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Citation for final published version:

Diz, Paula, Hernández-Almeida, Iván, Bernárdez, Patricia, Pérez-Arlucea, Marta and Hall, Ian R. ORCID: <https://orcid.org/0000-0001-6960-1419> 2018. Ocean and atmosphere teleconnections modulate east tropical Pacific productivity at late to middle Pleistocene terminations. *Earth and Planetary Science Letters* 493 , pp. 82-91. 10.1016/j.epsl.2018.04.024 file

Publishers page: <http://dx.doi.org/10.1016/j.epsl.2018.04.024>  
<<http://dx.doi.org/10.1016/j.epsl.2018.04.024>>

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**OCEAN AND ATMOSPHERE TELECONNECTIONS MODULATE EAST TROPICAL  
PACIFIC PRODUCTIVITY AT LATE TO MIDDLE PLEISTOCENE TERMINATIONS**

Paula Diz<sup>1\*</sup>, Ivan Hernández-Almeida<sup>2</sup>, Patricia Bernárdez<sup>1</sup>, Marta Pérez-Arlucea<sup>1</sup>, Ian R.  
Hall<sup>3</sup>

<sup>1</sup>Dept. Marine Geosciences, Faculty of Sciences, University of Vigo, 36310, Spain

<sup>2</sup>Geological Institute, Department of Earth Science, ETH, 8092, Zürich, Switzerland

<sup>3</sup>School of Earth and Ocean Sciences, Cardiff University, CF10 3AT, U.K.

\* Corresponding author, pauladiz@uvigo.es

23 **Abstract**

24 The modern Eastern Equatorial Pacific (EEP) is a key oceanographic region for regulating  
25 the Earth's climate system, accounting for between 5–10% of global marine production  
26 whilst also representing a major source of carbon dioxide efflux to the atmosphere.  
27 Changes in ocean dynamics linked to the nutrient supply from the Southern Ocean have  
28 been suggested to have played a dominant role in regulating EEP productivity over  
29 glacial–interglacial timescales of the past 500 ka. Yet, the full extent of the climate and  
30 oceanic teleconnections and the mechanisms promoting the observed increase of  
31 productivity occurring at glacial terminations remain poorly understood. Here we present  
32 multi-proxy, micropaleontological, geochemical and sedimentological records from the  
33 easternmost EEP to infer changes in atmospheric patterns and oceanic processes  
34 potentially influencing regional primary productivity over glacial-interglacial cycles of the  
35 mid-late Pleistocene (~0-650 ka). These proxy data support a leading role for the north-  
36 south migration of the Intertropical Convergence Zone (ITCZ) in shaping past productivity  
37 variability in the EEP. Productivity increases during glacial periods and notably peaks at  
38 major and "extra" glacial terminations (those occurring 1-2 precession cycles after some  
39 major terminations) coincident with the inferred southernmost position of the ITCZ. The  
40 comparison of our reconstructions with proxy records of climate variability suggests the  
41 intensification of related extratropical atmospheric and oceanic teleconnections during  
42 deglaciation events. These processes may have re-activated the supply of southern sourced  
43 nutrients to the EEP, potentially contributing to enhanced productivity in the EEP and thus  
44 counterbalancing the oceanic carbon dioxide outgassing at glacial terminations.

45

46 **KEYWORDS:**

47 East Equatorial Pacific, Intertropical Convergence Zone, benthic foraminifera,  
48 paleoproductivity, teleconnections, Pleistocene terminations.

49

50 **HIGHLIGHTS**

- 51 • New multi-proxy record from the East Equatorial Pacific for the last 650 ka
- 52 • ITCZ latitudinal shifts drove productivity changes
- 53 • Ocean tunnelling likely contributed to increased productivity at terminations
- 54 • Tropical atmospheric changes key in deglaciations
- 55 • EEP contributes to the deglacial atmospheric carbon dioxide regulation

56

57

58 **1. Introduction**

59 The modern East Equatorial Pacific (EEP) plays an important role in climate regulation as  
60 it is an important source of carbon dioxide (CO<sub>2</sub>) to the atmosphere (Takahashi et al.,  
61 2009). Yet, it accounts for 5-10% of the global oceanic primary production while  
62 comprising only 9% of the ocean area (Pennington et al., 2006). Nutrients and CO<sub>2</sub>-rich  
63 waters are currently supplied to the EEP thermocline via Subantarctic Mode  
64 Water (Sarmiento et al., 2003). Modern biogeochemical models suggest that Subantarctic  
65 Mode Water provides a substantial fraction (30-50%) of the nutrients that reach the EEP,  
66 thereby sustaining a large proportion of the export production in this area (Palter et al.,  
67 2010). However, the mechanisms driving glacial to interglacial changes in the biological  
68 productivity and export production in the EEP remain equivocal. The supply of  
69 micronutrients (i.e., iron) have long been proposed as one of the main influences on the  
70 efficiency and strength of the oceanic biological pump in the past (e.g. Murray et al.,  
71 2012). Yet, a recent study have argued that variability in the atmospheric dust input (a  
72 major source of iron) to the EEP was not large enough to trigger a substantial increase in  
73 glacial productivity and that nutrient supply from the Southern Ocean might have played a  
74 crucial role in controlling the equatorial Pacific productivity over the Late Pleistocene  
75 (Winckler et al., 2016). The south to equatorial connection, through so called “oceanic

76 tunnelling” (Spero and Lea, 2002) appears to have been active in the past, in particular  
77 during the last deglaciation (Martinez-Boti et al., 2015) and likely during older  
78 deglaciations (Rippert et al., 2017). However, little is known about the functioning of the  
79 oceanic tunnelling during other mid-late Pleistocene terminations and its influence on the  
80 biological pump in the EEP and therefore global climate.

81 Furthermore, the EEP is involved in interhemispheric thermal and moisture transport  
82 through changes in the mean position and strength of the Hadley circulation cells, which  
83 are intimately linked to the meridional position of the Intertropical Convergence Zone  
84 (ITCZ) (Schneider et al., 2014). Changes in the average position of the ITCZ are relevant  
85 not only at a global scale, controlling global atmospheric reorganizations (Chiang et al.,  
86 2014), but also regionally, involving changes in the position of oceanographic structures  
87 such as the Costa Rica Dome (CRD). The CRD is an open-ocean upwelling system in the  
88 EEP that develops seasonally off the coast of Central America (Fiedler, 2002). It has been  
89 previously suggested that past changes in the intensity and location of the CRD upwelling  
90 system depends on the intensity of the trade winds linked to the meridional position of the  
91 ITCZ (Hofmann et al., 1981), and that such variability could influence regional  
92 productivity patterns in the EEP during the last glacial cycle (Ivanova et al., 2012). It is  
93 unclear to what extent atmospheric processes (e.g., ITCZ-related CRD variability), in  
94 addition to oceanic processes (e.g., ocean tunnelling), might have influenced past  
95 productivity patterns in the EEP during the mid to late Pleistocene.

96 Here we present a multi-proxy record to investigate the mechanisms controlling past  
97 variability in productivity in the EEP at glacial-interglacial time scales. The record is  
98 obtained from the Integrated Ocean Drilling Program (IODP), Expedition 344, Site U1381  
99 (Hole U1381C) located off the Costa Rica margin (Figure 1). The core site is ideally  
100 located to capture signals related to the past changes in the EEP productivity which might

101 have occurred either through variations in the position of the ITCZ, which controls the  
102 extension and location of the CRD, and/or through fluctuations in the nutrient supply from  
103 southern sourced waters. Accordingly, we use proxies providing information for the  
104 quantity and quality of the organic carbon supply to the seafloor (e.g., benthic  
105 foraminiferal faunal composition, planktonic foraminiferal abundance, organic carbon and  
106 opal content) and sediment chemical composition (e.g., calcium carbonate and major  
107 elemental content). These multi-proxy derived records allow us to investigate the  
108 mechanisms controlling past variability in productivity and make inferences on the  
109 contribution of atmospheric and oceanic processes at the glacial terminations throughout  
110 the Middle to Late Pleistocene (the last 650 ka).

111

## 112 **2. Core location and oceanography**

113 The Hole U1381C (08°25.7027'N; 84°09.48'W, Harris et al., 2013, Figure 1) is located  
114 ~4.5 km offshore the Osa Peninsula, on the Costa Rica margin at the southern end of the  
115 East Pacific Warm Pool (Fiedler and Talley, 2006). The core site was recovered at 2065  
116 meters, well above the depth of the modern sedimentary lysocline, which is established at  
117 ~ 2900 meters water depth for the Panama basin (Thunell et al., 1981). At present, primary  
118 production in surface waters at Site U1381 is relatively low as its location is not directly  
119 influenced by the seasonal (wind-driven) upwelling or the current position of the open  
120 ocean upwelling center of the CRD (Figure 1a-b). The lack of seasonal coastal (wind-  
121 driven) upwelling at our site is because of the proximity to the Talamanca mountains  
122 (3000-4000 m height) which favour the convergence of local wind curl patterns  
123 (Pennington et al., 2006). This contrasts with the seasonal coastal upwelling processes  
124 occurring south (Gulf of Panama, Panamá) and north (Gulf of Papagayo, Nicaragua) of the  
125 Site U1381 (Figure 1c-d). The CRD is a “permanent” anticyclonic thermal structure flowing

126 cyclonically and is currently centred around 9°N and 90°W with a diameter ranging  
127 between 100 to 900 km (Figure 1a-b). The CRD position and magnitude is related to the  
128 seasonal migration of the ITCZ and associated wind stress curl patterns, and can be  
129 identified by shallowing of the thermocline, which corresponds to the isotherm of 20°C  
130 (Fig. 1a-b).

