

1 **Oceanographic and climatic evolution of the southeastern subtropical Atlantic over the last 3.5 Ma**

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20 **Abstract**

21 The southeast Atlantic Ocean is dominated by two major oceanic systems: the Benguela

22 Upwelling System, one of the world's most productive coastal upwelling cells and the Agulhas

23 Leakage, which is important for transferring warm salty water from the Indian Ocean to the Atlantic

24 Ocean. Here, we present a multi-proxy record of marine sediments from ODP Site 1087. We
25 reconstruct sea surface temperatures (U_{37}^K and TEX_{86} indices), marine primary productivity (total
26 chlorin and alkenone mass accumulation rates), and terrestrial inputs derived from southern Africa
27 (Ti/Al and Ca/Ti via XRF scanning) to understand the evolution of the Southeast Atlantic Ocean since
28 the late Pliocene. In the late Pliocene and early Pleistocene, ODP Site 1087 was situated within the
29 Benguela Upwelling System, which was displaced southwards relative to present. We recognize a
30 series of events in the proxy records at 3.3, 3.0, 2.2, 1.5, 0.9 and 0.6 Ma, which are interpreted to
31 reflect a combination of changes in the location of major global wind and oceanic systems and local
32 variations in the strength and/or position of the winds, which influence nutrient availability.
33 Although there is a temporary SST cooling observed around the initiation of Northern Hemisphere
34 glaciation (iNHG), proxy records from ODP Site 1087 show no clear climatic transition around 2.7 Ma
35 but instead most of the changes occur before this time. This observation is significant because it has
36 been previously suggested that there should be a change in the location and/or strength of
37 upwelling associated with this climate transition. Rather, the main shifts at ODP Site 1087 occur at
38 ca. 0.9 Ma and 0.6 Ma, associated with the early mid-Pleistocene transition (EMPT), with a clear loss
39 of the previous upwelling-dominated regime. This observation raises the possibility that
40 reorganisation of southeast Atlantic Ocean circulation towards modern conditions was tightly linked
41 to the EMPT, but not to earlier climate transitions.

42

43 **1.1 Introduction**

44 Over the last 3.5 Ma, Earth's climate transitioned from warmer climates of the Pliocene to
45 cooler Pleistocene climates (Haug et al., 2005; McClymont et al., 2013). Two of the biggest climate
46 transitions were the intensification of Northern Hemisphere glaciation (iNHG; 3.0 and 1.5 Ma), when
47 Northern Hemisphere ice sheets expanded and the oceans cooled (Haug et al., 2005), and the early
48 mid-Pleistocene transition (EMPT; 1.2 and 0.6 Ma), when glacial-interglacial cycles shifted to a quasi-

49 100ka period (Chalk et al., 2017; Maslin and Brierley, 2015; McClymont et al., 2013). Shifts in the
50 location and intensity of the major ocean upwelling cells are thought to play an important role in
51 global climate during the Plio-Pleistocene (Lawrence et al., 2013; März et al., 2013). For example, the
52 equatorward migration of the major wind cells between 3.3 and 1.0 Ma resulted in a concomitant
53 shift of the subtropical and polar upwelling zones and increased global carbonate production,
54 affecting the global atmosphere-ocean CO₂ exchange (Lawrence et al., 2013; Martínez-García et al.,
55 2011). Additionally, models show that cooler sea surface temperatures (SSTs) in upwelling zones can
56 affect mean global atmospheric temperatures, as upwelling cells supply cooler deeper waters to the
57 surface ocean (Barreiro et al., 2005).

58 Debate exists about the precise timing of upwelling shifts during the Plio-Pleistocene and
59 whether the changes in location and focus of the different upwelling systems reflect local, rather
60 than global, factors (Dekens et al., 2007; Lawrence et al., 2013; Rosell-Melé et al., 2014). Lawrence
61 et al. (2013) proposed that between 3.3 and 2.5 Ma, the build-up of ice sheets in the Northern
62 Hemisphere caused the westerlies to shift equatorward and the Hadley Cells to contract, shifting the
63 location of the trade winds. These authors propose that the shift in the wind fields resulted in
64 cooling and increased productivity in major North and South Atlantic Ocean upwelling cells. Others
65 have suggested, based on SST cooling around 3.3 Ma (Dekens et al., 2007), that upwelling cells were
66 invigorated before the intensification of glacial stages at 2.7 Ma (MIS 96-100) (Haug et al., 2005).
67 Later upwelling intensification in the Benguela System around 2 Ma has been inferred from SST
68 cooling and increased productivity (Etourneau et al., 2010, 2009). Thus, it remains unclear whether
69 changes in upwelling activity across the Plio-Pleistocene transition were influenced by global climate
70 transitions or occurred independently.

71 ODP Site 1087 (31°28'S, 15°19'E; 1374 m water depth) is located near the southern cell of
72 the modern Benguela Upwelling System (Figure 1). Foraminiferal assemblages, SST reconstructions,
73 and marine organic matter inputs indicate that ODP Site 1087 was influenced by the Benguela

74 Upwelling System during the Pliocene (3.5–3.0 Ma; Petrick et al., 2015a). However, during the mid to
75 late Pleistocene (0–0.6 Ma), foraminiferal assemblage, SST, and salinity records indicate that the site
76 was primarily influenced by Indian Ocean waters via the Agulhas Leakage, with evidence of
77 upwelling limited to a few glacial periods (Caley et al., 2014, 2012; McClymont et al., 2005; Petrick et
78 al., 2015b). What remains unclear is the nature and timing of the transition from an upwelling-
79 dominated to a leakage-dominated regime, and whether this shift occurred as part of the iNHG or
80 the EMPT. The timing of this transition may have important climatic implications, as intensification
81 of Agulhas leakage enhances heat and salt transfer into the Southeast Atlantic Ocean, which may
82 influence the strength of the AMOC (Biajoch et al., 2008). The continuous Plio-Pleistocene sediment
83 sequence from ODP Site 1087 provides an ideal archive from which to reconstruct the evolution of
84 the southern Benguela Upwelling and Agulhas Leakage Systems over the Plio-Pleistocene.

85

86 **1.2 Oceanographic Setting and paleoclimate history**

87 The Benguela Upwelling System is a key oceanographic upwelling region that developed
88 around the mid-Miocene (Diester-Haass, 1988). The Benguela Upwelling is one of the few major
89 temperate upwelling sites in the world. It is an area that releases CO² and is important for biological
90 cycling in the ocean (Compton et al., 2009; West et al., 2004). Therefore, understating the history of
91 the System under different climate regimes is important for understanding the effects and impacts
92 of climate change. It has been proposed that the main focus of the Benguela Upwelling System has
93 migrated northward from the southern Benguela region to its current location since the mid-
94 Pliocene (Christensen and Giraudeau, 2002; Petrick et al., 2015a; Rosell-Melé et al., 2014). Changes
95 in temperature and productivity have been well documented in the northern (ODP Sites 1082 and
96 1081; Figure 1) and central Benguela upwelling cells (ODP Site 1084) over the last 3.5 Ma (Etourneau
97 et al., 2009; Marlow et al., 2000; Rosell-Melé et al., 2014). Initial cooling began gradually in the
98 northern and central cells around 3.5 Ma, with a 0-1°C gradient from the northern to central

