

This is the peer reviewed version of the following article:

Large-scale response of the Eastern Mediterranean thermohaline circulation to African monsoon intensification during sapropel S1 formation / Tesi, T; Asioli, A; Minisini, D; Maselli, V; Dalla Valle, G; Gamberi, F; Langone, L; Cattaneo, A; Montagna, P; Trincardi, F. - In: QUATERNARY SCIENCE REVIEWS. - ISSN 1873-457X. - 159:(2017), pp. 139-154. [10.1016/j.quascirev.2017.01.020]

*Terms of use:*

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

04/12/2024 02:59

(Article begins on next page)

---

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

Tesi T. <sup>1,\*</sup>, Asioli A. <sup>2</sup>, Minisini D. <sup>3</sup>, Maselli V. <sup>4</sup>, Valle G. Dalla <sup>1</sup>, Gamberi F. <sup>1</sup>, Langone L. <sup>1</sup>, Cattaneo Antonio <sup>5</sup>, Montagna P. <sup>1</sup>, Trincardi F. <sup>1</sup>

<sup>1</sup> CNR, CNR ISMAR, Ist Sci Marine, Via Gobetti 101, I-40129 Bologna, Italy.

<sup>2</sup> CNR, IGG, Via G Gradenigo 6, I-35131 Padua, Italy.

<sup>3</sup> Shell Int Explorat & Prod Inc, 3333 Highway 6 South, Houston, TX 77082 USA.

<sup>4</sup> Univ Aberdeen, Dept Geol & Petr Geol, Kings Coll, St Marys Bldg, Aberdeen AB24 3UF, Scotland.

<sup>5</sup> IFREMER, Geosci Marines EDROME, Ctr Brest, BP70, F-29280 Plouzane, France.

\* Corresponding author : T. Tesi, email address : [tommaso.tesi@bo.ismar.cnr.it](mailto:tommaso.tesi@bo.ismar.cnr.it)

---

### 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

49

50

51

52

## 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  
163 (Trincardi et al., 2007), in particular from outer-shelf coarser/sandy (Spagnoli et al., 2010) deposits  
164 formed during the LGM and presently swept by NAdDW.

165 ~~Reworked species used as bottom current proxy include the modern living inner-shelf species such~~  
166 ~~as *Ammonia* spp, *Elphidium* spp, *Haynesina* spp. and epiphytic species (*Asterigerinata* spp, *Buccella*~~  
167 ~~*granulata*, *Patellina corrugata*) (Jorissen, 1988) corresponding to Biofacies II and III in the Adriatic. We~~  
168 ~~interpret the presence of these displaced species by sediment shedding from shallower waters (Trincardi et~~  
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 were wet sieved at 63  
191  $\mu\text{m}$ . A few drops of wet samples were checked with the microscope to examine the presence of  
192 microfossil remains. 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(NH<sub>4</sub>)<sub>2</sub>(SO<sub>4</sub>)<sub>2</sub>·6H<sub>2</sub>O 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 N<sub>2</sub> 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<sup>-1</sup> 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 <sup>14</sup>C 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 <sup>14</sup>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 δ<sup>18</sup>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 <sup>14</sup>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 <sup>14</sup>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 <sup>14</sup>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 <sup>14</sup>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<sup>-1</sup>). 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 <sup>14</sup>C 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 <sup>14</sup>C) 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  $^{14}\text{C}$ -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/TiO<sub>2</sub>; 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/TiO<sub>2</sub>) 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/TiO<sub>2</sub> 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 MnO<sub>2</sub> (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<sub>Adriatic</sub>)  
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<sup>-1</sup> 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  $10.2 \pm 0.3$  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<sub>Adriatic</sub>) 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<sub>Adriatic</sub> ~~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)<sup>45</sup>, 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~~<sub>d, e</sub>), 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 <sup>14</sup>C 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 <sup>14</sup>C 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 <sup>14</sup>C) 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  $\Delta R$  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.

633

634

#### 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. 11-12). 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, Aa 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<sub>Adriatic</sub> (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

701

## 702 **Acknowledgments**

703 This study was supported by Shell International Exploration and Production Inc. We thank the *R/V*  
704 *URANIA* crew for at sea assistance. This is the ISMAR contribution n. XXXX. We thank Dr. L.  
705 Capotondi and Dr. L. Vigliotti for their constructive comments on the first draft of the manuscript. We  
706 also thank Dr. Daria Pasqual (University of Padova, Dept. of Geosciences) for her assistance in XRF  
707 analyses. We thank two anonymous reviewers and the Editor H. Bauch for their constructive comments.

708 We also acknowledge Prof. Gerhard Schmiedl (Universität Hamburg) and Associate Prof. Syee Weldeab  
709 (Earth Science, UC Santa Barbara) for providing published data used in this study.

710

711

712

713

714

## 715 **References**

716 Ariztegui, D., Asioli, A., Lowe, J.J., Trincardi, F., Vigliotti, L., Tamburini, F., Chondrogianni, C., Accorsi, C.A.,  
717 Bandini Mazzanti, M., Mercuri, A.M., Van der Kaars, S., McKenzie, J.A., Oldfield, F., 2000. Palaeoclimate  
718 and the formation of sapropel S1: inferences from Late Quaternary lacustrine and marine sequences in  
719 the central Mediterranean region. *Palaeogeography, Palaeoclimatology, Palaeoecology* 158, 215-240.  
720 Asioli, A., Trincardi, F., Lowe, J., Ariztegui, D., Langone, L., Oldfield, F., 2001. Sub-millennial scale climatic  
721 oscillations in the central Adriatic during the Lateglacial: palaeoceanographic implications. *Quaternary*  
722 *Science Reviews* 20, 1201-1221.

723 Asioli, A., Trincardi, F., Lowe, J., Oldfield, F., 1999. Short-term climate changes during the Last Glacial-  
724 Holocene transition: comparison between Mediterranean records and the GRIP event stratigraphy.  
725 *Journal of Quaternary Science* 14, 373-381.

726 Béthoux, J.-P., Pierre, C., 1999. Mediterranean functioning and sapropel formation: respective influences  
727 of climate and hydrological changes in the Atlantic and the Mediterranean. *Marine Geology* 153, 29-39.

728 Bianchi, G., Hall, I.R., McCave, I., Joseph, L., 1999. Measurement of the sortable silt current speed proxy  
729 using the Sedigraph 5100 and Coulter Multisizer II: Precision and accuracy. *Sedimentology* 46, 1001-  
730 1014.

731 Blockley, S.P., Lowe, J.J., Walker, M.J., Asioli, A., Trincardi, F., Coope, G.R., Donahue, R.E., 2004. Bayesian  
732 analysis of radiocarbon chronologies: examples from the European Late-glacial. *Journal of Quaternary*  
733 *Science* 19, 159-175.

734 Bouloubassi, I., Rullkötter, J., Meyers, P.A., 1999. Origin and transformation of organic matter in  
735 Pliocene-Pleistocene Mediterranean sapropels: organic geochemical evidence reviewed. *Marine*  
736 *Geology* 153, 177-197.

737 Bröder, L., Tesi, T., Salvadó, J.A., Semiletov, I.P., Dudarev, O.V., Gustafsson, Ö., 2016. Fate of terrigenous  
738 organic matter across the Laptev Sea from the mouth of the Lena River to the deep sea of the Arctic  
739 interior. *Biogeosciences* 13, 5003-5019.

740 Calanchi, N., Dinelli, E., 2008. Tephrostratigraphy of the last 170 ka in sedimentary successions from the  
741 Adriatic Sea. *Journal of Volcanology and Geothermal Research* 177, 81-95.

742 Calvert, S., Nielsen, B., Fontugne, M., 1992. Evidence from nitrogen isotope ratios for enhanced  
743 productivity during formation of eastern Mediterranean sapropels.

744 Capotondi, L., Borsetti, A.M., Morigi, C., 1999. Foraminiferal ecozones, a high resolution proxy for the  
745 late Quaternary biochronology in the central Mediterranean Sea. *Marine Geology* 153, 253-274.

746 Caron, B., Siani, G., Sulpizio, R., Zanchetta, G., Paterne, M., Santacroce, R., Tema, E., Zanella, E., 2012.  
747 Late Pleistocene to Holocene tephrostratigraphic record from the Northern Ionian Sea. *Marine Geology*  
748 311, 41-51.

749 Cheddadi, R., Rossignol-Strick, M., 1995. Improved preservation of organic matter and pollen in eastern  
750 Mediterranean sapropels. *Paleoceanography* 10, 301-309.

751 Combourieu-Nebout, N., Peyron, O., Bout-Roumazeilles, V., Goring, S., Dormoy, I., Joannin, S., Sadori, L.,  
752 Siani, G., Magny, M., 2013. Holocene vegetation and climate changes in the central Mediterranean  
753 inferred from a high-resolution marine pollen record (Adriatic Sea). *Climate of the Past* 9, 2023-2042.

754 De Lange, G.J., Thomson, J., Reitz, A., Slomp, C.P., Principato, M.S., Erba, E., Corselli, C., 2008.  
755 Synchronous basin-wide formation and redox-controlled preservation of a Mediterranean sapropel.  
756 *Nature Geoscience* 1, 606-610.

757 Favaretto, S., Asioli, A., Miola, A., Piva, A., 2008. Preboreal climatic oscillations recorded by pollen and  
758 foraminifera in the southern Adriatic Sea. *Quaternary International* 190, 89-102.

759 Filippidi, A., Triantaphyllou, M.V., De Lange, G.J., 2016. Eastern-Mediterranean ventilation variability  
760 during sapropel S1 formation, evaluated at two sites influenced by deep-water formation from Adriatic  
761 and Aegean Seas. *Quaternary Science Reviews* 144, 95-106.

762 Giunta, S., Negri, A., Morigi, C., Capotondi, L., Combourieu-Nebout, N., Emeis, K., Sangiorgi, F., Vigliotti,  
763 L., 2003. Coccolithophorid ecostratigraphy and multi-proxy paleoceanographic reconstruction in the  
764 Southern Adriatic Sea during the last deglacial time (Core AD91-17). *Palaeogeography,*  
765 *Palaeoclimatology, Palaeoecology* 190, 39-59.

766 Gogou, A., Bouloubassi, I., Lykousis, V., Arnaboldi, M., Gaitani, P., Meyers, P.A., 2007. Organic  
767 geochemical evidence of Late Glacial-Holocene climate instability in the North Aegean Sea.  
768 *Palaeogeography, Palaeoclimatology, Palaeoecology* 256, 1-20.

769 Gordon, E.S., Goñi, M.A., 2003. Sources and distribution of terrigenous organic matter delivered by the  
770 Atchafalaya River to sediments in the northern Gulf of Mexico. *Geochimica et Cosmochimica Acta* 67,  
771 2359-2375.

772 Grimm, R., Maier-Reimer, E., Mikolajewicz, U., Schmiedl, G., Müller-Navarra, K., Adloff, F., Grant, K.M.,  
773 Ziegler, M., Lourens, L.J., Emeis, K.-C., 2015. Late glacial initiation of Holocene eastern Mediterranean  
774 sapropel formation. *Nature communications* 6.

775 Hennekam, R., Jilbert, T., Schnetger, B., Lange, G.J., 2014. Solar forcing of Nile discharge and sapropel S1  
776 formation in the early to middle Holocene eastern Mediterranean. *Paleoceanography* 29, 343-356.

777 Hilgen, F., 1991. Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and  
778 implication for the geomagnetic polarity time scale. *Earth and planetary science letters* 104, 226-244.

779 Jorissen, F.J., 1988. Benthic foraminifera from the Adriatic Sea: principles of phenotypic variation.  
780 *Utrecht Micropaleontological Bulletins* 37.

781 Jorissen, F.J., 1999. Benthic foraminiferal successions across Late Quaternary Mediterranean sapropels.  
782 *Marine Geology* 153, 91-101.

783 Jorissen, F.J., Asioli, A., Borsetti, A., Capotondi, L., De Visser, J., Hilgen, F., Rohling, E., Van der Borg, K.,  
784 Grazzini, C.V., Zachariasse, W., 1993. Late quaternary central Mediterranean biochronology. *Marine*  
785 *Micropaleontology* 21, 169-189.