131

### 132 **3. Material and methods**

#### 133 *3.1. Sediment samples*

134 Sediment samples from Site U1381 (Hole U1381C) were obtained during IODP  
135 Expedition 344 (Harris et al., 2013). We analysed the uppermost 47 m cored depth scale  
136 (CSF-B, meters below sea floor, mbsf, from U1381C 344-1H-1W 0-2 cm to 344-6H-1W  
137 89-91 cm) which is characterised by a monotonous sequence of light greenish gray  
138 hemipelagic silty clay (Harris et al., 2013). Two cm thick sediment samples for faunal  
139 analysis samples (~10 cm<sup>3</sup>) were collected at a 10 cm spacing for the upper 20 mbsf and in  
140 20 cm intervals for 20-47 mbsf. Samples for geochemical analysis (2 cm thick, ~10 cm<sup>3</sup>)  
141 were typically taken immediately below intervals sampled for faunal analysis.

142

#### 143 *3.2. Stable isotope analysis and age model development*

144 The age model of Hole U1381C is constructed by the combination of radiocarbon dates, a  
145 planktonic biostratigraphic event and graphical correlation of the the benthic oxygen  
146 isotopic ( $\delta^{18}\text{O}$ ) record from Hole U1381C to the LR04 benthic foraminiferal  $\delta^{18}\text{O}$  stack  
147 (Lisiecki and Raymo, 2005). The age control of the upper sections (4.3 mbsf) is  
148 constrained by seven accelerator mass spectrometry <sup>14</sup>C ages on planktonic foraminifera  
149 from the >150  $\mu\text{m}$  (mixed species or monospecific depending on the availability of  
150 individuals weighing between ~2 to 10 mg; see Supplementary Information S.I.1). The

151 accelerator mass spectrometry ages were measured at the Center for Applied Isotope  
152 Studies, University of Georgia (U.S.A.) and were calibrated ( $2\sigma$  confidence limits) with  
153 the Calib 7.0 software using the Marine13 calibration dataset (Reimer et al., 2013). The  
154 oldest radiocarbon age was too old for calibration and was discarded for the age model  
155 construction. The last occurrence of the planktonic foraminifera *Globigerinoides ruber*  
156 (pink variety) occurring at 8.95 mbsf which corresponds to an age of  $\sim 127$  ka (Ivanova et  
157 al., 2012), was also used as a dating point (See supplementary information S.I.1). Beyond  
158 the radiocarbon limits, the U1381C benthic  $\delta^{18}\text{O}$  was correlated graphically to the orbitally  
159 tuned LR04 benthic  $\delta^{18}\text{O}$  stack record using the AnalySeries program. For this purpose, 3-  
160 4 visually clean individuals of *Uvigerina auberiana* d'Orbigny were selected per sample  
161 from the 250-300  $\mu\text{m}$  size fraction. Stable isotope analyses were performed on a  
162 ThermoFinnigan MAT 253 mass spectrometer coupled to a Kiel IV carbonate preparation  
163 device at Cardiff University (UK). The spectrometer was calibrated through the  
164 international standard NBS-19, and all isotopic results are reported as a per mil deviation  
165 from the Vienna Pee Dee Belemnite scale ( $\text{‰ VPDB}$ ). The reproducibility of the  $\delta^{18}\text{O}$   
166 analyses is  $\pm 0.05\%$ , based on replicate measurements of carbonate standards. According  
167 to our age model, the studied interval covers the last  $\sim 650$  ka. Average sedimentation rates  
168 are  $6.7 \text{ cm ka}^{-1}$ , ranging from very low values of  $\sim 1.6 \text{ cm ka}^{-1}$  during Marine Isotope Stage  
169 (MIS) 2, MIS 4 and MIS 14 (which remain poorly resolved in our record) to high values of  
170  $\sim 9 \text{ cm ka}^{-1}$  from MIS 5 through MIS 11 (See Supplementary Figure S1). The mean  
171 temporal resolution of the records is 2 ka.

172

### 173 3.3. Foraminiferal faunal analyses

174 Benthic foraminiferal assemblages provide information about the quality, quantity and  
175 sustainability of the organic carbon flux to the seafloor as well as oxygenation conditions



176 in the sediment and bottom waters (Gooday, 2003). Samples for benthic foraminifera  
177 analyses were dried at 45°C, weighed and sieved to 63 µm, and then weighed again after  
178 drying. The weight percent of the >63 µm fraction was calculated from dried samples (%  
179 coarse fraction, CF). To investigate benthic foraminiferal assemblages, a representative  
180 split of at least ~ 200 individuals (when possible) from the > 125 µm fraction was  
181 identified and counted and the relative abundance (percentage) of the characteristic  
182 species calculated. The abundance of benthic foraminifera (BF) was calculated from the  
183 number of individuals counted in the split (or the whole sample when the abundance was  
184 low) per gram of total dry weight sediment (number of benthic foraminifera >125 µm /g).  
185 While a detailed analysis of the benthic foraminiferal fauna assemblage is out of the scope  
186 of this study, ecological information is provided for the most characteristic species, or  
187 group of species, relevant for a broad interpretation of paleoenvironmental conditions. In  
188 order to describe the patterns of planktonic foraminifera abundance along the core, a split  
189 of whole planktonic foraminifera from the >150 µm size fraction was counted and used to  
190 calculate the abundance of planktonic individuals per gram of dry weight sediment  
191 (number of planktonic foraminifera >150 µm /g).

#### 192 *3.4. Organic and inorganic carbon, total nitrogen and opal contents*

193 Total bulk sediment samples for organic carbon and nitrogen content were dried at 45°C,  
194 ground and homogenized using a zircon ball mill. The total weight percent of sedimentary  
195 carbon (% C) and nitrogen (% N), as well as inorganic carbon (% C<sub>inorg</sub>) and organic  
196 carbon (% C<sub>org</sub>) were measured using a macro elemental analyzer LECO CNS2000 at  
197 CACTI (University of Vigo). The % C and % N measurements were calibrated against a  
198 standard reference material (Ethylenediaminetetraacetic acid-EDTA and pure CaCO<sub>3</sub>). The  
199 detection limit was 0.02 % for % C and 0.01 % for % N, respectively, while repeat  
200 analyses (n = 5) of the standards yielded precisions of ± 0.14 for % C and ± 0.3 % N

201 respectively. For the estimation of %C<sub>inorg</sub> an aliquot of the homogenized sample was  
202 heated at 450°C for 3 hours to remove organic carbon. The total weight percent of calcium  
203 carbonate (% CaCO<sub>3</sub>) was calculated as 8.33 x % C<sub>inorg</sub>. The % C<sub>org</sub> content was calculated  
204 as the difference between % C and % C<sub>inorg</sub>.

205 The concentration of sedimentary biogenic silica (i.e., % opal) is considered as a proxy for  
206 siliceous export production (Anderson et al., 2009). Opal abundance was determined using  
207 the method of Mortlock and Froelich (1989). The precision and accuracy of opal analysis  
208 were monitored using replication of an in-house standard. The coefficient of variability  
209 (e.g. standard deviation) is ± 0.2 %. The Si<sub>opal</sub>/C<sub>org</sub> (hereinafter Si/C) were calculated after  
210 transformation of the biogenic silica (opal) and % C<sub>org</sub> into molar ratios. The Si/C ratios are  
211 used here as a proxy for the contribution of siliceous producers to non-siliceous primary  
212 producers (Ragueneau et al., 2000).

213 Sedimentary mass accumulation rates are provided for geochemical and sedimentological  
214 tracers to complement the information provided by relative abundance values. Mass  
215 accumulation rates are calculated as the weight percentage of sedimentary component x  
216 dry bulk density (g cm<sup>-3</sup>) x linear sedimentation rates (cm ka<sup>-1</sup>). Linear sedimentation rates  
217 are calculated from the tie points obtained for the construction of the age model  
218 (Supplementary Table S1). Dry bulk density values are from Harris et al. (2013). Mass  
219 accumulation rates range from 1 to 9 g cm<sup>-2</sup> ka<sup>-1</sup> and are within the range previously  
220 estimated for the Panama basin (Kienast et al., 2007).

221

### 222 *3.5. Sediment chemical elements*

223 Sediment composition and provenance was evaluated by the quantification of elemental  
224 concentrations of major elements (Ca, Ti, Al). For the analysis of chemical elements, dried  
225 and ground sediments were prepared on pressed pellets and measured by X-ray

226 Fluorescence (XRF) using Mo as the X-ray source on a Siemens SRS 3000 spectrometer at  
227 CACTI (University of Vigo). Reference samples (NRC MESS-3 and NRC PACS-2) were  
228 analyzed and used as routine quality control samples, to assess the instrument accuracy and  
229 to obtain quantitative values. Quantification was done using the Spectraplus Software  
230 through the EVAL program by k-factor of proximity of reference samples. Replicate  
231 measurements (n = 5) show good agreement between certified and analytical values.  
232 Recovery was in general over 87% for MESS-3, whereas for PACS-2 it was nearly 100%  
233 for all the studied elements. The typical absolute error for each element determination is  
234 lower than 5%. The Ti was normalized to the Al content, an indicator of the  
235 aluminosilicate fraction of the sediments. The Ti (unlike Fe) is less sensitive to  
236 environmental redox variations and it is used here as a terrigenous proxy (Tribovillard et  
237 al., 2006). The Ca content was normalized to Ti (Ca/Ti) and it is used here as an indirect  
238 proxy for the carbonated versus terrigenous fraction of the sediment.

