Proceedings of the Geologists' Association 134 (2023) 517–525

Contents lists available at ScienceDirect

Proceedings of the Geologists' Association

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

Terrestrial carbon isotope stratigraphy of the Eocene–Oligocene transition, Petrockstowe and Bovey basins, Devon, UK

Mohammed S. Chaanda [a], Stephen T. Grimes [a], Rhodri M. Jerrett [b], Mark Anderson [a], Melanie J. Leng [c], Meriel E. Fitzpatrick [a], Gregory D. Price [a,*]

[a] School of Geography, Earth and Environmental Sciences, Plymouth University, Drake Circus, Plymouth PL4 8AA, UK
[b] Department of Earth and Environmental Sciences, University of Manchester, Oxford Road, Manchester M13 9PL, UK
[c] British Geological Survey, Keyworth, Nottingham NG12 5GG, UK

ARTICLE INFO

Article history:
Received 25 October 2022
Received in revised form 19 May 2023
Accepted 26 May 2023
Available online 9 June 2023

Keywords:
Eocene–Oligocene Petrockstowe Bovey terrestrial carbon isotope
Palynological analyses

ABSTRACT

The terrestrial sediments of the Petrockstowe and Bovey basins in Devon, UK were examined. Their age is considered to be Eocene and Oligocene. The sediments (kaolinitic clays, silts, sands, gravels, and lignites) from both basins were analysed for carbon isotopes of organic material, in conjunction with total organic carbon and palynological analyses used to unravel the type of and provenance of organic matter present. Within the Petrockstowe Basin, the lowermost interval examined shows a palynological distribution dominated by phytoclasts, whilst the upper part of the core is dominated by higher concentrations of palynomorphs (up to 90 %) and an increase in amorphous organic matter consistent (up to 37 %) with a change from sand-filled fluvial channels followed by an ephemeral lake or lake margin setting. Our palynological data from the South John Acres Lane Quarry section, Bovey Basin, show that within the lignites palynomorphs are high again (up to 95 %) consistent with them representing more ephemeral lakes or lake margins periodically exposed with mires. Our palynological data set further allows us to determine that isotope trends are not overly determined by the source of carbon in the basins. Our study suggests that the observed patterns were primarily produced by variations of the isotope ratios of terrestrial atmospheric carbon reservoirs. Even with our less than well constrained biostratigraphical control, the data indicate that the carbon isotope excursions seen in the Eocene and Oligocene could be associated with several transient carbon isotopic shifts (associated with the Paleocene–Eocene Thermal Maximum). Our findings therefore appear to lend support to the surface ocean and atmosphere behaving as coupled reservoirs at this time.
© 2023 The Geologists' Association. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

The terrestrial sediments of the Petrockstowe and Bovey basins in Devon, UK offer an opportunity to examine the carbon cycle during the Eocene–Oligocene transition (~33.9 million years ago), an interval, that saw a climate shift from a largely ice-free greenhouse conditions to an icehouse world (Miller et al., 2009; Coxall and Wilson, 2011; Hutchinson et al., 2021). At this time major changes in fauna and flora record a shift toward more cold-climate-adapted species (*e.g.*, Sun et al., 2014). For this pivotal interval in Earth's climate, our understanding of the role of the carbon cycle, is much more limited (Coxall and Wilson, 2011; Armstrong McKay et al., 2016). Across the Eocene–Oligocene boundary a positive carbon isotope (δ^{13}C) excursion of ~1.0 ‰ is typically recorded in the marine record followed by a decline to pre-excursion values (~0.7 ‰) in the Oligocene (*e.g.*, Nilsen et al., 2003; Armstrong McKay et al., 2016). This well-documented perturbation may be used to correlate marine and terrestrial sections from around the globe as previous studies have shown that δ^{13}C obtained from terrestrial organic material such as wood and lignites typically records a global signal (*e.g.*, Heimhofer et al., 2003; Collinson et al., 2003; Gröcke et al., 2005; Bechtel et al., 2008; Hodgson et al., 2011; Jerrett et al., 2015; Lenz et al., 2022).

The Petrockstowe and Bovey basins lie on the Sticklepath–Lustleigh Fault and owe their origin to subsidence within this zone (Blyth, 1962; Dearman, 1963). About 600 m of Eocene–Oligocene sediments are present in the Petrockstowe Basin (Freshney et al., 1979) and ~1200 m in the Bovey Basin (Edwards, 1976). In this study, we present new organic δ^{13}C data from terrestrial Eocene–Oligocene aged sediments from these basins. Our data is used to improve age constraints on the succession *via* comparison of our terrestrial δ^{13}C record with that of the extensively described time-equivalent marine sections. The similarity and magnitude of the δ^{13}C excursions between terrestrial and marine records can also be used to assess whether these archives behaved as coupled reservoirs during this time.

* Corresponding author.
E-mail address: g.price@plymouth.ac.uk (G.D. Price).

https://doi.org/10.1016/j.pgeola.2023.05.003
0016-7878/© 2023 The Geologists' Association. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

2. Location and geological setting

The Petrockstowe Basin, nr Newton Abbott, Devon, UK (Fig. 1), lies on the Sticklepath–Lustleigh Fault (Dearman, 1963; Holloway and Chadwick, 1986). The fault became active during the Paleogene and most activity ceased before deposition of the upper part of the Bovey Formation (Blyth, 1962). Bristow and Robson (1994) proposed a structural model for the development of the basin – a pull–push model – and suggested that the development was in two phases: an early, transitional phase, during which much of the sedimentation occurred, and a subsequent transpressional phase in which boundary thrust faults developed. Geophysical measurements, confirmed by a British Geological Survey (BGS) borehole from the centre of the basin proved a basin fill of 660 m of sands and silts (Freshney et al., 1979). The sediments, kaolinitic clays, silts, sands, gravels, and lignite, were likely to have been derived from weathering granite under warm temperate or sub-tropical conditions of the early Paleogene (Bristow, 1968; Edwards, 1976). The succession consists of fining-upwards cycles comprising of one or more of a gravel lag, gravelly sands, and silty sands, and is probably representative of point bar and swale-fill deposits of a river system. These interstratify with clays and silts of lacustrine origin (Freshney, 1970; Freshney et al., 1979). Based on palynological evidence, Turner (cited by Freshney et al., 1979) suggested these were deposited in a subtropical climate with palms, ferns and heathers and many plants with swamp affinities.

The Bovey Basin is located between Newton Abbot, Kingsteignton and Bovey Tracey, Devon UK (Fig. 2) and is 45 km southeast of the Petrockstowe Basin. The Bovey Basin lies southeast of the Dartmoor granite and is approximately 7 km from east to west and 5 km from north to south. In the northern and eastern boundaries of the basin there are sedimentary contacts between the Dartmoor granite and the Upper Greensand and Aller Gravel. The bulk of the basin is filled by a thick (~1200 m) succession of Paleogene kaolinitic clays, silty clays, silts, lignites and sands, referred to as the Bovey Formation (Edwards, 1976). Edwards (1976) proposed a morphological sub-division of the basin into two parts, lying to the north and to the south of Newton Abbot. The part between Bovey Tracey and Newton Abbot is considered as the main basin; the second part lies south of Newton Abbot and is referred to as Decoy Basin (Fig. 2). Edwards and Freshney (1982) proposed an informal sub-division of the Bovey Formation into 'lower', 'middle' and 'upper'. The 'lower' is not exposed and the 'middle' and 'upper' Bovey Formation includes 14 members, some of uncertain stratigraphical position or lateral equivalents and are described in detail by Edwards and Freshney (1982) and Selwood et al. (1984). Of the top 350 exposed at the surface (Edwards, 1976), 48 m of the Abbrook Clay and Sand and Southacre Clay and Lignite members of the 'middle' Bovey Formation were examined in the exposed working section at the South John Acre Lane Quarry. Chandler (1957) and Edwards (1976), suggest that during the Oligocene the lignites accumulated in swamps with associated fluvial sands and plant debris swept in from a warm hinterland into a lake basin lying on Paleozoic strata (see also Selwood et al., 1984). The lake was surrounded by marshland tree covered slopes (Chandler, 1957).

