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Large-scale response of the Eastern Mediterranean thermohaline circulation to African monsoon intensification during sapropel S1 formation

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Abstract :

The formation of Eastern Mediterranean sapropels has periodically occurred during intensification of northern hemisphere monsoon precipitation over North Africa. However, the large-scale response of the Eastern Mediterranean thermohaline circulation during these monsoon-fuelled freshening episodes is poorly constrained. Here, we investigate the formation of the youngest sapropel (S1) along an across-slope transect in the Adriatic Sea. Foraminifera-based oxygen index, redox-sensitive elements and biogeochemical parameters reveal – for the first time – that the Adriatic S1 was synchronous with the deposition of south-eastern Mediterranean S1 beds. Proxies of paleo thermohaline currents indicate that the bottom-hugging North Adriatic Dense Water (NAdDW) suddenly decreased at the sapropel onset simultaneously with the maximum freshening of the Levantine Sea during the African Humid Period. We conclude that the lack of the “salty” Levantine Intermediate Water hampered the preconditioning of the northern Adriatic waters necessary for the NAdDW formation prior to the winter cooling. Consequently, a weak NAdDW limited in turn the Eastern Mediterranean Deep Water (EMDWAdriatic) formation with important consequences for the ventilation of the Ionian basin as well. Our results highlight the importance of the Adriatic for the deep water ventilation and the interdependence among the major eastern Mediterranean water masses whose destabilization exerted first-order control on S1 deposition.

Highlights

► The Adriatic S1 is coeval with the Eastern Mediterranean S1 deposits. ► The Adriatic S1 onset is synchronous with the shutdown of the NAdDW. ► African monsoons weakened the LIW which in turn hampered the NAdDW formation.

Keywords : Sapropel S1, Mediterranean sea, African monsoons, Anoxia, Thermohaline circulation

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53 **1. Introduction**

54 Periodic perturbations of marine ecology and geochemistry have occurred in the eastern
55 Mediterranean Sea (EMS) since the late Miocene (Nijenhuis et al., 1996). Signs of these changes are
56 preserved in the sediment record as organic carbon-rich deposits commonly known as sapropels. In this
57 study we focus on the most recent sapropel (S1) which formed during the last post-glacial eustatic rise (ca.
58 10-6 cal kyr BP (De Lange et al., 2008; Hennekam et al., 2014; Schmiedl et al., 2010). It is now largely
59 accepted (Rohling et al., 2015) that favourable conditions for S1 formation were associated with anoxic
60 bottom waters that developed during periods of insolation maxima (Hilgen, 1991; Rossignol-Strick, 1985;
61 Rossignol-Strick et al., 1982). The resulting effect of these orbital variations was the northward migration
62 of the African monsoons resulting in higher precipitation over the Nile river watershed which in turn
63 enhanced the freshwater supply to the EMS-southeastern Mediterranean Sea (Hennekam et al., 2014;
64 Weldeab et al., 2014). In addition, the mid-Holocene increase of river runoff from northern borderlands
65 and the post-glacial inflow of less saline Atlantic waters have further contributed to maintaining reduced
66 surface water salinities and high nutrient concentrations in the euphotic zone (Grimm et al., 2015;
67 Kotthoff et al., 2008; Spötl et al., 2010; Toucanne et al., 2015). To date, whether and to what degree either
68 water stratification or enhanced primary productivity has resulted in anoxic bottom waters is still a matter
69 of debate despite several decades of extensive study (Calvert et al., 1992; De Lange et al., 2008; Grimm et
70 al., 2015; Sachs and Repeta, 1999).

71 A survey of the current literature dealing with S1 reveals that most of the focus has been placed on
72 south-eastern Mediterranean sediments while the Adriatic Sea – that today plays a first-order control on
73 Eastern Mediterranean ventilation (Klein et al., 2000) – has received markedly less interest. In particular,

74 it has been suggested (Rohling et al., 1997; Rohling et al., 2015) that the onset of critical oxygen
75 conditions in the Adriatic (ca. 8.8 cal. ky BP) lagged behind the fairly synchronous anoxia which
76 developed over the rest of the EMS (ca. 10 cal. ky BP) (De Lange et al., 2008; Schmiedl et al., 2010). This
77 implies that the ventilation regime under which the Adriatic sapropel formed must have been necessarily
78 different compared to the south-eastern Mediterranean sapropels. In particular, it was inferred that
79 persistent ventilation in the Adriatic during the early stage of ~~the~~ sapropel formation hampered the initial
80 development of oxygen-depleted conditions justifying the delayed S1 onset in respect to the rest of the
81 EMS (Mercone et al., 2000; Rohling et al., 2015).

82 This high-resolution (decadal-~~millennial~~centennial) study aims at testing this hypothesis by
83 reconstructing the oceanographic regime under which Adriatic sapropels formed. Our analysis builds on
84 three well-dated sediment cores collected in three different water depths from the shelf to the deep basin
85 (Fig. 1 and 2). With the objective of understanding timing and conditions which promoted anoxic bottom
86 waters, we present a suite of complementary analyses which include foraminifera assemblages, inorganic
87 elemental composition and organic matter composition. The relatively young age of S1 makes it an ideal
88 target to develop a precise radiocarbon-based Bayesian age model across the three sites establishing also a
89 robust chronological link to other S1 ~~deposits~~deposits across the EMS. Thus, by identifying coeval and
90 genetically linked ~~deposits~~strata, we will evaluate the necessary conditions leading to the sapropel S1
91 formation in Adriatic sediments and test to what extent these prerequisites are linked to the deposition of
92 sapropel beds in the rest of the EMS.

93

94 **2. Material and methods**

95 **2.1 Sediment cores**

96 The dataset presented here consists of three piston cores retrieved in the Adriatic Sea with variable
97 barrel lengths (5–20 m) (Fig.1 and 2). Core AMC99-1 (45°51'.80 N & 14°45'.68 E, 260 m; Fig. 1) was
98 collected in the central Adriatic basin from the bottom of the mid-Adriatic depression (MAD, Fig. 2b).

99 Core INVAS12-10 (41°30'.25 N & 17°10'.78 E, 570m; Fig 3) and core SA03-1 (41°30'.25 N &
100 17°10'.78 E, 567 m) were collected 5 m apart from each other (i.e., twin cores; Fig. 1 and 2c) in the
101 southwest Adriatic slope. Finally, core ST04-1 (41°27'.46 N & 17°31'.05 E, 1085 m; Fig. 3) was retrieved
102 in the deep basin plain of the south-western Adriatic Sea (Fig. 1 and Fig. 2c).

103

104 **2.2 Seismic acquisition and core handling**

105 The seismic dataset used in this study has been collected by ISMAR-CNR (Bologna) on board R/V
106 Urania, in the last two decades. Seismic data were acquired with a hull-mounted Chirp-Sonar Profiler with
107 16 transducers, characterized by 2–7 kHz sweep-modulated bandwidth, equivalent to a 3.5 kHz profiler,
108 with a recording length up to 1500 ms, depending on water depth, and a penetration of 50–100 m, with
109 vertical resolution of ca. 0.5 m. Track line positioning was based on differential GPS navigation, assuring
110 a position accuracy of 10 m and transformed to geographic coordinates referred to the ED-50 datum.

111

112 **2.3 Digital x-ray radiograph**

113 Prior to subsampling, cores were x-rayed using a Gilardoni MPX160 as a source and an amorphous 30 cm
114 long silicon (a-Si) flat panel sensor as a detector (Kodak) typically exposed at 70 kV and 5 mA for ca. 6.4
115 s. For each digital image the pixel dimension is 125 µm and resolution is 1932×2348 pixels.

116

117 **2.3.4 Foraminifera**

118 Sediment samples (1-cm thick interval) were oven dried at 50°C, washed through a 63 µm sieve and
119 dried again at 50°C. Each sample was subsequently split into aliquots using a Jones microsplitter. Aliquots
120 were counted to reach at least 300 specimens of planktonic foraminifera and 300 specimens of benthic
121 foraminifera. In anoxic beds only planktonic foraminifera were observed. The quantitative study was
122 performed on the fraction >10660µm to avoid juvenile specimens, consistent with the existing Adriatic

123 literature (Favaretto et al., 2008; Narciso et al., 2012; Piva et al., 2008). However, the <1606 μm fraction
124 was always checked in order to identify those specimens which can pass the mesh because of an elongated
125 shape of their shell (e.g. *Fursenkoina*) or because of the small size of their adult stage (e.g. *Epistominella*).

126 -Foraminifera concentration is reported as the number of specimens per gram of dry sediment. Data
127 were then integrated with previous published studies (core SA03-1 and AMC99-1; (Favaretto et al., 2008;
128 Narciso et al., 2012; Piva et al., 2008)) to gain higher resolution within the time interval studied.
129 Specifically, twenty-two new samples from SA03-01 were merged with published data (Favaretto et al.,
130 2008; Narciso et al., 2012) while 42 new samples from core AMC99-1 were integrated with data
131 published (Piva, 2007; Piva et al., 2008). Finally, fifty-three samples of core INVAS12-10 were examined
132 with a semi-quantitative analysis to identify key levels (bioevents) for stratigraphic and chronologic
133 purposes (i.e., correlation with the sister core SA03-1), as all geochemical analyses were performed on
134 core INVAS12-10.

135 The Oxygen Index (OI) (Schmiedl et al., 2003) was used to provide a general trend of bottom
136 oxygen conditions. It is calculated as $(HO/(HO+LO)+Div) \times 0.5$ where HO is the relative abundance of
137 high oxygen indicators (*Miliolids*, *Articulina tubulosa*+*Cibicidoides pachydermus*+*Gyroidinoides*
138 *orbicularis*), LO is the relative abundance of low oxygen indicators (*Fursenkoina* spp., *Chilostomella*
139 *oolina*, *Globobulimina* spp.), and Div is the normalized benthic foraminiferal diversity H(S). The term is
140 multiplied by 0.5 to distinguish between anoxic (minimum value = 0) and oxic (maximum value = 1)
141 conditions (Schmiedl et al., 2010; Schmiedl et al., 2003). The index has been calculated for cores ST04-1
142 and SA03-1, while for core AMC99-1 the term LO (=species of the group A by (Jorissen, 1999) with a
143 deep infaunal microhabitat, especially resistant to low oxygen conditions), has been replaced by the
144 infaunal benthonic taxa of the group B by Jorissen (1999), that is *Bolivina* spp/*Brizalina* spp, *Bulimina*
145 *costata/ inflata* and *Uvigerina peregrina*, with an infaunal microhabitat, more opportunistic than the
146 species of group A , but less resistant for low oxygen conditions (Schmiedl et al., 2003) because deep
147 infaunal species were absent, or near-absent, during the time equivalent to the Sapropel 1a deposition, as

148 already reported in the central Adriatic by Ariztegui et al. (2000). The absence/near-absence of species of
149 the LO term would have resulted into not realistic values indicating highly oxygenated bottom condition
150 in the OI index during the Sapropel 1a interval, making necessary the use of the abundant taxa of group B.

151 Reworked species used as bottom current proxy include the modern living inner-shelf species such
152 as *Ammonia* spp, *Elphidium* spp, *Haynesina* spp. and epiphytic species (*Asterigerinata* spp, *Buccella*
153 *granulata*, *Patellina corrugata*) (Jorissen, 1988) corresponding to Biofacies II and III in the Adriatic. We
154 interpret the presence of these displaced species by sediment shedding from shallower waters (Trincardi et
155 al., 2007), in particular from outer-shelf coarser/sandy (Spagnoli et al., 2010) deposits formed during the
156 LGM and presently swept by NAdDW. The Oxygen Index (Schmiedl et al., 2003) has been calculated for
157 cores ST04-1 and SA03-1, while for core AMC99-1 the term LO (=low oxygen indicators, corresponding
158 to the deep infaunal benthonic species (Jorissen, 1999)) has been replaced by infaunal benthonic species
159 (*Bolivina* spp/*Brizalina* spp, *Bulimina costata/inflata* and *Uvigerina peregrina*) (Schmiedl et al., 2003) as
160 deep infaunal species were absent. Reworked species used as bottom current proxy include *Ammonia* spp,
161 *Elphidium* spp, and epiphytic species corresponding to Biofacies II and III in Adriatic (Jorissen,
162 1988). We interpret the presence of these displaced species by sediment shedding from shallower waters
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169 ~~al., 2007), in particular from outer-shelf coarser/sandy (Spagnoli et al., 2010) deposits formed during the~~
170 ~~LGM and presently swept by NAdDW.~~

171 Radiocarbon measurements on monospecific tests (5-7 mg) of the planktonic foraminifer
172 *Globigerinoides ruber* (species living above the thermocline) were performed at the National Ocean

173 Sciences Accelerator Mass Spectrometry (NOSAMS) Facility (USA). On average, 400-600 specimens
174 were hand-picked from the size fraction $> 0.180 \mu\text{m}$. Specimens were ultrasonicated in distilled water to
175 remove potential sediment impurities. For level ST040-1 XII 61-62 cm, the planktonic foraminifer
176 *Globorotalia inflata* was used due to the lack of a sufficient amount of *G. ruber* specimens.

177

178 **2.6.5 X-ray fluorescence (XRF)**

179 The inorganic composition of bulk sediments was characterized using a wavelength dispersive
180 sequential Philips PW2400 XRF spectrometer (Mercone et al., 2001) ~~(at the Department of Geosciences,~~
181 ~~University of Padova)~~. The XRF instrument was operated under vacuum conditions on samples prepared
182 as glass beads using lithium tetraborate and melted with a fluxer Claisse Fluxy (~1150°C). The standard
183 error (based on several measurements of the same sample) is less than 0.6% and 3% for major element and
184 trace elements, respectively. For this study, we focused on selected elements which include Ti, V, Mn and
185 ~~S. Sediments corresponding to tephra layers (characterized by high Zr excess) were analyzed but the data~~
186 ~~are not shown.~~

187

188 **2.7.6 Grain-size**

189 About 3 g of dried sediments were resuspended in a 40 ml solution of sodium metaphosphate
190 (0.6%) and sonicated for 20 minutes at high energy. Prior to the analysis, samples ~~d~~ were wet sieved at 63
191 μm . A few drops of wet samples were checked with the microscope to examine the presence of
192 microfossil remains. ~~P~~Particle size distribution of the $<63 \mu\text{m}$ fraction was measured using a
193 Micromeritics SediGraph™ III 5120, according to the settling velocity method (Bianchi et al., 1999).
194 Sortable silt concentration was calculated as the fraction by weight of the total mass ranging between 10
195 and $63 \mu\text{m}$ (McCave and Hall, 2006).

196

197 **2.8.7 Organic Geochemistry**

198 Samples for organic carbon (OC) content were placed in silver capsules and pre-treated with HCl
199 (1.5 M) to remove the inorganic carbon (Nieuwenhuize et al., 1994). Oven-dry samples were analysed
200 using a Thermo Quest-Finnigan Delta Plus isotope ratio mass spectrometer, directly coupled to a FISOONS
201 NA2000 Elemental Analyzer by means of a CONFLO II interface.

202 Lignin analyses (terrigenous biomarkers) were carried out using a Microwave digestion system
203 (Tesi et al., 2014). Dry samples were placed in Teflon vessels with 8 ml of alkaline solution (2N NaOH),
204 500 mg of CuO, 50 mg of Fe(NH₄)₂(SO₄)₂·6H₂O and oxidized for 1.5 h at 150 °C. After the oxidation, a
205 known amount of recovery standards (ethylvanillin and trans-cinnamic acid) were added to each vessel
206 and acidified to pH 1 with HCl. Reaction products were then extracted with ethyl acetate, evaporated to
207 dryness under N₂ and redissolved in pyridine. Reaction products were analysed as trimethylsilyl
208 derivatives (BSTFA reagent) via GC-MS. Compounds were separated chromatographically in a 30 m×250
209 µm DB1 (0.25 µm film thickness) capillary GC column, using an initial temperature of 100 °C, a
210 temperature ramp of 4 °C min⁻¹ and a final temperature of 300 °C. Phenol biomarkers were quantified
211 using the response factors of commercially available standards (Tesi et al., 2014).

212

213 **3. Chronology**

214 **3.1 Age-depth models**

215 Bayesian age-depth models were performed using the OxCal 4.2 program
216 (<https://c14.arch.ox.ac.uk/embed.php?File=oxcal.html>) and a comprehensive dataset, which includes both
217 ¹⁴C measurements carried out on monospecific foraminifera samples (this study) as well as radiocarbon-
218 dated bioevents based on a detailed event biostratigraphy from each sediment core (Fig. 4 and 5).
219 Radiocarbon age (uncalibrated) of well-known bioevents was based on published studies in the Adriatic
220 (Table 1).

221 Bioevents (uncalibrated) used for the age-depth models include the following planktonic species or
222 planktonic assemblage turnovers (Fig. 4 and Table 1):

223 - Bioevent I (10450 ± 90 ^{14}C yBP), abrupt increase of *Globigerinoides ruber*, a warm-water species
224 ~~signalingsignalling~~ the top of the Younger Dryas dated in core CM92-43 (Asioli et al., 2001). This
225 bioevent marks the end of the Greenland Stadial 1 (GS1) and the beginning of the Holocene (top ecozone
226 V) (Asioli et al., 2001; Asioli et al., 1999; Blockley et al., 2004) and also the top of ecozone 7 (Siani et al.,
227 2010). The GS-1/Holocene transition is also testified by the lowering of the $\delta^{18}\text{O}$ values (Asioli et al.,
228 1999; Jorissen et al., 1993; Narciso et al., 2012; Siani et al., 2000);

229 - Bioevents II and III (9860 ± 60 and 9360 ± 50 ^{14}C yBP, respectively), two peaks in the abundance of
230 *Globorotalia inflata* (i.e., younger and older). These bioevents were described and dated in core SA03-1
231 (Favaretto et al., 2008) before its temporary disappearance at the base of the Sapropel S1;

232 - Bioevent IV (5880 ± 60 ^{14}C yBP), last Occurrence of *G. inflata* dated in core RF93-30 (Trincardi et al.,
233 1996). This is a well-documented bioevent recognized in the whole Adriatic after the sapropel
234 S1 termination (Ariztegui et al., 2000; Asioli et al., 1999; Capotondi et al., 1999; Siani et al., 2010).