239

## 240 **4. Results**

### 241 *4.1.-Calcium carbonate related proxies*

242 As the Hole U1381C is ~850 m above the regional carbonate saturation horizon in the  
243 Panama Basin (Thunell et al., 1981) it is not expected to have experienced severe  
244 carbonate dissolution (López-Otálvaro et al., 2008). However, previous studies in the area  
245 have identified some episodes of carbonate dissolution during the last glacial cycle  
246 (Ivanova et al., 2012). In order to interpret the CaCO<sub>3</sub> variability at the core site and to  
247 assess whether carbonate dissolution influenced the composition of benthic foraminiferal  
248 assemblages, we used several independent proxies for CaCO<sub>3</sub> dissolution and  
249 CaCO<sub>3</sub> production (e.g., LaMontagne et al., 1996): % CaCO<sub>3</sub> and mass accumulation of  
250 CaCO<sub>3</sub>, major elemental ratios (Ca/Ti), % >63 μm coarse fraction, relative abundance of

251 benthic to planktonic plus benthic foraminifera (B/P+B), % C<sub>org</sub>, and the absolute  
252 abundances of benthic and planktonic foraminifera (number of BF or PF/g) (Figure 2b-f).  
253 The CaCO<sub>3</sub> record (% and mass accumulation) of Hole U1381C shows high values during  
254 glacial periods (5-15%) and low values during interglacials (<5%) (Figure 2b). The %  
255 CaCO<sub>3</sub> concentrations (and indirect proxies for sedimentary CaCO<sub>3</sub> content such as Ca/Ti)  
256 peaks at major and so-called “extra terminations” (i.e., terminations exhibiting patterns of  
257 events similar to main terminations, but occurring 1-2 precession cycles before), such as  
258 Termination IIIa (TIIIa, between MIS 7c and 7d) and Termination VIIa (TVIIa, between  
259 MIS 15a and 15b) (Cheng et al., 2016). Paleoproductivity related proxies; % C<sub>org</sub>,  
260 abundance of planktonic and benthic foraminifera and % >63 μm (which is mainly  
261 composed by planktonic and benthic foraminifera with occasional skeletons of diatoms and  
262 radiolaria) exhibit generally high values during glacial periods and terminations and low  
263 values during interglacial periods (Figure 2 c-f). The observed trends are statistically  
264 supported by positive correlations (see Supplementary Table S.I.2). The relationship  
265 between parameters seems to be noticeable at major and extra terminations, where there is  
266 a significant correspondence with peaks in % CaCO<sub>3</sub> (and indirect proxies i.e., Ca/Ti,  
267 Figure 2b), % >63 μm fraction (Figure 2c) benthic foraminifera absolute abundance (Figure  
268 2d) and % C<sub>org</sub> (Figure 2f). Benthic foraminifera generally outnumber planktonic  
269 foraminifera (B/P+B > 0.5, Figure 2e) except for glacial stages, terminations and sub-  
270 stages.

#### 271 4.2.-Geochemical proxies.

272 The %C<sub>org</sub> ranges from 0.2 to 2.2% (mean 1.9%) and concentrations increase at glacial  
273 periods and peak at terminations (Figure 2f). The C<sub>org</sub>/N values range from 4.4 to 13  
274 (mean=9, see supplementary data), suggesting that the C<sub>org</sub> at the core site is mainly of  
275 marine provenance (Meyers, 1997). In contrast to %C<sub>org</sub>, the % opal, which varies between

276 7% and 11%, shows only minor glacial-interglacial variability, (Figure 2g), but a clear  
277 decrease in % opal at terminations. The Si/C, a proxy for the abundance of siliceous to  
278 non-siliceous primary producers, shows higher values during interglacials than during  
279 glacials, with the lowest values occurring at terminations (Figure 3g). The record of Ti/Al,  
280 a proxy for the terrigenous provenance of the sediments, varies between 0.05 and 0.09  
281 (Figure 3h). This variability range is comparable to other published Ti/Al records used to  
282 infer terrigenous influence in marine sediments (e.g., Yarincik et al., 2000, Figure 3i). The  
283 values of Ti/Al in the core U1381C show an increasing trend from interglacials to  
284 terminations when ratios show the highest values (Figure 3h).

#### 285 4.3.- Benthic foraminifera assemblages

286 The abundance of benthic foraminifera increases during glacial periods and peaks at  
287 terminations (Figure 3a-b). Interglacial periods are characterized by low foraminiferal  
288 numbers and the dominance of *Uvigerina peregrina* (Cushman) and *Uvigerina auberiana*  
289 (d'Orbigny) together showing abundances higher than 40 % (Figure 3c) and therefore  
290 grouped under the so-called “*Uvigerina* spp.”. This contrasts with the abundance pattern of  
291 *Cassidulina carinata* Silvestri (Figure 3e) and secondary species *Valvulineria glabra*  
292 Cushman and *Rotamorphina laevigata* (Phleger and Parker) (Figure 3f). *Cassidulina*  
293 *carinata* almost disappears from the assemblage during interglacials (0-5%) but shows  
294 increased concentrations and percentages (10-30%) during glacials and terminations. A  
295 similar glacial-interglacial pattern is shown by *V. grabra* and *R. laevigata*. The last  
296 deglacial period is characterized by a different set of species to the other terminations  
297 (Figure 3d). *Bolivina interjuncta* Cushman, *Bolivina seminuda* (Cushman), *Bolivina* cf.  
298 *plicata* d'Orbigny, *Epistominella pacifica* (Cushman), and *Epistominella smithi* (Steward  
299 and Steward) characterize the assemblage of the last termination.

300

301 **5. Discussion**

302 *5.1. The carbonate record of Hole U1381C*

303 The factors explaining EEP CaCO<sub>3</sub> variability are still under debate (Winckler et al., 2016)  
304 with some studies suggesting that CaCO<sub>3</sub> productivity is the main driver (Lyle et al., 2002)  
305 and others instead proposing deep water carbonate chemistry (Sexton and Barker, 2012).  
306 Separating the signals of production and dissolution in CaCO<sub>3</sub> related proxies is difficult  
307 because both influences might have acted either concurrently or differently over time. It  
308 therefore requires the use of several independent proxies for both CaCO<sub>3</sub> production and  
309 dissolution (see section 4.1). The overall correlation between % CaCO<sub>3</sub> and indirect  
310 proxies for paleoproductivity (% Corg, absolute abundance of benthic and planktonic  
311 foraminifera) suggests that CaCO<sub>3</sub> production played a prime role in shaping sedimentary  
312 CaCO<sub>3</sub> content at our EEP Site (Figure 2b-d). The strong correspondence between peaks of  
313 % CaCO<sub>3</sub> and foraminiferal absolute abundance suggests that CaCO<sub>3</sub> production, rather  
314 than minimum dissolution (preservation), is also the most likely cause for CaCO<sub>3</sub> deglacial  
315 peaks at the core site. As an exception to this general relationship is a period of moderate  
316 dissolution identified between ~ 20 and 110 ka. This interval is characterized by high  
317 B/P+B ratios (Figure 2e) and planktonic assemblages dominated by dissolution resistant  
318 species, such as *Globorotalia menardii* (see Supplementary Information, Figure S2).  
319 Intense dissolution intervals are identified around the transition between maximum  
320 interglacial and glacial declines of MIS 11 and MIS 5 (Figure 2; brown bars). These  
321 intervals are represented by the extremely low abundance of whole shells of planktonic  
322 foraminifera, low numbers of benthic foraminifera, low mass accumulation rate of the  
323 coarse fraction, and depressed % CaCO<sub>3</sub> content. These samples might be affected by  
324 dissolution and paleoenvironmental interpretation has been considered with caution.

325 Inferred peaks of organic export and CaCO<sub>3</sub> production occur at all seven major glacial  
326 terminations (except for Termination V) and the “extra terminations”. Notably, the CaCO<sub>3</sub>  
327 accumulation and benthic foraminiferal abundance peaks exhibit comparable values at both  
328 major and extra terminations (including terminations occurring during the period of mild  
329 interglacials MIS13 and MIS15). The pattern described by our records at Termination V  
330 differs from the other terminations in that the high % CaCO<sub>3</sub> values do not occur at the  
331 termination but rather during mid glacial MIS 12 (Figure 2a-b, f).

### 332 5.2. *Paleoproductivity from benthic foraminifera: the influence of the CRD*

333 As outlined above, the productivity proxies at Site U1381C (e.g., C<sub>org</sub> and benthic  
334 foraminiferal abundance) at Site U1381C typically exhibit high values during glacial  
335 periods and terminations and low values during interglacial periods (Figure 2a, d-f, Figure  
336 3a-b). The deglacial productivity maxima are consistent with results from other studies in  
337 the EEP for the last deglaciation (Ivanova et al., 2012) and older terminations (Winckler et  
338 al., 2016). Benthic foraminiferal assemblages can provide additional information about the  
339 potential mechanisms involved in those paleoproductivity changes over the last 650 ka.  
340 The group *Uvigerina* spp. occurs in higher relative abundances during interglacial periods  
341 (Figure 3c). One of the species within the group, *Uvigerina auberiana* is an infaunal  
342 species considered well adapted to high fluxes of organic carbon under perennial upwelling  
343 regimes and low to moderate oxygenation environments (e.g., Licari and Mackensen,  
344 2005). Similar ecological preferences are considered for *U. peregrina*, for which some  
345 studies also indicate its preference for refractory organic material (Morigi et al., 2001).  
346 Therefore, high relative abundance of *Uvigerina* spp. during interglacials is suggested to  
347 indicate relatively high to moderate, but sustained organic carbon flux to the seafloor. At  
348 the same time, glacial periods and terminations (TII-TVII) are characterized by higher  
349 benthic foraminifera abundances and increased numbers of *Cassidulina carinata* and

