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## Quaternary Science Reviews

### Dinocyst assemblages and water surface conditions in the Sea of Marmara during MIS 6 and 5 from two long cores

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<b>Abstract:</b>	<p>The Sea of Marmara is the connection between the vast Black Sea-Caspian Sea basin (Pontocaspian) and the Global Ocean via the Mediterranean Sea. Its water levels and water conditions has widely varied over times. Combining two cores in the Sea of Marmara (Turkey) and using organic-walled dinoflagellate cysts as the main proxy (allied to alkenones, diatoms and benthic foraminifera), allow qualitatively reconstructing water conditions during Marine Isotopic Stage (MIS) 6 and 5. A clear main marine phase is illustrated in MIS 5e. A minor marine phase occurred during MIS 5c, mostly supported by alkenone data. The rest of the record indicates brackish Pontocaspian conditions, with more <i>Spiniferites inaequalis</i> in MIS 6 and more <i>S. cruciformis</i> in MIS 5.</p> <p>An earlier initial marine flooding in the Marmara Sea (MIS 6/MIS 5) in comparison to the Black Sea was highlighted on the base of difference in terrestrial vegetation reconstructed from pollen analyses in the same Marmara cores. Understanding the hydrologic evolution of the Sea of Marmara during MIS 5 implies taking into account the consequences of the disconnection of the Black Sea at the Bosphorus on the hydrodynamics and sediment transport processes in the Dardanelles Strait.</p> <p>The sapropels of the Marmara Sea form when marine water penetrates at depth from the Aegean Sea. Combining surface water proxies with benthic foraminifera (shells and inner organic lining), it suggests that the sapropels over time formed under decreasing anoxic conditions. A comparison between the two cores suggests anoxia did not rise up to 291 m water depth.</p>
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	Katarina Kouli National and Kapodistrian University of Athens akouli@geol.uoa.gr she has published a dino diagram from the G of Corinth with similar assemblages to the Marmara Sea
	Laurent Londeix University of Bordeaux l.londeix@epoc.u-bordeaux1.fr

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1 Dinocyst assemblages and water surface  
2 conditions in the Sea of Marmara during  
3 MIS 6 and 5 from two long cores

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5

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17

18 **Abstract**

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20 basin (Pontocaspian) and the Global Ocean via the Mediterranean Sea. Its water  
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24 reconstructing water conditions during Marine Isotopic Stage (MIS) 6 and 5. A clear  
25 main marine phase is illustrated in MIS 5e. A minor marine phase occurred during  
26 MIS 5c, mostly supported by alkenone data. The rest of the record indicates brackish  
27 Pontocaspian conditions, with more *Spiniferites inaequalis* in MIS 6 and more *S.*  
28 *cruciformis* in MIS 5.

29 An earlier initial marine flooding in the Marmara Sea (MIS 6/MIS 5) in comparison to  
30 the Black Sea was highlighted on the base of difference in terrestrial vegetation  
31 reconstructed from pollen analyses in the same Marmara cores. Understanding the  
32 hydrologic evolution of the Sea of Marmara during MIS 5 implies taking into account  
33 the consequences of the disconnection of the Black Sea at the Bosphorus on the  
34 hydrodynamics and sediment transport processes in the Dardanelles Strait.

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36 from the Aegean Sea. Combining surface water proxies with benthic foraminifera  
37 (shells and inner organic lining), it suggests that the sapropels over time formed  
38 under decreasing anoxic conditions. A comparison between the two cores suggests  
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#### 40 **Key words**

41 Dinocysts, MIS 6 and 5, Marmara Sea, connection, sea level, sapropel

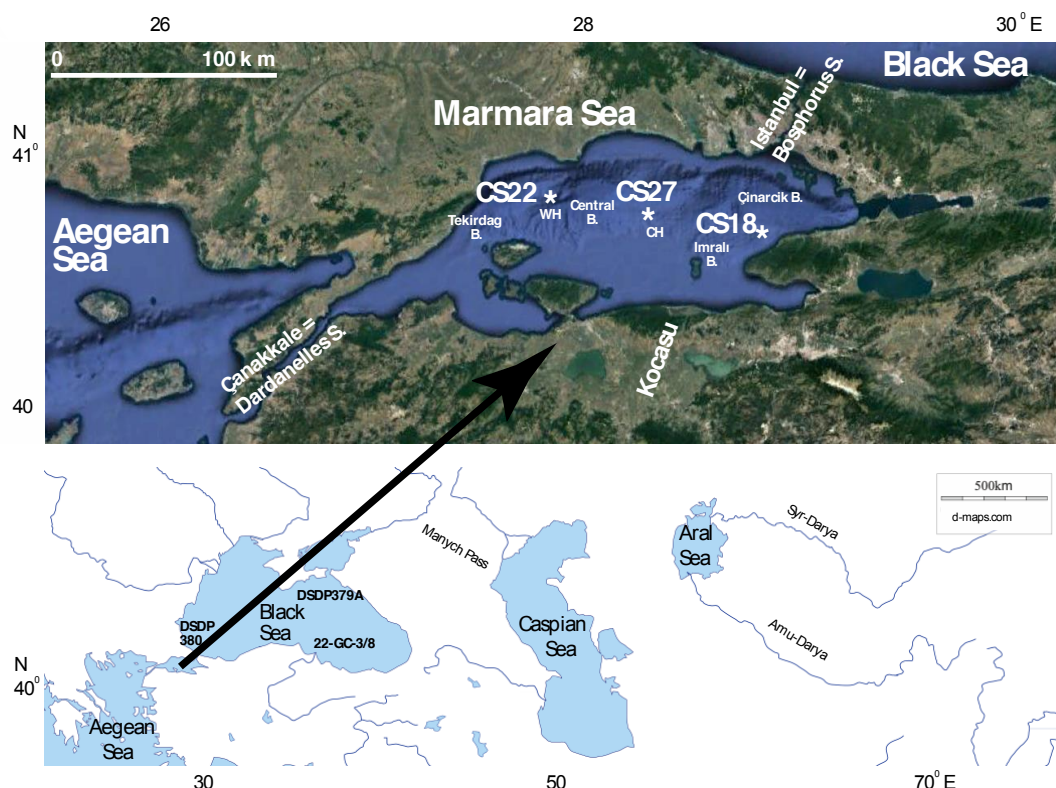
42

## 43 **1 Introduction**

44           The Sea of Marmara (SoM) is a gateway between the Mediterranean Sea and  
45 the Black Sea in Turkey, and has experienced water-level fluctuations and  
46 hydrological variations during the late Quaternary, which were mainly controlled by  
47 bedrock sills at the Marmara Sea exit of Çanakkale Strait (Dardanelles) and the  
48 Black Sea entrance of the Istanbul (Bosphorus) Strait, respectively. The variations in  
49 water depths of these sills were possibly governed by longer-term vertical  
50 displacements related to tectonics and erosion/sedimentation balance due to sea-  
51 level changes and water exchanges between the Black and Aegean seas, or  
52 between the Ponto-Caspian ensemble and the Global Ocean ([Yaltrak, 2002](#);  
53 [Gökaşan et al., 2008](#), [Çağatay et al., 2009, 2019](#); [Vidal et al., 2010](#); [Eriş et al., 2011](#))  
54 ([Fig. 1](#)). The SoM is indeed a highly seismic area as it is located on the western end  
55 of the North Anatolian Fault; however, tectonics are mainly significantly affecting sea  
56 levels only in the long term. At the scale of the last climatic cycle, global ocean level  
57 change is the main factor controlling the water level in the SoM. For the last  
58 interglacial (Marine Isotope Stage 5, MIS 5), decreasing water level maxima are  
59 noted along the successive three warm stages: MIS 5e, 5c and 5a ([Rohling et al.,](#)  
60 [2021](#)). Moreover, the Black Sea level should be considered as another crucial  
61 influence on water level in the SoM, evidenced as the melting of the Eurasian icecap  
62 and the subsequent evacuation of the freshwater along large rivers flowing into the  
63 Black Sea ([Tudryn et al., 2016](#)) and, at times, the outflow from the Caspian Sea via  
64 the Manych Passage ([Chepalyga, 2007](#)). The SoM is the outlet of all the  
65 Pontocaspian basins (as far as the Tien-Shan via the Syr-Darya and the Chu River  
66 and the Pamir-Indu-Kush via the Amu-Darya) and hence this inland sea is the  
67 receptacle of the history of a large geographical area ([Fig. 1](#)). Thus, the water level

68 history of the SoM is quite complex (local, regional and global forcing) and its insight  
 69 clearly has an extra-regional relevance. Its history starts to be well-known for the  
 70 Last Glacial Maximum and the Holocene, but it remains much less clear before  
 71 (Leroy et al., 2020; Eriş et al., 2007, 2011; Çağatay et al., 2009, 2015a). Moreover,  
 72 the SoM forms sapropels under certain conditions. They are dark and finely  
 73 laminated sediment rich in organic matter and are important to study as they consist  
 74 of layers where carbon can be locked away from oxidation, thus contributing to the C  
 75 cycle. In the Mediterranean Sea, enhanced marine productivity increases organic  
 76 matter degradation and anoxia (Rohling et al., 2015; Zwiép et al., 2018).

77



78

79 **Figure 1:** Map of Marmara Sea with core locations (top panel) and map of the seas  
 80 that were potentially connected at times (lower panel). CH: Central High, WH:  
 81 Western High, S: Strait, B: Basin.

82

83 Owing to a major European research programme, long sediment cores (up to  
84 30 m) were taken in the SoM during the MARSITE cruise in 2014 to address some of  
85 those key questions (<https://cordis.europa.eu/project/id/308417>).

86 The aim of the current investigation is, by using organic-walled dinoflagellate  
87 cyst (herein called dinocyst) analysis (combined to other proxies such as alkenone,  
88 diatoms and benthic foraminifera), to establish the conditions at the surface of the  
89 water within MIS 5 (130-71 ka ago, [Lisiecki and Raymo, 2005](#)) and part of MIS 6 (>  
90 130 ka), and thus to contribute to water-level and surface-water-condition history in  
91 the SoM. A sister paper addresses past vegetation, palaeoclimates and chronology  
92 on the same samples ([Leroy et al., submitted](#)).

## 93 **2 Regional setting**

94 The SoM (275 km W-E by 80 km N-S) is located at the western end of the  
95 North Anatolian Fault where it splits into several strands; as a result, the sea  
96 comprises three deep basins (Tekirdag, Central and Çınarcık) separated by two  
97 highs: Western High and Central High ([Fig. 1](#)). Its deepest location is in the Çınarcık  
98 and Central Basins at 1270 m. Rivers are mostly inflowing from the south ([Kazancı  
99 et al., 2004](#)). The Imralı Basin in the SE SoM is nowadays a flat area of a water  
100 depth only around 300-400 m ([Yaltırak, 2002](#)). The Kocasu (or River Koca), the main  
101 river flowing into the SoM, exits now from the continent, south of the Imralı Island. At  
102 lower water levels, it has formed deltas prograding into the Imralı Basin and has  
103 largely contributed to fill it; later on, the sediment was fed into the Çınarcık Basin  
104 along a now-submerged canyon ([Kazancı et al., 2004](#); [Sorlien et al., 2012](#)) ([Fig. 1](#)).

105 The region immediately around the SoM is relatively flat, although mountains up to  
106 2500 m are found in the S and SE and 1000 m in the N.

107 Water salinity is 22-24 psu at surface and up to 37-39 psu at depth ([Beşiktepe](#)  
108 [et al., 1994](#); [Aydoğdu et al., 2018](#)). The brackish water of the Black Sea (18 psu),  
109 being less dense, outflows through the SoM above the deeper denser Mediterranean  
110 saline water moving eastwards ([Aydoğdu et al., 2018](#)). The pycnocline is at around  
111 25 m water depth. This delicate two-way setting is easily disturbed by water-level  
112 changes leading to deep salinity and oxygenation modifications crucial for the  
113 survival of aquatic ecosystems. Water temperature fluctuates at most from 4 to 28 °C  
114 annually. It displays a slight warming gradient from the NE to the SW: for example,  
115 surface water usually varies from 21 (NE) to 26 (SW) °C in summer. All year round,  
116 bottom water is relatively stable at c.15 °C ([Aydoğdu et al., 2018](#)). The water depth  
117 of the Dardanelles (Çanakale) Sill is nowadays 65 m, and that of the Bosphorus  
118 (Istanbul) Sill is 35 m ([Çağatay et al., 2009](#)).

119 The dinocyst assemblages of MIS 6 and 5 have, so far, not been studied in  
120 the SoM. However, three dinocyst analyses for these time intervals are available for  
121 the Black Sea. In cores DSDP 380 in the SW Black Sea and DSDP Site 379A in the  
122 E Black Sea, MIS 5 is covered by a few samples ([Ferguson et al., 2018](#); [Hoyle et al.,](#)  
123 [2021](#)). In the SE Black Sea, a detailed dinocyst diagram of core 22-GC3 includes the  
124 period from 129 to 119 ka, with a transition from brackish Pontocaspian to marine  
125 conditions at 128 ka ([Shumilovskikh et al., 2013](#)) ([Fig. 1](#)). More dinocyst records are  
126 available for the Late Glacial and Holocene in the SoM ([Mudie et al., 2001, 2002,](#)  
127 [2004](#); [Londeix et al., 2009](#)) where a change from brackish Pontocaspian to marine  
128 conditions was observed at c. 9.5-9 ka. A sapropelic layer, MSAP-1, was identified at  
129 11.5-7 ka ago ([Çağatay et al., 2000](#); [Tolun et al., 2002](#); [Vidal et al., 2010](#)). It is worth