235 All ^{14}C dates (new radiocarbon dates and bioevents) were converted to calendar years (cal yr BP)
236 using the latest Marine13 calibration curve (Reimer et al., 2013) in OxCal, prior to calibration, ages were
237 corrected for an extra 136 ± 41 ^{14}C -years regional reservoir effect (ΔR) using the values reported in the
238 Marine Reservoir Correction Database (<http://calib.qub.ac.uk/marine/>). ~~Above the sapropel unit (<5 kyr),~~
239 ~~the age-depth model of AMC99-1 relays on benthic monospecific tests (*Cibicidoides pachyderma*). For~~
240 ~~this reason, Only for core AMC99-1 and above the sapropel deposit, ΔR was set 336 ± 41 an extra 200~~
241 ~~years of reservoir correction was used for these for radiocarbon ages *Cibicidoides pachyderma* (benthic~~
242 ~~species) based according to on the difference offset between planktonic and benthonic organisms~~
243 ~~previously assessed in this core (Piva et al., 2008). Bayesian age-depth model (Lowe et al., 2007; Ramsey,~~
244 ~~1995; Ramsey and Lee, 2013) was implemented using variable rigidity for the Poisson-Process Modeling~~
245 (k variable ranging between 0.01 and 100 cm^{-1}). The Outlier-Model analysis was performed with the

246 *General setting* and the prior probability fixed to 0.05, which weighs down the radiocarbon measurement
247 that have statistical probability of more than 5% of being outliers. The output resulted in robust age
248 models with an overall solid structure of the dated sequence (Fig. 5) as defined by an excellent agreement
249 index (>90%) between calibrated and modelled ages.

250 It is worth mentioning that foraminifera assemblages were studied in SA03-1 core while the rest of
251 the analyses were performed on the sister core INVAS12-10 from the same site (Fig. 1 and 2c) on which
252 we have constructed the age-depth model based on a greater number of radiocarbon measurements. Cross-
253 correlation between twin cores was carried out relying on bioevents and tephra (magnetic susceptibility
254 anomalies). Events in chronological order include: top of the Younger Dryas, two *G. inflata* peaks (during
255 the Pre Boreal), peak of *C. bradyi*, a large magnetic susceptibility peak marking a tephra layer, two *G.*
256 *inflata* peaks (during S1 break and S1b, respectively) and the Last Occurrence of *G. inflata* (Fig. 4). Ages
257 between midpoints were estimated via linear interpolation.

258

259 **~~3.2. Comparison between stratigraphic records from the southern Adriatic basin~~**

260 ~~Prior studies have investigated the S1 in the southern Adriatic basin in the following cores: IN68-9~~
261 ~~(Jorissen et al., 1993; Rohling et al., 1997; Van Straaten, 1970), MD90-197 (Mereone et al., 2001;~~
262 ~~Mereone et al., 2000; Siani et al., 2013; Siani et al., 2000; Siani et al., 2010) and AD91-17 (Capotondi et~~
263 ~~al., 1999; Giunta et al., 2003; Sangiorgi et al., 2003) (Fig. 6A). Here, prior to presenting and discussing the~~
264 ~~data, we compare our record from the same region with these published records from the stratigraphic~~
265 ~~point of view. For the comparison, we selected five main widespread bioevents commonly observed in the~~
266 ~~Adriatic Sea (Fig. 6B) (Asioli et al., 1999; Narciso et al., 2012; Piva et al., 2008; Rohling et al., 1997;~~
267 ~~SantaCroce et al., 2008; Trincardi et al., 1996). Bioevents include:~~

268 ~~–bioevent I (top GS-1/YD): abrupt increase of *G. ruber*~~

269 ~~–bioevent II: older peak of *G. inflata*~~

270 ~~–bioevent III: younger peak of *G. inflata*~~

271 ~~–*G. ruber* maximum peak of frequency in S1a~~

272 ~~–*Globoturborotalita rubescens* peak in S1a~~

273

274 ~~Among these cores, IN68-9 core (i.e., core 362 in previous publications (Van Straaten, 1970) is~~
275 ~~particularly relevant because our current understanding of the S1 onset is largely based on this record~~
276 ~~(Rohling et al., 1997; Rohling et al., 2015). IN68-9 was collected at 1234 m water depth (Fig. 11A) and all~~
277 ~~the aforementioned biostratigraphic events (source PANGAEA, doi:10.1594/PANGAEA.407648) are~~
278 ~~present and stratigraphically coherent with ST04-1 (bioevent I corresponds in this core to the ecozones I/II~~
279 ~~boundary) (Fig. 6B). Another similarity includes the ash layer at cm 128–130. Geochemical analysis~~
280 ~~defined this event as Mercato tephra (Calanchi and Dinelli, 2008) which is positioned just below the~~
281 ~~increase of *G. rubescens*.~~

282 ~~Despite the overall coherence between IN68-9 and ST04-1 from a stratigraphy point of view,~~
283 ~~bioevents in IN68-9 exhibit a much younger age compared ST04-1, especially within S1a. To further~~
284 ~~investigate this discrepancy, we performed a new picking of planktonic foraminifera directly on IN68-9~~
285 ~~close to the *G. ruber* peak (137–138 cm). It was possible to date this interval in core IN68-9 because two-~~
286 ~~thirds of the original core are currently stored at ISMAR Bologna. The new radiocarbon date (9030±30 yr~~
287 ~~BP, uncalib.; NOSAMS-WHOI; Table S1) turned out much older than the age assessed with the previous~~
288 ~~age-depth model (ca. 8110 yr BP ¹⁴C age) but remarkably consistent with the chronology of ST04-1.~~

289 ~~The reason for this offset (ca. 1000 y) between the new radiocarbon date and the previous age-depth~~
290 ~~model (Rohling et al., 1997) is unknown and falls outside the scope of this manuscript. However, it is~~
291 ~~worth mentioning that the age-depth model of IN68-9 within the S1 interval essentially relies only on two~~
292 ~~radiocarbon dates (Rohling et al., 1997). We can only suppose that the problem might derive from the~~
293 ~~lowest radiocarbon date (155.5–157.5 cm, 9280±180 yBP ¹⁴C) which is somehow erroneously too young.~~
294 ~~In fact, this interval roughly corresponds to bioevent II which is again much younger (ca. 1000 years)~~
295 ~~when compared with our record. Furthermore, this offset is conservative considering that this radiocarbon~~

296 test at 155.5–157.5 cm corresponds to a mixture of benthic foraminifera (Jorissen et al., 1993). Thus, at
297 most, the radiocarbon date should have been older rather than younger.

298 Core MD90-197 was collected at 1010 m water depth (Fig. 6A). Three curves of planktonic species
299 (*G. ruber*, *G. inflata* and *Globigerinita glutinata*) were visually extrapolated based on the plot of
300 planktonic species vs age previously published (Siani et al., 2010). For this core only two bioevents of
301 core ST04-1 were recognized: Bioevent I and II. The *G. ruber* peak is present but it is coeval with the
302 tephra layer E1 (Gabelotto-Fiumebianco) located close to the S1 interruption and proved to be younger
303 than Mercato tephra (Caron et al., 2012; Marchini et al., 2014). What is striking about this core is the
304 relatively lower thickness of S1a compared to S1b which is unusual for S1 (Mereone et al., 2001; Mereone
305 et al., 2000). This might reflect either a condensed interval or a hiatus above the *G. glutinata* peak. To test
306 this hypothesis, we compared the V/A1 record that displays a large peak right after the S1 onset in both
307 Adriatic basin (ST04-1) and slope (INVAS12-10) (Fig. 6C). This peak is also well present in other south-
308 eastern S1 deposits (e.g., LC21, Aegean Sea (Mereone et al., 2001). The XRF analyses were performed
309 every cm in MD90-197. However, despite the high resolution, the V/A1 peak is not visible (Mereone et al.,
310 2001) (Fig. 12C)

311 An examination of all radiocarbon dates available for MD90-197 (both mixed planktonic
312 foraminifera and monospecific tests (Mereone et al., 2000) reveals a drastic drop in sedimentation rate
313 where the V/A1 is expected. This suggests once again either a condensed unit or a hiatus. Even considering
314 the error associated with pulling together monospecific radiocarbon tests and mixed planktonic species
315 (these latter integrate the signal of a thicker water column), the apparent drop of sedimentation seems to
316 be still evident in the radiocarbon data (Mereone et al., 2000). Unfortunately, benthic foraminifera are not
317 available for MD90-197 which hampers the direct comparison with ST04-1. For example, the *C. bradyi*
318 observed in both ST04-1 and IN68-9 at the base of S1a could have provided additional important clues.

319 Finally, core AD91-17 was collected at 844 m water depth. Two curves of planktic foraminifers (*G. ruber*
320 and *G. inflata*) were reported in Fig. 6A based on previous studies (Capotondi et al., 1999). A recent study

321 showed that the Mercato tephra in this core is present in correspondence of the S1 onset (Marchini et al.,
322 2014). However, Mercato is stratigraphically positioned ca. in the middle of S1a above the *G. ruber* peak
323 in both IN68-9 and ST04-1, this implies that the lower part of S1a is not present. Indeed, just below
324 Mercato, previous publications have highlighted the presence of a turbidite (Giunta et al., 2003).

325
326 Finally, core AD91-17, collected at 844 m water depth (6A), records the Sapropel 1 deposition between
327 cm 190 and 125 (Giunta et al., 2003, Marchini et al., 2014). Two curves of planktic foraminifers (*G. ruber*
328 and *G. inflata*) were reported in Fig. 6A based on previous studies (Capotondi et al., 1999).
329 Tephrostratigraphy of this core shows that the sapropel onset (190-191 cm) corresponded to upper limit of
330 Mercato tephra (Marchini et al., 2014). However, Mercato tephra is stratigraphically positioned ca. in the
331 middle of S1a, above the *G. ruber* peak in IN68-9 (Calanchi and Dinelli, 2008; Rohling et al., 1997) and
332 in ST04-1. The fact that this *G. ruber* positioned peak below Mercato is not visible in AD91-17 (Fig. 6A)
333 suggests that the lower portion of the S1a is missing. In fact, previous publications have highlighted the
334 presence of a turbidite just below Mercato between cm 200 and 196 (Giunta et al., 2003) which further
335 support the hypothesis of the stratigraphic gap.

336

337 4. Results and discussion

338 4.1 Coeval sapropel deposits cross-margin settings

339 In this study we present data from sediment cores retrieved in three different regions of the
340 Adriatic Sea: (i) the mid-Adriatic depression (MAD), (ii) the south-western continental slope and (iii) the
341 southern deep basin (Figs. 1 and 2). The mid-Adriatic depression represents a small remnant basin, which
342 was partially filled with sediment during the last glacial maximum (core AMC99-1, 260 m (Piva et al.,
343 2008); Fig. 2b). High-resolution chirp-sonar profile across the coring site shows continuous and high-
344 amplitude sub-parallel reflectors, which denote sedimentation in low-energy conditions.

345 The slope coring site is characterized by large-scale bottom-current deposits formed by prolonged
346 activity of the thermohaline circulation (core INVAS12-10 and SA03-1, from 570 and 567 m respectively
347 (Minisini et al., 2006) (Fig. 2c). On chirp profiles, these deposits are organized in fields of large sediment
348 waves characterized by wavy and high-amplitude reflectors (Fig. 2c). The coring site was selected on the
349 depositional (up-current) flank of one sediment wave.

350 Finally, the coring site in the southern Adriatic deep basin is characterized by pelagic
351 sedimentation as shown by sub-parallel reflectors, although dense NAdDW can occasionally reach and
352 impact this area (ST04-1, 1085 m; Minisini et al. (2006); Fig. 2d).

353 Despite the different bathymetric contexts, radiocarbon dates from monospecific tests indicated
354 that these three records represent coeval deposits within the time interval under examination (Table 1).
355 Detailed biostratigraphy examination for all three cores revealed the occurrence of bioevents commonly
356 observed in the study region, which were used to independently test the stratigraphic continuity of our
357 records (Fig. 4). High-resolution Bayesian ^{14}C -based age-depth models confirmed continuous deposition
358 consistent with bioevents and seismic profiles (Fig. 5).

359

360 **4.2 Adriatic Sapropel deposition**

361 **4.2.1 Pre-sapropel and S1 onset**

362 Sapropels are beds with elevated organic carbon (OC) content that contrast with overlying and
363 underlying sediments. In this study, S1 boundaries are defined based on the OC anomalies in respect to the
364 background level. The definition of sapropels can further extend to anomalies of several other parameters
365 including Ba/Ti ratio, redox sensitive elements, foraminifera assemblages and magnetic susceptibility or
366 simply changes in sediment colour (De Lange et al., 2008; Mercone et al., 2000; Rohling et al., 1997;
367 Santvoort et al., 1997; Schmiedl et al., 2010; Tachikawa et al., 2015; Vigliotti et al., 2008). Here, we will
368 also discuss these other parameters alongside ~~along~~ the OC data in order to provide a multifaceted view on
369 S1 formation.

370 Our deepest ~~water~~ record ~~in~~ from the southern Adriatic (ST04-01, 1085 m; Fig. [7a6a](#)) shows a
371 gradual OC increase since 11 cal. ky BP before the typical sapropel onset (ca. 10 cal. ky BP) (Hennekam
372 et al., 2014; Rohling et al., 2015; Schmiedl et al., 2010). This trend is consistent with the foraminifera-
373 based oxygen index (Schmiedl et al., 2010) (OI) which reveals a pre-sapropel deterioration of ~~pore-~~
374 waterbottom oxygen levels in the deep basin since ca. 11 cal. ky BP (Fig. [8a-7a](#) and Fig. [9a8a](#)). Analogous
375 pre-sapropel conditions, ascribed to stratification have recently been documented in the deep Levantine
376 basin at 1780 m water depth using a suite of redox-sensitive elements (Tachikawa et al., 2015). Post-
377 glacial freshening driven by the inflow of less saline Atlantic waters via the Gibraltar strait followed by
378 the African Humid Period have certainly exerted a major control on the surface water stratification,
379 vertical mixing and hence intermediate and deep water formation (Rohling et al., 2015; Weldeab et al.,
380 2014). ~~(Rogerson et al., 2008)~~ This is ~~also~~ in line with recent regional simulations which described a
381 gradual deterioration of the deep water ventilation in the EMS since the Heinrich-1 event ([H1](#), ca. 18-16
382 cal ky BP) (Grimm et al., 2015). Enhanced stratification since the H1 event was one of the major drivers
383 that promoted the formation of organic rich layers (ORLs) in the Alboran Sea (Rogerson et al., 2008). In
384 this western Mediterranean region, the continental run-off due to Alpine glacier thawing (i.e., enhanced
385 Rhone river discharge) combined with the Atlantic inflow likely weakened the Western Mediterranean
386 Deep Water ventilation promoting the deposition of ORLs (Rogerson et al., 2008).

387 The onset of relatively high OC content which marks the beginning of the Adriatic S1 (i.e., S1a)
388 was synchronous among our records and it was dated around 10 cal ky BP ~~in~~ across the all-three sites (Fig.
389 [7-6](#) a, b, c). After this coeval OC increase, the deep Adriatic basin (ST04-1) rapidly turned into an azoic
390 environment (Fig. [9a8a](#)). Specifically, as the pore water oxygen decreased in the basin (Fig. [8a](#)), only
391 infaunal foraminifera could initially tolerate oxygen-poor conditions although the benthic environment
392 rapidly became hostile even for deep infaunal taxa (Fig. [9b8b](#)). Azoic conditions in the basin are marked
393 also by authigenic vanadium enrichments (V/TiO₂; Fig. [9b8b](#)) as commonly observed in sapropel beds
394 (Mercone et al., 2001; Tachikawa et al., 2015). Vanadium precipitation is expected in highly reducing
395 environments as its solubility rapidly decreases at the oxic-anoxic boundary which is controlled via

396 diffusion processes across the sediment-water interface (Mercone et al., 2000). Sulphur enrichment
397 (S/TiO₂) in sapropel beds - likely in the form of authigenic pyrite (Passier et al., 1997) - further
398 corroborates the change of redox conditions characterized by microbial-driven sulfate reduction in
399 response to the oxygen-poor environment (Fig. ~~10-9~~ d, e, f).

400

401 **4.2.2 Sapropel break, sapropel S1b and sapropel termination**

402 An interruption within the sapropel unit is visible in our records between ca. 7.8 and 8.3 cal ky
403 BP. During the break both OC content and V/TiO₂ decreased while the OI increased indicating a
404 temporary re-oxygenation at the seabed (Fig ~~7a6a~~, b, c; Fig ~~87~~). The overall trend observed here has been
405 documented in several other S1 deposits further south-east and down to ca. 1,800 m water depth (De
406 Lange et al., 2008; Tachikawa et al., 2015). Reactivation of the convective overturn driven by heat loss
407 during cooling events in the northern Adriatic has been suggested as the most likely scenario to explain
408 the temporary re-oxygenation (Marino et al., 2009; Rohling et al., 1997). The interruption was particularly
409 evident over basin and slope sediments while in the shallower mid-Adriatic slope basin did not display
410 significant change over the break. Already being an oxic environment, it is likely that the mid-Adriatic
411 depression (AMC99-1) was not particularly affected by the temporary resumption of the ventilation.

412 After the sapropel break, the second phase of S1 deposition (i.e., S1b) lasted for ca. 1 ky. Both
413 V/Ti ratio and oxygen index indicate that the reducing conditions during S1b were not as severe in slope
414 sediments as during S1a (Fig. ~~8-7~~ c, d). This is also consistent with the presence of relatively lower
415 authigenic sulphur content, which suggests comparatively lower sulphate reduction rates during S1b (Fig.
416 ~~10-9~~ d, e, f). By contrast, the deep southern basin became azoic again for ca. 500 yr (Fig. ~~8a7 a and 8 a~~).

417 The transitory reappearance of benthic foraminifera and high OI value around 7.4 cal ky BP in the
418 deep basin (ST04-1) suggests another short-lived ventilation event within the S1b (Fig. ~~78a~~) prior to the
419 S1 termination. This was a rather short-lived event but widespread over the EMS as previously observed
420 in the Aegean and Ionian regions (Filippidi et al., 2016).

