Earth and Planetary Science Letters 353–354 (2012) 108–120

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Marine and terrestrial environmental changes in NW Europe preceding carbon release at the Paleocene–Eocene transition

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A R T I C L E   I N F O

Article history:
Received 27 March 2012
Received in revised form
25 July 2012
Accepted 10 August 2012
Editor: J. Lynch-Stieglitz
Available online 7 September 2012

Keywords:
Paleocene–Eocene boundary
PETM
carbon isotope excursion
paleoecology
paleoceanography
North Sea

A B S T R A C T

Environmental changes associated with the Paleocene–Eocene thermal maximum (PETM, ~56 Ma) have not yet been documented in detail from the North Sea Basin. Located within proximity to the North Atlantic igneous province (NAIP), the Kilda Basin, and the northern rain belt (paleolatitude 54 °N) during the PETM, this is a critical region for testing proposed triggers of atmospheric carbon release that may have caused the global negative carbon isotope excursion (CIE) in marine and terrestrial environments. The CIE onset is identified from organic matter $\delta^{13}C$ in exceptional detail within a highly expanded sedimentary sequence. Pollen and spore assemblages analysed in the same samples for the first time allow a reconstruction of possible changes to vegetation on the surrounding landmass. Multiproxy palynological, geochemical, and sedimentologic records demonstrate enhanced halocline stratification and terrigenous deposition well before (10^3 yrs) the CIE, interpreted as due to either tectonic uplift possibly from a nearby magmatic intrusion, or increased precipitation and fluvial runoff possibly from an enhanced hydrologic cycle. Stratification and terrigenous deposition increased further at the onset and within the earliest CIE which, coupled with evidence for sea level rise, may be interpreted as resulting from an increase in precipitation over NW Europe consistent with an enhanced hydrologic cycle in response to global warming during the PETM. Palynological evidence indicates a flora dominated by pollen from coastal swamp conifers before the CIE was abruptly replaced with a more diverse assemblage of generalist species including pollen similar to modern alder, fern, and fungal spores. This may have resulted from flooding of coastal areas due to relative sea level rise, and/or ecologic changes forced by climate. A shift towards more diverse angiosperm and pteridophyte vegetation within the early CIE, including pollen similar to modern hickory, documents a long term change to regional vegetation.

1. Introduction

The PETM was a period of geologically-rapid global warming that punctuated a warming Eocene climate 55.8 Ma ago (Charles et al., 2011), and saw sea surface temperatures rise by 5–8 °C from background levels (Zachos et al., 2005; Sluijs et al., 2007). It was associated with a substantial injection of $\delta^{13}C$-depleted carbon into the ocean-atmosphere system (see Pagani et al., 2006a) over <20 ka (Cui et al., 2011), causing a negative carbon isotope excursion (CIE) between −2 and −7‰ in marine and terrestrial sediments (see overview in Schouten et al., 2007) lasting 170 ka (Röhl et al., 2007), and a prominent dissolution horizon in the deep sea signifying deep ocean acidification (Kennett and Stott 1991; Zachos et al., 2005). The source and rate of released carbon are still under debate (Pagani et al., 2006a; Zeebe et al., 2009; Cui et al., 2011), but may have been linked to the dissociation of marine hydrates containing biogenic methane ($\delta^{13}C$ of <-60‰) (Dickens et al., 1995), thermogenic methane from marine sediments around the Norwegian Sea (Svensen et al., 2004), or dissolved methane from a silled Kilda Basin between Greenland and Norway (Nisbet et al., 2009).

The PETM may be a good analogue to test modelling studies that suggest current global warming trends may result in an enhanced hydrologic cycle (Seager et al., 2010), whereby increased precipitation in temperate rain belts is coupled with increased evaporation in lower latitudes. Modelling studies of the

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http://dx.doi.org/10.1016/j.epsl.2012.08.011

PETM have further indicated the potential importance of an increased hydrologic cycle (Lunt et al., 2010; Bice and Marotzke 2002), which could have altered ocean circulation causing methane hydrate reservoirs to destabilise, triggering massive carbon release (Bice and Marotzke, 2002). Palynological evidence from Arctic Spitsbergen (Harding et al., 2011) and New Zealand (Crouch et al., 2003a) suggests increased terrestrial runoff occurred at the onset of the CIE which may be related to hydrologic changes, and massive Pyrenees conglomerate deposits have been interpreted as the result of an abrupt increase in extreme precipitation within the early CIE (Schmitz and Pujalte, 2007). In addition, hydrogen and carbon isotope measurements of terrestrial plant and aquatic-derived *n*-alkanes from the central Arctic Ocean indicate that the core of the PETM was associated with increased precipitation and hence hydrologic cycle (Pagani et al., 2006b), although the onset of PETM warming was not recovered in the sediment core. Despite numerous additional evidence for changes in terrestrial runoff and potentially hydrology during the PETM (see overview in McInterney and Wing, 2011), there is a lack of clear evidence for hydrologic changes from high resolution sections able to resolve important lead/lag relationships, and therefore there remains a need for studies of hydrologic changes in sensitive locations over the onset of the CIE in order to understand the relationship between precipitation and global carbon release.

