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1 **Imprint of seasonality changes on fluvio-glacial dynamics across**  
2 **Heinrich Stadial 1 (NE Atlantic Ocean)**

3  
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20

## 21 **Abstract**

22 The northern Bay of Biscay has previously proven its great potential for recording the *'Fleuve*  
23 *Manche'* paleoriver (i.e., the largest Pleistocene river in Europe) fluvio-glacial activity. In this  
24 study, new dinoflagellate cyst (dinocyst) analyses have been carried out at sub-centennial  
25 resolution in core MD13-3438 to reconstruct the deglacial history of the *'Fleuve Manche'*  
26 paleoriver runoff coupled with European Ice Sheets (EIS) fluctuations across Heinrich Stadial  
27 1 (HS1: 18.2–14.6 ka BP), a key extreme climatic event of the last glacial period. Prior to  
28 Heinrich Event (HE) 1 (16.7–14.6 ka BP), the onset of HS1 (18.2–16.7 ka BP) appears here  
29 marked by enhanced *'Fleuve Manche'* paleoriver runoff, materialized by laminated deposits.  
30 Our work suggests a novel sub-centennial scale subdivision of the early HS1 (laminated)  
31 interval into 5 sub-phases when episodes of substantial fluvio-glacial delivery concomitant  
32 with warm summers alternate with episodes of moderate runoff associated with extended cold  
33 winters. We argue that multidecadal seasonal changes played a key role in the hydrological  
34 regime of western Europe during this HS1 interval, with the retreat of the southern limb of the  
35 EIS, and associated influx of meltwater and fluvio-glacial delivery, which were strongly  
36 influenced by those multidecadal changes in seasonality. Interestingly, our paleoclimatic  
37 record not only evidences the crucial role of seasonality in controlling climate and  
38 hydrological variations during HS1 but also shows a remarkable echo with reconstructions  
39 from the western Mediterranean Basin, highlighting common climate forcings at regional  
40 scale during the last deglaciation.

41 *Keywords: Heinrich Stadial 1; Dinoflagellate cysts; northern Bay of Biscay; 'Fleuve*  
42 *Manche' paleoriver; European Ice Sheets*

43

## 44 **1. Introduction**

45 The last glacial period was accompanied by millennial-scale abrupt climate shifts, portrayed  
46 in Greenland ice-cores as rapid transitions from cold atmospheric phases termed Greenland  
47 Stadials (GS) to warm atmospheric phases referred to as Greenland Interstadials (GI; e.g.,  
48 Dansgaard et al., 1993; Rasmussen et al., 2014). Despite their original designation, these  
49 climate excursions had an impact across the globe (e.g., Voelker, 2002). In the North Atlantic  
50 Ocean, some GS were associated with massive iceberg surges mainly from the Laurentide Ice  
51 Sheet (LIS) *via* the Hudson Strait Ice Stream (e.g., Bond et al., 1992, 1993; Broecker et al.,  
52 1992, 1994; Hemming, 2004), identified in marine sediments as Ice Rafted Debris (IRD)-  
53 enriched layers (e.g., Bond et al., 1993; Broecker, 1994; Heinrich, 1988). These massive  
54 iceberg (and thus freshwater) surge events are known as Heinrich Events (HEs including  
55 HE1), with their corresponding stadial phases called Heinrich Stadials (HSs including HS1;  
56 Barker et al., 2009; Sanchez Goñi and Harrison, 2010). The associated huge freshwater  
57 releases resulted in large reductions of the Atlantic Meridional Overturning Circulation  
58 (AMOC; e.g., McManus et al., 2004; Stanford et al., 2006, 2011; Ng et al., 2018; Toucanne et  
59 al., 2021). Numerous studies demonstrated that Greenland Iceland and European Ice Sheets  
60 were also major contributors to the oceanic disturbances in the North Atlantic Ocean,  
61 especially when considering the surge sequencing along time (e.g., Bond et al., 1997, 1999;  
62 Grousset et al., 2000, 2001; Hemming et al., 2000, 2004; Knutz et al., 2001, 2007; Hall et al.,  
63 2006; Peck et al., 2006; Nygård et al., 2007; Toucanne et al., 2008, 2010, 2015).

64 HS1, including the HE1 layer, occurred at the onset of the last deglaciation (~19-11 ka BP;  
65 Clark et al., 2012a), just before the abrupt Bølling-Allerød (B/A) warming event starting at ca.  
66 14.7 ka BP (Rasmussen et al., 2014) and after the Last Glacial Maximum (LGM; Mix et al.,  
67 2001). Over the LGM, which was characterized by a large European Ice Sheet (EIS) including  
68 the British-Irish (BIIS) and Scandinavian (SIS) Ice Sheets, the '*Fleuve Manche*' paleoriver  
69 (Channel River) was one of the largest river systems that drained western Europe (e.g.,  
70 Gibbard, 1988; Toucanne et al., 2009, 2010, 2015). This huge fluvial system included the  
71 French, Belgian and British rivers, and the merged German, Polish and Dutch rivers, on the  
72 exposed English Channel and North Sea Basin, respectively. Multiproxy studies conducted  
73 along the northwestern European margin and especially from the northern Bay of Biscay (e.g.,  
74 Zaragosi et al., 2001; Auffret et al., 2002; Mojtahid et al., 2005, 2017; Eynaud et al., 2007,  
75 2012; Penaud et al., 2009; Toucanne et al., 2009, 2010), identified recurrent phases of  
76 meltwater inputs at the onset of HS1 (between 18.3 and 17 ka BP). Materialized in sediments



77 as millimeter- to centimeter-scale laminations, they were attributed to the seasonal melting of  
78 the EIS and seasonal subsequent freshwater discharge from the '*Fleuve Manche*' paleoriver.  
79 Further works provided new evidence of a differential contribution from ice sheets to the  
80 laminated deposit, with a particularly large SIS/Baltic sourced part during the last  
81 deglaciation and the HS1 interval (Toucanne et al., 2015). Until now, palynological  
82 investigation of this laminated facies (Eynaud, 1999, 2007, 2012; Auffret et al., 2000;  
83 Zaragosi et al., 2001; Penaud et al., 2009) was performed at resolution varying between 70  
84 and 250 years only, due to the strong dilution of palynomorphs in sediments. Such laminated  
85 facies, corresponding to exceptionally high sedimentation rates, appear as ideal candidates to  
86 increase the temporal resolution of marine records and thus improve our understanding of  
87 short-lived fluctuations in the regime of the '*Fleuve Manche*' paleoriver and associated EIS  
88 dynamics.

89 Our study thus constitutes the first detailed dinocyst study encompassing the HS1 interval in  
90 the Bay of Biscay with a special focus on the laminated facies deposited at the onset of HS1.  
91 Our main objective was to decipher the set and sequence of events that occurred during this  
92 period over the northern Bay of Biscay. Our high-resolution palynological study was  
93 conducted on core MD13-3438 and combined with micropaleontological, geochemical and  
94 sedimentological analyses available for the twin reference core MD95-2002. Our multiproxy  
95 approach led to:

- 96 (1) the reconstruction of the coupled EIS and '*Fleuve Manche*' paleoriver dynamics across  
97 HS1;
- 98 (2) the study of high frequency seasonal variability within the laminated deposit, providing  
99 the first reconstruction of the sub-centennial climate variability across HS1 in the NE  
100 Atlantic;
- 101 (3) and the characterization of sea surface conditions over the northern Bay of Biscay using  
102 dinocyst quantifications (keeping in mind their potentialities and limits in the study area).

## 103 **2. Environmental context**

### 104 **2.1. Location of the studied core**

105 The Calypso long piston core MD13-3438 (47°27' N; 8°27' W; 2180 m water depth; 36 m  
106 long) and twin core MD95-2002 (47°27' N; 8°32' W; 2174 m water depth) were respectively  
107 collected during the VT 133 / MERIADZEK (Woerther, 2013) and MD101-IMAGES  
108 (Bassinot and Labeyrie, 1996) oceanographic cruises on board the R/V Marion Dufresne  
109 (Table 1).

110 These marine sedimentary archives were retrieved from the Meriadzek Terrace, northern Bay  
111 of Biscay, directly off the mouth of the '*Fleuve Manche*' paleoriver (Fig. 1a). Their recovery,  
112 on a structure lying 600 m above the abyssal plain, guarantees few disturbances from gravity  
113 processes despite the proximity of deep-sea turbidite systems (Auffret et al., 2000; Zaragosi et  
114 al., 2000, 2001). The late Quaternary sedimentation of this area was imprinted by supplies  
115 from the northwestern European drainage catchments *via* the '*Fleuve Manche*' paleoriver  
116 during glacial lowstands (Auffret et al., 2000; Bourillet et al., 2003; Mojtahid et al., 2005;  
117 Zaragosi et al., 2006; Eynaud et al., 2007; Toucanne et al., 2008, 2009).

118 At present, the water column is structured by the deep Labrador Sea Water (~1500-2000 m  
119 depth) characterized by salinity ranging from 35 to 35.5 psu (Cossa et al., 2004) and the  
120 intermediate warm and salty (35.7 psu) Mediterranean Outflow Water (800-1500 m depth).  
121 Down to 800 m depth, the modern European Slope Current carries warm and salty waters to  
122 the Nordic Seas (Berx et al., 2013). Surface waters over the study area correspond to the  
123 southward recirculation of the North Atlantic Current (NAC; Fig. 1a), i.e., the south-eastern  
124 branch of the subpolar North Atlantic gyre (e.g., Sutton and Allen, 1997; Daniault et al.,  
125 2016). At the study site, modern (i.e., pre-21<sup>st</sup> century) mean Sea Surface Temperature (SST)  
126 and Salinity (SSS) are 11.7±0.6 °C and 35.54±0.05 psu in winter, and 17.5±1.0 °C and  
127 35.58±0.10 psu in summer (World Ocean Atlas, 2001; Conkright et al., 2002).

128

### 129 **2.2. Climatic changes in the northern Bay of Biscay during the last** 130 **40 kyr with focus on HS1**

131 A large number of studies have shown that core MD95-2002 (Fig. 1a) has archived the history  
132 of deglacial pulses and meltwater discharge from the EIS (Zaragosi et al., 2001; Ménot et al.,  
133 2006; Eynaud et al., 2007, 2012; Penaud et al., 2009; Toucanne et al., 2009, 2015; Fig. 1b).

134 Data acquired on MD95-2002 (Fig. 1b) indeed provided nearshore marine to terrestrial  
135 information (Table 1 for related references).

136 In the North Atlantic Ocean, HS can be recognized on the basis of *Neogloboquadrina*  
137 *pachyderma* abundances close to 100% (e.g., Broecker et al., 1992; Eynaud et al., 2009). At  
138 site MD95-2002, HS1 (blue band on Fig. 1b) is thus identified as the interval between 18.2–  
139 14.6 ka BP (Fig. 1b). Early HS1 is evidenced by repeated alternation of millimeter- to  
140 centimeter-scale deposits (i.e., laminae) of mud and Coarse Lithic Grains (CLG) (Zaragosi et  
141 al., 2001). This facies results from an intense activity of the ‘*Fleuve Manche*’ paleoriver in  
142 response to the substantial EIS retreat (e.g., Mojtahid et al., 2005; Zaragosi et al., 2006;  
143 Eynaud et al., 2007; Toucanne et al., 2008). This laminated interval is associated with high  
144 concentrations of the freshwater micro-algae *Pediastrum* (Penaud et al., 2009), high values of  
145 the Ti/Ca-XRF ratio (i.e., detrital *versus* biogenic proxy for enhanced terrigenous supply;  
146 Toucanne et al., 2009, 2012, 2015) and of the Branched and Isoprenoid Tetraether (BIT)  
147 index (i.e., a proxy for the relative fluvial input of terrestrial organic matter in the marine  
148 environment; Ménot et al., 2006). All those tracers highlight strong fluvial inputs and  
149 terrestrial-sourced organic sediment advections over the northern Bay of Biscay. This period  
150 is concomitant with major EIS melting events, especially from the Baltic Ice Stream of the  
151 SIS, accompanied by seasonal spring-summer meltwater discharge into the Bay of Biscay  
152 (Zaragosi et al., 2001; Mojtahid et al., 2005; Ménot et al., 2006; Eynaud et al., 2007, 2012;  
153 Penaud et al., 2009; Toucanne et al., 2008, 2009, 2015). Within the laminated interval, the  
154 concentrations of CLG (Fig.1b) include both, Laurentide and European-sourced IRDs and  
155 also fluvial lithic grains transported *via* the ‘*Fleuve Manche*’ paleoriver. Increased CLG  
156 concentrations then recorded between 16.7 and 15 ka BP (Fig.1b; Zaragosi et al., 2001)  
157 characterize the HE1 phase. This interval contains the ‘conventional’ HE1 layer marked by  
158 notable peaks of magnetic susceptibility and carbonates (low Ti/Ca values) at ~16 ka BP  
159 characterizing the typical LIS surge (Grousset et al., 2000; Toucanne et al., 2015; Fig.1b).

160

## 161 **3. Material and methods**

### 162 **3.1. Stratigraphy of core MD13-3438**

163 The age model of core MD13-3438 is wedged on the last updated chronostratigraphy of core  
164 MD95-2002 (Toucanne et al., 2015). This latter was built with the Clam software (Blaauw,  
165 2010) by integrating 22 AMS-<sup>14</sup>C dates over the last 40 kyr with additional tie-points: (i) 4  
166 AMS-<sup>14</sup>C dates tied from the neighbouring cores MD03-2690 and MD03-2692, and (ii) *N.*  
167 *pachyderma* abundances correlated with the NGRIP  $\delta^{18}\text{O}$  signal. Modern reservoir age  
168 correction is estimated to about  $352 \pm 92$  years. Prior to HS1 and during the Holocene, the  
169 reservoir age constantly averaged around  $400 \pm 200$  <sup>14</sup>C years. During HS1, the B/A and the  
170 Younger Dryas, average reservoir ages were respectively estimated to about 970, 680 and 875  
171 years with uncertainties of 200 years (1s) (Toucanne et al., 2015).