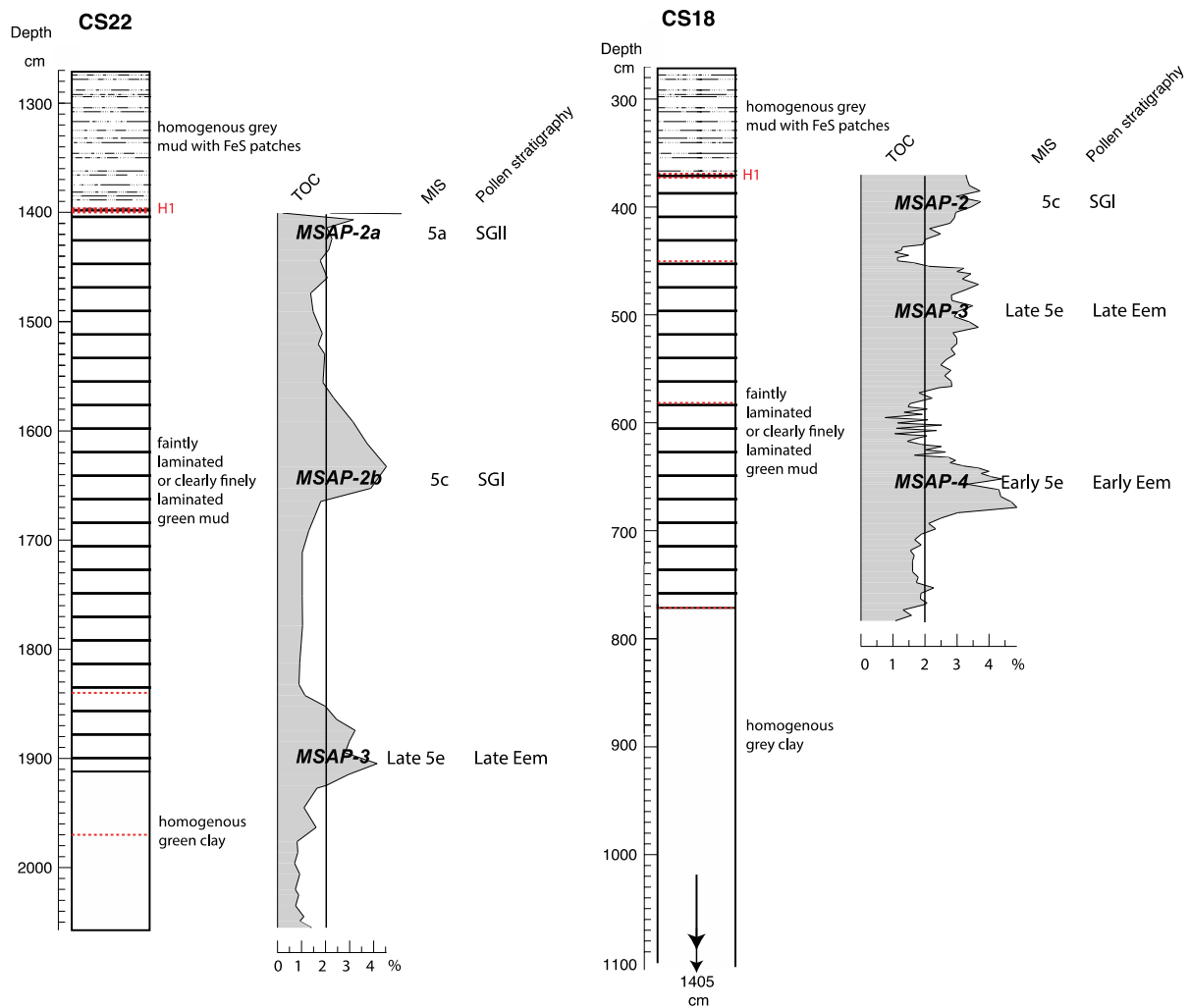


130 mentioning the recent study of dinocyst assemblages on a long core in the Gulf of  
131 Corinth, covering the MIS 6 and MIS 5, although further afield, due to the similarity of  
132 isolation-connection history of its basin ([Fatourou et al., 2023](#)).

133 Dinoflagellates, a major component of the marine phytoplankton, have a  
134 complex life cycle involving a theca that lives in the photic zone and, for about 13 to  
135 16% of the species, an organic-walled cyst is produced in the water column, and  
136 settling at the bottom of the sea floor for an obligatory dormancy period (e.g. [de](#)  
137 [Vernal and Marret, 2007](#); [Bravo and Figueroa, 2014](#); [Mudie et al., 2021](#)). Therefore,  
138 the distribution of dinocysts in recent sediments has been linked to surface  
139 environmental conditions and this relationship has enabled robust quantitative  
140 reconstructions of past sea-surface temperature, salinity, productivity and sea-ice  
141 cover duration (e.g. [de Vernal et al., 2020](#)). A study of 181 surface samples in the  
142 Pontocaspian region has clearly highlighted that the dinocyst assemblages reflect  
143 surface conditions such as salinity, especially from January to March ([Mudie et al.,](#)  
144 [2017](#)).

### 145 **3 Previous investigations on cores CS22 and CS18**

146 Calypso cores were taken by the vessel “Pourquoi Pas?” in November 2014.  
147 Core MRS-**CS22** (20.42 m long) was obtained close to the top of the Western High  
148 at 40,83863 latitude N, 27,79906 longitude E and 551 m water depth ([Fig. 1](#)). Core  
149 MRS-**CS18** (14.25 m long) was acquired from a slope of the Imralı Basin at  
150 40,66206 latitude N and 28,87958 longitude E by 291 m water depth. The core  
151 depths of interest are located below a major seismic reflector, i.e. the red-H1  
152 reflector.



153

154

155 **Figure 2:** Lithology of cores CS22 and CS18, total organic carbon in percentage  
 156 (TOC). Vertical line at 2 % delimiting the sapropels. MIS: Marine Isotopic Stages. Me  
 157 I = Melisey I Stadial, SG I = Saint-Germain I Interstadial, Me II = Melisey II Stadial,  
 158 SG II = Saint-Germain II Interstadial, Eem = Eemian Interglacial.

159

160 Detailed lithological descriptions can be found for cores CS22 and CS18  
 161 respectively in [Kende \(2018\)](#) and [Çağatay et al. \(2019\)](#). The sediment is a grey or  
 162 green clay to silty clay at times clearly finely laminated ([Fig. 2](#)). Total Organic Carbon  
 163 (TOC) values in core CS22 were obtained by using an *Fisons* NA1500 elemental  
 164 analyser and for core CS18 by the catalytic combustion method using a Shimadzu

165 TOC analyzer (Kende, 2018; Çağatay et al., 2009; Leroy et al., submitted). In core  
166 CS18, foraminifera were counted in the sand size fraction and their abundance were  
167 qualitatively recorded. Only rare benthic foraminifera are present in the 770-700 cm  
168 interval, but benthic, with some pelagic foraminifera, become abundant in 700-670  
169 cm and 630-580 cm intervals. However, they are absent in the interval 580-430 cm  
170 (Çağatay et al., 2019).

171 Below the red-H1 reflector, the three sapropels (here > 2%) were attributed to  
172 MIS 5e, 5c and 5a based on correlation of the  $\mu$ -XRF Ca with the NGRIP  $\delta^{18}\text{O}$ , the  
173 TOC correlation with regional pollen records (outside of the SoM), oxygen isotope  
174 records in the Mediterranean and global sea level. These are for core CS18: MSAP-  
175 4 at 699-623 cm, MSAP-3 at 568-455 cm and MSAP-2 at 430-370 cm depth  
176 (sapropel numbering proposed by Çağatay et al., 2009, 2019). These are for core  
177 CS22, MSAP-3 at 1920-1853 cm and MSAP-2 in two parts: MSAP-2b at 1653-1570  
178 cm and to a lesser extent MSAP-2a at 1460-1407 cm (their naming follows what was  
179 proposed in Çağatay et al. (2009)). The latter authors have proposed a correlation of  
180 the MSAP-4, 3 and 2 to the Mediterranean sapropels S5, S4 and S3. A revision of  
181 the two Marmara sequence ages, based on geochemistry and pollen analysis,  
182 indicates that for core CS22, MSAP-3 is Late Eemian Interglacial, MSAP-2b is Saint-  
183 Germain I Interstadial, and MSAP-2a is Saint-Germain II Interstadial, or  
184 approximately MIS late 5e, 5c and 5a (Fig. 2; Leroy et al., submitted). In core CS18,  
185 MSAP-4 is early Eemian Interglacial, MSAP-3 is late Eemian and MSAP-2 is Saint-  
186 Germain I, or approximately MIS early 5e, late 5e and 5c (Fig. 2; Leroy et al.,  
187 submitted).

188 Minor and major hiati are defined and discussed in Leroy et al. (submitted)  
189 and shown as red lines on figure 2 and following.

## 190 **4 Material and Methods**

### 191 4.1 Dinocyst analysis

192 Fifty-one sediment samples were treated in core CS22 and 79 in core CS18  
193 mostly below the red-H1 reflector for their palynomorph content. The sampling  
194 resolution varied between 10 and 20 cm. After measurement of the sediment volume  
195 (between 0.5 and 2.5 ml), one tablet of *Lycopodium clavatum* was added. The  
196 sediment was then soaked in tetrasodium pyrophosphate, followed by acid attacks:  
197 cold HCl (10% dilution), cold HF (between 40 and 60%) and again cold HCl.  
198 Samples were then rinsed with distilled water and sieved on nylon meshes at 125  
199 and 10 µm. The residues were transferred to vials and slides mounted in glycerol. At  
200 least 60 dinocysts were counted in each sample, except in core CS22 above 1400  
201 cm, and in core CS18 above 369 cm and below 786.5 cm. Some gritty samples in  
202 core CS18 were also centrifuged in Sodium Polytungstate at a density of 2.4. All  
203 samples were rich in dinocysts except one at 364 cm depth in core CS18 and one at  
204 2026.7 cm in core CS22. All percentages are calculated based on the sum of all  
205 dinocysts, except varia (indeterminate, indeterminable and reworked specimens) and  
206 foraminiferal organic linings. Concentration of palynomorphs is calculated in ml of  
207 wet sediment. The P/D ratio is the ratio of the concentration of pollen on dinocysts. It  
208 reflects the continentality of the sample ([McCarthy and Mudie, 1998](#)). The H/A ratio  
209 is the ratio of heterotrophic (dependent on nutrients synthesised by other organisms)  
210 taxa on autotrophic (whose energy source is the light) ones. Zonation (on 23 and 22  
211 dinocyst taxa respectively in cores CS22 and CS18) was made by CONISS after  
212 square-root transformation, available in the psimpoll software ([Bennett, 2007](#)), which  
213 was also used for plotting dinocyst diagrams. The diversity was calculated using the

214 Margalef's species richness ([Margalef, 1958](#)) and an ordination analysis with non-  
215 Metric Multidimensional Scaling (NMDS) (Primer 7; [Clarke and Gorley, 2015](#))  
216 allowing distinguishing groups of samples of similar composition.

217       Identifications were made with the support of the atlas of [Mudie et al. \(2017\)](#),  
218 and plates in [Marret et al. \(2004\)](#), [Sorrel et al. \(2006\)](#), [Londeix et al. \(2009\)](#) and  
219 [Leroy \(2010\)](#). *Spiniferites cruciformis* specimens were grouped in three different  
220 forms (A – standard form, B – pointed apex and C – short and folded processes) as  
221 in [Marret et al. \(2004\)](#). *Lingulodinium machaerophorum* ss indicates the sensu stricto  
222 form ([Leroy et al., 2006](#); [Mertens et al., 2009](#); [Mudie et al., 2017](#)). The “*L.*  
223 *machaerophorum* bulbous” form has short but clearly bulbous (as in [Mudie et al.](#)  
224 [\(2017\)](#)) and non-clavate processes. *L. machaerophorum* B is described in [Leroy et](#)  
225 [al. \(2006\)](#), as having short microgranulate processes with a large striated conical  
226 base. *Impagidinium* sp. A is a form defined in [Londeix et al. \(2009\)](#). The name  
227 *Spiniferites inaequalis* is conservatively used, although some ongoing discussions  
228 propose to move the species to the genus *Impagidinium* ([Mertens et al., 2018](#)). In  
229 the cumulative diagram, the marine taxa are on the left and the brackish  
230 Pontocaspian ones on the right. In the middle, are the heterotrophic taxa and the  
231 various forms of *Lingulodinium machaerophorum*. Warm-loving dinocysts are defined  
232 by the presence of *Operculodinium israelianum*, *Spiniferites pachydermus*,  
233 *Polysphaeridinium zoharyi*, *Tuberculodinium vancampoae* and *Spiniferites mirabilis*  
234 as they reflect temperatures higher than nowadays ([Marret and Zonneveld, 2003](#);  
235 [Londeix et al., 2009](#); [Shumilovskikh et al., 2013](#); [de Vernal et al., 2020](#); [Marret et al.,](#)  
236 [2020](#)). Seasonal contrast in sea-surface temperature (SST) is reflected by  
237 *Bitectatodinium tepikiense*, *Pentapharsodinium dalei* and *Scrippsiella trifida* ([Head et](#)  
238 [al., 2006](#); [Mudie et al., 2017](#)).

239 Although not dinocysts, coiled organic linings of foraminifera were found and  
240 added to this investigation, rather than to the pollen diagram (Leroy et al.,  
241 submitted), as they usually belong to the marine environments. The inner organic  
242 lining is often produced by benthic foraminifera (de Vernal, 2009; Mudie et al., 2021).

#### 243 4.2 Other proxies in core CS22

244 **Alkenones** were measured in sediment samples from core CS22 between  
245 2050 and 1370 cm. After freeze-drying and grinding, samples were extracted using  
246 an accelerated solvent extraction system (ASE350, Thermo Scientific). After a clean-  
247 up procedure using silica gel column chromatography with a mixture of  
248 dichloromethane: hexane (1:1), the total lipid extract was analysed by gas  
249 chromatography and flame ionization detection (GC-FID, Trace GC, Thermo  
250 Scientific). Identification and purity of alkenones were checked in several samples by  
251 gas chromatography coupled to quadrupole mass spectrometry (Trace GC DSQII,  
252 Thermo Scientific). GC conditions were similar to those described by Sonzogni et al.  
253 (1997). When present, they are considered as marine indicators.

254 **Benthic foraminiferal faunas** were quantitatively investigated in the 125 µm  
255 fraction from nine samples. At first a qualitative downcore check of foraminiferal  
256 content was performed in the coarse fraction at a 1 m sampling resolution, then  
257 refined to 20 cm between 2035 and 1915 cm where very rich benthic foraminifera  
258 assemblages were found. Two additional samples were investigated at 1632 and  
259 1631 cm. When possible, 300 specimens were counted in sediment aliquots, and  
260 identified to the lowest taxonomic level possible, mainly at the species level. To  
261 describe major faunal trends, the species Benthic Foraminiferal Number (BFN,  
262 expressed as individuals per g or ind.g<sup>-1</sup>) and frequency data of main species (>1%)  
263 were used.

264 Sediment samples for **diatom and chrysophyte** analyses were collected at  
265 20 cm intervals in each section of core CS22. Smear slides were prepared with a  
266 suspension made of known amounts of dry sediment and distilled water. 200 µl of  
267 this suspension were spread onto a cover slip, air-dried and mounted on a glass  
268 slide using Naphrax mounting medium. Diatom valves were counted along transects  
269 and expressed as number of valves per gram of dry sediment. Chrysophycean cysts  
270 were also counted; but morphotypes were not identified.

