on interannual time scales. However, numerous paleohydrological records point to a
68 major role of the SPG on longer time scales (see references below). During the early
69 Holocene, a reorganization of the mid-depth (200-800 m) circulation has been highlighted at
70 about 7-6 ka, with a weakened SPG leading to a stronger northward penetration of temperate
71 water masses in the North-East Atlantic (Thornalley et al., 2009; Colin et al., 2010). Other
72 studies based on cold-water corals from the Bay of Biscay and the Rockall Trough have
73 highlighted an existing link between SPG intensity and the North Atlantic Oscillation (NAO),

74 i.e. atmospheric circulation (Copard et al., 2012; Montero-Serrano et al., 2013). Between 1950
75 and 1990, periods characterized by a dominant negative phase of NAO were associated with a
76 stronger influence of mid-depth STG water (Montero-Serrano et al., 2013). Over the last 1500
77 yrs, the warm Medieval Climatic Anomaly (between 1000 AD and 1250 AD), characterized
78 by a persistently positive NAO phase, resulted in greater eastward extension of the mid-depth
79 SPG in the North Atlantic (Copard et al., 2012). Conversely, the Little Ice Age (between 1350
80 AD and 1850 AD), characterized by a persistently negative NAO phase, is associated with the
81 westward contraction of the mid-depth SPG (Copard et al., 2012). Overall, these records have
82 shown that Holocene climatic anomalies are associated with mid-depth SPG dynamics which
83 are in turn affected by changes in wind stress and/or freshwater input from the Labrador Sea
84 (Thornalley et al., 2009; Colin et al., 2010; Copard et al., 2012). Subsequent variations in the
85 heat and salt budgets at intermediate depths may have contributed to changes in the properties
86 of North Atlantic inflow to the Nordic Seas and thus to deep-water formation.

87 The Mingulay Reef Complex, located on the Western British continental shelf (Fig. 1), is a
88 potential target to track past changes of the SPG extension using the ϵNd proxy because it
89 receives waters from the NAC. In addition, cold-water corals (CWCs) have been shown to act
90 as useful archives for identifying rapid changes in the dynamics of water masses (Lutringer et
91 al., 2005; Colin et al., 2010; van de Flierdt et al., 2010; Copard et al., 2010, 2012; Montero-
92 Serrano et al., 2013; Wilson et al., 2014; Chen et al., 2015; Dubois-Dauphin et al., 2016;
93 Douarin et al., 2016). Firstly, their aragonitic skeleton can be precisely dated thanks to U-
94 series disequilibrium methods (Adkins et al., 1998; Cheng et al., 2000; Douville et al., 2010).
95 Secondly, they do not suffer from the same problems often encountered in marine sediment
96 cores, which are often affected by bioturbation, smoothing the original signals, and which are
97 characterized by low sedimentation rates that limit our ability to obtain records with
98 centennial resolutions. Furthermore, the Nd isotopic composition, expressed as $\epsilon\text{Nd} =$

99 $([(^{143}\text{Nd}/^{144}\text{Nd})_{\text{sample}}/({}^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}}] - 1) \times 10000$ (CHUR: Chondritic Uniform Reservoir
100 [Jacobsen and Wasserburg, 1980]), of living and fossil scleractinian CWCs faithfully traces
101 water mass provenance and mixing in the ocean (e.g. van de Flierdt et al., 2010; Copard et al.,
102 2012; Struve et al., 2017). Taking into consideration that mid-depth STG and SPG water
103 masses are characterized by contrasted Nd isotopic signatures ($\epsilon\text{Nd} \approx -10$ and $\epsilon\text{Nd} \approx -15$,
104 respectively; Lambelet et al., 2016; Dubois-Dauphin et al., 2017), CWC ϵNd records obtained
105 previously in the Rockall Trough and in the northern Bay of Biscay have been used to
106 reconstruct the eastward extension of the mid-depth SPG (Colin et al. 2010; Copard et al.,
107 2012; Montero-Serrano et al., 2011, 2013).

108 In this paper we present a high-resolution ϵNd record for the last 4500 yrs, which is derived
109 from CWCs from the Mingulay Reef Complex, located at the sub-surface under the strong
110 influence of NAC water. Our objective is to track hydrological changes in the SPG dynamics
111 during the Holocene. Ambient seawater ϵNd was also investigated to assess seawater ϵNd of
112 the Western British continental shelf and margin and to verify that ϵNd is a reliable proxy for
113 tracking past changes in the influence of the SPG in this region. This CWC ϵNd record was
114 compared to previously published $\Delta^{14}\text{C}$ performed by Douarin et al. (2016) that was
115 interpreted in terms of changes in water mass origin. It also complements well previous
116 studies based on ϵNd in the Rockall Trough (Colin et al., 2010; Copard et al., 2012) that have
117 highlighted major variations of the mid-depth SPG dynamics throughout the Holocene. Our
118 study permits us to re-interpret $\Delta^{14}\text{C}$ with a proxy of water mass origin and provides new
119 evidence of abrupt changes in the composition of water masses entering the Nordic Seas;
120 these changes are linked to variations in the shape and strength of the SPG.

121

122 **2. Hydrological setting**

123 Presently, the deepest waters (>100 m) and the waters overlying the outer parts of the shelf of
124 west Scotland are of Atlantic origin (Inall et al., 2009). At the surface, the northward flowing
125 Scottish Coastal Current (SCC) brings cooler and fresher waters from the Irish and Clyde
126 Seas (Ellett and Edwards, 1983) (Fig. 1). The Mingulay Reef Complex (56°50'N; 7°20'W;
127 100-260 m water depth) is thus primarily bathed by Atlantic water (Dodds et al., 2007). The
128 upper-layer Atlantic water off the Mingulay Reef Complex, carried by the NAC, results from
129 the mixing of saline Eastern North Atlantic Central Water (ENACW) originating from the
130 Bay of Biscay (Ellett and Martin, 1973; Ellett et al., 1986; Pollard et al., 1996) and the fresher
131 Modified North Atlantic Water (MNAW) originating in the North-West Atlantic (New and
132 Smythe-Wright, 2001). The MNAW is formed by the mixing of the Western North Atlantic
133 Central Water (WNACW), which flows from the Caribbean Sea, with the Sub-Arctic
134 Intermediate Water (SAIW). The SAIW is characterized by low temperatures and salinity and
135 is formed in the upper layers of the southern Labrador Sea (Arhan, 1990). Both WNACW and
136 SAIW are transported north-eastwards into the NAC where vertical mixing occurs (Arhan,
137 1990). The NAC is composed of three main branches (Daniault et al., 2016). The northern and
138 central branches bifurcate west of the Rockall Trough and feed the cyclonic circulation in the
139 Iceland Basin and the Irminger Sea (Fig. 1). The southern branch penetrates into the Rockall
140 Trough (Fig. 1)

141 All along the European margin, the Shelf Edge Current (SEC) forms a northward-flowing
142 boundary current that brings warm and saline upper water with ENACW characteristics
143 through the Rockall Trough and the Scottish margin (Hill and Mitchelson-Jacob, 1993; White
144 and Bowyer, 1997; Holliday et al., 2000) (Fig. 1). Below this, the Mediterranean Sea Water
145 (MSW) flows northwards from the Gulf of Cadiz with a main core located at 1000-1200 m
146 water depth. Nevertheless, the MSW cannot be traced through ϵNd , salinity and potential
147 temperature at mid-depth further north than the Porcupine Seabight (Iorga and Lozier, 1999;

148 McCartney and Mauritzen, 2001; New and Smythe-Wright, 2001; Lavender et al., 2005;
149 Dubois-Dauphin et al., 2017).

150 The NAC strength, direction and composition respond to SPG dynamics (Hátún et al., 2005):
151 when the SPG circulation is stronger and presents a more pronounced east–west shape the
152 SPG water influence on the NAC is increased relative to the STG water, coupled with a strong
153 AMOC. Conversely, when the SPG circulation is weaker and forms a more pronounced
154 north–south shape, a lower contribution of SPG water flows to the NW European Margin
155 relative to the STG water (Larsen et al., 2012; Hansen et al., 2015).

156

157 **3. Material and methods**

158 **3.1.1. CWC samples**

159 This study has investigated 23 well-preserved fossil CWCs of the species *Lophelia pertusa*,
160 collected in two cores from the Mingulay Reef Complex located on the Western British
161 continental shelf (Fig. 1 and Table 1). The cores, +56-08/929VE (56°49'19"N - 7°23'27"W,
162 127 m water depth) and +56-08/930VE (56°49'20"N -7°23'47"W, 134 m water depth), were
163 collected in October 2007 by the British Geological Survey during a survey (Cruise 15) on
164 board of the NERC vessel RRS James Cook (Stewart and Gatliff, 2008) (Table 1). The coring
165 sites are located within 300 m of each other at quite a similar water depth on small carbonate
166 mounds of the Mingulay Reef Complex (Figure 1; Table 1). The sediment cores are
167 composed of biogenic fragments (mainly CWC fragments) in a carbonate matrix. Three
168 additional surface videograb samples (GRAB 15.5.5.10; GRAB 56.08.928 ; GRAB 1151)
169 were retrieved from the seafloor with a Remotely Operated Vehicle close to the location of
170 the cores (see location in Fig. 1 and Table 1).

171 U-Th ages obtained for CWC samples collected in the Mingulay Reef Complex were
172 published by Douarin et al. (2016) (Table 1). They document three major peaks in growth rate
173 that are centered at 3.7, 4, and 4.2 ka BP. Two major reductions in growth rate were observed
174 at 1.75–2.8 ka and 3.2–3.6 ka BP. The coral fragments investigated in this study, from cores
175 +56-08/929VE and +56-08/930VE, range between 4.29 ± 0.26 and 2.09 ± 0.018 ka BP (Table
176 1). In addition, GRAB 56.08.928, GRAB 1151 and GRAB 15.5.5.10 samples have been dated
177 to 2.67 ± 0.014 , 1.31 ± 0.011 and 0.02 ± 0.013 ka BP, respectively (Table 1).