350 secondary species *Valvulineria glabra* and *Rotamorphina laevigata* (Figure 3e,f).  
351 Ecological studies indicate that *C. carinata* favours the seasonal delivery of food to the  
352 seafloor occurring during phytoplankton bloom events (Goineau et al., 2011) and that the  
353 species of the genus *Valvulineria* (*V. bradyana*, *V. mexicana*) prefer eutrophic conditions  
354 (Mojtahid et al., 2010). This allows for the interpretation of the occurrence of *C. carinata*  
355 (and secondary species) as an indicator of the seasonal delivery of fresh and abundant  
356 organic carbon to the seafloor (likely from phytoplankton blooms) in an overall context of  
357 high productivity during glacials and terminations. This suggests that glacial-interglacial  
358 changes in productivity are related to a variable influence of organic carbon supply from a  
359 seasonal versus permanent source. There are at least two potential sources to consider that  
360 which might have driven the seasonal productivity changes at Hole U1381C: (i) coastal  
361 upwelling and (ii) the CRD upwelling system. Coastal (wind-driven) upwelling is not  
362 favoured at the core site because of proximal high mountain ranges (See description of  
363 core location and oceanography in Section 2); therefore, the most plausible source of a  
364 seasonally variable organic carbon supply to Site U1381, during glacial periods and their  
365 terminations, is the seasonal CRD open-ocean upwelling system. Thus, interglacial  
366 conditions characterized by species related to sustainable organic carbon flux to the  
367 seafloor, are interpreted as prevailing during a weak influence of the CRD over the study  
368 site (similarly to the present conditions) in contrast to glacials and terminations, which are  
369 interpreted as occurring when the influence of the CRD over the core site is at its highest  
370 and the organic carbon input to the seafloor occurs seasonally. The similar composition of  
371 modern benthic foraminiferal assemblages, as those described above, under the influence  
372 of the CRD (9-11°N; Heinz et al., 2008) and outside its influence (4-8°N; Betancur and  
373 Martinez, 2003) supports our interpretation. Recent foraminiferal assemblages under the  
374 influence of the CRD show increased abundances of *Cassidulina carinata* (Heinz et al.,



375 2008) in comparison with assemblages from areas not directly affected by (or outside) the  
376 influence of this open ocean upwelling system, which are dominated by *Uvigerina* species  
377 (Betancur and Martinez, 2003). Following the arguments discussed above, we suggest  
378 using the abundance of *Uvigerina* spp. group as an indirect proxy for the relative influence  
379 of the CRD at Hole U1381C, with increased (decreased) abundance of these species being  
380 related to distal (proximal) influence of the CRD (Figure 3c).

381 The suggestion of increased influence of the CRD over the core site during glacials and  
382 terminations is also consistent with the record of sedimentary Si/C ratios (Figure 3g). The  
383 CRD is a unique open ocean upwelling system as, in contrast to other upwelling systems  
384 where productivity is dominated by large size diatoms, productivity is governed by  
385 cyanobacteria of the *Synechococcus* group (Krause et al., 2016 and references therein).  
386 Consequently, the contribution of diatoms to the organic matter export is low (Krause et  
387 al., 2016). Therefore, low sedimentary Si/C ratios are expected when the CRD is close to  
388 the Site U1381. Indeed, Si/C ratios are low during glacials and reach their lowest values  
389 coincident with terminations (Figure 3g) further supporting the interpretation of changes in  
390 the position of the CRD based on the benthic foraminiferal assemblages.

391 The foraminiferal assemblages characterizing the last deglacial period and the early  
392 Holocene suggest the occurrence of intermediate to strong oxygen depletion in the bottom  
393 waters, based on the known tolerance of *Bolivina interjuncta*, *Bolivina seminuda*, *Bolivina*  
394 *cf. plicata* and *Epistominella smithi* and *E. pacifica* for hypoxic conditions (Silva et al.,  
395 1996) (Figure 3e). Intermediate hypoxic conditions in the bottom waters are likely the  
396 result of a combination of physical (i.e., reduced oxygen ocean solubility, water  
397 stratification and warming) and biological processes (Tetard et al., 2017 and references  
398 therein) including the excess of organic carbon supply to the sea floor delivered from  
399 enhanced productivity under the influence of the CRD. The latter is supported by low Si/C

400 ratios. A similar hypoxic deglacial event has been also described in areas to the north of  
401 our location such as Baja California and Santa Barbara basin (Tetard et al., 2017).

402

403

### 404 5.3.-Atmospheric control on the local oceanography

405 In the modern ocean, the trajectory of the CRD varies seasonally with the position of the  
406 ITCZ (Fiedler, 2002, Figure 1). Thus, change in the CRD position to be more (less)  
407 frequently over the site during glacial intervals and terminations (interglacials) requires a  
408 southward (northward, similar to nowadays) shift in the relative position of the ITCZ.  
409 Additionally, a northern (southern) position of the ITCZ would lead to increased  
410 (decreased) precipitation in the EEP (Chiang et al., 2014). Hence, an increased influence of  
411 the CRD over our site should parallel evidence for decreased precipitation and fluvial  
412 input. The influence of freshwater inputs to Site U1381 can be assessed from the relative  
413 influence of the detrital signal recorded in the elemental ratios Ti/Al (Figure 3h). The  
414 variations in the Ti/Al ratios are interpreted to be driven by changes in the terrestrial run  
415 off with low (high) ratios indicating more (less) run off (Yarincik et al., 2000). There is an  
416 overall clear relation between low relative abundance of the *Uvigerina* spp. group  
417 interpreted as increased influence of the CRD over the site (southern position of the ITCZ),  
418 with high Ti/Al values indicating low terrestrial runoff. This correspondence, together with  
419 other available proxies for the migration of the ITCZ in the tropical Atlantic (i.e., Ti/Al  
420 record from the Cariaco Basin (Figure 3i, Yarincik et al., 2000), strongly supports the  
421 suggestion that Hole U1381C is primarily recording the relative position of the ITCZ and  
422 its influence on the regional hydrography of the EEP. This interpretation is further  
423 supported by the similarity of the U1381C Ti/Al record and foraminiferal patterns during

424 terminations to the  $\Delta\delta^{18}\text{O}$  record from Chinese speleothems (Figure 4e). The speleothem  
425  $\delta^{18}\text{O}$  record is interpreted to represent abrupt changes in the precipitation regime in Central  
426 Asia related to the seasonal shifts in the ITCZ position that influences the strength of the  
427 Asian Monsoon (Cheng et al., 2016). When the ITCZ is displaced northward (southward)  
428 the northern hemisphere summer monsoon strengthens (weakens), increasing precipitation  
429 and yielding lower (higher) speleothem  $\delta^{18}\text{O}$  values (higher  $\Delta\delta^{18}\text{O}$ , Figure 4e). The  
430 correspondence between the southernmost position on the ITCZ recorded in U1381C and  
431 the weakening of the Asian monsoon supports previous suggestions that such ITCZ shifts  
432 are coherent over long distances (Schneider et al., 2014). Notably, our data extends  
433 previous inferences from marine records (Jacobel et al., 2016) for the southward migration  
434 of the ITCZ during the last two glacial terminations, indicating that comparable latitudinal  
435 ITCZ variability likely characterised earlier terminations as well, such as TIV, TV, TVI,  
436 TVII and the extra terminations TIIIa, TVIIa. This finding reinforces the idea that tropical  
437 atmospheric changes play an essential role in the deglaciation process (Denton et al.,  
438 2010).

#### 439 *5.4.- Potential contribution of extra-tropical waters to EEP productivity during* 440 *terminations*

441 The deglacial productivity maxima observed at U1381C are related to the southward  
442 migration of the ITCZ. This tropical atmospheric shift is relevant for interhemispheric  
443 oceanic and atmospheric connectivity, which play a role in the increase of productivity at  
444 terminations in the EEP. Thus, the inferred southward shifts in the ITCZ are coincident  
445 (within age model uncertainties of  $\sim 4\text{ka}$ ) with evidence for the delivery of ice-rafted  
446 debris (IRD) to the high latitude North Atlantic sediments (Figure 4f), an indirect proxy for  
447 perturbations in the Atlantic Meridional Overturning Circulation (e.g., Barker et al., 2015).  
448 This linkage can be explained by atmospheric teleconnections which are reproduced in

449 coupled ocean-atmosphere models showing that large reductions in the Atlantic Meridional  
450 Overturning Circulation can induce a southward shift in the ITCZ over the Pacific (Chiang  
451 et al., 2014). Climate models indicate that a southward migration of the ITCZ during  
452 Atlantic Meridional Overturning slowdown in the Northern Hemisphere could also cause a  
453 southward shift and intensification of the Southern Hemisphere westerlies (Ceppi et al.,  
454 2013). A southward displacement of the southern hemisphere westerlies would have  
455 contributed to warming the Southern Ocean and Antarctica (Denton et al., 2010). Besides,  
456 a weak mode of the Atlantic Meridional Overturning Circulation triggers a heat transport  
457 to the Southern Hemisphere, also warming the Southern Ocean and Antarctic continent via  
458 the thermal bipolar seesaw (Stocker and Johnsen, 2003). Ocean warming (i.e., retrieval of  
459 glacial ice) and the shift in the Southern Ocean wind pattern would have favoured the  
460 upwelling of nutrient rich deep waters in the Antarctic sector of the Southern Ocean, as  
461 inferred from marine sedimentary records (Anderson et al., 2009; Jaccard et al., 2013). The  
462 nutrient and carbon laden southern waters would also have advected northward, via  
463 Subantarctic Mode Water (Spero and Lea, 2002), and upwelled at the EEP providing extra  
464 nutrients to the equatorial thermocline, promoting primary production during the last  
465 deglaciation and possibly at older terminations (Winckler et al., 2016). The effective  
466 transfer of nutrients northwards is also conditioned by nutrient utilization in the Southern  
467 Ocean. Low nutrient utilization in the Antarctic Sector during deglaciations, caused by low  
468 iron fluxes to the Southern Ocean (Jaccard et al., 2013), implies a large proportion of  
469 nutrients being transported to low latitudes. The discussed ocean and atmospheric  
470 teleconnections set a favourable scenario for an active connection between Southern Ocean  
471 and Equatorial waters during deglacial periods as suggested by other authors for the last  
472 two glacial cycles (Rippert et al., 2017). The correspondence between the peaks in  
473 productivity during glacial terminations at the core site and the abrupt rise in productivity in

474 the Antarctic sector of the Southern Ocean (ODP 1094, Ba/Fe, Jaccard et al., 2013)  
475 suggests an intensification of the ocean tunnelling and an additional supply of nutrients  
476 from the Southern Ocean to the U1381C site. This supply of nutrients could have  
477 contributed to the increase in the productivity occurring at terminations in the easternmost  
478 part of the EEP.