421 The complete recovery of the deep-water ventilation, which marks the sapropel termination, was
422 fairly synchronous among our records according to the OC anomalies (ca. 6.8 cal ky BP, Fig. 7-6 a,b,c).
423 However, the OI displayed a bathymetric gradient (Fig. 8a7a, b, c) consistent with what observed in the
424 Levantine and Aegean regions where the ventilation started in shallow environment and gradually
425 extended towards greater water depths ~~towards deeper sediments~~ (Schmiedl et al., 2010). As the oxygen
426 reached the seabed, the authigenic enrichment of MnO₂ (Fig. 10a9a) provides a geochemical redox marker
427 to track the maximum penetration of oxygen in sediments after the anoxic period (Reitz et al., 2006;
428 Tachikawa et al., 2015).

429 While OC concentration levels were re-established after the sapropel over basin and slope, the
430 OC remained relatively high in the mid-Adriatic depression (AMC99-1; Fig. 7-6 c) even after the S1
431 termination. The OI based on intermediate infaunal foraminifera reveals a relatively moderate but
432 continuous decrease of the pore-water oxygen concentration in this region throughout the S1 deposition
433 (Fig. 8e7c). This trend likely reflected the sea level rise which pushed towards land the main path of the
434 North Adriatic Deep Water (NAdDW) causing a less efficient ventilation of the Adriatic depression. It is
435 well documented that the modern NAdDW path is mainly confined to the western shelf due to the Coriolis
436 force as it moves southwards (Vilibić and Supić, 2005). Today, only major events of dense water
437 formation can efficiently ventilate the deepest region of the Adriatic depression (Marini et al., 2015).
438 When this occurs, the dense plume lifts the old water mass which is characterized by relatively low
439 oxygen concentrations testifying its long residence time within the morphological depression (i.e., one or
440 several years) (Marini et al., 2015).

441

442 **4.3 Sediment waves growth and thermohaline forcing**

443 In the South Adriatic slope within the field of upslope-migrating sediment waves (core SA03-1,
444 567 m; Fig. 2c), the relative abundance of reworked inner-shelf foraminifera suddenly decreased at the S1
445 onset (Fig. 67d). The presence of allochthonous taxa at this depth is expected considering the

446 thermohaline forcing that generates these sedimentary bodies (Trincardi et al., 2007). Specifically,
447 sediment waves are essentially swept by protracted thermohaline currents which have sufficient energy to
448 resuspend inner-shelf taxa and disperse them towards greater depths (Langone et al., 2015). Bottom
449 currents in the southern Adriatic slope are principally controlled by LIW and NAdDW as well as their
450 interaction which ultimately generates the Adriatic Eastern Mediterranean Deep Water (EMDW_{Adriatic})
451 (Millot, 1999). Mooring lines deployed just down-flow respect to the sediment wave field showed that the
452 modern NAdDW-driven bottom currents can reach over 60 cm s⁻¹ during the cascading season (Langone
453 et al., 2015) (i.e., the modern NAdDW forms around Jan-Feb and reaches the southern margin around
454 March-April (Langone et al., 2015; Turchetto et al., 2007). Consequently, the sudden decrease of inner-
455 shelf taxa coeval with the S1 onset likely reflects the virtual shutdown of the NAdDW or, more precisely,
456 a shallow ventilation confined to the uppermost region of the water column.

457 This explanation is indeed consistent with the general temporal trend shown by the shedding of
458 allochthonous foraminifera from the shelf throughout the S1 deposition. For example, as previously
459 mentioned, the S1 interruption is likely the expression of a cooling phase which promoted the temporary
460 reactivation of the dense water formation in the northern Adriatic Sea (Rohling et al., 1997) and,
461 consequently, the advection of reworked inner-shelf taxa over the slope (Fig. 7d6d). Likewise, S1b and S1
462 termination are associated with decrease and increase of inner-shelf taxa, respectively (Fig. 7d6d).

463 The non-cohesive fraction of marine sediments - generally known as “sortable silt” (SS, 10–63
464 μm) - further supports the decrease of the deep-water ventilation during the S1 deposition (Fig. 7e6e). The
465 sortable silt is operationally defined as the fraction of fine-grained sediments whose sorting and
466 concentration vary in response to hydrodynamic processes (McCave and Hall, 2006). As large errors
467 affect the SS mean grain estimates for low concentrations of SS, here we report only the SS% by weight
468 as a qualitative proxy for paleo-current regimes (Fig. 7e6e). The SS% suggests a progressive decrease of
469 the bottom-current energy since the end of the Younger Dryas (ca. 11.5 cal ky BP) with the minimum
470 observed just at the S1 onset. Overall, the SS trend is consistent with the general distribution of the inner-

471 shelf foraminifera (Fig. 7d6d), which further highlights drastic changes of the thermohaline forcing
472 associated with the pace of the NAdDW.

473

474 **4.4 Weakening of LIW as main trigger for Adriatic S1 deposits**

475 Our results from the sediment wave field revealed that the onset of the sapropel S1 in Adriatic
476 sediments is coeval with the drastic weakening of the North Adriatic Deep Water (NAdDW, Fig. 1).
477 Based on this evidence, we envision a direct relation of cause and effect in which suddenly weakened
478 deep water ~~ventilation-formation~~ resulted in oxygen depleted bottom waters.

479 Several combined factors might have caused the abrupt decrease of the thermohaline forcing in
480 the Adriatic Sea. A key aspect to consider lies in the evident similarities with the south-eastern
481 Mediterranean Sea. First of all, the comparison with the Levantine, Aegean and Ionian Seas reveals that
482 the S1 onset in the Adriatic is ~~remarkably~~ coeval (within age-depth model uncertainties) with the sapropel
483 formation in these regions. Specifically, a recent review (Schmiedl et al., 2010) that has compiled several
484 south-eastern Mediterranean cores indicated that the onset of critical oxygen concentrations (i.e. oxygen
485 index being less than 0.5) occurred around 10.2 ± 0.3 cal ky BP. The collapse of the Adriatic benthic fauna
486 in slope and basin sediments based on the same oxygen index threshold occurred within this time interval
487 (Fig. 810-a, b). This comparison thus reveals that S1 onset in the Adriatic was coeval with the rest of the
488 south-eastern Mediterranean sapropel beds. Further evident similarities ~~with the south-eastern~~
489 ~~Mediterranean sapropels~~ emerge when comparing the temporal anomalies of several other geochemical
490 parameters such as bulk OC (Filippidi et al., 2016; Hennekam et al., 2014; Vigliotti et al., 2011) and
491 redox-sensitive elements (Filippidi et al., 2016; Hennekam et al., 2014; Mercone et al., 2001; Tachikawa
492 et al., 2015) (notably vanadium).

493 ~~A synchronous S1 onset across the entire EMS — including the Adriatic — is a new element that~~
494 ~~corrects previous literature which inferred a delayed S1 onset of ca. 1ky in the Adriatic due to protracted~~
495 ~~ventilation during the early phase of the sapropel formation (Rohling et al., 1997). In the 3.2 section~~

496 ~~(Comparison between stratigraphic records from the southern Adriatic basin) we have further analysed the~~
497 ~~differences between our results and previous published studies from a stratigraphic point of view. Here we~~
498 ~~show how time differences are most likely the result of low-resolution age-depth models combined with~~
499 ~~gravity-driven processes (e.g., erosion, turbidites) which likely altered the original stratigraphy.~~

500 In light of this ~~new new insight~~information, we postulate that the synchronous onset of sapropel
501 S1 over the entire EMS (Fig. 10) necessarily involves the Levantine Intermediate Water (LIW) (Fig. 12)
502 which is the binding element of the ~~eastern~~ Mediterranean thermohaline circulation (Millot, 1999). More
503 specifically, we suggest that the most plausible scenario to explain (i) the coeval S1 onset and (ii) the
504 sudden weakening of the NAdDW must be related to the freshening of the south-eastern Mediterranean
505 Sea. According to our hypothesis, because the salty LIW exerts first-order control on the NAdDW
506 formation by pre-conditioning the northern Adriatic waters (Vilibić and Orlić, 2002; Vilibić and Supić,
507 2005) before the winter cooling, we infer that the freshening of the Levantine Sea during the African
508 Humid Period ~~must have considerably reduced the deep-water formation in the northern Adriatic Sea~~
509 ~~eventually leading to the deep-water anoxia (Fig. 12b).~~

510 To test our hypothesis ~~(Fig. 12b)~~ and in particular the link between the south-eastern
511 Mediterranean region and Adriatic Sea, we have compared our data with a recent reconstruction of the
512 Nile River discharge based on the Ba/Ca ratio measured on *Globigerinoides ruber* (Weldeab et al., 2014)
513 (Fig. 7-6f). The Ba/Ca record essentially reflects the degree of the freshening of the Levantine surface
514 waters as a function of the African monsoon extent (Weldeab et al., 2014). We found that the maximum
515 freshwater supply to the Levantine Sea (ca. 10 cal ky BP) indeed corresponds to the temporarily NAdDW
516 shutdown (i.e., drop in the inner-shelf taxa and SS, Fig. 7-6 d, e) and the corresponding S1 onset in the
517 Adriatic Sea (Fig. 7-6 a, b, c and 8-7 a, b, c).

518 Furthermore, considering that the formation of the ~~Adriatic-Eastern Mediterranean Deep Water~~
519 ~~sourced from the Adriatic EMDW~~(EMDW_{Adriatic}) largely depends on the NAdDW (Vilibić and Orlić,
520 2002; Vilibić and Supić, 2005) (Fig. 1), our results imply that the reduced deep water formation in the

521 Adriatic had in turn drastically hampered the ventilation of those deep regions under the direct influence
522 of the EMDW_{Adriatic} ~~which today such as the Ionian basin (Fig. 12b). Today the Adriatic~~ represents the
523 major ~~cold and EMDW dense water source of~~ for the EMS (Klein et al., 2000); ~~although under certain~~
524 ~~climate conditions (commonly known as the Eastern Mediterranean Transient, EMT), the south-eastern~~
525 ~~surface waters can become particularly salty and generate large volumes of dense water (Lascaratos et al.,~~
526 ~~1999; Malanotte-Rizzoli et al., 1997). The EMS freshening certainly had important effects on both~~
527 ~~NAdDW and EMT.~~

528 Recent studies have also pointed out that ~~that~~ the progressive stagnation of the EMS occurred
529 prior to the African Humid Period due to the inflow of less saline North Atlantic waters into the
530 Mediterranean via the Gibraltar strait (Béthoux and Pierre, 1999; Grimm et al., 2015; Rohling and Bryden,
531 1994; Rohling et al., 2015). Therefore, the peak of the African monsoon occurred over a period already
532 characterized by enhanced water-column stratification. Evidence of weakened deep-water ventilation prior
533 to S1 has been well documented in the Levantine Basin (Tachikawa et al., 2015)⁴⁵, which is consistent
534 with our record in the Adriatic basin (notably ST04-1; Fig. 98). ~~The~~ presence of pre-sapropel conditions in
535 our deepest record further highlights the coherence between the Adriatic and the rest of the EMS as well
536 as the importance of pre-freshening as a prerequisite for the sapropel formation (Grimm et al., 2015).

537 Among other relevant similarities with the south-eastern Mediterranean sapropels, it is worth
538 mentioning that the S1 termination in the Adriatic was coherent with the progressive reoxygenation
539 observed in the Levantine and Aegean sediments (Fig. 10). Specifically, according to the foraminifera-
540 based oxygen index (values > 0.5) (Schmiedl et al., 2010) in these regions, the ventilation was initially
541 confined within the uppermost water column and gradually increased water depth with time. A similar
542 water depth- trend characterized our Adriatic records. Using the same oxygen-index threshold as for the
543 Aegean and Levantine basins (Schmiedl et al., 2010), the re-oxygenation over the slope (SA03-1, Fig.
544 ~~8b7b and 10~~) occurred ~~much~~ earlier than ~~the~~ deep benthic environment (ST04-1, Fig. ~~8a7a and 10~~). In
545 line with the bottom-~~current~~ proxies (Fig. ~~7-6~~_{d, e}), these results suggest a gradual reactivation of the

Comment [TT1]:

546 NAdDW. The reason for the observed bathymetric trend across all Eastern Mediterranean basins probably
547 involves the gradual weakening of the African monsoons (Weldeab et al., 2014) (Fig. 7f) coupled with
548 the sea surface cooling towards the end of the sapropel (Marino et al., 2009; Siani et al., 2013).

549

550 4.5 Comparison with published stratigraphic records from the southern Adriatic basin

551 Our results revealed Aa synchronous S1 onset across the entire EMS which —includes in the
552 Adriatic setting. -This- is a new element that corrects previous literature which inferred a delayed S1 onset
553 (of ca. 1ky) in the Adriatic due to protracted ventilation during the early phase of the sapropel formation
554 (Rohling et al., 1997). In the 3.2In this section, we revisit published studies dealing with the Adriatic S1 to
555 evaluate the stratigraphic coherence with our results and, thus, further understand the origin of this
556 discrepancy. section (Comparison between stratigraphic records from the southern Adriatic basin) we have
557 further analysed the differences between our results and previous published studies from a stratigraphic
558 point of view. Here we show how time differences are most likely the result of low resolution age depth
559 models combined with gravity driven processes (e.g., erosion, turbidites) which likely altered the original
560 stratigraphy.

561 Prior Adriatic studies focused on the following cores: IN68-9 (Jorissen et al., 1993; Rohling et al.,
562 1997; Van Straaten, 1970), MD90-197 (Meroni et al., 2001; Meroni et al., 2000; Siani et al., 2013;
563 Siani et al., 2000; Siani et al., 2010) and AD91-17 (Capotondi et al., 1999; Giunta et al., 2003; Sangiorgi
564 et al., 2003) (Fig. 1 and 11). For the comparison with our records, we selected five main widespread
565 bioevents commonly observed in the Adriatic Sea (Fig. 11) (Asioli et al., 1999; Narciso et al., 2012; Piva
566 et al., 2008; Rohling et al., 1997; Santacrose et al., 2008; Trincardi et al., 1996). Bioevents include:

567 - bioevent I (top GS-1/YD): abrupt increase of *G. ruber*

568 - bioevent II: older peak of *G. inflata*

569 - bioevent III: younger peak of *G. inflata*

570 - *G. ruber* maximum peak of frequency in S1a

571 - *Globoturborotalita rubescens* peak in S1a

572 Among these cores, IN68-9 core (i.e., core 362 in previous publications (Van Straaten, 1970) is
573 particularly relevant because our current understanding of the S1 onset is largely based on this record
574 (Rohling et al., 1997; Rohling et al., 2015). IN68-9 was collected at 1234 m water depth (Fig. 11a) and all
575 the aforementioned biostratigraphic events (source PANGAEA, doi:10.1594/PANGAEA.407648) are
576 present and stratigraphically coherent with ST04-1 (bioevent I corresponds in this core to the ecozones I/II
577 boundary) (Fig. 11a). Another similarity includes the ash layer at cm 128-130. Geochemical analysis in
578 IN68-9 defined this event as Mercato tephra (Calanchi and Dinelli, 2008) which is positioned just below
579 the increase of *G. rubescens*. Although the geochemical fingerprint is not available for ST04-1, the age
580 and the stratigraphic position suggest that this ash layer is likely Mercato tephra.

581 Despite the overall coherence between IN68-9 and ST04-1 from a stratigraphy point of view,
582 bioevents in IN68-9 exhibit a much younger age compared to ST04-1, especially within S1a. To further
583 investigate this discrepancy, we performed a new picking of planktonic foraminifera directly on IN68-9
584 close to the *G. ruber* peak (137-138 cm). It was possible to date this interval in core IN68-9 because two-
585 thirds of the original core are currently stored at ISMAR Bologna. The new radiocarbon date (9030±30 yr
586 BP ¹⁴C age.; NOSAMS reference OS-127850; Table 1) turned out much older than the age assessed with
587 the previous age-depth model (ca. 8110 yr BP ¹⁴C age) (Rohling et al., 1997) but remarkably consistent
588 with the chronology of ST04-1.

589 The reason for this offset (ca. 900 y) between the new radiocarbon date and the previous age-depth
590 model (Rohling et al., 1997) might explain why the Adriatic sapropel S1 exhibited a delayed onset. It is
591 worth mentioning that the age-depth model of IN68-9 within the S1 deposit, essentially relies only on two
592 radiocarbon dates (Rohling et al., 1997). Thus, it possible that the problem might derive from the lowest
593 radiocarbon date (UTC-501, 155.5-157.5 cm, 9280±180 yr BP ¹⁴C) which is somehow erroneously too
594 young. To test this hypothesis, we re-modelled in Oxcal the sediment accumulation of core IN68-9 using
595 the new radiocarbon date (OS-127850) and the bioevents as used in our records (supplementary material).

596 The goal of this exercise was to examine the agreement between the model (*prior*) and the observational
597 data (*likelihood*) which is quantitatively expressed with the “agreement index”. As expected, test UTC-
598 501 exhibited a low agreement index and, thus, turned out being an outlier. Furthermore, the agreement
599 index would further decrease considering that the suspicious radiocarbon test (UTC-501) corresponds to a
600 mixture of benthic foraminifera (Jorissen et al., 1993). In fact, if we applied a larger ΔR respect to
601 planktonic foraminifera, the new reservoir correction would make the calibrated age even younger and,
602 thus, less coherent with the rest of the dates.