786 Klein, B., Roether, W., Civitarese, G., Gacic, M., Manca, B.B., d'Alcala, M.R., 2000. Is the Adriatic returning  
787 to dominate the production of Eastern Mediterranean Deep Water. *Geophys. Res. Lett* 27, 3377-3380.

788 Kotthoff, U., Pross, J., Müller, U.C., Peyron, O., Schmiedl, G., Schulz, H., Bordon, A., 2008. Climate  
789 dynamics in the borderlands of the Aegean Sea during formation of sapropel S1 deduced from a marine  
790 pollen record. *Quaternary Science Reviews* 27, 832-845.

791 Langgut, D., Almogi-Labin, A., Bar-Matthews, M., Weinstein-Evron, M., 2011. Vegetation and climate  
792 changes in the South Eastern Mediterranean during the Last Glacial-Interglacial cycle (86 ka): new marine  
793 pollen record. *Quaternary Science Reviews* 30, 3960-3972.

794 Langone, L., Conese, I., Miserocchi, S., Boldrin, A., Bonaldo, D., Carniel, S., Chiggiato, J., Turchetto, M.,  
795 Borghini, M., Tesi, T., 2015. Dynamics of particles along the western margin of the Southern Adriatic:  
796 Processes involved in transferring particulate matter to the deep basin. *Marine Geology*.

797 Lowe, J.J., Blockley, S., Trincardi, F., Asioli, A., Cattaneo, A., Matthews, I.P., Pollard, M., Wulf, S., 2007.  
798 Age modelling of late Quaternary marine sequences in the Adriatic: Towards improved precision and  
799 accuracy using volcanic event stratigraphy. *Continental Shelf Research* 27, 560-582.

800 Magny, M., Combourieu-Nebout, N., De Beaulieu, J., Bout-Roumazeilles, V., Colombaroli, D., Desprat, S.,  
801 Francke, A., Joannin, S., Peyron, O., Revel, M., 2013. North-south palaeohydrological contrasts in the  
802 central Mediterranean during the Holocene: tentative synthesis and working hypotheses. *Climate of the*  
803 *Past Discussions* 9, 1901-1967 (IF 1903,1509).

804 Magny, M., Joannin, S., Galop, D., Vannièrè, B., Haas, J.N., Bassetti, M., Bellintani, P., Scandolari, R.,  
805 Desmet, M., 2012. Holocene palaeohydrological changes in the northern Mediterranean borderlands as  
806 reflected by the lake-level record of Lake Ledro, northeastern Italy. *Quaternary Research* 77, 382-396.

807 Marchini, G., Zanchetta, G., Santacrose, R., Vigliotti, L., Capotondi, L., Sulpizio, R., 2014.  
808 Tephrostratigraphy of marine core AD91-17 (Adriatic Sea) Revised. *Alpine and Mediterranean*  
809 *Quaternary* 27, 77-84.

810 Marini, M., Maselli, V., Campanelli, A., Fogliani, F., Grilli, F., 2015. Role of the Mid-Adriatic deep in dense  
811 water interception and modification. *Marine Geology*.

812 Marino, G., Rohling, E.J., Sangiorgi, F., Hayes, A., Casford, J.L., Lotter, A.F., Kucera, M., Brinkhuis, H., 2009.  
813 Early and middle Holocene in the Aegean Sea: interplay between high and low latitude climate  
814 variability. *Quaternary Science Reviews* 28, 3246-3262.

815 McCave, I., Hall, I.R., 2006. Size sorting in marine muds: Processes, pitfalls, and prospects for  
816 paleoflow-speed proxies. *Geochemistry, Geophysics, Geosystems* 7.



817 Mercone, D., Thomson, J., Abu-Zied, R., Croudace, I., Rohling, E., 2001. High-resolution geochemical and  
818 micropalaeontological profiling of the most recent eastern Mediterranean sapropel. *Marine Geology*  
819 177, 25-44.

820 Mercone, D., Thomson, J., Croudace, I., Siani, G., Paterne, M., Troelstra, S., 2000. Duration of S1, the  
821 most recent sapropel in the eastern Mediterranean Sea, as indicated by accelerator mass spectrometry  
822 radiocarbon and geochemical evidence. *Paleoceanography* 15, 336-347.

823 Millot, C., 1999. Circulation in the western Mediterranean Sea. *Journal of Marine Systems* 20, 423-442.

824 Minisini, D., Trincardi, F., Asioli, A., 2006. Evidence of slope instability in the Southwestern Adriatic  
825 Margin. *Natural Hazards and Earth System Science* 6, 1-20.

826 Möbius, J., Lahajnar, N., Emeis, K.-C., 2010. Diagenetic control of nitrogen isotope ratios in Holocene  
827 sapropels and recent sediments from the Eastern Mediterranean Sea. *Biogeosciences* 7, 3901-3914.

828 Narciso, Á., Flores, J.-A., Cachão, M., Piva, A., Asioli, A., Andersen, N., Schneider, R., 2012. Late Glacial-  
829 Holocene transition in the southern Adriatic Sea: Coccolithophore and Foraminiferal evidence.  
830 *micropaleontology*, 523-538.

831 Nieuwenhuize, J., Maas, Y.E.M., Middelburg, J.J., 1994. Rapid analysis of organic carbon and nitrogen in  
832 particulate materials. *Marine Chemistry* 45, 217-224.

833 Nijenhuis, I., Schenau, S., Van der Weijden, C., Hilgen, F., Lourens, L., Zachariasse, W., 1996. On the origin  
834 of upper Miocene sapropelites: a case study from the Faneromeni section, Crete (Greece).  
835 *Paleoceanography* 11, 633-645.

836 Passier, H.F., Middelburg, J.J., de Lange, G.J., Böttcher, M.E., 1997. Pyrite contents, microtextures, and  
837 sulfur isotopes in relation to formation of the youngest eastern Mediterranean sapropel. *Geology* 25,  
838 519-522.

839 Piva, A., 2007. *Stratigrafia ad alta risoluzione dei depositi Quaternari in Adriatico centrale e*  
840 *meridionale: impatto di cambiamenti climatici a scala sub-Milankoviana sulla circolazione in*  
841 *Mediterraneo*, University of Bologna. Bologna, Bologna.

842 Piva, A., Asioli, A., Trincardi, F., Schneider, R.R., Vigliotti, L., 2008. Late-Holocene climate variability in the  
843 Adriatic sea (Central Mediterranean). *The Holocene* 18, 153-167.

844 Ramsey, C.B., 1995. Radiocarbon calibration and analysis of stratigraphy; the OxCal program.  
845 *Radiocarbon* 37, 425-430.

846 Ramsey, C.B., Lee, S., 2013. Recent and planned developments of the program OxCal. *Radiocarbon* 55,  
847 720-730.

848 Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H.,  
849 Edwards, R.L., Friedrich, M., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000  
850 years cal BP.

851 Reitz, A., Thomson, J., de Lange, G.J., Hensen, C., 2006. Source and development of large manganese  
852 enrichments above eastern Mediterranean sapropel S1. *Paleoceanography* 21.

853 Rogerson, M., Cacho, I., Jimenez-Espejo, F., Reguera, M.I., Sierro, F.J., Martinez-Ruiz, F., Frigola, J.,  
854 Canals, M., 2008. A dynamic explanation for the origin of the western Mediterranean organic-rich layers.  
855 *Geochemistry, Geophysics, Geosystems* 9, n/a-n/a.

856 Rohling, E., Bryden, H., 1994. Estimating past changes in the Eastern Mediterranean freshwater budget,  
857 using reconstructions of sea level and hydrography. *Proceedings of the Koninklijke Nederlandse*  
858 *Akademie van Wetenschappen* 97, 201-217.

859 Rohling, E., Jorissen, F., De Stigter, H., 1997. 200 year interruption of Holocene sapropel formation in the  
860 Adriatic Sea. *Journal of Micropalaeontology* 16, 97-108.

861 Rohling, E., Marino, G., Grant, K., 2015. Mediterranean climate and oceanography, and the periodic  
862 development of anoxic events (sapropels). *Earth-Science Reviews* 143, 62-97.

863 Rossignol-Strick, M., 1985. Mediterranean Quaternary sapropels, an immediate response of the African  
864 monsoon to variation of insolation. *Palaeogeography, palaeoclimatology, palaeoecology* 49, 237-263.

865 Rossignol-Strick, M., Nesteroff, W., Olive, P., Vergnaud-Grazzini, C., 1982. After the deluge:  
866 Mediterranean stagnation and sapropel formation.

867 Sachs, J.P., Repeta, D.J., 1999. Oligotrophy and nitrogen fixation during eastern Mediterranean sapropel  
868 events. *Science* 286, 2485-2488.

869 Sangiorgi, F., Capotondi, L., Combourieu Nebout, N., Vigliotti, L., Brinkhuis, H., Giunta, S., Lotter, A.F.,  
870 Morigi, C., Negri, A., Reichart, G.J., 2003. Holocene seasonal sea-surface temperature variations in the  
871 southern Adriatic Sea inferred from a multiproxy approach. *Journal of Quaternary Science* 18, 723-732.

872 Santacroce, R., Cioni, R., Marianelli, P., Sbrana, A., Sulpizio, R., Zanchetta, G., Donahue, D.J., Joron, J.L.,  
873 2008. Age and whole rock-glass compositions of proximal pyroclastics from the major explosive  
874 eruptions of Somma-Vesuvius: a review as a tool for distal tephrostratigraphy. *Journal of Volcanology  
875 and Geothermal Research* 177, 1-18.

876 Santvoort, P., Lange, G., Langereis, C., Dekkers, M., Paterne, M., 1997. Geochemical and paleomagnetic  
877 evidence for the occurrence of "missing" sapropels in eastern Mediterranean sediments.  
878 *Paleoceanography* 12, 773-786.

879 Schmiedl, G., Kuhnt, T., Ehrmann, W., Emeis, K.-C., Hamann, Y., Kotthoff, U., Dulski, P., Pross, J., 2010.  
880 Climatic forcing of eastern Mediterranean deep-water formation and benthic ecosystems during the past  
881 22 000 years. *Quaternary Science Reviews* 29, 3006-3020.

882 Schmiedl, G., Mitschele, A., Beck, S., Emeis, K.-C., Hemleben, C., Schulz, H., Sperling, M., Weldeab, S.,  
883 2003. Benthic foraminiferal record of ecosystem variability in the eastern Mediterranean Sea during  
884 times of sapropel S 5 and S 6 deposition. *Palaeogeography, Palaeoclimatology, Palaeoecology* 190, 139-  
885 164.

886 Siani, G., Magny, M., Paterne, M., Debret, M., Fontugne, M., 2013. Paleohydrology reconstruction and  
887 Holocene climate variability in the South Adriatic Sea. *Climate of the Past* 9, 499-515.

888 Siani, G., Paterne, M., Arnold, M., Bard, E., Métivier, B., Tisnerat, N., Bassinot, F., 2000. Radiocarbon  
889 reservoir ages in the Mediterranean Sea and Black Sea. *Radiocarbon* 42, 271-280.

890 Siani, G., Paterne, M., Colin, C., 2010. Late glacial to Holocene planktic foraminifera bioevents and  
891 climatic record in the South Adriatic Sea. *Journal of Quaternary Science* 25, 808-821.

892 Spagnoli, F., Dell'Anno, A., De Marco, A., Dinelli, E., Fabiano, M., Gadaleta, M.V., Ianni, C., Loiacono, F.,  
893 Manini, E., Marini, M., 2010. Biogeochemistry, grain size and mineralogy of the central and southern  
894 Adriatic Sea sediments: a review. *Chemistry and Ecology* 26, 19-44.

895 Spötl, C., Nicolussi, K., Patzelt, G., Boch, R., 2010. Humid climate during deposition of sapropel 1 in the  
896 Mediterranean Sea: Assessing the influence on the Alps. *Global and Planetary Change* 71, 242-248.