## 271 **5 Results**

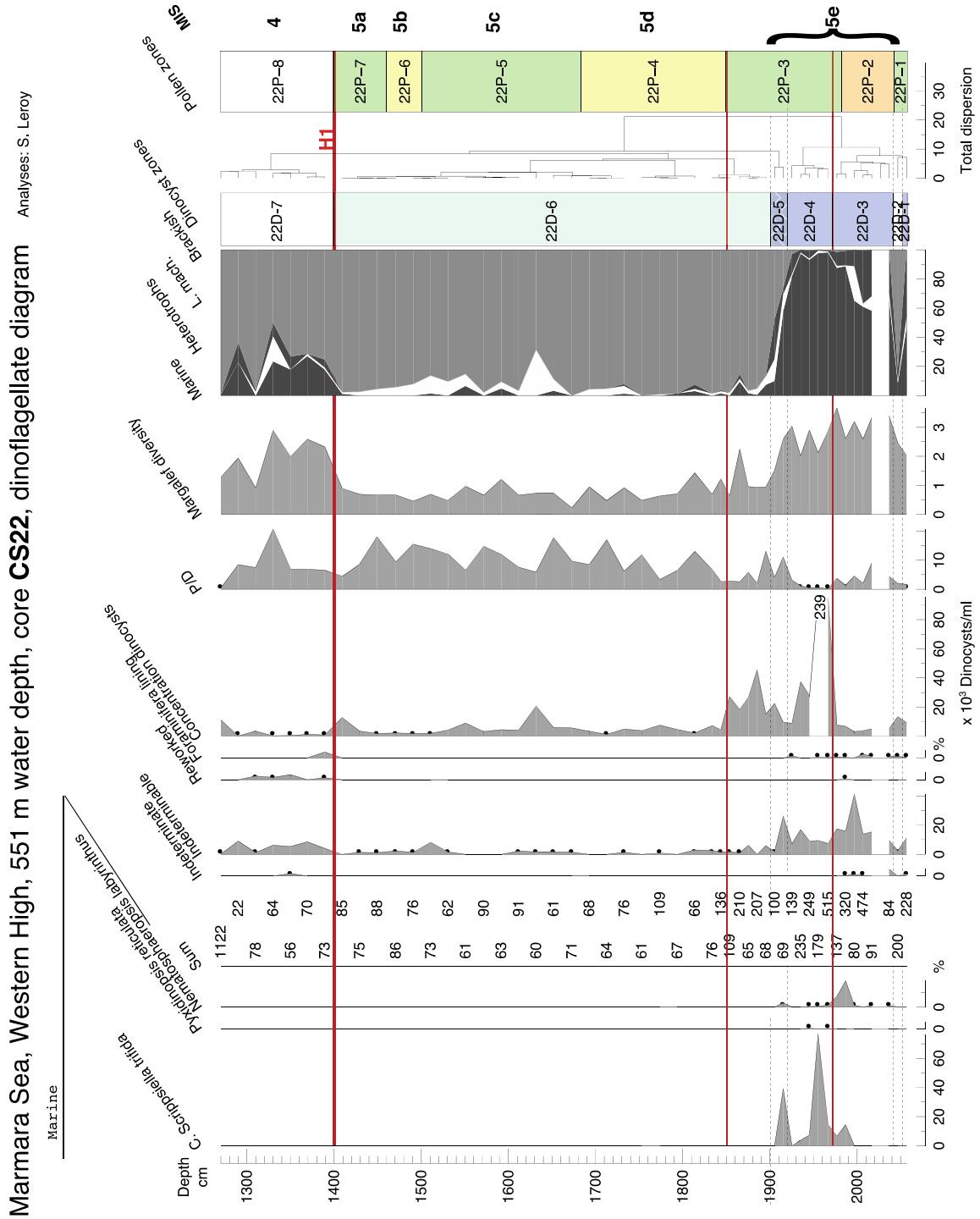
272 Two main types of dinocyst assemblages were observed ([Fig. 3 and 4](#)). The  
273 first one is largely dominated by *Spiniferites cruciformis* and *Pyxidinospis psilata*. By  
274 comparison to Black, Marmara and Caspian seas Lateglacial-early Holocene  
275 assemblages, they are attributed to brackish Pontocaspian conditions, perhaps in  
276 the range of ~7-12 psu, thus clearly lower than the surface conditions of the SoM  
277 ([Bradley et al., 2012](#); [Marret et al., 2004, 2009, 2019](#)). The second assemblage,  
278 called here marine, is an assemblage with diverse taxa also with no direct equivalent  
279 in the present. It represents salinities probably close to the surface waters of the  
280 modern-day Marmara ([Balkis et al., 2016](#)).

### 281 5.1 Dinocysts in core CS22

282







285

286

287 **Figure 3 a and b:** Percentage dinocyst diagram of core CS22. Black dots for < 5%.

288 Pollen zones to the right with chronological attributions. Horizontal brackets indicate

289 the warm indicators in the marine group.

290

291 The dinocyst assemblages show a diversity from 3 to 19 taxa, with notably  
292 higher numbers of taxa at the bottom of the core, i.e. below 1920 cm (Fig. 3).  
293 Broadly, the record shows a succession of two main assemblages, one mostly  
294 dominated by marine taxa, and the following one by brackish Pontocaspian taxa.  
295 The main change in the diagram according to the CONISS analysis is by far between  
296 zones 22D-4 and 5 at 1920 cm depth (Fig. 3). However, it is not sharp.  
297  
298 Zones 22D-1 and D-2 each consist of one sample (at 2057 and 2047 cm depth). In  
299 rapid alternation, the first assemblage is marine with a dominance of *L.*  
300 *machaerophorum* alongside: *Spiniferites* sp., *S. mirabilis*, cysts of  
301 *Pentapharsodinium dalei* and *Tuberculodinium vancampoeae*. The second sample  
302 has a brackish Pontocaspian assemblage, with the dominance of *Spiniferites*  
303 *cruciformis* A and *Pyxidinoopsis psilata* and low occurrence of *L. machaerophorum*.  
304 Foraminifera linings are observed in zones D-1 to D-4.  
305  
306 Zone 22D-3 (2042-1972 cm depth): Besides zone 22D-1, *L. machaerophorum*  
307 displays its highest values here, declining only in the last third of this zone. The  
308 percentages of *Operculodinium centrocarpum* increase progressively to a maximum  
309 at the end of this zone. *Spiniferites* sp. also has maximal values. The other taxa,  
310 mainly marine, are rather diverse (high Margalef diversity index). A high number of  
311 indeterminable cysts occur. The sample at 2027 cm depth is rich in pollen, but hardly  
312 contains any dinocysts.  
313  
314 Zone 22D-4 (1972-1920 cm depth): The assemblage is still marine and diverse, but  
315 rather different from the previous zone. The spectra are alternatively dominated by

316 cysts of *P. dalei* and cysts of *Scrippsiella trifida*. *L. machaerophorum* is present but in  
317 small amounts. The P/D ratio is at its minimum, largely because the concentration in  
318 dinocyst is very high, i.e. >230,000 cysts/ml. The number of indeterminable cysts is  
319 decreasing but still significant.

320

321 Zone 22D-5 (1920-1900 cm depth): This zone is a period of transition with the  
322 percentages of *S. cruciformis* A progressively increasing, and those of *P. psilata*  
323 starting a continuous curve, while the marine forms are less diverse (decreasing  
324 Margalef diversity index). *L. machaerophorum* makes a brief return. Brown baggy  
325 cysts form a bell-shape curve. *Operculodinium centrocarpum* has nearly  
326 disappeared. Cysts of *S. trifida* peak in one of the samples.

327

328 Zone 22D-6 (1900-1399 cm depth): This very long (5 m) and rather homogenous  
329 (minimal Margalef diversity index) zone is largely dominated by brackish  
330 Pontocaspian taxa such as *S. cruciformis* and *P. psilata*. Brown baggy cysts are  
331 occasionally more frequent, especially at 1632 cm depth (32%). *Bitectatodinium*  
332 *tepinkense* is only sub-continuously present in the middle of this zone between 1652  
333 and 1551 cm depth. *L. machaerophorum* is occasionally present at the beginning of  
334 this zone and soon disappears. All through this zone, the P/D ratio is relatively high.  
335 Cyst concentration drops drastically at the very beginning of this zone and remains  
336 low for the rest of the sequence.

337

338 Zone 22D-7 (1399-1270 cm depth): The values of *S. cruciformis* remain the same as  
339 in the preceding zone, but those of *P. psilata* significantly drop. The assemblage is  
340 diverse with many marine forms but with a low occurrence. *L. machaerophorum* is

22/03/2023

341 back with irregular presence between 0.2 and 14 %. Three foraminifera linings (4%)

342 were found at the base of this zone. Concentration is varying, at times below 500

343 dinocysts/ml. Reworked elements are frequent.

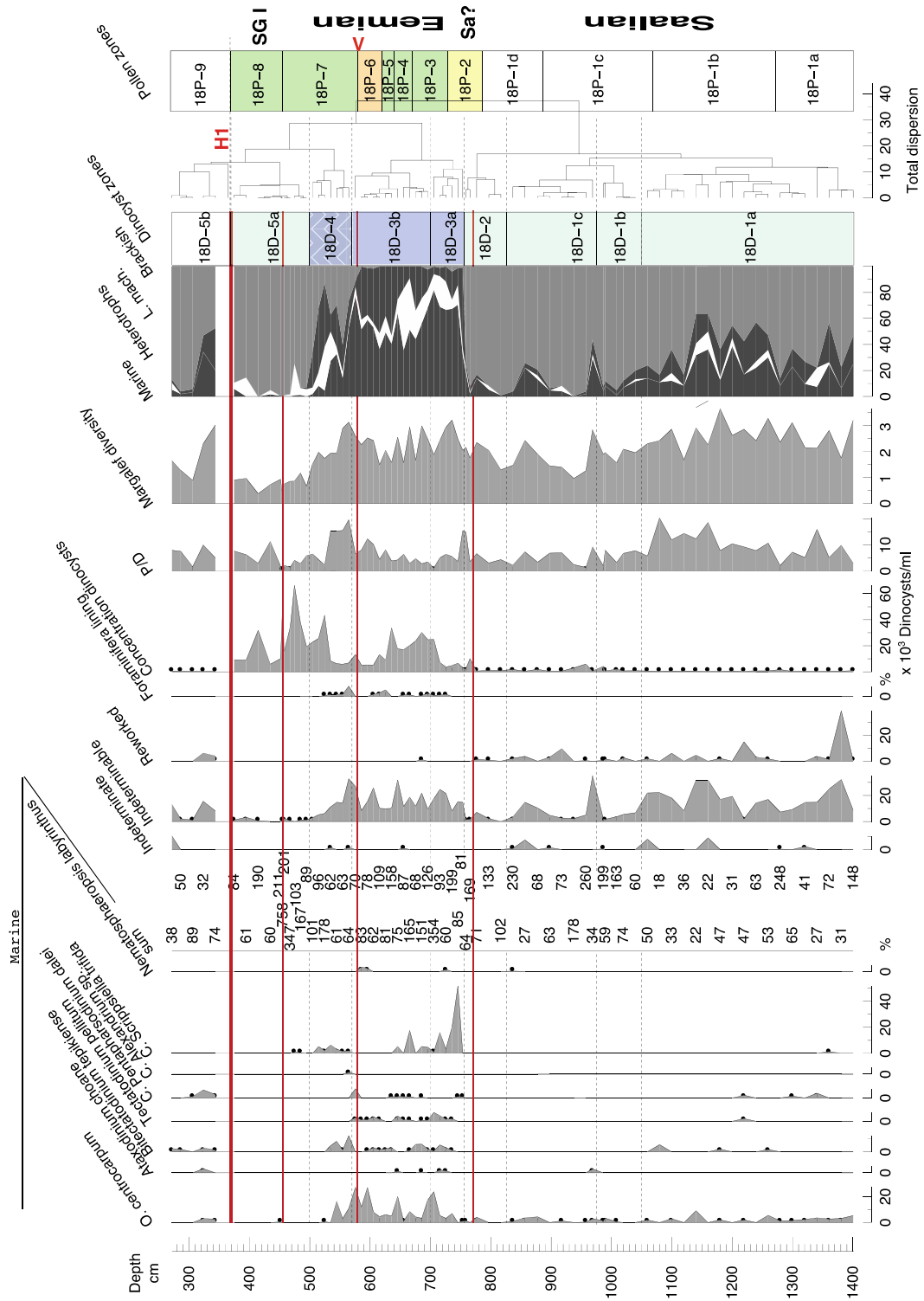
344 5.2 Dinocysts in core CS18

345



Marmara Sea, Imrali basin, 291 m water depth, core CS18, dinoflagellate diagram

Analyses: S. Leroy



347

348

349 **Figure 4 a and b:** Percentage dinocyst diagram of core CS18. Black dots for < 5%.

350 Pollen zones to the right with chronological attributions. Horizontal brackets indicate

351 the warm indicators in the marine group.

352

353 The dinocyst assemblages show a diversity from 3 to 17 taxa, with notably higher  
354 numbers of taxa below 1180 cm, and at 735 and 565 cm (Fig. 4). Broadly, the record  
355 shows the succession of three main assemblages, one mostly dominated by marine  
356 taxa in the middle, with below and above it two brackish Pontocaspian assemblages  
357 of two different types. The two main changes in this diagram are at 756 and 570 cm  
358 depth (Fig. 4).

359

360 Zone 18D-1, 1400.5 – 826.5 cm depth: This is a very long zone of nearly 6 m. It is  
361 dominated by brackish Pontocaspian taxa such as *P. psilata*, *S. cruciformis* A, *S.*  
362 *inaequalis* and *Caspidinium rugosum rugosum*, with a significant occurrence of *L.*  
363 *machaerophorum* ss. In general, concentrations are relatively low, mostly below  
364 1000 cysts/ml. Reworked cysts are frequent. This zone has been subdivided into  
365 three subzones, with subdivisions as followed. Subzone 18D-1a (1400.5-1049.5 cm)  
366 is dominated by *S. inaequalis*. *L. machaerophorum* ss, *P. psilata* and *S. cruciformis*  
367 A are abundant. A range of marine and brackish Pontocaspian taxa occur side by  
368 side. Indeterminable dinocysts are abundant. A large peak of reworked cysts occurs  
369 at 1381 cm depth. The P/D ratio remains high all through this zone, with maximal  
370 values towards the end, i.e. a maximum of up to above 20. Concentrations are very  
371 low, often lower than 500 cysts per ml. Subzone 18D-1b (1049.5-977 cm): This zone  
372 is characterised by a bell-shaped curve of *Impagidinium* sp. A. *S. inaequalis* is still  
373 abundant. *P. psilata* displays increasing values across this zone. In subzone 18D-1c  
374 (977-826.5 cm), *P. psilata* reaches maximal values, i.e. 54%. The percentages of *S.*  
375 *inaequalis* are still high. Less diverse marine forms are observed.

376

377 Zone 18D-2, 826.5-756 cm depth: This zone is characterised by many changes. *P.*  
378 *psilata* decreases and *S. cruciformis* A increases up to a brief maximum of 59%. *S.*  
379 *cruciformis* C is very abundant. A small bell-shaped curve of *S. belevius* occurs. *S.*  
380 *inaequalis* values drop. Very few marine taxa subsist. Concentrations are slightly  
381 increasing. This zone represents a transition that is truncated by a hiatus, recognised  
382 as one the strongest statistical changes according to CONISS.

383

384 Zone 18D-3, 756-570 cm depth, is a totally different zone, with *L. machaerophorum*  
385 (up to 52%) and *Spiniferites* sp. (up to 30%) widely dominant. Brown baggy cysts are  
386 very abundant in this zone and the following one, i.e. up to 30%. Many marine taxa  
387 are present. *S. ramosus*, *O. centrocarpum* and *Tuberculodinium vancampoae* are  
388 well represented. Concentrations are high, often around 10,000-20,000 dinocysts/ml.  
389 A split into subzones 3a and 3b at 700.5 cm depth is based on a maximum of *S.*  
390 *ramosus*, very large peak of cysts of *S. trifida* (52%), medium-high concentration and  
391 maximum percentage of marine taxa in subzone 3a; whilst in subzone 3b high *T.*  
392 *vancampoae* and high concentration occur. This zone ends with the second  
393 strongest diagram change (as calculated by CONISS). Foraminiferal linings are only  
394 present in this zone and in the following zone.