603 Core MD90-197 was collected at 1010 m water depth (Fig. 1). Three curves of planktonic species
604 (*G. ruber*, *G. inflata* and *Globigerinita glutinata*) were visually extrapolated based on the plot of
605 planktonic species vs age previously published (Siani et al., 2010). For this core only two bioevents of
606 core ST04-1 were recognized: Bioevent I and II. The *G. ruber* peak is present but it is coeval with the
607 tephra layer E1 (Gabelotto-Fiumebianco) located close to the S1 interruption and proved to be younger
608 than Mercato tephra (Caron et al., 2012; Marchini et al., 2014). What is striking about this core is the
609 relatively thin S1a compared to S1b which is unusual for S1 (Mercone et al., 2001; Mercone et al., 2000).
610 This might reflect either a condensed interval or a hiatus above the *G. glutinata* peak. To test this
611 hypothesis, we compared the V/Al record that displays a large peak right after the S1 onset in both
612 Adriatic basin (ST04-1) and slope (INVAS12-10) (Fig 11b). This peak is also present in other south-
613 eastern S1 deposits (e.g., LC21, Aegean Sea (Mercone et al., 2001). The XRF analyses were performed
614 every cm in MD90-197. However, despite the high resolution, the V/Al peak is not visible (Mercone et al.,
615 2001) (Fig. 11b). An examination of all radiocarbon dates available for MD90-197 (both mixed planktonic
616 foraminifera and monospecific tests (Mercone et al., 2000) reveals a drastic drop in sedimentation rate
617 where the V/Al is expected. This suggests once again either a condensed unit or a hiatus. Even considering
618 the error associated with pulling together monospecific radiocarbon tests and mixed planktonic species
619 (these latter integrate the signal of a thicker water column), the apparent drop of sedimentation seems to
620 be still evident in the radiocarbon data (Mercone et al., 2000). Unfortunately, benthic foraminifera are not

621 available for MD90-197 which hampers the direct comparison with our record. For example, the *C. bradyi*
622 observed in both ST04-1 and IN68-9 at the base of S1a could have provided additional important clues.

623 Finally, core AD91-17 was collected in the southern Adriatic at 844 m water depth (Giunta et al.,
624 2003, Marchini et al., 2014). Two curves of planktonic foraminifera (*G. ruber* and *G. inflata*) were
625 reported in Fig. 1 based on previous studies (Capotondi et al., 1999). Tephra-stratigraphy of core AD91-17
626 indicates that the reconstructed sapropel onset (190-191 cm) corresponded to the uppermost limit of
627 Mercato tephra (Marchini et al., 2014). However, Mercato tephra is stratigraphically positioned ca. in the
628 middle of S1a, above the *G. ruber* peak in both IN68-9 (Calanchi and Dinelli, 2008; Rohling et al., 1997)
629 and ST04-1 (this study). The fact that this large *G. ruber* peak below Mercato is not visible in AD91-17
630 (Fig. 11a) suggests that the lower portion of the S1a is missing. In fact, previous publications have
631 highlighted the presence of a turbidite just below Mercato between cm 200 and 196 (Giunta et al., 2003)
632 which further support the hypothesis of a possible stratigraphic gap.

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635 **4.65 Enhanced primary productivity or diagenetic signal?**

636 Alternatively, the deposition of the Adriatic sapropel could have been an expression of the high-
637 nutrient supply via freshwater discharge. Under these circumstances, the increased demand of benthic
638 oxygen, necessary to degrade the freshly deposited marine phytodetritus, eventually resulted in anoxic
639 sediments.

640 In this study, we used lignin – the second most abundant macromolecule on Earth after cellulose –
641 as a tracer of freshwater discharge because it has been shown that terrestrial organic biomarkers (notably
642 sediment-normalized concentrations) increase during sapropel deposition (Bouloubassi et al., 1999;
643 Gogou et al., 2007) (Fig. 112). In northern Mediterranean borderlands, ~~the abundance~~this evidence of
644 ~~terrestrial biomarkers~~ has been widely used to infer the link between enhanced freshwater supply and
645 sapropel formation (Bouloubassi et al., 1999; Gogou et al., 2007). Indeed, our results show that lignin

646 increased at the S1 onset but, ~~in all settings~~ at the same time, the lignin content markedly diminishes with
647 decreasing water depth (Fig. ~~4-12~~). While previous studies mainly drawn their conclusions based on deep
648 sapropel beds (Bouloubassi et al., 1999; Gogou et al., 2007), in this study we took the opportunity to focus
649 also on shallow water equivalent deposits which revealed this water depth trend. However, A pattern like
650 this is unexpected because typically lignin concentration diminishes with increasing distance from the
651 river outlets in all modern continental margins, including the Adriatic (Bröder et al., 2016; Gordon and
652 Goñi, 2003; Tesi et al., 2008; Tesi et al., 2007). Therefore, in our hypothesis, lignin concentration reflects
653 post-depositional degradation efficiency rather than original river input.

654 In this scenario, early diagenesis during burial is limited in the deep basin where anoxic sediments
655 hamper the complete OC breakdown including the terrestrial fraction. This would explain the relatively
656 high lignin content in the deepest station during S1 as well as the similarities between lignin content and
657 bulk OC (Fig. ~~7-6~~ a, b, c and ~~4-12~~). Taken together, our results indicate that terrestrial biomarkers in
658 sapropel beds do not necessarily reflect a primary signal (river input) but rather a secondary signal
659 (diagenesis) as observed for other “non-conservative” variables measured in sapropel bedss such as $\delta^{15}\text{N}$,
660 pollen assemblages as well as other organic biomarkers (Cheddadi and Rossignol-Strick, 1995; Langgut et
661 al., 2011; Versteegh et al., 2010). Another recent example is the $\delta^{15}\text{N}$ whose depleted isotope composition
662 has been interpreted for a long time as a sign of enhanced primary productivity (Calvert et al., 1992).
663 Recent works showed that the lack of isotopic fractionation during early diagenesis is essentially the
664 reason why sapropel beds display depleted $\delta^{15}\text{N}$ signatures (Möbius et al., 2010; Sachs and Repeta, 1999).
665 Thus, as observed for the terrestrial biomarkers, the $\delta^{15}\text{N}$ signature in sapropel beds reflects a preservation
666 signal (diagenesis) rather than the original marine OC fingerprint.

667
668 Given the evident complications with the use of terrestrial biomarkers we have looked into the
669 literature (Combourieu-Nebout et al., 2013; Magny et al., 2012; Spötl et al., 2010) to find indications of
670 enhanced river discharge from the northern Mediterranean borderlands to justify the sapropel onset at

671 around 10 cal ky BP. The collective evidence based on speleothems, pollen data and debris flow fans and
672 lake levels suggests precipitation anomalies around 7.3-8.2-7.3 cal. ky BP (Spötl et al., 2010; Zanchetta et
673 al., 2007) over the northern Mediterranean-Italian drainage basins regions (Alps and northern Apennine
674 chain)(i.e., Alps). (Magny et al., 2013)The wetter conditions during this period might have further
675 weakened the NADW during the sapropel deposition and stimulated the primary productivity. However,
676 other studies based on lake levels suggest conditions not particularly wet during the same period in
677 northern Italy (Magny et al., 2013). Despite the lack of agreement, (Spötl et al., 2010; Zanchetta et al.,
678 2007)it seems evident that this time interval (8.2-7.3 cal. ky BP) (Spötl et al., 2010; Zanchetta et al., 2007)
679 is more ~~which is more~~ consistent with the second phase of sapropel S1 (S1b) rather than ~~its~~ the onset (ca.
680 10 cal ky BP). In conclusions, there is no evidence in the literature or in our river-proxy data suggesting
681 that S1 in the Adriatic was initiated by enhanced freshwater discharge from local rivers. By contrast, the
682 synchronous onset across the entire EMS suggests a wide-basin, physical-driven mechanism such as the
683 abrupt weakening of the LIW which hampered the dense water formation over the entire Eastern
684 Mediterranean Sea.

685

686

687 **Conclusions**

688 This study has redefined the conditions under which the Adriatic S1 formed. Our multifaceted
689 study based on integrated ecological, organic and inorganic parameters indicates that the weakening of the
690 NAdDW-Northern Adriatic Deep Water exerted first-order control on the development of anoxic bottom
691 waters in the Adriatic as well as nearby deep basins such as the Ionian Sea. The emerging picture suggests
692 a chain of events in which the intensification of monsoon precipitation over North Africa followed by the
693 weakening of the LIW-Levantine Intermediate Water ultimately suppressed the Northern Adriatic Deep
694 Water formation whichNAdDW leading to the S1 formation in the Adriatic and in those basins further
695 south under, consequently, hampered the the direct influence of the Eastern Mediterranean Deep

696 ~~WaterEMDW_{Adriatic} (e.g. Ionian basin, development Fig.11).~~ As a result, the expression of the monsoon-
697 fuelled freshening was a synchronous ~~stagnation S1 formation~~ across the entire Eastern Mediterranean Sea
698 including the Adriatic. ~~Finally, our results rule out the increase of nutrient supply as the major driver for~~
699 ~~the S1 formation in Adriatic sediments.~~

700

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Captions

956 **Figure 1.** Map of the study area in the Adriatic Sea. Coring sites are displayed as filled dots and labelled
957 AMC99-1 (260 m water depth), SA03-1 (567 m water depth), INVAS12-10 (570 m water depth) and
958 ST04-1 (1085 m water depth) respectively. Arrows show the main water masses which include the
959 Levantine Intermediate Water (LIW, red, main path, and dashed red, northward intrusion with large inter-
960 decadal variability), North ~~and South~~-Adriatic Deep Water (NAdDW ~~and SAdDW~~, blue) and the Eastern
961 Mediterranean Deep Water (EMDW, green). Dashed line roughly displays the position of the shoreline at
962 the S1 onset. ~~The black line represents the location of the depth profile (Fig. 2a).~~ The upper right inset
963 shows the main path of the LIW in the eastern and central Mediterranean Sea and the Nile runoff input

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979 **Figure 2.** Chirp profiles of the coring sites along the shelf-basin continuum. (a) The depth profile graph
980 displays the general location of the sediment cores in respect to the dominant water masses (NAdDW and
981 LIW). Seismic profiles through the three coring sites: (b) shelf-adjacent (mid-Adriatic depression,
982 AMC99-1), (c) slope (sediment wave field, SA03-1 and INVAS12-10) and (d) deep basin (ST04-1).

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1009 **Figure 3.** Sediment cores from the Adriatic Sea (Fig. 1 and 2). Lithology, photo, false colours and XRAY
1010 of AMC99-1 (a); photo non available); INVAS12-10 (b); ~~and~~ ST04-1 (c).

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1031 **Figure 4.** Down-core biostratigraphy of ST04-1, SA03-1 and AMC99-1. Four bioevents were used for the
1032 age-depth model: I (top YD, blue line), II (older peak *G. inflata*, light green), III (younger peak *G. inflata*,
1033 dark green), IV (last occurrence *G. inflata*, red line). For further details on the bioevents see Table 1 and
1034 method section. The figure shows also the correlation between twins core Core SA03-1 and INVAS12-10.
1035 collected in the sediment wave field. Cross-correlation between twin cores relies on bioevents and tephra
1036 (magnetic susceptibility anomalies). Events in chronological order include: top of the Younger Dryas, two
1037 *Globorotalia inflata* peaks (during the Pre Boreal), peak of *Cassidulinoides bradyi*, a large magnetic
1038 susceptibility peak marking a tephra layer, two *G. inflata* peaks (during S1 break and S1b, respectively)
1039 and the last Occurrence of *G. inflata*

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1061 **Figure 5.** Bayesian age-depth model of Adriatic records (median, 1σ and 2σ). Filled symbols (circles,
1062 squares and diamonds) show the radiocarbon dates used for the Bayesian model. Dark gray areas display
1063 distinct bioevents used to increase the model resolution and synchronize the records. The model shows
1064 good agreement between bioevents and the new radiocarbon dates of monospecific tests. For further
1065 details about the age-depth model see the method section. The paleoceanographic (and stratigraphic)
1066 events were identified independently in each core; therefore, all dates in each core are consistent and
1067 independent as no age is exported from one core to another.

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~~Figure 6. Comparison between sediment cores collected in the southern Adriatic basin. ST04-1 (this study), IN68-9 (Rohling et al., 1997), MD90-197 (Mereone et al., 2001; Siani et al., 2010) and AD90-17 (Capotondi et al., 1999). A) Location of the sediment cores. B) Core description, biostratigraphy and~~

1088 bioevents (coloured lines). C) Core description and V/Al ratio (MD90-197 vs ST04-1). Radiocarbon dates
1089 shown in the figure refer to uncalibrated data (^{14}C yBP) for a direct comparison.

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Figure 76. Sapropel S1 along the Adriatic shelf-basin continuum and external environmental forcings. Organic carbon (OC) content of (a) ST04-1, (b) INVAS12-10 and (c) AMC99-1. Note the different scale of y-axes. Bottom current ~~proxies~~ proxies: abundance of reworked inner-shelf foraminifera (d) and sortable

1108 silt (e) over the slope (SA03-1). (f) Nile runoff proxy: Ba/Ca of *Globigerinoides ruber* (Weldeab et al.,
1109 2014). Light and dark grey areas denote pre-sapropel sediments, ~~the~~ S1 boundaries and the sapropel S1
1110 break based on the OC content of ST04-1.

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1129 **Figure 87.** Seafloor oxygen content and reducing conditions during the sapropel S1 deposition in Adriatic
1130 sediment along the shelf-basin continuum. Foraminifera-based oxygen index (OI, (Schmiedl et al., 2010)

1131 of (a) ST04-1, (b) SA03-01 and AMC99-1). Value of 1 refers to fully oxygenated conditions while 0
1132 represents azoic environment, respectively. Note, OI of AMC99-1 is based on intermediate infaunal
1133 foraminifera. Authigenic vanadium enrichment (V/Ti) of (ad) ST04-1, (be) SA03-01 and (f) AMC99-1.
1134 Light and dark grey areas show pre-sapropel sediments, ~~the~~ S1 boundaries and interruption based on the
1135 OC content of ST04-1 (see Fig. ~~46~~).

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1154 **Figure 98.** Pre-sapropel and sapropel S1 onset in the Adriatic basin (ST04-1, 1085 m). (a) Organic carbon
1155 (OC) and oxygen index. (b) Abundance of deep and intermediate infaunal foraminifera and authigenic
1156 vanadium enrichment (V/TiO₂). Light grey area shows the azoic environment.

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1179 **Figure 109.** Distribution of manganese and sulfur during the S1 deposition in Adriatic sediments along
1180 the shelf-basin continuum. Authigenic manganese enrichment of (a) ST04-1, (b) INVAS12-10 and (c)
1181 AMC99-1. Authigenic sulfur enrichment of (d) ST04-1, (e) INVAS12-10 and (f) AMC99-1. Light and
1182 dark grey areas show pre-sapropel sediments, S1 boundaries and interruption based on the OC content of
1183 ST04-1 (see Fig. 6). ~~Light and dark grey areas show the S1 boundaries and interruption based on the OC~~
1184 ~~content (see Fig. 1).~~ Note the different scale of y-axes.

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1187 **Figure 10.** Benthic ecosystem changes over water depth during the sapropel S1 deposition according to
1188 the foraminifera-based oxygen index. Changes were defined using the oxygen index threshold according
1189 to Schmieidl et al. (2010). Values less than 0.5 indicate the collapse of the benthic ecosystem while values
1190 more than 0.5 indicate the recovery of the benthic ecosystem. Solid line and grey area show mean and
1191 standard deviation of the S1 onset, respectively. Dashed line (interpolation water depth vs time) exhibits
1192 the progressive ventilation with increasing water depth over time. Aegean and Levantine data from
1193 Schmieidl et al. (2010).

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1195 **Figure 611.** Comparison between sediment cores collected in the southern Adriatic basin. ST04-1 (this
1196 study), IN68-9 (Rohling et al., 1997), MD90-197 (Merccone et al., 2001; Siani et al., 2010) and AD90-17
1197 (Capotondi et al., 1999). A) Location of the sediment cores. B) Core description, biostratigraphy and
1198 bioevents (coloured lines). C) Core description and V/Al ratio (MD90-197 vs ST04-1). Radiocarbon dates
1199 shown in the figure refer to uncalibrated data (¹⁴C yBP) for a direct comparison.

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1216 **Figure 121.** Terrigenous organic carbon concentration during the sapropel S1 deposition in Adriatic
1217 sediments along the shelf-basin continuum. Lignin concentration of (a) ST04-1, (b) INVAS12-10 and (c)
1218 AMC99-1. ~~Light and dark grey areas show the S1 boundaries and interruption based on the OC content~~
1219 ~~(see Fig. 1).~~ Light and dark grey areas show pre-sapropel sediments, S1 boundaries and interruption based
1220 on the OC content of ST04-1 (see Fig. 6). Note the different scale of y-axes.