897 Tachikawa, K., Vidal, L., Cornuault, M., Garcia, M., Pothin, A., Sonzogni, C., Bard, E., Menot, G., Revel, M.,  
898 2015. Eastern Mediterranean Sea circulation inferred from the conditions of S1 sapropel deposition.  
899 *Clim. Past* 11, 855-867.

900 Tesi, T., Langone, L., Goni, M., Turchetto, M., Miserocchi, S., Boldrin, A., 2008. Source and composition of  
901 organic matter in the Bari canyon (Italy): dense water cascading versus particulate export from the upper  
902 ocean. *Deep Sea Research Part I: Oceanographic Research Papers* 55, 813-831.

903 Tesi, T., Miserocchi, S., Goni, M.e.a., Langone, L., Boldrin, A., Turchetto, M., 2007. Organic matter origin  
904 and distribution in suspended particulate materials and surficial sediments from the western Adriatic Sea  
905 (Italy). *Estuarine, Coastal and Shelf Science* 73, 431-446.

906 Tesi, T., Semiletov, I., Hugelius, G., Dudarev, O., Kuhry, P., Gustafsson, Ö., 2014. Composition and fate of  
907 terrigenous organic matter along the Arctic land-ocean continuum in East Siberia: Insights from  
908 biomarkers and carbon isotopes. *Geochimica et Cosmochimica Acta* 133, 235-256.

909 Toucanne, S., Minto'o, C.M.A., Fontanier, C., Bassetti, M.-A., Jorry, S.J., Jouet, G., 2015. Tracking rainfall  
910 in the northern Mediterranean borderlands during sapropel deposition. *Quaternary Science Reviews*  
911 129, 178-195.

912 Trincardi, F., Cattaneo, A., Asioli, A., Correggiari, A., Langone, L., 1996. Stratigraphy of the late-  
913 Quaternary deposits in the central Adriatic basin and the record of short-term climatic events.  
914 MEMORIE-ISTITUTO ITALIANO DI IDROBIOLOGIA 55, 39-70.  
915 Trincardi, F., Verdicchio, G., Miserocchi, S., 2007. Seafloor evidence for the interaction between  
916 cascading and along-slope bottom water masses. *Journal of Geophysical Research: Earth Surface* 112.  
917 Turchetto, M., Boldrin, A., Langone, L., Miserocchi, S., Tesi, T., Foglini, F., 2007. Particle transport in the  
918 Bari canyon (southern Adriatic Sea). *Marine Geology* 246, 231-247.  
919 Van Straaten, L., 1970. Holocene and late-Pleistocene sedimentation in the Adriatic Sea. *Geologische*  
920 *Rundschau* 60, 106-131.  
921 Versteegh, G.J.M., Zonneveld, K.A.F., de Lange, G.J., 2010. Selective aerobic and anaerobic degradation  
922 of lipids and palynomorphs in the Eastern Mediterranean since the onset of sapropel S1 deposition.  
923 *Marine Geology* 278, 177-192.  
924 Vigliotti, L., Asioli, A., Bergami, C., Capotondi, L., Piva, A., 2011. Magnetic properties of the youngest  
925 sapropel S1 in the Ionian and Adriatic Sea: inference for the timing and mechanism of sapropel  
926 formation. *Italian journal of geosciences* 130, 106-118.  
927 Vigliotti, L., Verosub, K., Cattaneo, A., Trincardi, F., Asioli, A., Piva, A., 2008. Palaeomagnetic and rock  
928 magnetic analysis of Holocene deposits from the Adriatic Sea: detecting and dating short-term  
929 fluctuations in sediment supply. *The Holocene* 18, 141-152.  
930 Vilibić, I., Orlić, M., 2002. Adriatic water masses, their rates of formation and transport through the  
931 Otranto Strait. *Deep Sea Research Part I: Oceanographic Research Papers* 49, 1321-1340.  
932 Vilibić, I., Supić, N., 2005. Dense water generation on a shelf: the case of the Adriatic Sea. *Ocean*  
933 *Dynamics* 55, 403-415.  
934 Weldeab, S., Menke, V., Schmiedl, G., 2014. The pace of East African monsoon evolution during the  
935 Holocene. *Geophysical Research Letters* 41, 1724-1732.  
936 Zanchetta, G., Drysdale, R.N., Hellstrom, J.C., Fallick, A.E., Isola, I., Gagan, M.K., Pareschi, M.T., 2007.  
937 Enhanced rainfall in the Western Mediterranean during deposition of sapropel S1: stalagmite evidence  
938 from Corchia cave (Central Italy). *Quaternary Science Reviews* 26, 279-286.

939

940

941

942

943

944

945

946

947

948

949  
950  
951  
952  
953  
954  
955

**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

964  
965  
966  
967  
968  
969  
970  
971  
972  
973  
974  
975  
976  
977  
978

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).

983  
984  
985  
986

987  
988  
989  
990  
991  
992  
993  
994  
995  
996  
997  
998  
999  
1000  
1001  
1002  
1003  
1004  
1005  
1006  
1007  
1008

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).

1011  
1012  
1013  
1014  
1015  
1016  
1017  
1018  
1019  
1020  
1021  
1022  
1023  
1024  
1025  
1026  
1027  
1028  
1029  
1030

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*

1040

1041

1042

1043

1044

1045



1046  
1047  
1048  
1049  
1050  
1051  
1052  
1053  
1054  
1055  
1056  
1057  
1058  
1059  
1060

1061 **Figure 5.** Bayesian age-depth model of Adriatic records (median,  $1\sigma$  and  $2\sigma$ ). 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.

1068

1069  
1070  
1071  
1072  
1073  
1074  
1075  
1076  
1077  
1078  
1079  
1080  
1081  
1082  
1083  
1084  
1085  
1086  
1087

~~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 ( $^{14}\text{C}$  yBP) for a direct comparison.

1090  
1091  
1092  
1093  
1094  
1095  
1096  
1097  
1098  
1099  
1100  
1101  
1102  
1103  
1104

1105 **Figure 76.** Sapropel S1 along the Adriatic shelf-basin continuum and external environmental forcings.  
1106 Organic carbon (OC) content of (a) ST04-1, (b) INVAS12-10 and (c) AMC99-1. Note the different scale  
1107 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.

1111

1112

1113

1114

1115

1116

1117

1118

1119

1120

1121

1122

1123

1124

1125

1126

1127

1128

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~~).

1136

1137

1138

1139

1140

1141

1142

1143

1144

1145

1146

1147

1148

1149

1150

1151

1152

1153

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/TiO<sub>2</sub>). Light grey area shows the azoic environment.

1157

1158

1159

1160

1161

1162

1163

1164

1165

1166

1167

1168

1169

1170

1171

1172

1173

1174

1175

1176

1177  
1178  
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.

1185  
1186  
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).

1194  
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 (<sup>14</sup>C yBP) for a direct comparison.

1200

1201

1202  
1203  
1204  
1205  
1206  
1207  
1208  
1209  
1210  
1211  
1212  
1213  
1214  
1215

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.

1221  
1222  
1223  
1224



1225  
1226  
1227  
1228  
1229  
1230  
1231  
1232  
1233  
1234  
1235  
1236  
1237  
1238  
1239  
1240  
1241  
1242  
1243

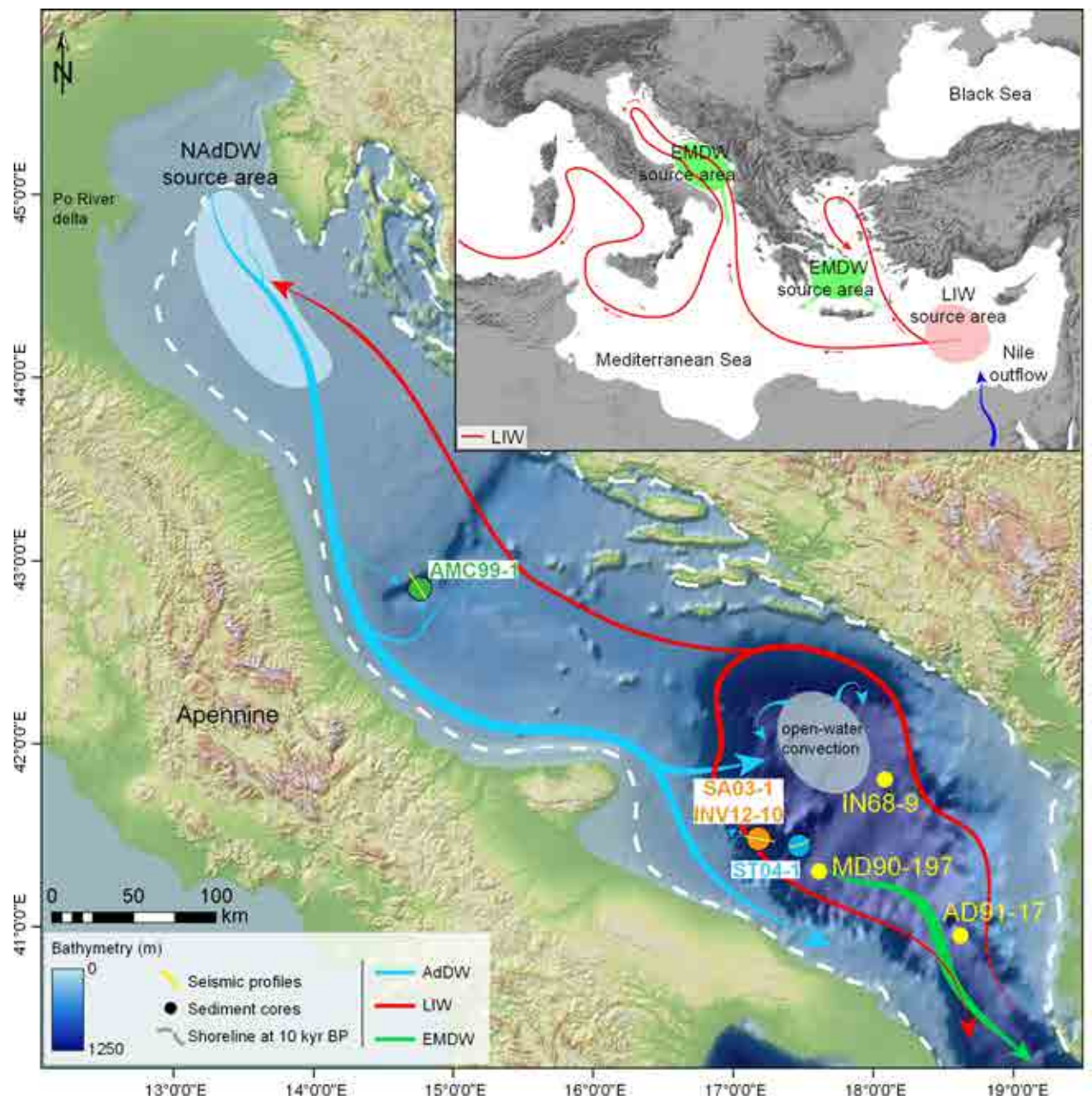
**Figure 12.** Cartoon of the thermohaline circulation: (a) modern conditions and (b) during the freshening of the Eastern Mediterranean Sea via the Nile (b). As the precipitation increases over North Africa, the Levantine Intermediate Waters (LIW) progressively decreases. This in turn hampers the preconditioning 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.