99 upwelling cells (Rosell-Melé et al., 2014). Around 3.0 Ma, there was an increase in diatom
100 production, marking the Matuyama Diatom Maximum (MDM), in the northern and central Benguela
101 regions (3.0–2.5 Ma) (Robinson and Meyers, 2002). Around 1.5 Ma, there was major cooling at all
102 three sites and the development of a 3–4°C gradient between the northern and central cells (Rosell-
103 Melé et al., 2014). Regional primary productivity was stable until 2.4 Ma, when it increased in the
104 central cells (Rosell-Melé et al., 2014); productivity increased in the northern cells at 0.6 Ma (Rosell-
105 Melé et al., 2014). Constriction and northward movement of the Hadley cells since the Pliocene is
106 hypothesized to have shifted the focus of upwelling equatorward (Etourneau et al., 2010; Rosell-
107 Melé et al., 2014). More recently, models indicate that tectonic mountain-building in West Africa
108 may have influenced the position and intensity of the trade winds, resulting in the onset and
109 northward migration of upwelling since the mid-Miocene (Jung et al., 2014).

110 Presently, sea surface conditions at ODP Site 1087 are influenced by the Agulhas Leakage
111 (Figure 1) (Gordon et al., 1987; Gordon and Haxby, 1990), which transfers rings of warm and salty
112 water from the Indian Ocean to the Atlantic Ocean. This is the primary way that surface water is
113 transferred from the Indian Ocean to the Atlantic Ocean. These rings are then advected northwards
114 and ultimately incorporated into the Atlantic Meridional Overturning Circulation (AMOC) (Hall and
115 Lutjeharms, 2011). Through its impact on salt transfer to the North Atlantic, the intensity of Agulhas
116 Leakage has been shown to influence the strength of the AMOC over centennial to millennial scale
117 times (Biaosoch et al., 2008; Knorr and Lohmann, 2003). In climate models, increases in the Agulhas
118 Leakage are able to restart the thermohaline circulation after a period of shutdown, for example in
119 response inputs of fresh waters to the North Atlantic; (Knorr and Lohmann, 2003). Increased Agulhas
120 Leakage has also been shown to be a prominent feature of deglaciations over the last 1200 kyr (Beal
121 et al., 2011) and may have prevented an early return to glacial conditions, such as during the
122 Younger Dryas, through increasing input of high salinity waters to the source of the Atlantic
123 thermohaline circulation (Dyez et al., 2014; Marino et al., 2013; Scussolini et al., 2015).
124 Furthermore, other studies have shown that this salt leakage seems to have existed since at least

125 500ka (Petrick et al., 2015)

126 Today, ODP 1087 does not receive much terrestrial input. The modern day site is on the
127 edge of the Namibian Dust Plume (Kienast et al., 2016; Mahowald et al., 2014). Therefore the
128 amount of dust reaching the site is limited. Additionally, the Orange River provides a minor source
129 of riverine input. While the majority of the input from the Orange River occurs far north of the site,
130 some finer particles are incorporated into the turbulent Cape Basin Area (Bluck et al., 2007; Boebel et
131 al., 2003; Compton and Maake, 2007). These then are transported throughout the Cape Basin
132 (Boebel et al., 2003). However, overall the amount of terrestrial material is low compared to other
133 sites in the region.

134 ODP Site 1087 preserves evidence of both Agulhas Leakage and Benguela Upwelling in the
135 same core, so it is ideal for understanding the relationship between these two oceanic systems. In
136 order to track shifts in upwelling strength over the last 3.5 Ma, we applied a multiproxy approach to
137 sediments from ODP Site 1087 (Figure 1). Two biomarker temperature proxies, the U_{37}^K and TEX_{86}
138 indices (Müller et al., 1998; Schouten et al., 2002), were used to reconstruct SSTs, which are
139 sensitive to upwelling strength. Additionally, concentrations of chlorins and alkenones were
140 determined to assess primary productivity and coccolithophore productivity, respectively (Harris et
141 al., 1996). Ca/Ti ratios from XRF scanning were used as a proxy of carbonate deposition/preservation
142 at the site, which may relate to changes in productivity. Terrestrial inputs were assessed using Ti/Al
143 counts, which have been shown for the SE Atlantic to track dust over riverine input (Govin et al.,
144 2012). For more information about the Interpretation and complications of the proxy signals, see the
145 supplemental data.

146 The U_{37}^K -derived SSTs and alkenone mass accumulation rate (MAR) data for the last 1.5 Ma
147 are published (McClymont et al., 2005; Petrick et al., 2015a). However, the new data we present
148 allow a better understanding of: 1) Changes in the vertical temperature structure of the upper water
149 column (U_{37}^K - TEX_{86}), which gives an indication of upwelling strength, because research shows that

150 in Benguela sourced water SST reconstructions are lower in TEX_{86} than U_{37}^{K} . By comparing periods
151 where the two proxies record different temperature to those where the SSTs are the same, we can
152 track the presence of upwelling sourced water; 2) Changes in terrestrial inputs (Ti/Al) and potential
153 wind-forcing of any upwelling changes; and 3) Associated changes in marine productivity (alkenone
154 and chlorin MAR). These new data are placed in a regional context through comparison to similar
155 datasets from the northern and central Benguela Upwelling System (ODP Sites 1081, 1082, and
156 1084; Fig. 1).

157 **2. Methods**

158 ODP Site 1087 is located in the SE Atlantic Ocean (Shipboard Scientific Party, 1998) (Figure
159 1). All of the sediments analysed in this study are from the shipboard-defined lithologic "Unit I",
160 which is described as a moderately bioturbated olive to olive-grey foraminifera-nannofossil ooze,
161 with 50-100 cm thick nannofossil oozes in the upper 45 m (Shipboard Scientific Party, 1998). The age
162 model between 0-1.5 Ma and 3.0-3.5 Ma and sampling strategy are based on foraminifera oxygen
163 isotope stratigraphies tuned to the LR04 $\delta^{18}\text{O}$ stack (McClymont et al., 2005; Petrick et al., 2015a,
164 2015b). We assume linear sedimentation rates between the shipboard nanofossil model tie-points
165 between 1.5-3.0 Ma (Shipboard Scientific Party, 1998). The average sampling resolution is 5 cm,
166 which translates to a temporal resolution of 3-kyr in the Pliocene and mid- to late-Pleistocene, and
167 10-kyr in the early Pleistocene.

168 **2.1 Biomarker analysis**

169 The biomarkers (alkenones, chlorins, and glycerol dialkyl glycerol tetraethers (GDGTs)) were
170 extracted from homogenised, freeze-dried sediment using a CEM microwave system with 12 ml of
171 DCM:MeOH (3:1, v/v). Internal standards were added for quantification (5 α -cholestane,
172 dotriacontane and tetracontane). The microwave temperature programme heats samples to 70°C
173 over a 5 minute temperature ramp, holds temperatures at 70°C for 5 minutes, and then cools over
174 30 minutes (Kornilova and Rosell-Mele, 2003). The supernatant was decanted into vials and dried

175 under a nitrogen stream. An aliquot was taken for chlorin concentration and TEX₈₆ analyses and the
176 remainder was derivatised using N,O- Bis(trimethylsilyl)trifluoroacetamide with trimethylchlorosilane
177 at 70 °C for 1 hour before alkenone analysis.

