

An Integrated Biostratigraphy and Chemostratigraphy for the Dawn of the Jurassic (the Hettangian Stage in the Cheshire Basin, UK)

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ABSTRACT: Highly resolved Earth System reconstructions of the Earliest Jurassic are hampered by complexities of existing reference sections. Here, an integrated stratigraphy of two core records is constructed, representing the expanded Hettangian sequence of the Cheshire Basin, UK. The combined record is based on ammonite and calcareous nannofossil biostratigraphy, organic carbon isotope ratios, and bulk rock chemical properties of legacy core material (Wilkesley) and Prees 2C, cored in 2020. Combination of ammonite records of these cores allows for substantial reductions in the uncertainties of ammonite zonal and subzonal boundaries. The new organic carbon isotope chemostratigraphy for the Hettangian of the Cheshire Basin improves temporal resolution compared to other published records, in particular for the Tilmanni and Planorbis zones. The limited occurrence of organic matter enrichment intervals associated with negative organic carbon isotope spikes in the Cheshire Basin allows for the identification of minor drifts throughout the Hettangian and into the Sinemurian which are likely of global significance. Organic carbon and macrofossil carbonate carbon isotope ratios largely follow the same trends in the Hettangian, but exhibit contrasting changes in the early Liasicus Zone, commensurate with a decrease in the isotopic difference of both records of ca. 2‰.

KEY WORDS: Hettangian, integrated stratigraphy, chemostratigraphy, biostratigraphy, paleoenvironment.

0 INTRODUCTION

Robust, integrated stratigraphic constraints that establish the precise relative timing of global tectonic processes and biotic turnover are critical for understanding how the Earth System evolves and how biota cope with environmental crises. Such stratigraphic frameworks are especially hard to construct where environmental perturbations occurred on a global scale with a strong impact on the sedimentation rates and lithofacies deposited at the time, which may have significantly departed from

background conditions. The Earliest Jurassic is marked by the recovery from the End-Triassic Mass Extinction (Damborenea et al., 2017; Toma  ov  ch and Sibl  k, 2007; Hallam, 1997), one of the major events to impact biotic diversity in the Phanerozoic (Wignall and Atkinson, 2020; Lucas and Tanner, 2015; Kiessling et al., 2007; Raup and Sepkoski, 1982). This period of time also saw the emplacement of the Central Atlantic Magmatic Province (CAMP, Ruhl et al., 2020; Davies et al., 2017; Blackburn et al., 2013; P  lfy, 2003) and rifting, eventually resulting in the formation of the Atlantic Ocean (Frizon de Lamotte et al., 2015), one of the key steps in the fragmentation of the supercontinent Pangea.

Formally, the base of the Jurassic and the Hettangian stage is defined in the Kuhjoch Section (Austrian Alps) at the level of the first occurrence of the ammonite

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Psiloceras spelae tirolicum (Hillebrandt et al., 2013). At this site, about 20 m of Hettangian strata are exposed in an overturned succession and have been analyzed using multiple techniques, including organic carbon isotope stratigraphy (Hillebrandt et al., 2013; Ruhl et al., 2009). Detailed correlation to this Global Stratotype Section and Point (GSSP) is, however, not straight-forward due to ambiguities in chemostratigraphic interpretations and the sparsity or lack of suitable biostratigraphic markers (Korte et al., 2018; Lindström et al., 2017). The stratigraphic coverage of the succession is too short, and complicated by tectonic processes, to characterize the long-term biotic recovery and element cycles in Early Jurassic paleoenvironments. Important geochronologic, biostratigraphic and chemostratigraphic information for a longer stratigraphic sequence has been obtained in the outcrops of Somerset, UK (e.g., Hüsing et al., 2014; Ruhl et al., 2010). In Somerset, records covering the entire Hettangian can be compiled and the area also hosts the GSSP for the base of the following Sinemurian stage (East Quantoxhead), which is defined by the first occurrence of the ammonite genera *Vermiceras* and *Metophioceras* (Bloos and Page, 2002). A detailed organic carbon isotope stratigraphy for the Latest Triassic reaching into the Sinemurian has been assembled here, using the coastal outcrops along this coast (Xu et al., 2017; Ruhl et al., 2010; Hesselbo et al., 2002).

The importance of the Somerset succession was further underlined by cyclostratigraphic analysis yielding an initial duration assessment of 1.8 Myr for the Hettangian proposed on the basis of organic carbon isotopes and other geochemical properties (Ruhl et al., 2010). This duration estimate was later replicated when re-evaluating the St Audrie's Bay succession with further geochemical and geophysical measurements (Hüsing et al., 2014). The agreement of these age models with radiometric ages from South America (Pucara Group, Peru) that underpin a duration estimate of 1.93 ± 0.20 Myr for the Hettangian stage (Hesselbo et al., 2020a; Guex et al., 2012; Schoene et al., 2010; Schaltegger et al., 2008) added confidence to their accuracy. However, the stated uncertainties of the radiometric ages do not encompass all the relevant factors, because long-range correlation from the GSSP sections and the adoption of different definitions for the stage boundary add unconstrained biases (Hesselbo et al., 2020a). Indeed, using a cyclostratigraphic evaluation of a composite of sites around the UK (Somerset, Dorset, South Glamorgan, Warwickshire) and inferring numerous gaps in these successions based on the correlation of ammonite biohorizons, a much longer duration of the Hettangian stage of at least ~4.1 Myr has since been proposed (Weedon et al., 2019). These discrepancies in interpretation highlight the need for additional, more expanded sequences with robust biostratigraphic control to resolve such disagreements.

A broad range of stratigraphic successions on multiple continents have been targeted to constrain better the chemostratigraphic signature of the Triassic-Jurassic

transition and Earliest Jurassic. In the Americas these include Kennecott Point, Canada (Williford et al., 2007), the Fundy Basin, Canada (Deenen et al., 2011), the Newark and Hartford basins, USA (Whiteside et al., 2010), New York Canyon, USA (Bartolini et al., 2012; McRoberts et al., 2007), Levanto, Peru (Yager et al., 2017), and Arroyo Malo, Argentina (Ruhl et al., 2020). Other records outside Europe were obtained from Japan (Fujisaki et al., 2018), Morocco (Dal Corso et al., 2014; Deenen et al., 2010) and the UAE (Ge et al., 2018). In addition to these, a wide range of European sections have been studied in detail (Ruhl et al., 2020; Korte et al., 2018 and references therein). Successions that are more expanded than the SW UK coastal exposures and that have a robust ammonite biostratigraphic framework that tie them faithfully to the GSSP sections are rare, however, and challenges remain for erecting a robust integrated stratigraphy for the Hettangian stage.

