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1 **The Late Miocene Biogenic Bloom : A globally**
2 **distributed but not an ubiquitous event**

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5 **Key Points:**

- 6 • The Late Miocene Biogenic Bloom (LMBB) is expressed in sediment cores in var-
7 ious oceanographic settings.
8 • Almost 40% of the sites in the compilation show no expression of the LMBB sig-
9 nal.
10 • The origin of the LMBB could be a generalised increase in upwelling activity.

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11 Abstract

12 The Late Miocene Biogenic Bloom (LMBB) is a late Miocene to early Pliocene oceano-
13 graphic event characterized by high accumulation rates of opal from diatoms and calcite
14 from calcareous nannofossils and planktic foraminifera. This multi-million year event
15 has been recognized in sediment cores from the Pacific, Atlantic and Indian Oceans. The
16 numerous studies discussing the LMBB lead us to believe that this event is omnipresent
17 in all oceans, although this hypothesis needs to be tested. Moreover, the origin of this event
18 is still widely discussed. In this study we aim to provide a comprehensive overview of
19 the geographical and temporal aspects of the LMBB by compiling published ocean drilling
20 (DSDP, ODP and IODP) records of sedimentation rates, CaCO_3 and opal and terrigenous
21 accumulation rates that cover the late Miocene and early Pliocene interval. Our
22 data compilation shows that traces of the LMBB are present in many different locations
23 but in a very heterogeneous way, highlighting that the LMBB is not a pervasive event.
24 The compilation in addition shows that the sites where the LMBB is recorded are mainly
25 located in areas with a high productivity regime (i.e. upwelling systems). We suggest
26 that the most likely hypothesis to explain the LMBB is a global increase in upwelling
27 intensity due to an increase in wind strength or an increase in deep water formation, ramp-
28 ing up global thermohaline circulation.

29 1 Introduction

30 The late Miocene is marked by a major event recognized in deep-sea sediments called
31 the Late Miocene Biogenic Bloom (LMBB). This event is characterized by high rates of
32 opal accumulation from diatoms and radiolarians and high rates of calcite accumulation
33 from calcareous nannofossils and planktonic foraminifera (e.g. Farrell et al., 1995; Dick-
34 ens & Owen, 1999; Grant & Dickens, 2002; Diester-Haass et al., 2005; Lyle & Baldauf,
35 2015; Drury et al., 2021; Bolton et al., 2022). The LMBB event, first described by Farrell
36 et al. (1995), has been recovered in multiple sites of the world ocean (Figure 1) but its
37 timing is heterogeneous across the sites and its signature in the data record has been iden-
38 tified from a variety of different proxies. Farrell et al. (1995) define the LMBB based on
39 an increase in biogenic deposits (CaCO_3 , biogenic silica (opal), and nannofossils) between
40 6.7 and 4.5 million years ago (Ma) in the Eastern Equatorial Pacific Ocean, and inter-
41 pret this increase to be related to increased biological productivity. The Eastern Equa-
42 torial Pacific region was also studied by Lyle and Baldauf (2015) who observed the LMBB
43 between 8 and 4.5 Ma, marked by long periods of high opal and CaCO_3 deposition. Records
44 from the same region, with better resolution and updated age models, were used by Lyle
45 et al. (2019) to estimate the end of the event at about 4.4 Ma, at a time of major de-
46 crease in sedimentation rate. Outside of the East Equatorial Pacific, Grant and Dick-
47 ens (2002) identified the LMBB event in the southwestern Pacific Ocean, where it takes
48 the form of an increase in CaCO_3 mass accumulation between 9 and 3.8 Ma with a max-
49 imum around 5 Ma. L. Zhang et al. (2009) identified the LMBB in records from the South
50 China Sea that exhibit increased mass accumulation of CaCO_3 and opal between 12 and
51 6 Ma. In the Atlantic Ocean, Diester-Haass et al. (2005) identified the LMBB in three
52 different regions. In the North Atlantic, CaCO_3 mass accumulation rate (MAR) and ben-
53 thic foraminiferal accumulation rates reached a maximum at 5 Ma. This maximum was
54 observed earlier in records from the tropical ocean (around 6 Ma) and the South Atlantic
55 Ocean (around 8.2 Ma). In the South Atlantic (ODP site 1264), Drury et al. (2021) stud-
56 ied the evolution of CaCO_3 MAR at orbital resolution. The onset of the LMBB is de-
57 tected at 7.8 Ma and the end at 3.3 Ma with an optimum between 7 and 6.4 Ma. Records
58 from lower productivity regions in the Atlantic and Indian Oceans have also been used
59 to identify the LMBB (Hermoyian & Owen, 2001). By measuring the rate of mass ac-
60 cumulation of phosphorus, they found a signature of the LMBB with peak productiv-
61 ity around 4-5 Ma. In the Indian Ocean, an increase in productivity between 9 and 3.5
62 Ma was identified by Dickens and Owen (1999) which is reflected in an increase in CaCO_3

63 mass accumulation as well as the spatial expansion of the Oxygen Minimum Zone. Nev-
64 ertheless, Lübbers et al. (2019) suggest a much earlier onset of the LMBB in the Indian
65 Ocean at 11.2 Ma based on an increase in Log (Ba/Ti) associated with a change in sed-
66 iment color from red to green.

67 This increase in biogenic sedimentation is coeval with significant changes in the global
68 climate system. Although the land-sea distribution has been quasi-stable since the late
69 Miocene, the configuration of several major seaways evolved during this period: the Cen-
70 tral American Seaway underwent final closure (O’Dea et al., 2016), the Bering Seaway
71 opened (Gladenkov & Gladenkov, 2004) and the Indonesian Seaway underwent progres-
72 sive restriction (Kuhnt et al., 2004), all of which likely triggered major changes in oceanic
73 circulation (e.g. Brierley & Fedorov, 2016). Alongside these paleogeographic changes,
74 global cooling occurred at the end of the Miocene, associated with an increase in the merid-
75 ional sea surface temperature gradient (Herbert et al., 2016; Martinot et al., 2022). The
76 global decrease in temperature is probably driven by a significant drop in the partial pres-
77 sure of CO₂ in the atmosphere (pCO₂) from about 600 ppm in the middle Miocene to
78 about 400 ppm in the early Pliocene (e.g. Rae et al., 2021). The establishment of a small
79 permanent ice on Greenland is also inferred during the late Miocene (Helland & Holmes,
80 1997; John & Krissek, 2002; Bierman et al., 2016). The expansion of deserts may also
81 be contemporary with this period (Schuster et al., 2006; Z. Zhang et al., 2014), although
82 recent data from the tropical Atlantic margin highlight that the Sahara desert already
83 existed 11 Ma ago (Crocker et al., 2022). Vegetation on land also underwent significant
84 changes with the rise to dominance of plants using C₄ photosynthesis at the detriment
85 of plants using C₃ photosynthesis (Tauxe & Feakins, 2020; Cerling et al., 1997). Some
86 of these changes have been suggested as possible triggering mechanisms for the LMBB.

87 Two hypotheses have been proposed to explain the origin of the LMBB. This event
88 could result from (1) an increase in nutrient supply from the continents to the oceans
89 (e.g. Gupta et al., 2004; Pisias et al., 1995; Hermoyian & Owen, 2001; Filippelli, 1997)
90 or (2) a redistribution of nutrients in the ocean due to a reorganization of oceanic cir-
91 culation (e.g. Farrell et al., 1995; Dickens & Owen, 1999; Pisias et al., 1995).

92 An increase in nutrient supply is usually attributed either to enhanced weather-
93 ing or to a shift in vegetation cover. A late pulse of uplift in the Tibetan Plateau region
94 during the late Miocene (C. Wang et al., 2014) responsible for intensification of the In-
95 dian monsoon could have been responsible for increased continental weathering (Filippelli,
96 1997; Yang et al., 2019; Holbourn et al., 2018; Clift et al., 2020). This hypothesis is sup-
97 ported by the global increase in Ca and Si fluxes to the ocean (Pisias et al., 1995). Hermoyian
98 and Owen (2001) also suggest that the uplift of the Andes at 8 Ma caused orographic
99 precipitation and increased sediment flux to the Atlantic Ocean (Curry et al., 1995). An
100 increase in nutrient supply from the continents could also be explained by an intensifi-
101 cation of trade winds at the end of the Miocene, linked to the increase in latitudinal tem-
102 perature gradient and also to widespread continental aridification (Dobson et al., 2001;
103 Hovan, 1995; Diester-Haass et al., 2006; Herbert et al., 2016). A further hypothesis also
104 suggests that the global spread of C₄ plants in the late Miocene would have resulted in
105 the input of siliceous phytoliths into the ocean reservoir and may have played a role in
106 increasing productivity by reducing silica limitation (Cortese et al., 2004; Pound et al.,
107 2012).