178 Alkenones were analysed using a gas chromatograph fitted with a flame-ionisation detector
179 (GC-FID) and a 30 m HP1-MS capillary column. The injector temperature was held at 300°C and the
180 detector at 310°C. The oven program is as follows: after injection, hold at 60°C for 1 min, increase to
181 120°C at 20°C m⁻¹, to 310°C at 6°C m⁻¹, and hold at 310°C for 30 min. The alkenone abundances were
182 converted to MAR using linear sedimentation rates and the shipboard dry bulk density
183 measurements (Shipboard Scientific Party, 1998). The U^K_{37'} was calculated using the relative
184 abundances of the C_{37:3} and C_{37:2} alkenones (Prahl and Wakeham, 1987), and converted to SSTs using
185 the Müller et al. (1998) core-top calibration. The error associated with the analytical measurement is
186 ±0.5°C, while the calibration error equates to ±1.0°C (Müller et al., 1998).

187 A subset of samples was selected for TEX₈₆ analysis, guided by our U^K_{37'} results, with the aim
188 of ensuring a broad spectrum of both warm and cold periods was represented. The GDGT fraction
189 was re-dissolved in 200 µl of hexane:n-propanol (98.5:1.5, v/v) and an internal standard was added.
190 The sample and standard was filtered through a 0.5 µm PTFE filter. The filtered samples were
191 analysed by High-Performance Liquid Chromatography Mass Spectrometry (HPLC-MS), using a
192 Dionex P680 HPLC coupled to a Thermo Finnigan TSQ Quantum Discovery Max quadrupole mass
193 spectrometer at the University of Barcelona Automatica, with an atmospheric pressure chemical
194 ionization (APCI) interface set in positive mode. The GDGTs were eluted through a Tracer Excel CN
195 column (Teknokroma) with a length of 20 cm, a diameter of 0.4 cm and a particle size of 3 µm. There
196 was a guard column on the other end of the set-up. The mobile phase was initially hexane:n-
197 propanol (98.5:1.5) at a flow of 0.6 mL min⁻¹. The proportion of n-propanol was kept constant at
198 1.5% for 4 minutes, increased gradually to 5% during 11 minutes, increased to 10% for 1 minute,
199 held for 4 minutes, decreased back to 1.5% during 1 minute, and held at these conditions for 9

200 minutes. The parameters of the APCI interface were set as follows to generate positive ion spectra:
201 corona discharge 3 μ A, vaporizer temperature 400 °C, sheath gas pressure 49 mTorr, auxiliary gas
202 (N₂) pressure 5 mTorr, and capillary temperature 200 °C. A subset of samples was analysed using
203 the HPLC system at University College London (UCL). The error associated with the analytical
204 measurement is $\pm 1.0^\circ\text{C}$, while the calibration error (BAYSPAR; Tierney and Tingley, 2014) varies
205 according to geographic location, but on average for this record equates to $\pm 7.0^\circ\text{C}$ at 95%
206 confidence.

207 Chlorins were analysed using an HPLC system coupled to a photo-diode array
208 spectrophotometer. Solvent extracts were dissolved in acetone and injected three times. The PDA
209 scanned across 350 – 800 nm and absorbance at the wavelengths 410 and 665 nm was quantified.
210 Sample means of the triplicate measurements are reported here. Analytical variability was
211 monitored using repeat measurements of a standard and was determined at 0.07 absorbance units
212 (abs). For all samples, the absorbance at 410 nm or 665 nm was divided by the total dry weight of
213 the sample to calculate absorbance/g and then converted to mass accumulation rate (MAR) using
214 the linear sedimentation rates and the shipboard dry bulk density measurements (Zachos et al.,
215 2004).

216

217 **2.2 XRF analysis**

218 Elemental data was collected using an XRF Core Scanner II (AVAATECH Serial No. 2) at the
219 MARUM, University of Bremen. The reported data here have been acquired by a Canberra X-PIPS
220 Silicon Drift Detector (SDD; Model SXD 15C-150-500) with 150eV X-ray resolution, the Canberra
221 Digital Spectrum Analyser DAS 1000, and an Oxford Instruments 50W XTF5011 X-Ray tube with
222 rhodium (Rh) target material. Elements (Fe, Ca, Ti) were collected at a resolution of 2-cm down-core,
223 over a 2 cm² area with down-core slit size of 10 mm, using generator settings of 10 kV, a current of
224 0.15 mA, and a sampling time of 20 seconds directly at the split core surface of the archive half. The
225 split core surface was covered with a 4-micron thin SPEXCerti Prep Ultralene1 foil to avoid

226 contamination of the XRF measurement unit and desiccation of the sediment. Raw data spectra
227 were processed by the analysis of X-ray spectra by the Iterative Least Square software (WIN AXIL)
228 package from Canberra Eurisys. Due to previous oversampling, it was impossible to scan the upper
229 four sections of the core. Additionally, because of the time between the core being taken and the
230 XRF scanning, it was impossible to normalize the XRF scanning data to the initial shipboard data.

231

232 **3. Results**

233 **3.1 Sea surface temperature trends**

234 Two separate biomarker indices were used to calculate SSTs: higher resolution data using
235 the U_{37}^K proxy (from alkenones), and lower resolution data using the TEX_{86} proxy (from GDGTs). For
236 more information about the calibrations used, see supplemental data. Over the last 3.5 Ma, U_{37}^K -
237 derived SST values at ODP Site 1087 range between 12 and 24°C (Figures 2 and 3), with an average
238 of around 18°C. Overall, the SST trends can be summarised as: stable SSTs between 3.5 and 1.7 Ma,
239 3° C cooling between 1.7 and 0.9 Ma, and 2° C warming SSTs from 0.9 Ma to present (Figures 2 and
240 3). The coldest SSTs of 12°C occurred around 0.5 Ma (Marine Isotope Stage (MIS) 13). The highest
241 SST variability (~10°C) across glacial-interglacial timescales occurs after 0.9 Ma.

242 The lower resolution TEX_{86} -derived SSTs range from 10 to 24°C over the last 3.5 Ma, with an
243 average of ~16 °C (Figure 2). The SSTs were relatively stable before ~0.9 Ma, after which there is
244 increased variability in the data and evidence for 2° C warming towards the present. Before 0.9 Ma,
245 the TEX_{86} -derived SSTs are cooler than coeval U_{37}^K -derived SSTs by up to 10°C. After 0.9 Ma, TEX_{86} -
246 derived SSTs are either similar to, or warmer than, the U_{37}^K -derived SSTs. The difference between
247 the two temperature proxies indicates that the U_{37}^K temperatures are only cooler after 0.6 Ma
248 (Figure 2).