Biome changes in response to modern global warming have been observed, but approaches to predict the vulnerability of ecosystems to future changes are still in development (Gonzalez et al., 2010). Vegetation shifts during the rapid warming associated with the PETM may provide a useful analogue to future biome responses. Whilst neotropical vegetation in Central America appears to have responded to warming during the PETM with increased diversity and origination rates (Jaramillo et al., 2010), central North America experienced a rapid migration of plant communities associated with lower precipitation at the onset of the CIE (Wing et al., 2005), and southern England may have experienced a major change in plant composition due to changes in local fire-regime (Collinson et al., 2009). To better understand biome responses to climatic change during the PETM, further high resolution vegetation cover studies are needed, specifically from temperate and boreal forests which may be amongst the most vulnerable ecosystems to global warming (Gonzalez et al., 2010).

In this study we focus on paleoenvironmental signals from a high resolution marine core collected from the central North Sea (Fig. 1), in order to understand changes to precipitation, ocean stratification, productivity and vegetation over the onset of the PETM. This core is located in a critical region proximal to the NAIP, as there are currently no high resolution records of environmental change during the PETM from the North Sea Basin. Furthermore, as overturning of a stratified Kilda Basin at the CIE onset is hypothesised as a possible trigger for dissolved methane release to the atmosphere (Nisbet et al., 2009), analysing the stratification history of the nearby North Sea is a possible way to test this hypothesis.

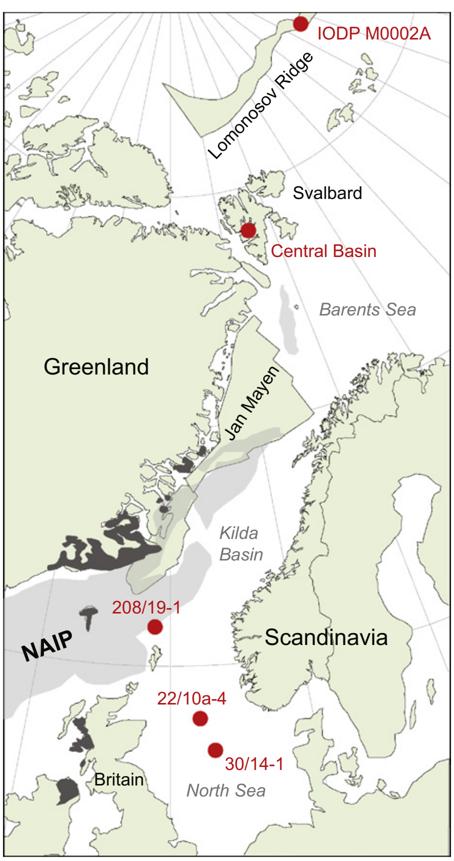

Fig. 1. Paleogeographic reconstruction of the continents at 54 Ma (Mosar and Torsvik, 2002), showing the location of core 22/10a-4 (this study), 30/14-1 (Sluijs et al., 2007), 208/19-1 (Mudge and Bujak, 2001), Spitsbergen Central Basin (Harding et al., 2011) and M0002A (Pagani et al., 2006b). Grey shading indicates regions of volcanism affected by the North Atlantic igneous province (NAIP).

2. Regional setting

During the late Paleocene–early Eocene the North Sea was a restricted marine basin, characterised by siliciclastic sedimentation and high terrigenous input, principally from the Scotland–Faeroe–Shetland landmass (Knox 1998, Fig. S1). Core 22/10a-4 is located in the central part of the basin (Figs. 1 and S1) and is therefore disconnected from many marginal marine processes that could mask oceanographic signals (e.g. tidal or storm-induced erosion and slumping). Paleobathymetry estimates in the North Sea during the Paleocene and Eocene are difficult to constrain accurately, as the extant benthic foraminifera present in the Paleogene are found today living between 200 and >1000 m water depth (Gradstein et al., 1992), and are controlled predominantly by substrate and bottom water properties. However using a number of paleoecologic micropaleontology methods together (Gillmore et al., 2001), along with 2D structural restoration (Kjennerud and Sylta, 2001), broad agreement was found and central parts of the northern North Sea appear to have had paleodepths of >0.5 km in the earliest Eocene near 22/10a-4 (Kjennerud and Gillmore, 2003, Fig. S1).

As 22/10a-4 is in the deep (>0.5 km) central part of the basin, it acted as a depocentre and exhibits a Paleocene-Eocene transition sequence that is not only expanded but is also close to being stratigraphically complete. The only evidence for breaks in the succession is minor erosion at the base of thin turbidite sandstones (typically <10 cm). Because these sandstones may contain reworked material, they were not sampled in this study. During the late Paleocene, the basin became restricted following a fall in in the order of 100 m that resulted from regional uplift associated with the proto-Iceland mantle plume in the North Atlantic (see Knox, 1996). This event is evident in 22/10a-4 as a lithologic change from unbedded to bedded mudstone (the Lista and Sele Formation boundary, Fig. 2). Restriction of the basin also led to the establishment of poorly oxygenated bottom waters, as is evident by a shift in the benthic foraminiferal assemblages towards low diversity low oxygen-tolerant agglutinated species (Knox, 1996). The CIE at the Paleocene–Eocene boundary was accompanied by a relative sea level rise, as documented in