178 **3.1.2. Seawater samples**

179 During the R/V Atalante MINGULAY-ROCKALL cruise in June 2016, 12 seawater samples
180 were collected at 2 full water column stations MR-4 ($56^{\circ}37.44'$ N; $9^{\circ}5.48'$ W) and MR-5
181 ($56^{\circ}46.04'$ N; $7^{\circ}25.98'$ W) (Fig. 1, Table 2). These samples, located on the Western British
182 continental shelf (station MR5) and margin (station MR4), were collected in order to assess
183 seawater ϵ Nd flowing around the Mingulay Reef Complex. The seawater samples and water
184 column hydrographic parameters (temperature and salinity) were collected using a CTD-
185 Rosette system equipped with 12 10-liter Niskin bottles and a standard Sea-Bird SBE 911plus
186 CTD-Rosette system. The samples were then filtered through 0.8-0.45 μ m AcroPak 500
187 capsule filters and transferred to 10-liter acid-cleaned bottles, and immediately acidified to a
188 pH of 2 using suprapur 2 N HCl.

189 **3.2.3 Analytical procedures for Nd isotope measurements**

190 Each coral fragment used in this study corresponded to one polyp of the *Lophelia pertusa*
191 species, integrating only a few years of growth (Freiwald et al, 2004; Sabatier and al., 2012a).
192 The CWC samples were subjected to a mechanical and chemical cleaning procedure (Copard
193 et al., 2010). The visible contaminations, such as Fe-Mn coatings and detrital particles, were
194 carefully removed from the inner and outermost surfaces of the coral skeletons using a small

195 diamond blade. The physically cleaned fragments were ultrasonicated for 10 min. with 0.1 N
196 ultra-clean HCl, followed by several MilliQ water rinses and finally dissolved in 2.5 N
197 ultraclean HNO₃. Neodymium was separated from the carbonate matrix using Eichrom TRU
198 and LN resins, following the analytical procedure described in detail in Copard et al. (2010).

199 Neodymium was purified from seawater samples following the analytical procedures
200 described in detail by Lacan and Jeandel (2001) and Wu et al. (2015). Briefly, seawater REEs
201 were preconcentrated using SepPak Classic C18 cartridges loaded with a HDEHP/H2MEHP
202 complexing agent. Solutions were then passed through a cationic resin (AG50W-X8) and
203 finally Nd was extracted and purified using an Eichrom Ln-Spec resin following the method
204 described in detail by Copard et al. (2010). This purification process and the measurement
205 techniques applied follow approved GEOTRACES protocols and GEOPS laboratory
206 participated in the international GEOTRACES intercalibration study (van de Flierdt et al.,
207 2012).

208 The ¹⁴³Nd/¹⁴⁴Nd ratios of seawater samples and of the CWCs from the Mingulay Reef
209 Complex, were analyzed using a Thermo Scientific Neptune Plus MC-ICPMS installed at the
210 Laboratoire des Sciences du Climat et de l'Environnement (LSCE, Gif-sur-Yvette, France).
211 The mass-fractionation correction was made by normalizing ¹⁴⁶Nd/¹⁴⁴Nd to 0.7219 by
212 applying an exponential-fractionation correction. During the analytical sessions, every two
213 samples were bracketed with analyses of appropriate standard JNdi-1 and La Jolla Nd
214 solutions, which are characterized by certified values of 0.512115±0.000006 (Tanaka et al.,
215 2000) and 0.511858±0.000007 (Lugmair et al., 1983), respectively. Standard JNdi-1 and La
216 Jolla solutions were analyzed at concentrations similar to those of the samples (4-10 ppb). The
217 external reproducibility (2σ) deduced from repeated measurements of the La Jolla standard
218 and JNdi-1, ranged from 0.2 to 0.4 Epsilon units for the different analytical sessions. The

219 analytical error associated with each sample analysis is taken as the external reproducibility of
220 the La Jolla standard for each session.

221

222 4. Results

223 4.1. Seawater samples

224 The Nd isotopic compositions of the seawater samples from stations MR-4 and MR-5 are
225 provided in Table 2 and Figure 2. Station MR-5 is located on the continental shelf, very close
226 to the Mingulay Reef Complex. At station MR-5, ϵNd values decrease downward from -
227 11.6 ± 0.2 at the surface to -13.1 ± 0.3 at a water depth of 240 m (Fig. 2). Temperature decreases
228 from 12 to 9.5°C between depths of 30 and 80 m, then remains constant (9.5°C) down to 240
229 m water depth (Fig. 2). Conversely salinity increases from 34.5 to 35.2 in the upper 100 m,
230 then displays a constant value of 35.2 down to 240 m water depth (Fig. 2).

231 On the other hand, station MR-4 was collected on the continental slope. Seawater samples
232 from station MR-4 exhibit similar ϵNd values at all depths, within the error bars, centered
233 around -14 from the surface to 540 m water depth (Fig. 2). Temperature decreases from 13 to
234 10°C between depths of 20 and 80 m, then displays a constant value of about 9.7°C down to
235 550 m water depth. Salinity displays an almost constant value of about 35.3. The upper 50 m
236 are, however, slightly less saline (Fig. 2).

237 4.2. Cold Water Coral samples

238 Overall, CWC ϵNd values from the Mingulay Reef Complex range from -14.5 ± 0.4 to -
239 11.8 ± 0.3 (Fig. 3). The earlier part of the record (4.5 – 3.5 ka) displays a narrow range of
240 values between -13.1 ± 0.3 and -12.5 ± 0.3 (Fig. 3). An abrupt increase of the ϵNd values for
241 corals occurred between 3.40 and 3.20 ka BP, reaching between -12.1 ± 0.3 and -11.8 ± 0.3 (Fig.

242 3). A return to lower values (-13.1 ± 0.3 to -12.4 ± 0.4) is observed between 3.12 and 2.82 ka
243 BP, followed by an abrupt and short decrease over 100 years to -14.5 ± 0.4 at 2.75 ka BP (Fig.
244 3). After 2.67 ka BP, only four specimens display ϵNd values from -12.0 ± 0.4 to -13.2 ± 0.5
245 (Fig. 3).

246

247 5. Discussion

248 5.1. Significance of the ϵNd record

249 The youngest CWC sample collected in the Mingulay Reef complex, with a modern age of
250 0.02 ± 0.013 ka BP (Douarin et al., 2016), displays an ϵNd value of -13.2 ± 0.5 (Fig. 3) which is
251 similar, within the error bars, to the present-day value of seawater flowing at depth of the
252 study site (between -12.9 ± 0.2 and -12.4 ± 0.2 at 101-152 m water depth; station MR-5) (Fig. 2
253 and 3). At station MR-4, located on the continental slope, seawater samples values range from
254 -14.4 ± 0.2 to -13.8 ± 0.2 down to 500 m water depth (Fig. 2). These values are in agreement
255 with seawater analyzed in the Rockall Trough (ICE-CTD 03; Dubois-Dauphin et al., 2017)
256 the values of which range from -14.0 ± 0.2 to -13.3 ± 0.2 for the same depth interval (Fig. 4),
257 implying that subsurface water masses brought by the NAC have a strong influence along the
258 continental slope near the study site. In contrast, station MR-5, located on the continental
259 shelf, exhibits more radiogenic values at all depths compared to the continental slope (MR-4)
260 and the Rockall Trough (ICE-CTD 03; Dubois-Dauphin et al., 2017). The ϵNd value of warm
261 and saline surface water (upper ENACW) flowing in the SEC is poorly constrained along the
262 European margin. It has been reported to be radiogenic in the Bay of Biscay (-10.7 ± 0.3 at 140
263 m in CAROLS stations; Copard et al., 2011), while there are no values shallower than 400 m
264 published for the Porcupine Seabight (-13 ± 0.2 at 400 m in station ICE-CTD 02; Dubois-
265 Dauphin et al., 2017) (Fig. 4). This radiogenic water brought by the SEC is expected to have a
266 strong influence on the Mingulay Reef Complex as seen at station MR-5.

267 Nevertheless, Nd isotopic signatures for the SCC that circulates from the Irish Sea and the
268 Firth of Clyde are unknown. However, rocks and river sediment samples from the northern
269 British Isles display a mean ϵNd value of -10.6 ± 0.4 (Davies et al., 1985), suggesting a rather
270 radiogenic Nd isotopic signature for seawater from interior Seas. Crockett et al. (2018) have
271 provided Nd concentrations (20 to 60 pmol.kg^{-1}) from seawater collected in a coastal station
272 (station 9G, 166 m bottom depth; Fig. 1) located close to the Mingulay Reef Complex
273 suggesting possible local desorption from resuspended sediments or pore water release to the
274 overlying water column. Seawater ϵNd obtained in the upper 50 m of the MR-5 water station,
275 collected above the Mingulay Reef Complex, allows us to establish for the first time the ϵNd
276 value of seawater flowing along the Scottish margin; this value is around -11.7 ± 0.2 and is
277 associated with a temperature and salinity of about $10\text{-}12^\circ\text{C}$ and $34.5\text{-}34.9$, respectively (Fig.
278 2). This suggests that surface water is likely affected by local inputs from the Scottish shelf
279 and/or the interior Seas. On the other hand, the ϵNd values are more unradiogenic (from -
280 13.0 ± 0.3 to -12.4 ± 0.2) below 100 m at water station MR-5 (in the range of Porcupine
281 Seabight; Dubois-Dauphin et al., 2017) and associated with salinity of ~ 35.2 suggesting that
282 CWCs from the Mingulay Reef Complex are under the influence of a mixing between SEC
283 and NAC waters. Furthermore, the initial $\delta^{234}\text{U}$ values of the samples considered in this study
284 ranged from 142.9 ± 2.4 to 150.0 ± 3.5 (2σ uncertainties; Douarin et al., 2013), which is in the
285 range of the modern seawater value (146.8 ± 0.1 ; Andersen et al., 2010), while ^{232}Th values for
286 all corals were low ($< 0.48 \pm 0.07$ ppb; Douarin et al., 2013). These arguments do not support
287 an influence of a local source on CWC ϵNd from the Mingulay Reef Complex. However, the
288 desorption from resuspended sediments cannot be ruled out.