108 The alternative hypothesis is the redistribution of nutrients caused by changes in
109 oceanic circulation. Based on microfossil and $\delta^{13}\text{C}$ studies, Berger et al. (1993) suggested
110 that an amplification of North Atlantic Deep Water (NADW, Wright and Miller (1996))
111 brought more nutrients into the Pacific Ocean, although Farrell et al. (1995) rather sug-
112 gest no temporal link between NADW evolution and the LMBB. The restriction of the
113 Central American Seaway may have played a role in the redistribution of nutrients by
114 changing oceanic circulation patterns (Pisias et al., 1995; Farrell et al., 1995). Diester-
115 Haass et al. (2002) also suggest that a change in the vertical distribution of nutrients could

116 result from an intensification of the global ocean circulation forced by an intensification
117 of trade winds or by an increase in latitudinal temperature gradient (caused by the global
118 decrease in $p\text{CO}_2$ and the growth of polar ice sheets).

119 While the initiation of the LMBB has been widely discussed in the literature (e.g.
120 Farrell et al., 1995; Diester-Haass et al., 2002, 2006; Dickens & Owen, 1999; Reghellin
121 et al., 2022), the termination of the event has been the subject of only a limited num-
122 ber of studies. Farrell et al. (1995) observe a distinct and permanent shift in the loca-
123 tion of the maximum opal MAR at 4.4 Ma synchronous with the end of the LMBB. The
124 authors attribute this shift to the final closure of the Central American Seaway that pre-
125 vented surface currents from exchanging between the Atlantic and Pacific Oceans. More
126 recently, Karatsolis et al. (2022) link the end of the LMBB with a decrease in insolation
127 due to a particular orbital configuration. This drop in insolation would have caused a
128 reduction in hydrological cycle intensity and therefore a decrease in continental weath-
129 ering and nutrient supply to the ocean.

130 Because most of the published work on the LMBB focuses on specific cores where
131 the event is recorded, we know where the bloom is present but mostly ignore places where
132 the event is potentially not expressed. A global overview of the event is therefore lack-
133 ing. The objective of this study is to provide a comprehensive perspective of the tem-
134 poral and geographical aspects of the LMBB to help better understand the causes of the
135 event and its impact on the carbon cycle. To do so we systematically compiled all avail-
136 able/published paleoceanographic records (from Deep Sea Drilling Project (DSDP), Oceanic
137 Drilling Program (ODP), Integrated Ocean Drilling Program (IODP) and International
138 ocean Discovery Program (IODP)), that inform on sediment accumulation during the
139 late Miocene to early Pliocene time period. This compilation contains records of sedi-
140 mentation rates as well as accumulation rates of CaCO_3 , opal, and terrigenous material
141 and provides an thorough analysis of the spatial and temporal distribution of the LMBB.
142 In contrast to Karatsolis et al. (2022) who choose to focus on high resolution records only,
143 we here choose a less selective approach because even lower resolution datasets or datasets
144 that show no signature of the LMBB can help us understand its origin.

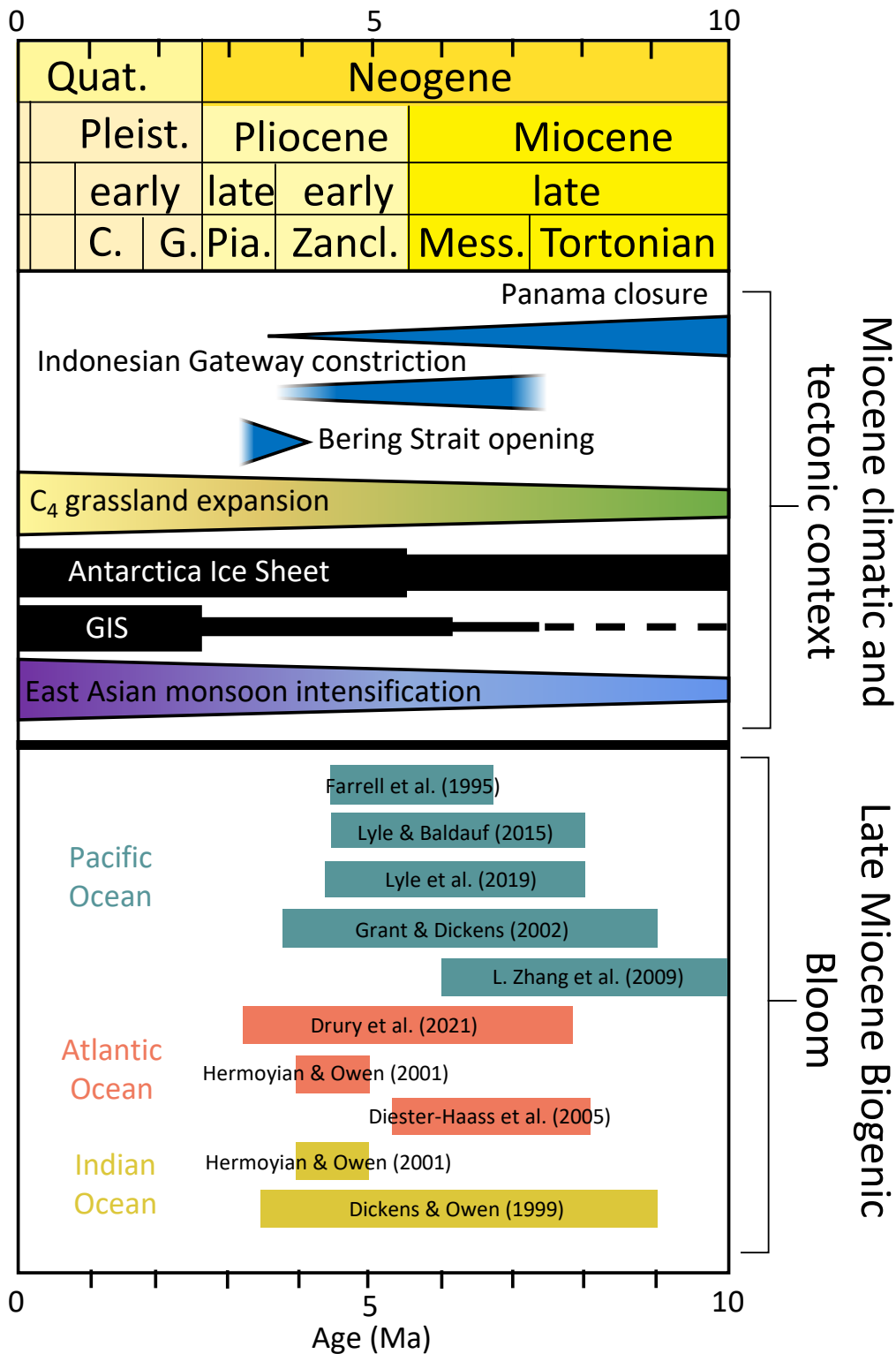


Figure 1. At the top, figure adapted from Steinhorsdottir et al. (2021). Climatic context (C₄ grassland expansion, Antarctica and Greenland Ice sheet evolution, East Asian monsoon intensification) and evolution of major seaways configuration during the late Miocene and Pliocene. GIS : Greenland Ice Sheet. Bottom, compilation of some publications related to the LMBB.

