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Mid-latitude continental temperatures through the early Eocene in western Europe

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A B S T R A C T

Branched glycerol dialkyl glycerol tetraethers (brGDGTs) are increasingly used to reconstruct mean annual air temperature (MAAT) during the early Paleogene. However, the application of this proxy in coal deposits is limited and brGDGTs have only been detected in immature coals (i.e. lignites). Using samples recovered from Schöningen, Germany (∼48°N palaeolatitude), we provide the first detailed study into the occurrence and distribution of brGDGTs through a sequence of early Eocene lignites and associated interbeds. BrGDGTs are abundant and present in every sample. In comparison to modern studies, changes in vegetation type do not appear to significantly impact brGDGT distributions; however, there are subtle differences between lignites – representing peat-forming environments – and siliciclastic nearshore marine interbed depositional environments. Using the most recent brGDGT temperature calibration (MAT_{mr}) developed for soils, we generate the first continental temperature record from central-western continental Europe through the early Eocene. Lignite-derived MAAT estimates range from 23 to 26 °C while those derived from the nearshore marine interbeds exceed 20 °C. These estimates are consistent with other mid-latitude environments and model simulations, indicating enhanced mid-latitude, early Eocene warmth. In the basal part of the section studied, warming is recorded in both the lignites (∼2 °C) and nearshore marine interbeds (∼2–3 °C). This culminates in a long-term temperature maximum, likely including the Early Eocene Climatic Optimum (EECO). Although this long-term warming trend is relatively well established in the marine realm, it has rarely been shown in terrestrial settings. Using a suite of model simulations we show that the magnitude of warming at Schöningen is broadly consistent with a doubling of CO_2, in agreement with late Paleocene and early Eocene pCO_2 estimates.

1. Introduction

Gradual surface ocean warming during the late Paleocene and early Eocene (Hollis et al., 2012; Frieling et al., 2014) culminated in the Early Eocene Climatic Optimum (EECO; 53–51 Ma), a long-term global temperature maximum associated with high atmospheric carbon dioxide concentrations (pCO_2) (Anagnostou et al., 2016) and the absence of large continental ice sheets (Zachos et al., 2001). During the EECO, TEX_{86}-based mid-to-high latitude sea surface temperature (SST) estimates exceed 25 °C, resulting in a reduced latitudinal SST gradient (Hollis et al., 2012; Bijl et al., 2013; Frieling et al., 2014; Inglis et al., 2015b). However, these climate conditions have proven difficult to reconcile with modelling simulations (Lunt et al., 2012), although recent progress has been made (Sagoo et al., 2013). As the terrestrial heat budget is more easily characterised in model simulations than the ocean heat budget (Huber and Caballero, 2011), workers have cited the need for additional terrestrial temperature records spanning the early Eocene (e.g. Huber and Caballero, 2011).

Palaeobotanical techniques, such as CLAMP (Climate-Leaf Analysis Multivariate Program), LMA (Leaf Margin Analysis) and CA (Coexistence Approach), have previously shown that mid-to-high lati-

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tude mean annual temperature estimates (MAT) were warmer than modern during the early Paleogene (Greenwood and Wing, 1995; Wilf, 2000; Greenwood et al., 2005; Eberle et al., 2010). However, most of these studies are restricted to a few, well-sampled regions (e.g. western North America) and provide only a 'snapshot' of climate (Fricke and Wing, 2004; Greenwood et al., 2005). As a result, the spatial and temporal evolution of terrestrial temperature change during the early Eocene remains poorly constrained. For example, there is currently no terrestrial temperature estimate for the early Eocene in Europe.

The MBT'/CBT proxy (methylation of branched tetraethers/cyclisation of branched tetraethers; Weijers et al., 2007; Peterse et al., 2012) can also provide long-term, quantitative temperature records and is increasingly used to reconstruct terrestrial temperature during the early Paleogene (Pross et al., 2012; Pancost et al., 2013). The proxy is based upon the distribution of bacterial, soil-derived branched glycerol dialkyl glycerol tetrathers (brGDGTs), where the degree of methylation, expressed as the MBT' ratio (methylation of branched tetraethers), is related to MAT and pH, and the number of cyclopentane rings, expressed as the CBT ratio (cyclisation of branched tetraethers), is related to soil pH (Weijers et al., 2007; Peterse et al., 2012). A new set of brGDGT isomers (6-methyl brGDGTs) have recently been identified and have enabled the development of more accurate pH and MAT calibrations (De Jonge et al., 2014a, 2014b). Although these new indices have not been applied in deep time investigations, previous iterations have been used to reconstruct terrestrial climate during the Quaternary (e.g. Sinninghe Damsté et al., 2012) and Paleogene (e.g. Pancost et al., 2013).

BrGDGTs are abundant in soils and peats; however, they are also transported via rivers and deposited in shallow continental shelves (Zell et al., 2014). As such, marginal marine sediments have been used to generate long-term continental temperature records during the geological record, especially during the early Palaeogene (e.g. Pross et al., 2012; Bijl et al., 2013; Pancost et al., 2013). However, recent work has highlighted challenges in its interpretation arising from uncertainty in the brGDGTs origin, with possible sources including *in-situ* production in the marine realm (Weijers et al., 2014), in rivers (Zell et al., 2014), in lakes (Weber et al., 2015) and in soils from the surrounding catchment (Bendle et al., 2010). Peats and lignites, in contrast, largely record *in-situ* environmental conditions and could provide unique new insights into terrestrial climate change.