479 The data and interpretation discussed in this study provide a strong case for the  
480 contribution of the EEP to the regulation of past ocean-atmosphere exchange of CO<sub>2</sub>. The  
481 intensification of the ocean tunnelling during terminations, evidenced by interhemispheric  
482 productivity patterns, would have brought up CO<sub>2</sub> rich waters to the surface of the EEP  
483 potentially contributing to the increase of the CO<sub>2</sub> atmospheric pool (e.g., Martinez-Boti et  
484 al., 2015). However, a portion of this carbon would be taken up and exported by the  
485 biological pump at the EEP, counterbalancing this oceanic CO<sub>2</sub> outgassing by transferring  
486 carbon to the EEP interior. Although the net ocean-atmosphere flux at the tropical Pacific  
487 over Middle to Late Pleistocene is yet unknown, the increase of productivity at  
488 terminations might have acted to dampen the global atmospheric CO<sub>2</sub> increase occurring at  
489 terminations (Bereiter et al., 2015). The described pattern might be applicable to other  
490 tropical areas where the injection of southern sourced nutrients to low latitude Atlantic has  
491 been interpreted to increase the productivity during the last deglaciation (Poggemann et al.,  
492 2017).

493

## 494 **6.-Conclusions**

495 In this study, we obtained a multiproxy data set of independent proxies (geochemical,  
496 micropaleoecological, sedimentological) that provide progress in our understanding of the  
497 mechanisms promoting productivity changes within the easternmost part of EEP region.  
498 We infer that the main processes promoting the increase of productivity in the EEP at

499 major and extra terminations over the last 650 ka is the shift of the ITCZ to a more  
500 southerly position (increased influence of the high productivity upwelling centre of the  
501 CRD) together with additional nutrient dvection from the Southern Ocean. From these  
502 arguments we infer that both interhemispheric oceanic and atmospheric mechanisms were  
503 involved in the productivity increase at terminations at the EEP. This deglacial  
504 productivity increase potentially played a role in the glacial-interglacial atmospheric CO<sub>2</sub>  
505 regulation by dampening the deglacial rise in atmospheric CO<sub>2</sub>. The new data presented  
506 here suggest that the EEP is a key region in climate regulation playing a role in the global  
507 atmospheric and ocean reorganizations occurring at Middle to Late Pleistocene  
508 terminations.

509

510 **Data availability:** Data presented in this manuscript are provided in an excel file, Data.xls.

511

## 512 **Acknowledgments**

513 Authors would like to thank IODP for providing the sample material used to carry out this  
514 work and also the curators of the Green Coast Repository. This manuscript benefited from  
515 discussion and valuable comments from Samuel Jaccard (University of Bern). Comments  
516 and suggestions of two anonymous reviewers contributed to the improvement of the  
517 manuscript We acknowledge financial support from the Xunta de Galicia through a Project  
518 grant EM2013/012. This study is a contribution to the project CGL2016-7987R. P.D. was  
519 funded by a Contrato Parga Pondal and Investigador Distinguido UVIGO. P.B was  
520 supported by a Contrato Juan de la Cierva (JC1-2011-08849). I.H.A was funded by Swiss  
521 National Science Foundation Advanced Postdoc Mobility Grant (P300P2\_164634).  
522 Authors appreciated the technical assistance of Rita González Villanueva.

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527 **References:**

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529 Anderson, R.F., Ali, S., Bradtmiller, L.I., Nielsen, S.H.H., Fleisher, M.Q., Anderson, B.E.,  
530 Burckle, L.H., 2009. Wind-Driven Upwelling in the Southern Ocean and the Deglacial  
531 Rise in Atmospheric CO<sub>2</sub>. *Science* 323, 1443-1448.

532 Barker, S., Chen, J., Gong, X., Jonkers, L., Knorr, G., Thornalley, D., 2015. Icebergs not  
533 the trigger for North Atlantic cold events. *Nature* 520, 333-336.

534 Bereiter, B., Eggleston, S., Schmitt, J., Nehrbass-Ahles, C., Stocker, T.F., Fischer, H.,  
535 Kipfstuhl, S., Chappellaz, J., 2015. Revision of the EPICA Dome C CO<sub>2</sub> record from 800  
536 to 600 kyr before present. *Geophysical Research Letters* 42, 542-549.

537 Betancur, M.J., Martinez, I., 2003. Foraminíferos bentónicos recientes en sedimentos de  
538 fondo de la Cuenca de Panamá (Pacífico Colombiano), como indicadores de productividad  
539 y oxigenación. *Boletín de Investigaciones Marinas y Costeras* 32, 93-123.

540 Ceppi, P., Hwang, Y.-T., Liu, X., Frierson, D.M.W., Hartmann, D.L., 2013. The  
541 relationship between the ITCZ and the Southern Hemispheric eddy-driven jet. *Journal of*  
542 *Geophysical Research: Atmospheres* 118, 5136-5146.

543 Cheng, H., Edwards, R.L., Sinha, A., Spötl, C., Yi, L., Chen, S., Kelly, M., Kathayat, G.,  
544 Wang, X., Li, X., Kong, X., Wang, Y., Ning, Y., Zhang, H., 2016. The Asian monsoon  
545 over the past 640,000 years and ice age terminations. *Nature* 534, 640-646.

546 Chiang, J.C.H., Lee, S.-Y., Putnam, A.E., Wang, X., 2014. South Pacific Split Jet, ITCZ  
547 shifts, and atmospheric North–South linkages during abrupt climate changes of the last  
548 glacial period. *Earth and Planetary Science Letters* 406, 233-246.

549 Denton, G.H., Anderson, R.F., Toggweiler, J.R., Edwards, R.L., Schaefer, J.M., Putnam,  
550 A.E., 2010. The Last Glacial Termination. *Science* 328, 1652-1656.

551 Fiedler, P.C., 2002. The annual cycle and biological effects of the Costa Rica Dome. *Deep*  
552 *Sea Research Part I: Oceanographic Research Papers* 49, 321-338.

553 Fiedler, P.C., Talley, L.D., 2006. Hydrography of the eastern tropical Pacific: A review.  
554 *Progress in Oceanography* 69, 143-180.

555 Goineau, A., Fontanier, C., Jorissen, F.J., Lansard, B., Buscail, R., Mouret, A., Kerhervé,  
556 P., Zaragosi, S., Ernoult, E., Artéro, C., Anschutz, P., Metzger, E., Rabouille, C., 2011.  
557 Live (stained) benthic foraminifera from the Rhône prodelta (Gulf of Lion, NW  
558 Mediterranean): Environmental controls on a river-dominated shelf. *Journal of Sea*  
559 *Research* 65, 58-75.

- 560 Gooday, A.J., 2003. Benthic foraminifera (protista) as tools in deep-water  
561 palaeoceanography: Environmental influences on faunal characteristics, *Advances in*  
562 *Marine Biology*. Academic Press, pp. 1-90.
- 563 Harris, R.N., Sakaguchi, A., Petronotis, K., Expedition 344 Scientists, 2013. Input Site  
564 U1381. *Proceedings of the Integrated Ocean Drilling Program Volume 344*  
565 doi:10.2204/iodp.proc.344.103.2013.
- 566  
567 Heinz, P., Ruschmeier, W., Hemleben, C., 2008. Live benthic foraminiferal assemblages at  
568 the Pacific continental margin of Costa Rica and Nicaragua. *The Journal of Foraminiferal*  
569 *Research* 38, 215.
- 570 Hofmann, E.E., Busalacchi, A.J., Q'Brien, J.J., 1981. Wind Generation of the Costa Rica  
571 Dome. *Science* 214, 552-554.
- 572 Ivanova, E.V., Beaufort, L., Vidal, L., Kucera, M., 2012. Precession forcing of  
573 productivity in the Eastern Equatorial Pacific during the last glacial cycle. *Quaternary*  
574 *Science Reviews* 40, 64-77.
- 575 Jaccard, S.L., Hayes, C.T., Martínez-García, A., Hodell, D.A., Anderson, R.F., Sigman,  
576 D.M., Haug, G.H., 2013. Two Modes of Change in Southern Ocean Productivity Over the  
577 Past Million Years. *Science* 339, 1419-1423.
- 578 Jacobel, A.W., McManus, J.F., Anderson, R.F., Winckler, G., 2016. Large deglacial shifts  
579 of the Pacific Intertropical Convergence Zone. *Nature Communications* 7, 10449.
- 580 Kienast, S.S., Kienast, M., Mix, A.C., Calvert, S.E., François, R., 2007. Thorium-230  
581 normalized particle flux and sediment focusing in the Panama Basin region during the last  
582 30,000 years. *Paleoceanography* 22, PA2213.
- 583 Krause, J.W., Stukel, M.R., Taylor, A.G., Taniguchi, D.A.A., De Verneil, A., Landry,  
584 M.R., 2016. Net biogenic silica production and the contribution of diatoms to new  
585 production and organic matter export in the Costa Rica Dome ecosystem. *Journal of*  
586 *Plankton Research* 38, 216-229.
- 587 LaMontagne, R.W., Murray, R.W., Wei, K.Y., Leinen, M., Wang, C.H., 1996. Decoupling  
588 of Carbonate Preservation, Carbonate Concentration, and Biogenic Accumulation: A 400-  
589 kyr Record from the Central Equatorial Pacific Ocean. *Paleoceanography* 11, 553-562.
- 590 Licari, L., Mackensen, A., 2005. Benthic foraminifera off West Africa (1°N to 32°S): Do  
591 live assemblages from the topmost sediment reliably record environmental variability?  
592 *Marine Micropaleontology* 55, 205-233.
- 593 Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed  
594 benthic  $\delta^{18}\text{O}$  records. *Paleoceanography* 20, PA1003.
- 595 Locarnini, R.A., Mishonov, A.V., Antonov, J.I., Boyer, T.P., Garcia, H.E., Baranova,  
596 O.K., Zweng, M.M., Paver, C.R., Reagan, J.R., Johnson, D., Hamilton, R.M., Seidov, D.,  
597 2013. *World Ocean Atlas 2013, Volume 1: Temperature*, in: Levitus, S. (Ed.). *Mishonov*  
598 *Technical Ed NOAA Atlas NESDIS 73*, p. 40.