3. Age of the Petrockstowe and Bovey basins

The age of the Bovey lignites has for a long time been debated (Chandler, 1964). Based upon the macroflora in the lignite beds of the Bovey Formation, these were originally regarded as Miocene, but later assigned to the Oligocene (Chandler, 1957, 1964). Likewise, Wilkinson (1979) cited by Selwood et al. (1984) noted that pollen from a borehole, near Heathfield penetrated 185 m of Blatchford Sand (upper Bovey Formation), 69 m of South Acre Clay and Lignite and 51 m of Abbrook Clay and Sand and from below 290 m depth, Eocene indicators like *Anacolosidites* and *Pompeckjoidaepollenites* were observed (Fig. 3). It is also important to note that the Blatchford Sand is an obsolete unit name and has been replaced by the Woolley Grit Member. The South Acre Clay and Lignite Member is therefore likely to be early to middle Oligocene in age (Selwood et al., 1984) and the Abbrook Clay and Sand Member would contain the Eocene–Oligocene boundary. Freshney et al. (1982) also suggested that the lowermost ~700–800 m of the Bovey Formation could probably be assigned to Eocene (see also Wilkinson et al., 1980; Wilkinson and Boulter, 1981). For the Petrockstowe Basin, Turner (cited by Freshney et al., 1979) reported that pollen data indicate a boundary between the Oligocene and Eocene at ~120 m depth in BGS Borehole No. 1 (Fig. 3).

4. Methods

From Petrockstowe 2 borehole cores (Petrockstowe 1A and 1B) held in the core repository at the BGS, Keyworth, Nottingham, UK were logged, and sub sampled. The sampled section was 640 m long, and

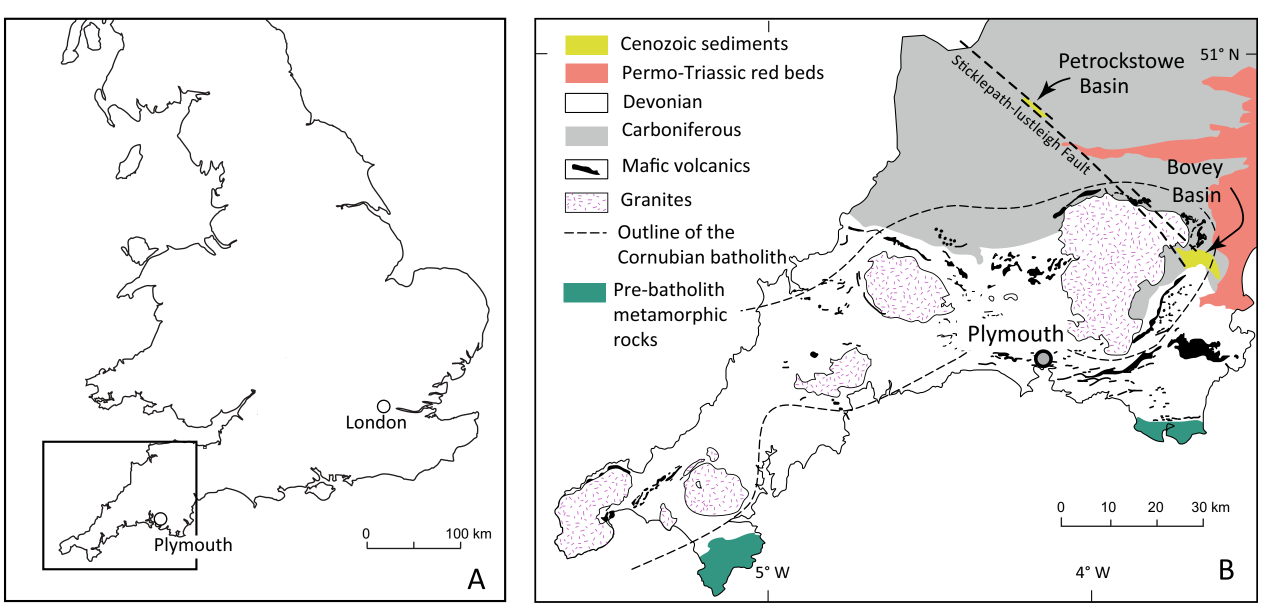

Fig. 1. A. Map showing the southern part of the UK and location of inset. B. General geological map of the southwest UK showing Petrockstowe and Bovey basins. (Modified from Bristow and Robson (1994).)