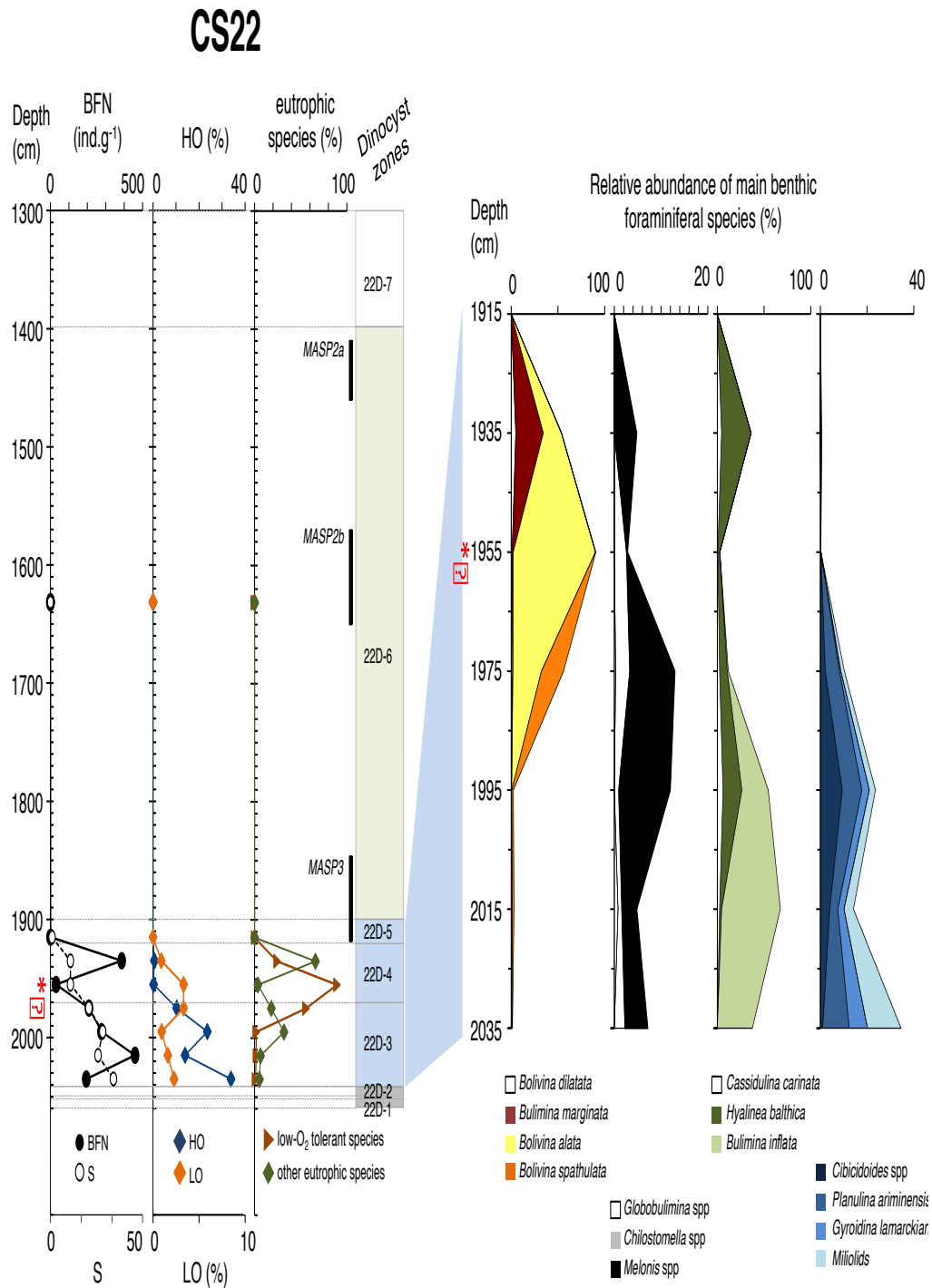
395

396 Zone 18D-4, 570–499.5 cm depth, appears as a transition, with mixed marine and  
397 brackish Pontocaspian assemblages. *P. psilata* and *S. cruciformis*, quasi absent in  
398 zone 18D-3, reappear. *L. machaerophorum* (with a peak of other forms of *L.*  
399 *machaerophorum* towards the end of this zone) and brown baggy cysts are still



400 abundant. Marine taxa remain present, but their values decrease. Concentrations,  
401 after moderate values, become high again. P/D is maximal, i.e. up to just below 20.  
402  
403 Zone 18D-5, 499.5-271.5 cm, is split in two by the seismic red-H1 reflector;  
404 moreover, a barren sample occurs a few cm above this stratigraphic hiatus. In  
405 subzone 18D-5a, 499.5-369 cm depth, *S. cruciformis* A very largely dominates with  
406 percentages up to 95%. Besides *P. psilata* and brown baggy cysts, hardly any other  
407 taxa are present. It is noteworthy that *L. machaerophorum* has only rare occurrences  
408 in this subzone, and only at its base. This is a very low diversity subzone (minimum  
409 in the Margalef index). Concentrations, after being very high, become high, i.e.  
410 66,000 to 10,000 dinocysts/ml. Subzone 18D-5b, 369-271.5 cm depth: The  
411 assemblages are similar to subzone 18D-5a (dominance of brackish Pontocaspian  
412 taxa), but brown baggy cysts have quasi disappeared and are replaced by *L.*  
413 *machaerophorum* that have re-appeared. A moderate range of marine taxa is  
414 present. Concentrations are very low as in subzones 18D-1a. Reworked elements  
415 are common in the lower half of this subzone, just above the barren sample.

416 5.3 Other proxies in core CS22



417

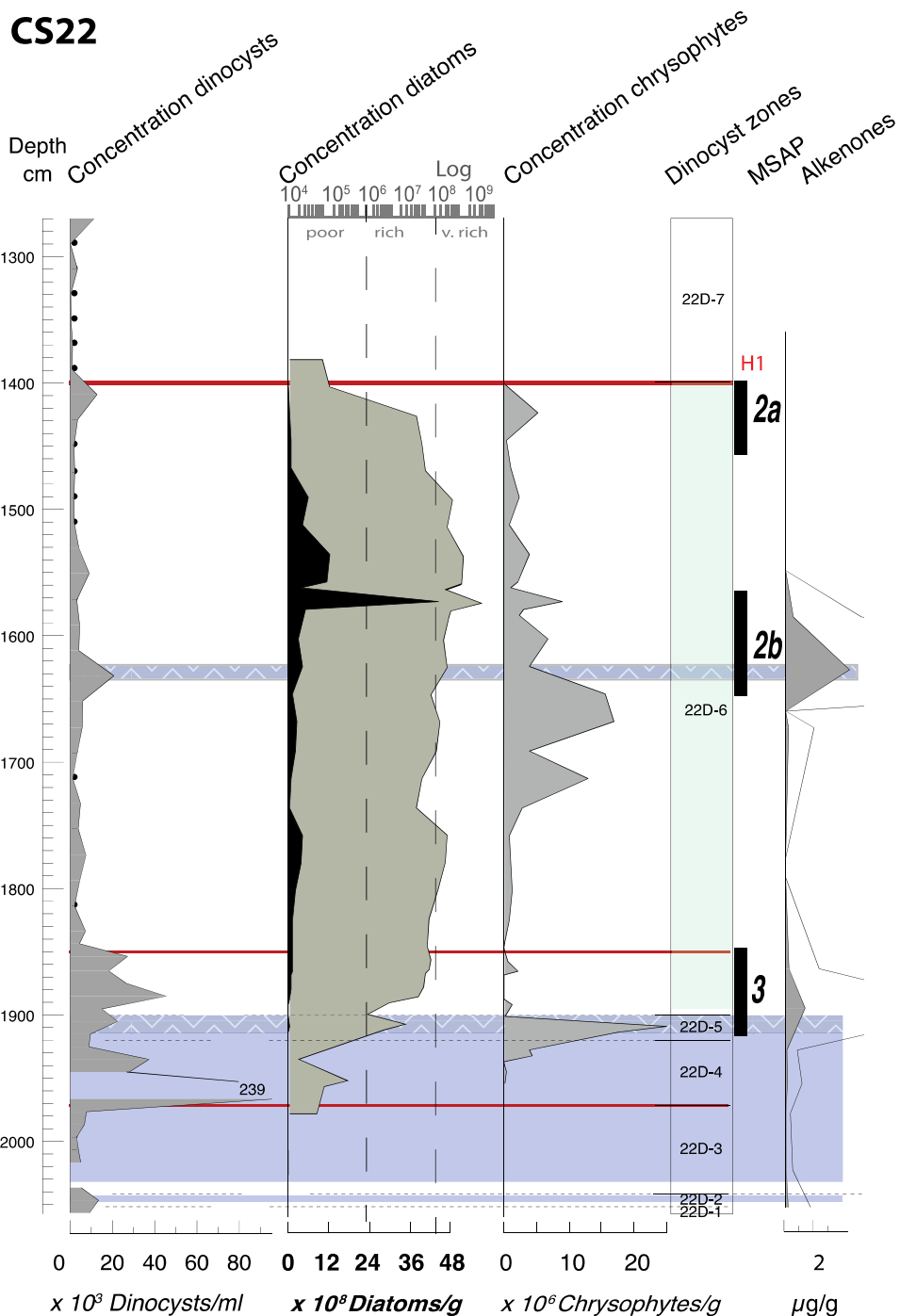
418 **Figure 5:** Benthic foraminiferal record of core CS22 with dinozones and Marmara  
 419 sapropels (MSAP). Right panel: relative abundance of main species (>3%) between  
 420 2035 and 1915 cm depth. Left panel: Benthic Foraminiferal Number, BFN (ind.g<sup>-1</sup>),

421 species richness S, relative abundance of ecological groups of species. HO =  
422 species adapted to high-oxygen level, LO = low-oxygen indicators, eutrophic species  
423 = species adapted to high organic carbon fluxes. For further explanation on  
424 ecological assignment of species, the reader is referred to the discussion and [Table](#)  
425 [SI2](#).

426

427 Quantitative investigation of benthic foraminiferal assemblages relies on the  
428 recovery of a well-preserved, abundant (164 to 361 specimens) and diverse (>60  
429 species overall) faunal content between 2035 and 1915 cm depth ([Table SI1](#)). Apart  
430 from a few individuals (< 10) belonging to neritic taxa (e.g. *Ammonia*, *Discorbinella*,  
431 *Elphidium*), assumed to be post-depositional, foraminiferal assemblages  
432 overwhelmingly consist of species from marginal to bathyal environments. The BFN  
433 ranges from 30 to 459 ind.g<sup>-1</sup>, with lowest values recorded at 1955 cm. Dominant  
434 species (>5%) belong to *Bolivina* spp, *Bulimina* spp, *Cassidulina carinata*,  
435 *Cibicidoides* spp, *Hyalinea balthica* and *Melonis* spp and indicate fully marine  
436 conditions at the seafloor at the base of the core. The foraminiferal record, though  
437 short, exhibits a marked species shift between 1995 and 1975 cm ([Fig. 5](#)). From  
438 2035 to 1995 cm, species number is highest, ranging from 31 to 41. Faunas are  
439 strongly dominated by *Bulimina inflata* (28-63%), together with various associated  
440 species including *Cibicidoides* spp (1-9%), *Gyroidina lamarckiana* (3-8%), *Planulina*  
441 *ariminensis* (3-11%) and miliolids (3-14%). Minor species (<3%) include *Bulimina*  
442 *aculeata*, *Uvigerina mediterranea* and *U. peregrina*. From 1975 up to 1935 cm, most  
443 of the afore-mentioned species disappear from the record. Dominant species consist  
444 mainly in *Bolivina alata*, *B. spathulata* and *Bulimina marginata*, which collectively  
445 account for 49 to 90% of the assemblage. Concomitant to this faunal shift, species

446 number drops from 25 to 13 (Fig. 5). By contrast, several other species such as  
447 *Cassidulina carinata*, *Hyalinea balthica*, *Melonis affinis* and *M. pompiloides* exhibit no  
448 clear upcore trend. Present along the whole record, these species show punctual  
449 increases, as especially marked for *H. balthica* at 1995 (32%) and 1935 (20%) cm.  
450 Sample at 1915 cm is considered barren of benthic foraminifera as fourteen  
451 reworked individuals only were found. Samples at 1632 and 1630 cm were devoid of  
452 any foraminifera.



453

454 **Figure 6:** Palaeoproductivity: concentrations of dinocysts, diatoms (in decimal and  
 455 log scales) and chrysophytes, with dinozones, alkenones and Marmara sapropels  
 456 (MSAP) in core CS22. The second marine phase at 1633-1632 cm depth is indicated  
 457 by a box with a blue zigzag highlight.

458

459 Diatom preservation is becoming better from bottom to the red-H1 reflector.  
460 Hardly any diatoms were found below 1915 cm (Fig. 6). Then only some  
461 occurrences are noted between 1915 and 1866 cm. From 1854 cm upwards and  
462 until 1470 m, the diatom concentrations are high to very high. Diatom concentrations  
463 are the highest between 1591 and 1491 cm depth. Chrysophycean cysts are  
464 abundant when diatom concentrations decrease. The diatom assemblages are  
465 composed of a mixture of fresh and brackish-water species. Dominant  
466 *Stephanodiscus* species (*S. minutulus*, *S. parvus*, *S. medius*, *S. neoastrea*, *S.*  
467 *hantzschii*) occurred with numerous fragments of *Entomoneis calixasini*, a fossil  
468 species so far only found in core sediments of the SoM (Pailles et al., 2014). The first  
469 occurrence of *E. calixasini* in core CS22 is recorded at 1834 cm depth. Spores of a  
470 marine planktonic diatom, *Chaetoceros*, are observed from 1850 to 1830 cm.

471 The values of alkenones are usually below detection limit, except at 2050-  
472 1865 cm and 1633-1592 cm, reaching respective maxima of 1.3  $\mu\text{g/g}$  at 1896 cm  
473 and 4.4  $\mu\text{g/g}$  at 1633 cm depth (Fig. 6).

## 474 **6 Interpretation and discussion**

### 475 6.1 Core CS22: taphonomy, surface water condition and chronology

#### 476 6.1.1 Taphonomy

##### 477 *Below the sapropel*

478 At 2027 cm in zone 22D-3, the sample is unexpectedly barren in dinocysts. It  
479 is one of the samples of zone 22P-2 with abundant *Pinus* pollen (76%) (Leroy et al.,  
480 submitted). The lithology shows a bioturbated sediment. Sediment disturbance may  
481 also contribute to explain the rapidly changing spectra in the short zones 22-D1 and

482 D2. The sharp zone limit at 1920 cm (between zones 22D-4 and 5) corresponds to a  
483 very thin silt layer and a change from bioturbated to unbioturbated sediment, that is  
484 the start of the sapropel attributed to MSAP-3 (1920-1853 cm).

485

486 *In the sapropel and above*

487 Dinocysts (as well as pollen) are well preserved and their concentrations are  
488 maximal as observed in other sapropels ([Cheddadi and Rossignol, 1995](#); [Kotthoff et](#)  
489 [al., 2008](#)) ([Fig. 6](#)).