249 **3.2 Productivity proxies**

250 Three proxies were used to track changes in the primary productivity of the site: 1) chlorin
251 MAR; 2) alkenone mass accumulation rates (MAR); and 3) Ca/Ti ratios generated from XRF scanning.
252 Chlorin MARs range between 0.001 and 1.0 g² abs cm⁻² kyr⁻¹ (Figure 3). Between 1.7 and 0.5 Ma,
253 chlorin MARs are elevated, which contrasts with low values (<0.05 abs cm⁻² kyr⁻¹) between 3.0–1.7
254 Ma. A return to low chlorin MARs for the last 0.4 Ma is recorded after a final high peak in chlorins
255 during MIS 10. Alkenone MAR ranges between 1 and 12 μg cm⁻² kyr⁻¹, with an overall zone of low
256 amplitude oscillations between 3.0 and 2.5 Ma (Figure 3). After 0.9 Ma, the highest values occur in
257 MISs 14, 12, 10, and 8. Ca/Ti values range between 100 and 1800 (Figure 4). The lowest values are
258 around 3.1 Ma; with a slight increase around 3.0 Ma, followed by stable Ca/Ti ratios. Ca/Ti then
259 increases towards the modern day, starting around 1.6 Ma, with the highest values around 0.4 Ma,
260 although there are no glacial-interglacial trends in the data.

261 3.3 Terrestrial proxy

262 Ti counts range from 1000 to 8000 counts at ODP Site 1087 (Figure 4). The highest Ti values
263 are before 3.0 Ma. At 3.0 Ma, Ti counts decrease, and then there is a brief increase around 2.5 Ma,
264 with three large Ti peaks around MIS 96-102. Outside of these periods, Ti remains relatively low (<
265 2000 counts). There is no clear glacial–interglacial variation in the Ti data.

266

267 4. Discussion

268 4.1 Climatic and oceanographic variability at ODP Site 1087 from 3.5 to 0.0 Ma

269 Overall, the Site 1087 records indicated a gradual transition from an upwelling-dominated
270 record in the Pliocene and early Pleistocene to an Agulhas Leakage-dominated record in the mid- to
271 late-Pleistocene (Figures 3; 4). During the late Pliocene (3.5–3.0 Ma), warmer SSTs, higher
272 productivity, and a 6–7°C offset in the TEX₈₆⁻ and U₃₇^K-derived temperatures suggest that more high
273 nutrient Upwelling-sourced water reached Site 1087 (Petrick et al., 2015a). A period of lower

274 productivity and lower Ti counts marked the late Pliocene–early Pleistocene (3.0–2.0 Ma), with less
275 terrestrial input and mostly stable SSTs. During this interval, there continued to be an offset
276 between TEX_{86} - and U_{37}^K -derived temperatures, but this varied between 4 and 11°C, indicating
277 variable upwelling intensity. The period between 1.5 and 0.6 Ma is characterised by an increase in
278 productivity, cooler SSTs, and a reduction in the TEX_{86} - U_{37}^K temperature offset (Figure 2). Finally, the
279 mid- to late-Pleistocene (0.6–0.0 Ma) is defined by warming SSTs, variable productivity with higher
280 productivity during glacials, and lower terrestrial input (from Ti). These trends, coupled with the
281 previously published data, indicate that, over the last 500 ka, there has been increased warm water
282 input through the Agulhas Leakage during prominent interglacials, punctuated by glacial periods with
283 high productivity (Petrick et al., 2015b). For a further analysis of the proxies used in making the
284 reconstruction, please see the supplemental material.

285 It has been proposed that tectonic uplift along the Namibian coast since the Pliocene could
286 have increased upwelling intensity and slowly shifted upwelling cells northward (Jung et al., 2014).
287 Overall, the data from Site 1087 is broadly consistent with this hypothesis, but this time interval also
288 includes several known global climate changes, which are hypothesised to have impacted
289 subtropical upwelling systems. Here, we evaluate the links to other potential forcing mechanisms
290 driven by Plio-Pleistocene climate evolution.

291 **4.2. Late Pliocene (3.5–3.0 Ma)**

292 The new XRF data from Site 1087 confirms that the oceanographic conditions during the late
293 Pliocene (3.5–3.0 Ma) were very different from those observed in the modern environment at this
294 location. The high Ti counts between 3.5 and 3.0 Ma are associated with high alkenone MAR (this
295 study) and a significant offset between U_{37}^K and TEX_{86} -derived temperatures (Petrick et al., 2015).
296 There is clear evidence of higher productivity, higher terrestrial input, and offsets in the different
297 temperature proxies during the Pliocene relative to the modern, which suggests an influence of
298 wind-driven upwelling at the site (Petrick et al., 2015a). The U_{37}^K SSTs at Site 1087 were much colder

299 than the Northern and Central Benguela Upwelling Systems (Fig. 5) (Rosell-Melé et al., 2014), but
300 very similar to those at Site 1085 (Rommerskirchen et al., 2011). This large temperature difference
301 between the northern/central and southern Benguela cells, over a relatively short area, is unusual in
302 the Pliocene, when equator to pole gradients were often reduced (Fedorov et al., 2015). Rosell-Melé
303 et al. (2014) suggested that the lower productivity in the northern and central cells during the
304 Pliocene was related to overall warming in the Benguela Upwelling System, which allowed a shallow
305 layer of warm water to restrict upwelling vigour, a phenomenon described as a “permanent
306 Benguela Nino” (Rosell-Melé et al., 2014). Therefore, this suggests that higher productivity at Site
307 1087 could be related to the colder temperatures, at least during the Pliocene, although the U_{37}^K -
308 TEX_{86} gradient is more indicative of an increased upwelling influence in the southern Benguela
309 region as the reason for enhanced productivity.

310 The XRF data indicates higher Pliocene Ti/Al values than in any other part of the record,
311 suggesting higher terrestrial input (Figure 5). Today the site only lies at the edge of both dust and
312 riverine input pathways. Thus, one can posit that the delivery pathways of terrestrial material to
313 ODP Site 1087 must have been different during the Pliocene. We infer that this was likely related to
314 the poleward shift in wind patterns in the Southern Hemisphere relative to today, which would have
315 shifted dust delivery southward (Lawrence et al., 2013). Given that Ti/Al values are found to reflect
316 dust input, this is the more likely assumption (Govin et al., 2012). However, it is also possible that
317 increased riverine input from the African continent could have increased the amount of terrestrial
318 input reaching the cape basin, as there is some evidence that Southwest Africa was wetter during
319 the Pliocene (Maslin et al., 2012). We are currently unable to disentangle the respective influence of
320 the two terrestrial inputs recorded here due to a lack of evidence, especially XRF records from other
321 sites in the region, which would allow a better understating of how the terrestrial input pathways
322 shifted during the Pliocene. However, what is clear is that, during the Pliocene, the Benguela
323 Upwelling System was operating differently from the present day.

324 4.3 INHG and the early Pleistocene (3.0–1.5 Ma)

325 Equatorward movement of the major upwelling cells may have played an important role in
326 the transition from the warm Pliocene to colder modern temperatures around the iNHG at 2.7 Ma
327 (Fedorov et al., 2007). However, a closer look at data from Site 1087 suggests a more complex story
328 than the standard narrative. Changes in the size and strength of permanent upwelling in the
329 Southern Benguela Upwelling System occurred at the beginning and end of the iNHG, but not
330 necessarily at 2.7 Ma. Between 3.0 and 2.4 Ma, when the majority of North Atlantic cooling
331 associated with iNHG occurred, the proxies at Site 1087 are stable.