145 2 Methods

146 We compiled oceanographic data from DSDP, ODP and IODP expeditions that cover
147 the late Miocene and early Pliocene. Data mining was performed by automatically col-
148 lecting the Pangaea datasets that correspond to the selected time interval and that have
149 at least one of the following variables: sedimentation rate, dry bulk density, mass accu-
150 mulation rate (MAR), CaCO_3 accumulation rate, bSiO_2 accumulation rate (biogenic SiO_2)
151 , $\%\text{CaCO}_3$, $\%\text{bSiO}_2$. The compilation was then improved by manually adding datasets
152 absent from Pangaea but relevant to our study. The data compilation contains 155 datasets
153 (122 are from Pangaea) from 118 different ocean drilling sites (Table 1). We consider here
154 that within a single publication containing data from multiple sites, data from each site
155 forms an individual dataset. There can therefore be several datasets per publication but
156 also several datasets per site if several publications have studied the site in question.

157 Data processing was then carried out manually to remove datasets that were not
158 relevant to the study, which include datasets that (1) do not provide any data between
159 9 and 3.5 Ma, (2) have a very coarse resolution (less than one data point per million years),
160 or (3) show numerically unrealistic data (e.g. flat time series over a very long time pe-
161 riod). The sites were additionally labeled to indicate whether they contained the LMBB
162 signature, which is defined as an increase in carbonate or biogenic opal MAR or sedi-
163 mentation rate between 9 and 3.5 Ma (which is the widest definition found in the liter-
164 ature, Dickens and Owen (1999)), with clearly identifiable increase and decrease phases.
165 The results are split into four categories as follows : i) 'No', if the dataset shows no LMBB
166 signature ; ii) 'Co', if the occurrence of the LMBB is controversial, that is, an increase
167 in biogenic production can be identified but the timing is not consistent with the LMBB
168 definition; iii) 'BB', if the LMBB is clearly identifiable; iv) "In", if there are not enough
169 data before or after the interval of interest to robustly identify an increase ("In" stand-
170 ing for "inconclusive"). In the later case, we cannot conclude whether the LMBB is present
171 in the dataset. In cases where there were several datasets for a single site, the label was
172 assigned based on all the datasets considered together; if there was a contradiction be-
173 tween datasets, the dataset with the highest temporal resolution was chosen.

174 In order to perform a temporal comparison of the datasets, we also harmonized the
175 geologic timescales used in all of the publications (Berggren et al., 1985, 1995; Gradstein
176 et al., 2004, 2012, 2020; Palike et al., 2006) using the most recent one – Gradstein et al.
177 (2020) – as a standard. This step was performed using the Neptune Sandbox Berlin database
178 (Renaudie et al., 2020).

179 In addition, a geographical and temporal averaging system was implemented in or-
180 der to plot time series. For a given oceanic basin (Pacific, Atlantic and Indian) and a
181 given variable, all values of the corresponding datasets were grouped and segmented into
182 500 kyr bins to obtain a single time series. 500 kyr was chosen because many datasets
183 – in particular Lyle (2003) – had a resolution of 500 kyr. Given that the resolution be-
184 tween different datasets is very heterogeneous, some datasets would have more weight
185 in this average as they have more values in the bins. To avoid this bias, we therefore first
186 averaged every dataset individually into 500 kyr bins before averaging them globally.

187 We then tried to identify potential oceanographic similarities between sites where
188 the LMBB is present or absent. In order to do so, we computed the paleoproductivity
189 at site locations using information from ocean biogeochemical simulations for the late
190 Miocene (Sarr et al., 2022) that were performed with the IPSL-CM5A2 (Sepulchre et
191 al., 2020) and PISCES-v2 (Aumont et al., 2015) models. To superimpose the position
192 of the sites on the simulation outputs, we calculated the paleocoordinates of the sites for
193 10 Ma using the GPlates software (Qin et al., 2012) and the plate rotation model from
194 Scotese (2016).

Table 1. Source of the data compilation. Sed rate : Sedimentation rate. Acc rate : Accumulation rate. MAR : Mass Accumulation Rate. DBD : Dry Bulk Density. A more detailed table can be found in the supplementary information.

Publication	Number of datasets	variables present in these data sets
Breza (1992)	1	Sed rate
Diester-Haass et al. (2004)	2	Acc rate CaCO ₃
Diester-Haass et al. (2005)	3	Sed rate, Acc rate CaCO ₃ , CaCO ₃ , DBD
Diester-Haass et al. (2006)	4	Sed rate, MAR, Acc rate CaCO ₃ , CaCO ₃
Drury et al. (2021)	1	Sed rate, CaCO ₃ , Acc rate CaCO ₃ , MAR, DBD
Dutkiewicz and Müller (2021)	16	Acc rate CaCO ₃ , DBD, CaCO ₃ , Sed rate
Farrell and Janecek (1991)	1	Sed rate, Acc rate CaCO ₃ , CaCO ₃ , DBD
Farrell et al. (1995)	11	Sed rate, Acc rate CaCO ₃ , CaCO ₃ , DBD
Gardner et al. (1986)	2	Sed rate, MAR, Acc rate CaCO ₃ , CaCO ₃
Grant and Dickens (2002)	1	Acc rate CaCO ₃ , CaCO ₃
Hayward et al. (2010)	1	Sed rate
Hermoyian and Owen (2001)	5	Sed rate, DBD
Janecek (1985)	2	Sed rate, MAR, DBD
Lyle et al. (1995)	11	Sed rate, Acc rate CaCO ₃ , CaCO ₃
Lyle (2003)	57	Sed rate, MAR, Acc rate CaCO ₃ , CaCO ₃ , DBD
Lyle et al. (2019)	7	Sed rate, MAR, CaCO ₃ , DBD, bSiO ₂
Müller et al. (1991)	1	Sed rate, MAR, Acc rate CaCO ₃ , DBD
Pälike et al. (2012)	4	Sed rate, MAR, CaCO ₃ , DBD, Acc rate CaCO ₃
Peterson and Backman (1990)	3	MAR, Acc rate CaCO ₃ , CaCO ₃
Si and Rosenthal (2019)	14	CaCO ₃ , MAR, Acc rate CaCO ₃ , Sed rate
Stax and Stein (1993)	4	MAR
Wagner (2002)	1	Sed rate, MAR
R. Wang et al. (2004)	1	Acc rate opal, bSiO ₂
Winkler (1999)	1	Sed rate, MAR, Acc rate CaCO ₃ , CaCO ₃
L. Zhang et al. (2009)	1	Sed rate, MAR, DBD

3 Results

3.1 Geographical analysis of the compilation

Among the 119 sites, the LMBB is present at 21 sites (Bb) while 33 other datasets remain controversial (Co). The LMBB is not present in 46 of the datasets (No) and its presence is inconclusive for 18 of the datasets (In). The LMBB is identified in both the Pacific, Atlantic and Indian Oceans (sites labeled "BB" and "Co", Figure 2). Most of the sites with a LMBB are localised at mid and low latitudes, suggesting that the LMBB is either absent or has not been recovered in the Southern or in the Arctic Oceans. The LMBB has been identified (certainly or controversially) in all the datasets from the northern part of the Indian Ocean. The presence of the LMBB in the Pacific and Atlantic Oceans is very heterogeneous. In some areas, sites with a LMBB and without a LMBB are very close geographically, such as in the Eastern Equatorial Pacific. The controversial sites have a more homogeneous distribution in terms of latitude.

The spatial distribution of sites where the LMBB has been clearly identified follows the same pattern as those where the presence of LMBB is controversial. There are only four sites that show a clear LMBB signature in the Atlantic basin, one in the Indian basin and all the remaining ones are located in the Pacific basin. Most of the LMBB sites are located in the low latitudes (between 30°S and 30°N, Figure 2a, 3a), except for ODP site 145-883 which is located in the northern Pacific.

In the Atlantic Ocean, areas where LMBB is clearly identifiable (off the American coastlines 5°N-40°E and off the African coastlines 30°S-4°W) are also areas where there are sites with no LMBB evidenced. Most of the isolated sites are sites without a LMBB and are located around the Mid-Atlantic Ridge. There is, however, a controversial presence of the LMBB at three isolated and open-ocean sites (ODP site 982B, ODP site 1088B and DSDP site 519).

In the Pacific Ocean, the LMBB signature is present off the coast of Australia, in the northern area of the Tasman Sea and also in the northern part of the Pacific Ocean. The LMBB is also mainly present in the eastern equatorial part although there are also many sites without the LMBB in this area. The Eastern Equatorial Pacific has a high concentration of sites with many of them showing the presence of the LMBB. Sites with a LMBB signature are mainly located between 5°N and 5°S while the sites without a LMBB are a few degrees further north and further south (except for DSDP site 572D).