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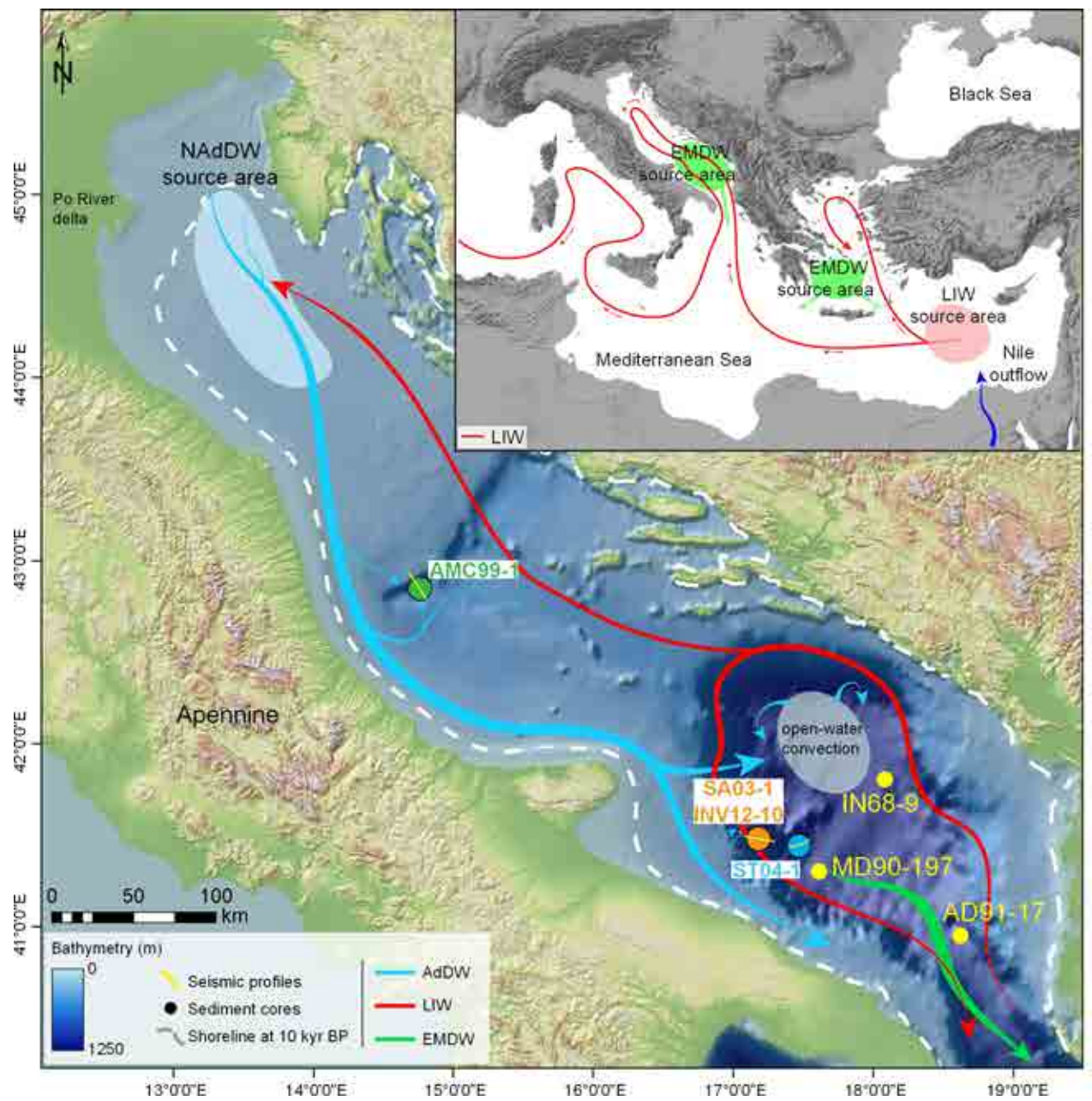
Figure 12. Cartoon of the thermohaline circulation: (a) modern conditions and (b) during the freshening of the Eastern Mediterranean Sea via the Nile (b). As the precipitation increases over North Africa, the Levantine Intermediate Waters (LIW) progressively decreases. This in turn hampers the preconditioning North Adriatic Deep Water with cascade effects on the Eastern Mediterranean Deep Water formation. The expression of the monsoon-fuelled freshening was a synchronous S1 formation across the Eastern Mediterranean Sea including the Adriatic.

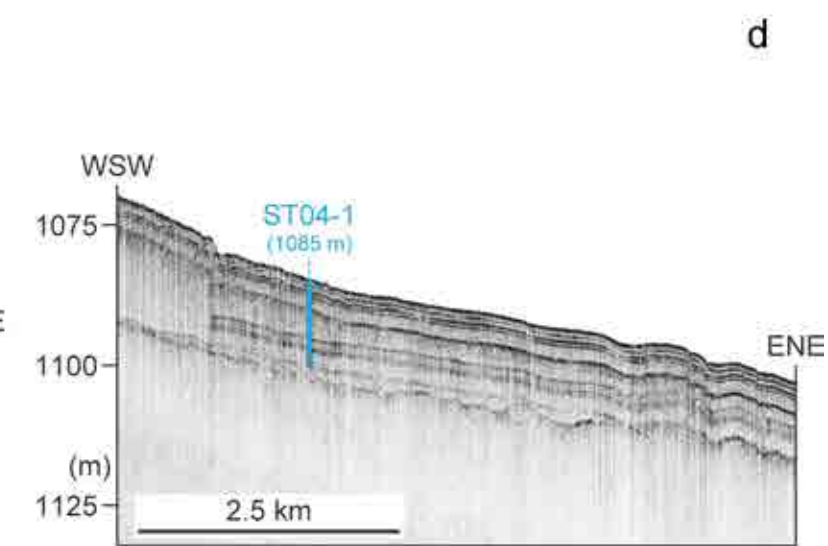
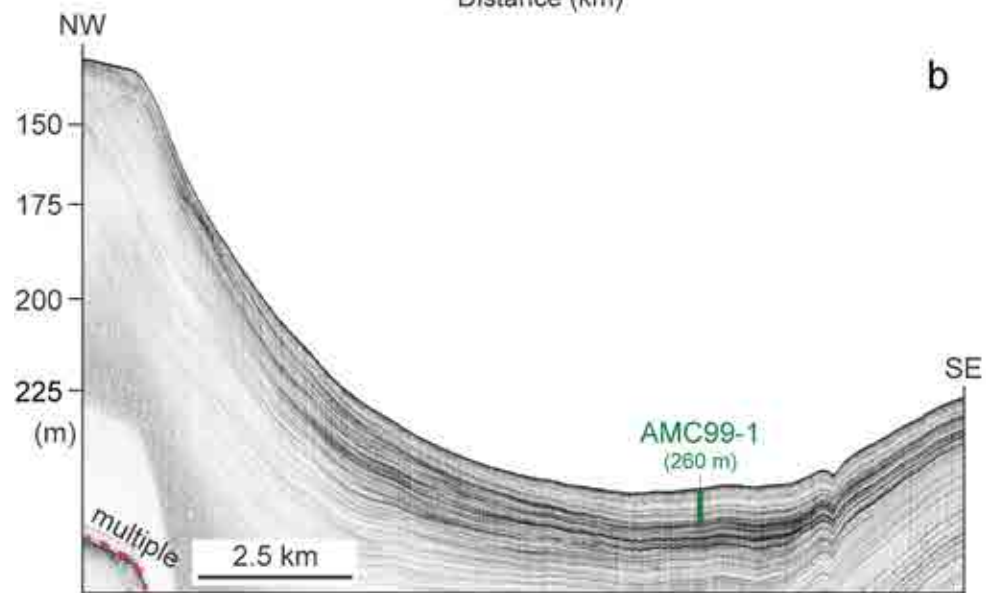
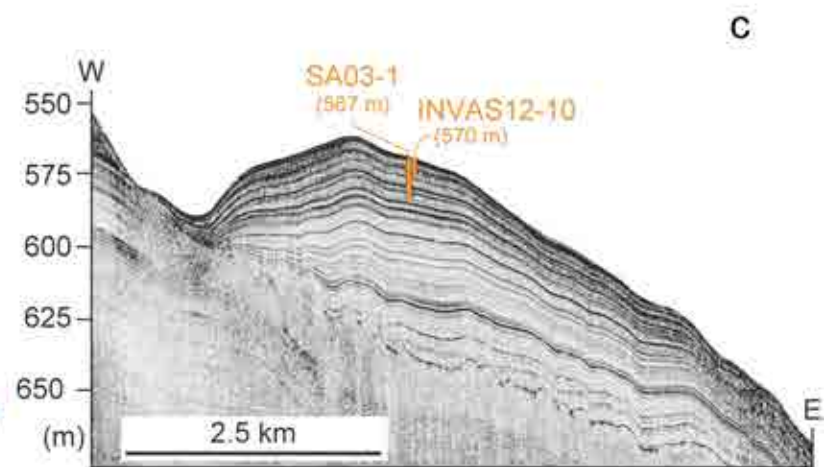
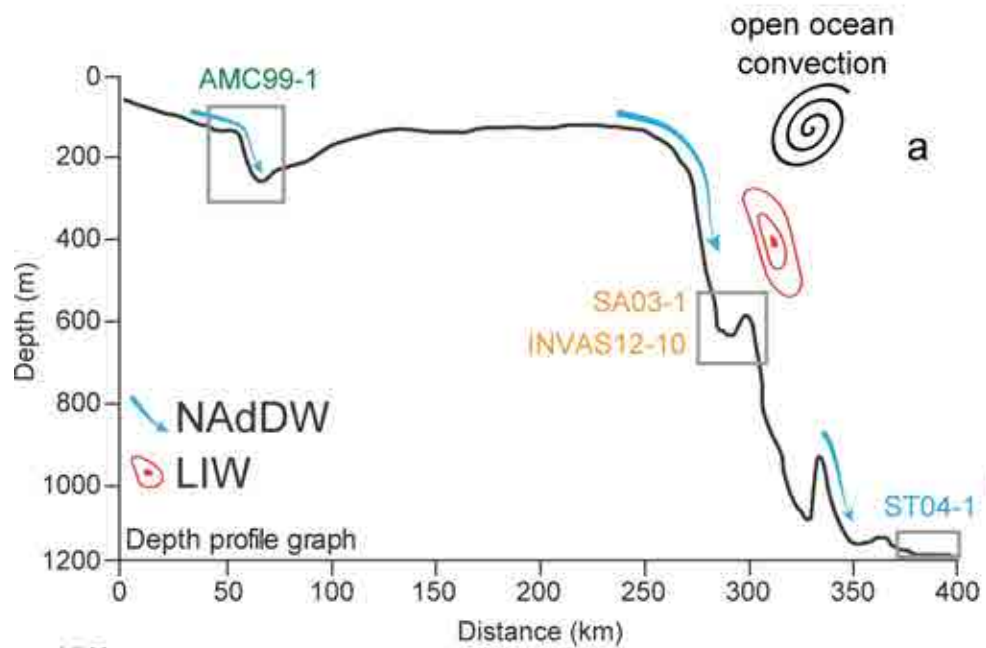
Table S1. Dated levels used for the Bayesian age-depth model of core AMC991, INVAS12-10, ST04-1. The table contains a new radiocarbon date of core IN68-9 as well.

| Lab. # | Core depth (cm) | Sample type | ¹⁴ C age (yBP) | Modelled age (median, cal yBP) | | Reference | |
|--------------------------------|-----------------|--------------------------------|---------------------------|--------------------------------|-------|-----------|--|
| | | | | -2σ | +2σ | | |
| AMC99-1 (260 m w.d.) | | | | | | | |
| Poz-16133 | 21-22 | <i>Cibicidoides pachyderma</i> | 1405 ± 30 | 629 | 720 | 530 | Piva et al. (2008) |
| Poz-16134 | 117-118 | <i>Cibicidoides pachyderma</i> | 2880 ± 40 | 2208 | 2331 | 2073 | Piva et al. (2008) |
| Poz-16135 | 222-223 | <i>Cibicidoides pachyderma</i> | 4200 ± 40 | 3889 | 4065 | 3724 | Piva et al. (2008) |
| Poz-16137 | 258-259 | mixed planktic | 4570 ± 50 | 4630 | 4798 | 4464 | Piva et al. (2008) |
| CAMS-33373 | 323-324 | mixed planktic | 5880 ± 60 | 6104 | 6265 | 5944 | Bioevent IV, LO <i>G. inflata</i> (core RF93-30); (Trincardi et al., 1996) |
| OS-104703 | 374-375.5 | <i>Globigerinoides ruber</i> | 6720 ± 50 | 7046 | 7201 | 6906 | this study |
| OS-104710 | 416-417 | <i>Globigerinoides ruber</i> | 7320 ± 60 | 7668 | 7805 | 7553 | this study |
| OS-104283 | 470-471.5 | <i>Globigerinoides ruber</i> | 8230 ± 45 | 8565 | 8721 | 8420 | this study |
| OS-104466 | 535-536 | <i>Globigerinoides ruber</i> | 9090 ± 35 | 9683 | 9856 | 9533 | this study |
| Poz-16142 | 550-551 | mixed planktic | 9360 ± 50 | 10049 | 10184 | 9886 | Bioevent III, Younger peak <i>G. inflata</i> (core SA03-1); (Favaretto et al., 2008) |
| Poz-16144 | 570-571 | mixed planktic | 9860 ± 60 | 10565 | 10727 | 10392 | Bioevent II, Older peak <i>G. inflata</i> (core SA03-1); (Favaretto et al., 2008) |
| CAMS-16305 | 610-611 | mixed planktic | 10450 ± 90 | 11301 | 11623 | 11112 | Bioevent I, Top YD (core CM92-43); (Asioli et al., 2001) |
| INVAS12-10 (570 m w.d.) | | | | | | | |
| CAMS-33373 | 275-276 | mixed planktic | 5880 ± 60 | 6116 | 6277 | 5937 | Bioevent IV, LO <i>G. inflata</i> (core RF93-30); (Trincardi et al., 1996) |
| OS-104282 | 305-306 | <i>Globigerinoides ruber</i> | 6450 ± 35 | 6833 | 7115 | 6647 | this study |
| OS-104380 | 319-320 | <i>Globigerinoides ruber</i> | 7340 ± 30 | 7648 | 7760 | 7558 | this study |
| OS-108068 | 327-328 | <i>Globigerinoides ruber</i> | 7530 ± 60 | 7864 | 7986 | 7725 | this study |
| OS-104381 | 347-348 | <i>Globigerinoides ruber</i> | 8240 ± 35 | 8565 | 8721 | 8421 | this study |

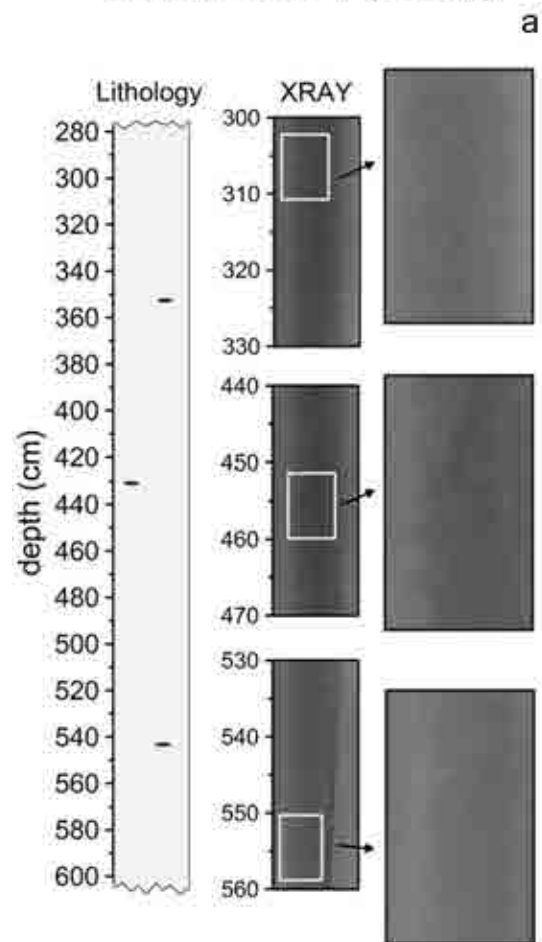
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|-----------------------------|---------|------------------------------|------------|---|-------|-------|--|
| OS-104382 | 375-376 | <i>Globigerinoides ruber</i> | 9140 ± 35 | 9596 | 9982 | 9151 | this study |
| Poz-16142 | 389-390 | mixed planktic | 9360 ± 50 | 10100 | 10232 | 9885 | Bioevent III, Younger peak <i>G. inflata</i> (core SA03-1); (Favaretto et al., 2008) |
| Poz-16144 | 395-396 | mixed planktic | 9860 ± 60 | 10577 | 10768 | 10373 | Bioevent II, Older peak <i>G. inflata</i> (core SA03-1); (Favaretto et al., 2008) |
| CAMS-16305 | 413-414 | mixed planktic | 10450 ± 90 | 11301 | 11682 | 11088 | Bioevent I, Top YD (core CM92-43); (Asioli et al., 2001) |
| ST04-1 (1085 m w.d.) | | | | | | | |
| CAMS-33373 | 80-81 | mixed planktic | 5880 ± 60 | 6103 | 6275 | 5925 | Bioevent IV, LO <i>G. inflata</i> (core RF93-30); (Trincardi et al., 1996) |
| OS-104464 | 102-103 | <i>Globigerinoides ruber</i> | 6510 ± 30 | 6878 | 7011 | 6735 | this study |
| OS-104378 | 113-114 | <i>Globigerinoides ruber</i> | 7160 ± 30 | 7521 | 7607 | 7425 | this study |
| OS-104465 | 120-121 | <i>Globigerinoides ruber</i> | 7800 ± 35 | 8110 | 8254 | 7985 | this study |
| OS-104281 | 139-140 | <i>Globigerinoides ruber</i> | 9040 ± 40 | 9562 | 9701 | 9455 | this study |
| OS-107637 | 142-143 | <i>Globigerinoides ruber</i> | 9180 ± 40 | 9755 | 9916 | 9580 | this study |
| Poz-16142 | 145-146 | mixed planktic | 9360 ± 50 | 10009 | 10181 | 9826 | Bioevent III, Younger peak <i>G. inflata</i> (core SA03-1); (Favaretto et al., 2008) |
| Poz-16144 | 153-154 | mixed planktic | 9860 ± 60 | 10669 | 10842 | 10505 | Bioevent II, Older peak <i>G. inflata</i> (core SA03-1); (Favaretto et al., 2008) |
| OS-104379 | 154-155 | <i>Globorotalia inflata</i> | 10050 ± 45 | 10761 | 10949 | 10624 | this study |
| CAMS-16305 | 169-170 | mixed planktic | 10450 ± 90 | 11442 | 11790 | 11165 | Bioevent I, Top YD (core CM92-43); (Asioli et al., 2001) |
| IN68-9 (1234 m w.d.) | | | | | | | |
| OS-127850 | 137-138 | <i>Globigerinoides ruber</i> | 9030 ± 30 | Not calibrated for direct comparison with previous studies Rohling et al. (1997) | | | |

* For further details about biostratigraphy and bioevents see the method section in the main text

