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Warming and environmental changes in the eastern North Sea Basin during the Palaeocene–Eocene Thermal Maximum as revealed by biomarker lipids

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ABSTRACT

Analysis of sediments deposited at different latitudes around the world during the Palaeocene–Eocene Thermal Maximum (PETM; ~56 Ma) have revealed a globally profound warming phase, regionally varying from 5–8 °C. Such records from Europe have not yet been obtained. We studied the variations in sea surface and continental mean annual air temperatures (SST and MAT, respectively) and the distribution patterns and stable carbon isotopes of higher plant derived *n*-alkanes in two proximal PETM sections (Fur and Store Bælt, Denmark) from the epicontinental North Sea Basin. A negative carbon isotope excursion (CIE) of 4–7‰ was recorded in land plant derived *n*-alkanes, similar to what has been observed for other PETM sections. However, differences observed between the two proximal sites suggest that local factors, such as regional vegetation and precipitation patterns, also influenced the CIE. The presence of S-bound isorenieratene derivatives at the onset of the PETM and increased organic carbon contents points to a rapid shift in depositional environment; from well oxygenated to anoxic and sulfidic. These euxinic conditions are comparable with those during the PETM in the Arctic Ocean. SSTs inferred from TEX_{86} show relatively low temperatures followed by an increase of ~7 °C across the PETM. At the Fur section, a remarkably similar temperature record was obtained for MAT using the MBT′/CBT proxy. However, the MAT record of the Store Bælt section did not reveal this warming.

1. Introduction

Climate conditions during the late Palaeocene and early Eocene were most likely the warmest of the Cenozoic Era (Zachos et al., 2001). Superimposed on the long term Late Palaeocene–Early Eocene warming trend are transient intervals with rapid warming and environmental changes. The Palaeocene–Eocene Thermal Maximum (PETM, ~56 Ma) is the largest event and has been documented in sediments all over the world. Besides a major temperature increase, the PETM is characterized by other environmental and climate changes, such as the extinction of ca. 50% of benthic foraminiferal species (Sluijs et al., 2007a and references cited therein), and a decrease in water column oxygen concentrations in deep oceans, coastal settings and isolated basins (e.g. Sluijs et al., 2006, 2014; Chun et al., 2010; Nicolo et al., 2010). It is further associated with a massive release of ^{13}C depleted carbon to the oceans and atmosphere as reflected by a negative carbon isotope excursion (CIE) of > 2.5‰ (e.g. Kennett and Stott, 1991; Schouten et al., 2007b; Sluijs et al., 2007a; McInerney and Wing, 2011).

Deep sea sediments have recorded a surface ocean warming of 4–8 °C (Fig. 1), based on the Mg/Ca ratio and $\delta^{18}O$ composition of planktonic foraminifera (Kennett and Stott, 1991; Thomas et al., 2002; Zachos et al., 2003; Tripati and Elderfield, 2005). Unfortunately, these records are often affected by redeposition of secondary calcite during early diagenesis (Schrag, 1999; Pearson et al., 2001) and carbonate dissolution due to the vertical progradation of the lysocline (Zachos et al., 2005; Zeebe and Zachos, 2007; Stap et al., 2009). Furthermore, the decrease in seawater pH, associated with the massive release of carbon to the oceans, may have increased $\delta^{18}O$ values causing a potential underestimation of PETM warming (Uchikawa and Zeebe, 2010).

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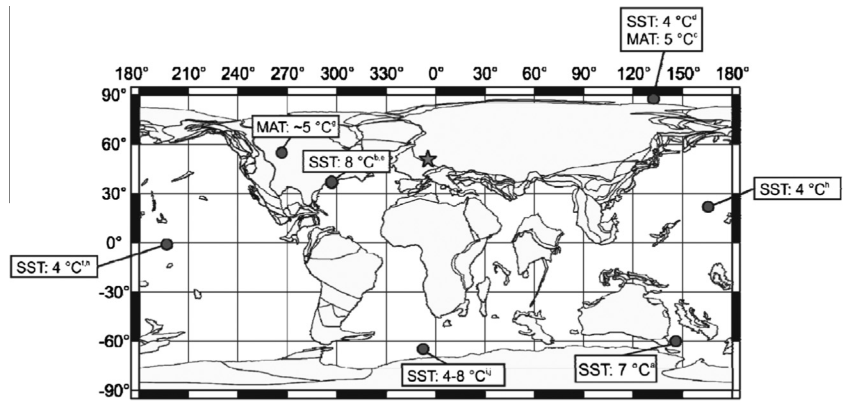

Fig. 1. Plate tectonic reconstruction of 55 Ma (www.odsn.de/odsn) and reconstructed warming during the PETM. The dots show locations where PETM SST and MAT warming have been reconstructed: [a]Hollis et al., 2012 (pTEX_{86}), [b]Sluijs et al., 2011 (TEX_{86}), [c]Sluijs et al., 2007b (TEX_{86}), [d]Peterse et al., 2012, recalculated from Weijers et al., 2007a (MBT/CBT), [e]Sluijs et al., 2006 (TEX_{86}), [f]Zachos et al., 2006 (TEX_{86}), [g]Tripati and Elderfield, 2005 (Mg/Ca and $\delta^{18}O$ of planktonic foraminifera), [h]Wing et al., 2005 (leaf margin analysis), [i]Zachos et al., 2003 (Mg/Ca and $\delta^{18}O$ of planktonic foraminifera), [j]Thomas et al., 2002 ($\delta^{18}O$ of planktonic foraminifera), [k]Kennett and Stott, 1991 ($\delta^{18}O$ of planktonic foraminifera). The star indicates the location of this study.

