Extreme warming of mid-latitude coastal ocean during the Paleocene-Eocene Thermal Maximum: Inferences from TEX$_{86}$ and isotope data

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ABSTRACT

Changes in sea surface temperature (SST) during the Paleocene-Eocene Thermal Maximum (PETM) have been estimated primarily from oxygen isotope and Mg/Ca records generated from deep-sea cores. Here we present a record of sea surface temperature change across the Paleocene-Eocene boundary for a nearshore, shallow marine section located on the eastern margin of North America. The SST record, as inferred from TEX$_{86}$ data, indicates a minimum of 8 °C of warming, with peak temperatures in excess of 33 °C. Similar SSTs are estimated from planktonic foraminifer oxygen isotope records, although the excursion is slightly larger. The slight offset in the oxygen isotope record may reflect on seasonally higher runoff and lower salinity.

Keywords: Paleocene, Eocene, isotopes, greenhouse.

INTRODUCTION

The Paleocene-Eocene Thermal Maximum (PETM) represents one of the more prominent and abrupt climate anomalies in Earth history with sea surface temperatures (SSTs) increasing by as much as 5 °C in the tropics and 8 °C in the high latitudes (Thomas et al., 2002; Zachos et al., 2003; Tripati and Eldredge, 2004). The peak warmth was sustained for several tens of thousands of years before gradually returning to pre-event levels. Several lines of evidence indicate that a rise in greenhouse carbon levels (CH$_4$ and/or CO$_2$) was responsible for this global warming (e.g., Dickens et al., 1997; Bowen et al., 2004). The approximate mass of carbon released is still unknown, but has been estimated to be in excess of 2000 GtC (Dickens et al., 1997), and possibly as high as 4500 GtC (Zachos et al., 2005).

If the rise in SST documented in open ocean sites was a consequence of greenhouse warming, the SST in coastal oceans should have risen by as much, if not more. Moreover, coastal oceans would have been particularly sensitive to changes in runoff, and hence precipitation, though the response would have been highly variable both spatially and temporally. Indeed, previous investigations of shallow marine sequences have found evidence of significant environmental perturbation of the coastal oceans during the PETM, including evidence of warming and changes in runoff (Bujak and Brinkhuis, 1998; Egger et al., 2003; Gibson et al., 1993). Much of the paleoclimatic information, however, has been derived from qualitative indexes such as fossil assemblages (Crouch et al., 2001, 2003), in part because traditional temperature proxies applied to deep-sea cores, such as oxygen isotopes, are not particularly well suited for application to shallow-marine, land-based sections. The general absence of planktonic foraminifera is one limitation. The effects of meteoric diagenesis, a process that can reset the primary oxygen isotopic composition of carbonates toward lower values, are another. Even where fossils are present and well preserved, deviations in local seawater salinity from the global mean increase the uncertainty in estimating temperature from δ$^{18}$O, a problem that would have been compounded with rapid greenhouse warming and changes in precipitation and runoff.

In this investigation, we estimate coastal SST during the PETM in a shallow marine sequence using an organic-based proxy of SST, TEX$_{86}$, which is derived from the membrane lipids of marine crenarchaeota, a common component of picoplankton (Schouten et al., 2002, 2003). Studies of core top sediments have demonstrated a strong correlation between the number of cyclopentane rings in crenarchaeota lipids and mean annual SST ($r^2$ = 0.92). Moreover, culture experiments show that changes in salinity and nutrients do not substantially affect the temperature signal recorded by TEX$_{86}$ (Wuchter et al., 2004), and it also seems to be unaffected by sedimentary redox conditions (Schouten et al., 2004). With the TEX$_{86}$-derived SST, we then use the oxygen isotopes to determine if this locality experienced substantial changes in salinity.

The section sampled for this study, Wilson Lake (Fig. 1), is located in New Jersey (39°39’N, 75°03’W) where the upper Paleocene–lower Eocene is accessible by coring. The Paleocene-Eocene boundary interval consists of unconsolidated siliciclastic sands and clays with low carbonate content (<15%) deposited during a sea-level transgression (Cramer et al., 1999; Gibson et al., 1993). Wilson Lake offers several advantages, one of which is high abundances of marine organic matter including dinoflagellates and cren-
The Wilson Lake foraminifera show distinct interspecies carbon isotope patterns not unlike those found in pelagic settings. For example, mixed-layer species, M. velascoensis and A. soldadoensis, yield the highest carbon isotope values, consistent with a near-surface habitat, while S. triangularis and benthic foraminifera yield the lowest carbon isotope values. The foraminiferal oxygen isotope values, on the other hand, exhibit weaker gradients, and in some intervals none at all.