- 599 López-Otálvaro, G.-E., Flores, J.-A., Sierro, F.J., Cacho, I., 2008. Variations in  
600 coccolithophorid production in the Eastern Equatorial Pacific at ODP Site 1240 over the  
601 last seven glacial–interglacial cycles. *Marine Micropaleontology* 69, 52-69.
- 602 Lyle, M., Mix, A., Pisias, N., 2002. Patterns of CaCO<sub>3</sub> deposition in the eastern tropical  
603 Pacific Ocean for the last 150 kyr: Evidence for a southeast Pacific depositional spike  
604 during marine isotope stage (MIS) 2. *Paleoceanography* 17, doi: 10.1029/2000PA000538.
- 605 Martinez-Boti, M.A., Marino, G., Foster, G.L., Ziveri, P., Henehan, M.J., Rae, J.W.B.,  
606 Mortyn, P.G., Vance, D., 2015. Boron isotope evidence for oceanic carbon dioxide leakage  
607 during the last deglaciation. *Nature* 518, 219-222.
- 608 McManus, J.F., Oppo, D.W., Cullen, J.L., 1999. A 0.5-Million-Year Record of Millennial-  
609 Scale Climate Variability in the North Atlantic. *Science* 283, 971-975.
- 610 Meyers, P.A., 1997. Organic geochemical proxies of paleoceanographic, paleolimnologic,  
611 and paleoclimatic processes. *Organic Geochemistry* 27, 213-250.
- 612 Mojtahid, M., Griveaud, C., Fontanier, C., Anschutz, P., Jorissen, F.J., 2010. Live benthic  
613 foraminiferal faunas along a bathymetrical transect (140–4800 m) in the Bay of Biscay  
614 (NE Atlantic). *Revue de Micropaléontologie* 53, 139-162.
- 615 Morigi, C., Jorissen, F.J., Gervais, A., Guishard, S., Borsetti, A.M., 2001. Benthic  
616 foraminiferal faunas in surface sediments off NW Africa: Relationship with organic flux to  
617 the ocean floor. *Journal of Foraminiferal Research* 31, 350-368.
- 618 Mortlock, R.A., Froelich, P.N., 1989. A simple method for the rapid determination of  
619 biogenic opal in pelagic marine sediments. *Deep Sea Research Part A. Oceanographic*  
620 *Research Papers* 36, 1415-1426.
- 621 Murray, R.W., Leinen, M., Knowlton, C.W., 2012. Links between iron input and opal  
622 deposition in the Pleistocene equatorial Pacific Ocean. *Nature Geoscience* 5, 270-274.
- 623 Palter, J.B., Sarmiento, J.L., Gnanadesikan, A., Simeon, J., Slater, R.D., 2010. Fueling  
624 export production: nutrient return pathways from the deep ocean and their dependence on  
625 the Meridional Overturning Circulation. *Biogeosciences* 7, 3549-3568.
- 626 Pennington, J.T., Mahoney, K.L., Kuwahara, V.S., Kolber, D.D., Calienes, R., Chavez,  
627 F.P., 2006. Primary production in the eastern tropical Pacific: A review. *Progress In*  
628 *Oceanography* 69, 285-317.
- 629 Poggemann, D.-W., Hathorne, E.C., Nürnberg, D., Frank, M., Bruhn, I., Reißig, S., Bahr,  
630 A., 2017. Rapid deglacial injection of nutrients into the tropical Atlantic via Antarctic  
631 Intermediate Water. *Earth and Planetary Science Letters* 463, 118-126.
- 632 Ragueneau, O., Tréguer, P., Leynaert, A., Anderson, R.F., Brzezinski, M.A., DeMaster,  
633 D.J., Dugdale, R.C., Dymond, J., Fischer, G., François, R., Heinze, C., Maier-Reimer, E.,  
634 Martin-Jézéquel, V., Nelson, D.M., Quéguiner, B., 2000. A review of the Si cycle in the  
635 modern ocean: recent progress and missing gaps in the application of biogenic opal as a  
636 paleoproductivity proxy. *Global and Planetary Change* 26, 317-365.

- 637 Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck,  
638 C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P.,  
639 Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hughen, K.A., Kaiser,  
640 K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M.,  
641 Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J., Hogg, A., 2013. IntCal13 and  
642 Marine13 radiocarbon age calibration curves 0-50,000 years cal BP. *Radiocarbon* 55,  
643 1869-1887.
- 644 Rippert, N., Max, L., Mackensen, A., Cacho, I., Povea, P., Tiedemann, R., 2017.  
645 Alternating Influence of Northern Versus Southern-Sourced Water Masses on the  
646 Equatorial Pacific Subthermocline During the Past 240 ka. *Paleoceanography* 32, 1256-  
647 1274.
- 648 Sarmiento, J.L., Gruber, N., Brzezinski, M.A., Dunne, J.P., 2003. High-latitude controls of  
649 thermocline nutrients and low latitude biological productivity. *Nature* 427, 56-60.
- 650 Schneider, T., Bischoff, T., Haug, G.H., 2014. Migrations and dynamics of the  
651 intertropical convergence zone. *Nature* 513, 45-53.
- 652 Sexton, P.F., Barker, S., 2012. Onset of 'Pacific-style' deep-sea sedimentary carbonate  
653 cycles at the mid-Pleistocene transition. *Earth and Planetary Science Letters* 321-322, 81-  
654 94.
- 655 Silva, K.A., Corliss, B.H., Rathburn, A.E., Thunell, R.C., 1996. Seasonality of living  
656 benthic Foraminifera from the San Pedro Basin, California Borderland. *The Journal of*  
657 *Foraminiferal Research* 26, 71-93.
- 658 Spero, H.J., Lea, D.W., 2002. The cause of Carbon Isotope Minimum Events on glacial  
659 Terminations. *Science* 296, 522-525.
- 660 Stocker, T.F., Johnsen, S.J., 2003. A minimum thermodynamic model for the bipolar  
661 seesaw. *Paleoceanography* 18, 1087.
- 662 Takahashi, T., Sutherland, S.C., Wanninkhof, R., Sweeney, C., Feely, R.A., Chipman,  
663 D.W., Hales, B., Friederich, G., Chavez, F., Sabine, C., Watson, A., Bakker, D.C.E.,  
664 Schuster, U., Metzl, N., Yoshikawa-Inoue, H., Ishii, M., Midorikawa, T., Nojiri, Y.,  
665 Körtzinger, A., Steinhoff, T., Hoppema, M., Olafsson, J., Arnarson, T.S., Tilbrook, B.,  
666 Johannessen, T., Olsen, A., Bellerby, R., Wong, C.S., Delille, B., Bates, N.R., de Baar,  
667 H.J.W., 2009. Climatological mean and decadal change in surface ocean pCO<sub>2</sub>, and net  
668 sea-air CO<sub>2</sub> flux over the global oceans. *Deep Sea Research Part II: Topical Studies in*  
669 *Oceanography* 56, 554-577.
- 670
- 671 Tetard, M., Licari, L., Beaufort, L., 2017. Oxygen history off Baja California over the last  
672 80 kyr: A new foraminiferal-based record. *Paleoceanography* 32, 246-264.
- 673 Thunell, R.C., Keir, R.S., Honjo, S., 1981. Calcite Dissolution: An in situ Study in the  
674 Panama Basin. *Science* 212, 659-661.
- 675 Tribovillard, N., Algeo, T.J., Lyons, T., Riboulleau, A., 2006. Trace metals as paleoredox  
676 and paleoproductivity proxies: An update. *Chemical Geology* 232, 12-32.

677 Winckler, G., Anderson, R.F., Jaccard, S.L., Marcantonio, F., 2016. Ocean dynamics, not  
678 dust, have controlled equatorial Pacific productivity over the past 500,000 years.  
679 Proceedings of the National Academy of Sciences 113, 6119-6124.

680 Wright, A.K., Flower, B.P., 2002. Surface and deep ocean circulation in the subpolar North  
681 Atlantic during the mid-Pleistocene revolution. *Paleoceanography* 17, 20-21-20-16.

682 Yarincik, K.M., Murray, R.W., Peterson, L.C., 2000. Climatically sensitive eolian and  
683 hemipelagic deposition in the Cariaco Basin, Venezuela, over the past 578,000 years:  
684 Results from Al/Ti and K/Al. *Paleoceanography* 15, 210-228.