172 The age model of core MD13-3438 was established by the correlation of its Ti/Ca-XRF signal  
173 with that of its twin core MD95-2002 (Fig. 1b). The XRF analysis of core MD13-3438 was  
174 performed at Ifremer (Plouzané) using an Avaatech X-Ray Fluorescence core scanner at 1  
175 cm-resolution. Tie points used to synchronize both Ti/Ca-XRF signals can be found in Table  
176 2. The correlation is supported by planktonic foraminiferal data (counts of the total  
177 assemblage performed on the >150  $\mu\text{m}$  sediment fraction and on >300 individuals for each  
178 sample at EPOC laboratory), especially the high *N. pachyderma* relative abundances  
179 delimiting the HS1 interval (Fig. 1b). Our 5 cm-sampling frequency for dinocyst analyses  
180 enables us to achieve a temporal resolution of about 18 to 186 years, with a mean resolution  
181 of 58 years in all the studied sections, and of about 29 years in the laminated sequence,  
182 characterized by sedimentation rate values around 185 cm/kyr (Fig. 1b). This resolution thus  
183 provides valuable new details on the deglacial climatic history of the northern European  
184 margin across the HS1 interval.

185 It is worth noting that recent studies showed that the rapid cooling marking the onset of HS1  
186 in the North Atlantic took place at  $17.48 \text{ ka} \pm 0.21 \text{ ka}$  ( $1\sigma$ ) (Missiaen et al., 2019; Waelbroeck  
187 et al., 2019) while maximal *N. pachyderma* abundances (i.e., allowing identifying HS 1) in  
188 core MD95-2002 between 880-390 cm, and between 575-245 cm in core MD13-3438, start at  
189 around 18.2 ka BP (Fig. 1b). Our chronologies are likely too old by about 700 years at the  
190 onset of HS1 as a result of underestimated reservoir ages over the last deglaciation.

191

192

### 193 **3.2. Dinocyst analyses**

#### 194 a. Laboratory procedure, dinoflagellate cyst identification and diversity indices

195 A total of 76 samples were analysed from the 18.4-14 ka BP interval encompassing HS1.  
196 Palynological treatments were performed at EPOC laboratory (University of Bordeaux,  
197 France) following a standard protocol described by de Vernal et al. (1999). Calibrated tablets  
198 of known concentrations of *Lycopodium clavatum* spores were added to each sample before  
199 chemical treatments in order to estimate palynomorph concentrations. Chemical treatments  
200 include cold HCl (10 %), cold HF (40 and 70%) and sieving through single-use 10 µm nylon  
201 mesh screens. For each sample, an average of about 400 specimens (minimal counts of 175  
202 cysts) was achieved using a Leica DM 2500 microscope at ×630 magnification except for the  
203 laminated sequence between 575 and 330 cm for which an average of 120 specimens  
204 (minimal counts of 100 cysts) was obtained due to strong dilution.

205 Dinocyst ecology has been thoroughly described through the progressive development and  
206 compilation of atlases of modern cyst distribution (Matthiessen, 1995; Rochon et al., 1999;  
207 Marret and Zonneveld, 2003; Zonneveld et al., 2013; van Nieuwenhove et al., 2020; Marret et  
208 al., 2020). For this study, taxonomic attribution and the grouping of some species were done  
209 in accordance with those atlases. *Brigantedinium* spp. taxa include all spherical brown cysts  
210 excluding *Dubridinium* spp. Other peridinioid cysts were grouped (i.e., *Quinquecuspis* spp.,  
211 *Lejeunecysta* spp., *Dubridinium* spp. and *Votadinium* spp.) as miscellaneous peridinioid cysts  
212 (MPCs). Dinocyst assemblages were described with the relative abundances of each taxon  
213 calculated on the basis of the total sum of specimens counted including unidentified taxa and  
214 excluding pre-Quaternary cysts. Finally, the species richness and Margalef index (Harper,  
215 1999), calculated using PAST v.1.75b (Hammer et al., 2001), have been used to estimate the  
216 dinocyst assemblage diversity as an additional ecological indicator. The species richness  
217 represents the number of different taxa identified within each studied sample. The Margalef  
218 diversity index (Margalef, 1958) is defined by: Margalef's Index =  $(S - 1) / \ln(N)$ , where S  
219 and N correspond to the total number of species (S) and of individuals (N) in the sample.

220

#### 221 b. Dinoflagellate cyst ratios and fluvial-derived palynological tracers

222 A “Warm/Cold” (W/C) ratio (Table 3) was used to qualitatively address SST variations  
223 (Turon and Londeix, 1988; Versteegh, 1994; Combourieu- Nebout et al., 1999; Eynaud et al.,  
224 2016; Penaud et al., 2016). Also, the “Heterotrophic/Autotrophic” (H/A) ratio (Table 3) was

225 calculated. This ratio is often used to discuss changes in primary productivity (PP) since  
226 heterotrophic dinoflagellates have a strict heterotrophic strategy of nutrition, being indirectly  
227 related to food resources, especially diatoms (Wall et al., 1977; Lewis et al., 1990; Marret,  
228 1994; Zonneveld et al., 1997, 2001, 2013). It is worth noting that a large part of  
229 gonyaulacoids cysts (phototrophic cyst producing taxa) may survive thousands of years in  
230 well oxygenated sediments but heterotrophic peridinioids are extremely sensitive and  
231 vulnerable to early diagenesis. Since availability of oxygen in the sediments is the most  
232 important diagenetic variable, it has been suggested that the amount of species-selective  
233 degradation (i.e., here calculated as the H/A ratio for instance) may also be related to bottom  
234 water oxygen concentration, itself related to the rate of deep-ocean ventilation (Zonneveld et  
235 al., 2008). Both PP and/or taphonomic issues have to be taken into account to fully understand  
236 the H/A ratio.

237 The “*Lingulodinium machaerophorum* / *Operculodinium centrocarpum*” (Lmac/Ocen) ratio  
238 was used to discuss continental *versus* oceanic influences at the core location (e.g., Penaud et  
239 al., 2020), *L. machaerophorum* being a taxon dominating (nearly monospecifically) in  
240 estuarine environments of the French Atlantic coast (Wall et al., 1977; Morzadec-Kerfourn,  
241 1977; Ganne et al., 2016; Lambert et al., 2017). Finally, a new ratio “*L. machaerophorum* /  
242 *Islandinium minutum*” (Lmac/Imin) has been used in this study as a proxy for summer *versus*  
243 winter prevailing seasonality modes. *I. minutum* is abundant in polar regions where surface  
244 waters do not exceed 0 °C in winter (Zonneveld et al., 2013).

245 In addition, pre-Quaternary dinocysts and Non Pollen Palynomorphs (NPP) including  
246 freshwater micro-algae *Pediastrum* spp. coenobia, *Botryococcus* spp. and *Concentricystes*  
247 spp.) were counted on the same palynological slides and expressed in absolute concentrations  
248 (palynomorphs/cm<sup>3</sup>). It has been demonstrated that *Pediastrum* spp. freshwater micro-algae  
249 are related to strong river discharge in marine environments (Zaragosi et al., 2001; Lézine et  
250 al., 2005; Eynaud et al., 2007; Penaud et al., 2009). Also, the biostratigraphical study of  
251 Kaiser (2001, unpublished data), based on the identification of reworked dinocysts in core  
252 MD95-2002 revealed that they were derived from the second half of the Mesozoic (Late  
253 Jurassic) to the Early Tertiary (Miocene), then characterizing the *Manche*, Parisian Basin and  
254 South England geological formations. Therefore, concentrations of *Pediastrum* spp. micro-  
255 algae and pre-Quaternary dinocysts, together with the ratio of “Reworked” (Rd, pre-  
256 Quaternary) *versus* “Modern” (Md) dinocysts (i.e., Rd/Md ratio), constitute robust proxies to  
257 discuss ‘*Fleuve Manche*’ paleoriver discharge in the Bay of Biscay (e.g., Zaragosi et al.,  
258 2001; Kaiser, 2001; Eynaud et al., 2007; Penaud et al., 2009). The Rd/Md ratio, reworked cyst

259 and *Pediastrum* spp. concentrations, together with *L. machaerophorum* occurrences and the  
260 Lmac/Ocen ratio will be referred to as Fluvial-derived Palynological Tracers (FPT) allowing  
261 discussing fluvio-glacial delivery to the NW European margin.

262

263 c. Dinocyst-based quantitative reconstructions of sea-surface parameters

264 The Modern Analogue Techniques (MAT), run on the “R version 2.7.0” software (R  
265 Development Core Team, 2008; <http://www.r-project.org/>), was applied on dinocyst  
266 assemblages to estimate past quantitative sea-surface environmental parameters. The MAT  
267 consists in the comparison of fossil records with modern dinocyst assemblages from the most  
268 recent update of the standardized Northern Hemisphere “modern” dinocyst database, which  
269 includes the abundance of 71 different taxa and 1968 sites in relation to 17 modern  
270 environmental parameters (de Vernal et al., 2020). This method relies on the assumption that  
271 modern relationships between hydrographical parameters and dinocyst assemblages were still  
272 valid in the past (e.g., Guiot and de Vernal, 2007). Sources of uncertainties, quantified with  
273 the Root Mean Square Errors (RMSE), could derive from the lack of modern analogues  
274 corresponding to fossil assemblages (Guiot and de Vernal, 2007; de Vernal et al., 2020).

275 The quantification of hydrological parameters is based on a weighted average of the values  
276 obtained for the five best modern analogues, with the maximum weight being given to the  
277 statistically closest analogue. Regarding the threshold distance ( $d_T=1.2$ ), analogues are i) good  
278 when the distance  $d < d_T/2$ , ii) acceptable when  $d_T/2 < d < d_T$ , and iii) poor when  $d > d_T$  (de  
279 Vernal et al., 2005). The n=1968 database and its related environmental database, allows the  
280 reconstruction of summer and winter SST and SSS, mean annual Primary Productivity (PP),  
281 and Sea Ice Cover Duration (SIC<sub>D</sub>), with RMSE of  $\pm 1.8$  °C for SST<sub>summer</sub>,  $\pm 1.2$  °C for  
282 SST<sub>winter</sub>,  $\pm 2.1$  psu for SSS<sub>summer</sub>,  $\pm 1.1$  psu for SSS<sub>winter</sub>,  $\pm 138$  gC m<sup>-2</sup> for PP<sub>annual</sub>,  $\pm 1.5$   
283 months year<sup>-1</sup> for SIC<sub>D</sub>.

284

## 285 **4. Palynological results**

286 Based on a cluster analysis run on dinocyst taxa percentages with the Psimpoll program, 9  
287 palynozones were identified in core MD13-3438. We labelled them according to the  
288 stratigraphic interval they match: LGM (595-578 cm), HS1-a as the onset of HS1 prior to  
289 HE1 – HS1-a being subdivided into 5 sub-palynozones termed HS1-a1 to HS1-a5 (578-330  
290 cm), and HS1-b (330-270 cm) and HS1-c (270-240 cm) as the first and second phase of HE1,  
291 respectively. Palynological data are presented and discussed according to these palynozones.  
292 They are plotted *versus* depth (cm) in result figures (Figs. 2 to 4), to exhibit the regularly  
293 sampled data without considering the strong impact of sedimentation rates, and then *versus*  
294 age (Cal ka BP) in the discussion figures (Figs. 5 to 7).

295

### 296 **4.1. Quaternary dinocyst and other palynomorph abundances and** 297 **derived indices**

#### 298 a. General observations on MD13-3438 results

299 A total of 31 different Quaternary dinocyst taxa (autotrophic or heterotrophic) have been  
300 identified (Table 3) with a species richness of about 15 different taxa per slide varying  
301 between 7 taxa at 580 cm and 25 taxa at 240 cm (Fig. 2). The Margalef index strongly  
302 matches the species richness with a general increasing trend from the bottom to the top of the  
303 studied section (Fig. 2), diversity being the lowest during the end of the LGM. Quaternary  
304 dinocyst concentrations vary from about 1200 to 47600 cysts/cm<sup>3</sup>, with average values of  
305 5200 cysts/cm<sup>3</sup> (Fig. 3). Overall, dinocyst assemblages are dominated by heterotrophic taxa  
306 (mean value of 57%) including especially *Brigantedinium* spp. (30%) and miscellaneous  
307 peridinioid cysts (MPCs) (21%), as well as *Islandinium minutum* (3%), cysts of  
308 *Protoperidinium nudum* grouped with *Selenopemphix quanta* (1%) as well as *Echinidinium*  
309 spp. (2%; Fig. 3). The H/A ratio trend (Fig. 2) seems to be mainly explained by fluctuations in  
310 *Brigantedinium* spp. (Fig. 2). The lowest values of this ratio are observed across the LGM,  
311 followed by high to moderate values across HS1-a and by a decreasing trend from the start of  
312 HS1-b to the onset of the B/A. Autotrophic taxa (mean value of 43%) are dominated by the  
313 following species: *Operculodinium centrocarpum* (16%), *Bitectatodinium tepikiense* (9%),  
314 *Lingulodinium machaerophorum* (4%), cysts of *Pentapharsodinium dalei* (3%),  
315 *Nematosphaeropsis labyrinthus* (3 %), *Spiniferites lazus* (2%), *Spiniferites ramosus* (2%)  
316 *Spiniferites belerius* (2%) and *Spiniferites septentrionalis* (2%) (Fig. 3).



317

318 b. Detailed observations according to the 9 palynozones

319 Each of the 9 palynozones can be described in terms of Quaternary dinocyst percentages,  
320 which they were statistically established from, but also in terms of other micropaleontological  
321 indicators. They are labelled from LGM to B/A (Fig. 2, Fig. 3):

322 • **LGM**: This lowermost zone exhibits the highest dinocyst concentrations (10000 to 47000  
323 cysts/cm<sup>3</sup>) explained by maximal values of *O. centrocarpum* occurrences (higher than 85%).  
324 *N. pachyderma* percentages show relatively low values (lower than 22%).