This impasse of lacking adequate successions to improve on existing datasets was tackled via scientific drilling in the Cheshire Basin (NW England, Hesselbo et al., 2023) in 2020. A 620 m long core of Upper Triassic and Lower Jurassic strata at Prees (Prees 2C core) was retrieved here, including a ca. 127 m long Hettangian succession which was recovered with essentially no core loss. While not quite as expanded as in the neighboring Cardigan Bay Basin (Copestake and Johnson, 2013), this is still nearly twice the thickness observed in the coastal outcrops in Somerset (Hüsing et al., 2014; Ruhl et al., 2010). Even though only the working half of the vertically sectioned 97 mm diameter core was available to build a biostratigraphic scheme, ammonite zonal boundaries could be placed with confidence for all Hettangian biozones (Hesselbo et al., 2023). Nevertheless, by its nature, the number of fossil finds is limited in core, and the completeness of the succession is hard to demonstrate.

Importantly, legacy core material from earlier drilling in the Cheshire Basin at Wilkesley, ca. 10 km NE of Prees 2C, where a research core was drilled in 1959–1960 to a depth of 1 686 m below surface, is still available at the British Geological Survey National Core Repository in Keyworth. For this large-diameter, fossiliferous core (>18 cm diameter in the Jurassic part), fossil specimens with precise depth information and bulk rock aggregates averaged over 1 foot (ft, = 30.48 cm) intervals were retained, constituting a very valuable additional resource for the construction of a Hettangian record for the Cheshire Basin and beyond. The merging of the stratigraphic information from the Prees 2C and Wilkesley cores is key to unlocking the potential of the Cheshire Basin records and evaluating the lateral continuity of strata in both cores.

Here, we report results from both cores on ammonite biozonation, calcareous nannofossil distribution, organic carbon-isotope stratigraphy, carbonate and total organic carbon content, as well as X-ray fluorescence-based chemical data for the Hettangian. We use these data to build a detailed correlation between the cores, to estab-

lish the lateral continuity of marker beds on a multi-km scale, and to improve fidelity of the Prees 2C record. We further tie the observed geochemical records to other key successions to test the super-regional relevance of chemostratigraphic markers and to propose a new reference organic carbon isotope curve for the entire Hettangian.

1 GEOLOGIC BACKGROUND

The Cheshire Basin is one of a series of basins surrounding the Welsh Massif and was established in the Early Permian, beginning with the deposition of aeolian and fluvial sands (Evans et al., 1993, Figure 1). The basin was initiated as a consequence of extensional tectonics following the Variscan orogeny, driven by active faulting and thermal subsidence (Chadwick 1997; Evans et

al., 1993). Synsedimentary faulting led to the rapid generation of accommodation space for > 5 km of Paleozoic and Mesozoic infill (Evans et al., 1993), allowing for the accumulation of erosion products derived from the Variscan orogenic belt in the south (Newell, 2018; Bourquin et al., 2011) with a likely source in the Armorican Highlands (Jones et al., 1996). While largely defined by continental deposits beginning with the Early Permian Collyhurst Sandstone (Naylor et al., 1989), intermittent marine influence on the basin fill may have occurred, initially in the Permian Manchester Marl Formation (Naylor et al., 1989). Increasingly prominent marine influence in the Triassic led to the deposition of thick evaporite sequences of the Middle Triassic Northwich Halite and Late Triassic Wilkesley Halite formations (Warrington et al., 1996; Wil-

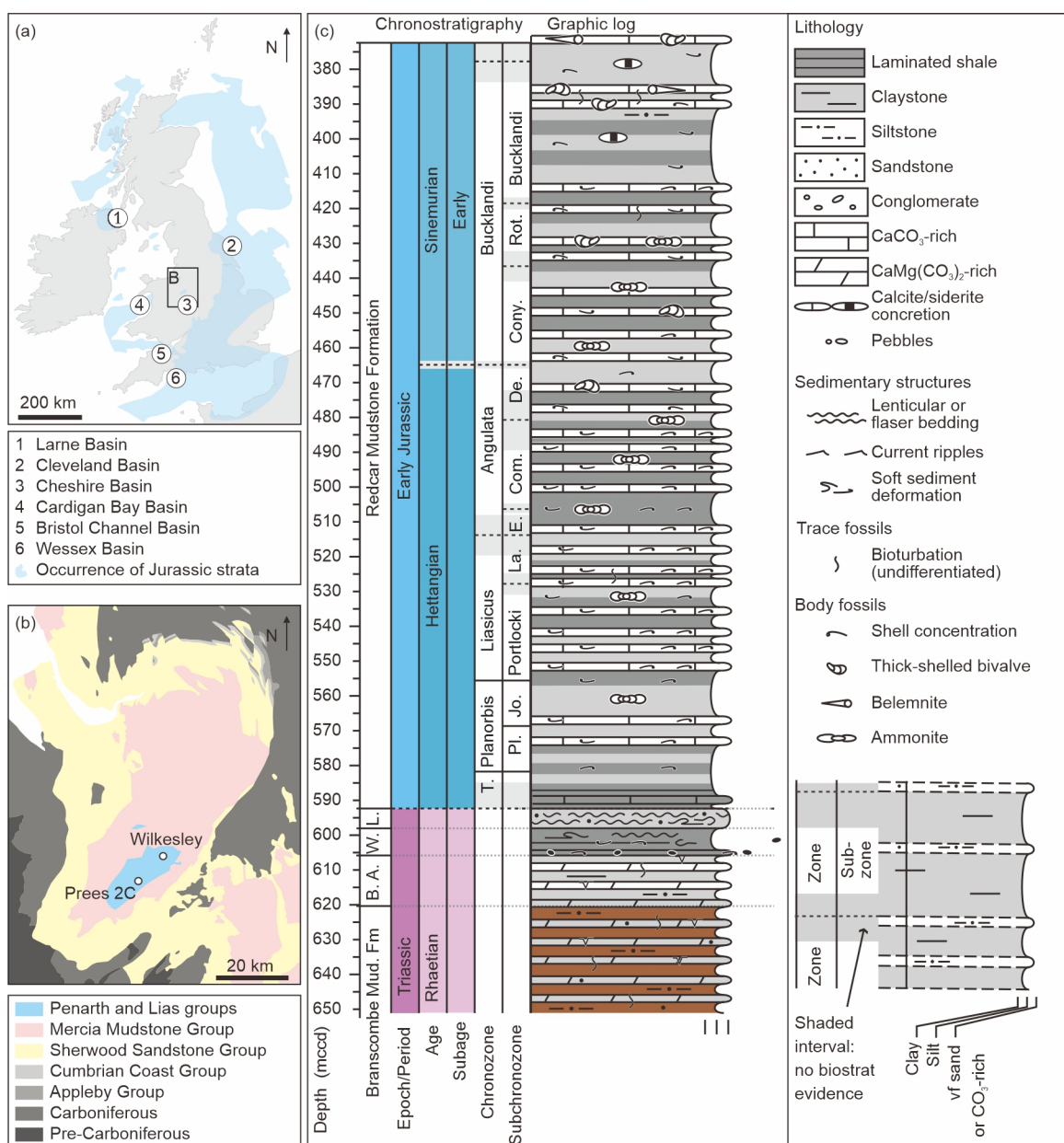


Figure 1. (a) Jurassic basins in the UK, Ireland and northern France, modified from Barron et al. (2012). (b) Geological map of the Cheshire Basin showing the position of the Jurassic basin infill (Wem-Audlem subbasin) and the location of the Prees 2C and Wilkesley sites within this sub-basin; map modified from Warrington et al. (1996). (c) Lithological column and biozonation for Prees.