289 ϵNd of CWC samples, collected at 747 m water depth at the SW Rockall Trough margin, has
290 been investigated by previous studies and has been shown to range from -11.9 ± 0.3 to -
291 14.4 ± 0.2 over the last 4500 yrs (Colin et al., 2010 ; Copard et al., 2012) (Fig. 3). These values

292 are close to those obtained at the Mingulay Reef Complex, with a generally good
293 correspondence between samples of the same age in both sites (Fig. 3). Seawater ϵNd
294 investigated in the Rockall Trough does not indicate significant variations of Nd isotopic
295 composition down to 1000 m water depth (-13.3 ± 0.2 to -14.0 ± 0.2 ; Dubois-Dauphin et al.,
296 2017) and presents similar values to those found at station MR-4 (Fig. 4). This implies a
297 relatively strong homogeneity of the Nd isotopic composition of the surface-to-mid water
298 masses of the Rockall Trough. On the other hand, station MR-5 displayed more radiogenic
299 values, as the Mingulay Reef Complex is likely to experience a strong mixing with STG
300 water. Nevertheless, both sites should be under the influence of the gyre circulation system. In
301 this instance, it is therefore possible to consider that the CWCs from the shallow Mingulay
302 Reef Complex record similar gyre dynamics than the mid-depth of the SW Rockall Trough
303 margin.

304 The ϵNd record from the Rockall Trough provides evidence of negative excursions during the
305 warm Medieval Climatic Anomaly (between 1000 AD and 1250 AD) and during the most
306 recent period (1950 AD to 2000 AD) (Fig. 3), which have been interpreted as indicating a
307 strengthened SPG and an increase in the subpolar water contribution to the Nordic Seas
308 (Copard et al., 2012). CWCs from the Mingulay Reef Complex do not record these events as
309 none of the sample ages match these periods. However, they indicate another major negative
310 excursion of ϵNd values at about 2.8 ka BP (Fig. 3).

311 The presence of Ice Rafted Debris (IRD) during the Holocene is evidenced in North Atlantic
312 sediment cores located in the Rockall Trough (cores MC52 and VM29-191; Bond et al., 2001)
313 (Fig. 1) by peaks in hematite-stained grains and Icelandic glass. It has been shown to have a
314 potential influence on ϵNd records during periods of northern-hemisphere ice sheet collapse
315 throughout the MIS2, due the input of very radiogenic volcanic material (Roberts and
316 Piotrowski, 2015). However, the Holocene is not marked by such variations in the Nd isotopic

317 signature of water masses (Roberts and Piotrowski, 2015). In addition, the ϵNd records
318 extracted from CWCs of the Mingulay Reef Complex (this study) and the Rockall Trough
319 (Colin et al., 2010) do not seem to be affected by this mechanism, at least not during the late
320 Holocene, as an increase in Icelandic glass concentration in the Rockall Trough (0.1-0.6 ka,
321 1.2-1.5 ka, 2.8-2.9 ka, 3.3-3.4 ka, 4.0-4.1 ka; Bond et al., 2001) is not linked to systematically
322 higher ϵNd values. Overall, a strong contribution of Nd input from volcanic material can
323 probably be excluded, suggesting that CWCs from the Mingulay Reef Complex record ϵNd
324 variability in the mixing between SEC and NAC water through time.

325 Fresh sub-surface water flowing into the SPG is characterized by unradiogenic ϵNd values (-
326 14 to -16) while subtropical water exhibits more radiogenic values (-10 to -12) (Lacan &
327 Jeandel, 2004, 2005; Lambelet et al., 2016; Dubois-Dauphin et al., 2017). It has been shown
328 that ϵNd of the NAC was dominated by the subpolar gyre signature due to higher Nd
329 concentrations in the subpolar surface waters compared to the northern subtropical gyre
330 waters (Lambelet et al., 2016; Dubois-Dauphin et al., 2017). Therefore, when the subpolar
331 gyre extension is enhanced, NAC seawater is expected to be even more unradiogenic than
332 today. Conversely, during times of westward contraction of the subpolar gyre, a stronger
333 influence of temperate subtropical water flowing northwards along the European margin
334 could increase the ϵNd value at the study site. ϵNd record of the Mingulay Reef Complex can
335 be associated to the spatial evolution of the interface between the SPG waters and the
336 ENACW carried northwards by the SEC. Thus, lower ϵNd recorded (2.8 ka) in the subsurface
337 Mingulay Reef Complex may reflect periods of intense, eastward extension of water from the
338 SPG, while higher ϵNd (3.4 ka) should point to a westward contraction of the SPG and a
339 subsequent stronger influence of the STG waters carried by the slope current and/or water
340 from interior Seas.

341 *5.2. Hydrological and climate implications of Nd isotope variations*

342 U-series dating and radiocarbon ages (Douarin et al., 2016) have been obtained for CWC
343 samples from the Mingulay Reef Complex investigated in this study, thereby allowing us to
344 calculate $\Delta^{14}\text{C}$ of the water (Douarin et al., 2016) so as to track changes in the circulation of
345 sub-surface water masses during the Holocene. The Marine Reservoir Effect (MRE) of the
346 NAC and derived branches averages about 400 years (Stuiver et al., 1998). However, the
347 fresher water flowing into the SPG is depleted in radiocarbon compared to the NAC,
348 displaying a MRE between 450 and 500 years (Eiriksson et al., 2011; Franke et al., 2008).
349 Along the western European margin, in the inter-gyre area, the mean MRE for sub-surface
350 water has been estimated at 380 ± 60 years (Tisnerat-Laborde et al., 2010). Consequently, high
351 MRE in the Mingulay CWCs has been interpreted as indicating a stronger influence of
352 subpolar water (Douarin et al., 2016), linked to the extension of the SPG (Hatun et al., 2005).

353 The ϵNd record obtained in this study co-varies with the reconstructed MRE values for the
354 Mingulay CWCs (Douarin et al., 2016), as older (younger) MRE is synchronous with more
355 (less) radiogenic ϵNd (Fig. 5). At 3.4, the coral ϵNd record shifts towards more radiogenic
356 values (~ -11.8) associated with an increase in MRE (up to 592 ± 41 years). Conversely, low
357 MRE values (down to 207 ± 38 years) occur at about 2.8 ka and are associated with more
358 unradiogenic values (~ -14.5) (Fig.3 and 5).

359 As STG water exhibits more radiogenic values than water flowing in the SPG (see section
360 5.1), a shift toward more radiogenic ϵNd values at Mingulay points to a weakened SPG,
361 promoting the northeastward advection of subtropical water to the Rockall Trough and the
362 Mingulay Reef Complex. This conclusion is inconsistent with the previous interpretation of
363 MRE variations in Mingulay corals (Douarin et al., 2016). Alternatively, MRE variations
364 could be interpreted as changes in gas exchange rates between the atmosphere and the surface
365 mixing layer (Ascough et al., 2009; Tisnérat-Laborde et al., 2010; Wanamaker et al., 2012). A
366 homogenization of the water column due to enhanced wind stress could result in a younger

367 MRE from Mingulay corals, as previously observed in CWCs from the Bay of Biscay
368 (Montero-Serrano et al., 2013). Previous studies have shown that downwelling phenomena
369 occur at the Mingulay Reef Complex (Davies et al., 2009). A long-term influence of
370 downwelling on the area of the Mingulay Reef Complex should have resulted in the transfer
371 of rather radiogenic ϵNd surface waters (-11.7 ± 0.2 , station MR-5) to depth at times of lower
372 MRE. However, this is not the case as ϵNd from Mingulay CWCs decreases when the marine
373 age reservoir is low (i.e. at 2.8 ka) and inversely (i.e. at 3.4 ka). Similarly, inputs of Scottish
374 fjords and coastal waters, which are likely to result in reduced regional MRE (Stuiver and
375 Braziunas 1993) and higher ϵNd values (Davies et al., 1985), are not supported by the data
376 trend from Mingulay CWCs. Furthermore, a moderate regional deviation in marine reservoir
377 age (-26 ± 14 years) has been estimated for the Interior Seas (Cage et al., 2006), suggesting a
378 limited influence on radiocarbon variations. Finally, the influences of ^{14}C -deficient carbon
379 derived from humus or carbonate bedrock are likely to be small (Cage et al., 2006). Taken
380 together, all the above evidences suggest that MRE variations recorded in the Mingulay Reef
381 Complex are the result of changes in vertical mixing occurring in the NAC and/or SEC and
382 that the source of the young MRE anomaly should be water of subpolar origin.

383 The more radiogenic ϵNd value between at 3.4 ka, associated with high MRE, is synchronous
384 with storminess maxima recorded in Icelandic eolian soil deposits (Jackson et al., 2005) (Fig.
385 6). On the basis of several paleostorm activity records, five Holocene storm periods have been
386 defined in the North-East Atlantic during the mid- to late Holocene (5.8-5.5 ka; 4.5-3.9 ka;
387 3.3-2.4 ka; 1.9-1.05 ka and 0.6-0.25 BP) with a frequency of about 1,500 years (Sorrel et al.,
388 2012). These storm periods have been shown to coincide with an enhanced upper-water-
389 column stratification south of Iceland and increases in temperature and salinity (Sorrel et al.,
390 2012). Enhanced stratification and changes in eastern Atlantic water properties are consistent
391 with a westward contraction of the SPG accompanied by a stronger northward penetration of

392 warm and saline waters of the STG (Sorrel et al., 2012). In addition, a decrease in the
393 temperature gradient of the North Atlantic has been linked to a southward shift of the
394 westerlies and low-pressure systems, leading to southward displacement of the storm tracks
395 along the European coasts (Sabatier et al., 2012b; Sorrel et al., 2012). These observations on a
396 multi-millennial timescale are consistent with centennial variations occurring at the Mingulay
397 Reef Complex. Hence, we propose the ϵNd maximum recorded in the Mingulay Reef
398 Complex at 3.4 ka, coeval with strong storms activity (Fig. 6), indicates a stronger influence
399 of subtropical water in the NAC, leading to a higher stratification of the water column in
400 agreement with older MRE (Fig. 6 and 7).