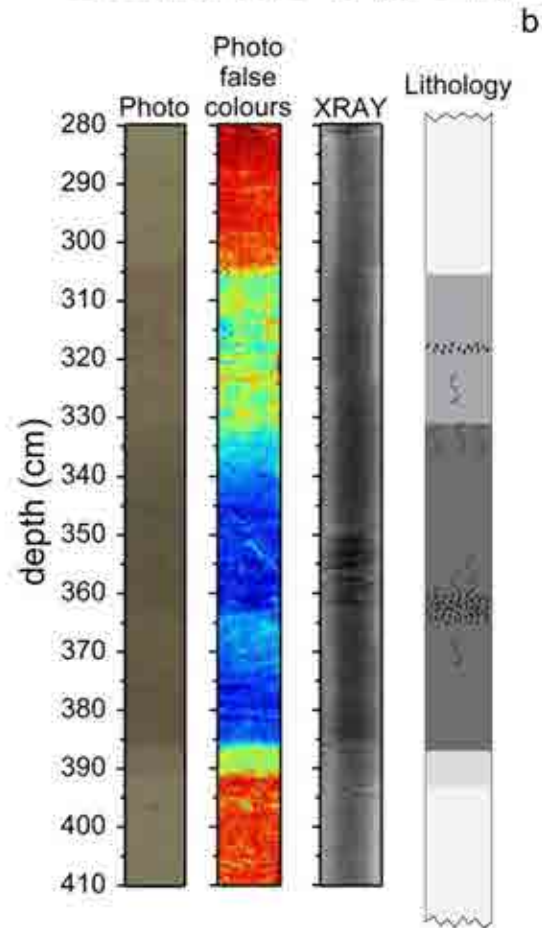




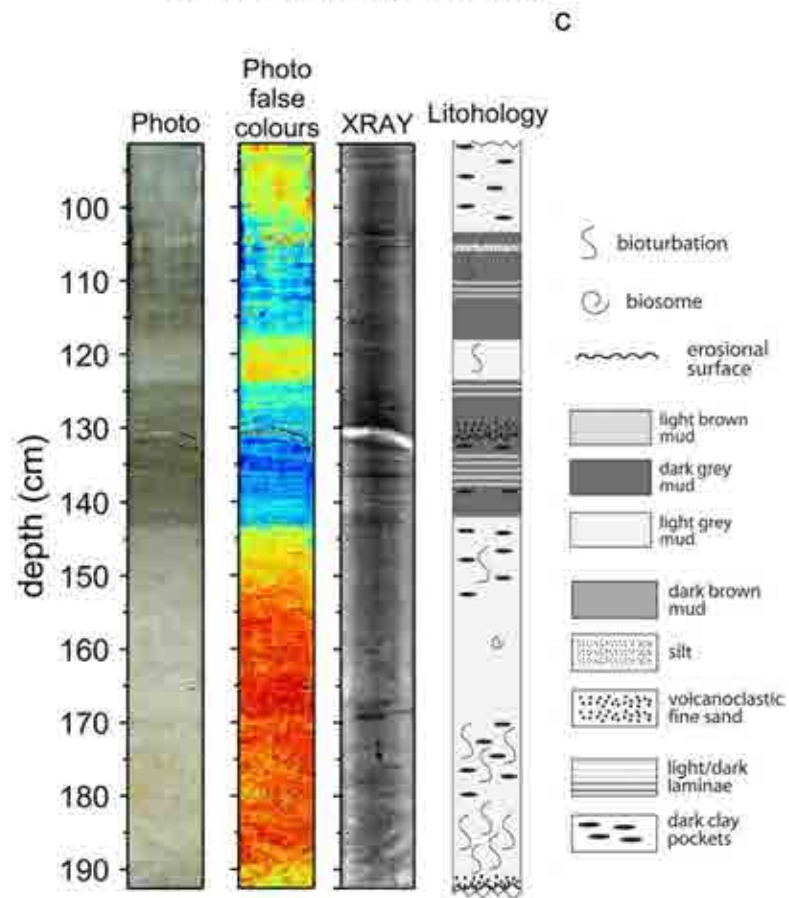
core AMC99-1 (260 m)



core INVAS12-10 (570 m)



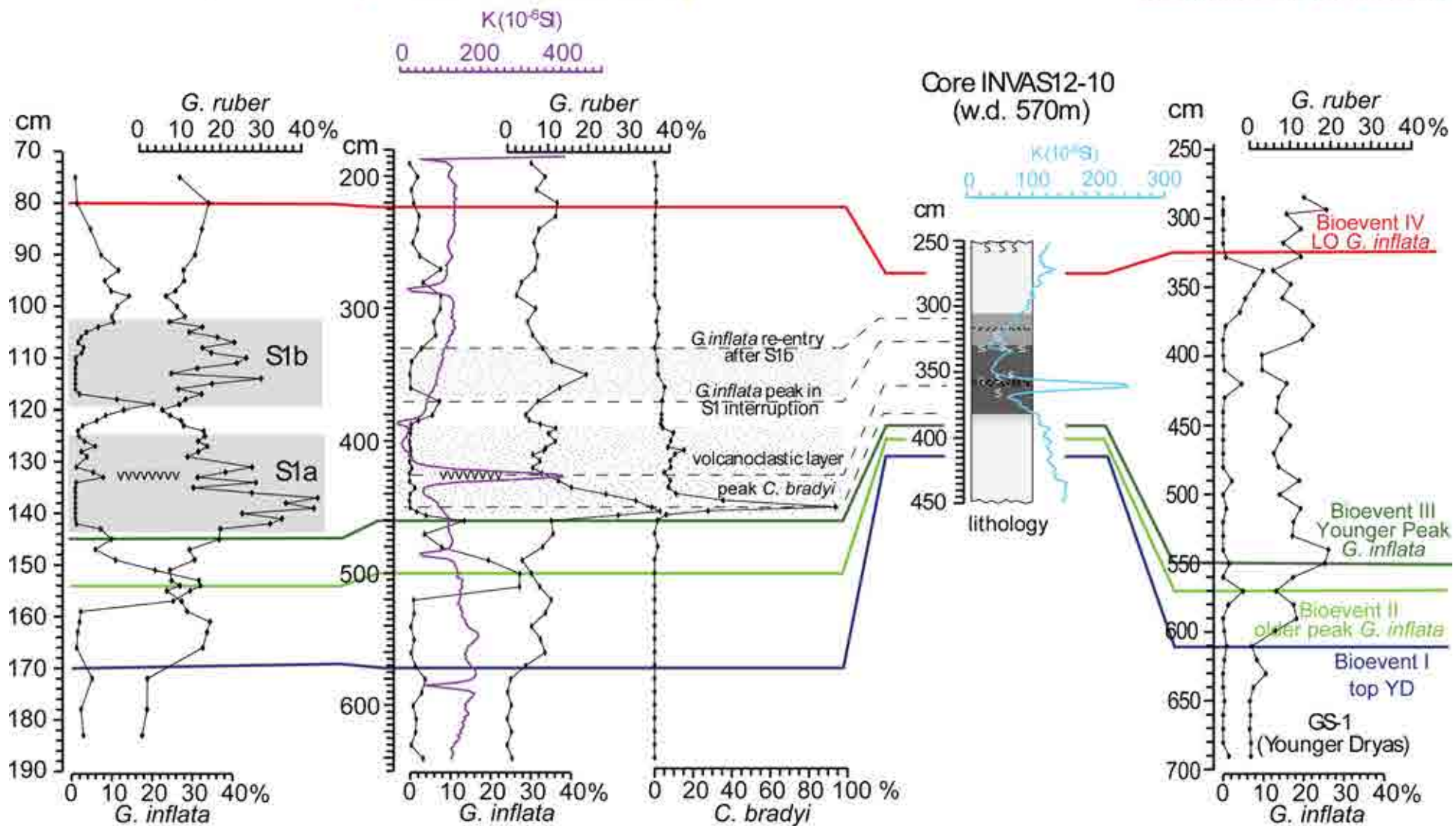
core ST04-1 (1085 m)

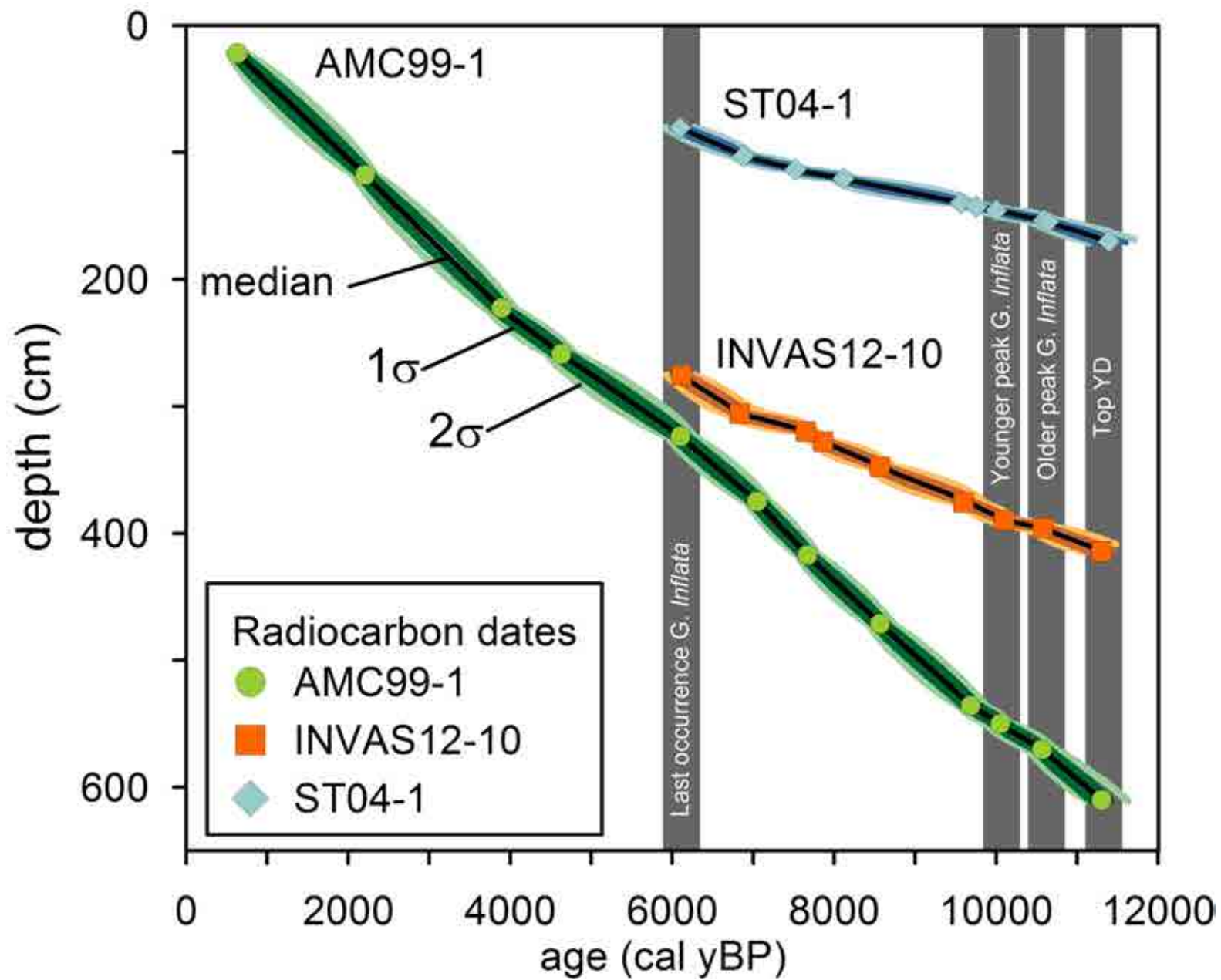


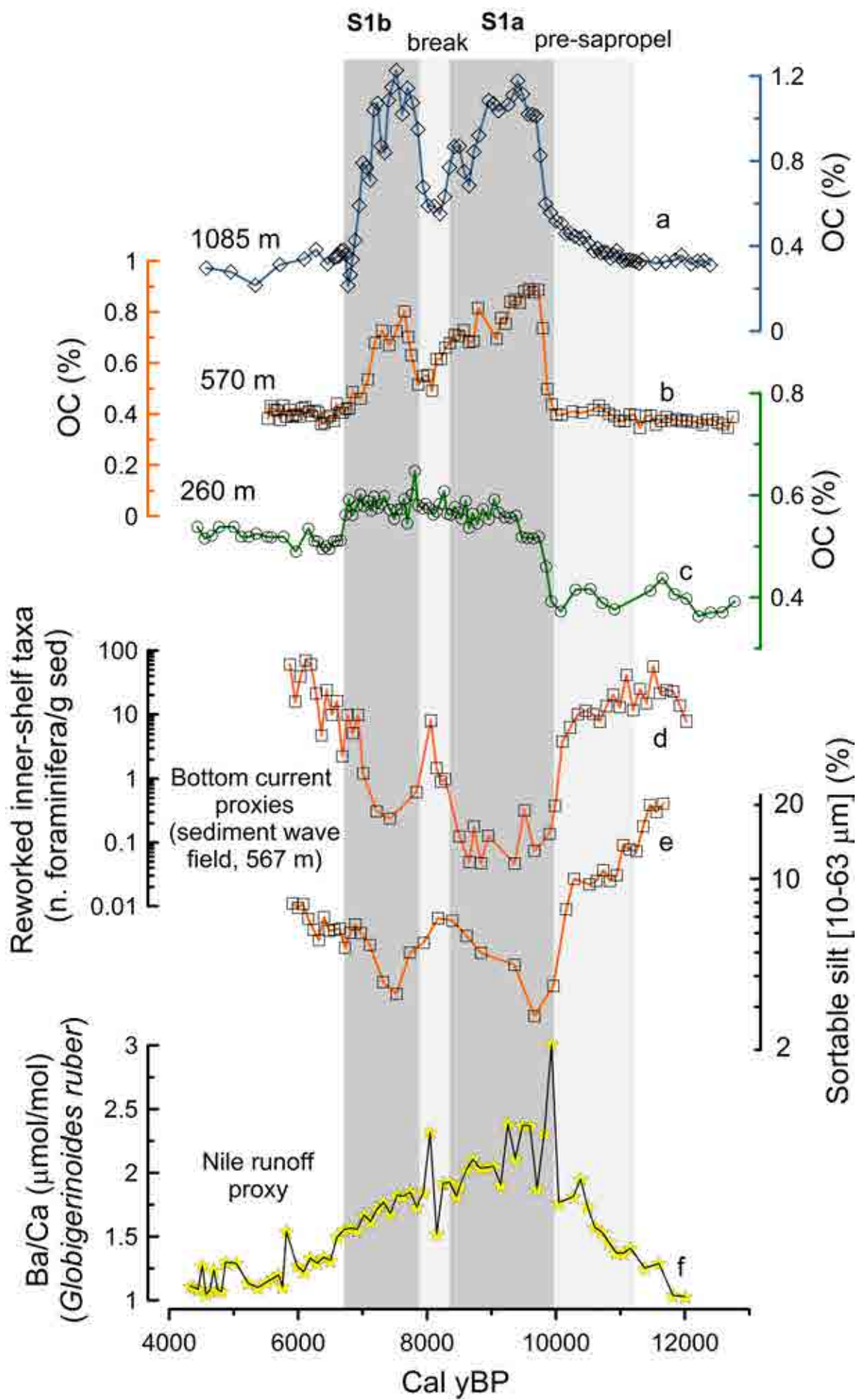
Core ST04-1 (w.d. 1085 m)

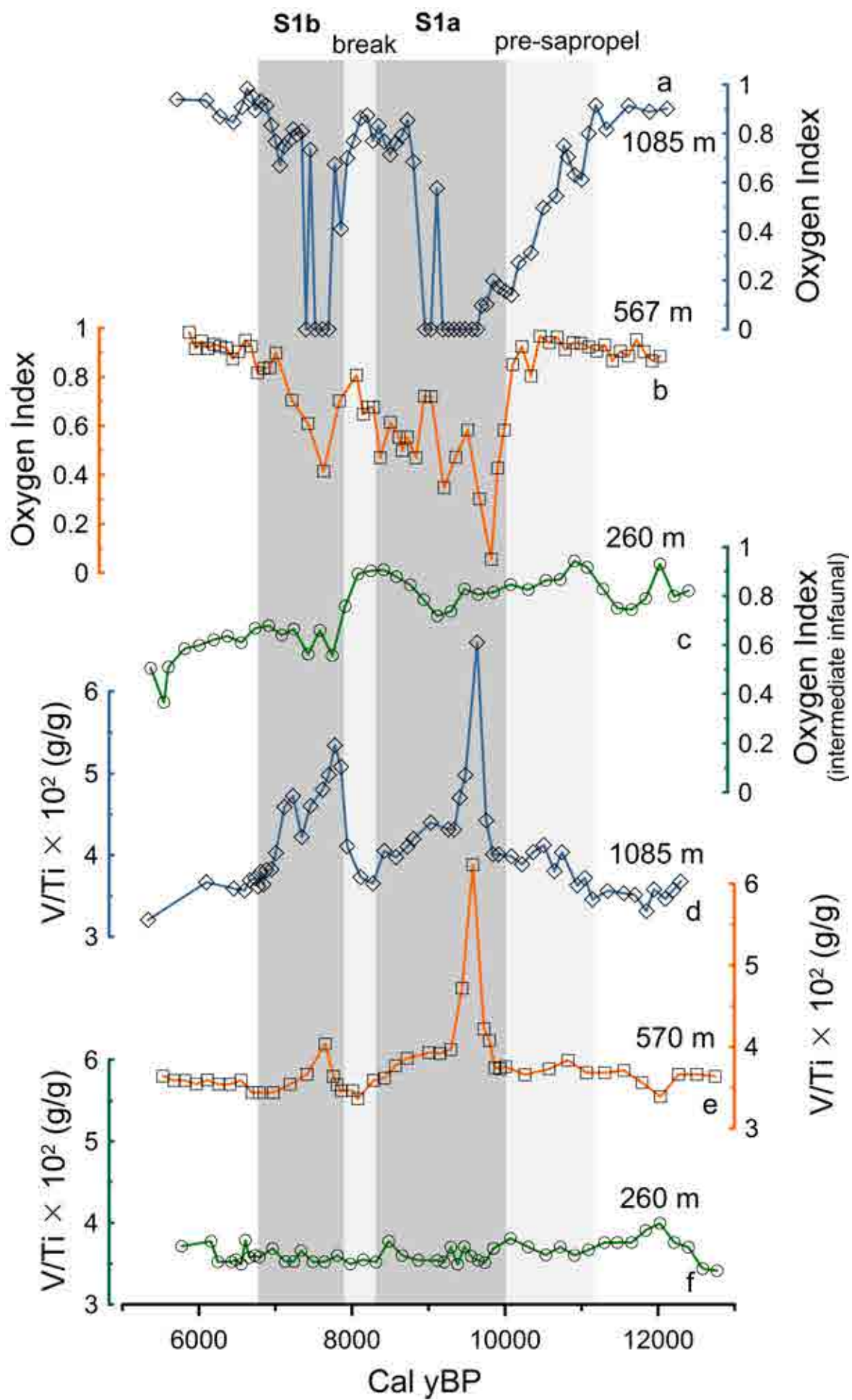
Core SA03-1 (w.d. 567 m)