332 Between 3.0 and 1.5 Ma, there is conflicting evidence about the strength of the Southern
333 Benguela Upwelling System at Site 1087. Colder SSTs continue to be recorded at Site 1087 relative to
334 the Northern and Central Upwelling System (Figure 5), coupled with the continuing offset between
335 $\text{TEX}_{86}^{\text{H}}$ and U_{37}^{K} -derived temperatures (Figure 2). Based on the recent work by Zhu et al. (2016), the
336 best explanation for the continued offset between the two temperature records is that TEX_{86} is
337 recording conditions in shallow waters (<100 m), most likely from the centre of the upwelling region
338 along the coast. Therefore, from the temperature proxies, it appears that water from the coastal
339 upwelling cells was reaching Site 1087 directly across the late Pliocene-early Pleistocene. However,
340 around 3.0 Ma, there was a decrease in primary productivity as recorded in the alkenone and chlorin
341 MAR combined with a corresponding decrease in Ti content, indicating a reduction in terrestrial
342 input (Figures 4, 6). Thus, a clear difference emerges between the productivity data, which suggests
343 reduced upwelling (lower productivity, less wind influence), and the temperature data, which
344 suggests that upwelled waters continued to influence the site.

345 The differences between the productivity and temperature proxy records in upwelling
346 systems can be explained by changes in the type of nutrients being delivered to the site, either
347 through shifts in the local nutrient delivery paths or the nutrient content of the upwelled water
348 (Dekens et al., 2007). The coupled decreases in Ti/Al and productivity around 3.0 Ma suggest a

349 connection between the loss of terrestrial input and productivity. One possibility is that a weakening
350 or northward migration of the trade winds might have moved the major African dust plume
351 northward (Figure 4; Etourneau et al., 2009; Martínez-García et al., 2011). It is thought that there
352 were northward shifts in both the trade winds and westerlies during the Plio-Pleistocene transition
353 (Etourneau et al., 2010). However, most of the shifts in the wind systems occur around 2.7 Ma, after
354 the Site 1087 Ti/Al decreased (Etourneau et al., 2009; Lawrence et al., 2013). It is also possible that
355 the Ti/Al decrease was related to changes in hydrology, as observed farther north at Site 1085,
356 suggesting a drier west Africa (Maslin et al., 2012). The change in terrestrial input suggests that shifts
357 occurred in the local wind fields and oceanic terrestrial delivery patterns around 3.0 Ma, which were
358 likely partially related to changes in nutrient delivery to the site.

359 The low (non-diatom) productivity at Site 1087 occurred within the same time interval as the
360 Matuyama Diatom Maximum (MDM; 3.0-2.0 Ma) in the rest of the Benguela Upwelling System
361 (Leduc et al., 2014; Robinson and Meyers, 2002) (Figure 6). Changes in the type and amount of
362 nutrients delivered to the upwelling zone could control the amount and type of primary productivity
363 in the zone (Lawrence et al., 2006; März et al., 2013). The MDM, which started around 3.0 Ma in the
364 northern and central cells, occurs at the same time as other biogenic silica increases in other
365 upwelling cells all over the world (März et al., 2013). Increases in the Si content of the Antarctic
366 Intermediate Water led to increases in the amount of biogenic silica production in global upwelling
367 cells (März et al., 2013). In the Northern and Central Benguela Upwelling, this increase in diatom
368 production occurred despite reduced upwelling strength (Leduc et al., 2014; Robinson and Meyers,
369 2002). We were unable to determine biogenic silica content at Site 1087, so we cannot consider
370 directly the role of silicate supply on diatom production. However, the similarity of the timing
371 between the start of the MDM and the decrease in upwelling means that it is likely that increases in
372 biogenic silica in the Antarctic Intermediate Water were responsible for the decrease in non-silica
373 productivity in the entire Benguela Upwelling System.

374 Between 2.4–2.0 Ma, U_{37}^K -derived SSTs decrease at Site 1087. There is a slight increase in
375 alkenone MARs, but no increase in chlorin MARs and no change in terrestrial inputs (Figures 2, 3,
376 and 6). During this interval, cooling of U_{37}^K -derived SSTs is also observed at Site 1084 (Figure 5),
377 accompanied by evidence of upwelling intensification (Robinson and Meyers, 2002; Rosell-Melé et
378 al., 2014), yet only alkenone MAR increases at Site 1087. Climate changes around 2.4 Ma have been
379 previously linked to increases in the Walker Circulation (Brierley and Fedorov, 2010; Liu et al., 2008;
380 Rosell-Melé et al., 2014). The increased Walker Circulation may have increased upwelling vigour,
381 allowing nutrients from the coastal southern upwelling cells to be delivered to Site 1087. There is an
382 increase in alkenone productivity at Site 1087 around 2.4 Ma. Therefore it is likely, given the similar
383 timing of temperature and productivity changes in Sites 1087 and 1084, that the increasing strength
384 of the Walker Circulation caused a northward expansion of upwelling in the Benguela Upwelling
385 System (Etourneau et al., 2010).

386 Shifting global winds were not likely controlling the location, extent, temperature, or
387 intensity of the Southern Benguela Upwelling System when other records show major equatorward
388 shifts in upwelling at 2.7 Ma (Lawrence et al. 2013). Most of the system-wide upwelling changes
389 seem to be driven by external shifts in the nutrients being delivered to the upwelling system from
390 around 3.0 Ma. Instead, around 2.7 Ma, the Benguela Upwelling System is responding more to local
391 changes in nutrient supply and upwelling temperatures. This is similar to the results seen in the
392 Peruvian Margin, where changes in the SST within the upwelling zone occurred before 2.7 Ma
393 (Dekens et al., 2007). Given the importance of coastal upwelling to nutrient cycling and CO₂
394 exchange, data emphasize the importance of understanding the impact of nutrient changes on
395 coastal upwelling cells.

396 **4.4 Mid- and Late Pleistocene (1.5–0.0 Ma)**

397 Around 1.5 Ma, there is a change in the relationship between the Southern Benguela
398 Upwelling System and the rest of the Benguela Upwelling System. SSTs decrease at Site 1087

399 between 1.5 and 0.9 Ma (across the MPT), accompanied by increases in Ca/Ti, with a later increase
400 in chlorin MAR from 1.5 Ma and an increase in alkenone MAR from 1.1 Ma (Figures 2; 3). The U_{37}^K -
401 SST cooling has a global component, as it was observed in all records from the SE Atlantic Ocean.
402 However, it was 300-kyr earlier than most other basins, which show cooling starting around 1.2 Ma
403 (Figure 4; Etourneau et al., 2010; Martinez-Garcia et al., 2010; McClymont et al., 2013; Rosell-Melé
404 et al., 2014). From 1.5 Ma, the observed increase in chlorin MAR at Site 1087 is also accompanied by
405 increases in the alkenone MAR in the northern and central cells (Rosell-Melé et al., 2014) (Figure 6).
406 Therefore, it appears that at 1.5 Ma, both the Northern and Southern Benguela Upwelling System
407 showed similar increase in productivity, which could indicate that there had been expansion of the
408 Benguela Upwelling System to the north. In the southern Benguela Upwelling System, the large
409 increases in Ca/Ti values coupled with increasing alkenone MARs indicate that the central upwelling
410 cells were moving away from Site 1087, which was now influenced instead by the edge of the
411 upwelling zone (Giraudeau et al., 1993; Giraudeau and Rogers, 1994). Increased coccolithophore
412 deposition in the Benguela Upwelling System indicates a shift towards less turbulent conditions and
413 a more marginal upwelling setting at Site 1087 (Giraudeau et al., 1993; Giraudeau and Rogers, 1994).