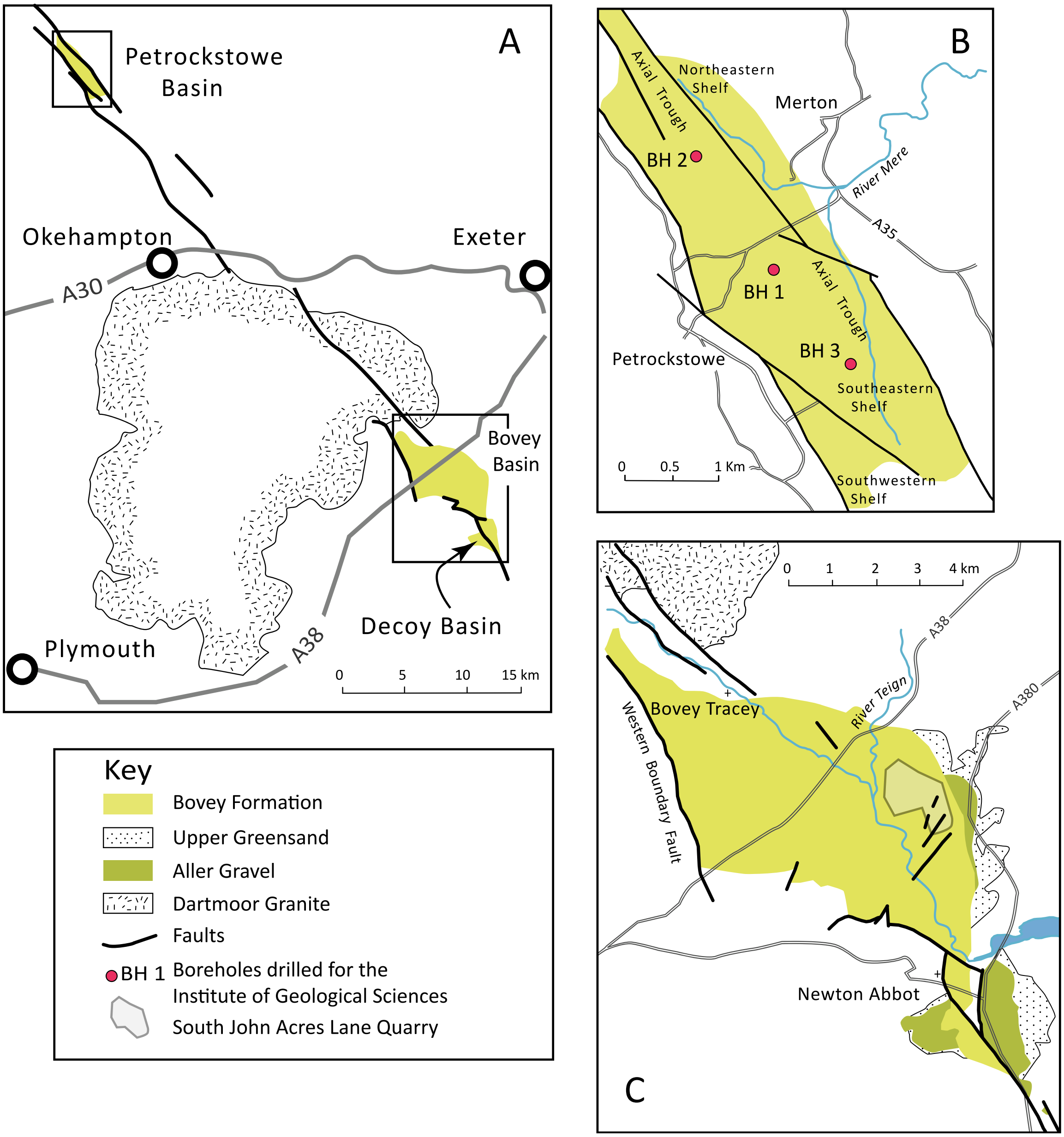

Fig. 2. A. Map showing the location of Petrockstowe and Bovey basins (modified from Bristow and Robson, 1994). B. Geological map of the Petrockstowe Basin showing the location of Borehole 1 (cores 1A and 1B) and the relative positions of the axial trough and the marginal shelves with their dividing fault (modified from Freshney, 1970; Freshney et al., 1979). C. Geological map of the Bovey Basin showing the location of the South John Acres Lane Quarry (modified from Selwood et al., 1984).

samples were collected, on average, every 6 m. Within the region of the Eocene Oligocene boundary as proposed by Turner (cited by Freshney et al., 1979), as well as the early Eocene of Core 1B higher resolution sampling was undertaken. In the Bovey Basin, the Abbrook Clay and Sand and Southacre Clay and Lignite members of the Bovey Formation from the accessible exposed working section at South John Acre Lane Quarry (Grid Reference SX 858758) were sampled. The sampled section was 48 m and samples were collected, on average, every 0.6 m. It was necessary to excavate the sediment surface by up to 0.5 m before sampling with a trowel to ensure fresh samples. All sediment types were sampled.

For the determination of the carbon isotope composition of total organic carbon ($\delta^{13}C_{TOC}$), samples were ground to a fine powder using an agate pestle and mortar. Powdered samples were decarbonated by placing each sample in a 50 ml polypropylene centrifuge tube and treating with 10 % HCl for 1 h until any carbonate had reacted. Samples were then rinsed with deionised water, centrifuged, and rinsed again until neutrality was reached (using universal indicator paper). For $\delta^{13}C_{TOC}$ analysis, samples were weighed, to achieve ~0.5 mg TOC, into a tin capsule and placed into a Carlo Erba 1500 EA for analysis using an online VG Triple Trap Mass Spectrometer. The $\delta^{13}C_{TOC}$ results were calibrated against Vienna PeeDee Belemnite (V-PDB) through laboratory (BROC1) and International Standards (NBS19, NBS22, CH6). Standards were evenly distributed throughout the individual isotope runs to correct for daily drift. The mean standard deviation on replicate $\delta^{13}C_{TOC}$ analyses of laboratory standard (BROC1) and soil (SOILB) was between $\pm$0.1 ‰ and 0.5 ‰ (1 standard deviation, σ) for $\delta^{13}C_{TOC}$. Replicate analyses showed an average precision of $\pm$0.1 %. TOC content for each sample was measured using a Carlo Erba 1500 elemental analyser with acetanilide used as the calibration standard.

Palynological analyses were used to unravel the type of organic matter associated with the sediments and as a means of determining the source of the carbon reservoir in the basins. Samples were processed using standard palynological processing (Brown, 2008) (hydrochloric

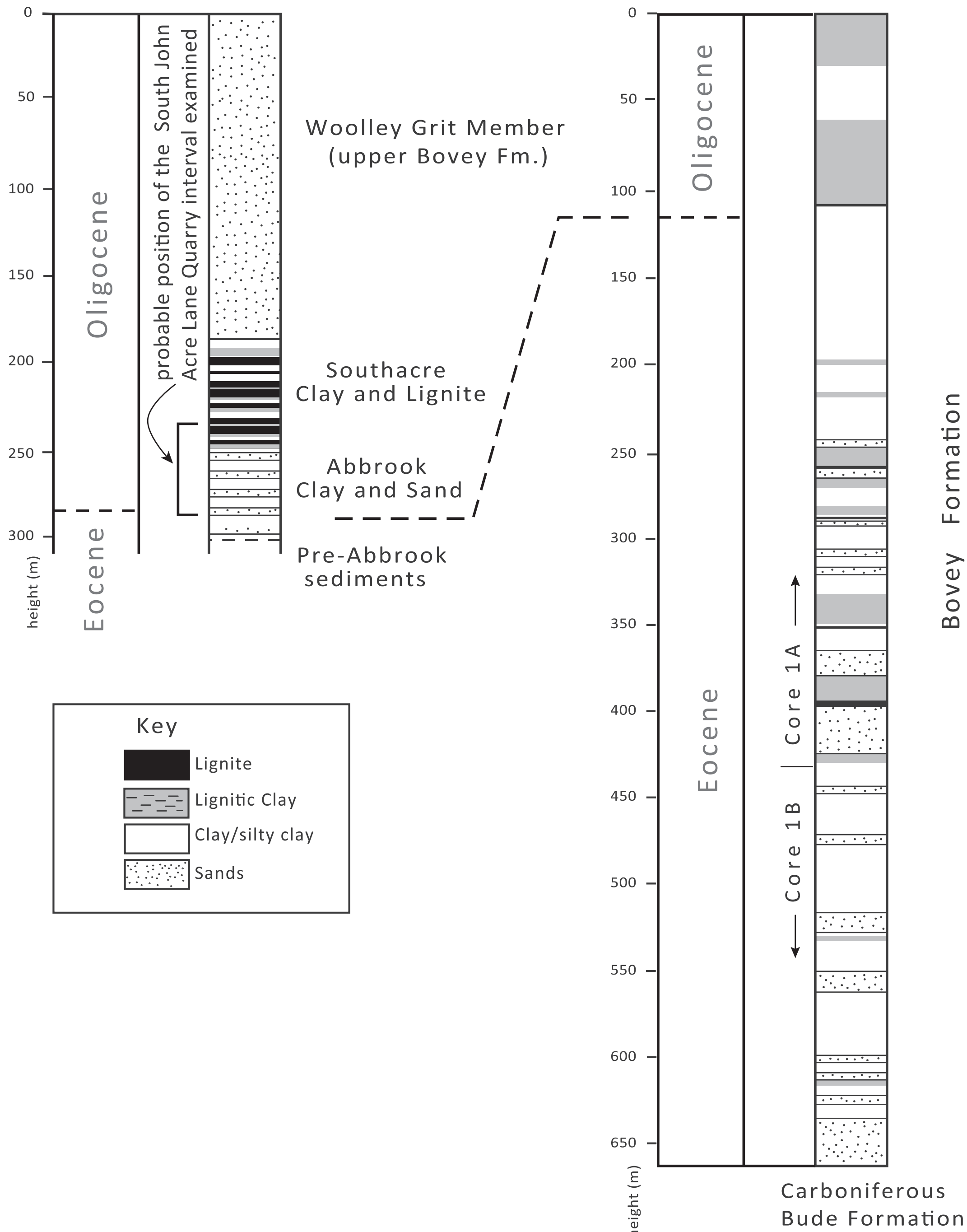

Fig. 3. Summary stratigraphical logs (and correlation) of the Bovey succession with data derived from Edwards (1976) and Wilkinson (1979) cited by Selwood et al. (1984) and Petrockstowe with age data from Turner (cited by Freshney et al., 1979).

acid followed by hydrofluoric acid for demineralisation). Slides were studied using a Zeiss standard microscope, normally using standard transmitted light. This is the first time such a method was used in both Petrockstowe and Bovey basins. To achieve this, counts of > 300 organic matter types from each sample were made. There are several schemes to classify different components of the particulate organic matter (*e.g.*, Tyson, 1995; Aggarwal et al., 2019). Four main categories of palynological matter were identified in this study (Fig. 4): (1) Non-opaque phytoclasts include woody remains, tracheid material, poorly lignified, tissue fragments derived from higher plants, and yellowish-brown organic remains; (2) opaque phytoclast includes palynodebris with irregular shapes and charcoal; (3) palynomorphs in this study include pollen, spores and undifferentiated forms; and (4) amorphous organic matter (AOM) and other palynodebris which appears grey, pale yellow or brown in colour, partly translucent masses of variable thickness and with no cellular detail. The AOM group probably originates from bacteria, phytoplankton and degraded organic aggregates. Their size varies from <5 to about 45 μm in diameter.