325 • **HS1-a**: The transition between LGM and HS1-a is marked by an abrupt decrease of *O.*  
326 *centrocarpum* percentages and the increase of heterotrophic taxa (*Brigantedinium* spp. and  
327 MPCs) representing more than 60% of the total cyst assemblages until 330 cm. Also, this  
328 interval is characterized by increasing *N. pachyderma* percentages. Five sub-zones have been  
329 distinguished: Sub-zone **HS1-a1** corresponds to the first evidence of increasing FPT values  
330 and shows higher percentages of *B. tepikiense*, *Brigantedinium* spp. as well as MPCs. In sub-  
331 zone **HS1-a2**, *B. tepikiense* percentages decrease while a diversification of the assemblage is  
332 observed, with especially higher relative abundances of *Spiniferites* spp., *L. machaerophorum*  
333 and cysts of *P. dalei*, while Quaternary dinocyst concentrations are the highest of the whole  
334 HS1-a interval. Importantly, concentrations of reworked cysts and of total freshwater micro-  
335 algae show maximal values during this HS1-a2 sub-zone (Fig. 2). Dinocyst concentrations  
336 reach minimal values (2500 cyst/cm<sup>3</sup>) within HS1-a3, HS1-a4 and HS1-a5, when important  
337 increases of MPCs are also recorded. While **HS1-a3** is characterized by the dominance of  
338 *Brigantedinium* spp., HS1-a4 and HS1-a5 are marked by maximal values of *L.*  
339 *machaerophorum* (16%) and the highest Lmac/Ocen values. A second peak of freshwater  
340 micro-algae concentrations associated with maximal values of Rd/Md ratio additionally  
341 characterises HS1-a4 (Fig. 2). *I. minutum* abundances increase from the beginning of HS1-a5  
342 at 360 cm concomitantly with decreasing FPT values (Fig. 2, Fig. 3).

343 • **HS1-b**: This interval is generally characterized by a strong drop of MPCs with low to near-  
344 zero values persisting all the way up to the top of the studied interval, and the gradual decline  
345 of *L. machaerophorum* percentages. Maximal values of *I. minutum* (maximum about 20%)  
346 and *S. septentrionalis* (maximum about 6%) occur in this zone.

347 • **HS1-c**: This interval is characterized by higher percentages of *O. centrocarpum* (20%), *B.*  
348 *tepikiense* (18%), and *Echinidinium* spp. (10%), while *I. minutum* and *L. machaerophorum*  
349 strongly decrease and are nearly absent until the end of the studied sequence.

350 • **B/A:** This interval is marked by the significant drop of *N. pachyderma* percentages from  
351 ~95% to ~35%. Dinocyst assemblages are characterized by the quasi-total disappearance of  
352 MPCs as well as significant percentages of *N. labyrinthus* (~15%). The first part of the B/A  
353 interval is characterized by increasing percentages of *Brigantedinium* spp. and occurrences of  
354 *Impagidinium* spp., while the second part of B/A (lowest *N. pachyderma* abundances) is  
355 characterized by increasing *B. tepikiense* and cysts of *P. dalei* percentages.

356

## 357 **4.2. Dinocyst-based sea-surface quantifications**

### 358 a. General observations on MD13-3438 results

359 Our MAT-based reconstructions rely on one to five modern analogues (Fig. 4a). Overall (76  
360 samples in total), 5 samples are scored as “good” (especially within the basal LGM interval  
361 and at the top of the B/A interval) and 45 samples are scored as “acceptable” and range  
362 between the threshold distance ( $d_T=1.2$ ) and  $d_T/2$  (Fig. 4a). Samples scoring as “poor” are  
363 more particularly found within HS1-b and HS1-c, intervals also characterized by fewer  
364 analogues. Fig. 4a shows that the  $d_T$  pattern is very close to that of the H/A ratio.  
365 Consequently, uncertainties in dinocyst quantifications are likely related with heterotrophic  
366 taxa occurrences and especially with the high abundances of the *Brigantedinium* spp. cysts.

367 From the  $n=1968$  modern dinocyst database (de Vernal et al., 2020), 30 modern analogues are  
368 selected as the best analogues during the MAT calculations. They are mainly distributed along  
369 the eastern and western northern coasts of Canada, eastern coasts of USA, along the eastern  
370 and western coasts of Greenland and in the northern Atlantic Ocean, as well as in the  
371 Norwegian and Arctic Seas (Fig. 4b). Boxes have been delimited in Fig. 4b to show the main  
372 locations of those best analogues across each time interval in Fig. 4a (color code at the right  
373 of the figure). Within the end of the LGM, best analogues are located in the western coasts of  
374 Canada and in the Norwegian Sea. Most of the modern analogues selected within HS1-a are  
375 located in the eastern coasts of USA and Canada. For HS1-b, analogues are located in the  
376 eastern and western coasts of Greenland and Svalbard. Analogues found within HS1-c are  
377 more diversified and located in the eastern coasts of USA, Canada and Greenland and in the  
378 North Sea, this latter representing the principal source of modern analogues for the upper B/A  
379 interval (Figs. 4a and b).

380

### 381 b. Dinocyst-based sea surface parameters estimates

382 Dinocyst-derived mean summer SSTs (Fig. 4a) vary between -0.9 and 29.6 °C (average of  
383 17.3 °C) and mean winter SSTs (Fig. 4a) range between -1.8 and 18.5 °C (average of 7.3 °C).  
384 SST<sub>summer</sub> and SST<sub>winter</sub> values show similar trends, with their highest values recorded within  
385 HS1-a (SST<sub>summer</sub> of 20 °C and SST<sub>winter</sub> of 9 °C). These atypically elevated values, especially  
386 for SST<sub>summer</sub>, exceed modern mean SSTs for the northern Bay of Biscay (modern average  
387 SST<sub>summer</sub> of 17.5 and SST<sub>winter</sub> of 11.7°C). This zone is characterized by strong occurrences  
388 of heterotrophic taxa (*Brigantedinium* spp. and MPCs), as also highlighted by the high H/A  
389 ratio (Fig. 2), and modern analogues have been found along the eastern coasts of USA in  
390 subtropical areas also characterized by highly productive (strong fluvial discharge) conditions  
391 (modern analogue value of PP<sub>annual</sub> around 1800 gC m<sup>-2</sup>).

392 Dinocyst-derived SSS<sub>summer</sub> and SSS<sub>winter</sub> (Fig. 4a) show low salinities along the studied  
393 section ranging between 25 and 34 psu (average of 30 psu), below mean average modern  
394 values of about 35.6 psu over the northern Bay of Biscay. The lowest salinities are recorded  
395 during the laminated interval HS1-a with SSS<sub>summer</sub> values of 29 psu, consistent with strong  
396 fluvial discharge such as observed today on the eastern coasts of USA where analogues were  
397 selected (Figs. 4a, b). The highest SSS values (around 34 psu) are recorded in the B/A  
398 interval.

399 Although quantifications are especially critical within HS1-b because of the lack of modern  
400 analogues across this interval (i.e., only 3 over 11 levels provided parameter estimates based  
401 on MAT), this latter appears characterized by maximal Sea Ice Cover duration (“SIC<sub>D</sub>” of ca.  
402 10 months per year; Fig. 4a) and the lowest SST<sub>summer</sub> and SST<sub>winter</sub> (ca. 5 °C and -2 °C,  
403 respectively; Fig. 4a). Finally, reconstructed PP<sub>annual</sub> appears the highest within HS1-a (950  
404 gC m<sup>-2</sup>; Fig. 4a).

## 405 **5. The Last Deglaciation on the northern Bay of Biscay**

406 Our compilation of MD13-3438 multiproxy signals indicative of fluvial discharge, allows us  
407 to describe for the first time the consequence of those hydrographic events at sub-centennial  
408 scale over the period covering the LGM to the B/A in the northern Bay of Biscay. We  
409 superimpose to our new and high-resolution results some of those previously published and  
410 established at lower temporal resolution (but longer time-scale) from twin core MD95-2002,  
411 (Fig. 5; Fig. 6; Zaragosi et al., 2001), and highlight the additional information provided by our  
412 new palynological study.

413

### 414 **5.1. The warm climatic conditions bracketing HS1**

415 Although the LGM and B/A are not the main targeted periods of our study, with consequently  
416 few samples documenting those intervals in core MD13-3438, it is important to describe the  
417 climatic context bracketing the main period of focus HS1. We thus, in the following, have  
418 synthesized information consistent with earlier works (especially including those relying on  
419 longer time-scale and multiproxy MD95-2002 records) and their derived climatic  
420 interpretations.

#### 421 a. The end of the LGM

422 This interval is characterized by extremely low abundances of *N. pachyderma* (Figs. 5 and 6)  
423 and the highest percentages of *O. centrocarpum* (Fig. 6), considered to be a tracer of the NAC  
424 (Turon, 1984; Eynaud et al., 2004, 2012; Penaud et al., 2008, 2009). It is also associated with  
425 relatively high SST<sub>winter</sub> (~9°C; Fig. 6) and high SSS (~34 psu; Fig. 6; see also Eynaud et al.,  
426 2012, focused on LGM salinities derived from multiproxy records). Those relatively warm  
427 conditions were suggested to be induced by a significant penetration of the warm and salty  
428 NAC in the Bay of Biscay (Eynaud, 1999; Zaragosi et al., 2001; Eynaud et al., 2007, 2012;  
429 Penaud et al., 2009) and more generally a more vigorous NAC in the NE Atlantic Ocean  
430 (Weinelt et al., 1996; Rosell-Melé and Comes, 1999; Kucera et al., 2005; de Vernal et al.,  
431 2000, 2002, 2005, 2006; Caille et al., 2013; Wary et al., 2015).

432 In parallel, a slight increase of the ‘*Fleuve Manche*’ paleoriver activity is recorded (through  
433 higher concentrations of reworked palynomorphs – Zaragosi et al., 2001 – and slight increase  
434 of the BIT-index and C/N ratio – Ménot et al., 2006; Fig. 5), synchronously with the 19-ka  
435 meltwater pulse identified in Europe by significant melting of the BIIS in Ireland (K-MWP:

436 Kilkeel event; Clark et al., 2004; Fig. 7) and of the southern SIS (i.e., R4 event; Toucanne et  
437 al., 2015; Fig. 7), while summer insolation at 65°N increases (Berger and Loutre, 1991; Fig.  
438 7). In core MD13-3438, the end of the LGM displays small amounts of terrestrial organic  
439 matter exported to the northern Bay of Biscay and moderate marine productivity as suggested  
440 by low to moderate values of inferred PP, moderate MPCs (Fig. 5) and the lowest values of  
441 *Brigantedinium* spp. cyst percentages (Fig. 3).

442

#### 443 b. The onset of the B/A

444 The onset of this relatively warm interval is characterized by a remarkable decrease in polar  
445 foraminiferal *N. pachyderma* percentages (Figs. 5 and 6) accompanied by a significant  
446 increase of *N. labyrinthus* percentages (Fig. 6) and a brief incursion of *Impagidinium* spp.  
447 (Fig. 3). Also, increases of dinocyst concentrations are coeval with a moderate TOC/N ratio in  
448 core MD95-2002 (Ménot et al., 2006; Fig. 5) suggesting a moderate PP increase. Since 14.6  
449 ka BP, warmer sea-surface conditions (high SST<sub>winter</sub> close to modern ones and high W/C  
450 ratio; Fig. 6) are associated with a rapid SSS increase (about 34 psu; Fig. 6) highlighting a  
451 vigorous NAC with warm and salty Atlantic surface waters carried to the study area,  
452 consistent with a concomitant strong AMOC as depicted in various records from the whole  
453 North Atlantic Ocean (e.g. McManus et al., 2004; Ng et al., 2018; Fig. 7). Data acquired in  
454 the northern North Atlantic (Caulle et al., 2013; Wary et al., 2015), the western Iberian  
455 margin (Bard et al., 2000; Martrat et al., 2007; Eynaud et al., 2009; Hodell et al., 2013;  
456 Salgueiro et al., 2014; Naughton et al., 2016) and the Alboran Sea (Cacho et al., 1999; Martrat  
457 et al., 2014; Català et al., 2019) support this observation of warmer conditions at a regional  
458 scale. It appears accompanied by rapid forest development as documented in the western  
459 Mediterranean borderlands and NW Iberia at the onset of the B/A (Naughton et al., 2007,  
460 2016; Fletcher and Sanchez-Goñi, 2008; Combourieu-Nebout et al., 2009; Camuera et al.,  
461 2019, 2021; Fig. 7) concomitant with increasing humidity, as also identified in speleothem  
462 records from southwestern Europe (Genty et al., 2006; Moreno et al., 2010; Jalut et al., 2010).  
463 An increase in seaward transfer of fluvially-derived sediments is reported directly north of the  
464 Meriadzek Terrace ca. 16-14 ka, indicating possible influence of the retreating Irish Ice Sheet  
465 (which is not connected to the 'Fleuve Manche' paleoriver) at that time (Toucanne et al.,  
466 2008). However, our data show no such evidence of deglacial meltwater fluxes at site MD13-  
467 3438, neither with FPT values (only a slight increase of *Pediastrum* spp. concentrations; Fig.  
468 5) nor with the BIT-index (Ménot et al., 2006; Fig. 5). This lack of deglacial evidence on the  
469 Meriadzek Terrace may be explained by the major episode of sea-level rise referred to as

470 “Meltwater Pulse 1A” (MWP-1A, Fig. 7) which occurred at around ~14.6-14.3 ka BP. This  
471 led to a ~20 m sea-level rise in less than 500 years (Weaver et al., 2003; Deschamps et al.,  
472 2012; Lambeck et al., 2014; Fig. 7) probably responsible for the displacement of the ‘*Fleuve*  
473 *Manche*’ mouth about 300 km eastward (Toucanne et al., 2012, 2010), thus rapidly halting  
474 any ‘*Fleuve Manche*’ imprint on the sedimentary record of our study site.