490

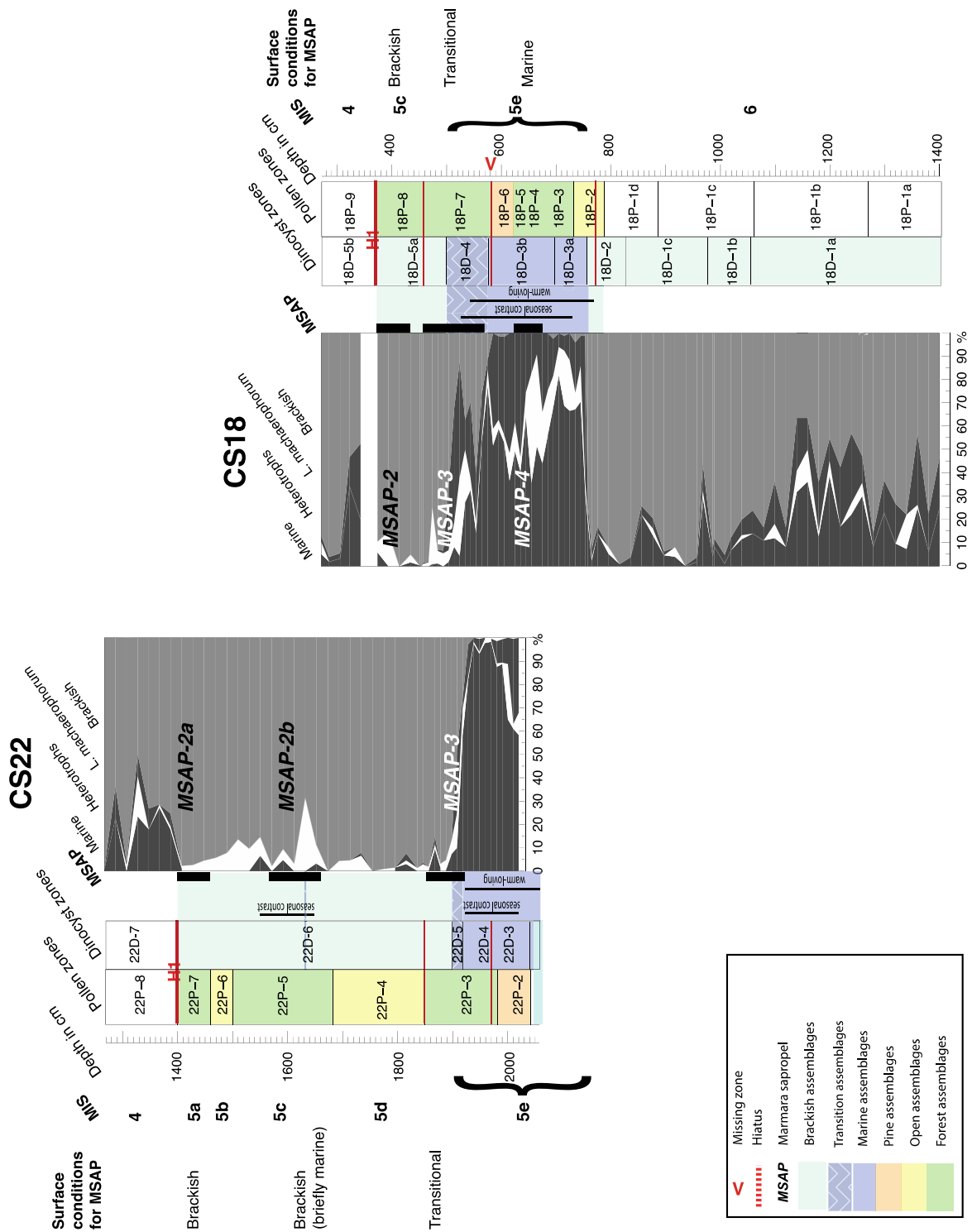
491 *Impact of red-H1 seismic reflector*

492 With the red-H1 reflector (a hiatus), a long-term change in taphonomy is  
493 initiated in the SoM. It is seen in the reworking of older marine layers and of soils.  
494 Firstly, some foraminifera (linings) are brought in the sediment. Secondly, the non-  
495 pollen palynomorphs *Glomus* (a fungal spore) is present, due to inwash of soil  
496 erosion products ([Leroy et al., submitted](#)). This reflects a turning point in the aquatic  
497 conditions of the SoM.

498 *6.1.2 Sea-surface and bottom conditions*

499 The depths of 2042-1920 cm (dinocyst zones 22D-3 and 4) are fully marine as  
500 clearly seen not only in the dinocyst assemblages but also in the alkenone values  
501 and the benthic foraminiferal content ([Fig. 3, 5 and 7](#)).

502



503 **Figure 7:** The cumulative diagrams sorting dinocyst groups/taxa by salinity. The four  
 504 groups are the marine ones (black) to the left, the brackish Pontocaspian dinocysts  
 505 (grey) to the right), and in the middle the heterotrophic cysts (white) and the  
 506 *Lingulodinium machaerophorum* forms (black). Dinocyst zones: blue highlight for  
 507 marine, light blue for brackish Pontocaspian. The distribution of warm-loving and



508 seasonal contrast indicators as vertical black lines. Pollen zones: green highlight for  
509 high arboreal taxa (minus *Pinus*) zones and yellow for low arboreal taxa % and high  
510 *Pinus* % zones. Horizontal bold V for pollen and dinocyst zones absent in core  
511 CS18.

512

513 Five indicators of warm sea-surface temperature (SST) are recorded: *O.*  
514 *israelianum*, *S. pachydermus*, *P. zoharyi*, *T. vancampoae* and *S. mirabilis* (Fig. 3 and  
515 7). They are especially abundant in zone 22-D3. Their occurrence suggests  
516 temperatures higher than nowadays. *B. tepikiense*, occurring in zones 22-D3 and 4,  
517 reflects marine conditions with seasonal amplitudes of SST. Thus conditions  
518 recorded in zone 22-D3 suggest a warm climate with seasonal contrast.

519 In zone 22D-4 at 1955 cm, high values of cysts of *P. dalei* and *S. trifida*  
520 suggest an increase in temperature seasonality and lower salinity (e.g. Head et al.,  
521 2006; Mudie et al., 2017). In contrast, very high concentrations point at surface  
522 waters rich in nutrients and possibly bottom waters with low oxygen (Mudie et al.,  
523 2017). This may be due to alternating deep-water upwelling - when the heavy saline  
524 marine waters penetrate the bottom of the basin from the Aegean Sea - and  
525 stratification. This occurs below the horizon with high TOC (sapropel MSAP-3 at  
526 1920-1853 cm depth and bottom anoxia, Fig. 2).

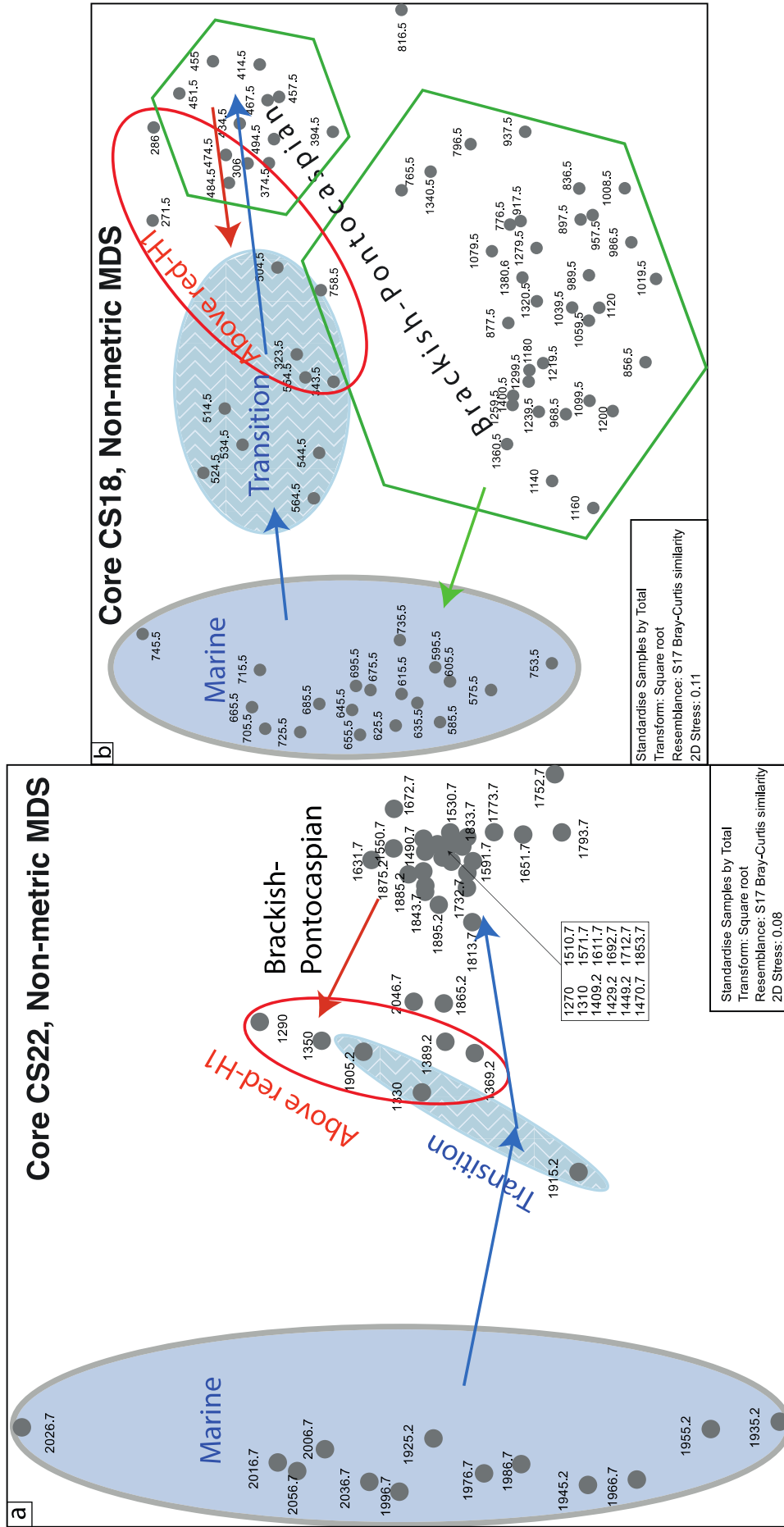
527 To tackle environmental changes at the seafloor, the approach of Cornuault et  
528 al. (2016, and references therein) was followed and foraminiferal species were  
529 gathered into three functional groups assumed to be representative of contrasted  
530 oxygen and trophic conditions at the seafloor: (1) species adapted to high oxygen  
531 conditions (HO), (2) low-oxygen indicators (LO), and (3) species adapted to  
532 eutrophic conditions (Fig. 5). Ecological assignment is given in Table SI2. The major

533 faunal shift observed at 1995 -1955 cm suggests contrasted oxygen conditions  
534 between zones 22D-3 and 22D-4, possibly related to the establishment of eutrophic  
535 conditions. In zone 22D-3, benthic foraminiferal assemblages are ecologically  
536 diverse and consist of a mix of epibenthic and various endobenthic species. This  
537 sequence and the high abundance of HO species suggest a mesotrophic  
538 environment where well-oxygenated conditions prevailed at the seafloor. By contrast,  
539 HO indicators disappearance in zone 22D-4 together with high abundance of species  
540 adapted to high organic fluxes points to reduced oxygen level during this phase.  
541 Assemblages from this zone are successively dominated by species adapted to  
542 contrasted oxygen conditions, suggesting variable oxygenation level during zone  
543 22D-4. In particular, the BFN decrease, high dominance of eutrophic species tolerant  
544 to low-oxygenation and slight increase of LO species suggest dysoxic conditions at  
545 the beginning of this period at 1935 cm, high dominance of species adapted to  
546 moderate oxygen depletion strongly suggest environmental changes recorded at the  
547 seafloor directly are related to eutrophication rather than ventilation changes. Overall  
548 the foraminiferal assemblages confirm the presence of oxygen at the bottom of the  
549 sea in zones 22D-3 and 22D-4.

550 In the dinocyst diagram ([Fig. 3](#)), the P/D ratio, informing on the intensity of  
551 terrestrial influence on the aquatic realm, is extremely low in zone 22-D4. It is low in  
552 general below the hiatus at 1845-1842 cm depth. It is relatively high above it with  
553 values frequently higher than 10. It is therefore suggested that the water level was  
554 the highest in zone 22-D4 (1972-1920 cm). This is just before the high TOC values  
555 linked to the MSAP-3 sapropel.

556

557

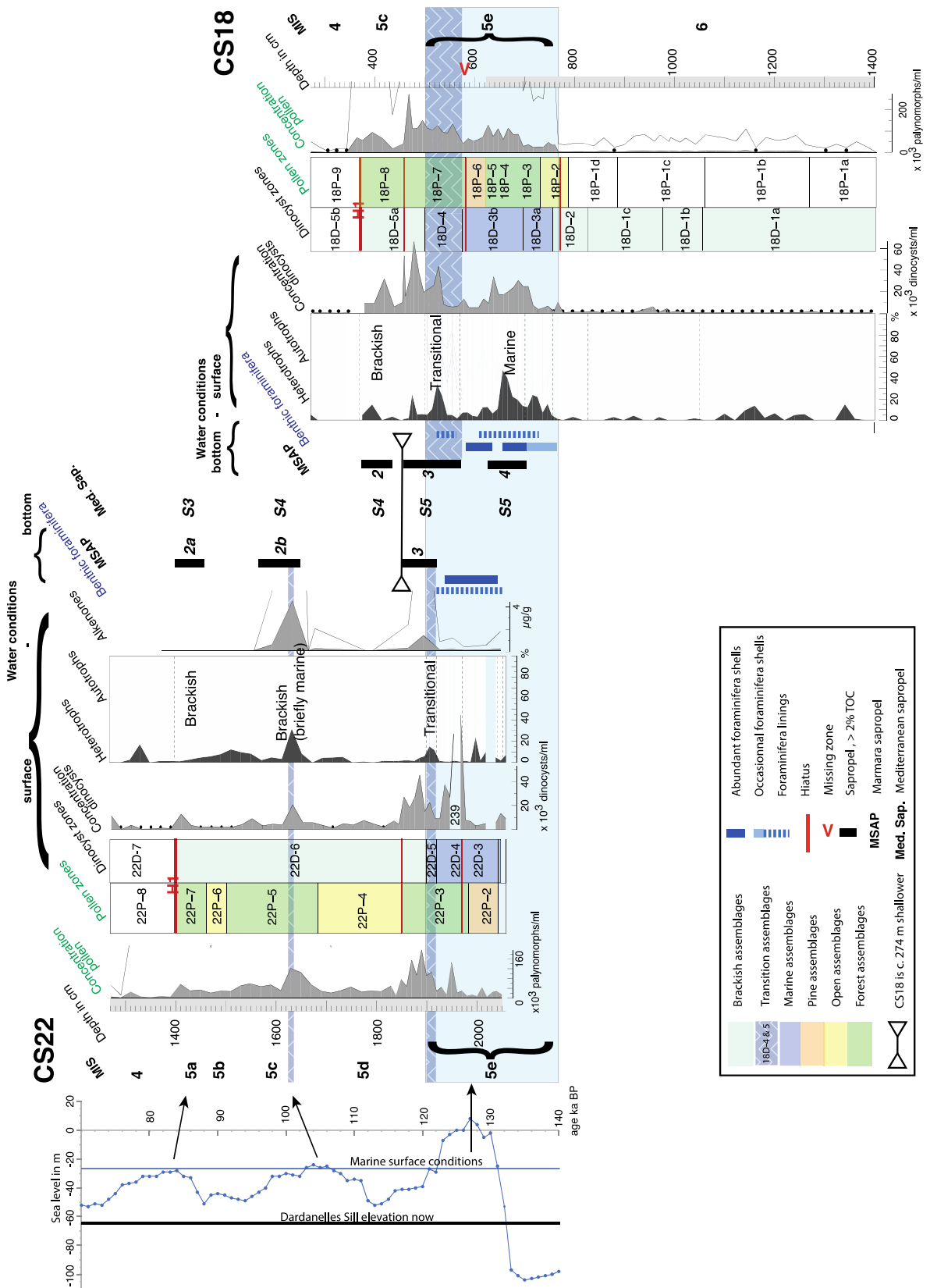


559 **Figure 8:** Results of the NMDS analysis on dinocyst percentages from cores CS22  
560 (a) and CS18 (b). Depth in cm.