5. Results

5.1. Total organic carbon (%TOC)

The sediments from the Petrockstowe core have highly varying wt% TOC values ranging from 0.02 to 42.7 wt% TOC (Fig. 5). Unsurprisingly, the highest %TOC values coincide with the lignitic clays and lignites.

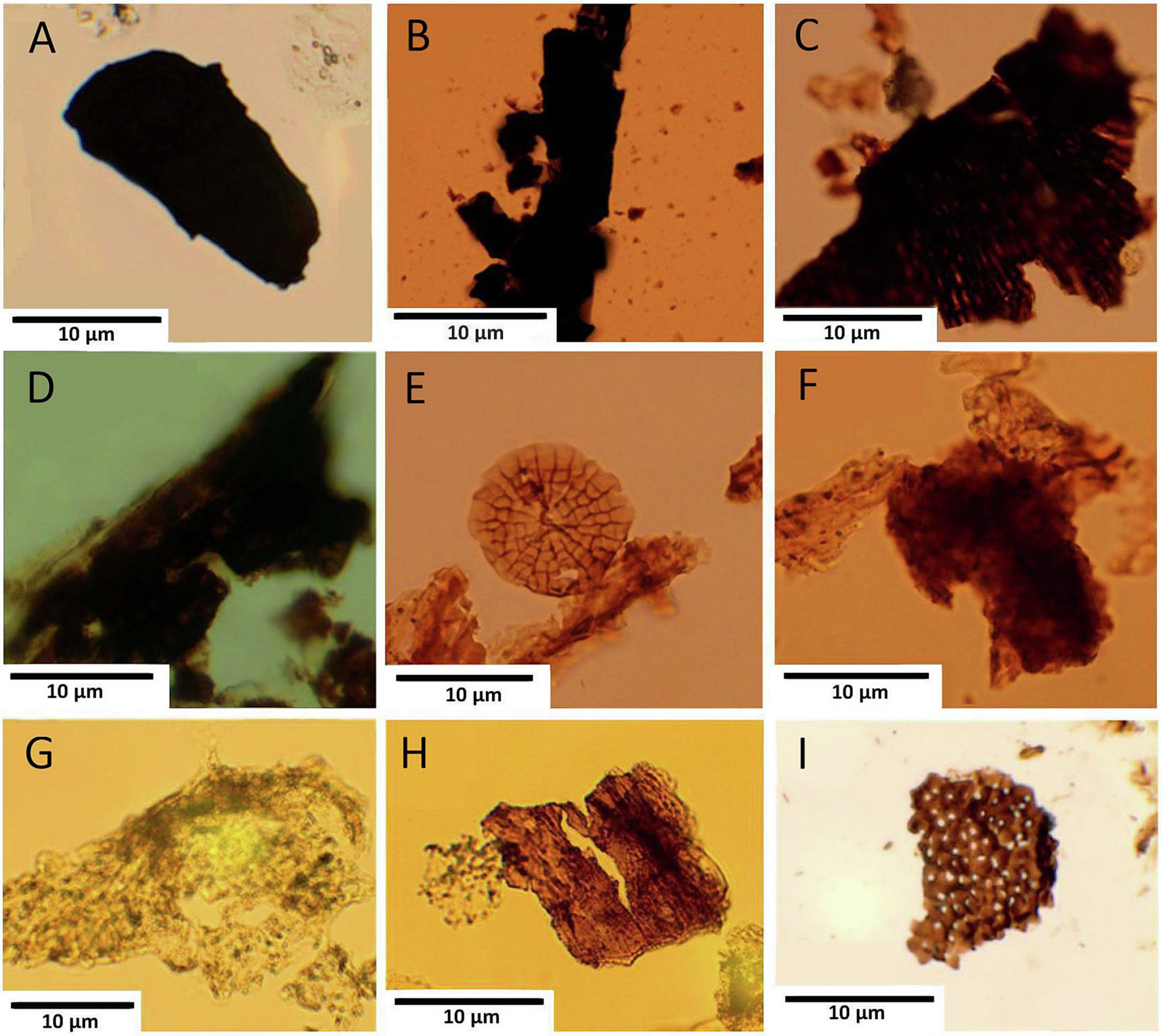

Fig. 4. Phytoclasts from the Petrockstowe and Bovey basins. (A) Opaque lath-shaped phytoclast, sample MC95 Petrockstowe Basin; (B) large opaque lath shaped phytoclast; sample MC3 Petrockstowe; (C) multicellular fungal 'fruiting body', sample MC19 Petrockstowe; (D) mass of melanised fungal hyphae; sample MC58, Petrockstowe. (E) Multicellular fungal 'fruiting body' sample MC19, Petrockstowe. (F) Well preserved, pale brown in colour, partly translucent AOM sample SJAL029, Bovey Basin. (G) Well preserved pale yellow AOM seen in transmitted white light; sample SJAL002, Bovey Basin. (H) A cross section of plant fragment sample SJAL013, Bovey Basin; (I) phytoclast (biostructured) composed of gymnosperm tracheids; sample MC76 Petrockstowe Basin.

These lignitic clays and lignites are seen in the middle and upper parts of the core (core 1A). The lower part (core 1B) consists mostly of gravels, sands, and clays with very low wt% TOC contents. The wt% TOC values from the South John Acres Lane Quarry section, Bovey Basin, range from 0.1 to 61.8 % (Fig. 6). As for the Petrockstowe Basin, the highest wt% TOC values coincide with either lignitic clays or the lignites. These sediments are seen within the Southacre Clay and Lignite Member whereas the underlying Abbrook Clay and Sand Member is dominated by sands and silty clays with fewer lignitic clay beds.

5.2. Palynology

Within the cores of the Petrockstowe Basin, the lowermost interval shows a palynological distribution dominated by phytoclasts with at certain intervals nearly 100 % and low palynomorphs and AOM. The upper part of the core is dominated by much higher concentrations of palynomorphs and an increase in AOM (up to 37 %) and low concentrations of phytoclasts.

With respect to the South John Acres Lane Quarry section, Bovey Basin, phytoclasts are highest in the Abbrook Clay and Sand Member. When phytoclasts are high (opaque phytoclasts reach 91 %), the palynomorphs show the lowest concentrations and *vice versa*. High AOM concentrations (up to 66 %) are seen at the base of the Abbrook Clay and Sand Member and decline upwards. In the overlying Southacre Clay and Lignite Member, dominated by lignites, opaque phytoclast concentrations are low, and palynomorphs consistently high (spore-pollen and non-opaque phytoclasts reach 95 %: Fig. 6).