However, the application of the brGDGT palaeothermometer in peat – and by extension lignite – can be complicated by additional effects on the brGDGT distribution (Weijers et al., 2011; Zheng et al., 2015). In modern settings, factors other than temperature and pH appear to influence brGDGT distributions (Weijers et al., 2011) and pH estimates are substantially higher than expected (Weijers et al., 2011), although these studies pre-date the recent advances in analytical techniques that allow for the separation of 5- and 6-methyl brGDGTs and do not utilise the most recent latest calibrations (De Jonge et al., 2014a, 2014b). Weijers et al. (2011) reported brGDGTs in one lignite sample from the late Palaeocene, but a more detailed and systematic study of branched GDGTs in lignites is lacking.

Here we examine brGDGT distributions in a series of thermally immature lignite seams from Germany inferred to represent ancient ombrotrophic bog deposits (Riegel et al., 2012; Inglis et al., 2015a). Sediments were recovered from Schöningen, central Germany (∼48°N palaeolatitude) and were deposited through the early Eocene (Riegel et al., 2012; Robson et al., 2015). We investigate the distribution of brGDGTs within these ancient peat-forming environments and assess the impact of vegetation upon brGDGT distributions. We then provide the first terrestrial temperature record from central-western continental Europe through

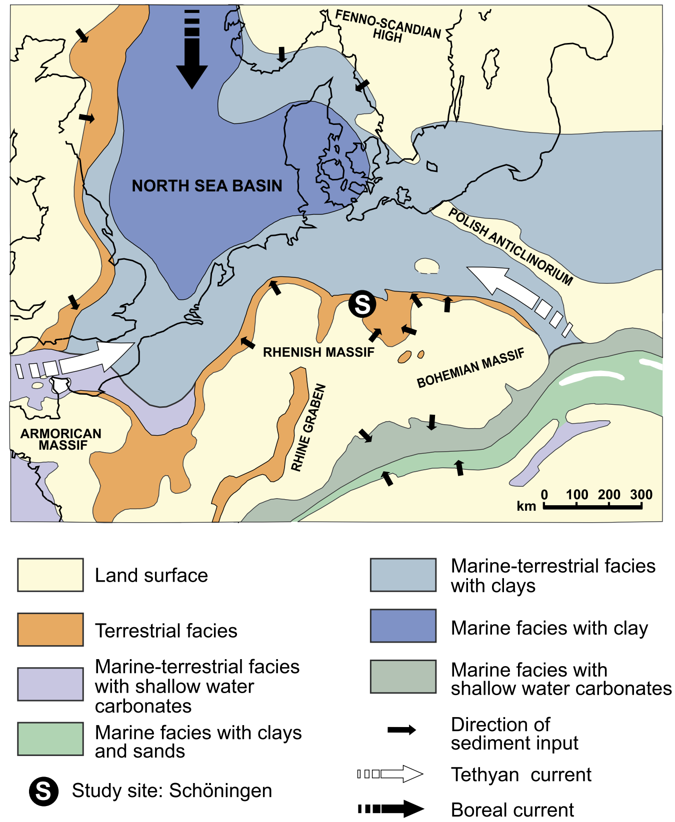

Fig. 1. Paleogeography of NW Europe during the early Eocene showing the location of Schöningen (modified from Riegel et al., 2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the early Eocene and compare this with other terrestrial climate records as well as a range of climate model simulations. In order to investigate the most likely driving mechanism of early Paleogene climate change, we also compare our results with climate model simulations spanning multiple CO_2 concentrations.

2. Methods

2.1. Site description

2.1.1. Schöningen Südfeld mine

Samples were collected from the Schöningen Südfeld mine (52.1333°N, 10.9500°E) in northern Germany, NW Europe (Fig. 1). Sediments were deposited in a low lying coastal setting at the southern shore of the North Sea (∼48°N palaeolatitude) (Riegel et al., 2012). The Schöningen Formation comprises 10 lignite seams, from the Main Seam to the base of Seam 9, with intercalated nearshore shallow marine deposits. Dinocyst zone D5b (∼55–56 Ma) was previously recognised above Main Seam in the nearby Emmerstedt area (Ahrendt et al., 1995). If Main Seam is coeval at both Schöningen and Emmerstedt, this would indicate that Seam 1 at Schöningen is earliest Eocene and that the Paleocene–Eocene boundary would be within Main Seam or below. However, within Interbed 2, above Seam 1, there is a dramatic increase in the abundance of the dinocyst *Apectodinium* (Riegel et al., 2012) which may represent the onset of the Paleocene–Eocene Thermal Maximum (PETM) as it does at other sites. As such, this would indicate that both Main Seam and Seam 1 are latest Paleocene. Based upon these observations, Main Seam and Seam 1 could be either latest Paleocene or earliest Eocene.

Two lines of evidence tentatively place Seam 4 and/or Seam 5 within or near to the EECO. Firstly, within Seam 4 there is a