401 Conversely, the minimum ϵNd value at 2.8 ka, which is in phase with a younger MRE, is not
402 associated with strong storm activity (Fig. 6). It is, however, characterized by periods of
403 elevated Na^+ in the Greenland Ice Sheet Project 2 (GISP2) ice core which are interpreted as
404 sea salt transported by strengthened westerly winds (O'Brien et al., 1995; Mayewski et al.,
405 2004; Jackson et al., 2005) (Fig. 6). Consequently, increased wind intensity at high latitudes
406 of the North Atlantic results in an extension of the SPG leading to more unradiogenic ϵNd
407 values and lower MRE in the Mingulay Reef Complex (Fig. 7).

408 The variability in north Atlantic gyre circulation could in turn impact the AMOC dynamics
409 (Oppo et al., 2003; Thornalley et al., 2009). High temporal resolution sea surface temperature
410 (SST) reconstructions for the late Holocene have been investigated in the Nordic Seas (core
411 MD99-2275, Sicre et al., 2008). SST variability in the North-East Atlantic and the Nordic
412 Seas has a strong influence on colder and warmer climate over Europe. Copard et al. (2012)
413 have demonstrated that coral ϵNd shifted towards values indicative of a stronger SPG during
414 the Medieval Climatic Anomaly and a weaker SPG during the Little Ice Age. Similarly, the
415 2.8 ka event recorded in CWCs from the Mingulay Reef Complex is coeval with a
416 temperature maximum in the Nordic Seas, while lower SSTs are associated with the 3.4 ka

417 event (Sicre et al., 2008) (Fig. 6). These findings are in agreement with a previous study that
418 shows a linkage between LSW formation, SPG strength and climate periods in North-West
419 Europe (Moffa-Sanchez and Hall, 2017). In addition, the lower ϵNd from subtler variations of
420 the Mingulay corals are often associated with higher temperatures north of Iceland (see
421 dashed lines in Fig. 6). We conclude that an extension (contraction) of the SPG and the
422 subsequent intensification (weakening) of the AMOC results in a higher (lower) latitudinal
423 heat flux in the North-East Atlantic and the Norwegian Seas (Fig. 7), as has been evidenced
424 during the last millennium (Wanamaker et al., 2012). By comparing SST variability in the
425 Nordic Seas and the subpolar Atlantic, Miettinen et al. (2012) have demonstrated a SST
426 seesaw between the two regions that could be a surface expression of the variability of the
427 NAC.

428 Furthermore, there is a link between the growth rate of Mingulay corals and the ϵNd of the
429 CWCs (Fig. 3). Small decreases in the ϵNd values are often associated with an increase in the
430 reef growth rate (Fig. 3). The sensitivity of corals and coral reefs to abrupt climatic and
431 oceanic changes has been pointed out in previous studies (Dodds et al., 2007; Davies et al.,
432 2008; Eisele et al., 2011; Frank et al., 2011; Thiagarajan et al., 2013; Henry et al., 2014;
433 Hebbeln et al., 2014; Douarin et al., 2014; Bonneau et al., 2018). This suggests that the
434 Mingulay Reef Complex is very sensitive to the origin of the water mass. A higher
435 contribution of water originating from the strongly ventilated SPG (such as that observed
436 around 2.8 ka) could cause favorable conditions for CWC growth. Further investigation will
437 be necessary to explain this relationship between changes in the origin of the water masses
438 and coral growth on the Mingulay reef.

439

440 **6. Conclusion**

441 ϵNd of seawater and cold-water coral (CWC) samples, collected at depths of 127-134 m in the
442 Mingulay Reef Complex on the Scottish continental shelf, have been investigated in order to
443 constrain subpolar gyre (SPG) dynamics over the past 4500 years.

444 ϵNd values obtained in the upper 30 m water depth collected above the Mingulay Reef
445 Complex permit us to establish, for the first time, the surface Nd isotopic signature of the
446 Scottish continental shelf which is around -11.7 ± 0.2 , probably due to the influence of
447 radiogenic interior Seas. Below 100 m ϵNd values vary from -13 ± 0.3 to -12.4 ± 0.2 , pointing to
448 a mixing between the Shelf Edge Current (SEC) water and the subpolar water brought by the
449 North Atlantic Current (NAC), as observed in the Porcupine Seabight (Dubois-Dauphin et al.,
450 2017). An influence of the interior Seas cannot be ruled out. In contrast, water station samples
451 collected on the continental slope display unradiogenic ϵNd values (from -14.4 ± 0.2 to -
452 13.8 ± 0.2), similar to the western Rockall Trough, meaning that NAC water has a strong
453 influence along the continental slope near the study site.

454 ϵNd values from the Mingulay Reef Complex show two major variations at 2.8 ka and 3.4 ka,
455 which are synchronous with changes in ^{14}C reservoir age. An unradiogenic ϵNd value of -
456 14.5 ± 0.4 at 2.8 ka indicated an eastward extension of the SPG associated with a lower ^{14}C
457 reservoir age (200 yrs). Conversely, a more radiogenic value at 3.4 ka (-11.8 ± 0.3) pointed to a
458 stronger northward penetration of the SEC water along the western European margin,
459 combined with a higher ^{14}C reservoir age (600 yrs). The link between ϵNd and ^{14}C records
460 highlights the fact that ^{14}C reservoir age cannot be used to track water mass origin as it has
461 been previously interpreted (Douarin et al., 2016) but rather vertical ventilations that occurred
462 in the NAC and the SEC.

463 The major negative excursion at 2.8 ka as well as subtler examples recorded in CWCs are
464 systematically associated with warmer climatic conditions in Northern Europe and the Eastern
465 Norwegian Sea linked to an intensification of the surface limb of the AMOC, as has been

466 previously observed for the Medieval Climatic Anomaly (Copard et al., 2012). Such
467 hydrological conditions have stimulated the growth rate of the Mingulay Reef Complex.

468

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475 **Data availability**

476 Data related to this article are all available in Tables 1 and 2.

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768

769 **Figure captions**

770 **Fig. 1.** Sampling map. The schematic circulations of surface currents are reported by black
771 arrows based on [Daniault et al. \(2016\)](#) and [Cage & Austin \(2010\)](#). NAC, North Atlantic
772 Current; SCC, Scottish Coastal Current; SEC, Shelf Edge Current; SPG, Subpolar Gyre; STG,
773 Subtropical Gyre. Seawater ϵNd values at 100-150m (in white) have been reported from
774 [Dubois-Dauphin et al. \(2017\)](#) and [Lambelet et al. \(2016\)](#). The location of CWCs investigated
775 by [Colin et al. \(2010\)](#) and [Copard et al. \(2012\)](#) in the Rockall Trough are indicated by a green
776 square. Marine cores discussed in the text are indicated by black dots: a. MD99-2275 ([Sicre
777 et al., 2008](#)); b. RAPiD-12-1K ([Thornalley et al., 2009](#)); c. VM29-191 and d. MC52 ([Bond et
778 al., 2001](#)). Water stations are indicated by open dots: e. ICE-CTD 03 ([Dubois-Dauphin et al.,
779 2017](#)); f. ICE-CTD 02 ([Dubois-Dauphin et al., 2017](#)); g. Carols Stations ([Copard et al., 2011](#));
780 h. Station 9G ([Crocket et al., 2018](#)). Seawater stations MR-4 (orange dot, continental slope)

781 and MR-5 (blue dot, continental shelf) investigated in this study are reported on the insert
782 map. The Mingulay Reef Complex is indicated by a red square.

783 **Fig. 2.** Potential temperature ($^{\circ}\text{C}$), salinity and ϵNd value depth profiles for stations MR-4
784 (continental slope) and MR-5 (continental shelf).

785 **Fig. 3.** (a) Marine Reservoir Effect (MRE) reconstructed from Mingulay Reef Complex
786 CWCs (Douarin et al., 2016); (b) ϵNd record from the Mingulay Reef Complex CWCs (blue
787 dots, this study) and from the Rockall Trough (green squares, Colin et al., 2010; Copard et al.,
788 2012). The blue star corresponds to the present day ϵNd value for station MR-5 at depth of the
789 Mingulay CWCs. The green star corresponds to the present day ϵNd value for station ICE-
790 CTD 03 (Dubois-Dauphin et al., 2017) at depth of the Rockall CWCs. (c) Reef growth rates
791 estimated from downcore +56-08/930VE (pink) and downcore +56-08/929VE (orange) U-
792 series chronologies; grey dots indicate ages for seabed surface *Lophelia* dated by radiocarbon
793 and/or U-series (Douarin et al., 2013).

794 **Fig. 4.** Seawater ϵNd profiles for stations MR-4 and MR-5 compared with previous ones
795 published for the Rockall Trough and the Porcupine Seabight (Dubois-Dauphin et al., 2017),
796 as well as for the Bay of Biscay (Copard et al., 2011)

797 **Fig. 5.** Crossplot of MRE (Douarin et al., 2016) versus ϵNd (this study) of the Mingulay Reef
798 Complex.