414 The data also shows less primary productivity during interglacials after 0.9 Ma (Petrick et al.,
415 2015b) (Figure 2). From 0.9 Ma onward, there is a clear shift in the SST gradient between Sites 1087
416 and 1084, the latter of which inhabits the central upwelling cell (Figure 4), demonstrating a reduced
417 connection between the two sites as upwelling at Site 1084 intensifies. We interpret this pattern as
418 indicating an increasingly reduced influence of the Benguela Upwelling System at Site 1087, in turn
419 reducing the productivity at the site during the glacial terminations and interglacials since 0.9 Ma,
420 consistent with modern oceanography (Boebel et al., 2003). However, this occurs as the northern
421 and central upwelling cells indicated increased productivity and cooling (Rosell-Melé et al., 2014),
422 suggesting that the modern day extent of upwelling started around 0.6 Ma (Rosell-Melé et al., 2014).
423 This is confirmed by coeval increases in the Ca/Ti ratio at Site 1087 across the entire mid- to late-
424 Pleistocene (Figure 3), which is supportive of a more marginal upwelling setting. Despite the overall

425 trend of decreasing upwelling influence at ODP Site 1087, during the earlier 'glacial' modes of the
426 upwelling there are often short increases in upwelling strength, as determined by increases in
427 chlorin MARs (Petrick et al. 2015a).

428 After 0.9 Ma, the TEX_{86} and $U^{K}_{37'}$ -derived temperatures at Site 1087 converged, and SSTs
429 warm by 2° C between 0.6 and 0.0 Ma. This increase was superimposed upon large amplitude
430 variations in all the proxy records (Figures 3; 4), which occurred at the same time as the onset of the
431 quasi-100-kyr glacial-interglacial cycles that mark the Early Mid-Pleistocene Transition (EMPT)
432 (Maslin and Brierley, 2015). After the EMPT, the pattern of glacials and interglacials changes to a
433 tripartite mode composed of an interglacial, a glacial and a full glacial (Maslin and Brierley, 2015). At
434 ODP Site 1087 productivity decreases, and the abundance of the Agulhas Leakage indicator
435 foraminifera, *G. menardii*, increases during the 'full glacial' portion of the deglaciation over the last
436 1.2 Ma (Caley et al., 2014, 2012). This is around the same time that the relationship between the
437 various SST proxies changes and average temperatures start increasing. Furthermore, previous work
438 has showed that increases in temperature at ODP 1087 had the exact same timings as temperature
439 increases in the leakage zone proper (Caley et al., 2014, 2012; Petrick et al., 2015b). Increased
440 Agulhas Leakage therefore might be linked to the start of the quasi-100-kyr post-EMPT cycles (Caley
441 et al., 2014, 2012; Peeters et al., 2004). However, the changes in temperature could also be linked to
442 the previously mentioned reduction in Benguela Upwelling around ODP 1087. Furthermore, studies
443 show that changes in temperature and salt leakage do not necessarily relate to changes in the
444 amount of Agulhas Leakage (Simon et al., 2015). Despite this, there is a major change in the effect
445 of the Agulhas Leakage on the site after the EMPT. Therefore, even if there was not any change in
446 the location or strength of the Agulhas Leakage, it is still clear that there was a major reorganization
447 of the SE Atlantic that allowed it to have a more direct impact on ODP site 1087. Future studies are
448 needed to better understand the changes in the Agulhas Leakage over the last 3.5 Ma.

449 **5. Conclusions**

450 New geochemical data from ODP Site 1087 reveal a complex timing of shifts in the intensity
451 of the Southern Benguela Upwelling System and the initiation of increased Agulhas Leakage over the
452 Pliocene and Pleistocene. First, records indicate that the Southern Benguela Upwelling System was
453 also influenced by the changes in nutrients and by warmer SSTs between 3.0 and 2.0 Ma. There is no
454 evidence for a northward movement of the focus or extent of upwelling around 2.7 Ma, suggesting
455 that changes in the wind fields had limited/no impact over the extent and strength of the upwelling
456 during the iNHG. Finally, northward movement of the Benguela Upwelling System occurred around
457 0.9 Ma, such that Site 1087 becomes dominated by the effects of Agulhas Leakage by 0.6 Ma. This
458 observation suggests that oceanographic changes during the MPT established the modern extent of
459 the Benguela Upwelling System and Agulhas Leakage. Considered together, these factors
460 demonstrate that the development of the modern extent of upwelling, at least in the SE Atlantic,
461 was complex and different from the linear northward progression that has been seen in other open
462 ocean upwelling cells. This emphasises the importance of reconstructing information from multiple
463 sites within an upwelling system to better understand the complete picture of upwelling
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476 **Citations**