son, 1993; Arthurton, 1980). A transition from terrestrial to marginal marine deposition is described for the upper part of the Triassic Mercia Mudstone, with the overlying Penarth Group strata of Latest Triassic age generally suggesting marginal marine conditions in the coastal outcrops of Somerset (Thomas et al., 1993). In the Cheshire Basin, fossil evidence for non-marine influence, however, persists to the late Rhaetian in the form of the conchostrocan *Euestheria minuta* (Poole and Whiteman, 1966), even though marine faunas are also present (Warrington et al., 1996). Early Jurassic sedimentation took place in fully marine environments, with sedimentary rocks reaching to latest Pliensbachian age still preserved in the area (Poole and Whiteman, 1966). Continued extension and sedimentation are indicated to have reached into the Early Cretaceous, and were followed by regional uplift and accompanying erosion from the Latest Cretaceous onward (Chadwick, 1997).

Evidence for Early Jurassic marine sedimentation is now only preserved in a small segment of the Cheshire Basin close to the bounding Wem fault in the southeast of the basin, the Wem-Audlem Sub-basin (Hesselbo et al., 2023; Evans et al., 1993; Poole and Whiteman, 1966; Figure 1). This sub-basin has been targeted for several deep drilling campaigns relating to oil and gas exploration, but also stratigraphic research. Geophysical, lithological and paleontological records for example were obtained for the drill sites Prees 1 (Evans et al., 1993; Penn, 1987), Wilkesley (Evans et al., 1993; Poole and Whiteman, 1966) and Platt Lane (Poole and Whiteman, 1966).

2 MATERIAL AND METHODS

2.1 The Wilkesley and Prees 2C Cores

Coring operations at Wilkesley were carried out from 1959 to 1960 by Foraky Boring and Shaft Sinking Company, 2.5 miles SW of Audlem (Single Onshore Borehole Index “SOBI” SJ64SW7). Vertical coring of this research core obtained for the British Geological Survey commenced at 255 ft (77.72 m) ordinance datum, reaching Jurassic strata at 58 ft (17.68 m) depth and a terminal depth of 5 531 ft 7 in (1 686.03 m below surface, mbs). The large diameter (ca. 18.3 cm diameter in the Jurassic part, Figure 2) Wilkesley core was largely broken up, but whole rounds of core material containing macrofauna and core fragments aggregated in bags at 1 ft spacing were retained and are available for study at the National Core Repository, British Geological Survey (BGS), Keyworth, UK. Geochemical analysis of the Wilkesley core is based on sub-samples taken from the aggregate bags in the depth range of 65 to 554 ft (19.81 to 168.86 mbs), while the ammonite biostratigraphy builds on a re-evaluation of the specimens earlier interpreted by Desmond Donovan (Donovan, 1966) and archived at the BGS, Keyworth.

Drilling for Prees 2 took place under the auspices of the International Continental Scientific Drilling Program (ICDP) in November 2020 to January 2021, and was carried out by PR Marriott Drilling Ltd (Hesselbo et al.,

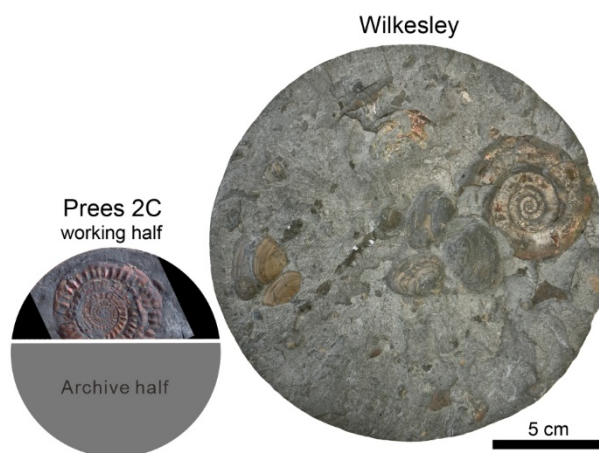


Figure 2. Comparison of Prees 2C and Wilkesley cores in terms of diameter and available portion to study for macrofauna. Prees 2C specimen is SSK120715, 562.11 mccd; Wilkesley specimen is AL 741, 138.30 mbs. The area available for ammonite study is nominally c. eight times smaller in Prees 2C versus Wilkesley due to differences in core diameter.

2023). The Prees 2C core (SOBI SJ53SE53) was drilled in close vicinity of the hydrocarbon exploration well Prees 1 (SOBI SJ53SE3), in a field west of Whitchurch Road and south of the access to Platt Farm (Northing 334478; Easting 355559). Coring was carried out in target core runs of 6 m length from 32.92 to 651.32 m corrected core depth (mccd, Hesselbo et al., 2023), and resulted in 97 mm diameter core in liner. The Prees 2C core was cut in half lengthways, creating an archive half for optical inspection and non-destructive analysis, and a working half that was broken up for biostratigraphic investigation, and sampling for geochemical and petrophysical properties (Figure 2). All of these materials were curated and archived at the BGS core repository in Keyworth. During sampling, special care was taken to maintain the correct stratigraphic sequence of core fragments within the working half. Element geochemical data were obtained on the archive half surface via core scanning X-ray fluorescence analysis, while ammonite and nannofossil finds, organic carbon content and isotope ratios relate to the working half.

2.2 Analytical Methods

Detailed analytical methods relating to the presented data for the two cores are available in the ESM I. In brief, calcareous nannofossil analysis was carried out on smear slides, counting 200 specimens per sample using a ZEISS polarising light microscope at 1 000× magnification.

Element concentrations were determined using portable XRF (Innov-X Delta Professional) for Wilkesley, with an estimated 2 r.s.d. (relative standard deviation) uncertainty of 2% for Ca and 9% for Rb/Zr based on multiple analysis of reference materials NIST2710a and 2711a. Element data for Prees 2C were obtained using a Cox Analytical ITRAX XRF core scanner, with sample spacing of 1 cm. Outputs of peak intensities were aver-

aged over intervals of 25 cm, with an estimated relative 95% confidence interval of $\pm 6\%$ for Rb/Zr ratios and better than $\pm 7\%$ for Ca.