475

## 476 **5.2. A sub-centennial subdivision of HS1 in the northern Bay of** 477 **Biscay**

### 478 a. Early-HS1, laminated interval (HS1-a): 18.2-16.7 ka BP

#### 479 **General observations**

480 Overall, the HS1-a interval is characterized by a huge increase in terrigenous sediment  
481 supplies in the study area, evidenced through higher values of the Ti/Ca-XRF ratio (Fig. 5)  
482 and higher sedimentation rates (mean values of about 200 cm/kyr at the study site) at site  
483 MD13-348, as well as through maximal values of the BIT-index (core MD95-2002; Ménot et  
484 al., 2006; Fig. 5) and low CLG concentrations mainly due to dilution by terrigenous sediment  
485 at site MD95-2002. This interval is also marked by a reduction of *O. centrocarpum*  
486 percentages from about 90% to 10 % and increasing percentages of *Spiniferites* spp. (i.e., *S.*  
487 *bentorii* and *S. lazus*), which point to a transition from a full-oceanic (end of the LGM) to a  
488 neritic to coastal influence (cf. Penaud et al., 2020 for modern ecological requirements of  
489 dinocyst taxa in the study area) with enhanced PP (Fig. 5). This is also confirmed by high  
490 values of the Lmac/Ocen ratio (Fig. 7) and, in general, by the substantial rise of FPT values.  
491 These indications support the progradation of a large outer-shelf delta on the margin at that  
492 time and huge delivery of the ‘*Fleuve Manche*’ sediment load close to the Meriadzek Terrace  
493 (Toucanne et al., 2012). Geochemical investigations suggested that the meltwater release  
494 pattern is mainly related to the Baltic Ice Stream of the SIS (R5 event; Toucanne et al., 2015;  
495 Fig. 7).

496 Enhanced proximal fluvio-glacial delivery from the ‘*Fleuve Manche*’ paleoriver was  
497 suggested to result from the seasonal influx of meltwater from the retreating EIS and  
498 responsible for the formation of the laminated facies (Zaragosi et al., 2001, 2006; Mojtahid et  
499 al., 2005; Ménot et al., 2006; Eynaud et al., 2007, 2012; Toucanne et al., 2008, 2009; Penaud  
500 et al., 2009; Fig. 7). Here, dinocyst-derived quantitative reconstructions further show a  
501 significant drop of SSS, especially of SSS<sub>summer</sub> (mean values about 29 psu; Fig. 6), with a  
502 large seasonal SSS amplitude (>2 psu; Fig. 6), suggesting that the EIS melting occurred

503 mainly during the spring-summer season (Mojtahid et al., 2005; Toucanne et al., 2009, 2015;  
504 Eynaud et al., 2012; see Fig. 8 for a conceptual scheme of past hydrographic changes in the  
505 study area).

506 The HS1-a interval is characterized by a sustainable increase in the H/A ratio (fig. 7).  
507 Interestingly, this pattern matches the AMOC trend (cf.  $^{231}\text{Pa}/^{230}\text{Th}$  values; McManus et al.,  
508 2004; Ng et al., 2018; Fig.7) with high values of heterotrophic cysts during the AMOC  
509 slowdown in the North Atlantic Ocean and conversely. This observation highlights the  
510 probable taphonomic issue linked to varying bottom water ventilation (Zonneveld et al.,  
511 2008). In our study, heterotrophics (Fig. 5) may be related to either increasing PP and/or  
512 better preservation of peridinioid cysts under low bottom-water oxygenation. Remarkably,  
513 benthic foraminiferal taxa, from the northern Bay of Biscay, indicated both a general  
514 eutrophication and a severe bottom water dysoxia in the sea floor (Mojtahid et al., 2017).  
515 Overall cold and dry conditions are observed in the southern and western Iberian Peninsula,  
516 with a strong reduction of the Mediterranean and temperate forests (Fletcher and Sanchez  
517 Goñi, 2008; Naughton et al., 2016; Camuera et al., 2021; Fig.7) and a notable increase of  
518 xerophytic taxa (i.e., steppic taxa) (Camuera et al., 2021; Fig.7).

519

#### 520 ***Sub-centennial variability of fluvio-glacial discharge on northern Bay of Biscay***

521 Our unprecedented high-resolution multiproxy study of the laminated facies shows a new sub-  
522 centennial-scale structure, following a multi-step scenario encompassing 5 intervals (Figs. 5  
523 to 7; cf. subsection 4.1). Enhanced fluvial inputs were recorded within HS1-a2 corresponding  
524 to maximal terrestrial advection and HS1-a4 consisting to the strongest stratification level of  
525 the surface water column and the strongest westward shift of the freshwater front toward the  
526 ocean (Fig. 5). Interestingly, these intervals are characterized by lower and fluctuating *N.*  
527 *pachyderma* percentages and increased values of SST and seasonality reconstructed from  
528 dinocysts at site MD13-3438, testifying warm sea-surface conditions (Fig. 6). Decreased  
529 fluvial discharge marked the HS1-a1, HS1-a3 and HS1-a5 intervals, this latter appears  
530 characterized by the establishment of cold sea surface conditions in the northern Bay of  
531 Biscay within the latter.

532 The oscillating pattern of '*Fleuve Manche*' paleoriver runoff illustrated here by the different  
533 phases identified in HS1-a finds a striking echo in the environmental fluctuations from arid to  
534 more humid conditions in the Iberian Peninsula between 18.4 and 16.4 ka BP (Camuera et al.,  
535 2021: Fig. 7), with phases of higher runoff matching those of increased humidity in southern

536 Europe. Furthermore, these observations are regionally supported by SST records from the  
537 Alboran Sea (Cacho et al., 1999, 2006; Martrat et al., 2014; Fig.7).

538

539 ***The role of multidecadal changes in seasonality on fluvio-glacial fluxes to the northern***  
540 ***Bay of Biscay***

541 The first conceptual model proposed by Mojtahid et al. (2005) suggested: (i) enhanced  
542 melting of EIS and surrounding glaciers, responsible for enhanced clay and CLG fluxes to the  
543 Bay of Biscay *via* the '*Fleuve Manche*' paleoriver during spring and especially summer  
544 seasons, and (ii) freezing SST and sea-ice cover establishment inhibiting EIS melting during  
545 winter seasons. While first studies attributed CLG-rich units to the seasonal calving of EIS  
546 icebergs onto the northern Bay of Biscay (Mojtahid et al., 2005; Zaragosi et al., 2006; Eynaud  
547 et al., 2007), Toucanne et al (2009) later proposed that the episodic rainout of these particular  
548 CLG originates instead from the '*Fleuve Manche*' paleoriver discharge of anchor-ice (i.e., ice  
549 attached to the riverbed) and of sediment-rich frazil-ice (Reimnitz and Kempama, 1987;  
550 Kempama et al., 2001).

551 Echoing the seasonal dynamic of the '*Fleuve Manche*' paleoriver, our data interestingly  
552 suggest warmer sea-surface conditions within HS1-a (mean SST values about  $\sim 9^{\circ}\text{C}$  and high  
553 values of the W/C ratio; Figs. 6) associated with a significant temperature seasonality increase  
554 ( $> 12^{\circ}\text{C}$ ; Fig. 6), especially within periods of maximal fluvial discharge, namely HS1-a2 and  
555 HS1-a4. To further investigate this, we specifically created a 'summer *versus* winter index' as  
556 the ratio between two major dinocyst taxa occurring regionally and illustrating two opposite  
557 environmental dynamics: the estuarine taxon *L. machaerophorum* and the polar taxon *I.*  
558 *minutum* (Lmac/Imin ratio; Fig.7). We consider *L. machaerophorum*, whose highest  
559 abundances at present are encountered in areas under strong fluvial influence, as  
560 characteristics of the '*Fleuve Manche*' paleoriver discharge induced by European ice sheet  
561 retreat and melting during the deglaciation, i.e., which occurred preferentially during summer  
562 seasons according to earlier sedimentological studies cited above. In contrast, occurrences of  
563 the polar species *I. minutum* are associated with cold sea-surface conditions and expansion of  
564 temporary sea-ice cover (1-3 months/year, Fig. 6) over the studied interval in the northern  
565 Bay of Biscay (as it is at present at high latitudes), then mostly expressing a winter signal  
566 (Fig. 8).

567 The Lmac/Imin ratio (Fig. 7) matches the seasonality signal (Fig. 6). It shows high values  
568 within most of the HS1-a interval and particularly during maximal runoff periods HS1-a2 and  
569 HS1-a4. On the contrary, intervals characterized by lower fluvio-glacial inputs (HS1-a1, HS1-



570 a3 and HS1-a5) depict low  $L_{mac}/I_{min}$  values, highlighting the limited influence of summer  
571 seasons and the prevalence of cold winters (Fig. 8). We thus argue that multidecadal changes  
572 of the seasonality pattern played a substantial role on the EIS and ‘*Fleuve Manche*’ paleoriver  
573 sub-centennial dynamics during the last deglaciation, with release of river ice and meltwater  
574 via the ‘*Fleuve Manche*’ paleoriver favoured during episodes with prevailing summer mode,  
575 and reversely formation of anchor- and frazil-ice in the ‘*Fleuve Manche*’ paleoriver favoured  
576 during episodes of winter prevailing mode (see Fig. 8 for a conceptual scheme of past  
577 hydrographic changes in the study area).

578 Such an enhanced warm summer-prevailing mechanism could then explain the EIS melting,  
579 as far as in the northern European lowlands, in an ‘apparent’ long cold climate stadial (Fig. 8).  
580 HS1 is generally seen as a very cold and dry interval in the North Atlantic Ocean and across  
581 Europe (Bard et al., 2000), marked by overall light NGRIP  $\delta^{18}O$  values, especially during  
582 HE1 (Fig. 7). The strong changes in SST seasonality observed in the northeastern Atlantic  
583 Ocean, and weakly expressed in high latitudes, may then support the hypothesis that  
584 Greenland temperatures mainly represent winter temperatures (Denton et al., 2005, 2010;  
585 Buizert et al., 2014, 2018). However, it is worth noting the occurrence of a plateau of slightly  
586 lighter NGRIP  $\delta^{18}O$  values over the HS1-a interval (Fig. 7) arguing for slightly warmer  
587 atmospheric conditions.

588

#### 589 b. Late-HS1, namely HE1 layer (HS1-b and HS1-c): 16.7–14.6 ka BP

590 In our study, at 16.7 ka BP, the onset of HE1 phase is characterized by the disappearance of  
591 laminae deposits as well as a drastic drop of sedimentation rates (from 156 to 41 cm/kyr; Fig.  
592 5) and in the BIT-index (Ménot et al., 2006; Fig. 5). Those changes are associated with a  
593 substantial decline of FPT values including the  $L_{mac}/O_{cen}$  ratio. All these observations point  
594 to a considerable decrease of the ‘*Fleuve Manche*’ paleoriver runoff. Also, high values of  
595  $C_{37:4}$  alkenones (i.e., a biomarker derived from haptophyte algae, and used as a proxy for low  
596 salinity water associated with icebergs; Ménot et al., 2006) are synchronous with high CLG  
597 concentrations (Fig. 6). The local hydrology is thus strongly impacted by both Laurentide-  
598 and European-derived icebergs at that time (Grousset et al., 2000). Increasing percentages of  
599 the polar species *I. minutum* (Fig. 6), recognized as a good tracer of cold surface waters  
600 seasonally to quasi-permanently covered with sea-ice (Zonneveld et al., 2013; Radi et al.,  
601 2013), are synchronous with low reconstructed  $SST_{winter}$  (Fig. 6) indicating cold sea-surface  
602 conditions (Fig. 6).

603 Dinocyst assemblages enabled us to determine two sub-zones, HS1-b and HS1-c, with a 120  
604 years study resolution on the entire HE1 interval:

605 **HS1-b (16.7–15.6 ka BP; 85 years study resolution)** is characterized by the drastic decrease  
606 of fluvial inputs (low FPT values, Fig. 5; decreasing  $L_{mac}/O_{cen}$  ratio, Fig. 7). Maximal *I.*  
607 *minutum* (Fig. 6) and *S. septentrionalis* (Fig. 3) occurrences are recorded at 16.4 ka BP,  
608 depicting the coldest conditions (Figs. 6 and 7). Low *O. centrocarpum* percentages  
609 additionally suggest a still weakened NAC, consistently with  $^{231}\text{Pa}/^{230}\text{Th}$  record which  
610 suggests that a weakened AMOC state persisted for over a millennium (~16.5–15 ka BP) in  
611 the North Atlantic Ocean (Ng et al., 2018; Fig. 7). These cold surface conditions recorded on  
612 the northern Bay of Biscay may have been responsible for a weaker EIS melting and are  
613 consistent with records from the IRD belt indicating a widespread cooling associated with a  
614 major calving episode of the LIS (Stanford et al., 2011; Hodell et al., 2017). This interval is  
615 indeed marked by a notable peak of magnetic susceptibility (Figs. 5 and 6) and significant  
616 CLG concentrations (core MD95-2002; Figs. 5 and 6) accompanied by minimal values of the  
617 Ti/Ca-XRF ratio at 16 ka BP (Fig. 5) indicative of carbonate-rich CLG (Auffret et al., 1996;  
618 Toucanne, 2009;). This may correspond to the ‘cemented marls’ of Hemming (2004)  
619 interpreted as the LIS (i.e., Hudson Strait) iceberg delivery to the North Atlantic Ocean  
620 (Toucanne et al., 2015).

621 Extremely cold conditions at our study site (Figs. 6, 7 and 8) are synchronous with extremely  
622 cold boreal temperatures (lightest NGRIP  $\delta^{18}\text{O}$  values of the entire HE1 phase; Fig. 7) and  
623 with the coldest and most arid environments documented in marine palynological sequences  
624 from the Alboran Sea (Combourieu-Nebout et al., 2002, Fletcher and Sanchez Goñi, 2008;  
625 Fig7) and off the Iberian Peninsula (Turon et al., 2003; Naughton et al., 2007, 2009, 2016).  
626 The dryness over the Mediterranean borderlands increased (Morellón et al., 2009; Camuera et  
627 al., 2019; Fig. 7) in relation with the southward migration of the polar front (Eynaud et al.,  
628 2009).