561

562 Zone 22D-5 (1920-1900 cm) is a transition zone towards brackish  
563 Pontocaspian conditions (also seen in the NMDS results in [figure 8](#)). The  
564 disappearance of foraminiferal shells at 1915 cm is attributed to bottom anoxic  
565 conditions in the subsequent MSAP-3 (1920-1853 cm).

566 Then zone 22D-6 (1900-1399 cm) is clearly brackish Pontocaspian, as seen  
567 in dinocysts and in the diatom species that indicate fresh to brackish conditions.  
568 Interestingly, marine *Chaetoceros* spores occur at 1850-1830 cm. The highest  
569 concentrations of Chrysophycean cysts indicating fresher / more oligotrophic  
570 conditions occurred between 1680 and 1611 cm depth when diatom concentration  
571 decreases. Later, between 1591 and 1491 cm, the highest diatom concentrations  
572 recorded suggest increased seasonal productivity.



573

574 **Figure 9:** Water conditions. At the surface, dinocyst concentration and the ratio  
 575 heterotrophic and autotrophic dinocysts (H/A). In the middle for core CS22, also the

576 alkenones. For the bottom: Marmara sapropels (MSAP, >2% TOC), benthic  
577 foraminifera shells and benthic foraminifera organic lining. The top of the marine  
578 horizon in core CS18 (hiatus between zones 18P-7 and 8) is c. 274 m deeper than  
579 that in core CS22 (hiatus between zones 22P-3 and 4). Horizontal bold V for pollen  
580 and dinocyst zones absent in core CS18. For linking with the sister paper on pollen  
581 ([Leroy et al., submitted](#)), pollen zones and pollen concentrations are also shown. By  
582 combining the two light grey vertical boxes, the most complete record is obtained.  
583 Sea-level curve from [Rohling et al. \(2021\)](#) with the position of the Dardanelles Sill  
584 elevation now (-65 m) and the sea-level threshold where transition from brackish to  
585 marine conditions occurred.

586

587         However this long 22D-6 zone is not homogenous. At 1632 cm, a peak of  
588 heterotrophic dinocyst is observed. It seems to correspond to the second peak in  
589 alkenones, indicating marine influence, at 1633 cm ([Fig. 9](#)). According to pollen  
590 analysis, it is in an interstadial (Saint-Germain I). Thus, a brief marine incursion is  
591 probable. It is located at the beginning of sapropel MSAP-2b at 1653-1570 cm.

592         Zone 22D-7 (above 1399 cm, above the red-H1 seismic reflector) suffers from  
593 taphonomical problems ([Leroy et al., submitted](#)). Nevertheless, it is mainly brackish-  
594 Pontocaspian, but the occurrence of marine taxa can be either attributed to limited  
595 marine influences or more likely to reworking (see above).

### 596 *6.1.3 Elements of chronology*

597         It is suggested that the high level of MIS 5e ([Bard et al., 1996](#); [Koeling et al.,](#)  
598 [2009](#)) is represented here by zones 22-D3 to 5. In the whole of MIS 5, it is mainly in  
599 the maximum sea level of MIS 5e that the Black Sea would have been connected to  
600 the Global Ocean and the Turkish Straights would have the two-way exchange of

601 water as today. It was established earlier that stratigraphic succession immediately  
602 above the red-H1 reflector belongs to MIS 4 (Kende, 2018; Çağatay et al., 2019),  
603 which can now be shown to reflect a brackish-Pontocaspian environment. During  
604 MIS 4, the SoM was an oligotrophic lake, with no evidence of water body  
605 stratification, and was almost certainly disconnected. During the late phases of MIS  
606 5, the inflow of Mediterranean water was restricted and this probably required a  
607 Dardanelles Sill depth higher than the present sill depth. We will come back to this  
608 point in the discussion and here only consider the phasing of the marine to brackish  
609 transition. In the age model proposed in Çağatay et al. (2019), this transition occurs  
610 after MIS 5d (in the 110 to 100 ka interval) at a time of sea-level rise, and that may  
611 be considered unlikely. This transition more probably occurred concurrently with sea-  
612 level drop either later in MIS 5c or during the transition from MIS 5e to 5d. Assigning  
613 this transition to later in MIS 5c would keep the sapropel correlation proposed by  
614 Çağatay et al. (2019) but imply that MIS 5d is not observed in the pollen record in  
615 either core (Leroy et al., submitted).

## 616 6.2 Core CS18: taphonomy, surface water condition and chronology

### 617 6.2.1 Taphonomy

618 Before the transition 18D-2 to 3 (756 cm) towards marine assemblages, thus  
619 already at the beginning of pollen zone 18P-2 (786.5-730.5 cm), one may see  
620 sudden changes. This is firstly a sediment change from homogenous to finely  
621 laminated around 772 cm and two round pebbles (of river origin?) are found at 775  
622 and 758.5 cm, in between them one finds a 2 mm-thick silt layer (773 cm). Moreover,  
623 at 771 cm a sharp increase of the concentration in pollen and spores (from <5000 to  
624 > 25,000 palynomorphs/ml) and at 762 cm a sharp and long-lasting reduction of the

625 reworked pollen. The sharp statistical limit at 756 cm in the dinocyst diagram is 17  
626 cm above the 2 mm-thick silt layer. These observations are in support of an increase  
627 of water level with the influx of marine water from the Aegean Sea (Çağatay et al.,  
628 2009) leading to sediment disturbance and taphonomical changes.

629         The dinocyst sharp limit at 570 cm is slightly above the hiatus at 580 cm (one  
630 sample). It is interesting to note here the absence of the equivalent to zone 22D-4  
631 with its very high percentages of cysts of *P. dalei* and *S. trifida*. The sediment in core  
632 CS 18 was probably lost by erosion linked to this hiatus.

633         In general, dinocysts and pollen are well preserved in the three sapropels and  
634 their concentrations are maximal, as observed in core CS22. Minimal concentrations  
635 are reached in MIS6 and 4.

636         After the red-H1 hiatus, a barren sample (neither pollen, nor dinocysts, but  
637 many *Dreissena* shell debris) is noted. In the following sample, a peak of *L.*  
638 *machaerophorum*, a large peak of reworked pollen, significant presence of reworked  
639 dinocysts and abundance of *Glomus* co-occur. Therefore, no marine invasion can be  
640 reconstructed; to the contrary a strong coastal, even soil, input should be  
641 recognised. The sediment taphonomy changes completely.

#### 642 6.2.2 Sea-surface conditions

643         The transition from brackish Pontocaspian to fully marine conditions (zones  
644 18D-2 to 3, main change highlighted by CONISS) seems to occur very abruptly at  
645 756 cm depth (Fig. 4 and 7). Then in zone 18D-3, the conditions are only fully  
646 marine. Zone 18D-4 is a transitional period, back towards a brackish-Pontocaspian  
647 environment. This transition zone is also well marked in the NMDS results (see  
648 green arrow in Fig. 8). The surface waters of subzone 18D-5a are clearly brackish-  
649 Pontocaspian. Subzone 18D-5b is mostly brackish-Pontocaspian but some



650 influences from the sea are felt, although as in core CS22 a taphonomical impact is  
651 very important. Below 756 cm, the assemblages of zones 18D-1 and 2 are brackish-  
652 Pontocaspian, with significant reworking in zone 18D-1 both in dinocysts and in  
653 pollen.

654         The group of dinocysts reflecting warm SST (Fig. 4 and 7) is especially  
655 abundant in zone 18-D3. The presence of *B. tepikiense*, as in the CS22 core,  
656 indicates seasonal temperature contrast at that time.

657         Two large peaks of *L. machaerophorum* are noted just above a hiatus, i.e. at  
658 the base of zone 18D-3 and at the base of zone 18D-5b. After the transition from  
659 zone 18D-2 to 3, a peak of cysts of *S. trifida* is also present. Both taxa are signs of  
660 nutrient enhancement.

661         The P/D ratio fluctuates throughout the record. One may note however high  
662 values in subzone 18-D1a and at the base of zone 18-D4. The values are especially  
663 low in the middle of zone 18D-3, suggesting high water levels.

### 664 *6.2.3 Elements of chronology*

665         Zones 18D-3 (marine taxa and low P/D) and 18D-4 (transition) reflect the MIS  
666 5e high sea levels. The warm-loving taxa are present in the same zone and confirm  
667 interglacial conditions as deduced from pollen analysis. However, it is likely that this  
668 zone is not complete as a characteristic dinozone in core CS22 (high percentages of  
669 cysts of *P. dalei* and cysts of *S. trifida*) is missing from it (Leroy et al., submitted).

670         Zones D18-1 and 2 are suggested to represent low water levels and, if the  
671 sequence is in continuity, glacial stage MIS 6. As a reminder, above the red-H1  
672 hiatus, brackish conditions have previously been related to MIS 4 (Kende, 2018;  
673 Çağatay et al., 2019).

674 In conclusion, the chronology proposed here represents an in-depth revision  
675 of that in [Çağatay et al. \(2019\)](#), with especially the occurrence of a larger part of MIS  
676 5e and of MIS 5c and fits the chronology based on geochemistry and pollen analysis  
677 proposed in [Leroy et al. \(submitted\)](#).

## 678 6.3 Comparison of the dinocyst records within the Sea of Marmara and to the 679 Black Sea

### 680 6.3.1 Diversity

681 The dinocyst assemblages are similar in core CS22 and core CS18, with  
682 slightly more marine taxa in CS22 and brackish-Pontocaspian taxa in CS18,  
683 reflecting the difference in the extension of glacial versus interglacial periods covered  
684 in the two sequences ([Table SI3](#)). The total number of taxa is larger in core CS18;  
685 the latter because of the long MIS 6 record. Taxa at play in core 22-GC3 in the SE  
686 Black Sea are similar to those in the two Marmara cores, although the Black Sea  
687 seems to have more heterotrophic cyst diversity and the SoM more brackish-  
688 Pontocaspian taxon diversity ([Table SI3](#)). Modern and Holocene records across the  
689 Black Sea show geographic differences in the distribution of heterotrophic taxa  
690 ([Mudie et al., 2017](#)). This may be due to variations in water turbidity, limitations to  
691 photosynthesis, or possibly competition with other phytoplankton groups.  
692 Remarkably, *S. inaequalis* and *S. trifida* are two particularities of the SoM versus the  
693 Black Sea.

### 694 6.3.2 MIS 5e

695 In core 22-GC3 (SE Black Sea), the transition from brackish Pontocaspian to  
696 marine conditions during MIS 5e is dated at 128 ka ([Shumilovskikh et al., 2013](#)). The  
697 change is progressive contrary to that in core CS18, underlining the possibility of a

698 hiatus in core CS18 at the beginning of the marine phase (see the earlier taphonomy  
699 section) linked to flooding by marine waters. The subsequent peak of nutrients in  
700 core CS18 is possibly due to shore erosion as sea level rose. The very high  
701 percentages of cysts of *P. dalei* and *S. trifida* in zone 22D-4 find no equivalent in  
702 core CS18. The transition from marine to brackish (mixed assemblages) is made  
703 over 20 cm only within zone 22D-5, whereas it is much longer in core CS18 (zone  
704 18D-4, 70.5 cm). These two observations suggest other significant hiatus and deeper  
705 waters in the west that were invaded quickly by saline waters.

706 In the middle of the marine phase, a *Pinus* zone (22P-2, 2042-1982 cm depth,  
707 and 18P-6, 621-581 cm depth) has been recognised in both cores and quantitative  
708 climatic reconstruction (based on pollen) proposed a cool-humid climate not  
709 suggestive of a stadial steppe (Leroy et al., submitted). Due to the presence of the  
710 warm-loving dinocysts before, during and after, this mid-Eemian phase thus has an  
711 ambiguous interpretation. A continental climate in the *Pinus* zone underlined by the  
712 presence of seasonal contrast dinocyst assemblages is nevertheless likely.

713 The end of the marine phase is not presented in core 22-GC3 due to a  
714 turbidite (Wegwerth et al., 2018). The end of the marine phase may however be  
715 studied in the two Marmara cores here and seems to have been progressive with a  
716 period when the two types of dinoflagellate assemblages co-existed (zones 22D-5  
717 and 18D-4), i.e. marine and brackish.

718 It is noteworthy to underline the peaks of *S. trifida* both at the beginning of the  
719 marine phase (zone 18D-3a) and at the end of it (zone 22D-4), in both cases  
720 attributed to fluctuating salinities between marine and brackish-Pontocaspian. At the  
721 end of the marine period in core CS22, in addition, the high values of cysts of *P.*

722 *dalei* may be attributed to terrigenous input, probably related to water level lowering,  
723 as proposed for the Holocene (Verleye et al., 2009).

724 The widely-spaced analyses on core DSDP Site 380 sampled a weakly  
725 marine phase as the occurrence of brackish dinocyst taxa (58%) is quite substantial  
726 (Ferguson et al., 2018). A diagram from DSDP Site 379A has one sample in MIS 5e  
727 (Hoyle et al., 2021). This unique spectrum shows abundance of *L. machaerophorum*  
728 with long processes, *Spiniferites* sp. and some marine taxa. The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio  
729 supports a marine connection at that time. The interglacial periods in the Gulf of  
730 Corinth were generally marine as Global Ocean level is high. In the lithostratigraphic  
731 unit correlated to MIS 5, the surface water conditions were generally warmer as  
732 established by similar warm-loving species to those found in the SoM (Fatourou et  
733 al., 2023).