799 **Fig. 6.** (a) High resolution Sea surface temperature (in $^{\circ}\text{C}$) derived from alkenone
800 paleothermometry (MD99-2275; Sicre et al., 2008). Temporal resolution of the blue curve
801 ranges from 2 to 5 years. The superimposed red curve is a 5 points running mean; (b) ϵNd
802 record from the Mingulay Reef Complex CWCs (blue dots, this study) and from the Rockall
803 Trough (green squares, Colin et al., 2010; Copard et al., 2012) (c) MRE reconstructed from
804 Mingulay Reef Complex CWCs (Douarin et al., 2016); (d) Sea surface temperatures at surface

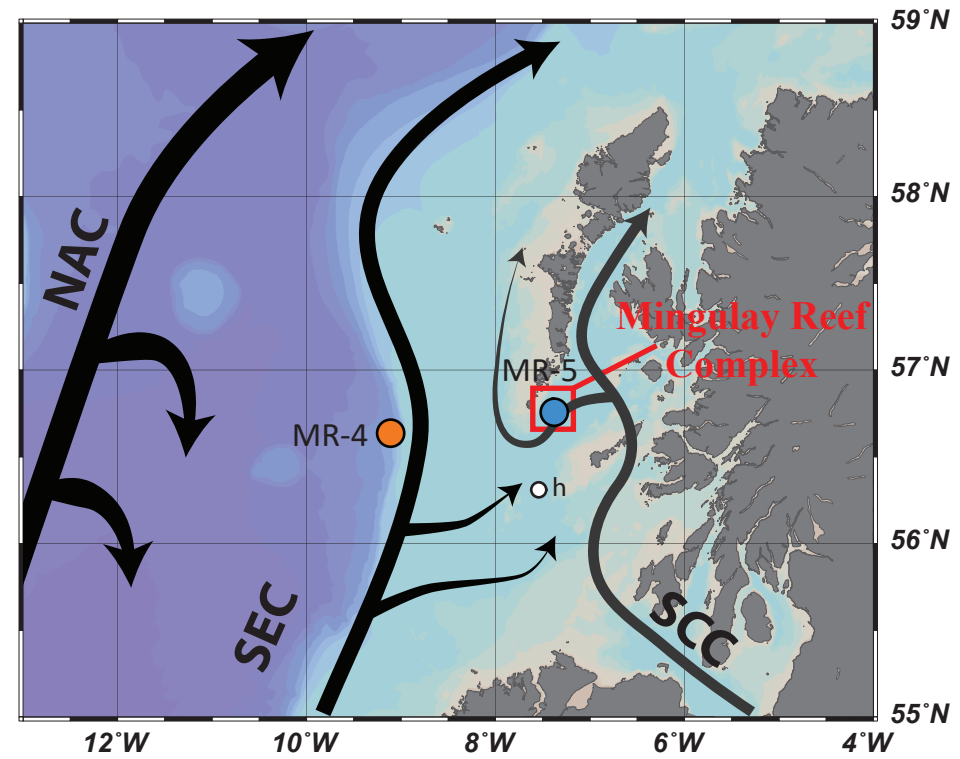
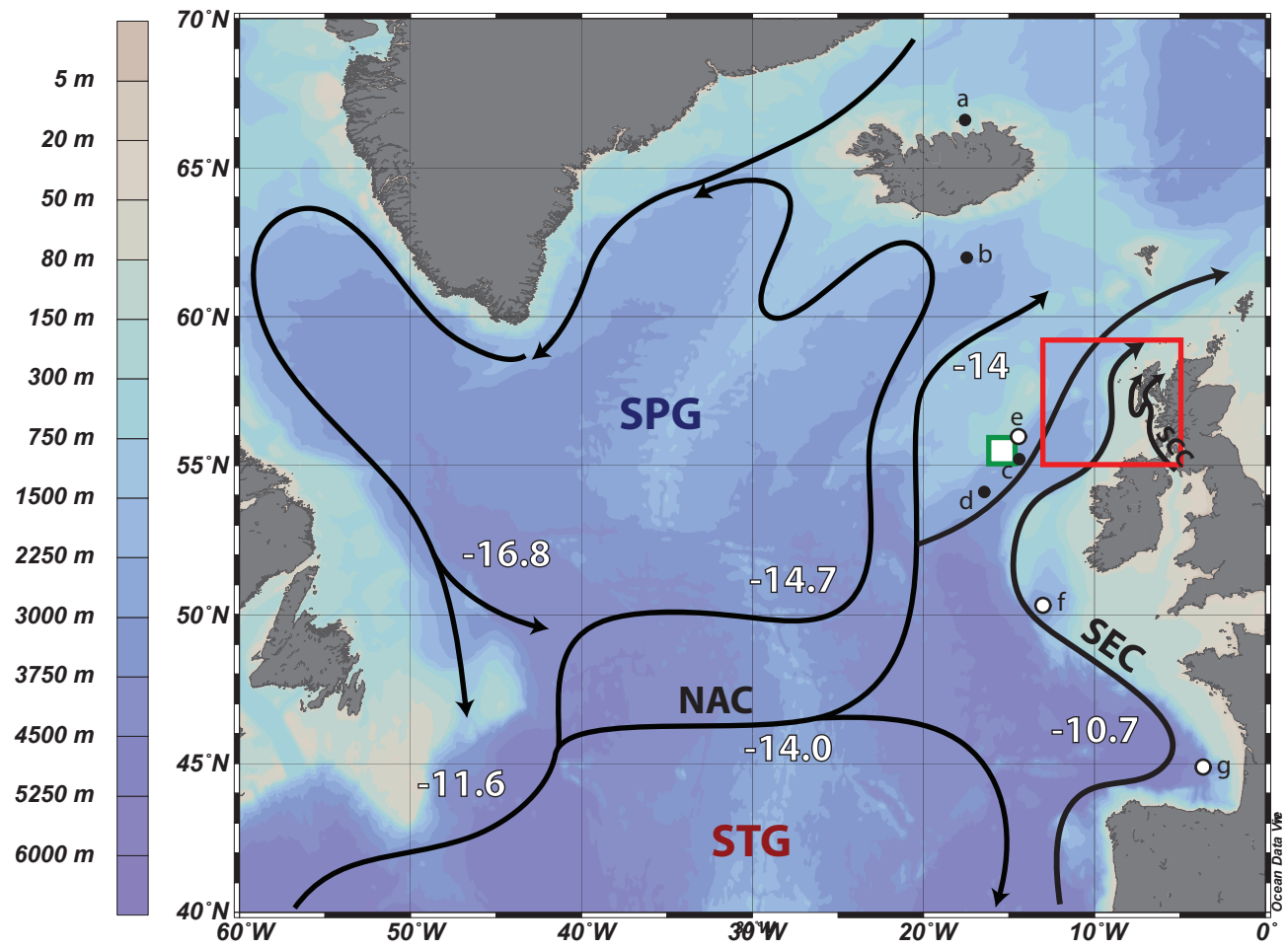
805 (red line) and at thermocline level (blue line) (RAPiD12-1K ; Thornalley et al., 2009).(e)
806 Mean grain size (μm) measured in south Icelandic loess (Jackson et al., 2005). (f) Greenland
807 Ice Sheet Project 2 sea-salt sodium as a proxy of westerly winds (O'Brien et al., 1995). MCA:
808 Medieval Climatic Anomaly. Dashed lines underline warm events in North Iceland.

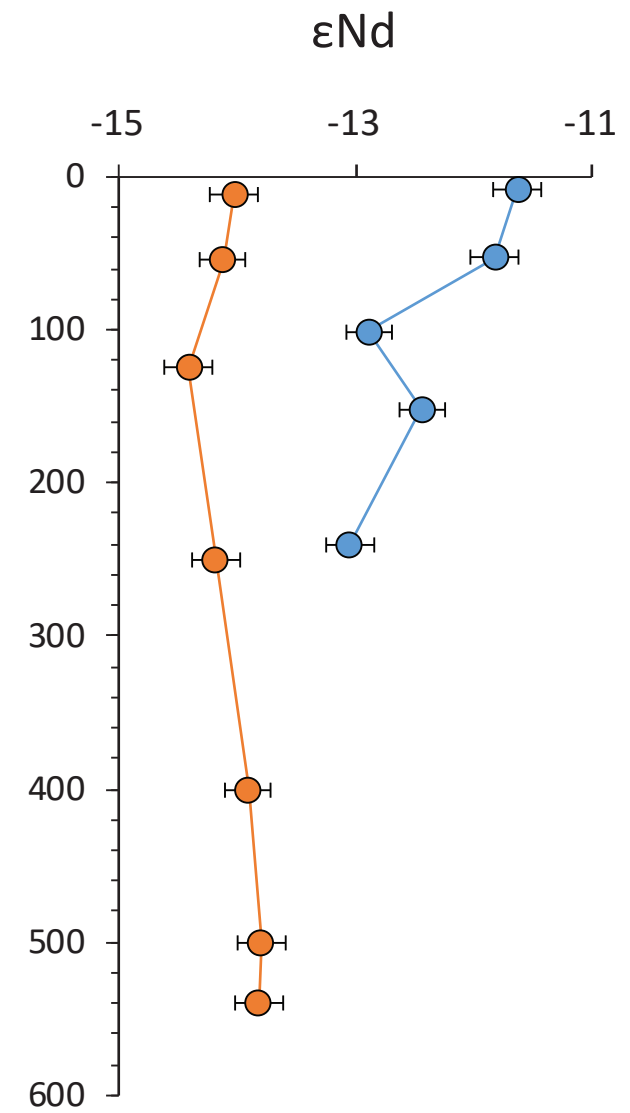
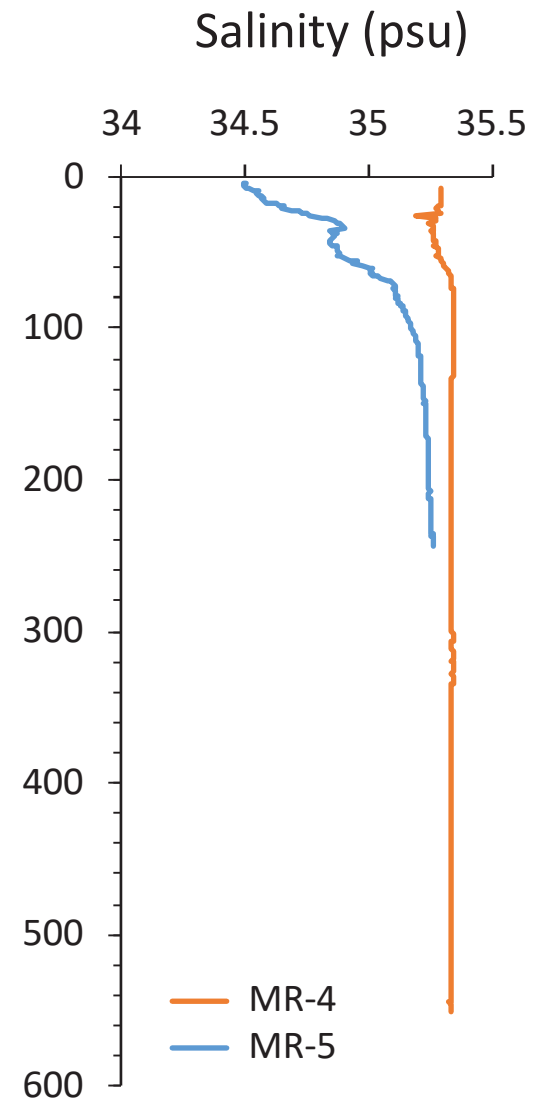
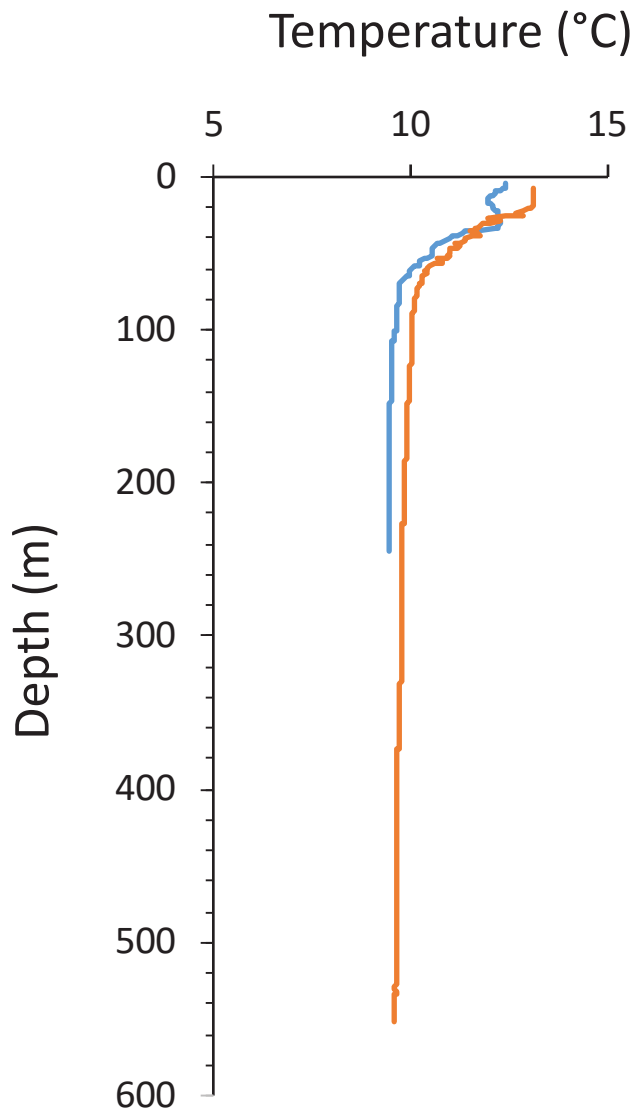
809 **Fig. 7.** Schematic representations of the dynamic of sub-surface circulation in the North
810 Atlantic during the 2.8 event (a) and 3.4 event (b).