Organic carbon isotope analysis of bulk rock powders was carried out after decarbonization with HCl and triple washing of the residuum with deionised water. Analyses for Wilkesley were done at University of Exeter, Penryn Campus, using a Sercon Integra IRMS, against calibrated in-house standards Sigma alanine ($\delta^{13}\text{C} = -19.62\text{‰}$) and bovine liver ($\delta^{13}\text{C} = -28.61\text{‰}$; TOC = 47.24 wt.%). Reproducibility of $\delta^{13}\text{C}$ was 0.14‰ or better for both standards, and better than 3‰ (2 r.s.d.) for carbon content of bovine liver. Analyses for Prees 2C were done at the British Geological Survey, Keyworth, using an IsoPrime IRMS with Elementar Vario ISOTOPE cube elemental analyzer. Measurements were calibrated against previously standardized in-house references B2162 (*Spirulina* algae, $\delta^{13}\text{C}_{\text{org}} = -18.7\text{‰}$) and BROCC3 ($\delta^{13}\text{C}_{\text{org}} = -27.6\text{‰}$) with a repeatability of better than 0.2‰ (2 s.d.) for $\delta^{13}\text{C}$ and better than 0.2% for (2 s.d.) for TOC.

Analytical data for nannofossil abundance, size, and taxonomic identifications for both cores are available as Tables S1–S3. Geochemical data for Wilkesley are listed in Table S4, while XRF data, and organic carbon isotope ratios and TOC values for Prees are given in Tables S5 and S6.

3 RESULTS

3.1 Geochemical Trends and Their Co-occurrence in Wilkesley and Prees 2C

Both the Wilkesley and Prees 2C record show distinct lithological and geochemical fluctuations that can be used to tie the two core records together and establish a reliable Hettangian stratigraphic framework for the Cheshire Basin (Figure 3).

The carbonate content of Hettangian strata in the Cheshire Basin is low compared to the UK lower Hettangian more generally, averaging 30% in the Wilkesley core. Both cores show a low point in carbonate content near the Rhaetian-Hettangian transition and a significant rise in CaCO_3 through the Tilmanni Zone. Carbonate content is then relatively stable, with two further intervals of low CaCO_3 encountered in the upper Portlocki Subzone of the Liasicus Zone. Following the latter low point, carbonate content in both cores rises and also exhibits higher-amplitude fluctuations which remain a permanent feature of the strata up to the top of the Wilkesley record.

The Rb/Zr ratios in the cores show a first order anti-correlation with carbonate content, where high Rb/Zr ratios, e. g., in the uppermost Rhaetian and the Portlocki Subzone, correlate with lows in carbonate content. However, further smaller-scale trends in the Rb/Zr record beyond this, for example a pronounced drop in Rb/Zr around the boundary between the Planorbis and Liasicus zones, allow for more detailed correlation between the two cores.

The TOC (of decarbonated material) is typically below 1% with a median of 0.83% in the Hettangian part of Wilkesley and a median of 0.78% in Prees 2C. However,

there are a series of organic matter enrichment intervals that cannot be explained by low carbonate dilution alone, with the most prominent organic-rich beds in the studied part of the cores seen in the upper Rhaetian and lowermost Jurassic, where TOC (of decarbonated material) can reach almost 8%. Additional intervals with various degrees of TOC enrichment occur occasionally in both cores in the Hettangian, and these also coincide with more strongly negative $\delta^{13}\text{C}_{\text{org}}$ values. Three prominent intervals of higher TOC are seen in the Planorbis Zone, two more well-developed spikes are present in the middle and uppermost Angulata Zone, and a set of lesser spikes characterises other intervals through the Hettangian succession.

3.2 Chemostratigraphic Correlation of the Wilkesley and Prees 2C Records

Taken together, the four geochemical tracers compiled for this study, Ca content, Rb/Zr ratio, TOC of decarbonated material, and $\delta^{13}\text{C}_{\text{org}}$ values allow for a highly resolved, robust correlation between the two core records (Figure 4, Table S7).

A generally slightly greater thickness of strata is observed in Prees 2C which is largely consistent throughout the Hettangian interval, yielding a sedimentation rate that is on average 14% higher in Prees 2C than in Wilkesley (Figure 5a).

The consistency of this trend, given the distance of 10.09 km between the two drill sites, suggests that at least at the stratigraphic resolution available for the Wilkesley core (c. 30 cm), there is no indication of differential preservation of strata in the Cheshire Basin. Also, the slightly higher sedimentation rate for Prees is not unexpected due to its position closer to the basin centre, providing somewhat more accommodation space through tectonic subsidence. This adds some confidence that local gaps in deposition would have been minor and a largely continuous record of carbon cycle changes was laid down in the Cheshire Basin in the Hettangian.

3.3 A Merged Ammonite Record for the Wilkesley and Prees 2C Cores

The detailed match of the chemostratigraphic records of Wilkesley and Prees 2C further allows merging of existing ammonite records for both cores into a common scheme (Figure 5b). This is particularly relevant for the Liasicus Zone, where the ammonite record of Wilkesley is rich and diverse, while ammonite finds from the Prees 2C core are scattered and identification beyond genus level not possible.

Using the stratigraphic tie points established from chemostratigraphy, core depths of ammonite specimens from Wilkesley were converted into the depth framework of Prees 2C, assuming constant sedimentation rates between these tie points, and an updated ammonite biozonation for both cores constructed (Table 1). The identification of zonal boundaries is principally based on an appraisal of the ammonite specimens in both cores, and yields a