In the Indian Ocean, the presence of the LMBB is in most cases controversial but one site clearly records it in the western tropical area, near the Seychelles archipelago (ODP site 707A). In the southern Indian Ocean the compilation has only two sites and they do not show any evidence of the LMBB. The remaining sites do not have enough data to conclude.

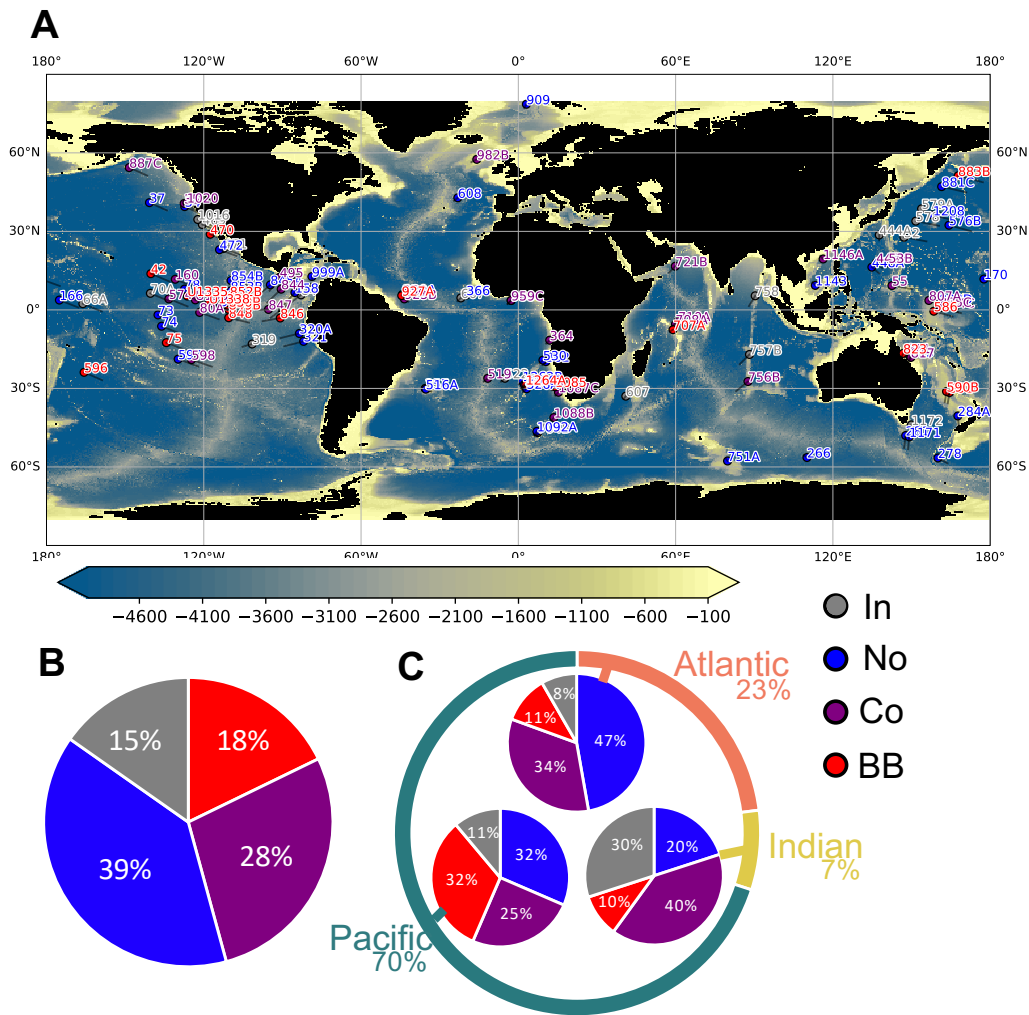


Figure 2. (A) Present-day bathymetry with dots showing the modern positions of the 118 labeled sites. The black line at the end of each point indicates the position of the site 10 million years ago. (B) Distribution of labels over the entire data compilation. (C) Distribution of the compilation for the three oceans.

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3.2 Statistical analysis of compilation

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The water depth of the sites where the LMBB is absent ranges between 1,000 and 5,000 metres with a large proportion of sites around 3,500 metres (Figure 3b). The depth of the sites where the LMBB is present is mainly between 1,500 and 4,000 metres. The average depth of sites where the LMBB is present (3,236 m) is almost equal to that of sites where the LMBB is absent (3,225 m). This suggests that the geographic distribution of sites where the LMBB is unambiguously identified is not biased by site depth thus by carbonate dissolution.

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The simulated paleoproductivity at sites where a LMBB signature is visible is 0.66 g/m²/day on average (Figure 3d). Although most of the sites are located in areas of high simulated palaeoproductivity (> 0.7 g/m²/day - e.g. East Equatorial Pacific, Southeast Atlantic Ocean), the LMBB is also identified in some oligotrophic areas (< 0.3 g/m²/day

244 - e.g. North Pacific, South Pacific Gyre, Figure S2). For sites where the LMBB is absent,
 245 absent, the average simulated palaeoproductivity is $0.48 \text{ g/m}^2/\text{day}$. However, two groups
 246 can be distinguished, one around $0.25 \text{ g/m}^2/\text{day}$ and one around $0.75 \text{ g/m}^2/\text{day}$. A group
 247 around $0.75 \text{ g/m}^2/\text{day}$ also emerged in controversial sites.

248 If we consider instead the present-day productivity at sites, which is computed from
 249 average chlorophyll mass concentration values in seawater (from remote-sensing data of
 250 AquaMODIS satellite NASA Goddard Space Flight Center (2022)), the average value
 251 is almost identical for sites with and without the LMBB (around 0.20 mg/m^3 , Figure
 252 3e). There is significant variability for sites where the LMBB is absent or controversial,
 253 but for sites where the LMBB is not present, the values are centered around 0.18 mg/m^3 .

254 To estimate the possible impact of continental nutrient inputs, the distance between
 255 each site and the nearest coastline was calculated (Figure 3f). On average the distance
 256 is higher for the sites where the LMBB is present (914 km) than for the sites where it
 257 is absent (786 km). However, the distribution is much more homogeneous for sites with
 258 the LMBB, while three groups of sites can be distinguished for the other labels, one around
 259 500 km, one around 1,300 km and one around 2,000 km.