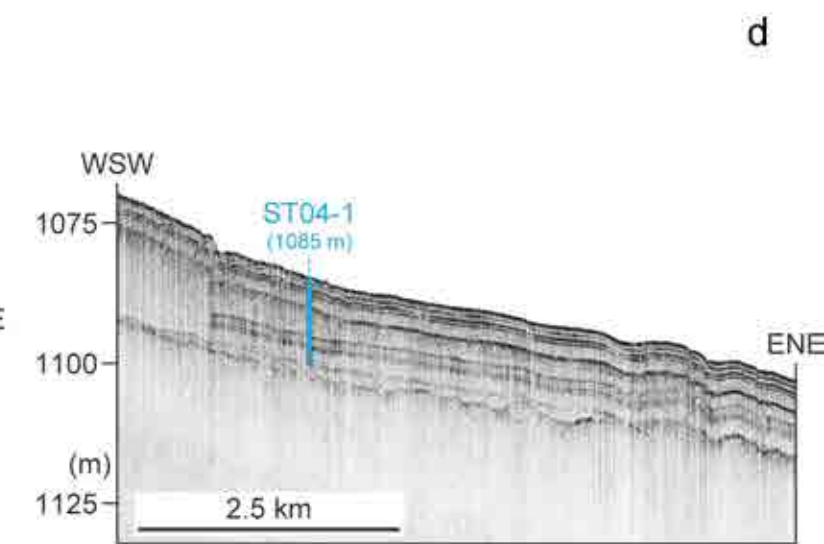
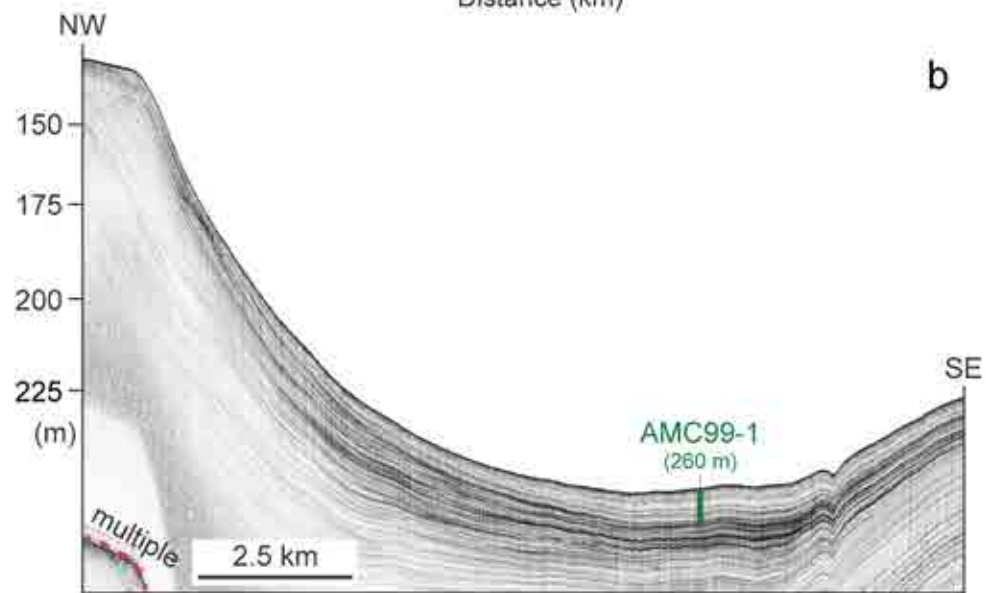
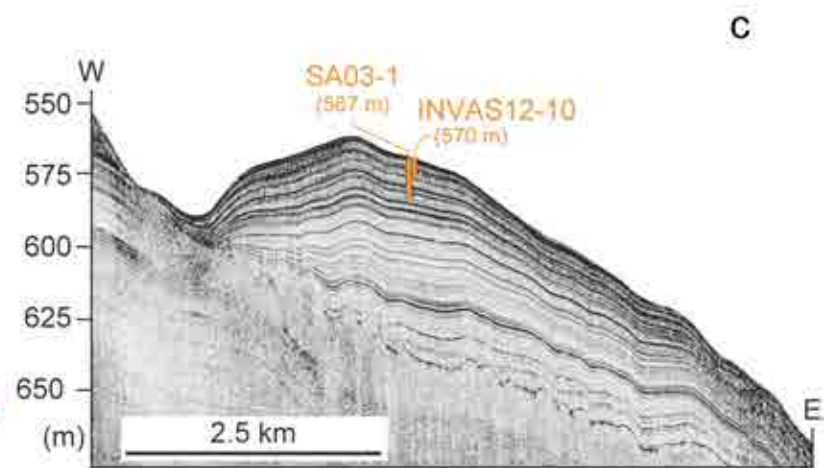
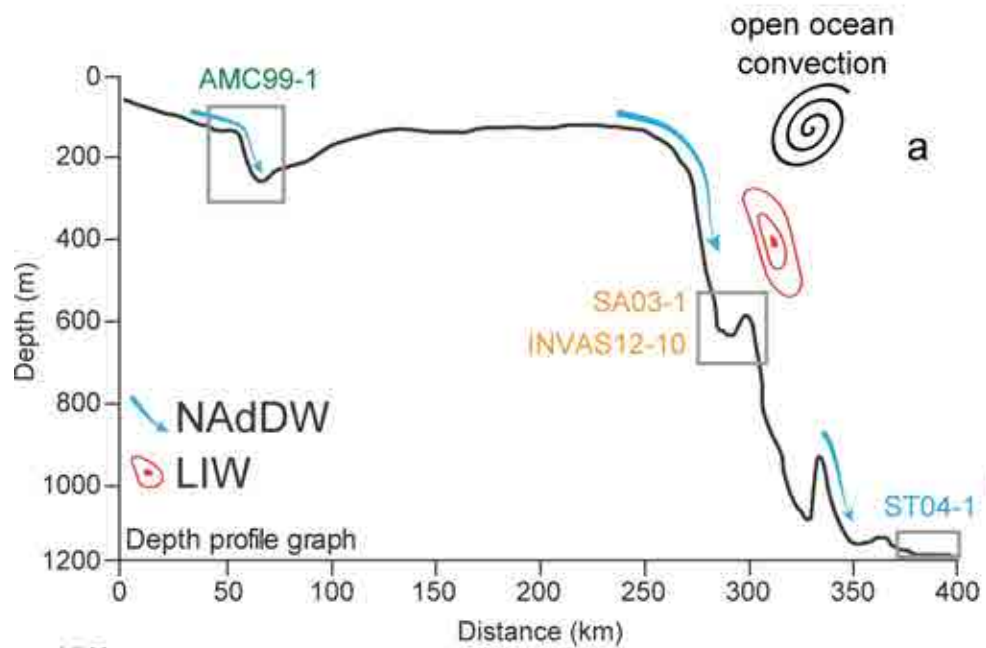
**Table S1.** Dated levels used for the Bayesian age-depth model of core AMC991, INVAS12-10, ST04-1. The table contains a new radiocarbon date of core IN68-9 as well.

Lab. #	Core depth (cm)	Sample type	<sup>14</sup> C age (yBP)	Modelled age (median, cal yBP)		Reference	
				-2σ	+2σ		
<b>AMC99-1 (260 m w.d.)</b>							
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)
<b>INVAS12-10 (570 m w.d.)</b>							
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

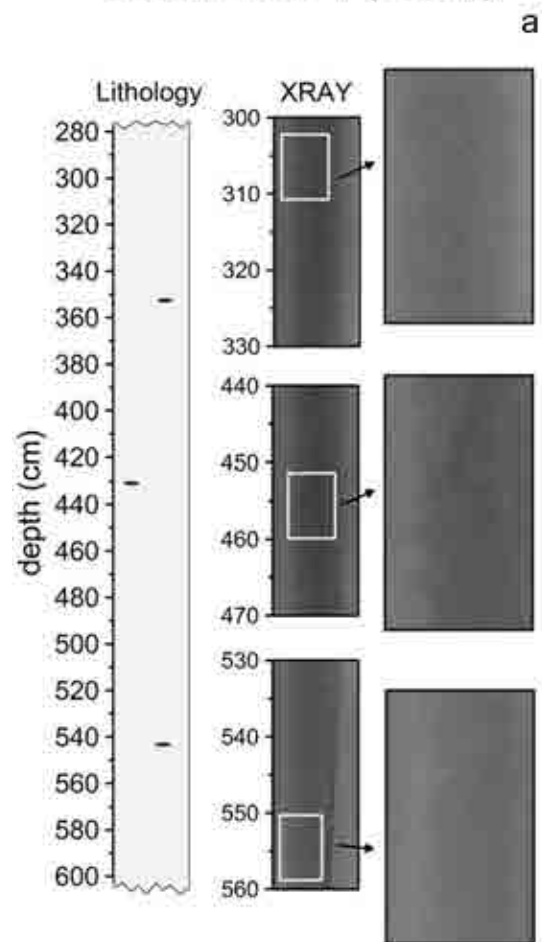
OS-104382	375-376	<i>Globigerinoides ruber</i>	9140 ± 35	9596	9982	9151	this study
Poz-16142	389-390	mixed planktic	9360 ± 50	10100	10232	9885	Bioevent III, Younger peak <i>G. inflata</i> (core SA03-1); (Favaretto et al., 2008)
Poz-16144	395-396	mixed planktic	9860 ± 60	10577	10768	10373	Bioevent II, 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)
<b>ST04-1 (1085 m w.d.)</b>							
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)
<b>IN68-9 (1234 m w.d.)</b>							
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

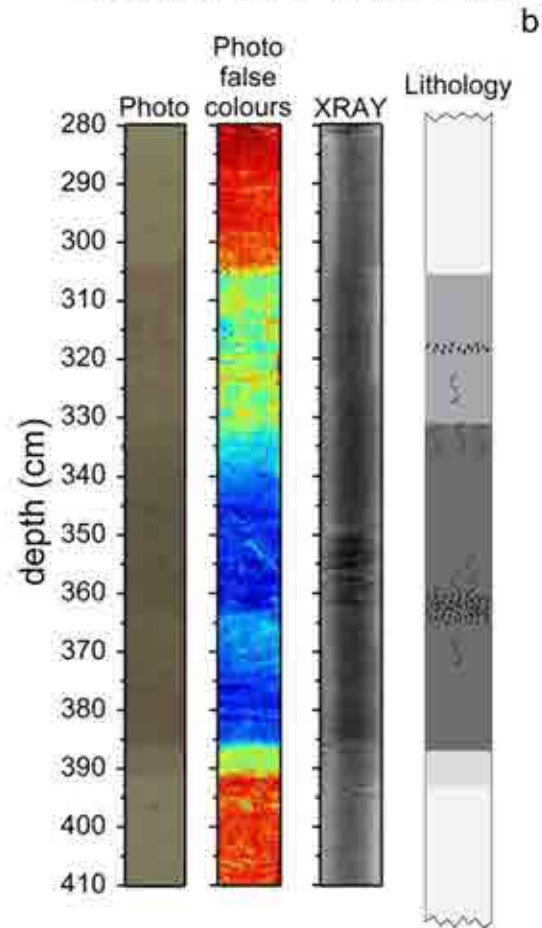




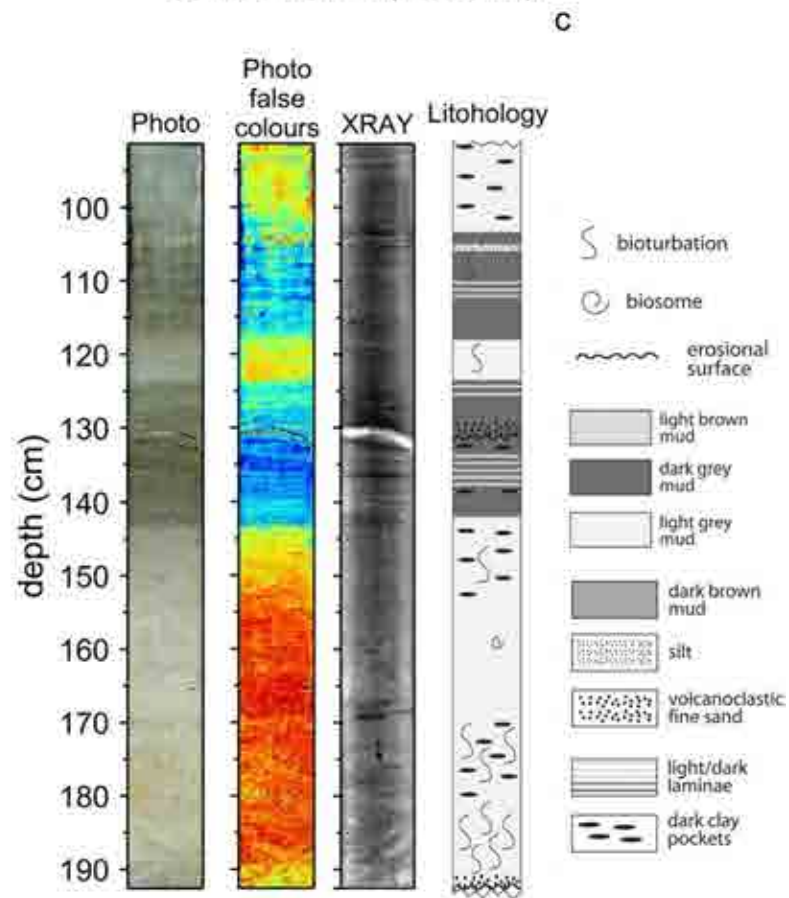
core AMC99-1 (260 m)



core INVAS12-10 (570 m)