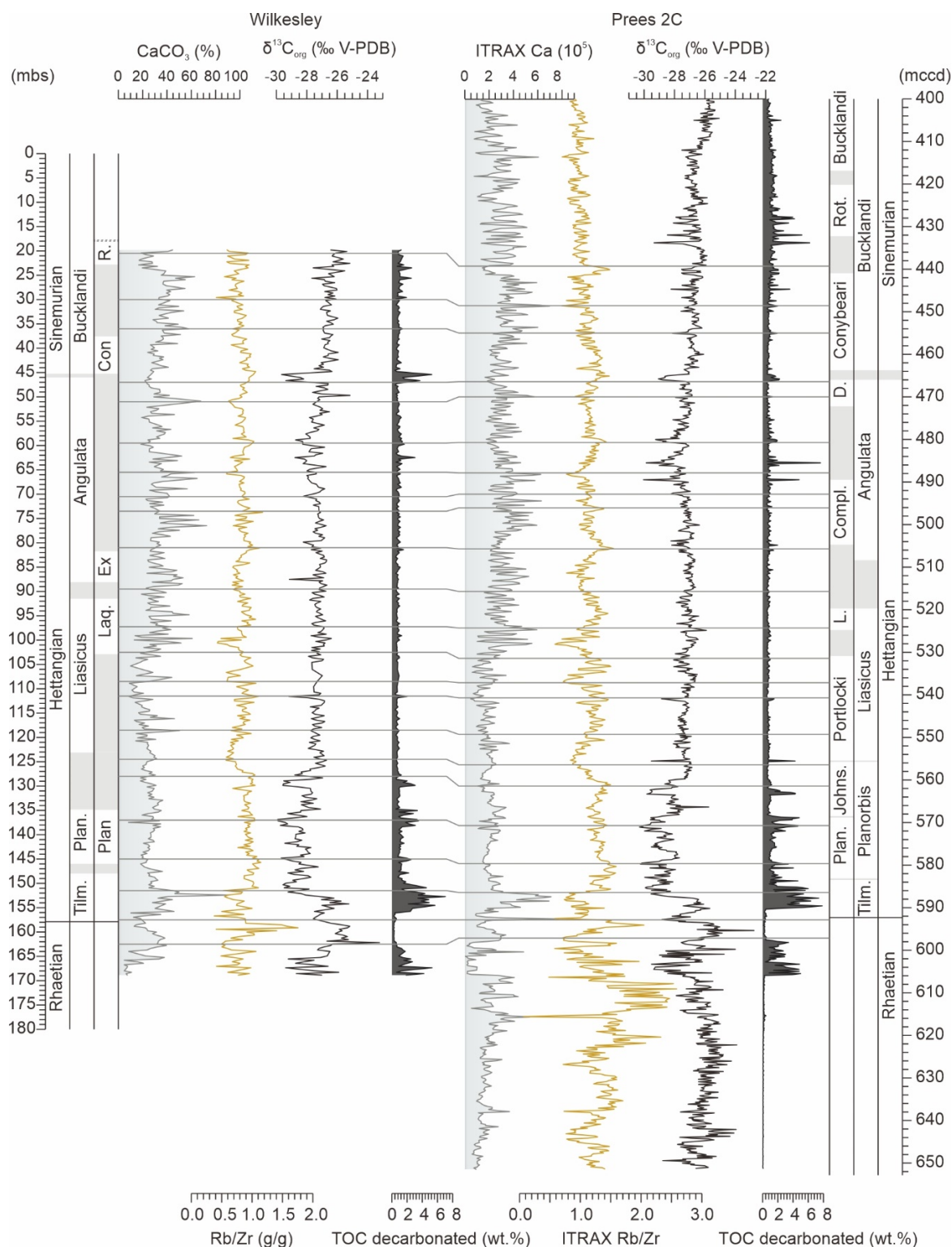


Figure 3. Chemostratigraphy, ammonite biostratigraphy, and correlation of the Wilkesley and Prees 2C records based on Ca, Rb/Zr, TOC and $\delta^{13}\text{C}_{\text{org}}$ values.

scheme which is in agreement within the uncertainty of chemostratigraphic resolution. However, the assignment of zonal ranges was additionally aided by chemostratigraphy in the case of the boundary of the Complanata and Extranodosa subzones within the Angulata Zone. The ammonite record of Wilkesley in the depth range of 80 to 67 mbs shows features compatible with the Extranodosa

Subzone, which conflicts with the more confident identification of the equivalent depth range in Prees 2C as Complanata Subzone. The Wilkesley ammonite record in this depth interval does not exclude representing the Complanata Subzone and hence, the lower boundary of the Complanata Subzone from Prees 2C, based on chemostratigraphic correlation, is adopted also for Wilkesley.

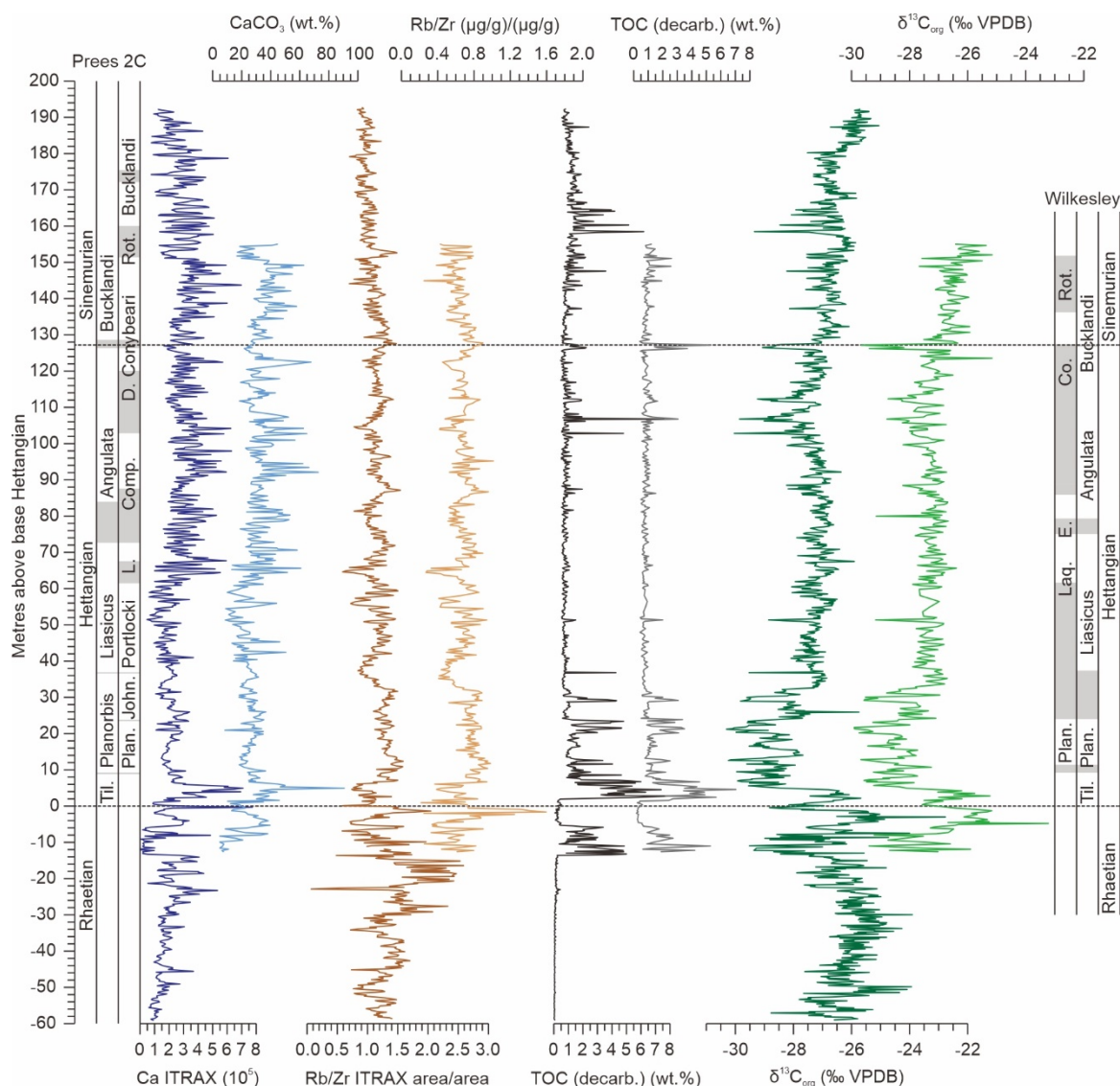


Figure 4. Correlation of Prees 2C (darker color, left curves) to Wilkesley (lighter colors, right curves) based on Ca, Rb/Zr, TOC and $\delta^{13}\text{C}_{\text{org}}$ values. The Wilkesley record is stretched to match Prees 2C.