5.3. Carbon isotopes ($\delta^{13}C_{TOC}$)

The $\delta^{13}C_{TOC}$ values of samples in the Petrockstowe cores range from −28.5 ‰ to −23.5 ‰ with a mean value of −26.5 ‰. As can be seen in Figure 5, values at the base of core 1B begin with a $\delta^{13}C_{TOC}$ value

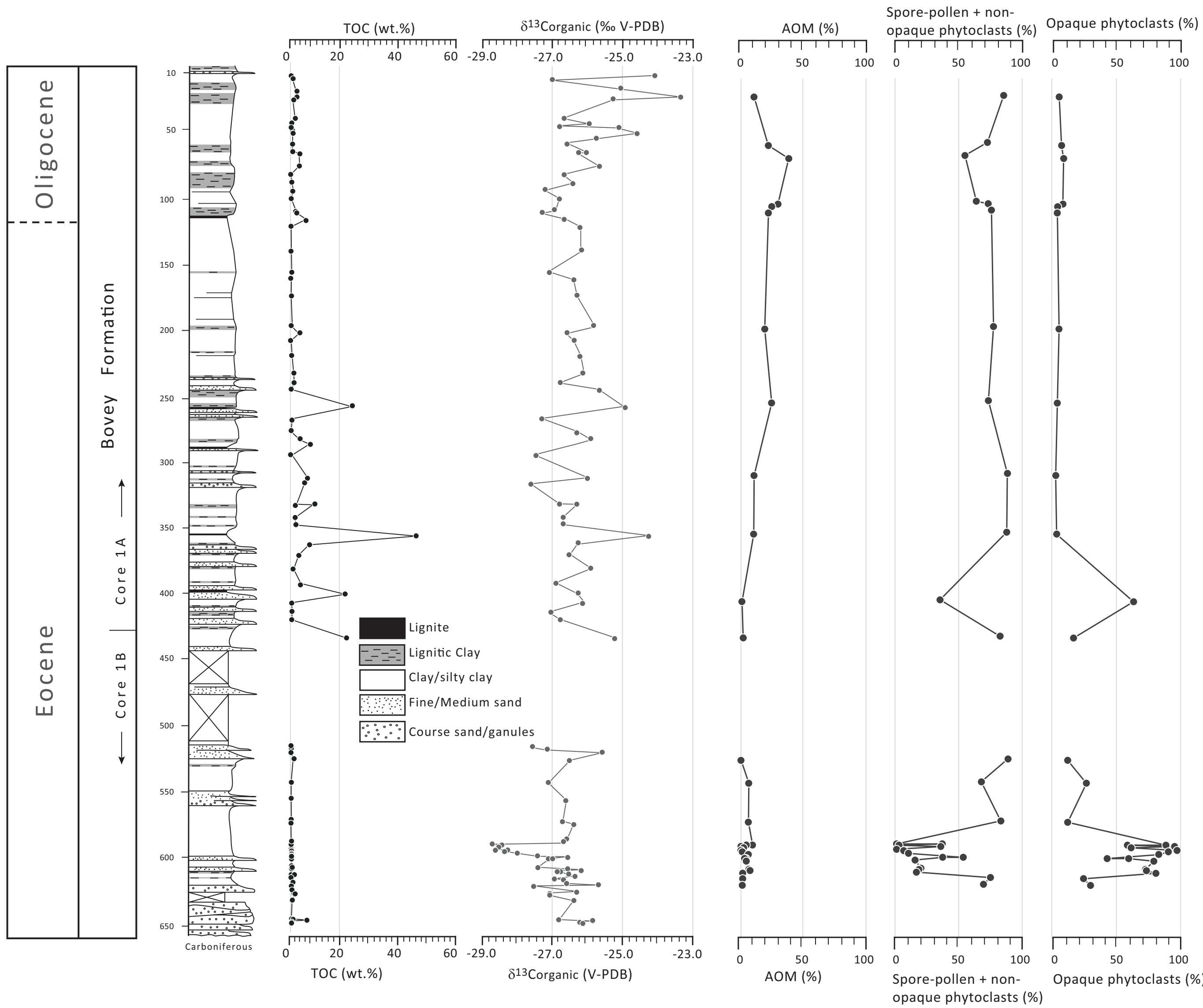

Fig. 5. TOC and $\delta^{13}C_{TOC}$ data, compared to palynological data, Petrockstowe Basin, Devon. Age assignments based on Wilkinson (1979) cited by Selwood et al. (1984).

of ~−26.1 ‰ at 645 m. A carbon isotope excursion with a magnitude of ~2.5 ‰ can be seen at ~586 m depth with $\delta^{13}C_{TOC}$ values reaching a minimum of −28.6 ‰. The entire excursion occurs over a thickness of ~19 m, from 586 to 605 m. The data then shows a return to more positive values of −26.2 ‰ at 585 m. Thereafter, the $\delta^{13}C_{TOC}$ values remain relatively consistent between 584 m and 540 m with $\delta^{13}C_{TOC}$ in the range of −27.0 ‰ and −26.3 ‰. There is a lack of core (because of poor recovery) between 513.59 m and 431.60 m. In the upper part of the Petrockstowe 1A core, the $\delta^{13}C_{TOC}$ values generally vary around −26.0 ‰. In the uppermost (Oligocene) part of the core the most positive $\delta^{13}C_{TOC}$ values are seen.

At the South John Acres Lane Quarry section, Bovey Basin the $\delta^{13}C_{TOC}$ values range between −27.8 ‰ and −22.5 ‰ with a mean value of −26.0 ‰ (Fig. 6). In this succession, $\delta^{13}C_{TOC}$ values show limited variability. In the uppermost (Oligocene) part of the section within the lignitic clays and lignites the most positive $\delta^{13}C_{TOC}$ values (−22.5 ‰) are found.

6. Discussion

6.1. Palynological interpretation

In the Petrockstowe 1A and 1B cores, close to the base of the succession the high opaque phytoclast content, together with low TOC values (down to 0.1 wt%), and low AOM and non-opaque phytoclast contents may be related to local oxidation of organic matter (Figs. 5, 7) or diagenesis. Opaque phytoclasts are typically derived from the oxidation of structured organic matters (translucent brown wood, tracheids, cuticle, *etc.*) and along with a low proportion of the other organic matter types have been documented in oxic swamps and river sediments (*e.g.*, Martín-Closas et al., 2005; Pieñkowski and Waksmundzka, 2009). In the upper part of the Petrockstowe section (Fig. 5) palynomorphs dominate which could indicate suboxic/anoxic waters (Tyson, 1995). Consequently, a restriction of water circulation rather than productivity, may serve as the controlling factor for the organic rich sediment accumulation. Also, the fluctuating, but relatively high percentages of palynomorphs and AOM (up to 37 %), could suggest diverse source of areas of the organic matter (*e.g.*, Martín-Closas et al., 2005) with deposition within an ephemeral lake or lake margin. These observations agree with the Petrockstowe 1A and 1B cores, representing a succession of sand-filled fluvial channels followed by an ephemeral lake or lake margin setting (Fig. 5, see Freshney et al., 1979). This represents an overall deepening-up sequence.