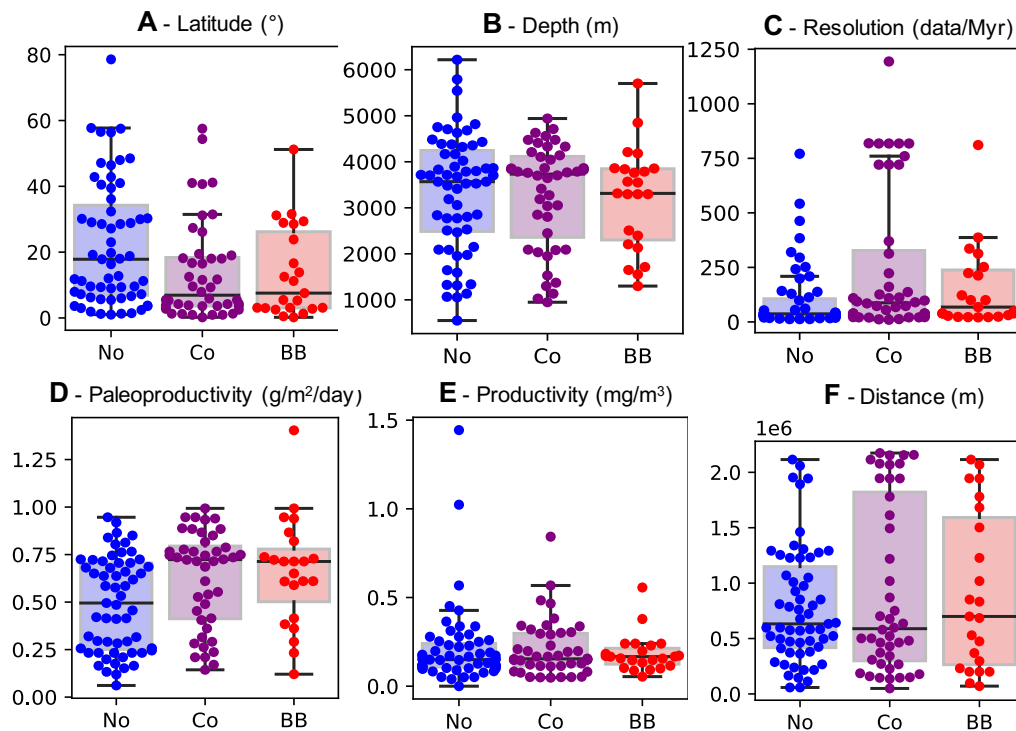


Figure 3. Box plot calculated for each label (each point represents a site). "No" - No LMBB ; "Co" - Controversial LMBB ; "BB" - LMBB is present. A: Average of absolute modern latitude values in degrees. B: Average depth of sites in metres. C: Average dataset resolution in number of data per million years. The site from Drury et al. (2021) is not shown because it is out of range (24,800 data/Myr). D : Average of the primary paleoproductivity value by phytoplankton from a late-Miocene simulation in $\text{g/m}^2/\text{day}$ (from Sarr et al., 2022). E: Average chlorophyll mass concentration value in seawater in mg/m^3 (from remote-sensing data of AquaMODIS satellite NASA Goddard Space Flight Center (2022)). F: Average of the distances between the coordinates of the sites and the nearest coast (m).

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3.3 Temporal analysis of the compilation

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We also looked at the synchronicity of the event between different oceanic basins using time series that we computed following the procedure described in the Methods section (Figure 4). The values indicated hereafter are those of the unweighted average, meaning that datasets with better resolution have a higher weighting in the average. In the Atlantic Ocean, the signal was constructed from 12 different datasets, with a maximum of 1,639 data and a minimum of 153 in one bin. On this timeserie, CaCO_3 accumulation rate increases since 15 Ma with a strong increase around 7.5 Ma ($+15.3 \text{ g/m}^2/\text{y}$). The maximum is reached around 7 Ma ($34.1 \text{ g/m}^2/\text{y}$) and then there is a decrease that starts around 6.5 Ma and ends around 2 Ma. In the Indian Ocean, the signal was constructed from 4 different datasets, with a maximum of 51 data and a minimum of 2 in a bin. There is an increase around 7.5 Ma ($+10 \text{ g/m}^2/\text{y}$) with a maximum around 7 Ma ($20.5 \text{ g/m}^2/\text{y}$) then a decrease around 5.5 Ma. In the Pacific Ocean, the signal was constructed from 46 datasets, with a maximum of 620 data and a minimum of 45 in one bin. There is an increase in the rate of CaCO_3 accumulation from 10 Ma with a more abrupt increase around 7.5 Ma ($+31.4 \text{ g/m}^2/\text{y}$). The maximum is around 7 Ma ($44.5 \text{ g/m}^2/\text{y}$) with a decrease until 2 Ma. The comparison shows that the phase of increasing CaCO_3 accumulation rate around 7.5 Ma is synchronous between the three oceanic basins. The synchronicity of the end of the event is less distinct, with the decrease in biogenic sediment accumulation being more abrupt in the Pacific Ocean than in the Atlantic and Indian Oceans.

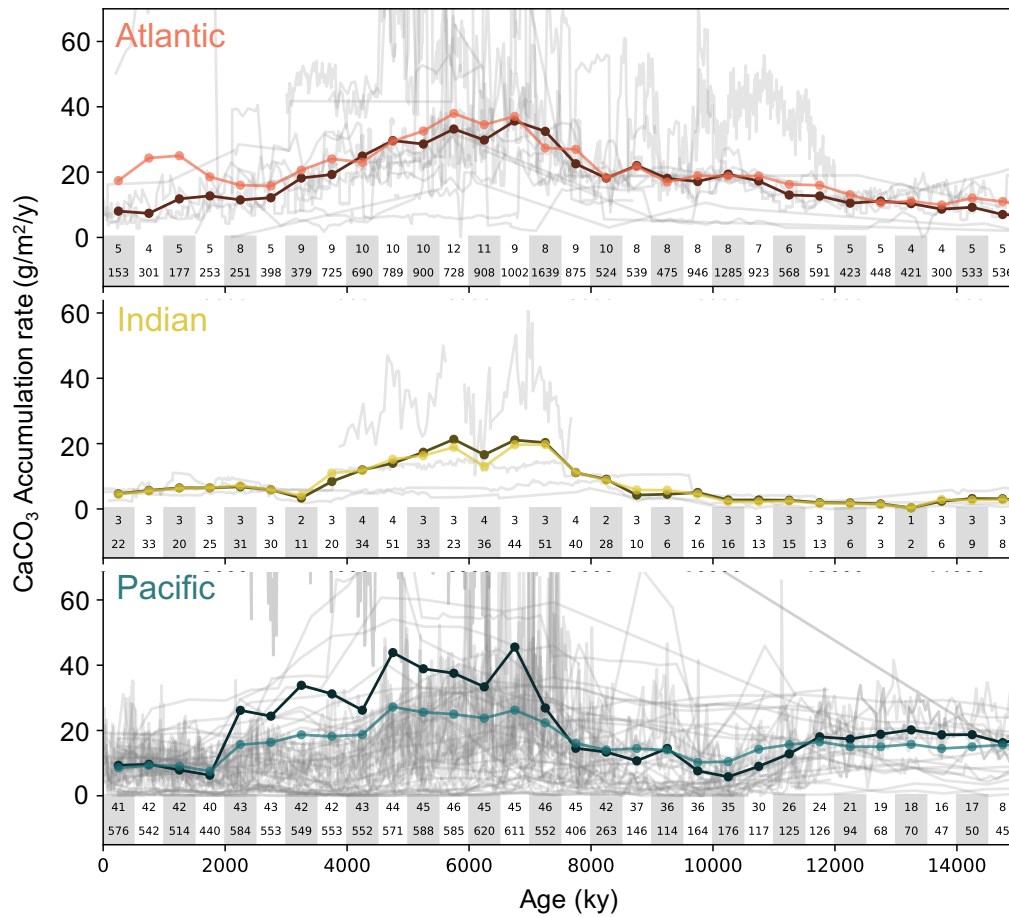


Figure 4. CaCO₃ accumulation rate from "BB" and "Co" labeled datasets for the three oceanic basins. Red, yellow and blue lines represent average weighted values to make each dataset equal (light colour) and unweighted average (dark colour) respectively, for each basin. The light grey lines represent the raw data used to calculate the average. Below each graph, we show the number of datasets used to calculate the average for each 500 kyr time bin (top line), and the number of data averaged (bottom line). The same figure with only the "BB" labeled sites can be found in supplementary Figure S1.

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4 Discussion

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4.1 Compilation biases and limitations

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Several biases need to be highlighted to evaluate the limitations of this compilation before discussing its contribution to the mechanistic understanding of the LMBB. In order to label the datasets, it was necessary to establish criteria that defined the LMBB. These criteria – stated in the methods section – are based on the literature but are not necessarily shared by all authors, which makes it difficult to quantitatively and unequivocally identify the LMBB. Early studies defined the event in a specific region depending on local parameters and a bias may come from applying this definition globally. Indeed, the compilation showed that there was significant heterogeneity between datasets, which makes it difficult to apply a "global" definition. Observational biases are also present because the labeling of datasets relied on manual classification, as an automatic evalu-

293 ation was very complicated due to the definition bias exposed previously. The "Co" label
 294 was created for this purpose ; in order to classify all datasets that showed potential
 295 traces of LMBB but that could be classified as "BB" or "No" depending on the person
 296 performing the evaluation.