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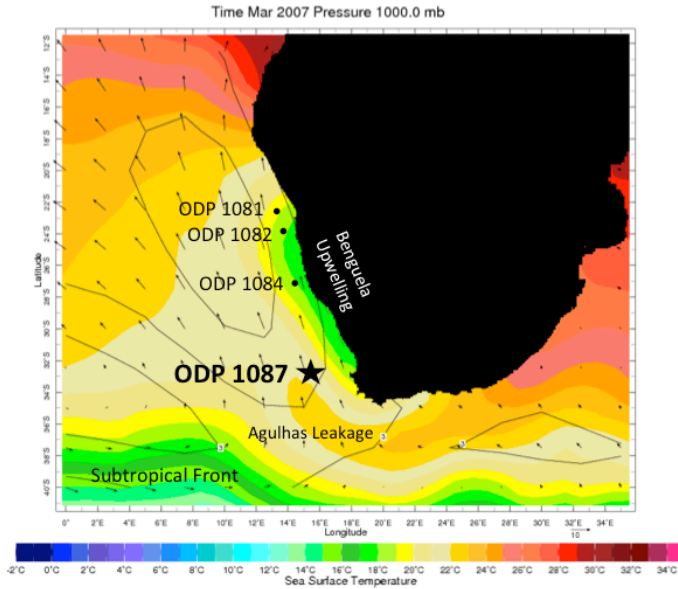
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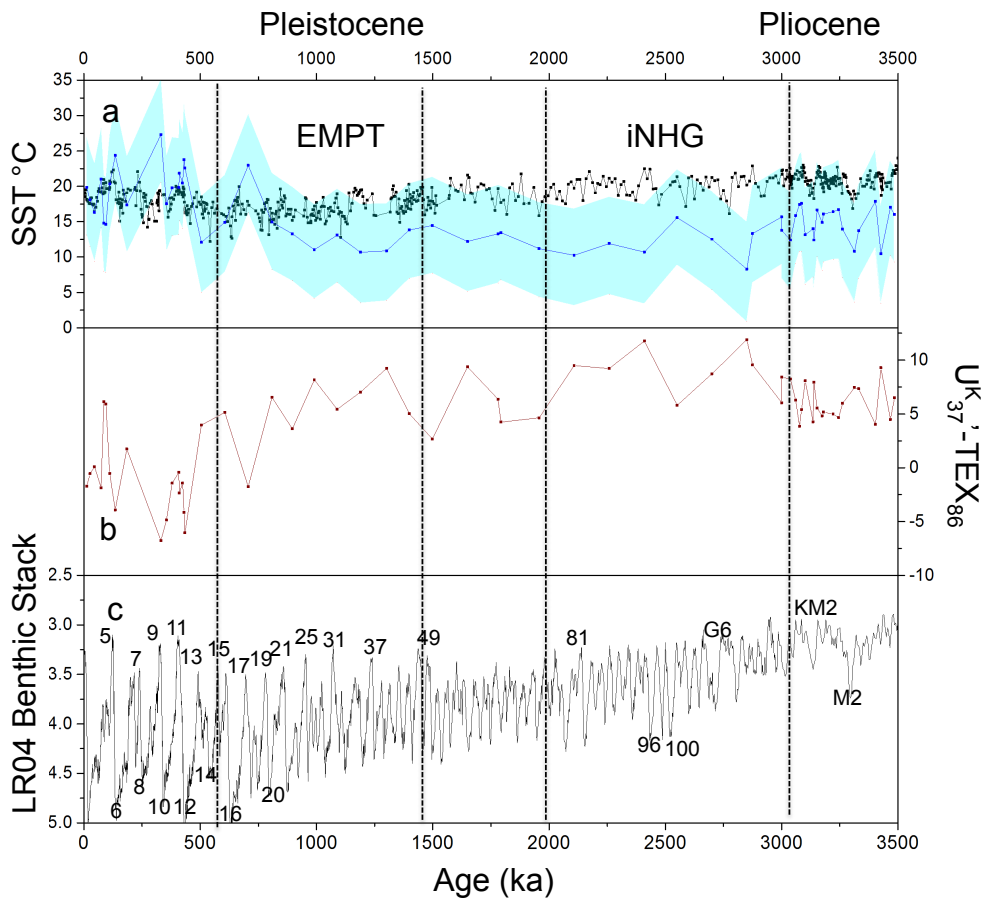
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648 Figure 1: SE Atlantic map and relevant ODP drilling sites on an average SST record based on
 649 observational data for March 2007 from <http://iridl.ldeo.columbia.edu/>. Also shown are wind
 650 direction and pressure contours. The location of complementary records from this region referenced
 651 in the paper and the location of major oceanic systems in their modern day positions are shown.

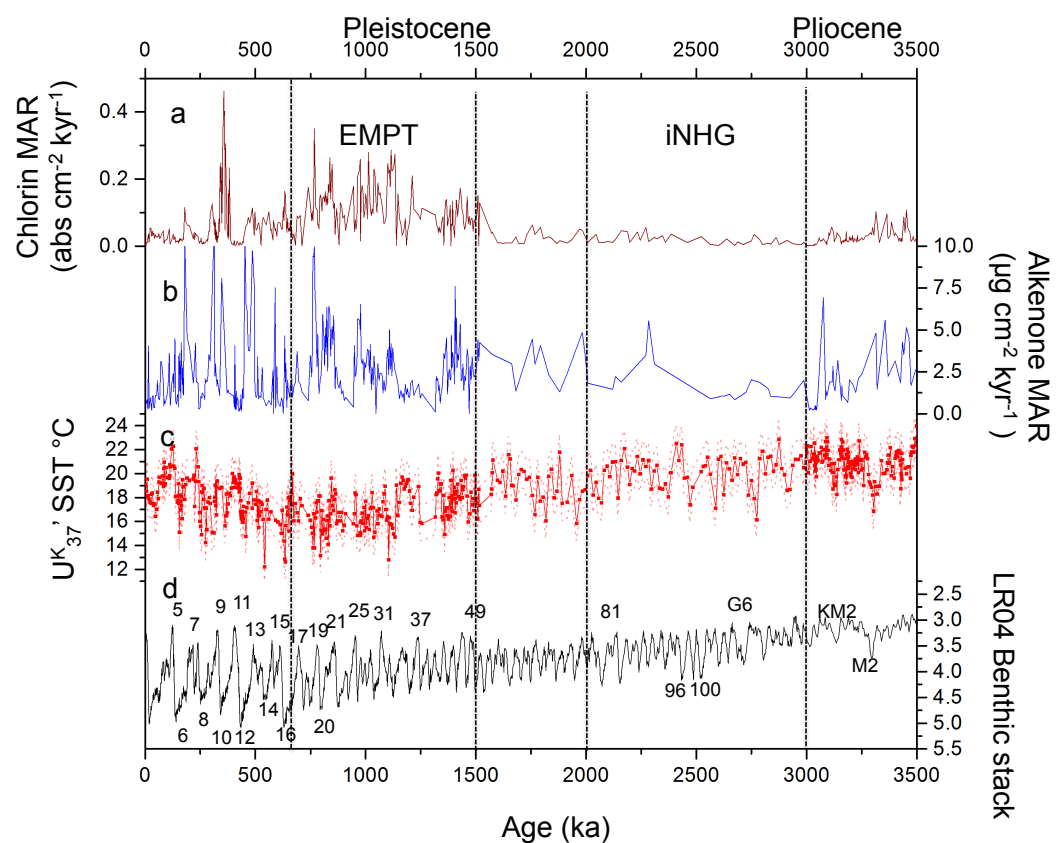
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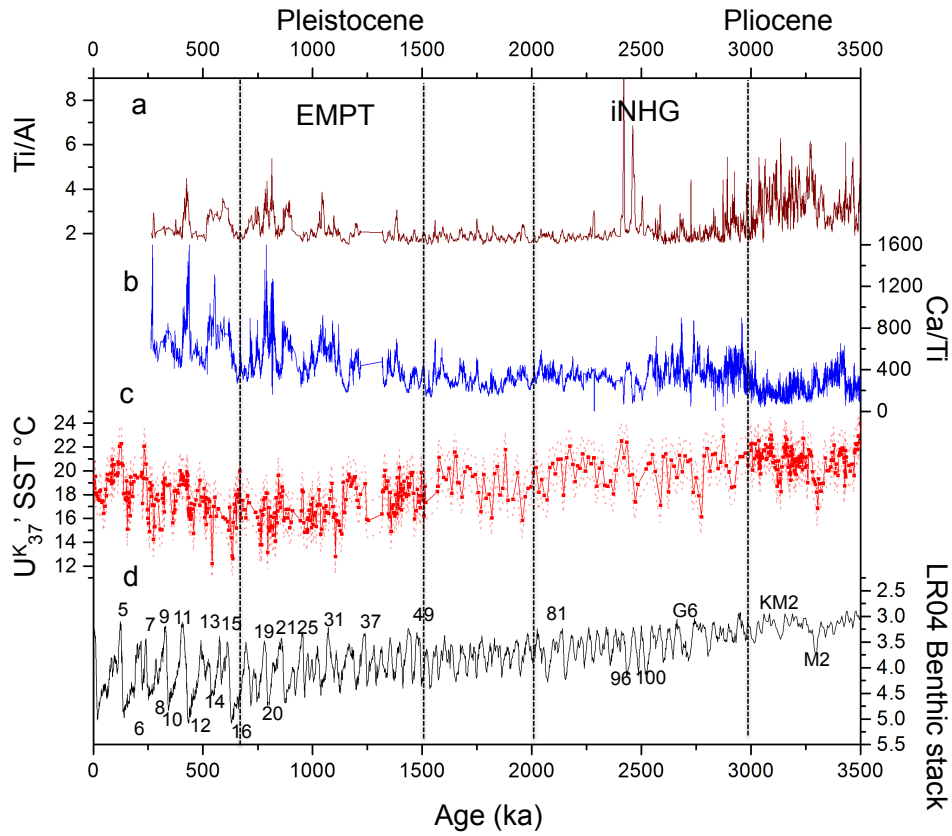
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654 Figure 2: Temperature proxies for ODP Site 1087: a) sea surface temperature estimates derived
 655 from U^{K}_{37} (black line) and TEX_{86} BAYSPAR (blue line with dots) with analytical + calibration error
 656 envelope (blue envelope); b) Difference between U^{K}_{37} and TEX_{86} BAYSPAR derived SST estimates;
 657 c) LR04 benthic oxygen isotope stack (Lisiecki and Raymo, 2005) with selected MIS shown. Also
 658 major transitions in the ODP site 1087 record are shown with dashed lines and the timings of the
 659 iNGH and EMPT are labelled.

