

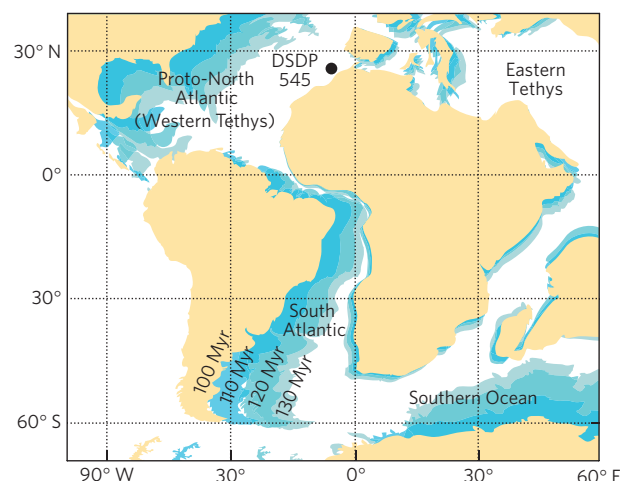
# Atlantic cooling associated with a marine biotic crisis during the mid-Cretaceous period

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**Most of the marine biotic crises that occurred during the hot Mesozoic era have been linked to episodes of extreme warmth<sup>1,2</sup>. Others, however, may have occurred during cooler intervals that interrupted Cretaceous greenhouse warmth<sup>3–5</sup>. There are some indications of cooling in the late Aptian<sup>6–8</sup> (116–114 Myr ago), but it has not been definitively linked to biotic crisis. Here we assess the timing and magnitude of late Aptian cooling and its association with biotic crises using a suite of geochemical and micropalaeontological assessments from a marine sediment core from the North Atlantic Ocean as well as global biogeochemical modelling. Sea surface temperatures derived from the TEX<sub>86</sub> proxy suggest that surface waters cooled by about 5 °C during the two million years, coincident with a positive  $\delta^{13}\text{C}$  excursion of approximately 2‰ in carbonates and organic carbon. Surface productivity was enhanced during this period, but the abundance of planktonic foraminifera and nannoconid phytoplankton declined. Our simulations with a biogeochemical model indicate that the  $\delta^{13}\text{C}$  excursion associated with the cooling could be explained by the burial of about 812,000 gigatons of carbon over 2.5 million years. About 50% of this carbon burial occurred in the Atlantic, Southern and Tethys ocean basins. We conclude that global cooling during greenhouse conditions can cause perturbations to marine ecosystems and biogeochemical cycles at scales comparable to those associated with global warming.**

The Aptian–Albian transition (~115–112 million years ago) was characterized by major evolutionary changes in calcareous marine organisms and a disruption of the warm and equable climate conditions of the mid-Cretaceous period by interludes of global cooling<sup>4,8,10,11</sup> and punctuated warming<sup>7,8</sup>. At present there are few studies supporting major oceanographic and climatic reorganizations during this period<sup>4</sup>; however, evidence includes a late Aptian–early Albian decline in  $p\text{CO}_2$  (ref. 12), the establishment of ocean gateways due to the separation of Africa and South America<sup>13</sup>, and a major biotic crisis that affected carbonate producers on a global scale<sup>2,3,14</sup>. Still, the exact timing of these massive perturbations in relation to global cooling and their consequences for marine biogeochemistry are poorly constrained, and importantly, independent quantitative proof of the proposed late Aptian cold snap<sup>3,4</sup> (Supplementary Information) is still lacking.

This study of Deep Sea Drilling Project Site 545 sediment cores provides a high-resolution, multi-proxy record from the eastern proto-North Atlantic (Mazagan Plateau, Fig. 1 and Supplementary Information). Sea surface temperature (SST) reconstructions are based on the TEX<sub>86</sub> palaeothermometry proxy<sup>15</sup> (the