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## 690 **FIGURES AND FIGURE CAPTIONS**

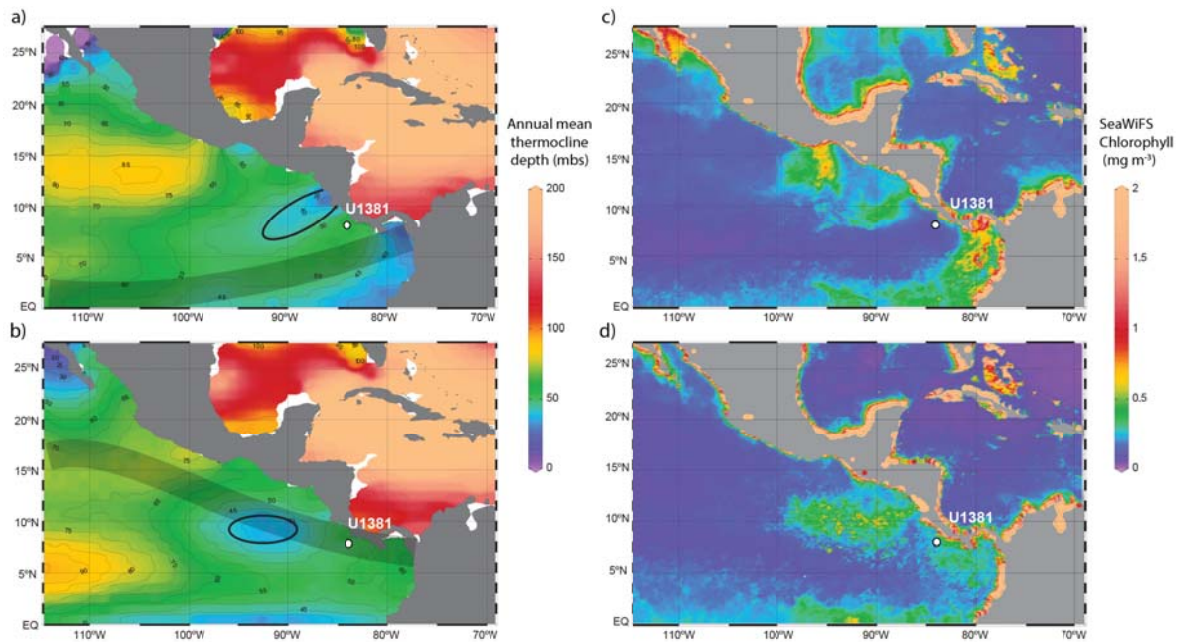
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### 692 **Figure 1: Location of Hole U1381C and regional hydrography**

693 Figures on the left (a, b) represent the seasonal (winter above; summer below) depth (in  
694 meters below surface, mbs) of the 20°C isotherm in region of the EEP, which is used to  
695 identify the position of the Costa Rica Dome (Fiedler, 2002). The shadowed area  
696 represents the position of the ITCZ in winter (a) and summer (b). Thermocline temperature  
697 data are from World Ocean Database 2013 (Locarnini et al., 2013). The white circle  
698 indicates the location of Hole U1381C. Plots on the right (c, d) represents the winter (c)  
699 and summer (d) mean fields of SeaWiFS (September 1997 to July 2001) chlorophyll  
700 concentration in the region of the Costa Rica Dome. SeaWiFS data produced by NASA  
701 SeaWiFS Project and distributed by the Distributed Active Archive Center at  
702 NASA/Goddard Space Flight Center (<http://oceancolor.gsfc.nasa.gov>, accessed on 1<sup>st</sup>  
703 February 2018).

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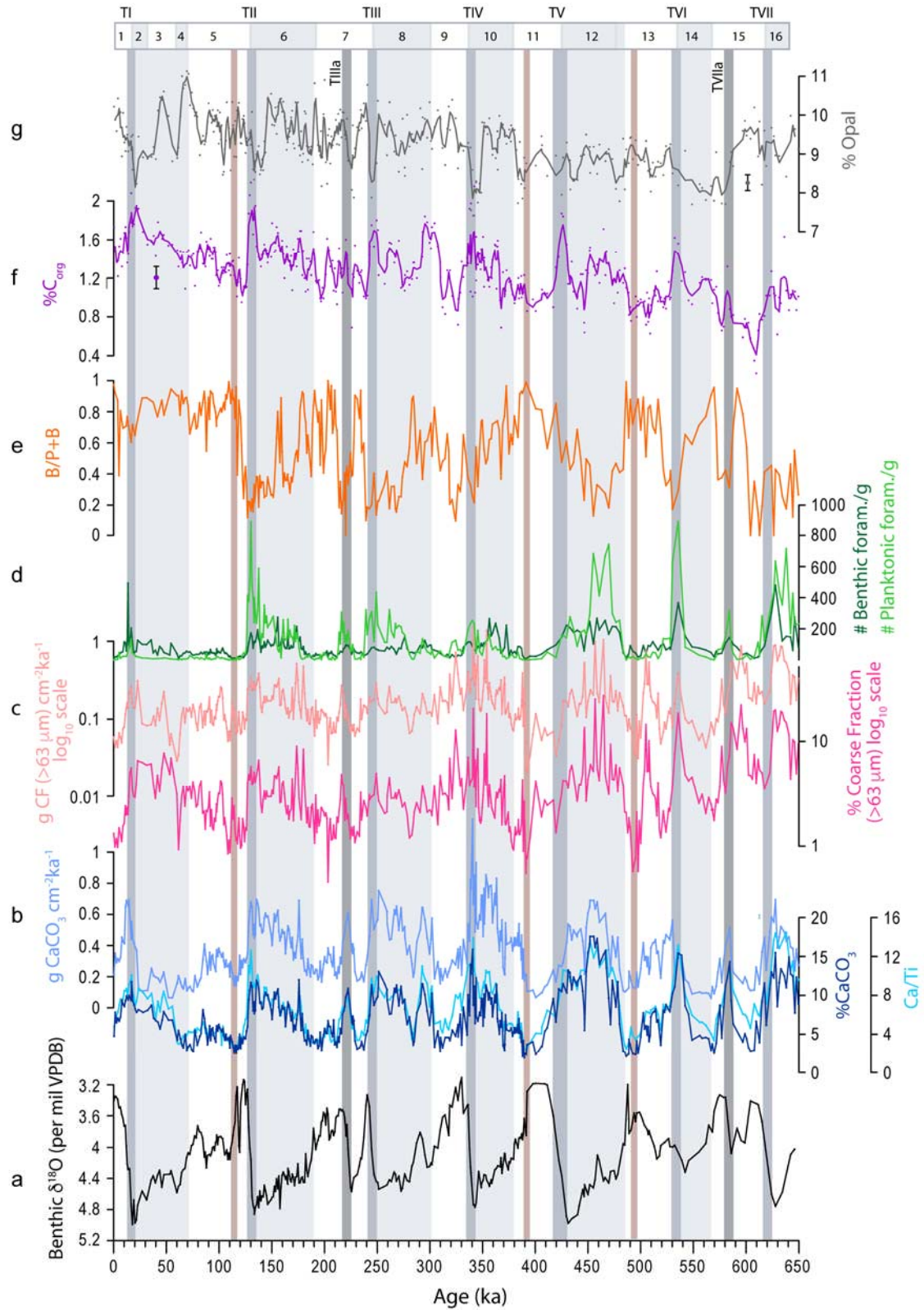
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708 **Figure 2: Calcium carbonate variability.**

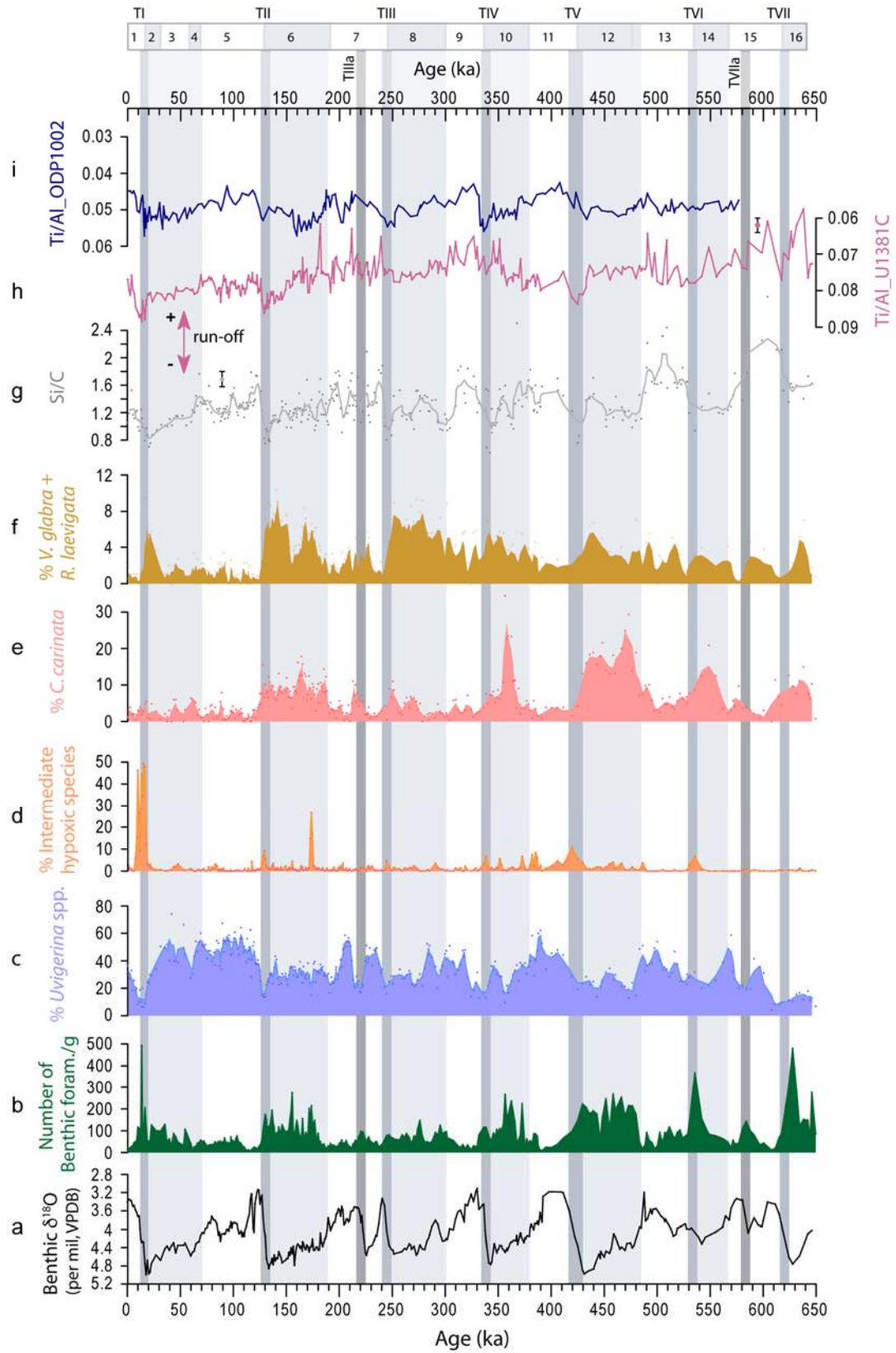
723 The benthic oxygen isotope record of *Uvigerina auberiana* (a) and carbonate records (b) of  
 724 Hole U1381C are compared with other proxies for carbonate dissolution/production  
 725 obtained in the same core (c-g). (b) %  $\text{CaCO}_3$  and Ca/Ti (right axis) and mass  $\text{CaCO}_3$   
 726 accumulation rate (left axis); (c) percent (right) and mass accumulation (left) of the coarse  
 727 fraction ( $\% > 63 \mu\text{m}$ ); (d) abundance of benthic foraminifera (number of benthic  
 728 foraminifera  $> 125 \mu\text{m}$  fraction per gram of dry weight sediment) and planktonic  
 729 foraminifera (number of planktonic foraminifera  $> 150 \mu\text{m}$  fraction per gram of dry weight  
 730 sediment). The relation of benthic foraminifera to planktonic and benthic foraminifera  
 731 (B/P+B) is indicated in (e). The organic carbon content of the core is used as a proxy for  
 732 organic production (f) and complements the information provided by benthic foraminifera  
 733 (d). The opal content (%) is indicated in (g). Lines for the content of  $\text{C}_{\text{org}}$  (f) and %opal (g)  
 734 represent the 3-points running average. Vertical bars to the side of plots (f) and (g) indicate  
 735 standard error of  $\text{C}_{\text{org}}$  ( $\pm 0.14\%$ ) and opal ( $\pm 0.2\%$ ) analyses. Vertical grey bars indicate  
 736 glacial periods (light grey) and major terminations (dark grey) and “extra terminations”  
 737 (very dark grey). Brown vertical bars indicate potentially heavily dissolved intervals.