629 **HS1-c (15.6–14.6 ka BP; 170 years study resolution)** is characterized by higher percentages  
630 of *B. tepikiense* and *P. dalei* cysts, currently observed in surface sediments from the subpolar  
631 North Atlantic basin (Harland, 1983; de Vernal et al., 1992; Dale, 1996; Rochon et al., 1999),  
632 and also clearly accompanied by both decreasing *I. minutum* percentages and CLG  
633 concentrations (Figs. 5 and 6) as well as increasing *O. centrocarpum* percentages (Fig. 3).  
634 This suggests warm sea-surface conditions (Fig. 6) with increased thermal seasonal  
635 amplitudes (Figs. 6, 7 and 8). The retreat of winter sea-ice marks the end of the HS1 interval  
636 in the northeastern Atlantic Ocean. Increasingly warm conditions on the northern Bay of

637 Biscay are consistent with an intensified NAC and increasing SSTs as detected at regional  
638 scale (e.g., Caille et al., 2013; Wary et al., 2015; Naughton et al., 2016; Hodell et al., 2013;  
639 Cacho et al., 1999; Martrat et al., 2014; Català et al., 2019). Also, warmer and more humid  
640 conditions are observed in the southern and western Iberian Peninsula (Fletcher and Sanchez  
641 Goñi, 2008; Naughton et al., 2009, 2016; Camuera et al., 2021; Fig.7) that may be attributed  
642 to the northward displacement of the polar front (Cayre et al., 1999; Naughton et al., 2009,  
643 2016).

## 644 **6. Conclusion**

645 The high-resolution palynological investigation of the last deglaciation in core MD13-3438  
646 (northern Bay of Biscay) highlights significant climatic and paleoenvironmental changes  
647 related to both the proximal European Ice Sheets (EIS) and the '*Fleuve Manche*' paleoriver  
648 dynamics. Dinocyst-based quantitative reconstructions provide an evaluation of past  
649 hydrographical changes. Seven short-scale sub-phases within the HS1 interval were identified  
650 for the first time on the northern Bay of Biscay:

651 **HS1-a** (i.e., laminated interval; 18.2–16.7 ka BP) is generally characterized by marked  
652 multidecadal changes in the seasonality range, i.e., warm summers resulting in enhanced EIS  
653 melting and '*Fleuve Manche*' paleoriver runoff, causing the largest drop of SSS and cold  
654 winters resulting in freezing conditions and lower '*Fleuve Manche*' paleoriver activity.  
655 Fluvial-derived palynological tracers indicate that this interval is subdivided into five sub-  
656 phases. Two maximal meltwater episodes (HS1-a2, 17.8–17.6 ka BP and HS1-a4, 17.4–17 ka  
657 BP) are detected, with substantial erosional processes in the '*Fleuve Manche*' basin and  
658 strong stratification of the water column. Both events correspond to strong seasonality phases  
659 dominated by summer-prevailing modes. Fluvio-glacial discharge of the '*Fleuve Manche*'  
660 paleoriver, although significant, is comparatively moderate during HS1-a1 (18.2–17.8 ka BP),  
661 HS1-a3 (17.6–17.4 ka BP) and HS1-a5 (17–16.7 ka BP), and possibly result from a decrease  
662 of the seasonality that could have limited the EIS melting at that time. Indeed, our new data  
663 suggest winter-prevailing modes at that time.

664 **HS1-b** (i.e., first phase of HE1; 16.7–15.6 ka BP) includes the Laurentide-sourced IRDs  
665 recorded at ~16 ka BP. This interval is characterized by a substantial decrease of proximal  
666 fluvial inputs and cold winters. Cooling sea-surface conditions are recorded with seasonal  
667 winter sea-ice cover occurrences and the lowest reconstructed SSTs.

668 **HS1-c** (i.e., second phase of HE1; 15.6–14.6 ka BP) is characterized by warmer sea-surface  
669 conditions, suggesting the advection of Atlantic surface waters conveyed by the NAC and  
670 leading to the transition to the warm B/A.

671 Our reconstructed sub-centennial variability suggests the crucial role of multidecadal seasonal  
672 changes, especially within the early HS 1 interval, for fluvio-glacial dynamics and the melting  
673 of the EIS. Furthermore, our records are in agreement with marine and terrestrial sequences  
674 from the western Mediterranean basin suggesting common regional forcings acting on the  
675 multi-scale climate variability across the last deglaciation.

676

677

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692

693

## 694 **8. Table caption**

695 **Table 1:** Datasets acquired on both cores MD95-2002 and MD13-3438 with their  
696 corresponding references.

697

698 **Table 2:** List of tie points defined by aligning the Ti/Ca-XRF signal of the well-dated core  
699 MD95-2002 with that of the studied core MD13-3438.

700

701 **Table 3:** List of identified autotrophic and heterotrophic dinocyst taxa according to their  
702 ecological preferences: cold surface-waters (in blue; C) and warm surface-waters (in orange;  
703 W). The Warm/Cold qualitative temperature index is based on these W and C species.

704

705

## 706 **9. Figure captions**

707 **Figure 1:** Paleogeographic reconstruction of western Europe during the LGM (~ 20 ka BP)  
708 modified from Toucanne et al. (2015) and records of the past fluvial activity of the '*Fleuve*  
709 *Manche*' paleoriver. **a)** The yellow star corresponds to the location of the study core MD13-

710 3438 and of the core MD95-2002. Black lines represent the extension of the Northern  
711 Hemisphere ice caps: (1) the European Ice Sheet (EIS) including the Scandinavian (SIS) and  
712 British-Irish Ice Sheets (BIIS) (Boulton et al., 2001; Clark et al., 2012b; Ehlers et al., 2011),  
713 with their main fluvio-glacial paths (black arrows), as well as the Alpine Ice Sheet; and (2)  
714 the Laurentide Ice Sheet (LIS) with main fluvio-glacial path (white arrow). The bold white  
715 arrow identifies the drainage of the 'Fleuve Manche' paleoriver. The North Atlantic surface  
716 circulation (red arrows for the warmer North Atlantic Current (NAC) and its branches) is also  
717 shown with the return flow pathway of the deep waters (blue arrows). White shading indicates  
718 the extent of the EIS and LIS. The trajectory of the icebergs from the LIS are represented  
719 with light blue arrows and white arrows indicate the main supply sources of freshwater to the  
720 North Atlantic. **b)** Interval from 40 to 5 ka BP: July insolation at 65°N (Berger and Loutre,  
721 1991), Greenland  $\delta^{18}\text{O}$  record (GICC05; Svensson et al., 2008, in black), Ti/Ca- XRF data  
722 and *N. pachyderma* abundances of core MD13-3438 (blue) compared with the MD95-2002  
723 dataset (in red) including: *N. pachyderma* abundances (Zaragosi et al., 2001), coarse lithic  
724 grain concentrations (CLG;  $10^3$  grains/g dry sed.; Zaragosi et al., 2001), magnetic  
725 susceptibility of bulk sediment ( $U_{em}$ ; Grousset et al., 2000), fluvial input proxies (number of  
726 laminae per cm, concentrations of freshwater micro-algae *Pediastrum* spp.; Zaragosi et al.,  
727 2001) and the branched and isoprenoid tetraether (BIT) index (Ménot et al., 2006). Light grey  
728 band represents the LGM (23–19 ka BP) while blue band allows visualizing HS1 in both  
729 cores MD95-2002 and MD13-3438 (18.4–14 ka BP). Dark grey band represents the  
730 conventional HE1 layer occurring at ~16 ka BP.

731

732 **Figure 2:** Palynological data against depth (cm) with taxonomical indices (species richness,  
733 black; Margalef index, grey), percentages of the most abundant taxa *Brigantedinium* spp.,  
734 ratio between Heterotrophic and Autotrophic (H/A) dinocysts (grey), percentages of *L.*  
735 *machaerophorum*, ratio between *L. machaerophorum* and *O. centrocarpum* (grey),  
736 concentrations of reworked dinocysts (blue) and of total freshwater microalgae (dark grey  
737 line: including *Botryococcus* spp. (purple), *Concentricystes* spp. (pink) and *Pediastrum* spp.  
738 (green)). The reworked (pre-Quaternary) vs. modern (in situ) cyst ratio (Rd/Md) is  
739 highlighted in grey. Horizontal lines delineate the nine palynozones / climatic subdivisions  
740 discussed in the manuscript. LGM: Last Glacial Maximum; HS1-a1 to HS1-a5: Laminated  
741 interval; HS1-b and HS1-c: Heinrich Event 1; B/A: Bølling/Allerød.

742

743 **Figure 3:** Diagram of dinocyst assemblages (i.e., major taxa with values higher than 2% at

744 least once in palynological assemblages) *versus* depth (cm) for core MD13-3438, compared  
745 with the relative abundances of the planktonic foraminiferal species *N. pachyderma* and with  
746 total dinocyst concentrations (black line) including autotrophic (black dotted line) and  
747 heterotrophic (grey dotted line) taxa (cysts/cm<sup>3</sup>). Red and black stars indicate AMS-<sup>14</sup>C dates  
748 obtained from cores MD95-2002 and MD03-2690 (Eynaud et al., 2012; Mojtahid et al., 2005;  
749 Toucanne et al., 2008; 2015; Zaragosi et al., 2006; Zaragosi et al., 2001) respectively, and  
750 grey star refers to the NGRIP tie point used for the MD95-2002 age model. These ages are  
751 here projected as equivalent depths for core MD13-3438 using the twins Ti/Ca-XRF signals  
752 of both MD95-2002 and MD13-3438 cores (Fig. 1b). Palynozones/climatic subdivisions were  
753 based on dinocyst clustering established by Psimpoll program. Horizontal lines delineate the  
754 nine palynozones discussed in the manuscript (same as in Fig. 2). High percentages of  
755 dinocyst taxa are shown by orange vertical arrows for long-lasting periods and by dotted  
756 orange vertical arrows for short periods.

757

758 **Figure 4: a)** Dinocyst-based environmental parameters reconstructed for core MD13-3438  
759 with the Modern Analog Technique (MAT) using the n=1968 modern dinocyst database (de  
760 Vernal et al., 2020) *versus* depth: SST and SSS for the summer (red dotted line) and winter  
761 (blue dotted line), PP<sub>annual</sub> (black dotted line), and Sea Ice cover Duration (months/year; grey  
762 dotted line). Number of analogues found for each assemblage (minimum of 0 and maximum  
763 of 5 allowed with the MAT; dark red). Distances between fossil MD13-3438 assemblages and  
764 their “closest” modern analogue (i.e., D<sub>min</sub>). Threshold distance value (d<sub>T</sub>=1.2; red line) for  
765 quantification robustness: good analogues if D<sub>min</sub> is between 0 (perfect analogue) and d<sub>T</sub>/2  
766 (orange line); acceptable analogues if D<sub>min</sub> is between 0.6 and d<sub>T</sub>=1.2, and poor analogues  
767 (i.e. caution with quantifications) if D<sub>min</sub> > d<sub>T</sub> (de Vernal et al., 2005). Horizontal lines  
768 delineate the nine palynozones / climatic subdivisions discussed in the manuscript (same as in  
769 Fig. 2 and 3). **b)** Map showing the geographical distribution of the closest analogues (i.e.,  
770 corresponding to D<sub>min</sub>) selected by the MAT for the studied section of core MD13-3438  
771 (environmental dataset also from de Vernal et al., 2020). Analogues have been grouped  
772 according to geographical areas (color code for boxes; also repeated in Fig. 4a for source area  
773 of closest analogues in each palynozone).

774

775 **Figure 5:** Deglacial records of the ‘*Fleuve Manche*’ paleoriver activity on the northern Bay of  
776 Biscay between 18.4 and 14 ka BP. For core MD13-3438 (in blue): *N. pachyderma*  
777 percentages, sedimentation rates (cm/kyr), Ti/Ca-XRF ratio, freshwater microalgae

778 *Pediastrum* spp. concentrations ( $10^3$  algae/cm<sup>3</sup>), reworked dinocyst concentrations ( $10^3$   
779 cysts/cm<sup>3</sup>), *L. machaerophorum* percentages and concentrations ( $10^3$  cysts/cm<sup>3</sup>),  
780 reconstructed PP<sub>annual</sub> ( $10^3$  g C m<sup>-2</sup>) and peridinioid cyst concentrations ( $10^3$  cysts/cm<sup>3</sup>). For  
781 core MD95-2002 (in red): *N. pachyderma* percentages, coarse lithic grain concentrations CLG  
782 ( $10^3$  grain/g dry sed.), number of laminae (laminae/cm), Reworked *versus* Modern dinocyst  
783 ratio (Rd/Md, shaded red), *L. machaerophorum* percentages (shaded red) (Zaragosi et al.,  
784 2001), magnetic susceptibility of bulk sediment (U em; Grousset et al., 2000), Ti/Ca-XRF  
785 ratio (Toucanne et al., 2015), branched and isoprenoid tetraether (BIT index; Ménot et al.,  
786 2006) and Carbon/Nitrogen ratio (C/N; Ménot et al., 2006). Yellow bands highlight periods of  
787 reduced runoff (HS1-a1, HS1-a3 and HS1-a5) and orange bands correspond to the periods of  
788 maximal fluvio-glacial discharge. Blue and pink bands highlight the HE1 phase (HS1-b,  
789 including the conventional HE1 layer at ~16 ka BP, and HS1-c, respectively). Horizontal lines  
790 delineate the nine palynozones / climatic subdivisions discussed in the manuscript (same as in  
791 Fig. 2, 3 and 4).