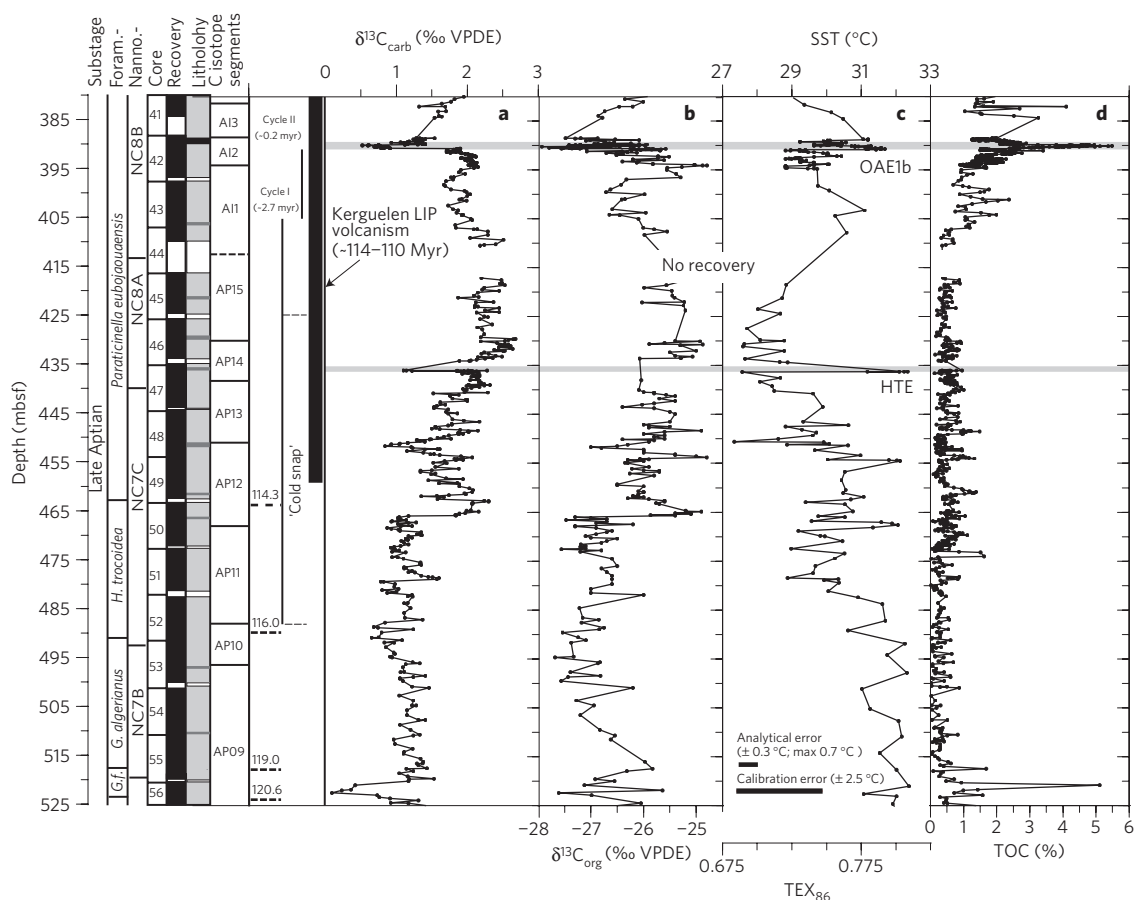


**Figure 1 | Palaeogeographic setting of late Aptian Deep Sea Drilling Project Site 545, Mazagan Plateau.** Reconstruction of the early-mid Cretaceous Atlantic Ocean, Southern Ocean and western Tethys region<sup>27,28</sup> (Supplementary Information) illustrating the progressive opening of the equatorial Atlantic gateway and all ocean basins for four time periods of the Cretaceous.

tetraether index of tetraethers consisting of 86 carbon atoms; see Supplementary Information for proxy calibration and analyses details), where results constrain the internal structure and magnitude of the late Aptian cooling trend at a subtropical site. A global biogeochemical simulation driven by both mid-Cretaceous circulation<sup>16</sup> and palaeogeography is used to quantify marine carbon burial associated with the global cooling, and to identify prominent areas of enhanced carbon burial (Supplementary Information).

A global, long-term cooling trend for surface waters in the eastern North Atlantic, linked to variations in carbon burial, is recorded in the SST and positive isotope excursions for carbonate and organic carbon (Fig. 2 and Supplementary Information for analytical procedures). The SST record shows two cooling and warming cycles between ~487–405 and ~405–390 mbsf, respectively (cycles I and II, Fig. 2). On the basis of reported stratigraphic frameworks<sup>2,9,14</sup> (Supplementary Information), the first prolonged climate cycle I lasted for ~2.7 Myr, with an initial cooling phase of ~2 Myr. This was followed by a second, smaller-amplitude and shorter (0.3 Myr) cycle II with surface waters cooling for approximately 0.2 Myr before renewed surface water