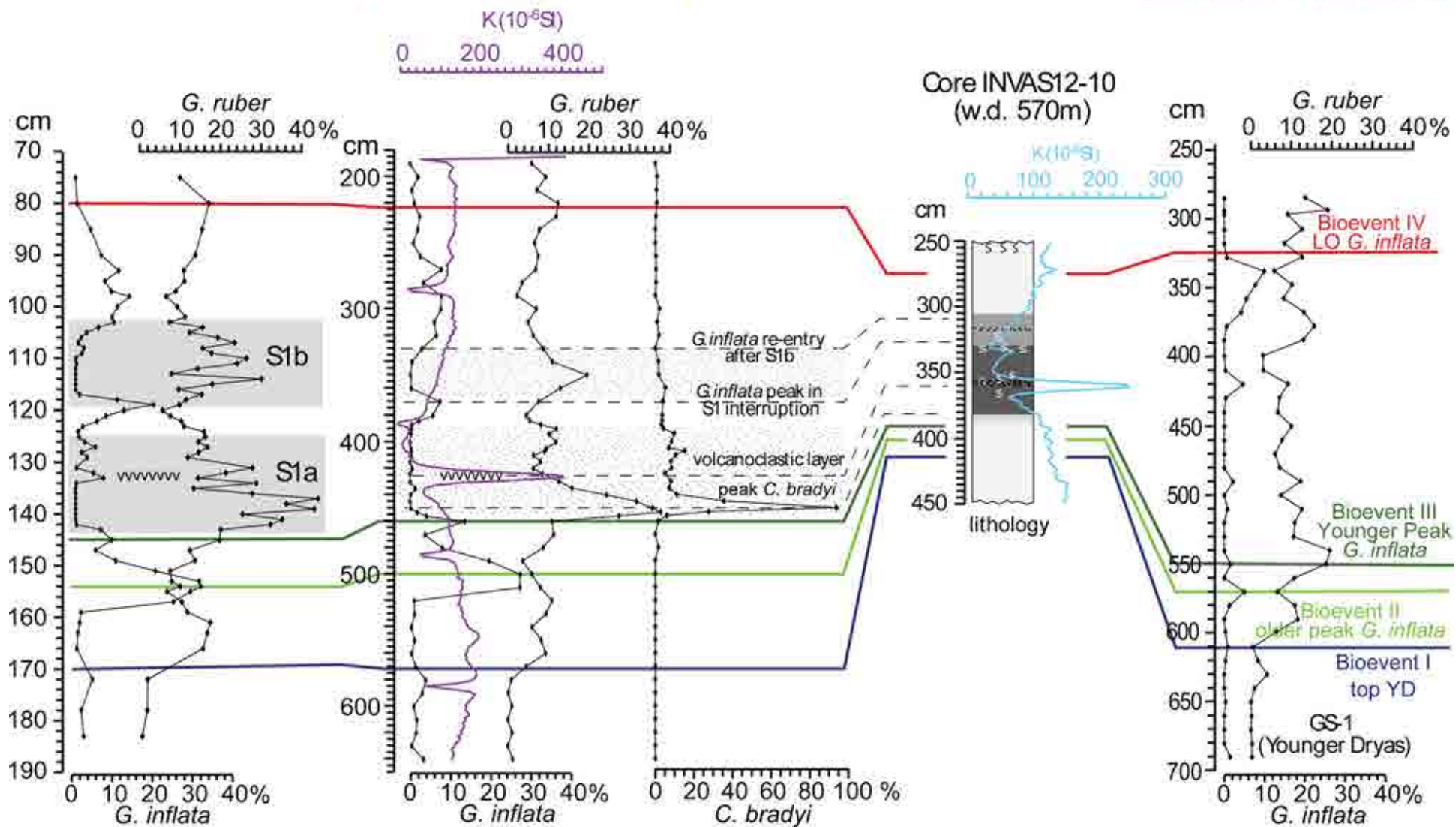
core ST04-1 (1085 m)

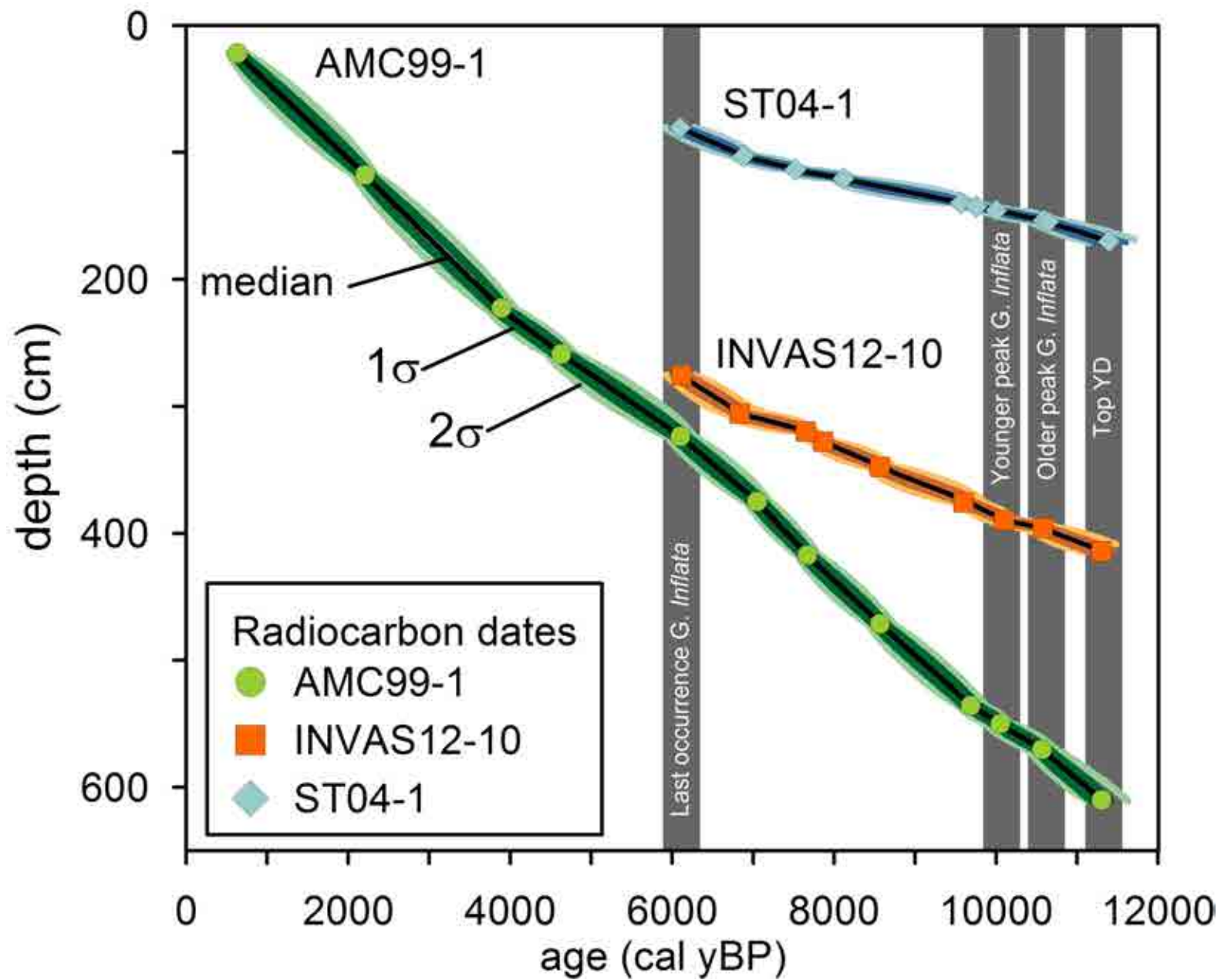


Core ST04-1 (w.d. 1085 m)

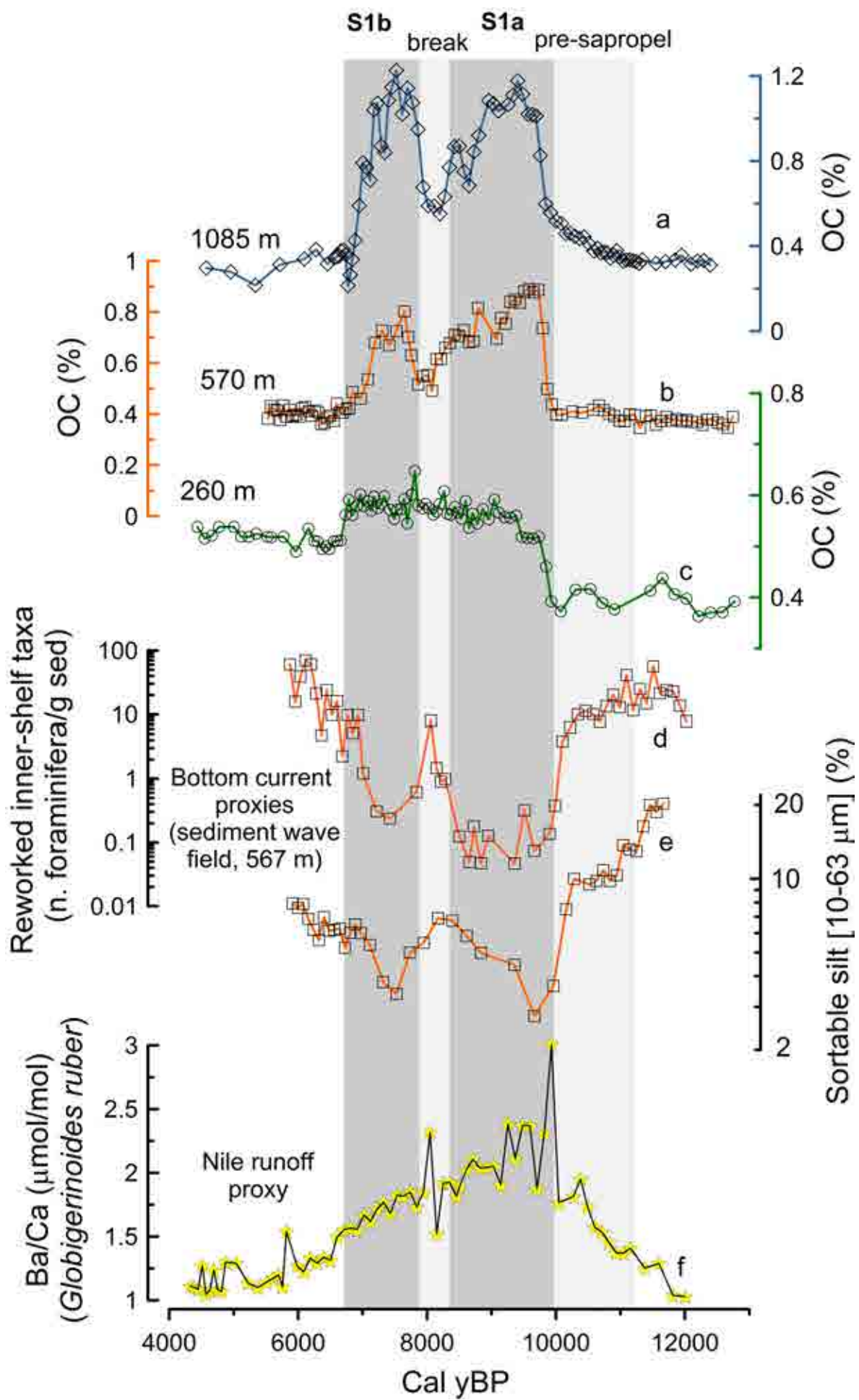
Core SA03-1 (w.d. 567 m)