792

793 **Figure 6:** Reconstructed hydrological parameters derived from dinocyst assemblages of the  
794 core MD13-3438 (in blue, this study) compared with data from MD95-2002 (in red; Zaragosi  
795 et al., 2001). *N. pachyderma* percentages, coarse lithic grain concentrations CLG, magnetic  
796 susceptibility of bulk sediment (U em ; Grousset et al., 2000), and number of laminae are  
797 compiled with relative abundances of the main dinocyst species, percentages of C37:4 among  
798 C37 alkenones (red, Ménot et al., 2006), Warm/Cold dinocyst ratio (W/C, This study),  
799 dinocyst-derived sea-surface parameters of MD13-3438 (Sea Surface Temperatures: SST<sub>winter</sub>  
800 in blue, SST<sub>summer</sub> in orange; Sea Surface Salinity: SSS<sub>summer-winter</sub>; Seasonality (SST<sub>summer</sub>–  
801 SST<sub>winter</sub>). Yellow bands highlight periods of reduced runoff (HS1-a1, HS1-a3 and HS1-a5)  
802 and orange bands correspond to the periods of maximal fluvio-glacial discharge. Blue and  
803 pink bands highlight the HE1 phase (HS1-b and HS1-c, respectively). Horizontal lines  
804 delineate the nine palynozones / climatic subdivisions discussed in the manuscript (same as in  
805 Fig. 2, 3, 4 and 5).

806

807 **Figure 7:** Synthesis of main information regarding regional paleoclimatic reconstructions for  
808 the last deglaciation and our climate subdivisions especially within HS1.

809 Composite Relative Sea Level (RSL) curve (Lambeck et al., 2014) with identified K-MWP at  
810 19 ka BP and MWP-1A at ~14.6 ka BP, July Insolation curve at 65°N (Berger and Loutre,  
811 1991),  $\delta^{18}\text{O}$  NGRIP record (GICCO05; Svensson et al., 2008), <sup>231</sup>Pa/<sup>230</sup>Th signal (Ng et al.,



812 2018), *N. pachyderma* percentages (blue, this study; red for the core MD95-2002 (Zaragosi et  
813 al., 2001)), H/A ratio (blue, this study; has been also translated and reversed for comparison),  
814 Runoff events (R) 4 and 5 (core MD95-2002, Toucanne et al., 2015), *L. machaerophorum*  
815 *versus* *O. centrocarpum* (Lmac/Ocen ratio, This study), *L. machaerophorum versus I.*  
816 *minutum* (Lmac/Imin ratio, This study), dinocyst-derived sea-surface seasonality  
817 (SSTsummer–SSTwinter) and three-point moving average of Xerophyte and Mediterranean  
818 forest percentages from southern Spain (Camuera et al., 2021) as well as temperate forest  
819 percentages from the Alboran Sea (Fletcher and Sanchez Goñi, 2008). The proposed  
820 comparison respects dating uncertainties and strong reservoir age impacts at that time may be  
821 responsible for generating temporal offsets between records.

822 Dashed grey lines correspond to original values, whereas continuous lines correspond to  
823 smoothed data. Yellow bands highlight periods of reduced runoff (HS1-a1, HS1-a3 and HS1-  
824 a5) and orange bands correspond to periods of maximal fluvio-glacial discharge. Blue and  
825 pink bands highlight the HE1 phase (HS1-b, including the conventional HE1 layer at ~16 ka,  
826 and HS1-c, respectively).

827

828 **Figure 8:** Conceptual model illustrating hydrological conditions and processes involved for  
829 fluvio-glacial dynamics across the HS1 interval in the northern Bay of Biscay.

830

831

## 832 **10. Appendix caption**

833 **Appendix:** Exhaustive table of palynological results (percentages, concentrations and  
834 reconstructed parameters)

835

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Table 1

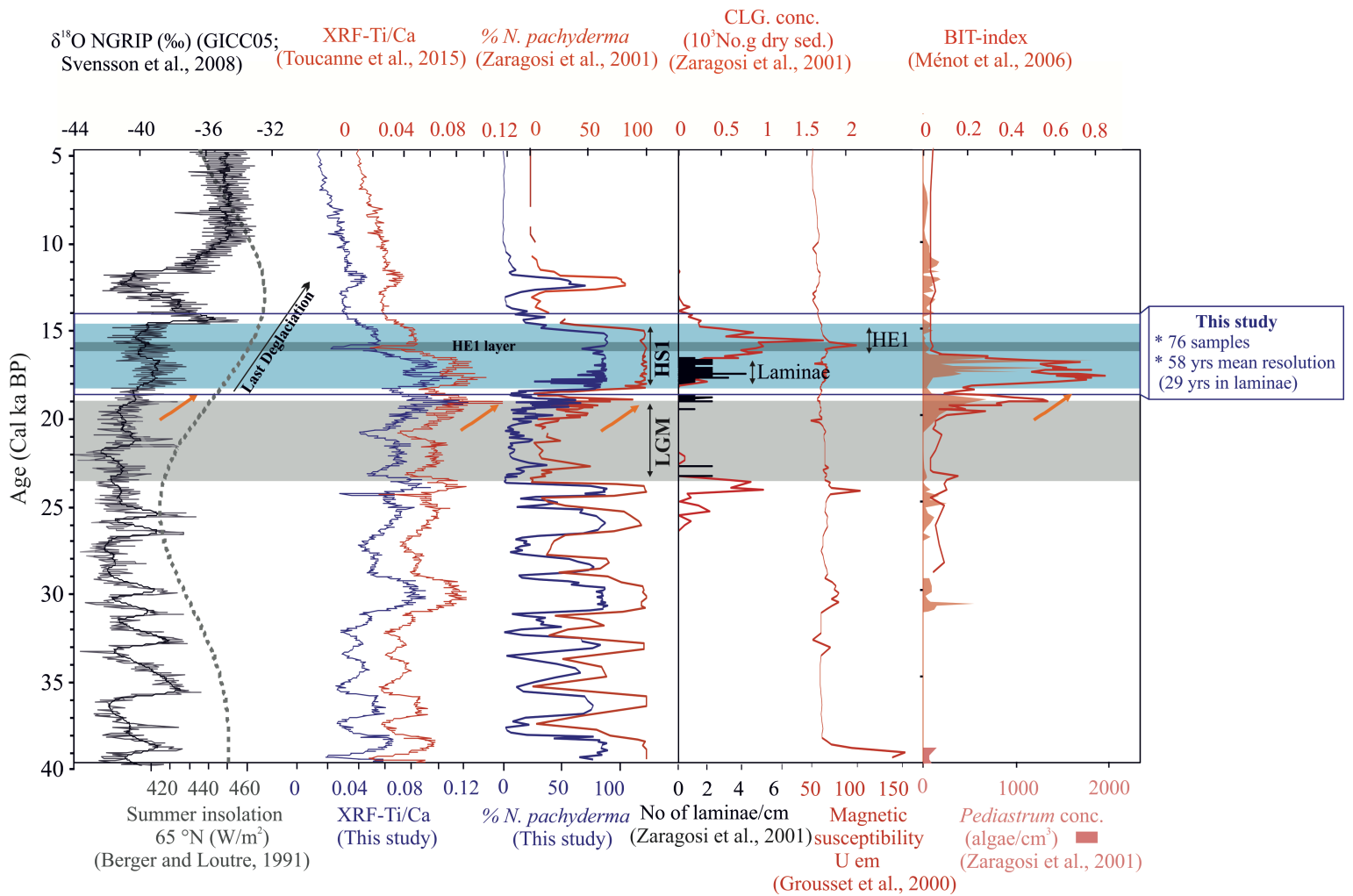
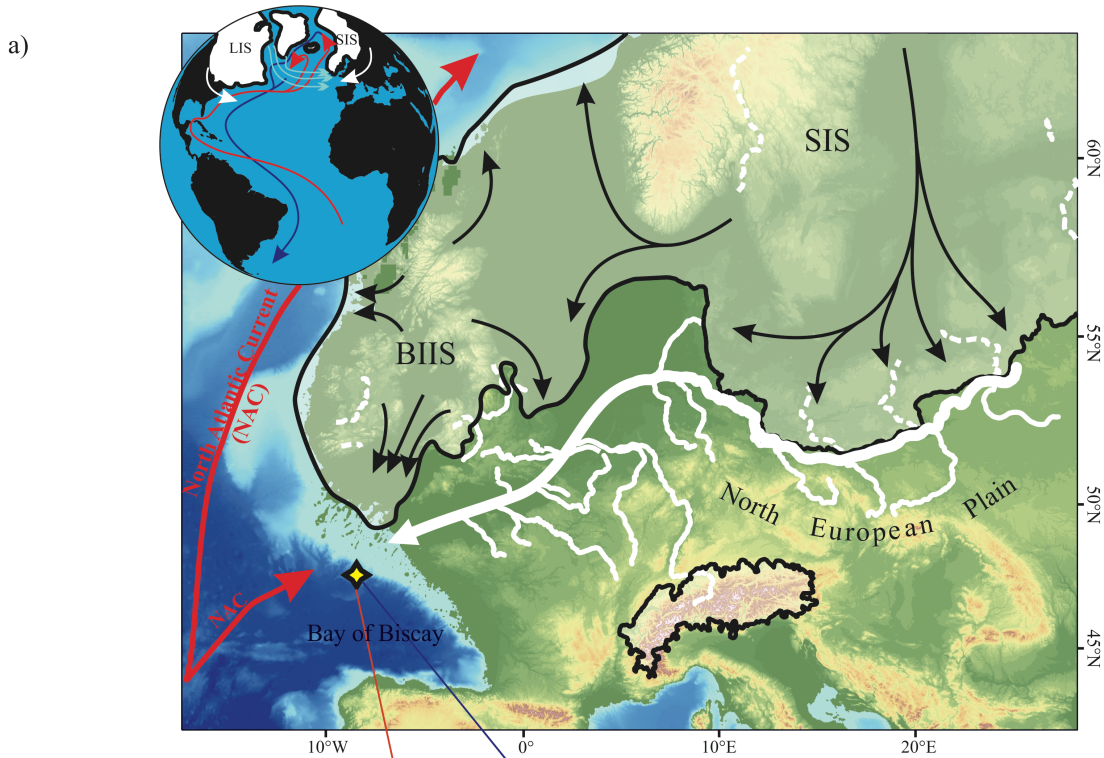
<b>Core name</b>	<b>Geographic coordinates</b> <b>Depth (m)</b>	<b>Dinocyst assemblages</b>	<b>Ti/Ca-XRF ratio</b>	<b>% <i>N.pachydermas</i></b>	<b>IRD conc (No g dry sed)</b>	<b>No Laminae/cm</b>	<b>BIT index + % COT</b>
<b>MD13-3438</b>  Studied core	47° 27' N 8° 27' W  2180 m	This study	S. Toucanne in this study	L. Rossignol in this study	No data	No data	No data
<b>MD95-2002</b>  Reference core	47°27' N 8°32' W  2174 m	Eynaud, 1999 ; Zaragosi et al., 2001 ; Eynaud et al., 2012	Toucanne et al., 2015	Zaragosi et al., 2001 ;  Eynaud et al., 2009	Zaragosi et al., 2001	Zaragosi et al., 2001	Ménot et al., 2006

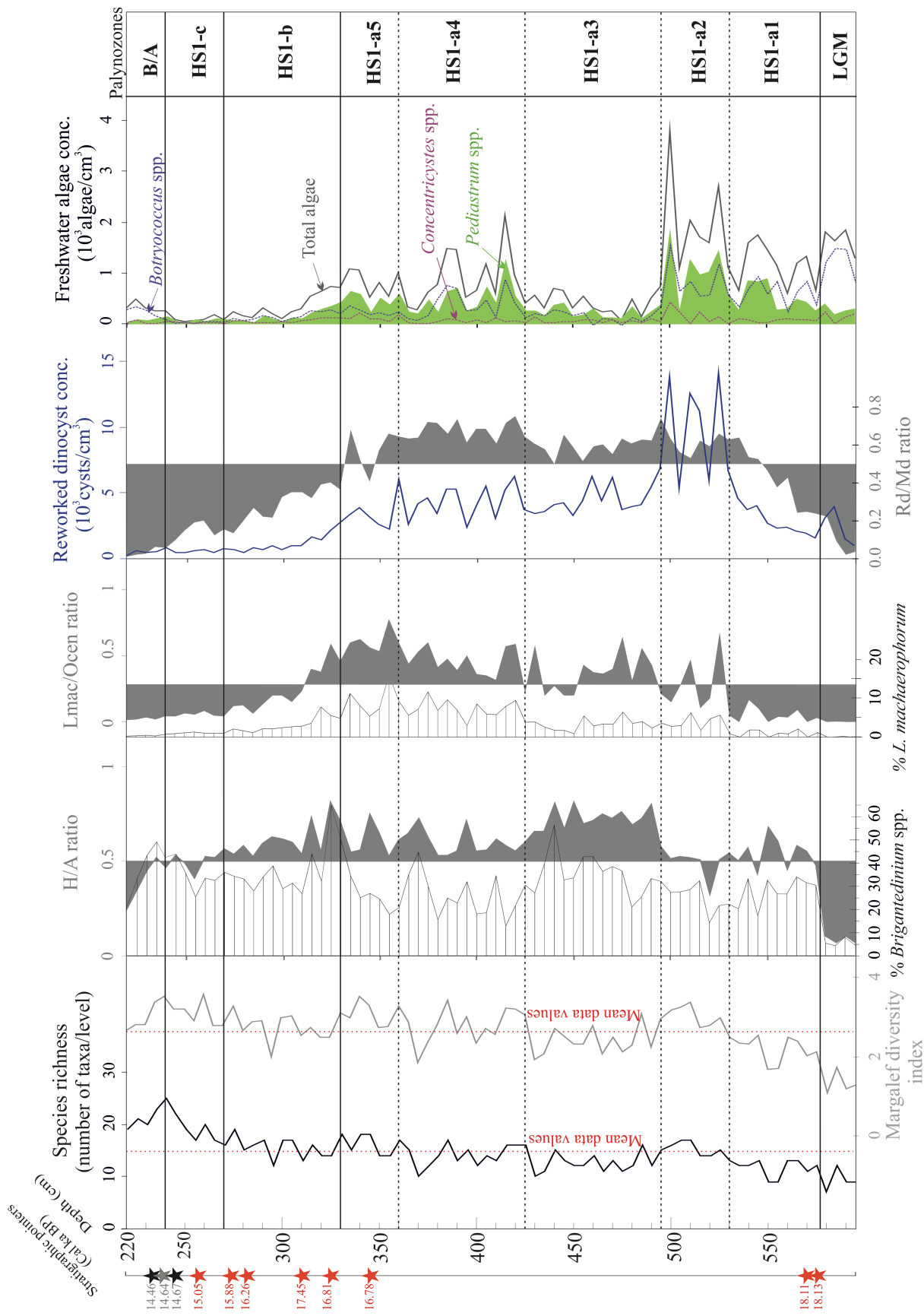
Table 2

<b>Tie points MD95-2002</b>	<b>Depth MD95-2002 (cm)</b>	<b>Equivalent depth MD13-3438 (cm)</b>	<b>Age cal BP (Toucanne et al.,2015)</b>
Top core	0	0	1629
End YD	190	126	11488
Onset YD	262	170	12442
End HS1	390	242	14699
HS1-5	455	277	15908
HS1-4	515	314	16482
HS1-3(2)	548	324	16724
HS1-3	690	428	17388
HS1-2	745	475	17559
<b>Onset HS1</b>	865	567	18100
<b>End LGM</b>	940	619	18570
LGM-6	970	640	18739
LGM-5	1000	663	18904
LGM-4	1040	697	19127
LGM-3	1145	788	19807
LGM-2	1260	881	21077
LGM-1	1340	952	22788
<b>Onset LGM</b>	1355	960	23001
<b>End HS2</b>	1375	981	23185
HS2-4	1415	1011	23560
HS2-3	1460	1050	24249
HS2-2	1495	1084	25031
Onset HS2	1550	1123	26551
<b>End GI-3</b>	1573	1155	27186
Onset GI-3	1593	1179	27720
End HS3 / Onset GI-4	1640	1218	28953
mid HS3	1695	1287	30116
<b>Onset HS3</b>	1745	1339	31050
Onset GI-5	1793	1389	32419
Onset-GI-7	1858	1458	35694
End GI-8	1880	1482	36900
End HS4 / Onset GI-8	1906	1511	37908
mid-HS4	1968	1575	39300