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 662 Figure 3: Productivity and temperature trends from ODP Site 1087: a) chlorin MARs; b) alkenone
 663 MARs; c) U^{K}_{37} -derived SSTs with error envelope; d) LR04 benthic oxygen isotope stack (Lisiecki and
 664 Raymo, 2005) with selected MIS shown. The vertical dashed lines indicate the major transitions
 665 observed in the data in terms of temperature and productivity. Also major transitions in the ODP
 666 site 1087 record are shown with dashed lines and the timings of the iNGH and EMPT are labelled.



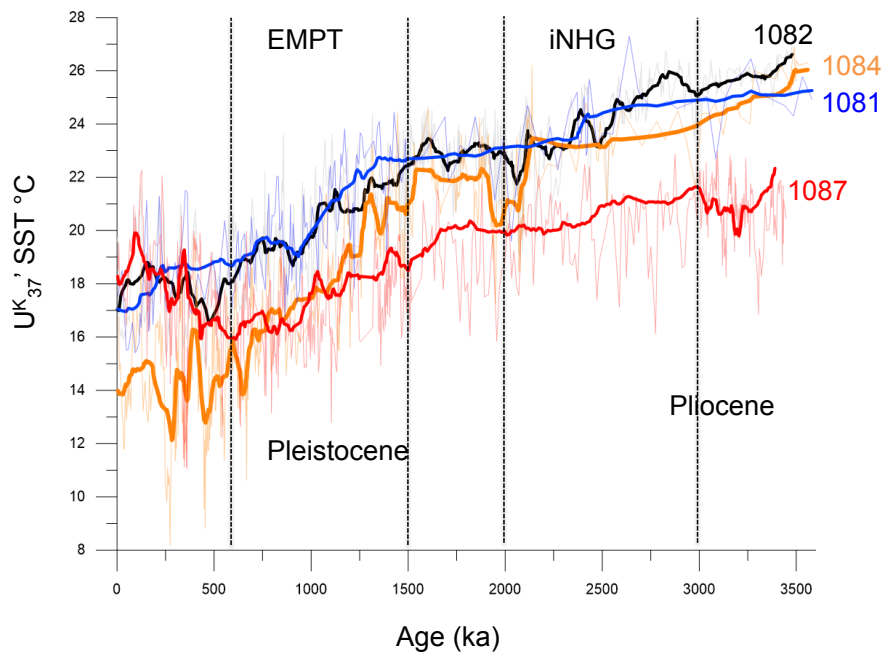
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669 Figure 4: XRF data and temperature from ODP Site 1087: a) Ti/Al generated by scanning XRF; b) Ca/Ti
 670 data; c) $U^{K}_{37'}$ -derived SSTs, with error envelope including analytical plus calibration error; d) LR04
 671 benthic oxygen isotope stack (Lisiecki and Raymo, 2005) with selected MIS shown. Major transitions
 672 in the ODP site 1087 record are shown with dashed lines and the timings of the iNHG and EMPT are
 673 labelled.

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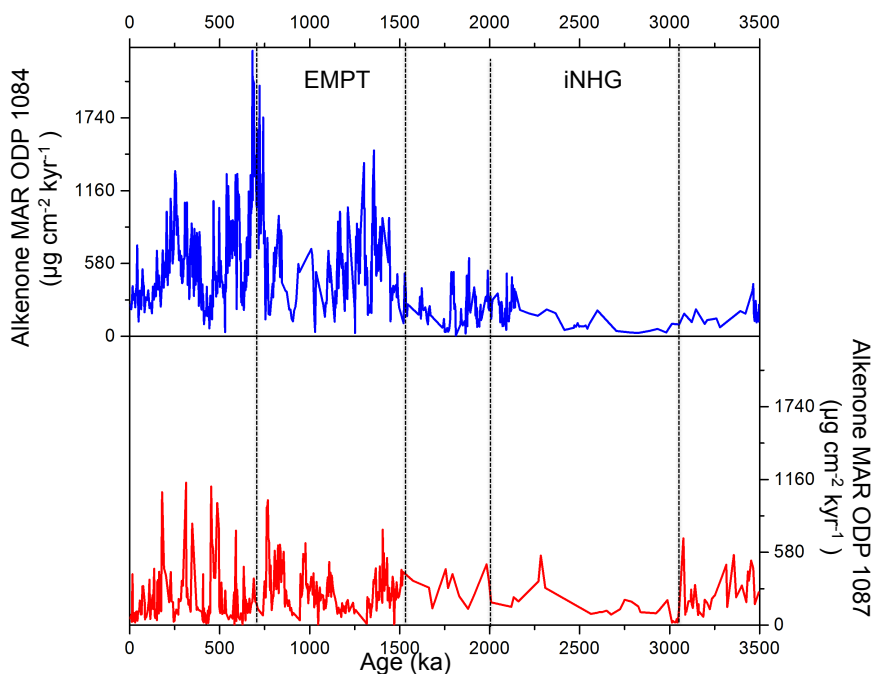
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677 Figure 5: Regional SST trends. Comparing the ODP Site 1087 $U^{K'}_{37}$ -derived SST record (red) to the
 678 three other Benguela Upwelling SST records: ODP Sites 1082 (black), Site 1084 (orange), and Site
 679 1081 (blue). The dark lines for each record represent 30 point running averages. Also, major
 680 transitions in the ODP site 1087 record are shown with dashed lines and the timings of the iNHG and
 681 EMPT are labelled.

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684 Figure 6: Alkenone MAR records from the Benguela Upwelling system over the Plio-Pleistocene:
 685 southern cells, ODP Site 1087 (red); central cells, ODP Site 1084 (blue). Both graphs are on the same
 686 scale so that a straight comparison of the two records can be done. Also, major transitions in the
 687 ODP site 1087 record are shown with dashed lines and the timings of the iNHG and EMPT are
 688 labelled.

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