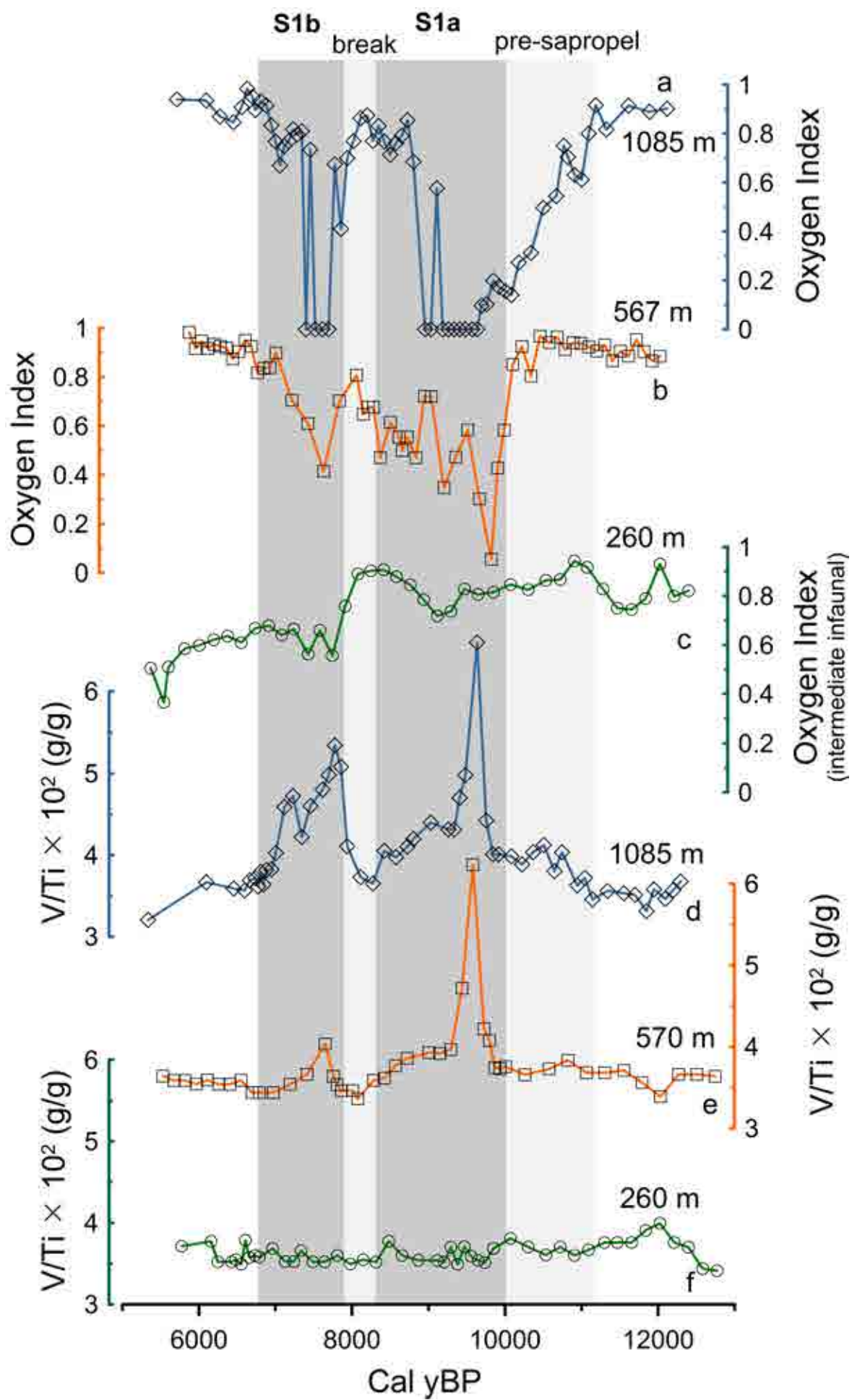
Core AMC99-1 (w.d. 260 m)