Core AMC99-1 (w.d. 260 m)

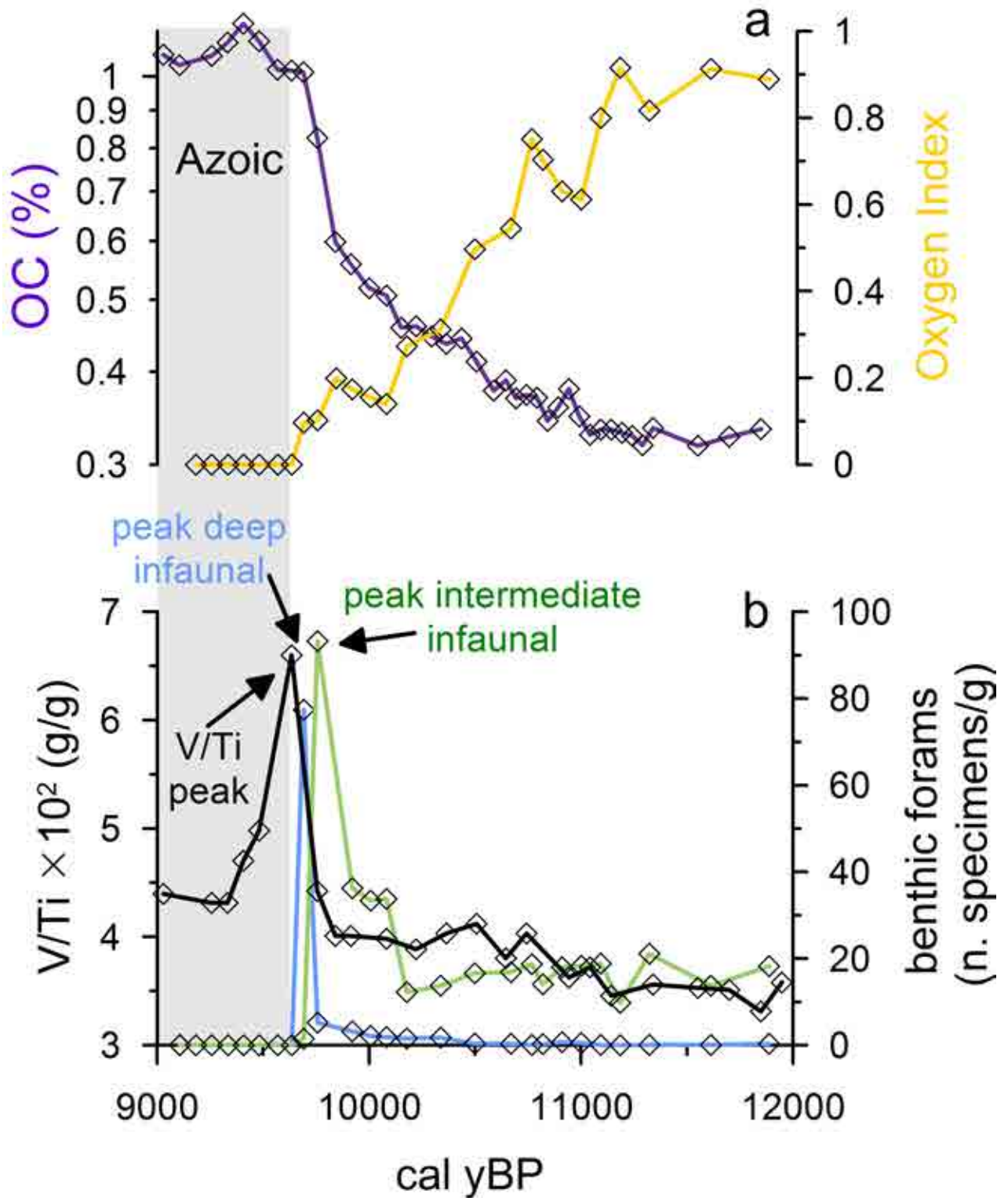


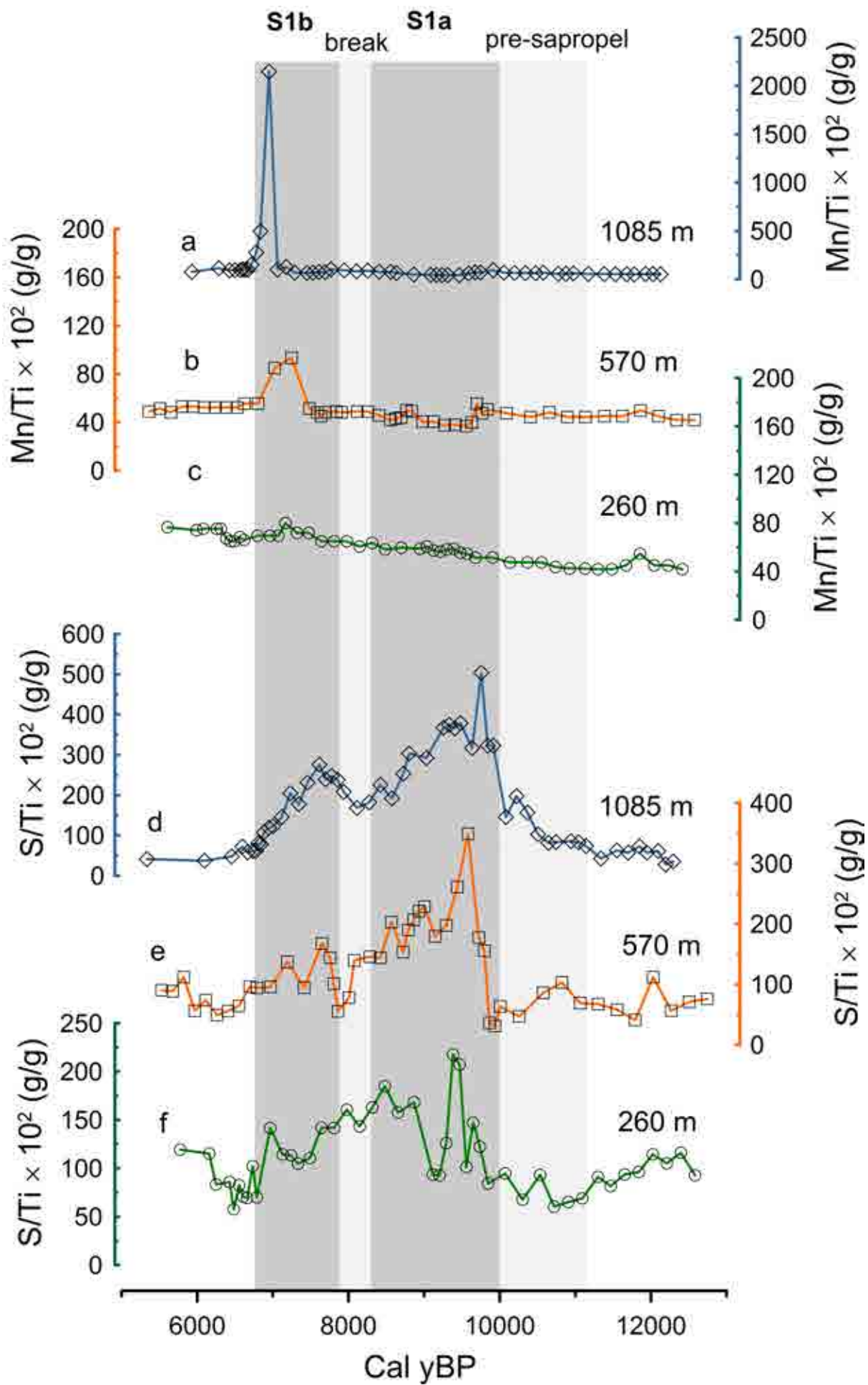




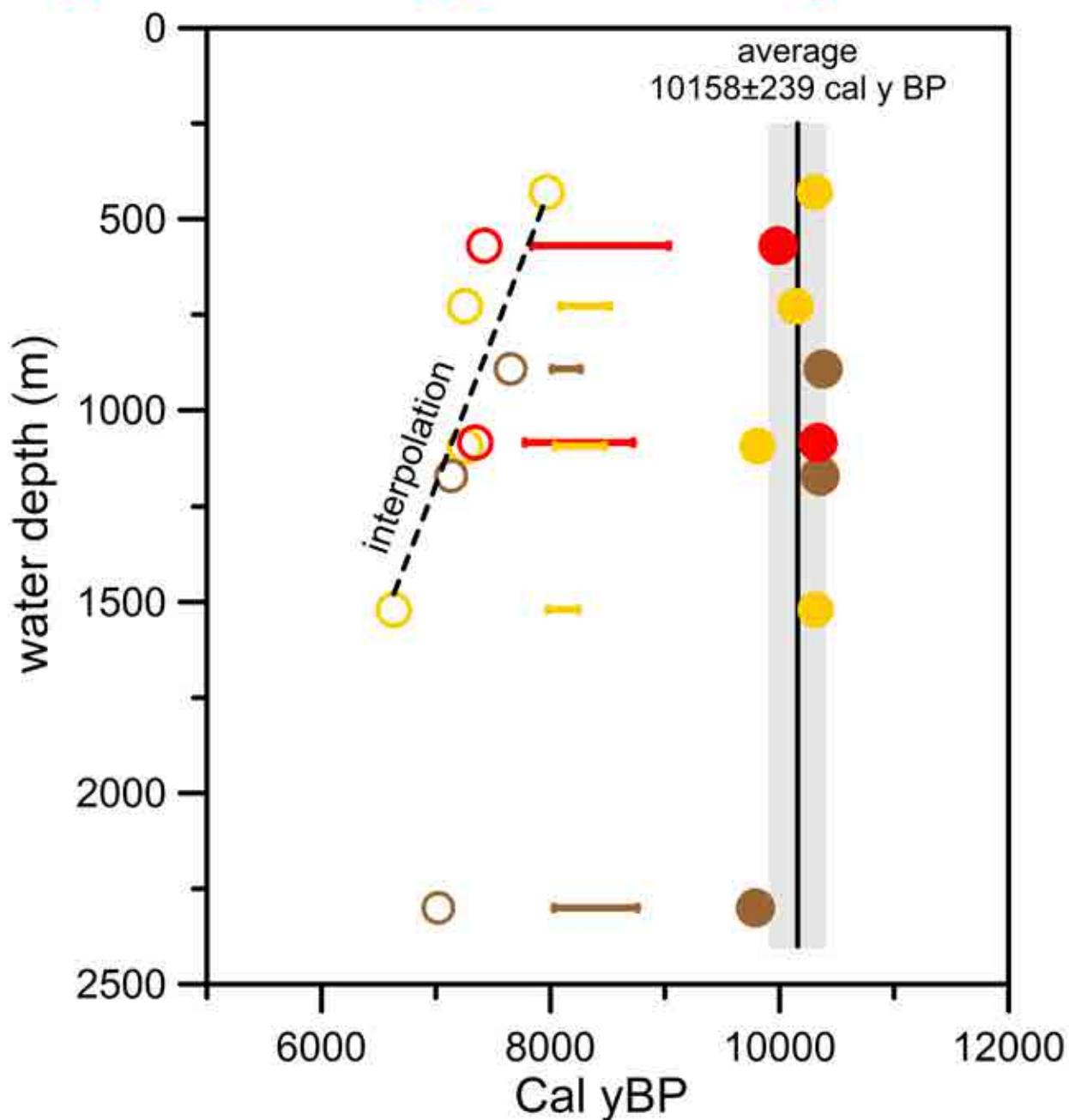


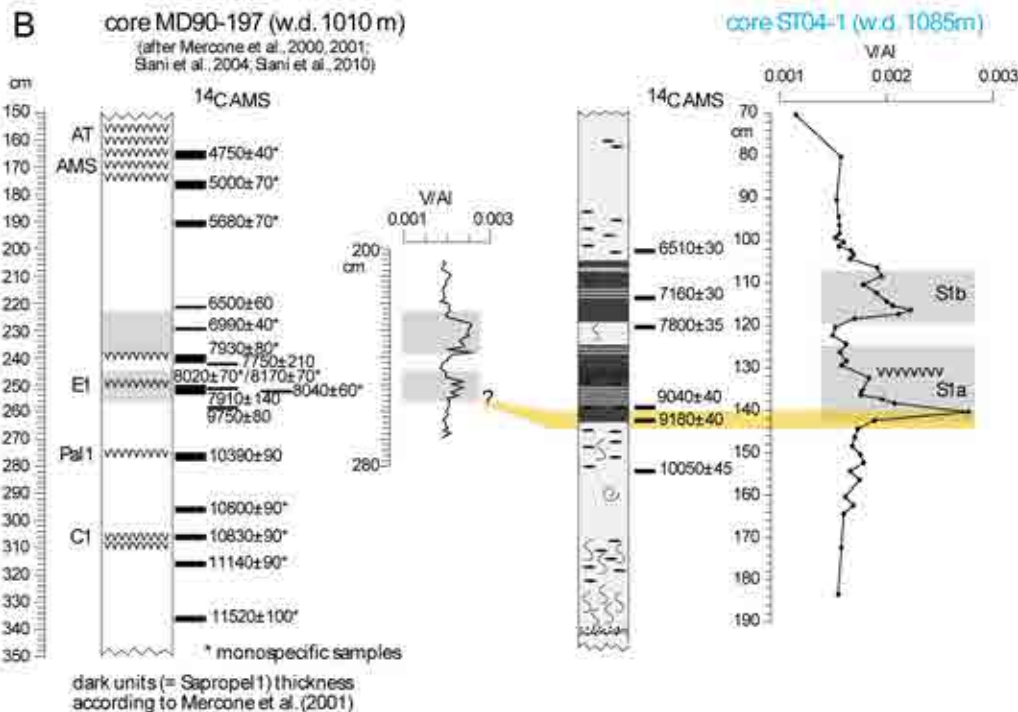
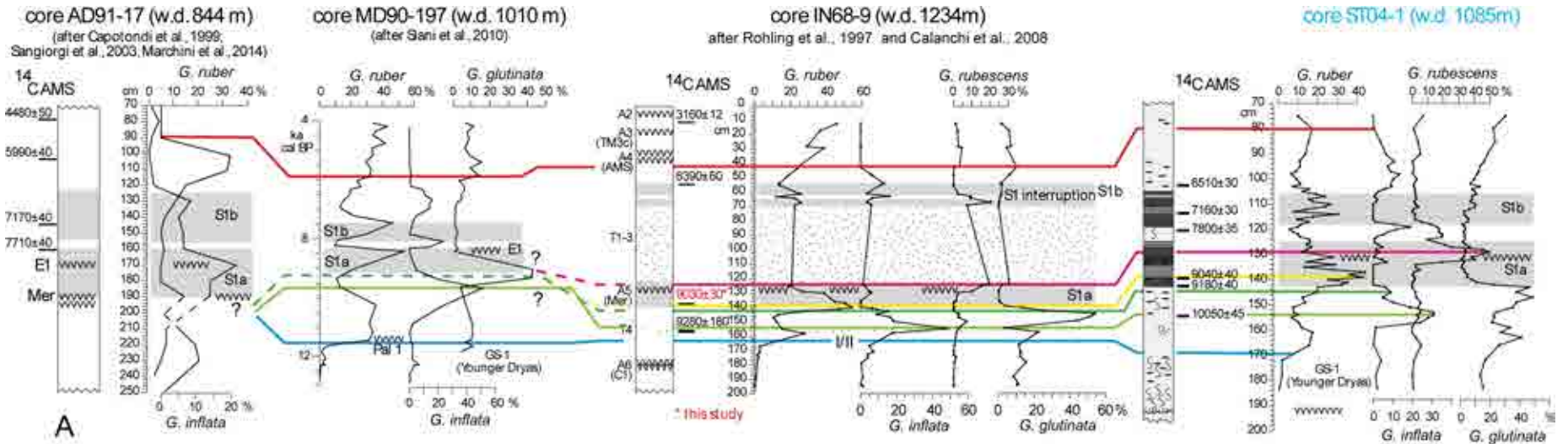
core ST04-1 (1085 m)