The most prominent feature of the isotope records are large negative excursions in both carbon and oxygen isotopes across the Paleocene-Eocene boundary (110–109 m) (Fig. 3). The foraminifer δ13C values decrease by 3‰–4‰, while the δ18O values decrease by 2.0‰–2.5‰. Minimum δ13C values of −3.5‰ are recorded by the benthic foraminifera, and δ18O values of −4.3‰ by the mixed-layer planktonic foraminifera. These low δ13C values are sustained over a 13 m interval to the base of the lower unconformity at ~96 m. After the initial δ18O decrease in the mixed-layer foraminifer, the records deviate with the A. soldadoensis values increasing to levels similar or lower than the benthics, while the M. velascoensis values remain low (~−4.0‰).

The TEX86 index shows a sharp increase across the boundary that is essentially coincident with the decrease in foraminiferal ox-
Table DR1, suggesting relatively high temperatures. However, the modern calibration is based on empirical core top data from 20 to 28 °C as proposed by Schouten et al. (2003) for SST ranges from 4 °C in winter to 28 °C in summer. Nevertheless, based on GCM simulations, it appears a zonally averaged summer temperature of 33 °C for this paleolatitude (~35°–37°N at 55 Ma) would require a CO₂ concentration in excess of 2000 ppm (Shellito et al., 2003).

Modern calibration of TEX₉⁶ is limited to temperatures below 28 °C, making the estimates of absolute temperatures above this value somewhat suspect. Yet, the absolute temperatures computed here are well within the range estimated from oxygen isotopes. In fact, if we use δ¹³O_shell to estimate temperature assuming an ice-free world (mean ocean δ¹³O of −1.0‰e), but with a local δ¹³O_shell of −0.5‰e due to evaporation (Zachos et al., 1994), the planktonic foraminiferal temperatures derived for the earliest Eocene are essentially identical to the TEX₉⁶ temperatures, though the upper Paleocene temperatures are offset by 2 °C (Fig. 4). Alternatively, if we just consider the temperature anomaly interpreted from TEX₉⁶ values (+8 °C), we can estimate relative changes in δ¹³O_shell/salinity using the plankton-
ic foraminiferal oxygen isotope records. An 8 °C rise in temperature should lower δ18Oshell by ~1.7‰. The benthic and A. soldadoensis excursions were roughly ~1.85‰ and ~2.2‰, respectively, implying a possible δ18O of change of ~0.20‰ to ~0.50‰. The discrepancy could reflect a decrease in local surface salinity (S) and δ18Oshell due to higher runoff during the PETM. Assuming a Δδ18O/Δsalinity relationship of 0.15‰/ppt (Fairbanks, 1982), the ~0.50‰ residual (Δδ18Osw = Δδ18Oshell−Δδ18OTEX) would require a modest salinity decrease of roughly 3–4 ppt.

Is a shift toward higher regional runoff and precipitation supported by the other lithologic and paleontologic data? The clay-rich excursion layer is relatively thick and dominated by kaolinite, patterns that have been observed elsewhere and attributed to higher humidity and more intense chemical weathering and runoff (e.g., Gibson et al., 2000; Egger et al., 2003). The Apectodinium acme is also associated with higher temperatures and enhanced runoff, stratification, and eutrophic conditions in coastal waters (Bujak and Brinkhuis, 1998; Crouch et al., 2003; Egger et al., 2003). This genus is morphologically very similar to modern cysts almost exclusively produced by heterotrophic dinoflagellates and thus would have required nutrient-rich conditions (Bujak and Brinkhuis, 1998). Nanofossil assemblages also indicate increased fertility during the PETM at Wilson Lake (Gibbs et al., 2006). Increased discharge by rivers likely supplied the necessary nutrients to fertilize the coastal ocean. On the other hand, there is very little terrestrial organic matter in this core. One possibility is that regional climate in this region became more seasonally extreme during the PETM, with a brief, intense wet season and prolonged dry season. Under this climate regime, the local landscape would have been sparsely vegetated and thus prone to excessive erosion during the wet season, which would explain both the increased flux of terrigenous sediment and scarcity of terrestrial organic matter.

Although the absolute SST and SSS values estimated for this location could be viewed with some caution until the uncertainties in the TEX13-14 temperature calibration are reduced, the estimated peak temperature of 33 °C (Suvitch et al., 2004), the estimated peak temperature of 33 °C (Suvitch et al., 2004), the estimated peak temperature of 33 °C (Suvitch et al., 2004), the estimated peak temperature of 33 °C (Suvitch et al., 2004), the estimated peak temperature of 33 °C (Suvitch et al., 2004), the estimated peak temperature of 33 °C (Suvitch et al., 2004), the estimated peak temperature of 33 °C (Suvitch et al., 2004), the estimated peak temperature of 33 °C (Suvitch et al., 2004)