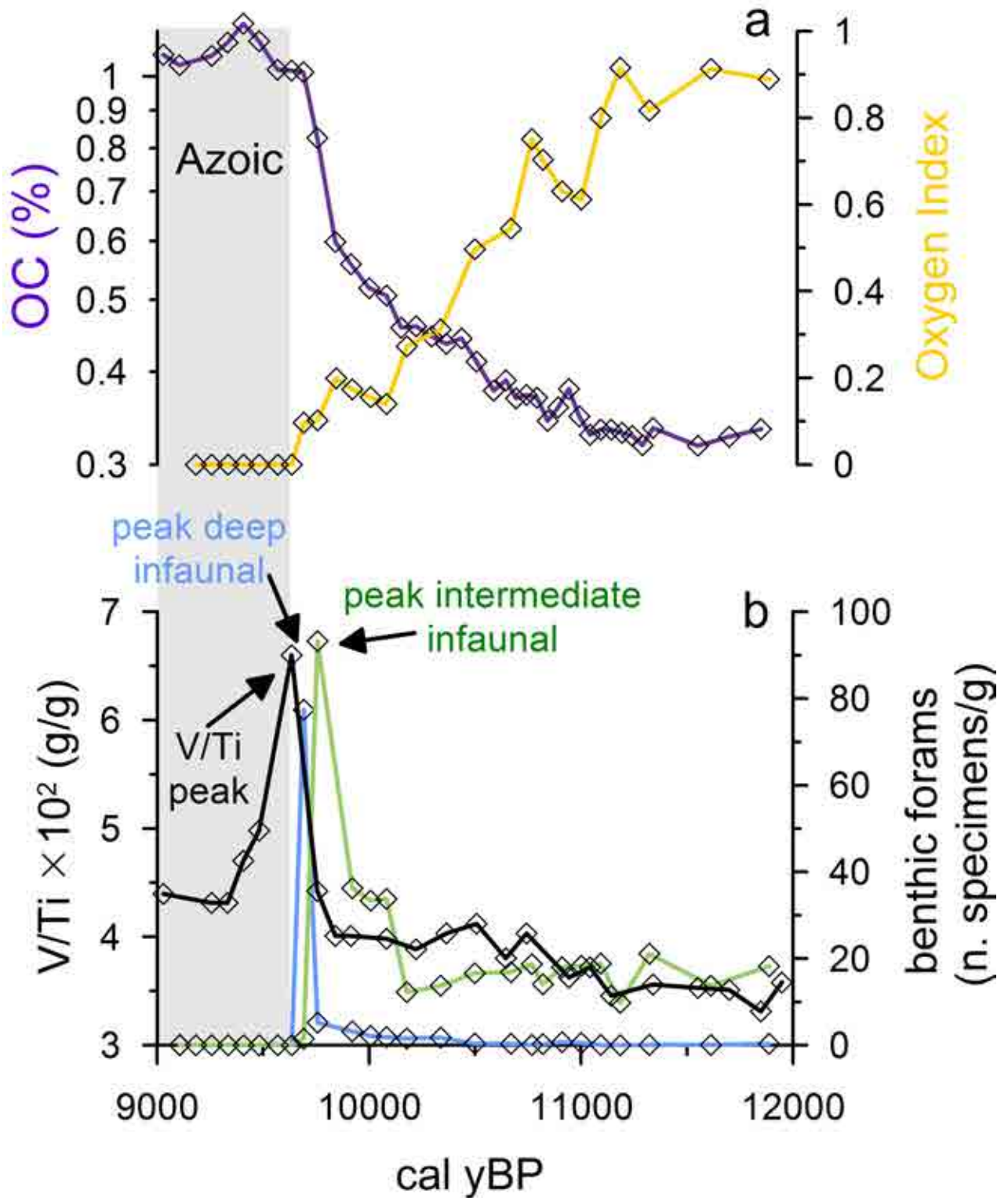


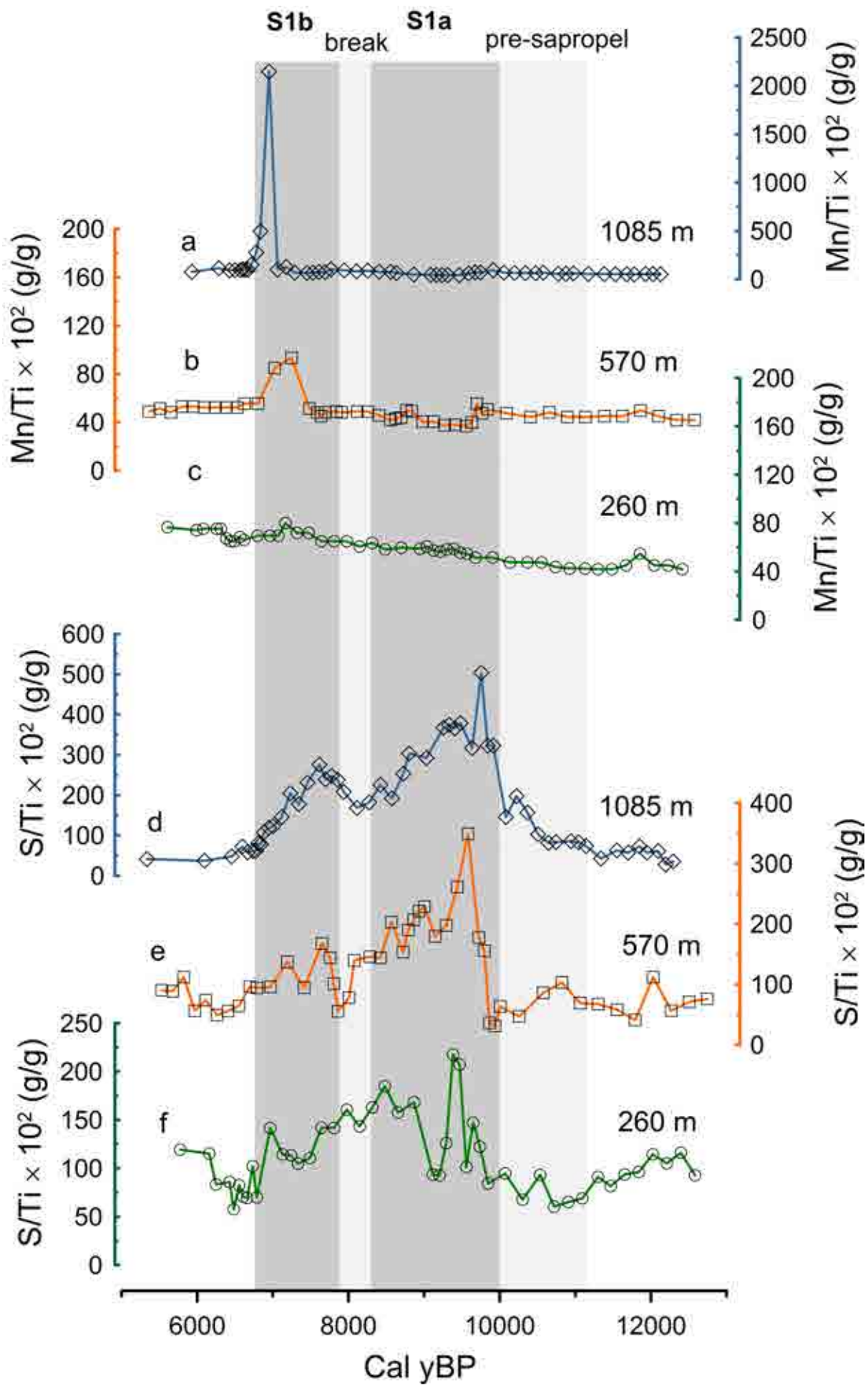




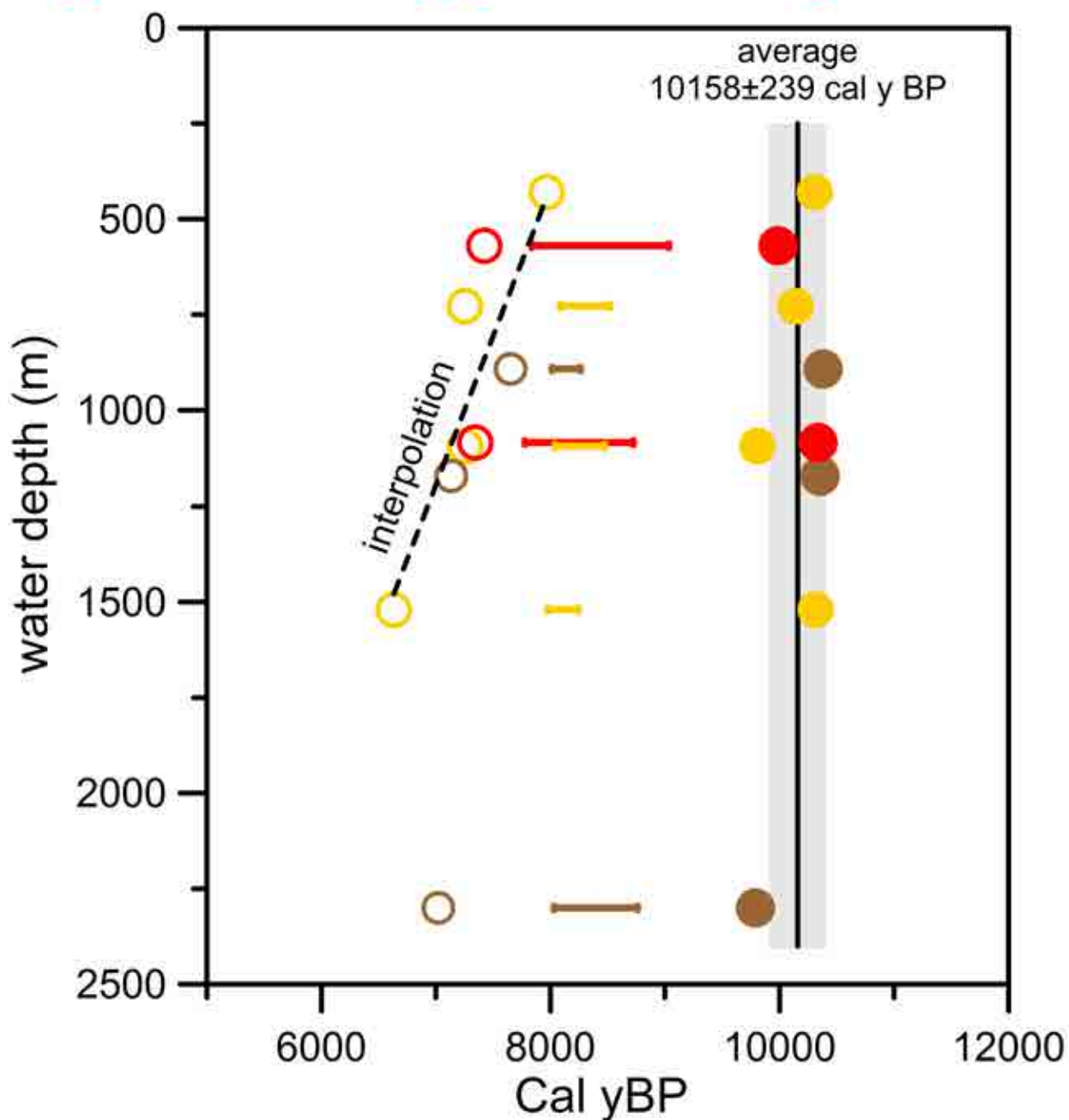


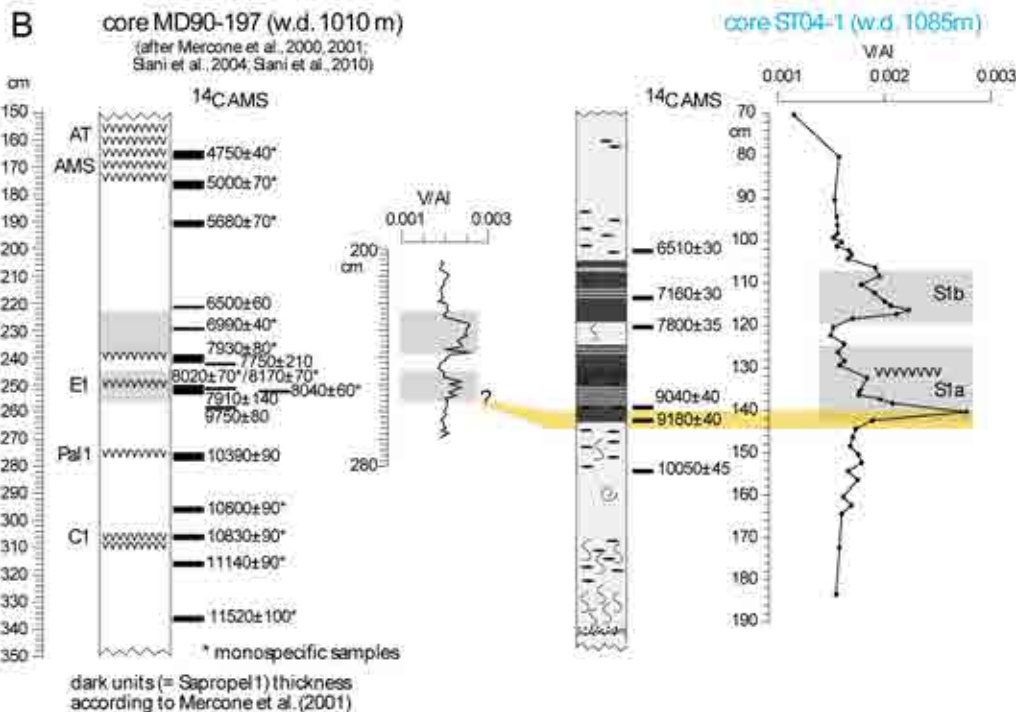
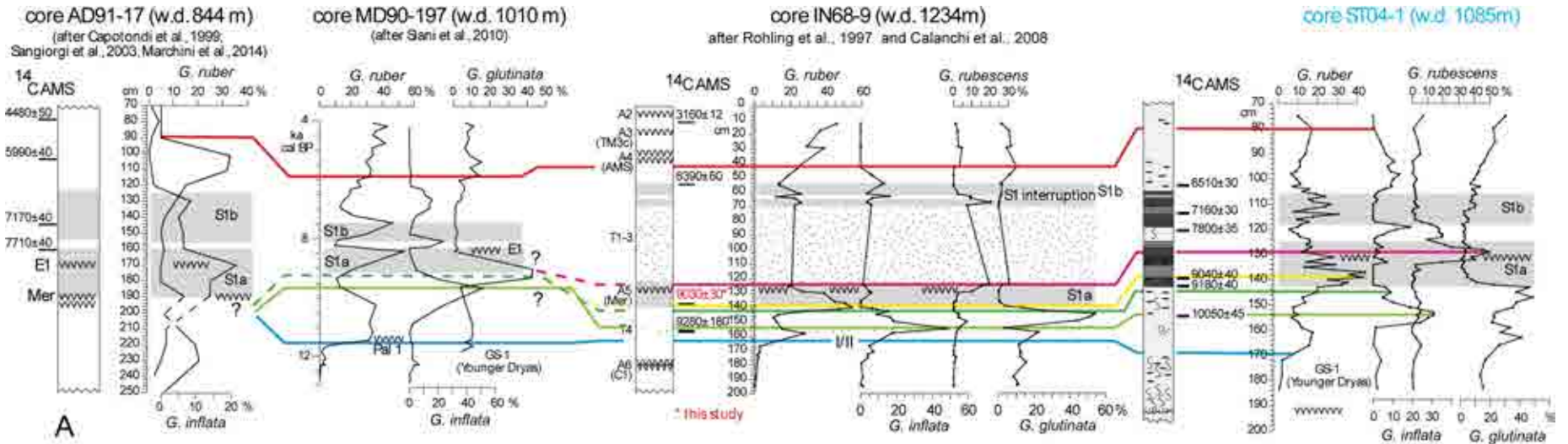
core ST04-1 (1085 m)





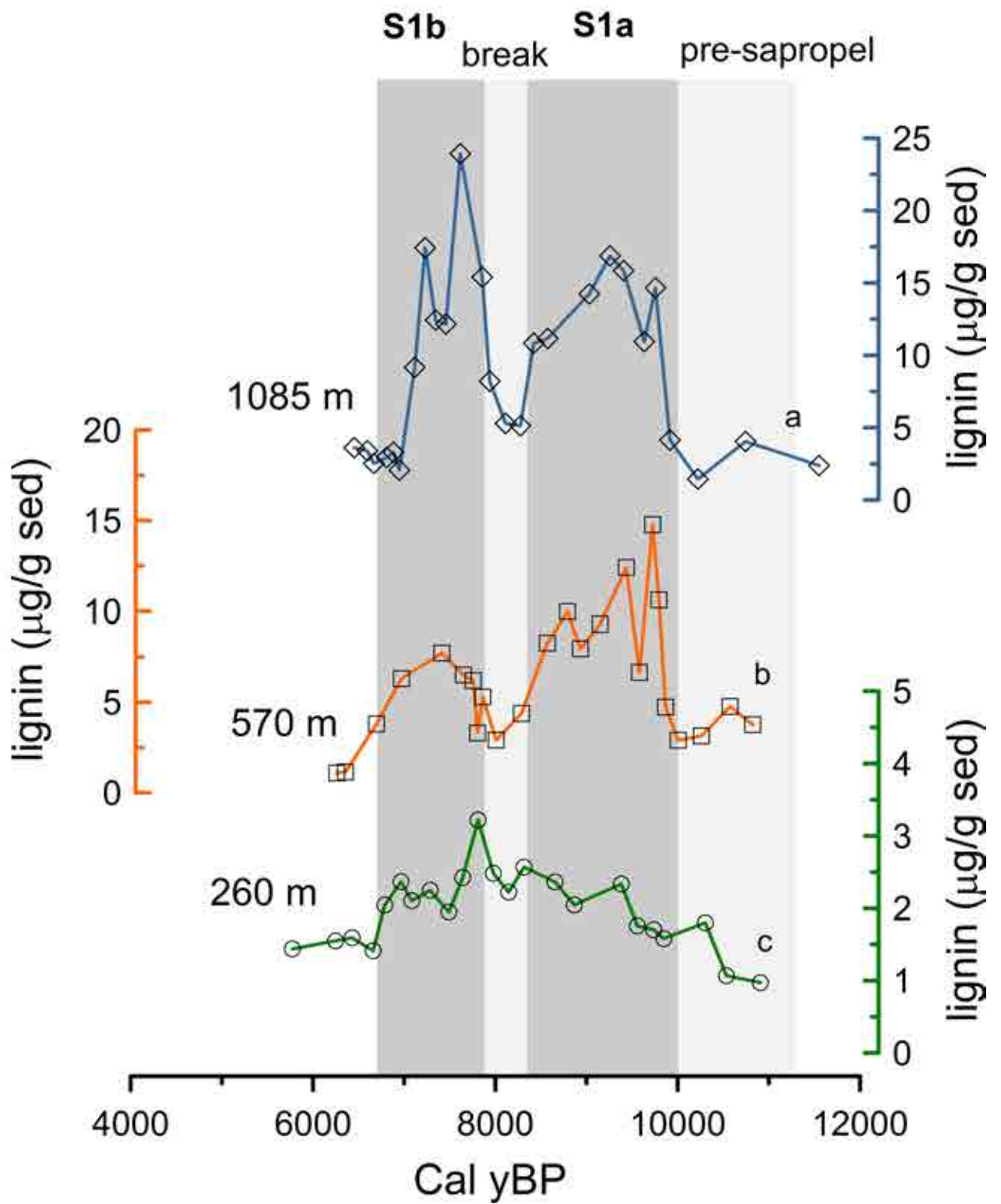
Benthic collapse oxygen index < 0.5	Intra-S1 recolonization oxygen index > 0.5	Benthic recovery oxygen index > 0.5
● Aegean	▬ Aegean	○ Aegean
● Levantine	▬ Levantine	○ Levantine
● Adriatic	▬ Adriatic	○ Adriatic