3.4 A Merged Calcareous Nannofossil Record for the Wilkesley and Prees 2C Cores

The calcareous nannofossil record spans the base Hettangian to lower Sinemurian interval for the Wilkesley core and the upper Hettangian to the lower Sinemurian for the Prees 2C core. Preservation of the nannofossils in both cores is largely poor, especially in the Hettangian part, but somewhat better in Wilkesley than in Prees 2C (Figure 6).

Nannofossil abundance per surface area (mm^2) of the prepared slides measured for the Wilkesley core samples is relatively low (< 50 specimens per mm^2) and close to 0 for most of the Hettangian interval (up to 80 mbs/515 mccd; Tilmanni to Angulata Zone, Figure 7). From 515 mccd upwards, nannofossil abundance attains relatively high values and, although fluctuating, reaches maximum values of up to 130 specimens per mm^2 in the lower Sinemurian. In the Prees 2C core, the interval where absolute abundance of nannofossils (specimens per gram of rock)

has been measured, is shorter than at the Wilkesley core. Where there is stratigraphic overlap in the observations (from 506 to 437 mccd), the patterns in abundance are comparable, with relatively higher abundance in the middle Angulata and lower Bucklandi Zone, and an interval of lower counts in the upper Angulata Zone, reaching into the Bucklandi Zone. No clear co-variation of abundance with TOC or carbonate content is observed (Figure 7).

The Hettangian interval (Tilmanni to base of Angulata Zone) presents a very low nannofossil diversity. Only the *incertae sedis* *Schizosphaerella* spp. and sporadic occurrences of *Crucirhabdus primulus* are recorded (Figure 6, Table S3). This latter species is reported to first occur in the Late Triassic and range through the Triassic – Jurassic boundary (Bown, 1987). Such an assemblage allows the definition of the JL1 nannofossil zone of Bown (1987), defined as between the first occurrence of *S. punctulata* and the first occurrence (FO) of *P. liasicus*, and comparable with the base of the NJB1 zone of

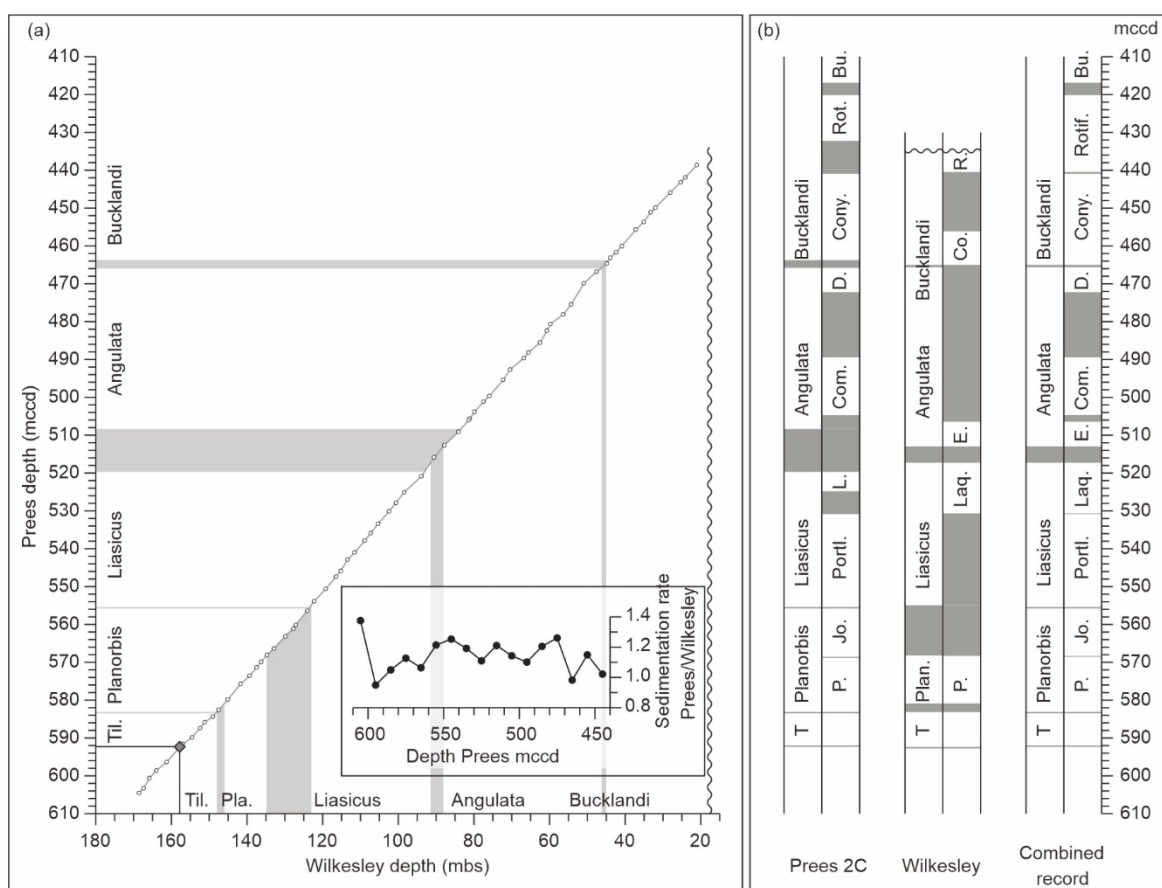


Figure 5. (a) Detailed correlation of Wilkesley and Prees 2C. Connected dots: chemostratigraphic correlation; grey diamond: placement of the top of the Langport Mb (top Lillstock Fm). Grey bars: position of ammonite zonal boundaries based on fossil evidence for either of the cores. Sedimentation rate differences between Prees 2C and Wilkesley averaged over 10 m intervals are shown in inset. Average difference between Prees 2C and Wilkesley is 14%. Til. = Tilmanni Zone. The Hettangian spans from the base of the Tilmanni Zone to the base of the Bucklandi Zone. (b) Ammonite zonation for Prees 2C (left) and Wilkesley (middle), and merged (right) based on chemostratigraphic correlation between the two cores. The resulting combined zonation scheme allows placement of most zonal and subzonal boundaries with much greater certainty, leaving only the Complanata-Depressa subzonal boundary with a high uncertainty.

Paulsen et al. (2023). This JL1 zone extends from the upper Rhaetian to the base of the Lower Sinemurian Bucklandi Zone. The FO of *P. liasicus*, which is used to define the base of the JL2 zone (Bown, 1987), is recorded at 49.07 mbs in the Wilkesley core, equivalent to 468.21 mccd, and at 464.52 mccd in the Prees 2C core. The base of this zone corresponds to the base of the Sinemurian and of the Bucklandi Zone, according to Bown (1987). In the Wilkesley core, the FO of *P. liasicus* is observed in the uppermost Hettangian, about three metres (2.90 ± 0.31 m) below the Hettangian-Sinemurian boundary as defined by ammonite stratigraphy. Contrasting this, in the Prees 2C core, this FO is in the lowermost Bucklandi Zone, 0.79 ± 0.31 m above the Hettangian-Sinemurian stage boundary. Within the stratigraphic resolution of the nannofossil sample sets for the two cores of ca. 4 m, these boundary positions are in agreement, however, and an uppermost Hettangian base of the NJ2 Zone is thus indicated for the Cheshire Basin.