In the Abbrook Clay and Sand and Southacre Clay and Lignite members, the base sees a diversity in palynological types (Fig. 6) with high percentage of AOM and phytoclasts potentially reflecting enhanced

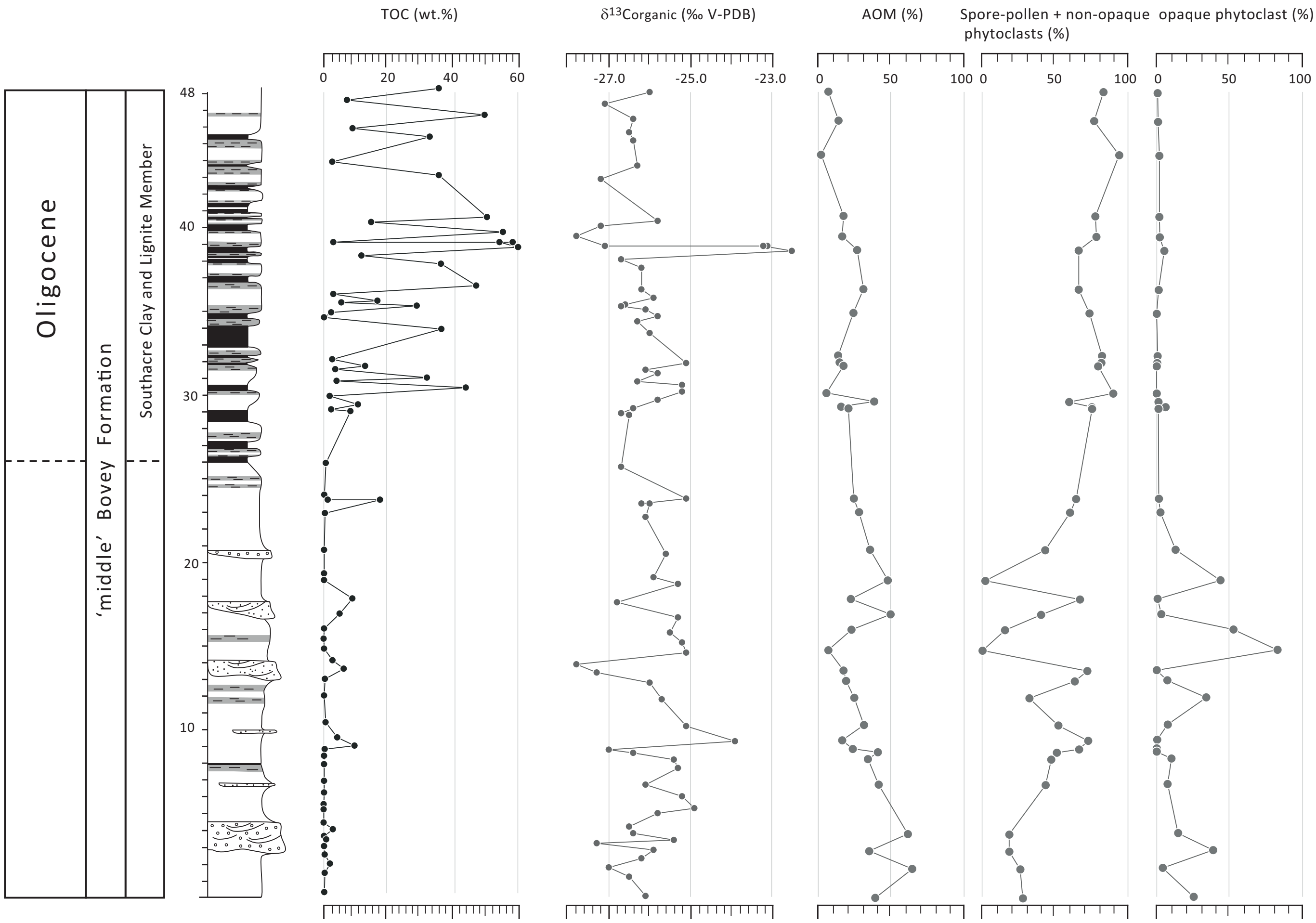

Fig. 6. TOC and $\delta^{13}C_{TOC}$ data, compared to palynological data, Bovey Basin, Devon. Age assignments of Turner (cited by Freshney et al., 1979).

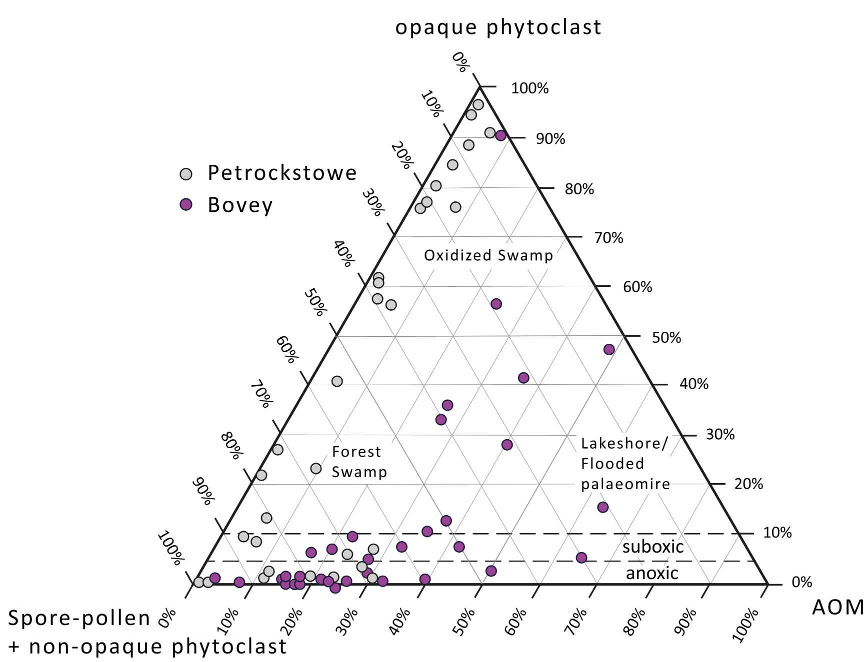

Fig. 7. Distribution of the different categories of palynological matter in the ternary diagram.
(Proposed by Hacquebard and Donaldson (1969) and modified by Marchionni (1980) and Aggarwal et al. (2022).)

preservation in a low energy, stagnant, oxygen depleted environment (Tyson, 1995, Fig. 7). Only a single high opaque phytoclast level is seen, possibly associated with deposition within an oxidising environment. In the overlying Southacre Clay and Lignite Member, dominated by lignites, palynomorph concentrations are consistently high and as such suggest a depositional environment associated with a swamp or ephemeral lake or marginal lake. These observations are in agreement that the Abbrook Clay and Sand and Southacre Clay and Lignite members of the Bovey Formation, represent a long-lived lake followed by sediments representing more ephemeral lakes or lake margins periodically exposed with mires (see Chandler, 1964; Edwards, 1976).

Our palynological data set further allows us to determine whether isotope trends are carbon source related. For example, within the Abbrook Clay and Sand Member, when phytoclasts are high, the palynomorphs show the lowest concentrations and *vice versa*. High, but variable, AOM concentrations are also seen. No correspondence is seen here with fluctuations in carbon isotopes, suggesting organic matter associated with the sediments is not overly determining the source of the carbon reservoir in the basins. Nevertheless, changes in the dominance of gymnosperms, angiosperms or pteridophytes/bryophytes within the vegetation could be of importance.

6.2. Carbon isotope trends

Carbon isotopic ratios from terrestrial organic materials have been previously used to study global carbon-isotope excursions in the Cenozoic (Collinson et al., 2003; Bechtel et al., 2008; Holdgate et al., 2009; Hodgson et al., 2011; Fang et al., 2013; Jerrett et al., 2015; Garel et al., 2020; Lenz et al., 2022). These studies (which use discrete plant fragments, lignites or disseminated organic matter) identify reproducible patterns in atmospheric carbon isotopic compositions. There are just a few terrestrially sourced high-resolution carbon isotope stratigraphies to compare our Eocene and Oligocene data to (*e.g.*, Holdgate et al., 2009; Garel et al., 2020). Nevertheless, our $\delta^{13}C_{TOC}$ data are, consistent with terrestrially sourced $\delta^{13}C$ values of the Eocene (*e.g.*, Collinson et al., 2003; Bechtel et al., 2008; Hodgson et al., 2011). Considering the carbon isotope excursion of −2.5 ‰ from the lower part of Petrockstowe core 1B (Fig. 5), the magnitude of this excursion falls within the lower limit of that associated with the Paleocene–Eocene Thermal Maximum (PETM), which ranges from −2.4 to −6.3 ‰ (see summary of McInerney and Wing, 2011). This suggests it could be related to this event. However, biostratigraphically there is limited data from the Petrockstowe core (see Turner cited by Freshney et al., 1979). The biostratigraphical constraints allow the carbon isotope excursion to also be associated with one of the other transient carbon isotopic shifts that occurred after the Paleocene–Eocene Thermal Maximum *i.e.*, the Eocene Thermal Maximum (ETM-2). For example, the magnitude of the ETM-2 carbon isotope excursion documented in the continental succession of the McCullough peaks, Bighorn Basin, Wyoming, USA, using palaeosol carbonate is −3.8 ‰ (Abels et al., 2012).