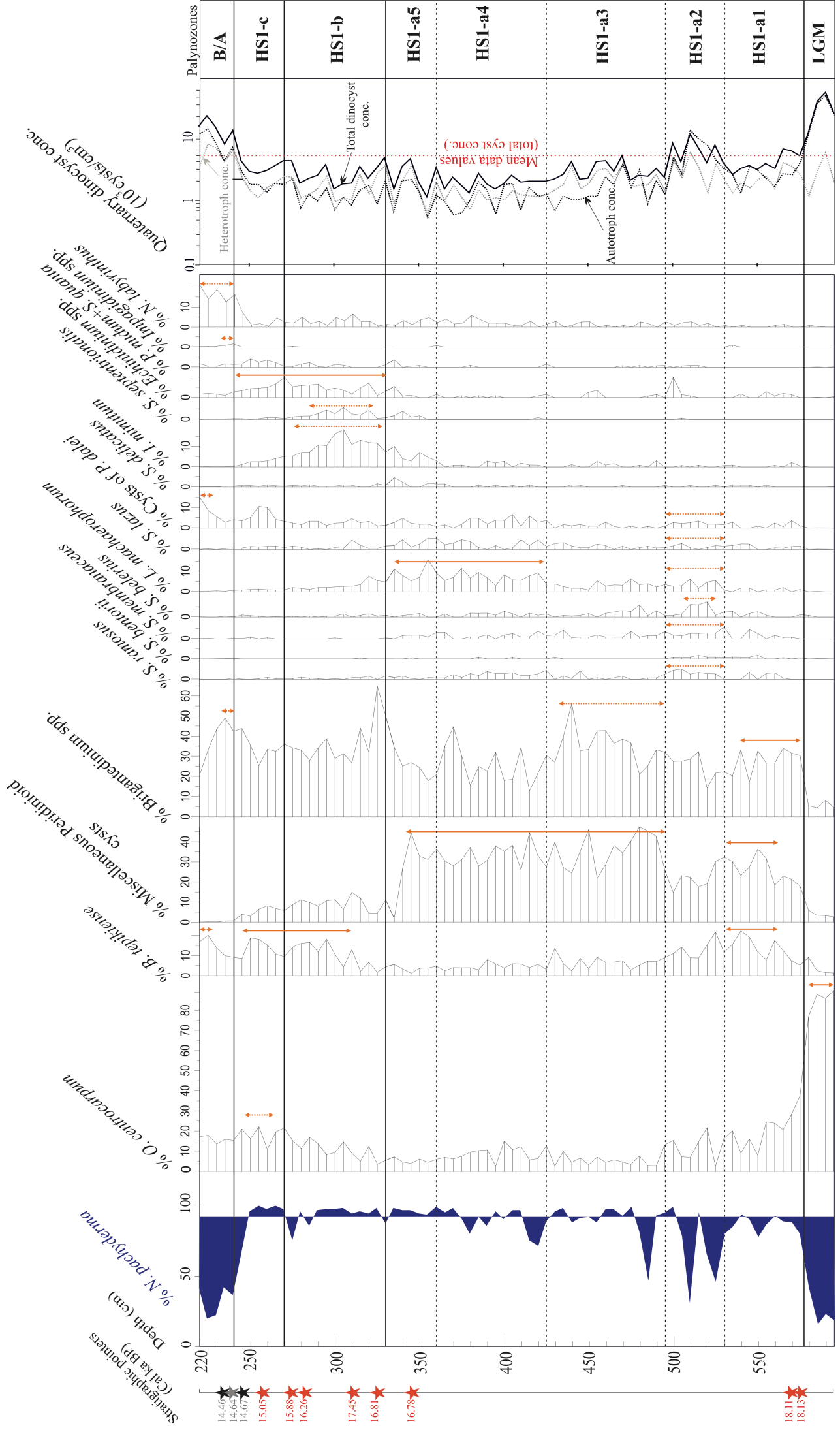
Table 3

	Name of taxa	Abbreviation
<b>Autotrophic taxa</b>	<i>Bitectatodinium tepikiense</i>	<b>Btep</b>
	<i>Impagidinium aculeatum</i>	<b>Iacu</b>
	<i>Impagidinium pallidum</i>	<b>Ipal</b>
	<i>Impagidinium paradoxum</i>	<b>Ipar</b>
	<i>Impagidinium patulum</i>	<b>Ipat</b>
	<i>Impagidinium sphaericum</i>	<b>Isph</b>
	<i>Lingulodinium machaerophorum</i>	<b>Lmac</b>
	<i>Nematosphaeropsis labyrinthus</i>	<b>Nlab</b>
	<i>Operculodinium centrocarpum</i>	<b>Ocen</b>
	<i>Operculodinium janduchenei</i>	<b>Ojan</b>
	<i>Polysphaeridium zoharyi</i>	<b>Pzoh</b>
	<i>Spiniferites membranaceus</i>	<b>Smem</b>
	<i>Spiniferites delicatus</i>	<b>Sdel</b>
	<i>Spiniferites elongatus</i>	<b>Selo</b>
	<i>Spiniferites ramosus</i>	<b>Sram</b>
	<i>Spiniferites belerius</i>	<b>Sbel</b>
	<i>Spiniferites bentorii</i>	<b>Sben</b>
	<i>Spiniferites lazus</i>	<b>Slaz</b>
	<i>Spiniferites mirabilis</i>	<b>Smir</b>
	<i>Spiniferites</i> spp.	<b>Sspp</b>
<i>Spiniferites septentrionalis</i>	<b>Ssep</b>	
<i>Cyst of Pentapharsodinium dalei</i>	<b>Pdal</b>	
<b>Heterotrophic taxa</b>	<i>Islandinium minutum</i>	<b>Imin</b>
	<i>Brigantedinium</i> spp.	<b>Bspp</b>
	<i>Quinquecuspis</i> spp.	<b>Qspp</b>
	<i>Lejeunecysta</i> spp.	<b>Lspp</b>
	<i>Dubridinium</i> spp.	<b>Dspp</b>
	<i>Votadinium</i> spp.	<b>Vspp</b>
	<i>Selenopemphix quanta</i>	<b>Squa</b>
	<i>Cyst of Protoperidinium nudum</i>	<b>Pnud</b>
	<i>Echinidinium</i> spp.	<b>Espp</b>

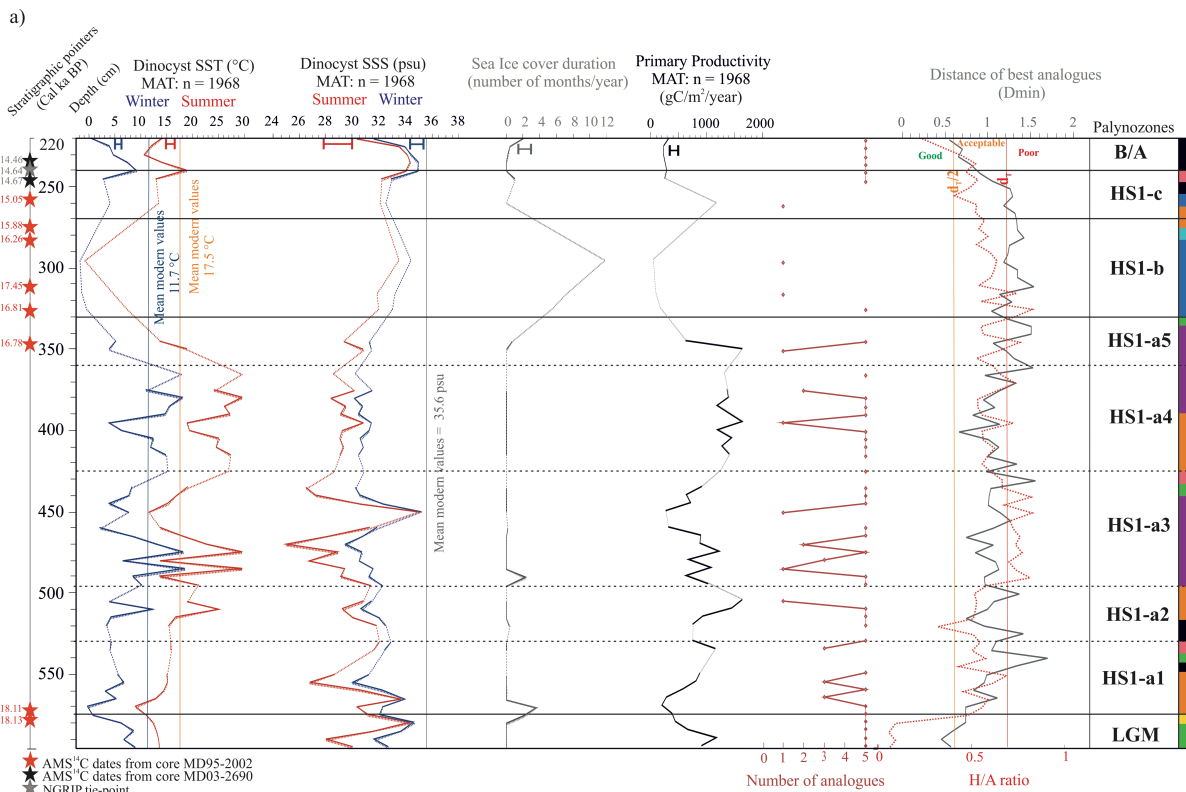




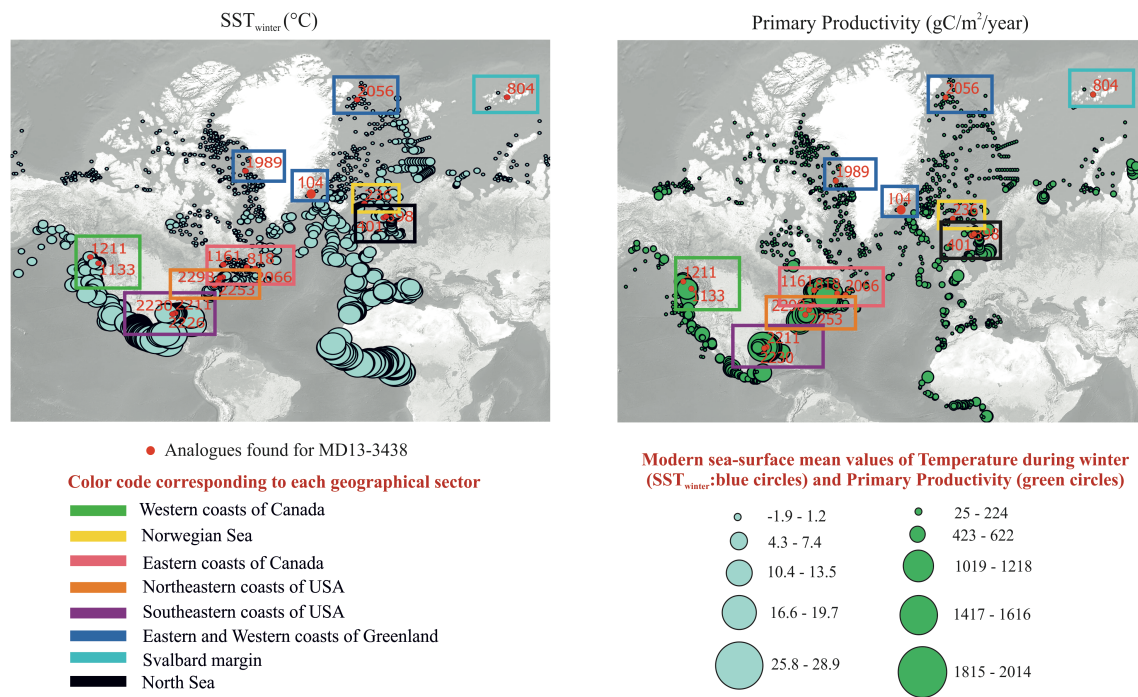
AMS-<sup>14</sup>C dates from core MD95-2002  
 AMS-<sup>14</sup>C dates from core MD03-2690  
 NGRIP tie-point