The Lower Sinemurian in both sections shows a higher diversity of nannofossils than the Hettangian, both in terms of number of species and of morphologies.

Here, *Parhabdolites liasicus liasicus* and *Tubirhabdus patulus* first occur with different-sized morphotypes. Also, different morphotypes of *Crepidolites primulus* occur, attesting to a large morphological plasticity of this species (Figures 6 and 8). Amongst these latter, a transitional form between *C. primulus* and *P. liasicus* is found very close to the Hettangian-Sinemurian boundary that possesses a central structure (symmetrical cross) aligned with the axes of the ellipse, which is very reduced along its major axis. The first occurrence of *Mitrolites elegans* is recorded in both sections in the lower Sinemurian (Bucklandi Zone) in both Wilkesley (23.47 mbs) and Prees 2C (444.50 mccd) cores. This event was used to define the NJB2a Subzone of Paulsen et al. (2023). Other species (such as *Parhabdolites marthae* or *P. robustus*) have a very discontinuous distribution in the Wilkesley and Prees 2C cores. Furthermore, very sporadic occurrences of some *Crepidolites* (such as *C. timorensis*, *C. granulatus* and *C. crassus*) were noticed, but further, more detailed studies will be needed to ascertain the range of such species in the Cheshire Basin.

Table 1 Ammonite zone ranges in the Prees 2C and Wilkesley cores and combined scheme with depth ranges in corrected core depth for Prees and mbs for Wilkesley. Specimen number taken as diagnostic for identification of the boundary is given for both cores (Prees 2C: SSK; Wilkesley: registered specimens AL). Note that the base of the Tilmanni Zone is defined via a lithological boundary and is thus not merged for both cores

Stage	Zone	Subzone		Prees			Wilkesley			Combined	
				SSK	mbs	mccd	AL	mbs	eq	W-mbs	mccd
Sinemurian	Bucklandi	Bucklandi	Base	119541	416.82	416.88					416.88
Sinemurian	Bucklandi	Rotiforme	Top	119533	420.13	420.17	123	17.98	435.37		420.17
Sinemurian	Bucklandi	Rotiforme	Base	119510	432.22	432.26	135	22.78	440.48	22.78	440.48
Sinemurian	Bucklandi	Conybeari	Top	120878	440.90	440.96	173-5	37.57	456.14	23.22	440.96
Sinemurian	Bucklandi	Conybeari	Base	119428	464.30	463.73	191	45.26	465.00	45.26	465.00
Hettangian	Angulata	Depressa	Top	119454	466.18	465.98	198	46.02	465.61	46.02	465.61
Hettangian	Angulata	Depressa	Base	119684	472.20	472.23				52.32	472.23
Hettangian	Angulata	Complanata	Top	120012	489.54	489.47				66.63	489.47
Hettangian	Angulata	Complanata	Base	119445	504.68	504.72	340	79.55	503.51	80.45	504.72
Hettangian	Angulata	Extranodosa	Top	119440	508.31	508.37	344	81.74	506.45	81.74	506.45
Hettangian	Angulata	Extranodosa	Base	119440	508.31	508.37	349	88.09	512.98	88.09	512.98
Hettangian	Liasicus	Laqueus	Top	120010	519.80	519.70	355	91.47	517.28	91.47	517.28
Hettangian	Liasicus	Laqueus	Base	120008	524.89	524.79	409	102.90	530.67	102.90	530.67
Hettangian	Liasicus	Portlocki	Top	120021	531.03	530.86				103.07	530.86
Hettangian	Liasicus	Portlocki	Base	120741	555.46	555.41	555	123.01	554.94	123.35	555.41
Hettangian	Planorbis	Johnstoni	Top	120737	555.74	555.76				123.61	555.76
Hettangian	Planorbis	Johnstoni	Base	120883	568.42	568.53	683-5	134.82	568.23	135.08	568.53
Hettangian	Planorbis	Planorbis	Top	120884	568.75	568.86	687	134.90	568.32	134.90	568.32
Hettangian	Planorbis	Planorbis	Base	120905	584.76	583.10	796	146.00	580.90	147.94	583.10
Hettangian	Tilmanni		Top	120924	585.16	583.50	802	147.98	583.14	147.98	583.14
Hettangian	Tilmanni		Base	-	592.54	592.33	-	157.89	592.56	157.89	592.33

3.5 Carbon Isotope Events in the Cheshire Basin

The position of the Triassic-Jurassic boundary in the Prees 2C core has been defined on the basis of lithostratigraphy and placed provisionally at a level of 592.33 mccd, at the top of the Langport Member (Lilstock Formation, Penarth Group, Hesselbo et al., 2023). This level is in close proximity to the peak of a c. 4 m long negative carbon isotope excursion that—within available sample resolution of 20 cm—reaches the most negative $\delta^{13}\text{C}_{\text{org}}$ values at 592.78 mccd. This negative CIE of c. 3.5‰ magnitude falls into an interval of generally low TOC (0.2 wt.% to 0.4 wt.% TOC in decarbonated material) and is followed immediately by rising TOC, showing a first substantial increase to 2.0% (in decarbonated material) at 590.20 mccd.

Following a brief interval of comparatively stable $\delta^{13}\text{C}_{\text{org}}$ values fluctuating around -26.5‰, another negative CIE follows, which has a sharp onset with a 3‰ drop from -26.4‰ (588.08 mccd) to -29.5‰ (586.78 mccd) and ranges over ca. 30 m, above which $\delta^{13}\text{C}_{\text{org}}$ values consistently return to ca. -27.3‰ at 559.74 mccd. This more protracted CIE is structured by a series of negative spikes in $\delta^{13}\text{C}_{\text{org}}$ values which consistently coincide with spikes in TOC, even though the magnitude of these isotope spikes of typically 2‰ is not clearly correlated with the magnitude of TOC enrichment. The TOC in this interval is generally higher than in the latest Rhaetian part of

the core, with baseline values fluctuating around 1% in decarbonated material and individual spikes often exceeding 4%. Following a slight overall increase in $\delta^{13}\text{C}_{\text{org}}$ values throughout this negative CIE, the transition from values around 28.5‰ to near pre-excursion values of -27.3‰ is sharp, occurring over just 40 cm from 560.14 to 559.74 mccd.