The distribution of archaeal and bacterial glycerol dialkyl glycerol tetraethers (GDGTs) can also be used to infer sea surface temperature (SST), using the TEX_{86} proxy (Schouten et al., 2002), and mean annual air temperature (MAT), using the MBT/CBT proxy (Weijers et al., 2007b; Peterse et al., 2012). So far, TEX_{86} palaeothermometry has been applied to a limited number of PETM sections (Sluijs et al., 2006, 2007b, 2011, 2014; Zachos et al., 2006; Hollis et al., 2012) covering only a few locations worldwide, whereas a PETM MAT record based on the MBT/CBT proxy is available only for a single site located in the Arctic Ocean (Weijers et al., 2007a). The temperature records based on TEX_{86} show a similar extent of warming as those recorded by Mg/Ca and $\delta^{18}O$ of foraminifera, i.e. 5–8 °C (Fig. 1). Arctic continental air temperatures inferred from MBT/CBT values increased by about 6 °C (Fig. 1; Weijers et al., 2007a). Temperature records of the New Jersey continental margin, as well as of southern high latitudes, show a somewhat larger warming than most other temperature records (Fig. 1). However, global coverage of the existing PETM temperature records is still relatively poor, limiting the understanding of the underlying mechanisms of heat transport that drive greenhouse climates, such as during the PETM (cf. Huber and Caballero, 2011). In addition, most records are based on a single location which prohibits an assessment of local variability compared to imposed global changes. Recently, Caballero and Huber (2013) were able to model the high Eocene temperatures, but with some significant regional data model discrepancies, emphasizing the importance of improving regional temperature proxy coverage.

In the eastern North Sea Basin, the PETM was previously identified by dinoflagellate stratigraphy and a 6–8‰ CIE in organic carbon (Heilmann-Clausen and Schmitz, 2000; Schmitz et al., 2004). Due to the close proximity to coastal areas it is likely that the sedimentary organic carbon contains large amounts of terrigenous organic matter, which may have a different stable carbon isotopic composition than marine organic matter (Bowen et al., 2004; Schouten et al., 2007b; Smith et al., 2007; Sluijs and Dickens, 2012). The relatively large CIE in organic carbon, compared to that in foraminiferal calcite (Dickens, 2011, and references cited therein) may, therefore, be attributed to variations in the ratio of terrigenous to marine organic carbon (cf. Sluijs and Dickens, 2012). On the other hand, such a large CIE is also observed in land plant derived *n*-alkanes at different PETM sites around the world (e.g. Pagani et al., 2006; Schouten et al., 2007b; Handley et al., 2008), and has led to the suggestion that the atmospheric CIE may have been larger than the generally accepted 2–3‰ recorded

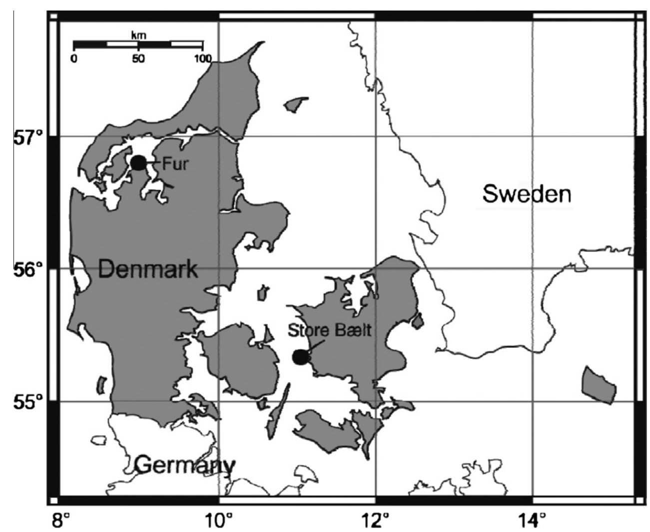

Fig. 2. Map of Denmark showing the location of the two study sites at Fur Island and Store Bælt.

by marine calcite (Pagani et al., 2006; Handley et al., 2008, 2011; Diefendorf et al., 2010).

In this study, we present new organic geochemistry records from two nearby PETM sections in Denmark, situated in the eastern part of the North Sea Basin at the time of deposition (Fig. 2). We analyzed the distribution of GDGTs to determine TEX_{86} derived sea water and MBT/CBT derived continental air temperatures thereby providing, to the best of our knowledge, the first European temperature records across the PETM. The aim of our study is to gain insight into the regional climate response of the carbon cycle perturbations during the PETM at this latitude, contributing to an improved geographic coverage of temperature proxy data for the Late Palaeocene–Early Eocene greenhouse climate. In addition, we analyzed the distribution and stable carbon isotopic composition of higher plant biomarkers to constrain the terrigenous CIE.

2. Site descriptions and depositional setting

In this study, we used sediments from two sections in Denmark covering the Palaeocene–Eocene transition (Figs. 1 and 2). The study area is situated in the Norwegian-Danish Basin, a sub-basin