297 An important bias may come from the sampling of the data compilation. Indeed,
 298 a non-negligible proportion of the datasets comes from studies focusing specifically on
 299 the LMBB, which therefore published data where the LMBB signature was visible. There
 300 is a potential bias of publication of data from this time interval restricted toward those
 301 showing a clear LMBB record, thereby artificially increasing the number of sites with
 302 a LMBB signature in the compilation. In addition, the spatial distribution of sites included
 303 in the compilation is very heterogeneous. The majority of the compilation constitutes
 304 datasets from sites located in the Pacific Ocean (70%), while only 23% of the sites
 305 are located in the Atlantic Ocean and 7% in the Indian Ocean (Figure 2c). Very few
 306 sites are located at high latitudes (above 50°N and 50°S), or in the gyres of the South
 307 and North Pacific and of the North Atlantic oceans. This results in a geographically
 308 biased view of the LMBB as we lack information on the large-scale extension of the event.
 309 There is also temporal heterogeneity, as not all datasets cover exactly the same time
 310 interval, indeed many do not cover the entire LMBB time interval. This heterogeneity may
 311 prevent a proper temporal analysis of the compilation. Finally, some datasets come from
 312 studies with an orbital resolution and astronomical timescale (Drury et al., 2021) while
 313 others have only a few data points for a time window of several millions of years (Lyle,
 314 2003). However, this resolution heterogeneity does not seem to impact labeling (Figure
 315 3c) : sites with an identified LMBB do not have a better resolution than the sites without
 316 a LMBB. These potential biases must be kept in mind when interpreting the data
 317 compilation.

318 **4.2 Does the compilation provide support for any of the LMBB hypotheses**
 319 **proposed in the literature ?**

320 Despite the potential biases discussed above, our compilation has a worldwide coverage
 321 which opens the discussion on the origin of the LMBB. The compilation shows that
 322 the LMBB is a globally distributed but not ubiquitous event. Two hypotheses have been
 323 suggested in the literature in order to explain the existence of the event: (1) a global increase
 324 in the supply of nutrients to ocean basins through changes in continental weathering
 325 (Filippelli, 1997) or (2) a major redistribution of nutrients in the oceans (Farrell
 326 et al., 1995).

327 The spatial heterogeneity of the LMBB in the data compilation could be an element
 328 that supports the scenario of a change in nutrient supply from the continents. If
 329 this hypothesis is correct, it would seem logical that the LMBB signal would be visible
 330 at some sites (close to nutrient input from the continents) and not at others (isolated
 331 from these inputs) or at least reducing with the increased distance from the source and
 332 without a specific local to regional effect of transfer from oceanic currents or winds. However,
 333 the compilation of data also showed the global nature of this event and a "local"
 334 cause such as the Himalayan uplift cannot produce a rise in productivity on a global scale
 335 without redistribution, or if it did, it would have been homogeneous for areas at a great
 336 distance from the source (i. e. in the Atlantic Ocean). Furthermore, sites in the data
 337 compilation that are located in the South China Sea (ODP sites 1143 and 1146), thus directly
 338 affected by the East Asian monsoon system, do not show a clear LMBB signal.
 339 Calculations of the distances of the sites from the nearest coastline show that the LMBB
 340 is not present in areas particularly close to the coastline compared to areas where the
 341 LMBB appears to be absent, which partly contradicts this scenario. Nevertheless, it is
 342 important to consider that there can be local changes in the location of inputs that affect
 343 a particular site. For example, proximity of river outlet that changes its flow over
 344 time or shifting rainfall patterns. There is also evidence of micronutrient supply by dust

345 fluxes which, due to wind, can be transported a long distance from their source (Hovan,
 346 1995; Diester-Haass et al., 2006). This wind-driven dust supply is particularly impor-
 347 tant as it is related to the cooling and aridification of the late Miocene (Pound et al.,
 348 2012; Herbert et al., 2016). However, our data compilation cannot highlight an increase
 349 in dust flux during this time interval. Moreover, the nutrient input would be then re-
 350 stricted to areas downwind of the arid and desert regions which is not clearly the case
 351 in our records. Karatsolis et al. (2022) suggest an end of the LMBB at 4.6-4.4 Ma re-
 352 lated to a decrease in insolation which in turn would have caused a reduction in hydro-
 353 logical cycle intensity and continental weathering. Our compilation shows a significant
 354 decline in carbonate-related productivity in the Pacific Ocean at this time, although it
 355 does not appear to correspond to the end of the LMBB. Moreover, there is no decline
 356 observed at this time in the Indian and Atlantic Oceans. Furthermore, the hypothesis
 357 of a particular orbital configuration as a trigger for the end of the LMBB is incompat-
 358 ible with our results because we show a slow and continuous decline of carbonate accu-
 359 mulation in the terminal part of the LMBB. This slow decrease started as soon as the
 360 maximum was reached, around 7-6.5 Ma. Eventually, the increase in nutrient supply hy-
 361 pothesis seems not corresponding to our geographic and stratigraphic record.

362 Regarding the nutrient redistribution hypothesis, the Eastern Equatorial Pacific
 363 is an interesting case study as it has been widely discussed in the LMBB literature (Farrell
 364 et al., 1995; Lyle et al., 2019; Reghellin et al., 2022). Our compilation shows that sites
 365 with a LMBB signature cluster between 6°N and 5°S and between 90°W and 127°W (Fig-
 366 ure 5). The LMBB signature is present at eight sites (plus three controversial ones) and
 367 is absent at DSDP site 572. A closer look at the data for DSDP site 572 shows that there
 368 is a decrease in productivity from 10 Ma and then an increase from 5 Ma to a peak at
 369 3.5 Ma. This site has not been labelled "BB" because instead of having an increase in
 370 productivity at the end of the Miocene there is a decrease and the peak is reached at the
 371 moment when the "LMBB period" is over. The presence of this site without a LMBB
 372 might either be due to an error (in the definition of the event or in the interpretation
 373 of the signal) or to a particular geographical reason that remains undetermined. With-
 374 out considering DSDP site 572, we observe that the sites where the LMBB is present were
 375 much closer to the Equator 10 Ma ago, which suggests an influence of equatorial upwelling
 376 on the increase in productivity (Lyle et al., 2019). Reghellin et al. (2022) suggested that
 377 the equatorial upwelling band was less parallel to the equator during the event and had
 378 a reduced spatial extent. Moreover, upwelling in this area appears to be strongest be-
 379 tween 6.5 and 4.5 Ma, based on alkenone analyses from ODP sites 806 and 850 (Y. G. Zhang
 380 et al., 2017). These observations, which are in agreement with the compilation, support
 381 the scenario of nutrient redistribution as a driver of the LMBB. This redistribution may
 382 be a consequence of the closure of the Central American Seaway, which would result in
 383 the intensification of upwelling in the Eastern Equatorial Pacific, strongly increasing the
 384 surface nutrient concentration and thus primary productivity (Schneider & Schmittner,
 385 2006). The Southeast Atlantic Ocean (around 30°S and 10°E) has also been studied in
 386 the context of the LMBB (Diester-Haass et al., 2004; Drury et al., 2021). In this area,
 387 the link between the LMBB and upwelling is more difficult to discern. Generally, sites
 388 where the LMBB is present are areas where simulated paleoproductivity is high (>0.5
 389 $\text{g/cm}^2/\text{day}$, Figure 5) with the exception of ODP site 1264 (which is nonetheless the site
 390 with the highest resolution), which is in an area of low productivity ($<0.4 \text{ g/cm}^2/\text{day}$)
 391 closely surrounded by five sites with no LMBB recorded. It is interesting to note that
 392 these sites are on the Walvis Ridge and that ODP site 1264 is much shallower than ODP
 393 sites 1262, 1265 and 1266 hence sometimes dissolution locally impact the record of the
 394 LMBB. Sites without the LMBB are generally in areas of low simulated paleoproductiv-
 395 ity with the exception of ODP site 530 and DSDP site 362 (for these sites, the hy-
 396 pothesis of redistribution remains open to discussion). The calculation of simulated palaeo-
 397 productivity for each site (Figure 3d) shows that on average, the LMBB signature is mostly
 398 recorded at sites located in areas of high productivity (upwelling areas for example). This
 399 is consistent with a scenario of intensification of ocean circulation which can change the