#### 734 6.3.3 MIS 6 and 4

735 The NMDS analysis shows that MIS 6 and MIS 4 dinocyst assemblages are  
736 clearly different, although both brackish-Pontocaspian (Fig. 8), i.e. more *P. psilata*  
737 and clear presence of *S. inaequalis* and *Caspidinium* in MIS 6, contrasted with more  
738 *S. cruciformis* in MIS 4. Some common points are noted between the MIS 6 and MIS  
739 4 assemblages of the current study and the MIS 3 assemblages of other Marmara  
740 cores (Mudie et al., 2004): all show a mix of dominant brackish-Pontocaspian  
741 dinocysts with some marine ones and all have low to very low cyst concentrations.  
742 The latter may be due to high sedimentation rates diluting the fossil content. Erosion  
743 is active in glacial stages, as seen by the percentages of reworked elements that are  
744 very high in the MIS 6 of core CS18 and in the MIS 4 of cores CS22 and CS18.  
745 Other investigators often do not count them, neither published them, but they are a  
746 significant indicator of erosion and inwash. Often reworking also shows proximity to

747 shores due to low water level. The water level must have been relatively low, most  
748 likely lower than at any time in MIS 5. The brackish-Pontocaspian periods during MIS  
749 5 are clearly different from those of MIS 6 and 4, in that the latter ones have a lot of  
750 reworking and contain abundant signs of erosion (Fig. 3, 4 and 8).

751 Core CS18 in the Imralı basin is not far from the North Imralı canyon that the  
752 Kocasu carved during lowstands (Çağatay et al., 2015a and b). This relative  
753 proximity to a river (if not to the shore) and submarine canyon may also explain the  
754 high amounts of reworked elements and the different taphonomy during the glacial  
755 times (Pope et al., 2022).

756 It is very likely that, as suggested in Hoyle et al. (2021) based on Sr ratio in  
757 the Black Sea, no marine connection occurred during the glacial periods for the SoM.  
758 Several indicators (oxygen isotopes of the Sofular Cave along the Turkish coast of  
759 the Black Sea (Badertscher et al., 2011) and Sr isotope ratio (Hoyle et al., 2021))  
760 suggest an overflow from the Caspian Sea to the Black Sea during MIS 6.  
761 Unfortunately, dinocyst assemblages cannot contribute evidence to this debate on  
762 water source.

763 For MIS 6, a progressive, even slow, freshening after marine conditions in the  
764 previous interglacial (MIS 7) was suggested on the basis of divergent trends in  
765 isotopic values, i.e.  $\delta^{18}\text{O}$  becomes more negative while  $\delta^{13}\text{C}$  becomes more positive  
766 (Çağatay et al., 2009). This may explain why here the marine dinocyst group is  
767 better represented in subzone 18D-1a than subzones 18D-1b and c, even 18D-2.  
768 This also suggests that the base of the core may have just missed the top of MIS 7.  
769 As a significant contribution of reworking of marine palynomorphs (as shown here) is  
770 revealed, no marine connection would have occurred during MIS 6 (zones 18D-1  
771 and 2). For that matter, at the transition from the marine phase to the lake phase at

772 MIS 5 to 4, [Grall et al. \(2014\)](#) and [Aziz et al. \(2019\)](#) suggest slope failure and strong  
773 turbidity currents entraining sediment that was stored on the shelf to deeper areas of  
774 the SoM, as the sea level fell. Recent investigations (modern discharge and  
775 geological data) aiming at disentangling the origin of the sediment in the SoM during  
776 low levels have however demonstrated that southern river input was more important  
777 than suspended load through one or both straits ([Hiscott et al., 2021](#)). Moreover, the  
778 latter authors further estimate that river input was higher than mass-wasting events  
779 and shoreface erosion. Nowadays, and most likely in the past, the Kocasu is the  
780 largest southern river and it drains a large basin in NW Anatolia ([Kazancı et al.,](#)  
781 [2004](#)).

782         The water levels in the Black Sea were most likely low during the cold parts of  
783 MIS 6. However, three major meltwater pulses of the Eurasian icesheets occurred;  
784 but it is not known if the lake level rise of the Black Sea was sufficient to cause an  
785 overspill to the SoM although it is likely ([Wegwerth et al., 2019](#)). So far these pulses  
786 cannot be seen in our record. For completeness of the record, it is noteworthy to  
787 underline that the glacials (MIS 6 and 4) in the Gulf of Corinth were generally  
788 brackish ([Fatourou et al., 2023](#)).

## 789 6.4 Sapropels

### 790 *6.4.1 Surface conditions and sapropel formation*

791         The sapropels deposited in SoM during MIS-5 clearly formed under three  
792 different surface water conditions ([Fig. 7](#)). MSAP-2 formed under brackish surface  
793 conditions (except briefly on a few cm within MSAP 2b), MSAP-4 under clearly  
794 marine surface conditions and MSAP-3 in a period of transition from marine to  
795 brackish surface conditions.

796           Although not a perfect fit, the dinocyst concentration increases in each  
797 sapropel. Admittedly dinocysts are only one part of the bloom-forming phytoplankton,  
798 diatoms being the main group. In order to appreciate the amount of other  
799 phytoplankton such as diatoms, the H/A ratio is used as an indicator of primary  
800 productivity, as heterotrophic dinoflagellate prey on diatoms (see [Triantaphyllou et](#)  
801 [al., 2009](#); [Sala-Perez et al., 2020](#)). The results show higher H/A ratio, thus higher  
802 palaeoproductivity, during the marine phase in MIS 5e in core CS18, especially in  
803 MSAP-4 ([Fig. 9](#)). The diatom assemblages (only available for MSAP-2 in core CS22)  
804 are freshwater-brackish. This H/A ratio is low in MSAP-2b, suggesting low  
805 productivity.

806           The origin of the sapropel formation in the SoM, the decreasing surface  
807 salinities and the decrease of the oxic condition at bottom over MIS 5 may be the  
808 reason why palaeoproductivity based on the H/A ratio is clearly higher in MSAP-4  
809 only.

#### 810 *6.4.2 Bottom conditions and sapropel formation*

811           In core CS22 below MSAP-3, the gradual shift of foraminifera assemblages,  
812 starting with genera needing oxic conditions towards suboxic-tolerant genera, is an  
813 effect of oxygen loss caused by the formation of water column stratification and  
814 organic matter mineralisation ([Fig. 9](#)). It is worth noting that the occurrence of  
815 foraminifera linings is only in the marine period. Accordingly in the marine phase of  
816 core CS22, the linings occur from the core base and stop at the beginning of the  
817 sapropel MSAP-3 at 1920 cm. Their occurrence is similar to that of the foraminifera  
818 shells ([Fig. 9](#)).

819           In contrast, in core CS18, foraminifer linings are present at 725.5-605.5 and  
820 564.5-524.5 cm depth, thus in sapropels MSAP-4 and 3. Moreover foraminifer shell

821 distribution (Çağatay et al., 2019) (Fig. 9) is like that for the linings, although  
822 somewhat shorter. In core CS18, shells are found in the first part of MSAP-4 and  
823 between MSAP-4 and 3.

824 This foraminifera distribution in the sapropels is therefore questioning the  
825 existence of full anoxia in MSAP-4 (core CS18) and in part of MSAP-3 (mostly in  
826 core CS18, no foraminifera in core CS22). For MSAP-2, it is unclear whether the  
827 deep water remained sufficiently saline for benthic foraminifera to live.

#### 828 *6.4.3 Sapropel trigger in the Sea of Marmara*

829 Combining the information from bottom and surface conditions (especially  
830 dinocysts, foraminifera shells and organic linings), it may be shown that the four  
831 Marmara sapropels (4, 3, 2b and 2a) clearly formed over times with decreasing  
832 marine influence and increasing stratification. Moreover they are different from each  
833 other. Only MSAP-2 may have had fully anoxic conditions during the whole sapropel  
834 time.

835 The difference between the two cores may be possibly explained by the  
836 shallower position of core CS18 in comparison to core CS22. The water depth  
837 difference is 260 m, adding another c. 14 m (at the end of MSAP-3) due to core  
838 depth difference, thus a total of c. 274 m difference (Fig. 9). The location of the  
839 shallower core CS 18 would make it harder to fall within the depths affected by full  
840 anoxia and would justify the occurrence of foraminifera in MSAP-4 and 3 in a dysoxic  
841 area. Our results also show that the anoxia did not rise up to 291 m water depth. In  
842 the east Mediterranean Sea, sapropels S5 (MIS5e) and S6 (MIS 6e) contained  
843 foraminifera. It is interesting to note that during MSAP-1 suboxic conditions extended  
844 over the shelf to depths of -75 m (Çağatay et al., 2009). These results (and the  
845 difference between cores CS22 and CS18) may be important to further understand



846 anoxia (or euxinia) development during the Eemian sapropel formation in the Black  
847 Sea, where it has been shown to be stronger than the Holocene one ([Wegwerth et](#)  
848 [al., 2018](#)).

849         The Marmara sapropels occur during warm periods, evidenced in the current  
850 joint pollen-dinocyst investigation i.e. Eemian, Saint-Germain I and II, which more  
851 likely facilitated algal blooms. Consequently, the proposed correlation between the  
852 Marmara sapropels and the Mediterranean sapropels becomes: MSAP-4 – S5,  
853 MSAP-3 – S5 too, MSAP 2b – S4 and MSAP-2a – S3 ([Fig. 9](#)), based on ages ([Grant](#)  
854 [et al., 2016](#)). The Marmara sapropels do not seem to be preconditioned by  
855 astronomical forcing as for the Mediterranean ones ([Rohling et al., 2015](#); [Grant et al.,](#)  
856 [2016](#)). Thus further to the astronomical cause of sapropel formation in the  
857 Mediterranean Sea, other sapropel formation triggers may be sought for the SoM. A  
858 specific trigger mechanism in the SoM is an inflow of marine water causing water  
859 column stratification ([Çağatay et al., 2009](#)).

## 860 6.5 Terrestrial and marine transitions in the Marmara and the Black seas

861         Understanding the facies transitions in the SoM or Lake requires taking into  
862 account the hydrodynamic processes and how they control sediment deposition and  
863 erosion in the straights. Obviously, the outflow from the Black Sea to the Sea of  
864 Marmara is governed by river inputs to the Black Sea and evaporation/precipitation.  
865 When the water budget of the Black Sea is positive, it will inevitably overflow into the  
866 SoM and then most likely into the Mediterranean Sea as the SoM has a  
867 comparatively small surface area for evaporation. On the other hand, the occurrence  
868 of a counter current of sea water from the Mediterranean Sea to the SoM when sea  
869 level is above the Dardanelles Strait and to the SoM to the Black Sea when sea  
870 level is above the Bosphorus Sill cannot be taken for granted. For instance, in the

871 present day with a sill depth of -35 m in the Bosphorus Strait, the seawater bottom  
872 current is blocked when the surface current exceeds  $30,000 \text{ m}^3 \cdot \text{s}^{-1}$  (Sannino et al.,  
873 2017). This situation occurs during transient events in the present conditions, but  
874 more generally the hydrodynamics of the straits implies that the influx of seawater  
875 is a function of water depth at the sill and of the freshwater outflow, which is in turn  
876 governed by river inputs and evaporation/precipitation. Moreover, in steady state, the  
877 only way out for seawater entering the Dardanelles Strait is by mixing with the  
878 fresher surface water layer in the SoM or in the Black Sea. In the present day, and  
879 considering yearly averages, the bottom current flux through the Dardanelles  
880 Strait is only about 12 % larger than the bottom current flux through the Bosphorus  
881 Strait (Beşiktepe et al., 1994). It follows that the halt of northward flux through the  
882 Bosphorus Strait would also greatly reduce the seawater flux into the SoM and  
883 thus increase the residence time of the SoM bottom water. The residence time of  
884 deep water in the SoM varies from two years in the Tekirdag and the Central Basin  
885 to 10-20 years in Çınarcık Basin (Beşiktepe et al., 1994), and this causes an  
886 eastward decrease of oxygen concentration from  $60$  to  $8 \mu\text{mol l}^{-1}$  (Henry et al.,  
887 2007). Increasing the residence time will further reduce oxygen content, which may  
888 in turn favour sapropel deposition.

889 Variations of sill elevation depend on tectonic movements, erosion and  
890 sedimentation. The shores of the Dardanelles Strait have been uplifting at a rate  
891 estimated in the  $0.25\text{-}0.75 \text{ mm yr}^{-1}$  range (Yaltırak et al., 2002). This may suggest  
892 that the level of the sill has risen with time. However, the Dardanelles Strait is at  
893 least in part structurally controlled (Yaltırak et al., 2000; Gökaşan et al., 2008) and  
894 active faults along part of its shore may locally cause subsidence of the channel  
895 floor. Two sedimentary units have been deposited on an erosional surface cutting

896 through Miocene and Pliocene sediments and their geometry gives clear indications  
897 on the erosion and sedimentation processes ([Gökaşan et al., 2008](#)). The lower unit  
898 is thickest (up to 80 m) at the mouths of rivers discharging in the Dardanelles  
899 Straight where they formed deltas that were subsequently incised. The upper unit is  
900 composed of Holocene sediment drifts that are thickest where the channel is wide  
901 and are incised by the active bottom current in the narrow parts. It thus appears that  
902 the strength of the bottom current in the Dardanelles Straight, which is in the  
903 present-day conditions controlled by the dynamics of the Bosphorus Straight,  
904 redistributes sediments and prevents clogging of the channel. All the above  
905 observations and reasoning leads to hypothesize that the interruption of the  
906 northward flux through the Bosphorus Straight leads to the restriction of the  
907 Dardanelles channel by deltas forming at the mouths of local rivers. In the  
908 Dardanelles Straight, the current sill depth is defined by the top of Unit I at -65 m  
909 while the basement sill is at -85 m and in the Bosphorus Straight, the present-day sill  
910 depth is at -35 m while the basement sill is at -70 m ([Çağatay et al., 2009](#)).

911 In core CS18, the brackish to marine transition occurs still within the Saalian  
912 Glacial (c. MIS 6), i.e. before the development of the thermophilic vegetation of the  
913 Eemian Interglacial. Moreover, the end of the marine phase occurs before the end of  
914 Eemian Interglacial in both cores. This offset is in line with the observation that the  
915 Eemian Interglacial and the MIS 5e are not exactly synchronous, with the Global  
916 Ocean level rising first, followed by vegetation changes ([Shackleton et al., 2003](#)).

917 In the SE Black Sea (core 22-GC3), the marine influence however starts only  
918 at 128 ka (or 815.5 cm depth) between *Quercus-robur*-type zone (22GC-E1) and the  
919 *Juniperus* zone (22GC-E2), i.e. well into the interglacial ([Shumilovskikh et al., 2013](#));  
920 whereas here in core CS18 it starts earlier at 756 cm depth, i.e. in the middle of zone

921 18P-2 dominated by *Artemisia* and that is probably still part of the Saalian Glacial.  
922 Although a large difference between the SoM and the Black Sea palynological  
923 diagrams, this can be explained by the marine inflow that has first to penetrate the  
924 SoM from the Aegean Sea and cross two sills, before reaching the Black Sea. For  
925 comparison, a delay of 4-6 ka has been observed for the Lateglacial-Holocene, with  
926 a marine incursion in the SoM starting at 14.7 ka followed by progressive salinisation  
927 with a facies transition defined at 12.6 ka (Vidal et al., 2010; Çağatay et al., 2015)  
928 and in the Black Sea at 8.9-8.3 ka (Shumilovskikh et al., 2013; Mudie et al., 2014;  
929 Yakupoğlu et al., 2022). This lag has been explained by the difference in sill depth  
930 between the Bosphorus and the Dardanelles Straights, the Bosphorus one being  
931 close to its present-day level (-35 m) at the time of reconnection and the Dardanelles  
932 one being somewhat deeper ( $-75 \pm 5$  m) than its present-day level. The situation  
933 during the MIS 6 to 5 transition may have been similar with a Bosphorus Strait at  
934 about -40 m (Çağatay et al., 2019). The early marine incursion in the SoM at the end  
935 of MIS stage 6 indicates that the Dardanelles sill depth was also deeper at that time.