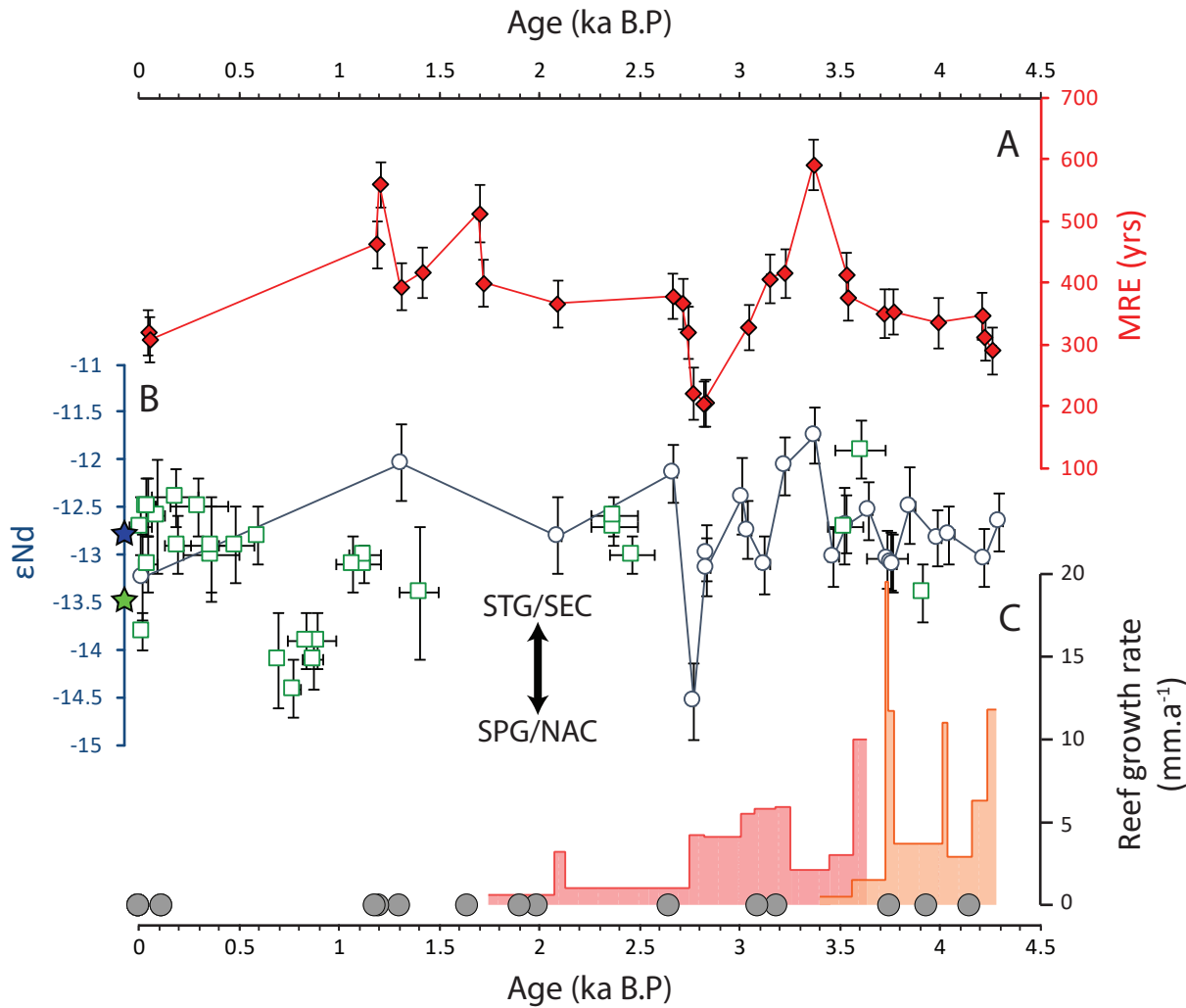
811 **Table 1.** ϵNd values obtained for cold-water corals from the Mingulay Reef Complex.
812 Internal error (2 SE) corresponds to error measurement based on 90 cycles of measurements.
813 External error (2 SD) corresponds to external reproducibility (2σ standard deviation) derived
814 from repeated measurements of La Jolla standard for each analytical session. When internal
815 error is larger than external error, internal error is used in the figures.

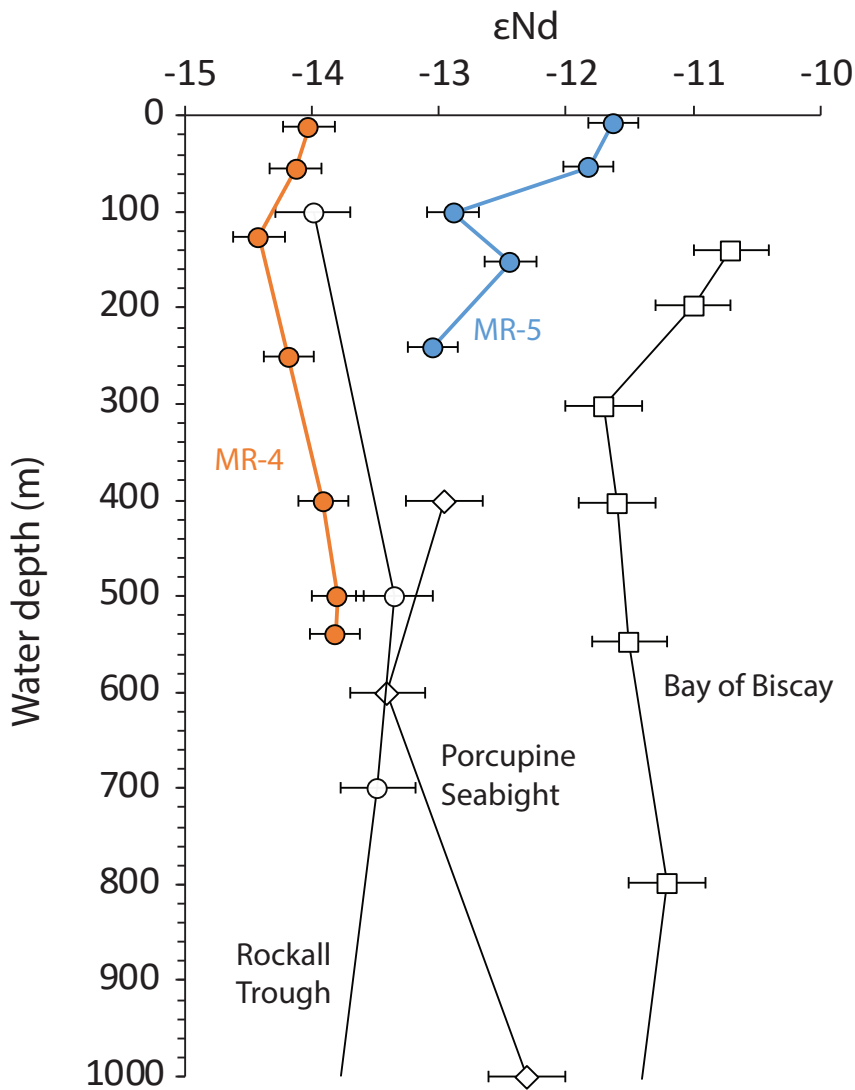
816 **Table 2.** Locations, water depth (m), potential temperature (θ , $^{\circ}\text{C}$), salinity (psu), potential
817 density (σ , kg.m^{-3}), $^{143}\text{Nd}/^{144}\text{Nd}$ and ϵNd values of seawater samples investigated in this
818 study. Error bars reported for ϵNd values correspond to external reproducibility (2σ standard
819 deviation) derived from repeated measurements of La Jolla standard for each analytical
820 session.