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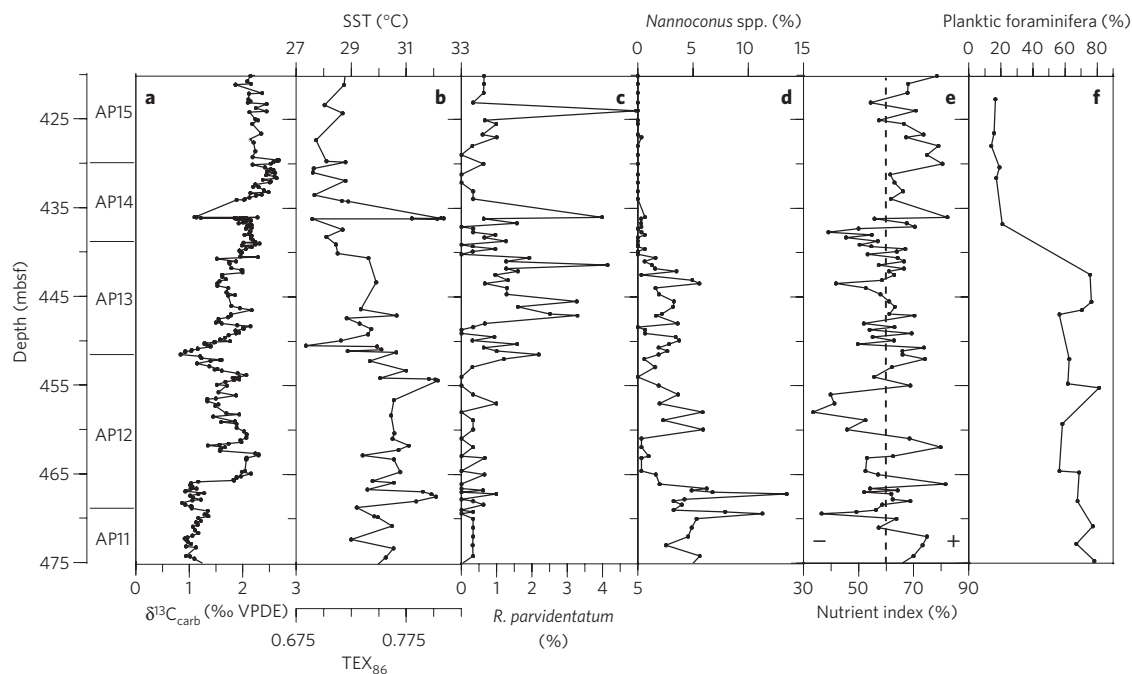
**Figure 2 | High-resolution geochemical records. a–d,** Carbonate (a) and organic carbon (b) isotopes,  $\text{TEX}_{86}$  SSTs (c) with associated analytical and calibration errors (Supplementary Information), and total organic carbon (TOC) concentration (d). Biostratigraphy and ages for biozones<sup>2,8,9,14</sup>, LIP volcanism (Supplementary Information), and both carbon and carbonate isotope data<sup>29,30</sup> are compiled from various sources including new data generated for this study. Climate cycles and the late Aptian cold snap, as discussed in the text, are shown alongside two high-temperature events, HTE and OAE1b (refs 7,29,30), which are shown as grey bars.

warming, linked to Oceanic Anoxic Event (OAE) 1b (ref. 7). At Mazagan Plateau we define the late Aptian cold snap as the interval between 490 and 425 mbsf, before which SST remained relatively stable. The cooling trend of cycle I is accompanied by short-term climate variability, as evident from repeated low-amplitude fluctuations in SST and nutrient availability (Figs 2 and 3). Most of these short SST fluctuations are within the range of uncertainty or error defined for the  $\text{TEX}_{86}$  proxy (Fig. 2 and Supplementary Information). However, two robust high-temperature events (HTE) were clearly identified; one at 436 mbsf and another previously reported as OAE1b (refs 2,7) at 390 mbsf (Fig. 2), showing features characteristic of hyperthermal events, that is a rapid temperature increase paralleled by a negative carbon isotope excursion. Maximum cooling is recorded between 440 and 430 mbsf, with SSTs of  $\sim 28^\circ\text{C}$  lasting approximately 0.2 Myr, before gradually recovering to reach pre-event levels ( $<32^\circ\text{C}$ ). Both carbon isotope records show a near mirror image of the SST profile with a broad  $\sim 2.5\text{‰}$  positive excursion, where lower SST corresponds to more positive  $\delta^{13}\text{C}$  values (Fig. 2). Therefore, the observed relationships between SST and  $\delta^{13}\text{C}$  isotopes suggest a unifying mechanism, which may have been linked to enhanced and widespread marine carbon burial<sup>18</sup>.