936 A new result from the present study that remains to be explained is the  
937 prevalence of brackish Ponto-Caspian conditions in surface water during the later  
938 phases of MIS 5 at times when sea level was well above the present-day  
939 Dardanelles sill level (Fig. 9). The explanation we propose is that the Bosphorus  
940 northward flow was first decreased then interrupted as sea level started decreasing  
941 before the end of MIS 5e, and that resulted in a progressive reduction of seawater  
942 inflow through the Dardanelles Strait. This decreased oxygen availability in the  
943 marine deep waters, as indicated by foraminifer assemblages, eventually enabled  
944 the sediment filling of the channel by local rivers, further limiting marine input. Low  
945 and/or episodic sea-water inputs during the later part of MIS 5 may have maintained

946 stratified conditions in the SoM with low salinity surface waters and nearly anoxic  
947 bottom water of intermediate salinity. Sea level drop during MIS 5d and 5b  
948 presumably interrupted the marine inflow, lowering the vertical salinity contrast and  
949 allowing better oxygenation of the deep waters. During the following glacial  
950 lowstands (MIS 4-3-2), the Marmara lake remained isolated and outflow (either  
951 permanent or episodic) may have incised the sedimentary deposits to allow  
952 reconnection at  $\approx$ -75 m at the end of the glaciation.

953         The  $\delta^{18}\text{O}$  of the well-dated Sofular stalagmite record reflects salinity of the  
954 Black Sea surface waters by way of evaporation and moisture availability  
955 ([Badertscher et al., 2011](#)). These authors propose one clear period of connection  
956 between the Black Sea and the Mediterranean Sea at roughly MIS 5e based on a  
957 threshold of  $-8.5 \pm 1\text{‰}$   $\delta^{18}\text{O}$  values. The next period below that threshold is at MIS 5c  
958 and also suggests connection but for a shorter period. The last period at MIS 5a  
959 would not have led to sufficiently high water levels to allow flowing of the  
960 Mediterranean marine waters into the Black Sea. This fits rather well our results in  
961 the SoM, with a full surface water connection at MIS 5e when global sea level  
962 reached 8 m above sea level, a marine incursion affecting surface waters during MIS  
963 5c when global sea level reached 24 m below sea level and no incursion during MIS  
964 5a when global sea level reached only 28 m below sea level ([Rohling et al., 2021](#)).

## 965 **7 Conclusions**

966         The results of this investigation have shown the widely changing states of the  
967 Sea of Marmara during the MIS 6 and 5, implying vastly changing connexions with  
968 the Pontocaspian basin and the Global Ocean.

969 From the methodological point of view, as for the Caspian Sea ([Leroy et al.,](#)  
970 [2013, 2014](#)) when using the palynological method (pollen and dinocysts), it is  
971 essential to study separately and objectively the terrestrial conditions and the aquatic  
972 ones. A comparison of the two approaches may then clearly demonstrate if the  
973 changes are synchronous or not, and if different forcing factors are at play.

974 As demonstrated for the Iberian margin by pollen and isotopic analyses, the  
975 Eemian starts and finishes respectively after the start and after the end of MIS 5e  
976 high levels. The same offset can be demonstrated here in this joint pollen - dinocyst  
977 study.

978 The combination of the two sequences, CS22 and CS18, following the  
979 chronology proposed in [Leroy et al. \(submitted\)](#), allows highlighting one main marine  
980 phase corresponding to MIS 5e (marine surface and bottom conditions) and a minor  
981 one (mixed surface conditions) in MIS5c. The rest of the record is brackish-  
982 Pontocaspian although with some differences across the sequence (e.g. MIS 6  
983 versus MIS 4). Based on climatic data (pollen) allowing linking the records, a delay in  
984 the marine influence between SoM and SE Black Sea is observed, perhaps due to  
985 the closure of the Bosphorus Sill and its late opening or a different sill height.

986 The current water level reconstruction corresponds well to the Global Ocean  
987 level curve and Black Sea salinity reconstructions, both indicating progressively  
988 lower high stands (i.e. from MIS 5e to 5a) and decreasing connections between the  
989 Black Sea and the SoM across MIS 5.

990 The four sapropels (MSAP-4, 3, 2a and 2b) formed under very different  
991 surface water conditions ranging from marine to brackish-Pontocaspian, but always  
992 under a warm climate. Moreover, the shallower site (CS18) in the east (Imralı basin)  
993 does not form as often full anoxia than the western and deeper site (CS22). For

994 example: the top limit of the bottom anoxia in sapropel MSAP-4 would not have  
995 reached 291 m water depth (location of core CS18).

996 In the future, it would be interesting to apply palynological investigations  
997 (pollen and dinocysts) on long cores on both sides of the Bosphorus Strait to define  
998 better for example the timing difference for the marine reconnection at the boundary  
999 MIS 6-5.

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## 1011 **Data availability**

1012 The dinocyst data are available in PANGEA.

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22/03/2023

1302 **Supplementary information**

1303 **Table SI1:** Benthic foraminifera census data in nine samples from core CS22

Core CS22												
benthic foraminifera census data		depth (cm)	1631	1632	1915	1935	1955	1975	1995	2015	2035	
shallow-water species	<i>Ammonia parkinsoniana</i>				2							
	<i>Ammonia</i> sp						1					
	<i>Discorbinella bertheloti</i>								1	3	3	
	<i>Elphidium</i> sp				1							
	<i>Haynesina depressula</i>				5							
	<i>Rosalina</i> sp							1		1	2	
	<i>Porosonion granosum</i>				1							
hyaline bathyal species	<i>Amphicoryna scalaris</i>								1			
	<i>Bolivinita quadrilatera</i>							1				
	<i>Bolivina striatula</i>										2	
	<i>Bolivina alata</i>					64	371	101				
	<i>Bolivina dilatata</i>					16	4	5			1	
	<i>Bolivina spathulata</i>					1	2	78	9	7	2	
	<i>Bulimina aculeata</i>						5	6	8	11	5	
	<i>Bulimina inflata</i>							1	4	151	235	115
	<i>Bulimina elongata</i>					7	6	5			1	1
	<i>Bulimina marginata</i>					98	5	1	3	4	1	
	<i>Bulimina</i> sp									7	2	
	<i>Cassidulina carinata</i>					15	2	8	32	9		
	<i>Cassidulina obtusa</i>											2
	<i>Chilostomella oolina</i>									2	3	7
	<i>Chilostomella ovoidea</i>							11	10	3		
	<i>Chilostomella</i> sp							3				
	<i>Cibicidoides pachyderma</i>							1	6	35	15	
	<i>Cibicidoides pseudoungerianus</i>									7		1
	<i>Cibicidoides</i> sp								1	8		2
	<i>Dentalina</i> sp										1	
	<i>Fissurina staphyllearia</i>									1		
	<i>Globobulimina</i> spp								1		3	
	<i>Globocassidulina oblonga</i>									1	2	8
	<i>Gyroldinoidea lamarckiana</i>						1		2	17	10	24
	<i>Gyroldinoidea soldanii</i>										1	
	<i>Hyalinea balthica</i>				1	105	9	27	108	8		
	<i>Lagena</i> spp										2	2
	<i>Lenticulina calcar</i>										1	9
	<i>Lenticulina</i> sp					1						
	<i>Melonis affinis</i>					8	1	23	44	3	5	
	<i>Melonis pompilioides</i>					8		9	15	9	10	
	<i>Neolenticulina variabilis</i>											1
	<i>Nonionella turgida</i>											1
	<i>Planulina ariminensis</i>								20	45	13	35
	<i>Pullenia quadriloba</i>											6
	<i>Robertina</i> sp									1		
	<i>Robertina translucens</i>										1	1
<i>Saracenaria</i> sp											3	
<i>Siphogenerina columellaris</i>											1	
<i>Siphonina</i> sp											1	
<i>Sphaeroidina bulloides</i>									2		2	
<i>Stainforthia concava</i>					3							
<i>Uvigerina mediterranea</i>									12		1	
<i>Uvigerina peregrina</i>								4	3	6	7	
<i>Valvulineria bradyana</i>								13	2	11	1	
porcelaneous species	<i>Adelosina</i> sp								1		1	
	<i>Articulina tubulosa</i>									1	2	
	<i>Biloculinella</i> sp										11	
	<i>Comuloculina foliacea</i>									2		
	<i>Pyrgo depressa</i>								1	2	2	
	<i>Pyrgo elongata</i>									2	4	
	<i>Pyrgoella irregularis</i>							1	2			
	<i>Quinqueloculina padana</i>							2	2	2	11	
	<i>Quinqueloculina stelligera</i>							1	2		3	
	<i>Quinqueloculina</i> sp									2	8	
	<i>Sigmoilopsis schlumbergeri</i>					1		1	1	3	1	
	<i>Siphonaperta</i> sp								1			
	<i>Spiroloculina excavata</i>									2	1	
	<i>Triloculina tricarinata</i>									2		
<i>Triloculina</i> sp										1		
<i>Textularia</i> spp											2	
unidentified species				4	4	1			2	1	2	
total number of counted foraminifera	0	0	14	332	423	331	535	377	310			
total number of shallow water individuals	0	0	9	0	1	1	1	4	5			
total number of bathyal individuals	0	0	5	332	422	330	534	373	305			
BFN (bathyal species only, ind.g <sup>-1</sup> )	0	0	0	386	30	209	277	459	194			
S (number of bathyal taxa)	0	0	1	13	13	24	34	30	40			

1305 **Table SI2:** Ecological assignment of main foraminiferal species in core CS22  
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<b>Species adapted to high oxygen conditions (HO)</b>	
<i>Cibicidoides</i> spp	
<i>Gyroidina lamarckiana</i>	
Miliolids excluding <i>Articulina tubulosa</i>	
<b>Low-oxygen indicators (LO)</b>	
<i>Chilostomella</i> spp	
<i>Globobulimina</i> spp	
<i>Stainforthia concava</i>	
<b>Species adapted to high organic fluxes (eutrophic indicators)</b>	
<u>adapted to low oxygenation</u>	
<i>Bolivina alata</i>	
<i>Bolivina dilatata</i>	
<i>Bolivina spathulata</i>	
<u>not tolerant to low oxygenation</u>	
<i>Bulimina marginata</i>	
<i>Hyalinea balthica</i>	
(after Cornuault et al. 2016 and references therein; Fontanier et al. 2016)	

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1315 **Table SI3:** Comparative list of taxa between the Marmara Sea (cores CS22 and  
 1316 CS18) and the SE Black Sea (core 22-GC3; [Shumilovskikh et al., 2013](#)).

	CS22	CS18	22-GC3	
	Pyxidinoopsis psilata, <b>Spiniferites cruciformis/Galeacysta etrusca,</b>	Pyxidinoopsis psilata, <b>Spiniferites cruciformis/Galeacysta etrusca,</b> <b>Galeacysta etrusca,</b>	Pyxidinoopsis psilata,	VV
	S. cruciformis A, S. cruciformis B, S. cruciformis C,	S. cruciformis A, S. cruciformis B, S. cruciformis C,	S. cruciformis, S. cruciformis, S. cruciformis,	0
	<b>S. Inaequalis,</b>	<b>Pterocysta cruciformis,</b> <b>S. Inaequalis,</b>		0
		<b>Romanodinium areolatum,</b> Caspidinium rugosum, <b>C. rugosum rugosum,</b> <b>Impagidinium sp. A,</b> <b>I. caspiense,</b>	Caspidinium rugosum,	VV
				0
6/13				only in MIS6
				only in MIS6
				0
	Lingulodinium machaerophorum ss,	Lingulodinium machaerophorum ss, <b>L. machaerophorum B,</b> <b>L. mach. bulbous,</b>	Lingulodinium machaerophorum,	0
1/3				0
		Dubridinium caperatum, <b>Lejeunecysta marieae,</b>	Dubridinium caperatum,	0
			<b>Lejeunecysta sabrina?</b> <b>Quinquecuspis sp.</b> <b>Quinquecuspis concreta</b>	0
	Votadinium calvum, Brown baggy cyst,	Votadinium calvum, Brown baggy cyst,	Votadinium calvum, Brigantodinium sp. <b>B. cariaceense</b> <b>B. simplex</b> <b>C. Gymnodinium microret./nolleri</b>	VV
				V
				V
	Xandarodinium xanthum, C. Protoperidinium nudum, <b>C. Polykrikos hartmanii,</b>	Xandarodinium xanthum, C. Protoperidinium nudum, C. Protoperidinium stellatum, <b>C. Polykrikos hartmanii,</b>	Xandarodinium xanthum, C. Protoperidinium cf nudum C. Protoperidinium stellatum, <b>C. Polykrikos schwartzii</b> <b>Echinidinium sp.</b> <b>E. zonneveldiae</b>	0
5/8				0
	S. belerius, S. bentorii,	S. belerius, S. bentorii,	S. belerius, S. bentorii, <b>S. bulloideus</b>	0
	S. elongatus, <b>S. halnanensis,</b>		S. elongatus, <b>S. hyperacanthus</b> <b>S. membranaceus</b>	V
				VV
	S. ramosus, S. septentrionalis, Spiniferites sp., S. mirabilis, S. pachydermus, <b>Polysphaeridium zoharyi,</b> Tuberculodinium vancampoae, Operculodinium israelianum, O. centrocarpum, Ataxodinium choane, Bitectatodinium tepikiense, Tectatodinium pellitum, C. Pentapharsodinium dalei, <b>C. Scripsiella trifida,</b> <b>Pyxidinoopsis reticulata,</b>	S. ramosus, S. septentrionalis, Spiniferites sp., S. mirabilis, <b>Polysphaeridium zoharyi,</b> Tuberculodinium vancampoae, Operculodinium israelianum, O. centrocarpum, Ataxodinium choane, Bitectatodinium tepikiense, Tectatodinium pellitum, C. Pentapharsodinium dalei, <b>C. Alexandrium sp.,</b> <b>C. Scripsiella trifida,</b>	S. ramosus, S. septentrionalis, Spiniferites sp., S. mirabilis, S. pachydermus, Tuberculodinium vancampoae, O. centrocarpum, Ataxodinium choane, Bitectatodinium tepikiense, Tectatodinium pellitum, C. Pentapharsodinium dalei, <b>Achomosphaera cf andalousiense</b>	VV
				0
				VV
				0
21/17	Nematosphaeropsis labyrinthus,	Nematosphaeropsis labyrinthus,	Nematosphaeropsis labyrinthus, <b>Achomosphaera cf andalousiense</b>	VV
	33	41		
				0 = insignificant
				V = different
				VV = very different

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22 March 2023

We have no competing interests

Dinocyst assemblages and water surface conditions in the Sea of  
Marmara during MIS 6 and 5 from two long cores

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