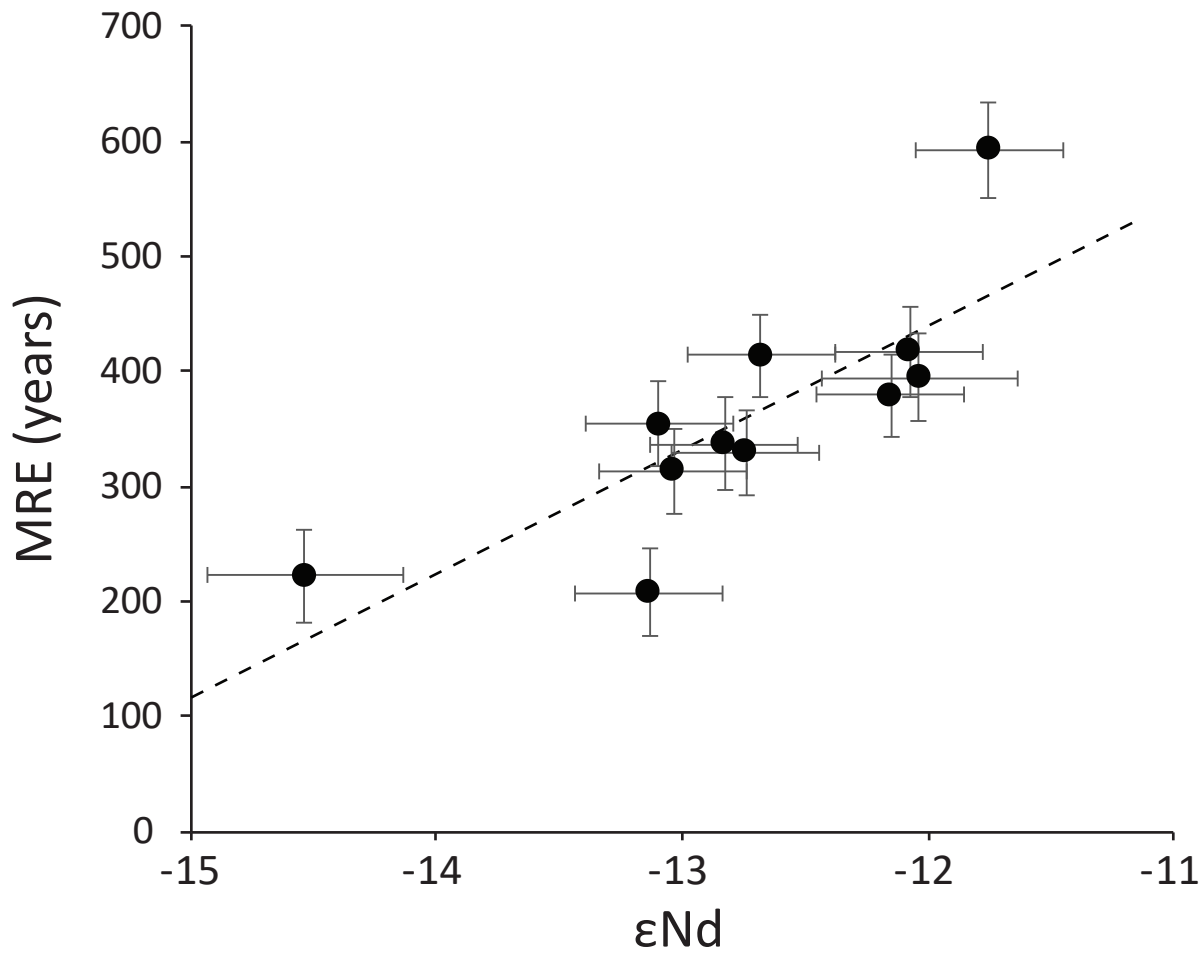
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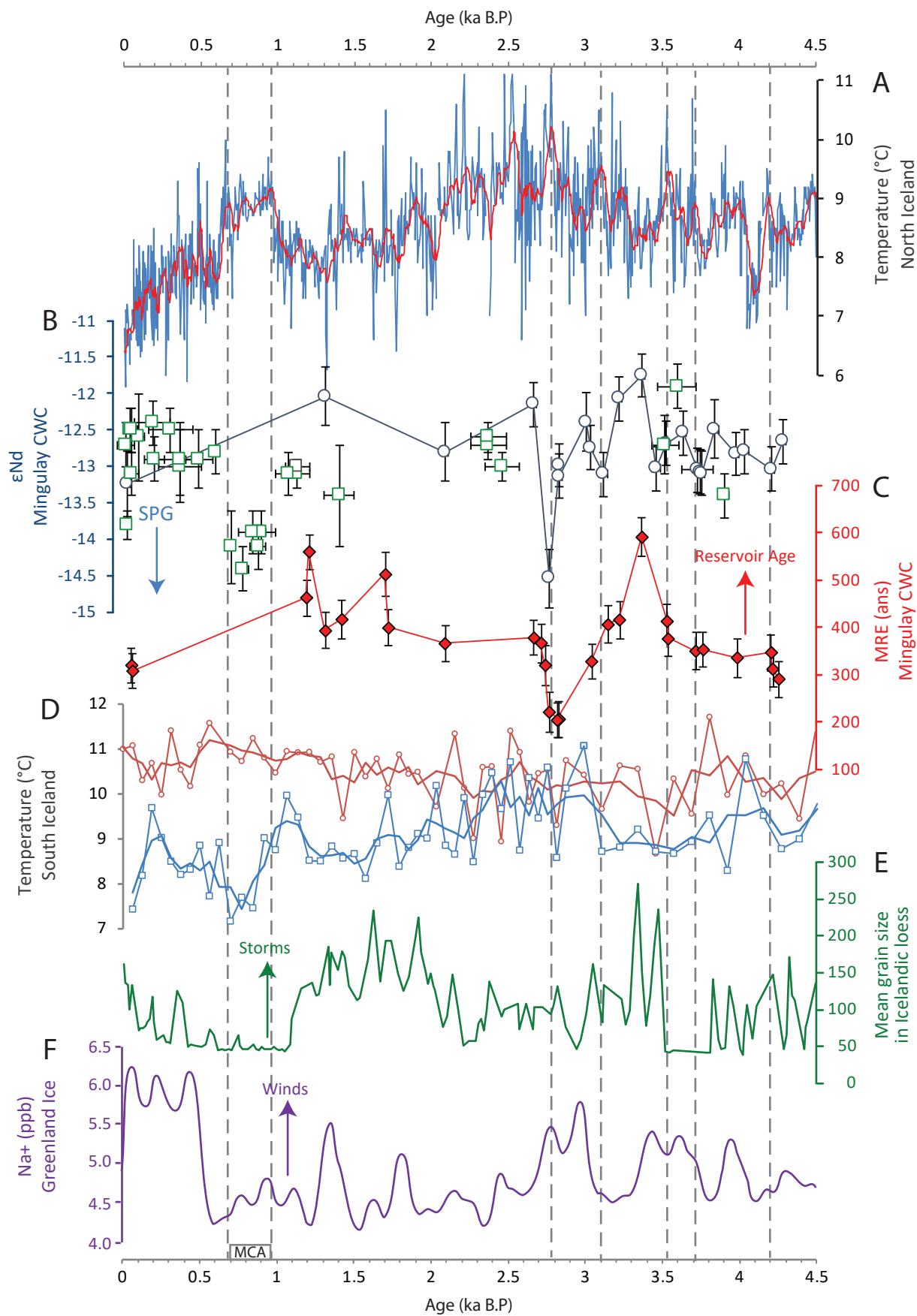