To test this mechanism and estimate the amount of carbon draw-down from the atmosphere, we applied a global biogeochemical modelling approach simulating marine, terrestrial and atmospheric carbon and phosphorous cycles. Oceanic and atmospheric circulation driving the model biogeochemistry from a mid-Cretaceous

atmosphere–ocean global circulation model<sup>16</sup> set-up was used, and fixed, and therefore did not vary with transient climate changes. To compensate for this limitation, other variables including weathering rate, terrestrial nutrient export and marine biogeochemistry were forced by transient  $p\text{CO}_2$ /temperature. The model generates carbonate carbon isotope data tuned to match the measured values from the Mazagan Plateau record (as shown in Fig. 2), where outputs were extracted for individual ocean basins constrained by mid-Cretaceous palaeogeography. Our model results suggest that a perturbation of the global carbon cycle with excess carbon burial of  $\sim 812,000$  gigatons (Gt) over a period of  $\sim 2.5$  million years would be required to explain the observed positive carbon isotope excursion. Details regarding model set-up, experiments, sensitivity and results are provided in the Supplementary Information.

The long-term cooling at Site 545 was paralleled by adaptations of the phytoplankton community. Studies of calcareous nannofossils indicate an increase in the abundance of the boreal cold-water taxon *Repagulum parvidentatum* and a decline of the deeper-dwelling *Nannoconus* spp. (Fig. 3), consistent with surface-water cooling and a weakened stratification<sup>4</sup>. A stepped increase of the average nannofossil-based nutrient index<sup>17</sup> with maximum cooling (Fig. 3) suggests the onset of enhanced surface-water productivity at about 440 mbsf. In addition, cooling is also associated with a marked reduction in the abundance of planktic foraminifera and nannoconid abundances<sup>17,18</sup> (Fig. 3), mirroring the synchronous decline of nannoconids reported for sediments from the subtropical Pacific Ocean<sup>19</sup>.



**Figure 3 | Marine biotic response to late Aptian cooling.** **a**, Carbonate carbon isotopes. **b**, SST estimates (based on  $\text{TEX}_{86}$ ). **c**, Percentages of the boreal cold-water taxon *Repagulum parvidentatum*. **d**, Percentages of deep-dwelling nannoconids relative to total calcareous nannofossils. **e**, Nannofossil-based nutrient index<sup>17</sup>. **f**, Percentages of planktic foraminifera relative to total foraminifera<sup>2</sup>.

Whilst deep-dwelling nannoconids decreased in the latest Aptian, siliceous organisms including diatoms<sup>20</sup> experienced their first widespread bloom around Antarctica, in the Lower Saxony Basin, and in Australia since their first appearance in the late Jurassic, probably because of higher reproductive rates compared with calcareous nannofossils during the late Aptian<sup>4,19</sup>. This is also documented at Mazagan Plateau, where siliceous sponges explode in abundance whereas planktic foraminifera and nannoconids decrease<sup>2</sup>. At the same time, a further major biotic crisis associated with carbonate platform drowning events also affected the higher levels of the marine food chain, as indicated by the massive decline of reef-building organisms in the Caribbean and western Tethys<sup>21</sup>.

The causes of these pronounced biotic changes around the Aptian–Albian transition have been attributed to fluctuations in carbonate chemistry, vertical stratification and surface-water productivity<sup>2</sup>. Our data support the concept that late Aptian cooling caused a widespread collapse of ocean stratification, corresponding to an increase in nutrient availability and productivity. This progressive modification of environmental conditions was probably a first step in the reduction of the ecospace for selected planktic species, which led to the stepwise extinction of planktic foraminifera at the Aptian–Albian boundary<sup>18</sup> ~1.5 million years after the peak cooling of the late Aptian cold snap.

The extended duration and the gradual nature of the cooling phase argues for tectonic processes as an underlying forcing mechanism rather than for climate modulations at orbital or shorter timescales. In the latest Aptian, long-term tectonic processes included a major plate tectonic rearrangement associated with the opening of the South Atlantic Ocean (Fig. 1) and the emplacement of new large igneous provinces (LIPs) in the Indian Ocean<sup>9</sup> (Supplementary Information). At present, there is no model available that captures the transient and long-term evolution of global tectonics and biogeochemistry in the Cretaceous that occurred over tens of millions of years. We therefore use a fixed palaeogeography as an average representation of the mid-Cretaceous ocean to simulate carbon cycling over a comparably short time interval of ~2.5 Myr (Supplementary Information).