The presence of the Eocene–Oligocene boundary in Petrockstowe core 1A has been proposed, based on pollen data, by Turner (cited by Freshney et al., 1979). The Abbrook Clay and Sand Member is also likely to contain the Eocene–Oligocene boundary (Selwood et al., 1984) but because of the limited biostratigraphical data the exact positioning of the boundary is less certain. The Eocene–Oligocene boundary is one of the most prominent abrupt climatic events in the Cenozoic and is considered to represent the initiation of major permanent Paleogene ice sheets on Antarctica (Miller et al., 2009; Coxall and Wilson, 2011; Hutchinson et al., 2021). The glaciation of Antarctica is thought to result from the tectonic opening of Southern Ocean gateways, which enabled the formation of the Antarctic Circumpolar Current and the subsequent thermal isolation of the Antarctic continent (*e.g.*, Zachos et al., 2001) Modelling studies implicate low atmospheric CO_2 also as an important factor (DeConto and Pollard, 2003). The carbon isotope changes across this boundary are, however, less pronounced, and certainly less well documented in the terrestrial system. This is perhaps due to the lack of suitable terrestrial sections to study.

Nevertheless, the marine records (Zachos et al., 2001; Coxall and Wilson, 2011) show a $\delta^{13}C$ excursion of ~1.0 ‰ in benthic foraminifera, peaking in the earliest Oligocene and followed by a decline to ~0.5 ‰, 1 million years after the boundary. The Petrockstowe and Bovey $\delta^{13}C_{TOC}$ data do show some correspondence with this marine record whereby for the Eocene stable but the most negative carbon values are observed, whereas the most positive carbon isotope values are present in the Oligocene. More positive $\delta^{13}C_{TOC}$ values have been linked to increased organic carbon burial (Coxall and Wilson, 2011). Our study therefore supports the notion that the surface ocean and atmosphere behaved as coupled reservoirs at this time, similar to other times in the Cenozoic (Jerrett et al., 2015; Cui et al., 2021; Lenz et al., 2022), as opposed to a decoupled system (*cf.*, Holdgate et al., 2009; Fang et al., 2013), but more data is required to fully test this possibility.

7. Conclusions

In conclusion, and in agreement with Freshney et al. (1979), our palynological observations show that the Petrockstowe 1A and 1B cores, represent a succession of sand-filled fluvial channels followed by an ephemeral lake or lake margin setting. The Abbrook Clay and Sand and Southacre Clay and Lignite members of the Bovey Formation, represent a long-lived lake followed by sediments representing more ephemeral lakes or lake margins periodically exposed with mires (see Chandler, 1964; Edwards, 1976). Our palynological data set further allows us to determine that isotope trends are not overly determined by the source of carbon in the basins.

Our study suggests that the observed $\delta^{13}C_{TOC}$ trends in the Eocene–Oligocene of the Petrockstowe and Bovey basins were primarily produced by variations of the carbon isotope ratios of terrestrial atmospheric carbon reservoirs. Even with our less than well constrained biostratigraphical control, the data indicate that the carbon isotope excursions seen in the Eocene and Oligocene could be associated with a number of transient global carbon isotopic shifts (*e.g.*, the PETM). Our findings therefore appear to lend support to the surface ocean and atmosphere behaving as coupled reservoirs at this time.

Declaration of competing interest

Our m/s has not been published previously (except in the form of an abstract) and it is not under consideration for publication elsewhere. The publication is approved by all authors.

Acknowledgements

We would like to thank the British Geological Survey for access to cores and Sibelco UK for access and information regarding South John Acres Lane Quarry. MC was funded by the Tertiary Education Trust Fund (TETFund) Abuja, *via* the intervention of academic staff training and development programme to the Federal University of Petroleum Resources, Effurun, Nigeria. This manuscript benefited from the extensive and constructive reviews of two anonymous reviewers, who are duly thanked.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pgeola.2023.05.003.

References

Abels, H.A., Clyde, W.C., Gingerich, P.D., Hilgen, F.J., Fricke, H.C., Bowen, G.J., Lourens, L.J., 2012. Terrestrial carbon isotope excursions and biotic change during Palaeogene hyperthermals. Nature Geoscience 5, 326–329.

Aggarwal, N., Agrawal, S., Thakur, B., 2019. Palynofloral, palynofacies and carbon isotope of Permian coal deposits from the Godavari Valley Coalfield, South India: insights into the age, palaeovegetation and palaeoclimate. International Journal of Coal Geology 214, 103285.

Aggarwal, N., Mathews, R.P., Ansarie, A.H., Thakur, B., Agrawal, S., 2022. Palaeoenvironmental reconstruction for the Permian (lower Gondwana) succession of the Godavari Valley Coalfield in southern India based on a combined palynofacies, carbon isotope, and biomarker study. Journal of Palaeogeography 2022 (11), 123–144.

Armstrong McKay, D.I., Tyrrell, T., Wilson, P.A., 2016. Global carbon cycle perturbation across the Eocene–Oligocene climate transition. Paleoceanography 31, 311–329.

Bechtel, A., Gratzer, R., Sachsenhofer, R.F., Gusterhuber, J., Lucke, A., Puttmann, W., 2008. Biomarker and carbon isotope variation in coal and fossil wood of Central Europe through the Cenozoic. Palaeogeography, Palaeoclimatology, Palaeoecology 262, 166–175.

Blyth, F.G.H., 1962. The structure of the north-eastern tract of the Dartmoor granite. Quarterly Journal of the Geological Society 118, 435.

Bristow, C., 1968. The derivation of the Tertiary sediments in the Petrockstowe Basin, North Devon. The Proceedings of the Ussher Society 2, 29–35.

Bristow, C., Robson, J., 1994. Palaeogene basin development in Devon. Transactions of the Institution of Mining and Metallurgy. Section B. Applied Earth Science 103, B163–B173.

Brown, C.A., 2008. In: Riding, J.B., Warny, S. (Eds.), Palynological Techniques, Second Edition American Association of Stratigraphic Palynologists, Dallas, USA (137 pp.).

Chandler, M.E.J., 1957. The Oligocene Flora of the Bovey Tracey Lake Basin, Devonshire. British Museum (Natural History), pp. 73–123.

Chandler, M.E.J., 1964. The Lower Tertiary Floras. British Museum (Natural History), London (151 pp.).

Collinson, M., Hooker, J., Gröcke, D., 2003. Cobham lignite bed and penecontemporaneous macrofloras of southern England: a record of vegetation and fire across the Paleocene–Eocene Thermal Maximum. Special Papers-Geological Society of America 333–350.

Coxall, H.K., Wilson, P.A., 2011. Early Oligocene glaciation and productivity in the eastern equatorial Pacific: insights into global carbon cycling. Paleoceanography 26, PA2221. https://doi.org/10.1029/2010PA002021.