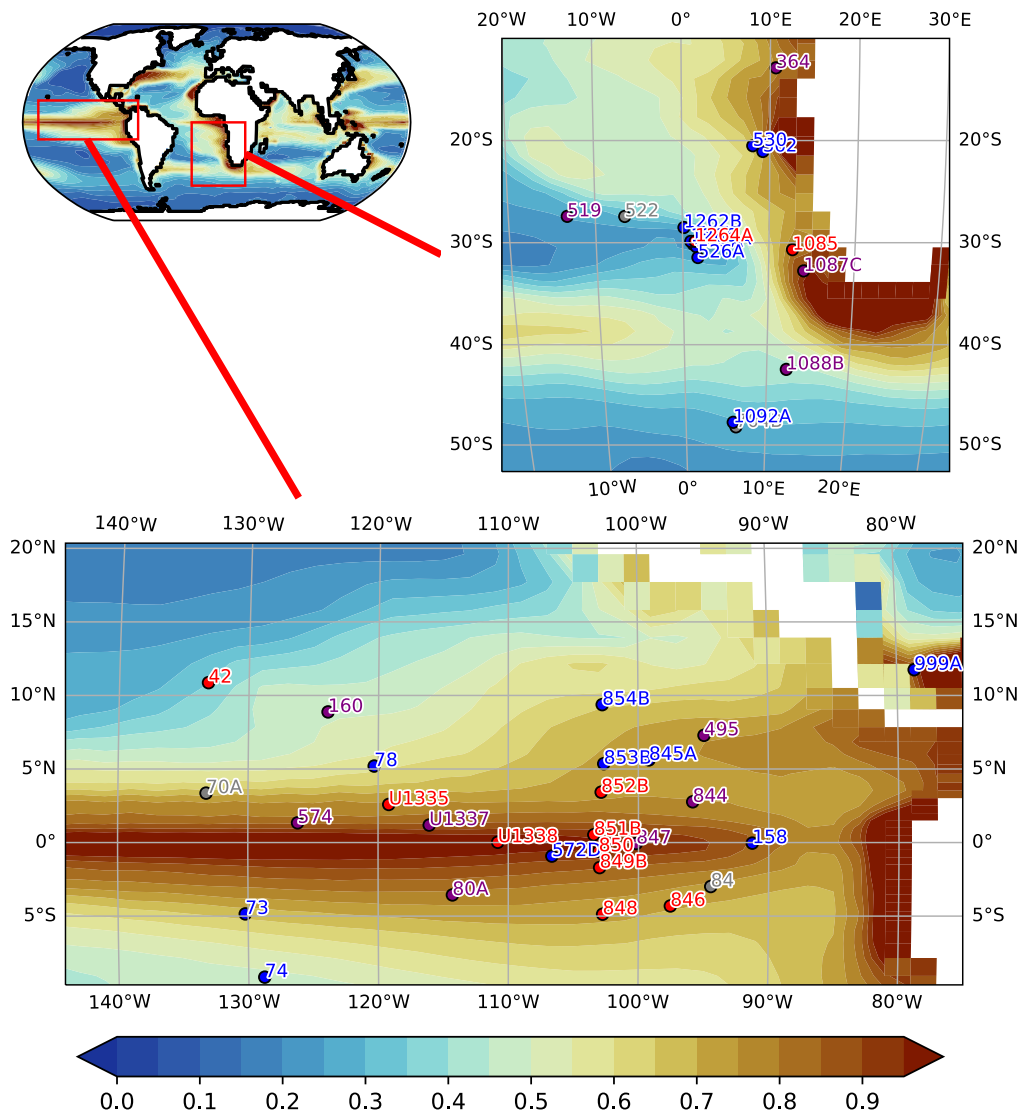


Figure 5. Primary productivity by phytoplankton in $\text{g/m}^2/\text{day}$ for the late Miocene (simulation output from Sarr et al. (2022)) with dots showing the paleo-positions (10 Ma) of the labeled sites.

400 intensity of upwelling and induce a change in the vertical distribution of nutrients (Diester-
 401 Haass et al., 2002). Nutrient redistribution may also imply a transfer of nutrients from
 402 some geographic regions to others (Dickens & Owen, 1996). This would be consistent
 403 with the heterogeneous nature of LMBB in the data compilation. But according to this
 404 model, some sites should show a reverse signal, i.e. a decline in productivity between 9
 405 and 3.5 Ma. Considering low influence of depth and dissolution on carbonate accumu-
 406 lation rates compiled (Figure 3b), no reverse signals are observed in the data compila-
 407 tion arguing against the redistribution hypothesis.

408 An alternative scenario would be to consider an increase in nutrients on a global
 409 scale without i) a redistribution with an increase of productivity in some regions com-
 410 pensated by a decrease elsewhere and ii) increase in continental inputs. This increase

411 in nutrients could come from the generalized intensification of upwelling systems. This
 412 intensification could have two origins, an intensification of the wind regime or an increase
 413 in deep water formation at high latitudes. The end of the Miocene is marked by a sig-
 414 nificant global cooling due to a decrease in the CO₂ level and a strengthening of the tem-
 415 perature gradient between the equator and the poles (Herbert et al., 2016; Martinot et
 416 al., 2022). The strengthening of this gradient leads to more air mass movement in the
 417 atmosphere and thus to an intensification of the Walker and Hadley cells (Kamae et al.,
 418 2011). Trade wind intensification is one consequence of this atmospheric reorganization,
 419 evidence of which has been observed in marine sediments (Hovan, 1995). The intensi-
 420 fication of trade winds causes an increase in upwelling by Ekman pumping, especially
 421 in the equatorial Pacific (Bjerknes, 1969; Shankle et al., 2021) and results in increased
 422 productivity (Diester-Haass et al., 2006; Y. G. Zhang et al., 2017; Huguet et al., 2022).
 423 The late Miocene is also a period when the thermohaline circulation dominated by NADW
 424 and Antarctic Bottom Water became perennial (Poore et al., 2006). In general, NADW
 425 formation is thought to have intensified from the Miocene to the present day but its evo-
 426 lution is difficult to quantify (Poore et al., 2006). There are many factors that could have
 427 increased NADW production/strength in the late Miocene. For example, the decrease
 428 in CO₂ levels (Rae et al., 2021) in the late Miocene may have intensified NADW pro-
 429 duction (Bradshaw et al., 2015) as well as the transition from a mid-Miocene to present
 430 day geography (Herold et al., 2012). NADW may also be enhanced by the closure of the
 431 Central America Seaway (Nisancioglu et al., 2003; Schneider & Schmittner, 2006; Sepul-
 432 chre et al., 2014), thought to have occurred during the Miocene (Montes et al., 2015).
 433 Bierman et al. (2016) showed that a small ice sheet might have existed on Greenland over
 434 the past 7.5 Ma. An ice sheet on Greenland can lead to an intensification of NADW, through
 435 atmospheric forcing (Pillot et al., 2022). Finally, NADW production also varied with the
 436 depth of the Greenland Scotland Ridge, which had phases of uplift and subsidence in the
 437 late Miocene (Wright & Miller, 1996; Poore et al., 2006; Hossain et al., 2020). Increased
 438 deep water formation results in the intensification of overturning cells (such as the AMOC)
 439 and therefore intensified upwelling systems. Following the same logic, a decrease in NADW
 440 production could have caused the end of the LMBB. The opening of the Bering Seaway
 441 in the early Pliocene (Gladenkov & Gladenkov, 2004), which according to modeling could
 442 have caused a weakening of the AMOC (Brierley & Fedorov, 2016), could potentially have
 443 been linked to the end of the LMBB.