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724 **Figure 3: Benthic foraminiferal assemblages**

725 The benthic  $\delta^{18}\text{O}$  curve and the abundance of benthic foraminifera (number of benthic  
726 foraminifera >125  $\mu\text{m}$  per gram of dry weight sediment) are shown for reference in (a) and  
727 (b). The records of the most characteristic species of benthic foraminifera in Hole U1381C  
728 expressed in percentage are indicated in (c-f). Filled areas represent the 3-point running  
729 average. The Si/C ratio (g, 3-point running average) is used here as a proxy for the  
730 abundance of siliceous to non-siliceous primary producers. The Ti/Al record in the Hole  
731 U1381C is plotted on inverted axis on the right (h) and the record of Ti/Al of ODP-1002  
732 on the left (Yarincik et al., 2000) (i). The Ti/Al records indicate decreased (increased)  
733 runoff - high (low) Ti/Al ratios- which are related to the relative movement of the  
734 terrestrial ITCZ with high (low) ratios corresponding to a southerly (northerly)-most  
735 position of the ITCZ. The average error of Ti/Al and Si/C measurements is indicated by  
736 vertical bars to the side of plots (g) and (h). The *Uvigerina* spp. group includes *Uvigerina*  
737 *auberiana* and *Uvigerina peregrina*. The group of the so called intermediate hypoxic  
738 species includes *Bolivina interjuncta*, *Bolivina seminuda*, *Bolivina* cf. *plicata*,  
739 *Epistominella pacifica* and *Epistominella smithi*. Vertical grey bars are as indicated in  
740 Figure 2.



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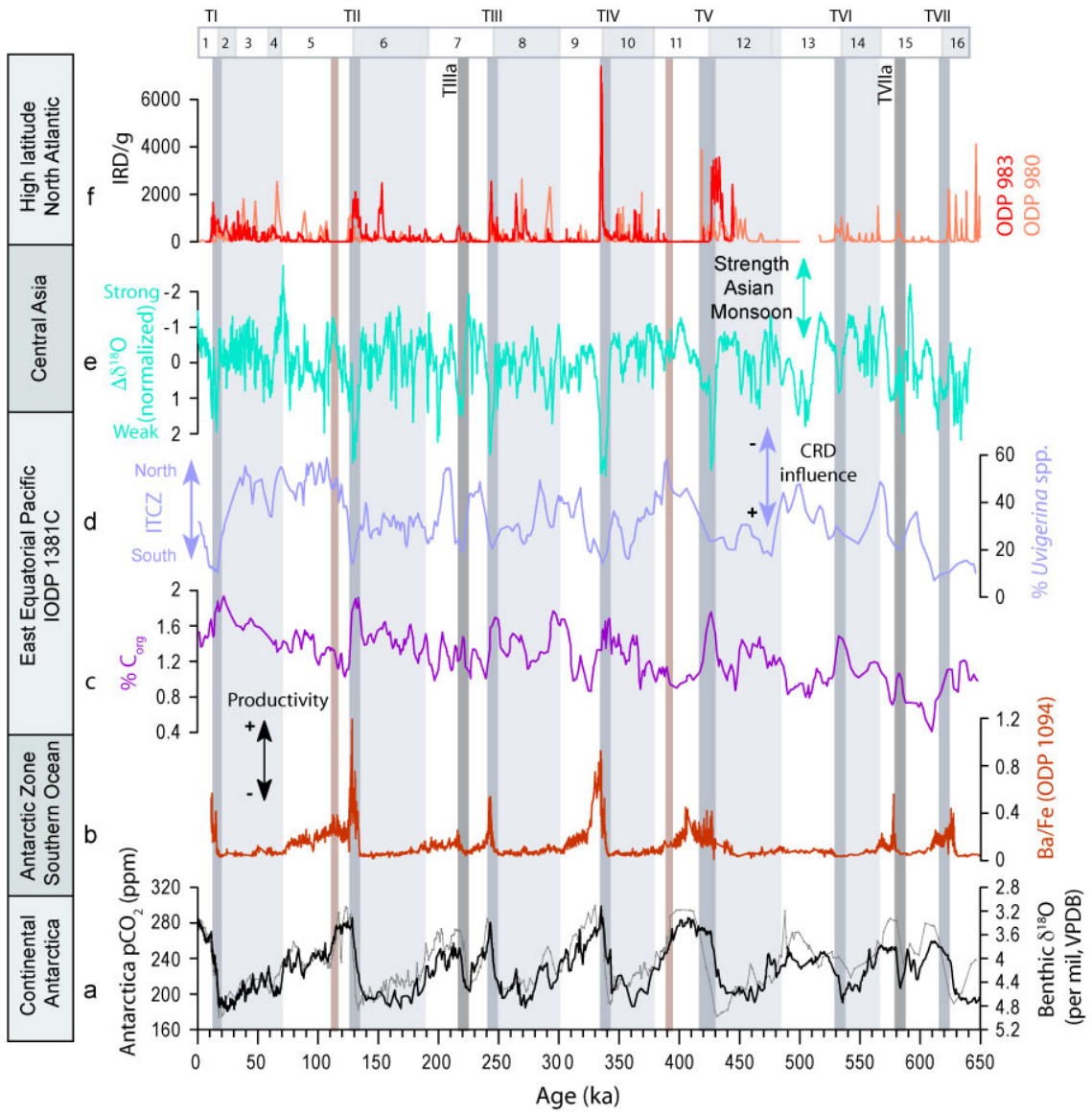
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744 **Figure 4: Atmospheric and oceanic interplay at terminations.**

745 Proxies for the Antarctic Continent (a), the Antarctic sector of the Southern Ocean (b) are  
746 compared to proxies obtained in the EEP (c-d; Hole U1381C, this study), central Asia (e)  
747 and the high latitude North Atlantic (f). The oxygen isotope record of Hole U1381C (a,  
748 grey) is plotted to the right of the Antarctic CO<sub>2</sub> composite (Bereiter et al., 2015). The  
749 productivity record of the Antarctic sector of the Southern Ocean (b) is represented by the  
750 Ba/Fe record of ODP Site 1094 (Jaccard et al., 2013) and is compared to Hole U1381C  
751 records of (c) %C<sub>org</sub> as a proxy for productivity and (d) the percentage of *Uvigerina* spp.  
752 group, which is related to the influence of the Costa Rica Dome and therefore, a proxy for  
753 the relative position of the ITCZ. The increased (decreased) abundance of *Uvigerina* spp.  
754 is related to the northward (southward) position of the ITCZ. Data from this study lead to  
755 the suggestion that the southernmost position of the ITCZ in the EEP is attained at  
756 terminations (both major and extra terminations) in close correspondence with abrupt  
757 weakening of the Asian Monsoon (e). The record of  $\Delta\delta^{18}\text{O}$  (e) from Chinese caves  
758 represents a cave composite  $\delta^{18}\text{O}$  signal obtained after removing the orbital insolation  
759 component (Cheng et al., 2016). Records of Ice Rafted Detritus (IRD, number/g) in the  
760 high latitude North Atlantic (ODP Site 983 data from Barker et al., 2015, redline; ODP Site  
761 980 data from McManus et al., 1999 and Wright and Flower, 2002, orange line) are  
762 indicated in (f). Note that age models are plotted on their published age scales; ODP Sites  
763 983 and 1094 are tuned to ice core records whereas Hole U1381C and ODP Site 980 are  
764 tuned to an orbital stack. Vertical bars are as indicated in Figure 2.





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