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

turbidite



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	<sup>14</sup> 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

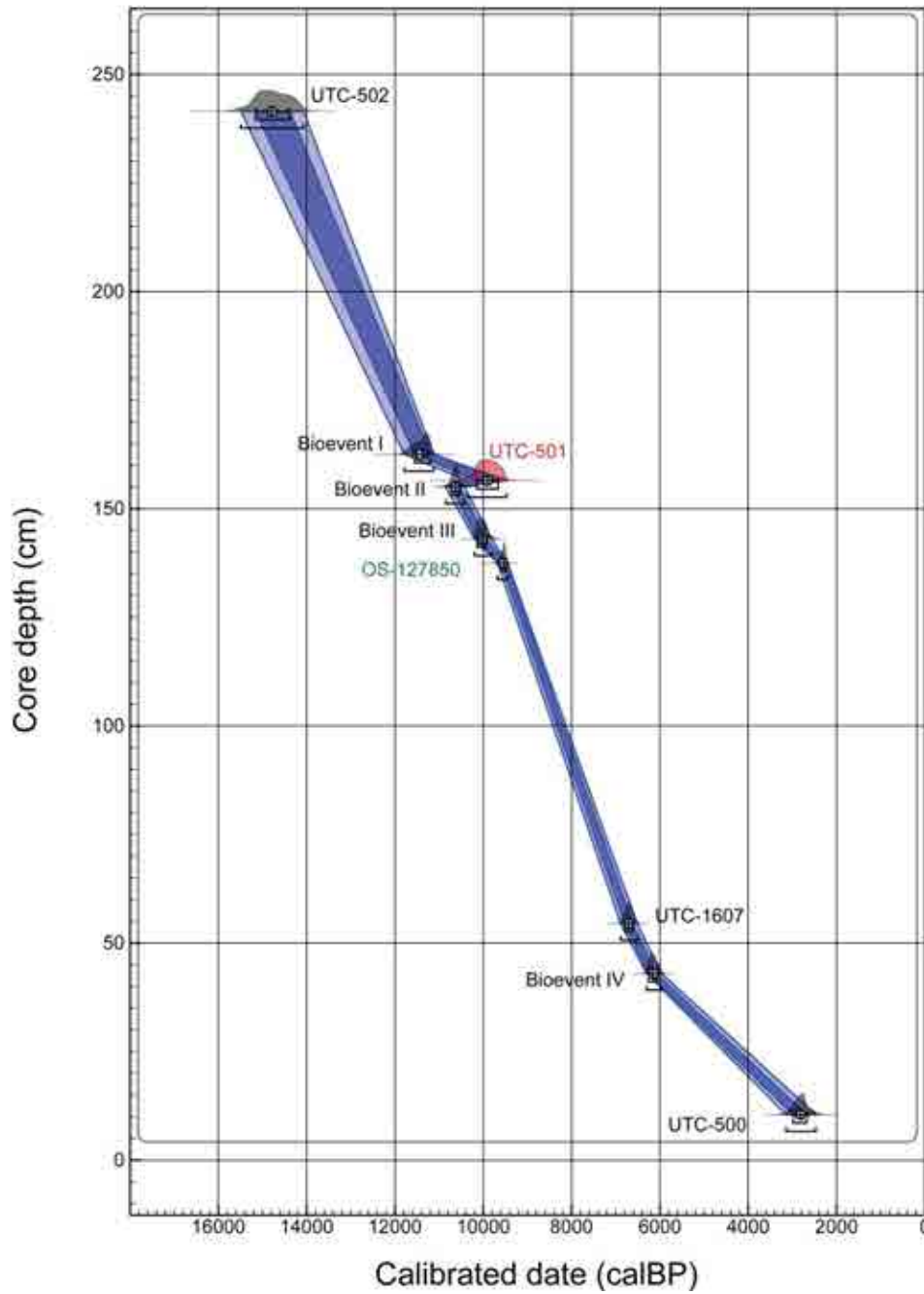


Fig. S1. Likelihood probability distributions of calibrated radiocarbon dates Light and dark blue show  $1\sigma$  and  $2\sigma$ , respectively.

# Posteriori

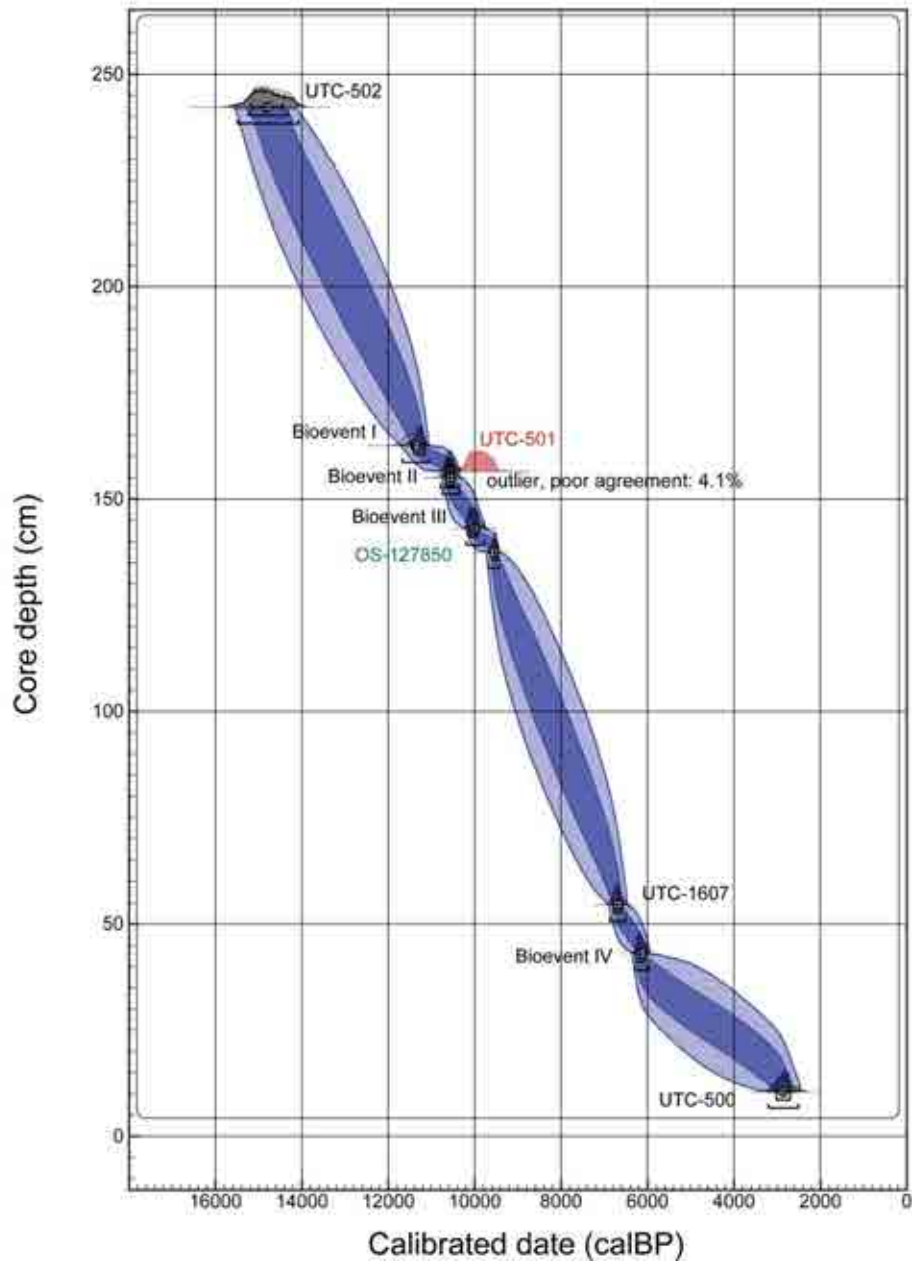


Fig. S2. Posterior probability distributions of calibrated radiocarbon dates Light and dark blue show  $1\sigma$  and  $2\sigma$ , respectively

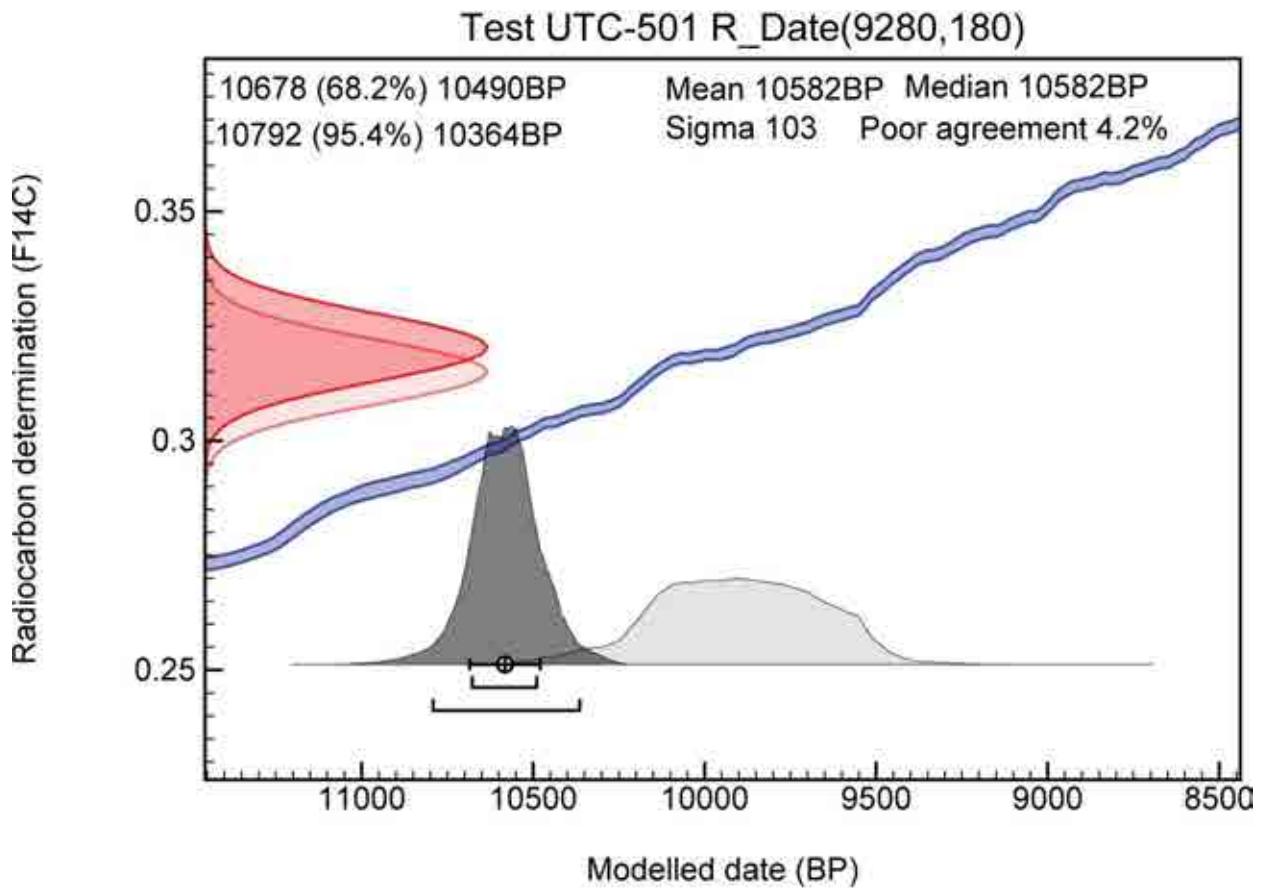


Fig. S3. Posterior probability distribution (dark grey) vs likelihood probability distribution (light gray) of test UTC-501.

- Asioli, A., Trincardi, F., Lowe, J., Ariztegui, D., Langone, L., Oldfield, F., 2001. Sub-millennial scale climatic oscillations in the central Adriatic during the Lateglacial: palaeoceanographic implications. *Quaternary Science Reviews* 20, 1201-1221.
- 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