Our modelling shows that the South Atlantic experienced an overproportionately high rate of excess carbon burial in the course of the positive carbon isotope excursion when compared with other ocean basins. Modelling results indicate that ~132,000 Gt of carbon (equivalent to ~16% of the total global carbon burial) were deposited during the late Aptian in the South Atlantic Ocean, which at that time represented only ~1% of the global ocean surface (Supplementary Fig. S6). In comparison, the Southern Ocean accommodated 19% of global carbon burial (~160,000 Gt) on 4% of the global ocean area. Furthermore, carbon burial in the North Atlantic and eastern Tethys region (summarized as Tethys in our model; see Supplementary Information) reached ~109,000 Gt during the positive isotope excursion, equivalent to ~13% of the global burial. Geological evidence (that is, late Aptian black shales in the Tethys and the South Atlantic Ocean<sup>22–24</sup>) supports these modelling results. We therefore propose that the emerging Southern Ocean, Atlantic Ocean and Tethys Ocean basins served as globally important carbon sinks during the late Aptian, leading to enhanced  $p\text{CO}_2$  drawdown and subsequent global cooling.

The termination of the late Aptian cold snap was probably related to enhanced global warming, triggered by large-scale volcanism in the Indian Ocean associated with the emplacement of the Kerguelen LIP (ref. 9). Another factor contributing to global warming may have been reduced carbon burial in the progressively widening South Atlantic region (Fig. 1). This widening allowed the inflow of more oxic water masses into the previously oxygen-depleted sub-basins, finally leading to the deposition of oceanic red beds from the late Aptian onwards<sup>22</sup>. We suggest that the combination of LIP volcanism and tectonically induced changes in the rate of global carbon burial could ultimately have led to the termination of the late Aptian cold snap.

The Mazagan Plateau records further indicate that long-term late Aptian cooling was modified by multi-directional climate instability, as evident from short-term (<100 kyr) positive and negative excursions in temperature and carbon isotopes (Figs 1 and 2). Some of these excursions (OAE1b; ref. 7, and HTE in Fig. 2) may relate to hyperthermal events, represented by a sharp increase

in SST accompanied by a negative carbon isotope excursion. Other excursions show no clear association between both variables, arguing against a direct coupling between temperature and global carbon perturbation, and hence the underlying mechanisms for these multi-directional modifications still need to be confirmed. They may, however, include the effects of regional processes, such as fluctuations in the rate of inflow of warm and shallow water masses from the western Tethys through the Gibraltar gateway<sup>25</sup>. Such variations in regional surface water currents could have been caused by the slight northward drift of Africa in the mid-Cretaceous (Fig. 1), in addition to orbital-driven fluctuations of the subtropical trade wind circulation.

Our results identify the late Aptian cold snap as a fundamental step in the biotic turnover that preceded the Aptian–Albian transition. The evidence presented supports the concept that tectonically induced long-term cooling played a substantial role in the global evolution of calcareous organisms during global greenhouse conditions. Long-term tectonic–climate–biota feedback mechanisms have been recently shown for Mesozoic–Cenozoic planktic foraminifera<sup>26</sup>, emphasizing that the frequency, internal structure and importance of physical environmental factors relative to marine ecosystem interactions still need to be constrained. Our study supports the view that global marine biotic crises can be induced by plate tectonic rearrangements and LIP emplacement through long-term sequestration of atmospheric CO<sub>2</sub> into sedimentary organic carbon, leading to a global cooling. We conclude that a fundamental component favouring the enhanced burial of marine organic carbon that caused cooling was the generation and early evolution of multiple ocean basins linked to the progressive breakup of the supercontinent Pangaea.

## Methods

For detailed descriptions of the analytical methods used in this study, see the Supplementary Information.

**Data.** The new data presented in this study are available for download at [ftp://ftp.ncdc.noaa.gov/pub/data/paleo/contributions\\_by\\_author/mcanena2013/](ftp://ftp.ncdc.noaa.gov/pub/data/paleo/contributions_by_author/mcanena2013/).

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## Author contributions

S.F., J.O.H., P.H., J.P., K.W. and T.W. designed the study; S.F., A.G., A.M., J.R., H.M.T. and K.W. performed analyses and contributed to the discussion; S.F., P.H., J.O.H., A.M. and T.W. wrote the paper, with overall coordination by T.W.

## Additional information

Supplementary information is available in the [online version of the paper](#). Reprints and permissions information is available online at [www.nature.com/reprints](http://www.nature.com/reprints). Correspondence and requests for materials should be addressed to T.W.

## Competing financial interests

The authors declare no competing financial interests.