Cui, Y., Diefendorf, A.F., Kump, L.R., Jiang, S.J., Freeman, K.H., 2021. Synchronous marine and terrestrial carbon cycle perturbation in the high Arctic during the PETM. Paleoceanography and Paleoclimatology 36, e2020PA003942.

Dearman, W., 1963. Wrench-faulting in Cornwall and south Devon. Proceedings of the Geologists' Association 74, 265–287.

DeConto, R.M., Pollard, D., 2003. Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2. Nature 421, 245–249.

Edwards, R.A., 1976. Tertiary sediments and structure of the Bovey Basin, south Devon. Proceedings of the Geologists Association 87, 1–26.

Edwards, R.A., Freshney, E.C., 1982. The Tertiary sedimentary rocks. In: Durrance, E.M., Laming, D.J.C., Selwood, E.B. (Eds.), The geology of Devon. University of Exeter Press, Exeter, pp. 204–237.

Fang, L., Bjerrum, C.J., Hesselbo, S.P., Kotthoff, U., McCarthy, F.M.G., Huang, B., Ditchfield, P.W., 2013. Carbon-isotope stratigraphy from terrestrial organic matter through the Monterey event, Miocene, New Jersey margin (IODP Expedition 313). Geosphere 9, 1303–1318.

Freshney, E., 1970. Cyclical sedimentation in the Petrockstowe Basin. Proceedings. Ussher Society 2, 179–189.

Freshney, E.C., Beer, K.E., Wright, J.E., 1979. Geology of the Country around Chulmleigh. Institute of Geological Sciences (69pp.).

Freshney, E.C., Edwards, R.A., Isaac, K.P., Witte, G., Wilkinson, G.C., Boulter, M.C., Bain, J.A., 1982. A Tertiary basin at Dutson, near Launceston, Cornwall, England. Proceedings of the Geologists Association 93, 395–402.

Garel, S., Dupuis, C., Quesnel, F., Jacob, J., Yans, J., Magioncalda, R., Flehoc, C., Schnyder, J., 2020. Multiple early Eocene carbon isotope excursions associated with environmental changes in the Dieppe–Hampshire Basin (NW Europe). BSGF - Earth Sciences Bulletin 191, 33.

Gröcke, D.R., Price, G.D., Robinson, S.A., Baraboshkin, E., Ruffell, A.H., Mutterlose, J., 2005. The Valanginian (Early Cretaceous) positive carbon-isotope event recorded in terrestrial plants. Earth and Planetary Science Letters 240, 495–509.

Hacquebard, P.A., Donaldson, J.R., 1969. Carboniferous coal deposition associated with floodplain and limnic environments in Nova Scotia. In: Dapples, E.C., Hopkins, M.E. (Eds.), Environment of Coal DepositionGeol. Soc. America Spec. Papers, vol. 114, pp. 143–191.

Heimhofer, U., Hochuli, P.A., Burla, S., Andersen, N., Weissert, H., 2003. Terrestrial carbon-isotope records from coastal deposits (Algarve, Portugal): a tool for chemostratigraphic correlation on an intrabasinal and global scale. Terra Nova 15, 8–13.

Hodgson, E., Grimes, S.T., Fitzpatrick, M.E.J., Price, G.D., Hart, M.B., Leng, M.J., 2011. Paleogene carbon isotope excursions in the Bunkers Hill borehole: Hampshire Basin, UK. Proceedings of the Geologists Association 122, 460–471.

Holdgate, G.R., McGowran, B., Fromhold, T., Wagstaff, B.E., Gallagher, S.J., Wallace, M.W., Sluiter, I.R.K., Whitelaw, M., 2009. Eocene–Miocene carbon-isotope and floral record from brown coal seams in the Gippsland Basin of southeast Australia. Global and Planetary Change 65, 89–103.

Holloway, S., Chadwick, R.A., 1986. The Sticklepath–Lustleigh fault zone: Tertiary sinistral reactivation of a Variscan dextral strike-slip fault. Journal of the Geological Society, London 143, 447–452.

Hutchinson, D.K., Coxall, H.K., Lunt, D.J., Steinthorsdottir, M., de Boer, A.M., Baatsen, M., von der Heydt, A., Huber, M., Kennedy-Asser, A.T., Kunzmann, L., Ladant, J.B., Lear, C.H., Moraweck, K., Pearson, P.N., Piga, E., Pound, M.J., Salzmann, U., Scher, H.D., Sijp, W.P., Sliwinska, K.K., Wilson, P.A., Zhang, Z.S., 2021. The Eocene–Oligocene transition: a review of marine and terrestrial proxy data, models and model data comparisons. Climate of the Past 17, 269–315.

Jerrett, R.M., Price, G.D., Grimes, S.T., Dawson, A.T., 2015. A paleoclimatic and paleoatmospheric record from peatlands accumulating during the Cretaceous–Paleogene boundary event, Western Interior Basin, Canada. Geological Society of America Bulletin 127, 1564–1582.

Lenz, O.K., Montag, M., Wilde, V., Methner, K., Riegel, W., Mulch, A., 2022. Early Eocene carbon isotope excursions in a lignite-bearing succession at the southern edge of the proto-North Sea (Schöningen, Germany). Climate of the Past 18, 2231–2254.

Marchionni, D.L., 1980. Petrography and depositional environments of the Liddel seam, Upper Hunter Valley, New South Wales. International Journal of Coal Geology 1, 36–61.

Martín-Closas, C., Permanyer, A., Vila, M.-J., 2005. Palynofacies distribution in a lacustrine basin. Geobios 38, 197–210.

McInerney, F.A., Wing, S.L., 2011. The Paleocene–Eocene thermal maximum: a perturbation of carbon cycle, climate, and biosphere with implications for the future. Annual Review of Earth and Planetary Sciences 39, 489–516.

Miller, K.G., Wright, J.D., Katz, M.E., Wade, B.S., Browning, J.V., Cramer, B.S., 2009. Climate threshold at the Eocene–Oligocene transition: Antarctic ice sheet influence on ocean circulation. SPE452: The Late Eocene Earth—Hothouse, Icehouse, and Impacts, Geol. Soc. of Am. Spec. Pap., vol. 452, p. 80301.

Nilsen, E.B., Anderson, L.D., Delaney, M.L., 2003. Paleoproductivity, nutrient burial, climate change and the carbon cycle in the western equatorial Atlantic across the Eocene/Oligocene boundary. Paleoceanography 18, 1057. https://doi.org/10.1029/2002PA000804.

Pieñkowski, G., Waksmundzka, M., 2009. Palynofacies in Lower Jurassic epicontinental deposits of Poland: tool to interpret sedimentary environments. Episodes 32, 21–32.

Selwood, E.B., Edwards, R., Chester, J., Hamblin, R., Henson, M., Riddolls, B., Waters, R., 1984. Geology of the Country Around Newton Abbot. Natural Environment Research Council. HMSO, London (212 pp.).

Sun, J., Ni, X., Bi, S., Wu, W., Ye, J., Meng, J., Windley, B.F., 2014. Synchronous turnover of flora, fauna, and climate at the Eocene–Oligocene Boundary in Asia. Scientific Reports 4, 7463.

Tyson, R.V., 1995. Sedimentary Organic Matter: Organic Facies and Palynofacies. Springer.

Wilkinson, G.C., Boulter, M.C., 1981. Oligocene pollen and spores from the western part of the British Isles. Palaeontographica Abteilung B 175, 27–83.

Wilkinson, G.C., Bazley, R.A.B., Boulter, M.C., 1980. The geology and palynology of the Oligocene Lough Neagh Clays, Northern Ireland. Journal of the Geological Society, London 137, 65–75.

Zachos, J.C., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292, 686–693.