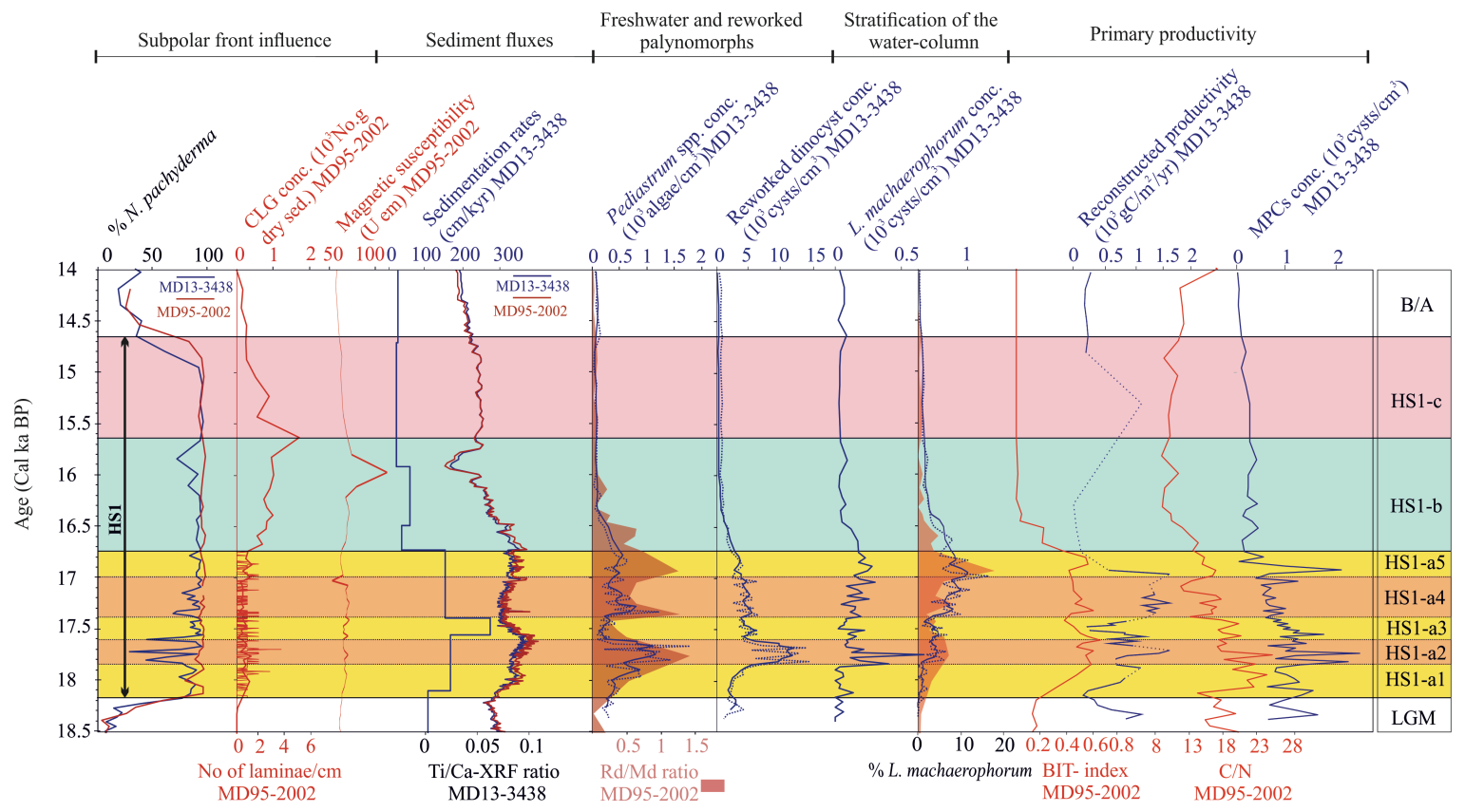
★ AMS <sup>14</sup>C dates from core MID95-2002  
 ★ AMS <sup>14</sup>C dates from core MID03-2690  
 ★ NGRIP tie-point



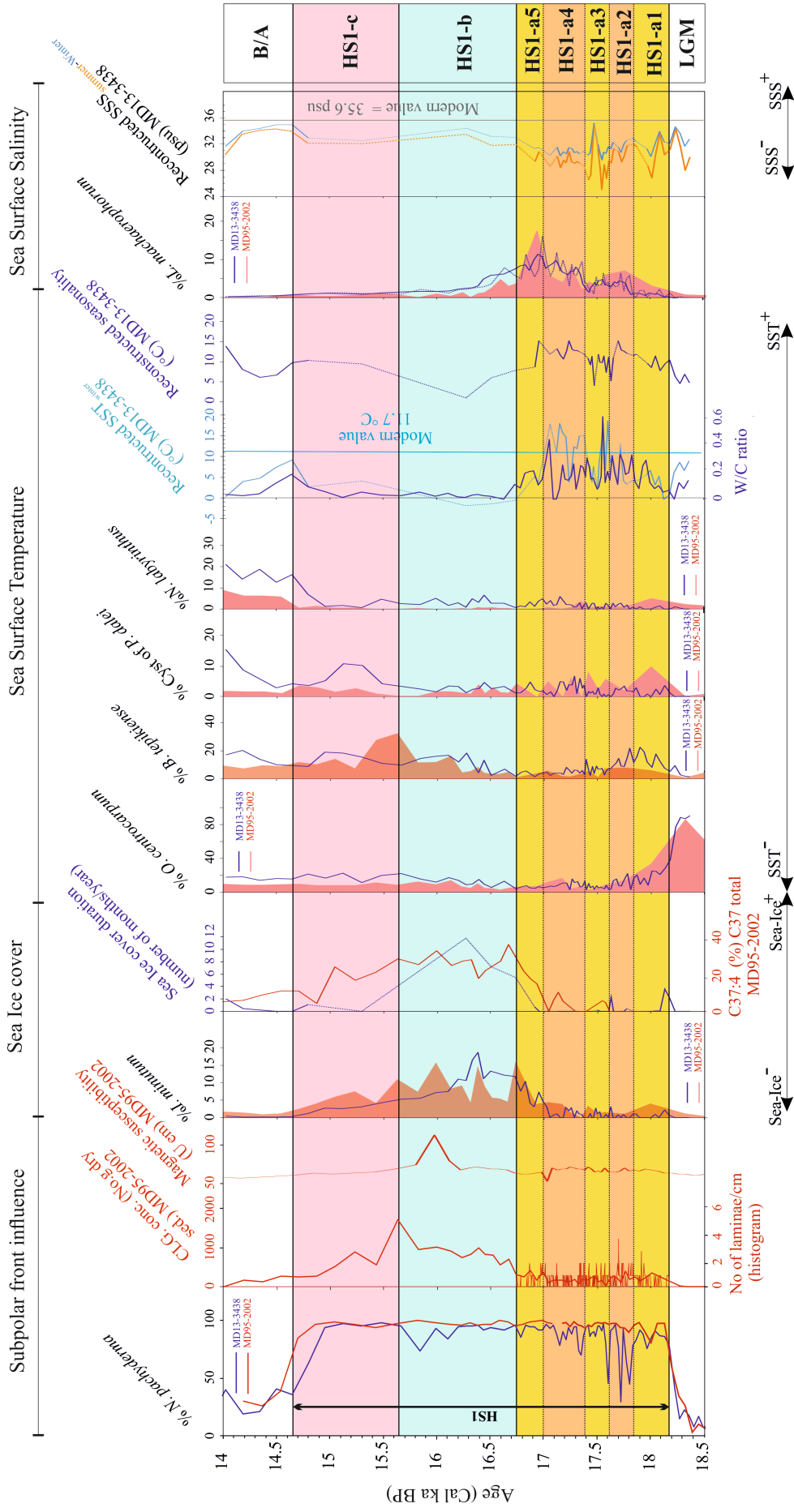
b) Database n=1968 (de Vernal et al., 2020)

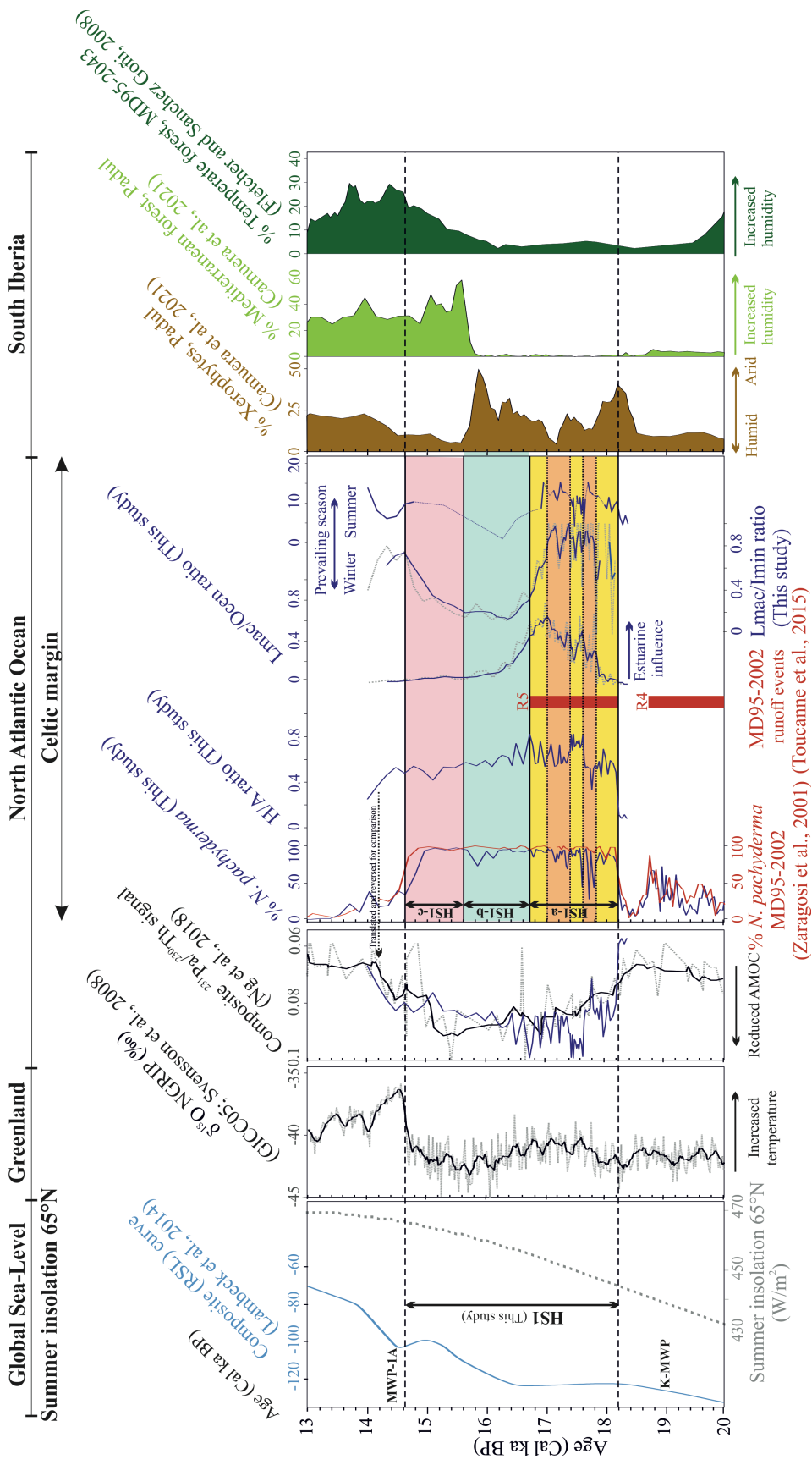






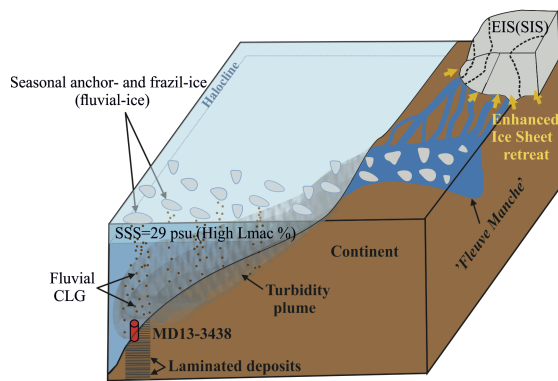




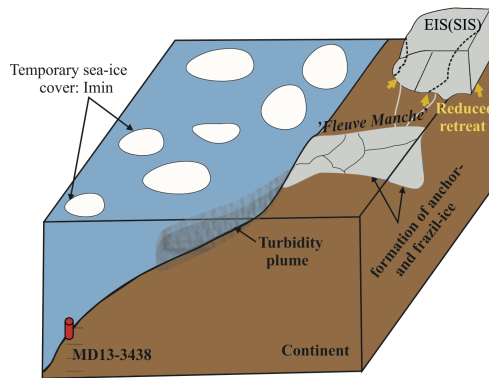


**HS1-a: Laminated interval (18.2 - 16.7 ka BP)**

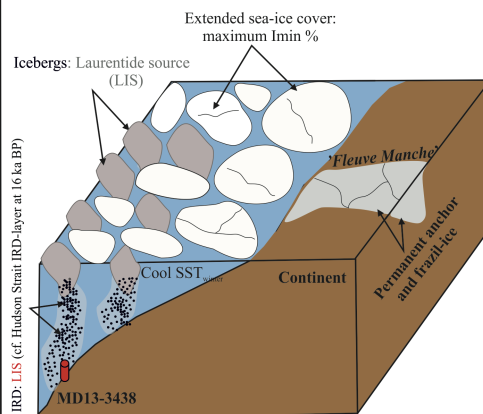
**Summer-prevailing mode  
(HS1-a2, HS1-a4)**



**Winter-prevailing mode  
(HS1-a1, HS1-a3, HS1-a5)**



**HS1-b: Early-HE1 (16.7- 15.6 ka BP)**



**HS1-c: Late-HE1 (15.6- 14.6 ka BP)**