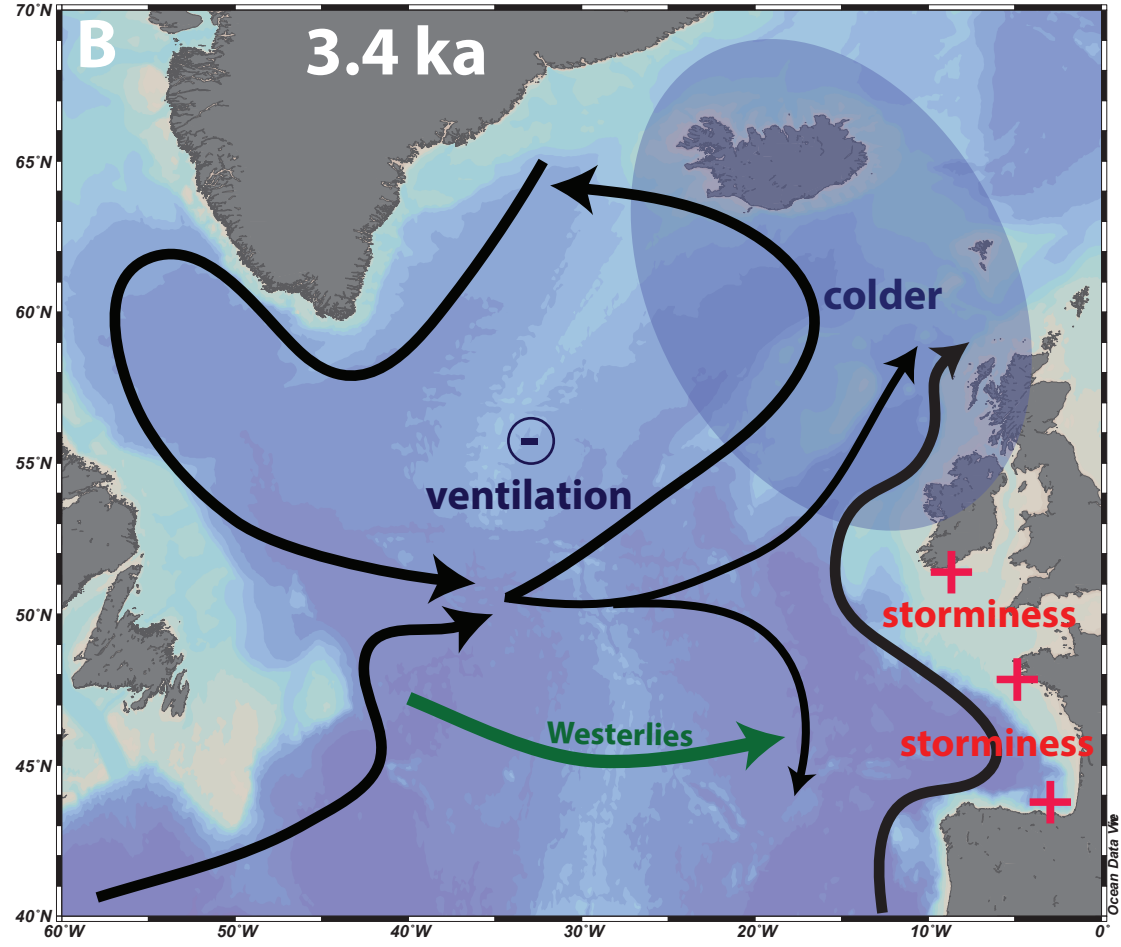
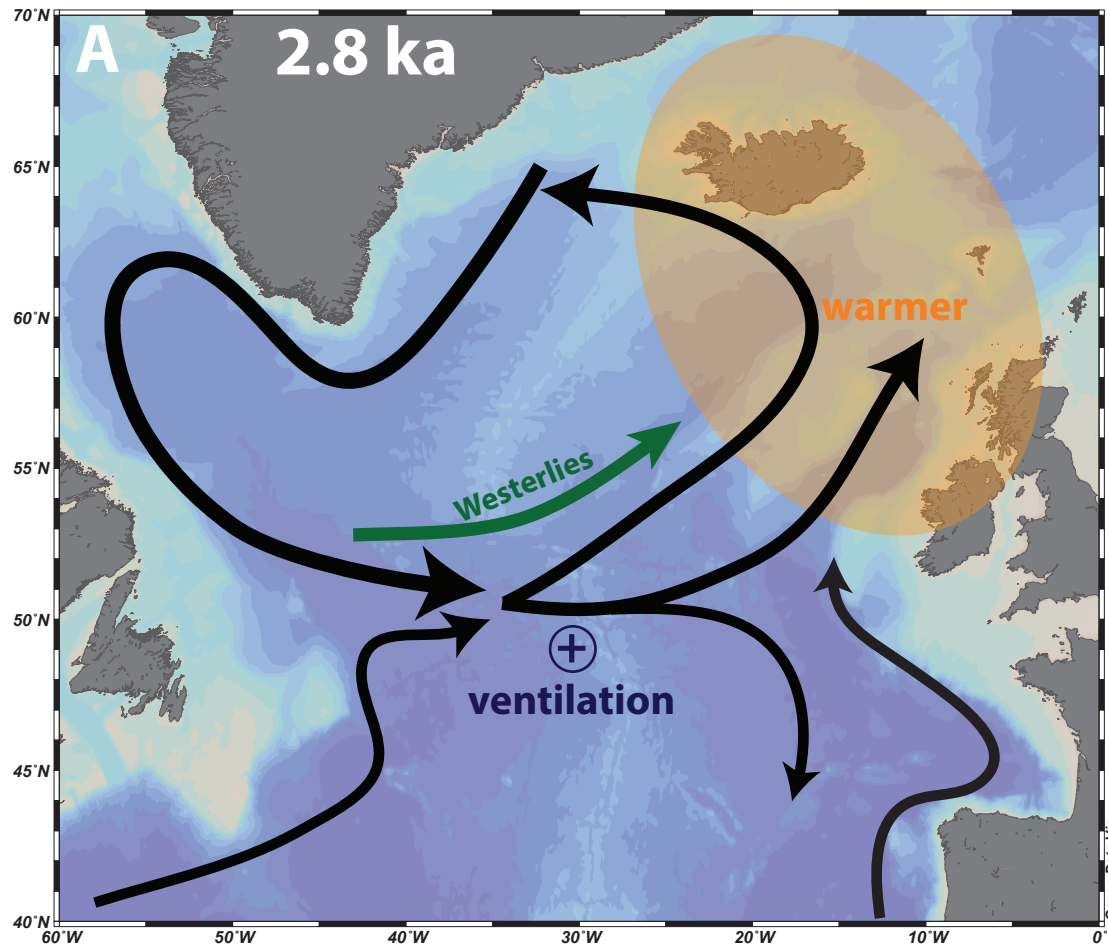












Sample Name	Latitude	Longitude	Depth (m)	Age (yrs)	$^{143}\text{Nd}/^{144}\text{Nd}$	error (2 SE)	ϵNd	error (2 SE)	error (2 SD)
<i>GRAB 15.5.5.10</i>	56°47'08" N	7°25'48" W	seafloor	21 ±13	0.511959	±0.000023	-13.24	±0.45	±0.40
<i>GRAB 1151</i>	56°49'08" N	7°23'36" W	seafloor	1312 ±11	0.512021	±0.000021	-12.04	±0.40	±0.40
930 A6 42-45	56°49'20" N	7°23'47" W	134	2088 ±18	0.511982	±0.000018	-12.80	±0.36	±0.40
<i>GRAB 56.08.928</i>	56°47'08" N	7°25'48" W	seafloor	2666 ±14	0.512015	±0.000008	-12.15	±0.15	±0.30
930 B6 142-146	56°49'20" N	7°23'47" W	134	2765 ±16	0.511893	±0.000021	-14.53	±0.40	±0.40
929 A4 100-101	56°49'19" N	7°23'27" W	127	2828 ±13	0.511973	±0.000008	-12.98	±0.15	±0.30
930 B6 134-137	56°49'20" N	7°23'47" W	134	2830 ±19	0.511965	±0.000016	-13.13	±0.31	±0.30
930 C6 214-217	56°49'20" N	7°23'47" W	134	3012 ±17	0.512003	±0.000018	-12.39	±0.36	±0.40
930 C6 251-254	56°49'20" N	7°23'47" W	134	3040 ±11	0.511985	±0.000016	-12.74	±0.31	±0.30
930 D6 388-392	56°49'20" N	7°23'47" W	134	3119 ±26	0.511966	±0.000008	-13.11	±0.15	±0.30
930 D6 356-358	56°49'20" N	7°23'47" W	134	3221 ±18	0.512019	±0.000012	-12.07	±0.23	±0.30
929 A4 3-9 cm	56°49'19" N	7°23'27" W	127	3367 ±18	0.512036	±0.000011	-11.75	±0.21	±0.30
930 D6 377-379	56°49'20" N	7°23'47" W	134	3461 ±27	0.511970	±0.000011	-13.03	±0.22	±0.30
929 A4 12-17	56°49'19" N	7°23'27" W	127	3530 ±16	0.511988	±0.000008	-12.68	±0.16	±0.30
930 F6 505-510	56°49'20" N	7°23'47" W	134	3641 ±22	0.511995	±0.000008	-12.54	±0.15	±0.30
929 A4 38-41	56°49'19" N	7°23'27" W	127	3734 ±104	0.511970	±0.000009	-13.04	±0.18	±0.30
929 A4 64-67	56°49'19" N	7°23'27" W	127	3747 ±17	0.511968	±0.000015	-13.07	±0.29	±0.30
929 A4 90-91	56°49'19" N	7°23'27" W	127	3765 ±13	0.511967	±0.000010	-13.09	±0.19	±0.30
930 E6 459-461	56°49'20" N	7°23'47" W	134	3847 ±24	0.511998	±0.000019	-12.49	±0.37	±0.40
929 B4 188-189	56°49'19" N	7°23'27" W	134	3986 ±18	0.511980	±0.000012	-12.83	±0.24	±0.30
929 C4 213-216	56°49'19" N	7°23'27" W	127	4043 ±23	0.511982	±0.000009	-12.79	±0.18	±0.30
929 C4 284-290	56°49'19" N	7°23'27" W	127	4216 ±16	0.511970	±0.000010	-13.03	±0.19	±0.30
929 D4 349-353	56°49'19" N	7°23'27" W	127	4287 ±26	0.511989	±0.000011	-12.66	±0.22	±0.30

Table 1

Station	Latitude	Longitude	Depth (m)	θ ($^{\circ}\text{C}$)	S (psu)	σ ($\text{kg}\cdot\text{m}^{-3}$)	$^{143}\text{Nd}/^{144}\text{Nd}$	error (2 SD)	ϵNd	error (2 SD)
MR-4	56°37.44' N	9°5.48'W	12	13.10	35.29	26.60	0.511919	± 0.000010	-14.0	± 0.20
MR-4	56°37.44' N	9°5.48'W	55	10.78	35.30	27.05	0.511914	± 0.000014	-14.1	± 0.30
MR-4	56°37.44' N	9°5.48'W	125	9.99	35.34	27.22	0.511899	± 0.000011	-14.4	± 0.20
MR-4	56°37.44' N	9°5.48'W	250	9.80	35.34	27.25	0.511911	± 0.000012	-14.2	± 0.20
MR-4	56°37.44' N	9°5.48'W	400	9.65	35.33	27.27	0.511925	± 0.000011	-13.9	± 0.20
MR-4	56°37.44' N	9°5.48'W	500	9.63	35.33	27.27	0.511931	± 0.000011	-13.8	± 0.20
MR-4	56°37.44' N	9°5.48'W	540	9.60	35.33	27.28	0.511930	± 0.000012	-13.8	± 0.20
MR-5	56°46.04' N	7°25.98'W	8	12.33	34.51	26.15	0.512042	± 0.000011	-11.6	± 0.20
MR-5	56°46.04' N	7°25.98'W	53	10.39	34.89	26.80	0.512032	± 0.000011	-11.8	± 0.20
MR-5	56°46.04' N	7°25.98'W	101	9.60	35.18	27.16	0.511977	± 0.000012	-12.9	± 0.20
MR-5	56°46.04' N	7°25.98'W	152	9.47	35.23	27.22	0.512000	± 0.000011	-12.4	± 0.20
MR-5	56°46.04' N	7°25.98'W	240	9.43	35.26	27.25	0.511969	± 0.000014	-13.0	± 0.30

Table 2