444 **4.3 Speculation on the link between the beginning of the LMBB and**
 445 **the Late Miocene Carbon Isotope Shift (LMCIS)**

446 The new data compilation shows that there is a synchronicity between the onset
 447 of the LMBB and the LMCIS (Keigwin, 1979; Drury et al., 2017; Westerhold et al., 2020)
 448 for the three oceanic basins, a synchronicity that has already been discussed in the lit-
 449 erature (Diester-Haass et al., 2005; Dickens & Owen, 1999; Grant & Dickens, 2002). This
 450 approximately 1‰ negative shift in benthic foraminiferal δ¹³C extends from 7.5 to 6.7
 451 Ma and corresponds to the last major carbon cycle change in Earth’s history (Steinhorsdottir
 452 et al., 2021). The period of the δ¹³C shift (7.5 to 6.7 Ma) corresponds to the most im-
 453 portant phase of increasing productivity in the compilation and the productivity max-
 454 imum (approx. 500,000 years, Figure 6). However, the isotopic shift lasts just under a
 455 million years and δ¹³C never returns to its initial state, whereas the LMBB lasts sev-
 456 eral million years and biogenic sediment accumulation returns to a pre-event state. The
 457 causes of the LMCIS shift are still poorly understood. It may result from a global shift
 458 in δ¹³C_{DIC} (Hodell et al., 2001; Bickert et al., 2004) caused by fractionation of organic
 459 matter in surface waters (Bickert et al., 2004) or a change in continental carbon flux (Du
 460 et al., 2022). This change may have been caused by the rapid expansion of C₄ plants be-
 461 tween 8 and 6 Ma (Cerling et al., 1997), although this hypothesis appears to be tempo-
 462 rally inconsistent (Drury et al., 2017; Tauxe & Feakins, 2020). The LMCIS may also have
 463 originated from a global high productivity event in the surface ocean (Grant & Dickens,

464 2002; Diester-Haass et al., 2005). The link between the LMBB and LMCIS supposes that
465 the input of nutrients from the continents would produce a peak in dissolution and there-
466 fore a decrease in $\delta^{13}\text{C}$ values of dissolved inorganic carbon (Berger H, 1981; Diester-Haass
467 et al., 2005; Bickert et al., 2004), yet this hypothesis is not consistent with our compi-
468 lation, which shows no dissolution event. The LMCIS could also be a consequence of a
469 change in global ocean circulation, in particular the contribution of NADW, which would
470 result in a greater difference in $\delta^{13}\text{C}$ between deep waters from the north and those from
471 the south (Hodell & Venz-Curtis, 2006; Butzin et al., 2011; Thomas & Via, 2007; Poore
472 et al., 2006; Crichton et al., 2021). Considering the timing of the LMCIS (7.5 to 6.7 Ma),
473 this hypothesis would support the NADW intensification scenario for the origin of the
474 LMBB. In this case the LMCIS would not be a consequence of the LMBB but a paral-
475 lel consequence of a common cause.

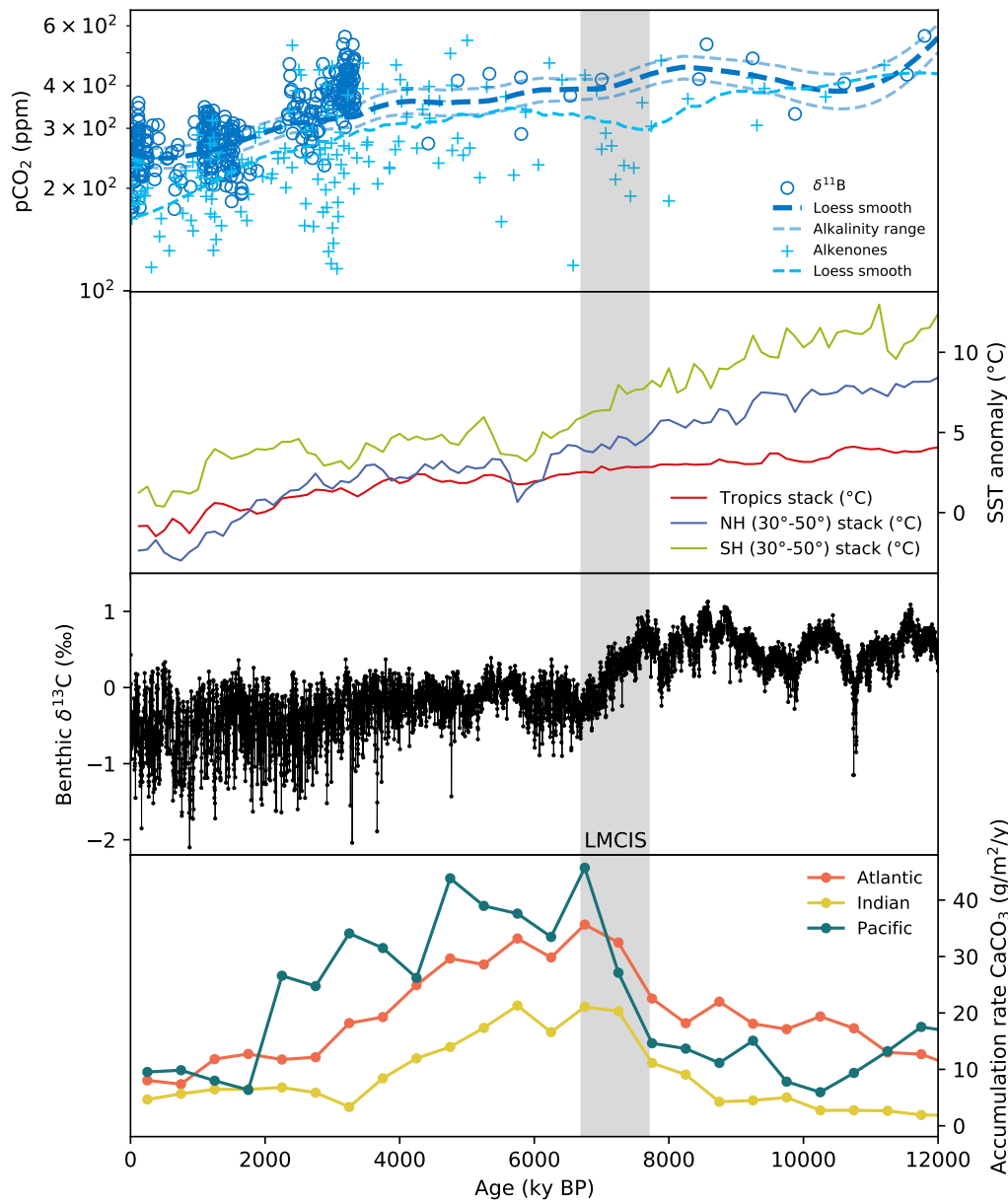


Figure 6. Top to bottom: Atmospheric $p\text{CO}_2$ reconstructions (ppm) from boron isotopes and alkenone $\delta^{13}\text{C}$ compiled in Rae et al. (2021). SST anomaly stacks for different latitudinal bands from Herbert et al. (2016). Megasplice benthic $\delta^{13}\text{C}$ evolution (‰) from Westerhold et al. (2020). CaCO_3 accumulation rate from "BB" and "Co" labeled datasets for the three ocean basins (Figure 4).

476 **5 Conclusion**

477 Our data compilation shows that traces of the LMBB are present at many differ-
 478 ent locations but in a very heterogeneous way. We therefore show that the LMBB is not
 479 a global event, as it is often considered in the literature to date, because its signature
 480 is absent from many sites. The compilation also shows that for the three oceanic basins,
 481 productivity shows a strong increase around 7.5 Ma, peaks around 7 Ma and then de-
 482 creases until it reaches a pre-event state around 3.5 Ma. To explain the origin of the LMBB,
 483 the scenarios of increased nutrient input to the oceans and a redistribution of nutrients
 484 in the ocean cannot be ignored, although some aspects of our findings do not support
 485 these hypotheses. However, the compilation shows that the sites where the LMBB is recorded
 486 are mainly located in areas where there is a high productivity regime (i.e. upwelling sys-
 487 tems). We propose that the most likely hypothesis to explain the LMBB is a global in-
 488 crease in upwelling intensity due to an increase in wind strength or an increase in deep
 489 water formation, ramping up global circulation. These increases may have been the re-
 490 sult of major tectonic or climatic changes at the end of the Miocene, such as the closure
 491 of the Central American Seaway, the general decrease in temperature and CO₂ levels,
 492 subsidence of the Greenland-Scotland Ridge or the establishment of the Greenland ice-
 493 sheet. In future work, the forcing factors at the origin of the LMBB could be identified
 494 using a set of simulations from a coupled ocean/atmosphere models with late Miocene
 495 paleogeography and integrating a marine biogeochemistry module.

496 **6 Open Research**

497 All data used in this study have been previously published. The sources are avail-
 498 able in Table 1 and in the Supplementary Table.

499 **7 Author Contributions**

500 Q. P. performed the data compilation and drafted the manuscript. The sites were
 501 labeled by Q. P. and B. S-M. All authors analyzed and discussed the results and con-
 502 tributed to the final version of the manuscript.

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