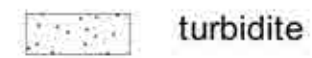


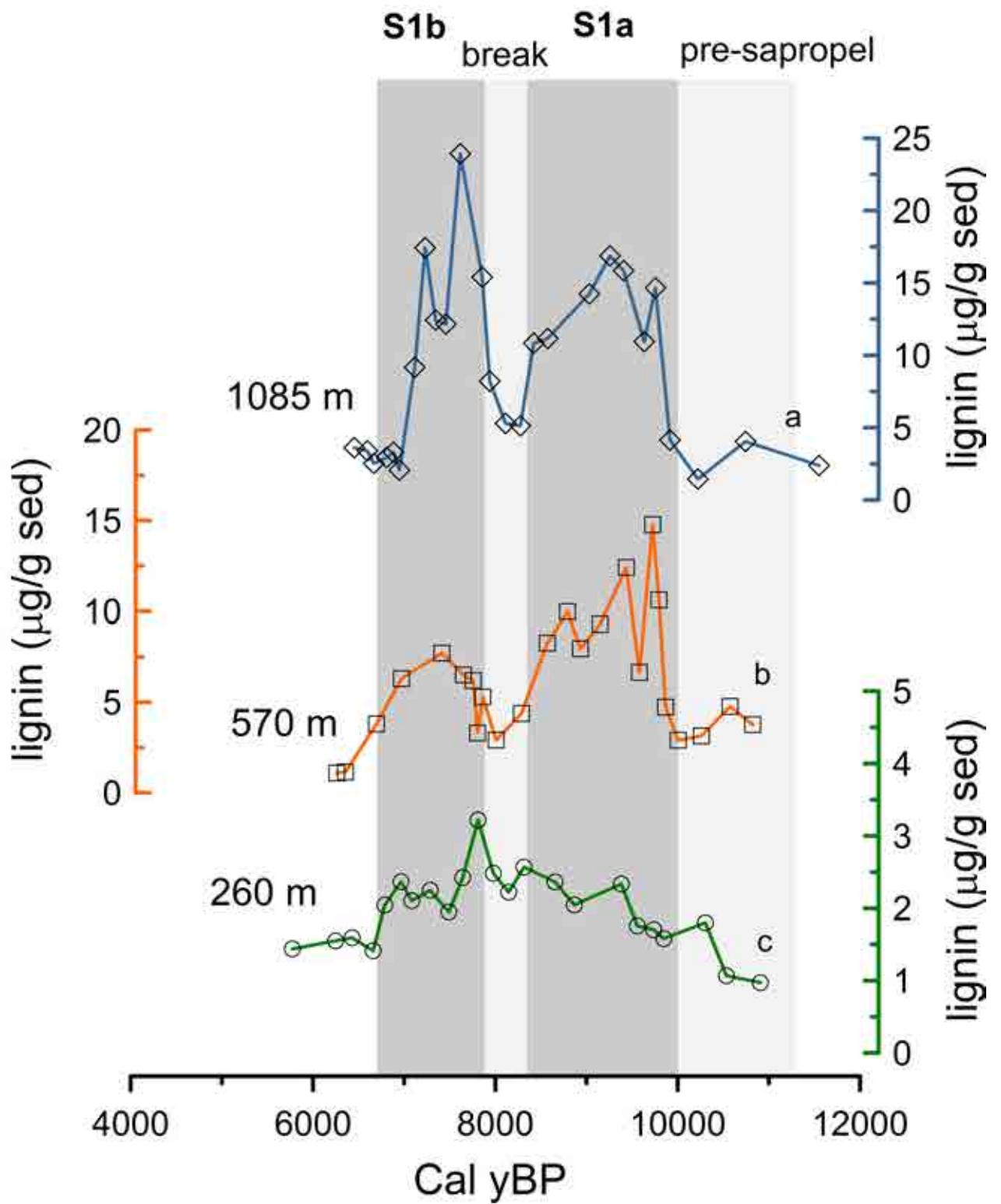
| | | |
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| Benthic collapse oxygen index < 0.5 | Intra-S1 recolonization oxygen index > 0.5 | Benthic recovery oxygen index > 0.5 |
| ● Aegean | ▬ Aegean | ○ Aegean |
| ● Levantine | ▬ Levantine | ○ Levantine |
| ● Adriatic | ▬ Adriatic | ○ Adriatic |





- Tephra layers**
- AT Astroni
 - AMS Agnano Monte Spina
 - E1 Gabellotto-Fiumebianco
 - Mer Mercato
 - Pal1 Capo Palinuro
 - C1 Agnano Pomici Principali





In this section, we revisit the age-depth model originally presented by Rohling et al. (1997) using Oxcal. The new model allows for random fluctuations in sediment deposition (P_sequence) and benefits of a new radiocarbon date (monospecific planktonic test, *G. ruber*, reference OS-127850) (Table S1). In addition to the radiocarbon tests, the model relies on well-characterized, radiocarbon dated bioevents (I,II, III, IV) as specified in the main text and Table S1. Our overarching goal is to understand whether the offset (ca. 1ky) between our results and Rohling et al. (1997) is a consequence of the age-depth model constrain. The Oxcal script used to generate the model is reported below. Particular attention was given to the agreement index which measures the coherence between the model (prior) and the observational data (likelihood).

Radiocarbon test UTC-501 (Table 1; Fig. S1,S2,S3) turned out having a low agreement index (ca. 4%) (Fig. S3) and thus considered as an outlier. Altogether, our analysis revealed that the offset derives from this radiocarbon value being relatively young.

Table S1. Radiocarbon dates of core IN68-9

| Lab. # | depth (cm) | Sample | ¹⁴ C age (yr BP) | Source |
|------------|------------|------------------------------|-----------------------------|---|
| UTC-500 | 11.5 | benthic forams | 3160 ± 120 | Rohling et al. (1997) |
| CAMS-33373 | 43 | mixed planktic | 5880 ± 60 | Bioevent IV, LO <i>G. inflata</i> (core RF93-30); Trincardi et al. (1996) |
| UTC-1607 | 54.5 | mixed planktic | 6390 ± 60 | Rohling et al. (1997) |
| OS-127850 | 137.5 | <i>Globigerinoides ruber</i> | 9030 ± 30 | this study |
| Poz-16142 | 143 | mixed planktic | 9360 ± 50 | Bioevent III, Younger peak <i>G. inflata</i> (core SA03-1); Favaretto et al. (2008) |
| Poz-16144 | 155 | mixed planktic | 9860 ± 60 | Bioevent II, Older peak <i>G. inflata</i> (core SA03-1); Favaretto et al. (2008) |
| UTC-501 | 156.5 | benthic forams | 9280 ± 180 | Rohling et al. (1997) |
| CAMS-16305 | 162.5 | mixed planktic | 10450 ± 90 | Bioevent I, Top YD (core CM92-43); Asioli et al. (2001) |
| UTC-502 | 241.5 | mixed planktic | 13100 ± 200 | Rohling et al. (1997) |

Oxcal script

```
Options()
{
  BCAD=FALSE;
};
Plot()
{
  Curve("Marine13","Marine13.14c");
  Delta_R("DeltaR based on Calib", 136, 41);

P_Sequence("variable", 1,1,U(-2,2))

  {

Boundary("bottom")

  {

    z=242;

  };

R_Date("IN68-9 241.5", 13100,200)

  {

z=241.5;

  };

R_Date("BIO I", 10450,90)

  {

z=162.5;

  };

R_Date("IN68-9", 9280,180)

  {

z=156.5;

  };

R_Date("BIO II", 9860,60)

  {

z=155;

  };
```

```
R_Date("BIO III", 9360,50)
{
z=143; };

R_Date("IN68-9 137.5", 9030,30)
{
z=137.5; };

R_Date("IN68-9 54.5", 6390,60)
{
z=54.5; };

R_Date("BIO IV", 5880,60)
{
z=43;
};

R_Date("IN68-9 10.5",3160,120)
{
z=11.5;
};

Boundary();

};
};
};
```

Likelihood

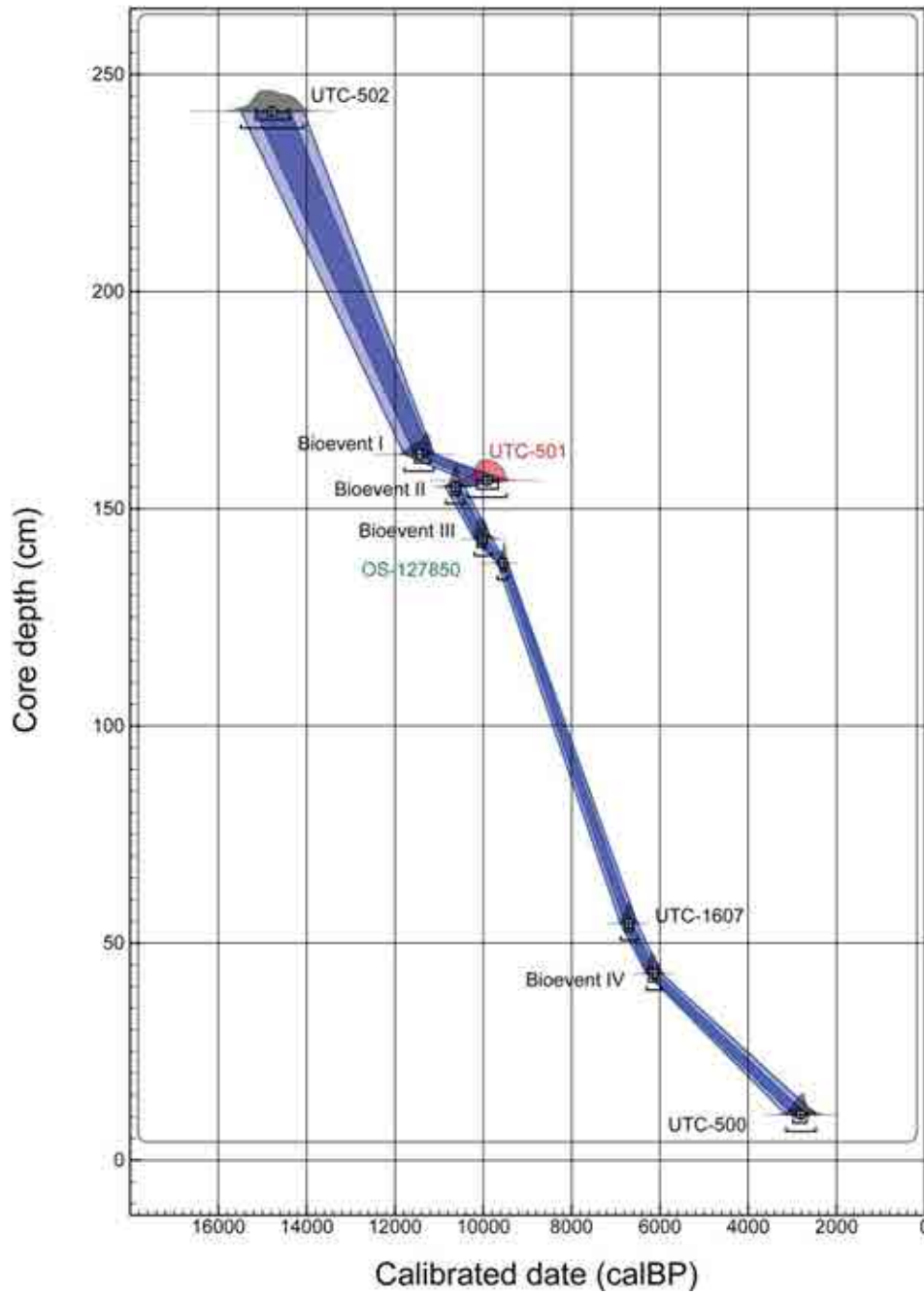


Fig. S1. Likelihood probability distributions of calibrated radiocarbon dates Light and dark blue show 1σ and 2σ , respectively.

Posteriori

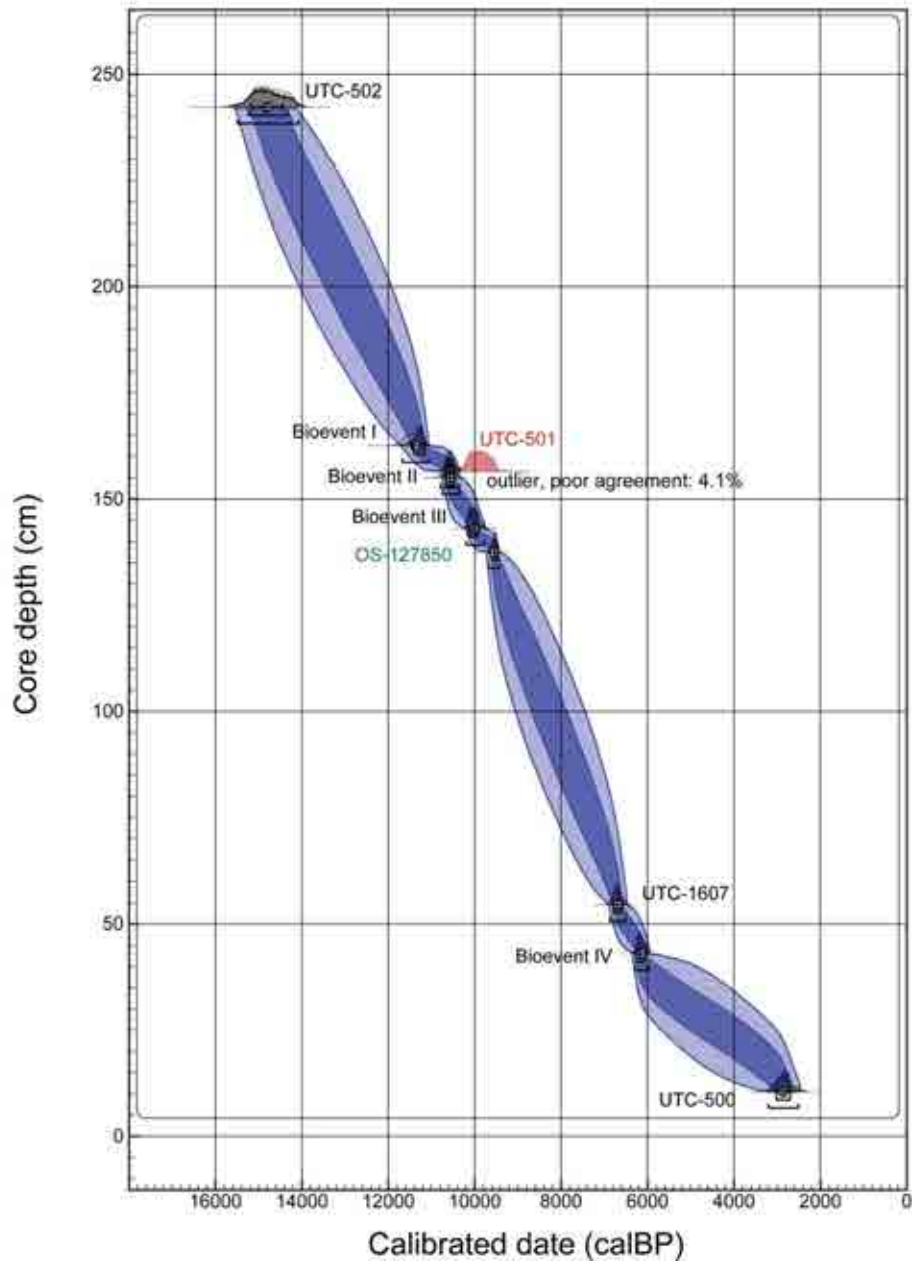


Fig. S2. Posterior probability distributions of calibrated radiocarbon dates Light and dark blue show 1σ and 2σ , respectively

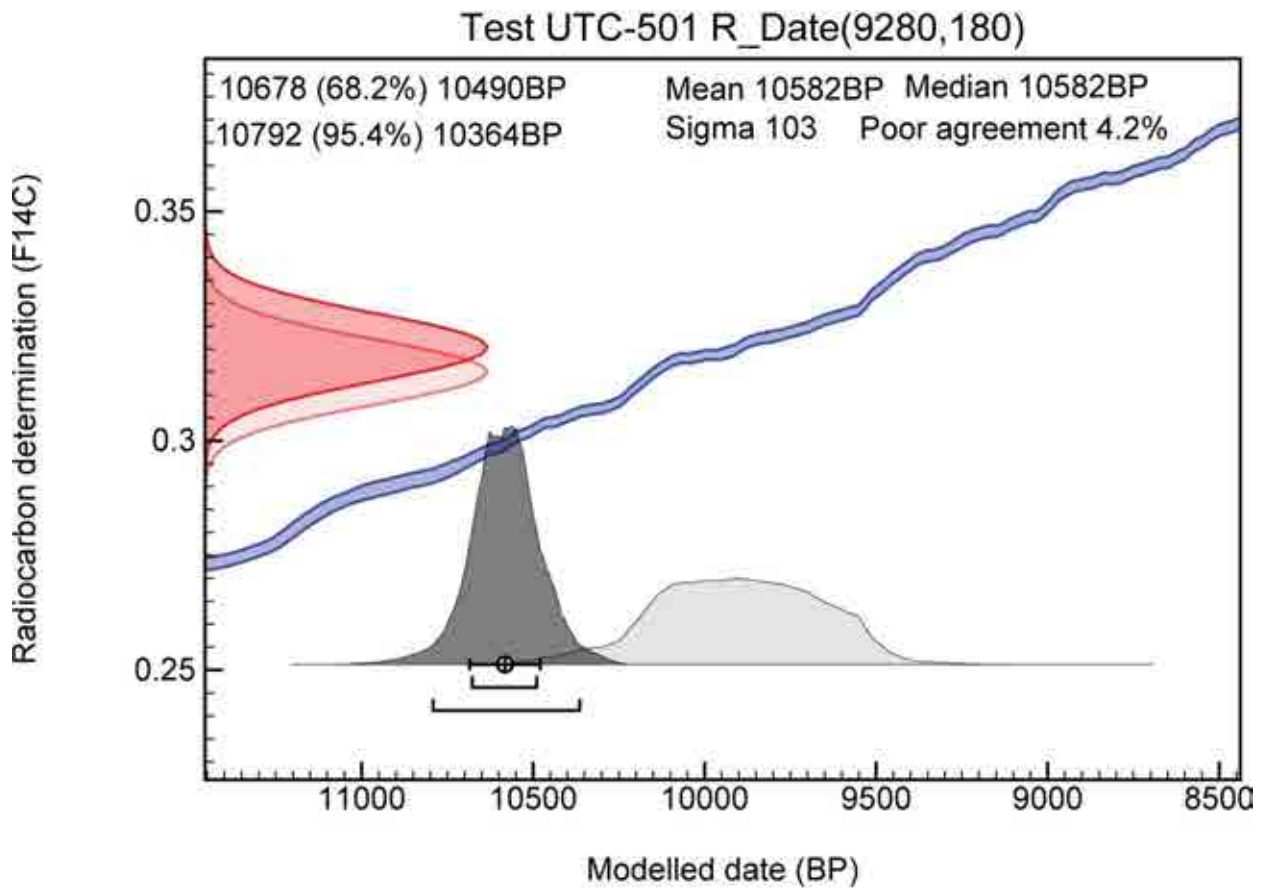


Fig. S3. Posterior probability distribution (dark grey) vs likelihood probability distribution (light gray) of test UTC-501.

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- Favaretto, S., Asioli, A., Miola, A., Piva, A., 2008. Preboreal climatic oscillations recorded by pollen and foraminifera in the southern Adriatic Sea. *Quaternary International* 190, 89-102.
- Rohling, E., Jorissen, F., De Stigter, H., 1997. 200 year interruption of Holocene sapropel formation in the Adriatic Sea. *Journal of Micropalaeontology* 16, 97-108.
- Trincardi, F., Cattaneo, A., Asioli, A., Correggiari, A., Langone, L., 1996. Stratigraphy of the late-Quaternary deposits in the central Adriatic basin and the record of short-term climatic events. *MEMORIE-ISTITUTO ITALIANO DI IDROBIOLOGIA* 55, 39-70.

The Adriatic S1 is coeval with the Eastern Mediterranean S1 deposits

The Adriatic S1 onset is synchronous with the shutdown of the NAdDW

African monsoons weakened the LIW which in turn hampered the NAdDW formation