Throughout the Hettangian and lower Sinemurian part of the Prees 2C record, modest but significant drifts in $\delta^{13}\text{C}_{\text{org}}$ values are observed which are punctuated by short-lived negative isotope spikes that coincide with TOC enrichments. Where TOC enrichments of 1.5 wt.% or greater are reached in decarbonated material, the Jurassic part of the studied record shows moderate to strong correlations between TOC and $\delta^{13}\text{C}_{\text{org}}$ values down to ca. 581 mccd (Figures 3 and 4). For 6-m intervals centred around such TOC enrichments, the median correlation coefficient for co-variation between TOC and $\delta^{13}\text{C}_{\text{org}}$ in this depth range is $r^2 = 0.65$ (0.26 to 0.86; $n = 108$). This correlation breaks down in the remaining Jurassic segment roughly equivalent to the Tilmanni Zone, where the median correlation coefficient for this co-variation is $r^2 = 0.01$ (0.00 to 0.07; $n = 30$).

To draw out the subtler trends within the Planorbis to Bucklandi zones with a minimal number of somewhat subjective data manipulation steps, a LOESS smoothing was run from 585 to 400 mccd where samples that have

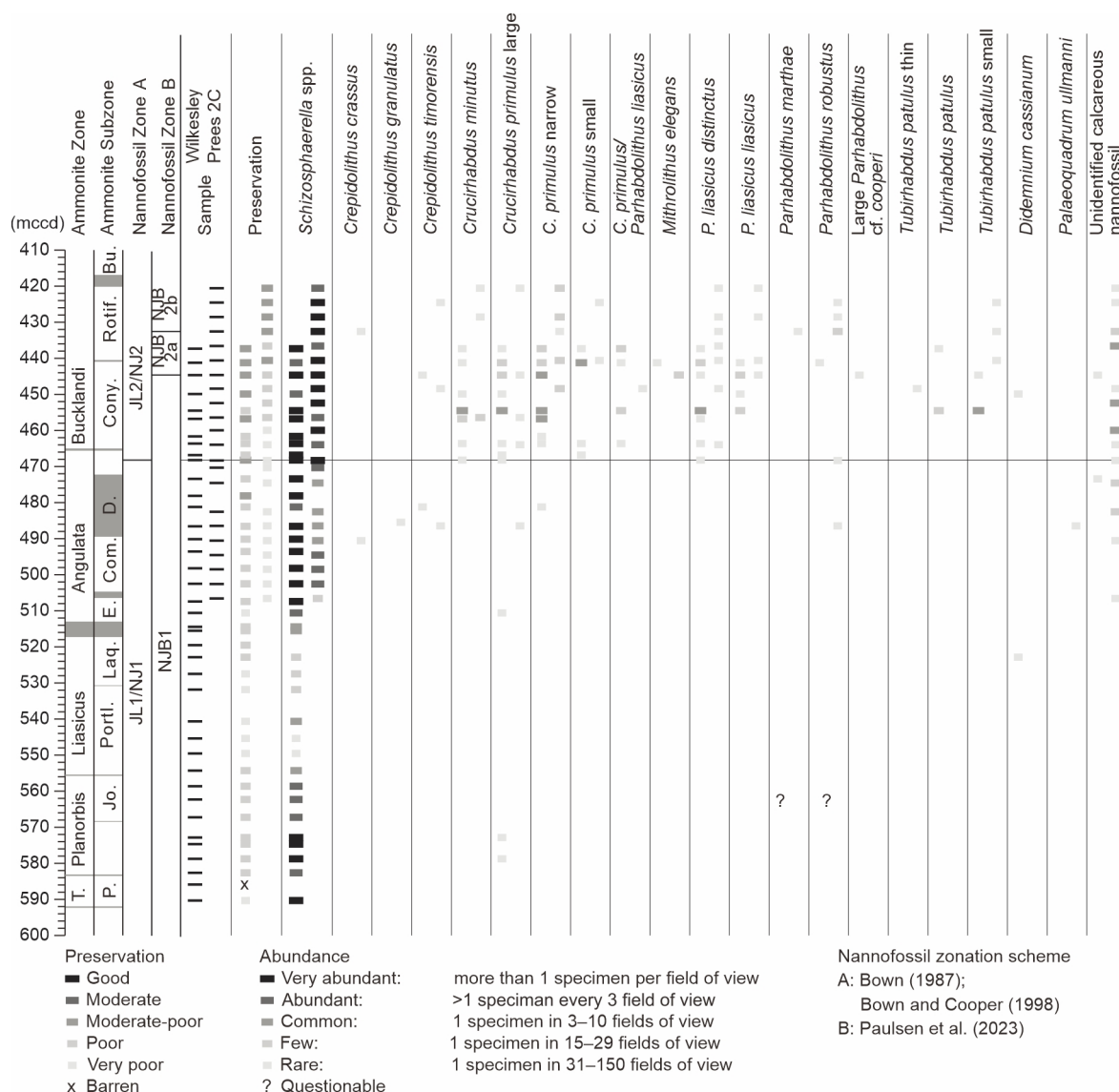


Figure 6. Distribution chart of calcareous nannofossils in the Wilkesley and Prees 2C cores. Information for Wilkesley core is on the left of individual columns, data for Prees 2C on the right.

decarbonated TOC of >1.5 wt.% were removed (Figure 9, Table S6). This smoothed record shows that above the prominent negative CIE located in the Tilmanni and Planorbis zones, $\delta^{13}\text{C}_{\text{org}}$ values continue to increase to about the zonal boundary of the Liasicus and Angulata zones, followed by a trend to slightly lower values which reach their minimum in the uncertain interval between the Complanata and Depressa subzones of the Angulata Zone. This is followed by a gradual rise through the Hettangian-Sinemurian boundary approximately up to the lowermost part of the Rotiforme Subzone of the Bucklandi Zone. Here, a transient, minor, negative excursion in $\delta^{13}\text{C}_{\text{org}}$ values is seen, which appears amplified in TOC-rich samples that occur more abundantly here than in any other part of the core above the Planorbis Zone. Beginning with the lower Bucklandi Subzone of the Bucklandi Zone, $\delta^{13}\text{C}_{\text{org}}$ values then show a comparatively steep rise to the end of the studied part of the Prees 2C record.

The $\delta^{13}\text{C}_{\text{org}}$ record of the Wilkesley core is compatible

with the Prees 2C record both in trends and absolute isotope ratios, barring minor deviations. These deviations can be explained by sampling of individual horizons of one to a few centimetres thickness in Prees 2C with 20 cm steps and rock fragments of similar stratigraphic range at 30 cm resolution in the case of Wilkesley, causing a degree of stratigraphic noise. Because of the inclusion of the Wilkesley $\delta^{13}\text{C}_{\text{org}}$ record in the proxy records used for correlation to Prees 2C, it is not described separately here.

4 DISCUSSION

4.1 A Spliced Ammonite Record for the Cheshire Basin

Splicing of core records is common and essential, e.g. in ocean and lake drilling projects, allowing for the correlation and construction of continuous core records from multiple parallel coring efforts affected by incomplete recovery (e.g., Hatfield et al., 2020; Tada et al., 2018). For

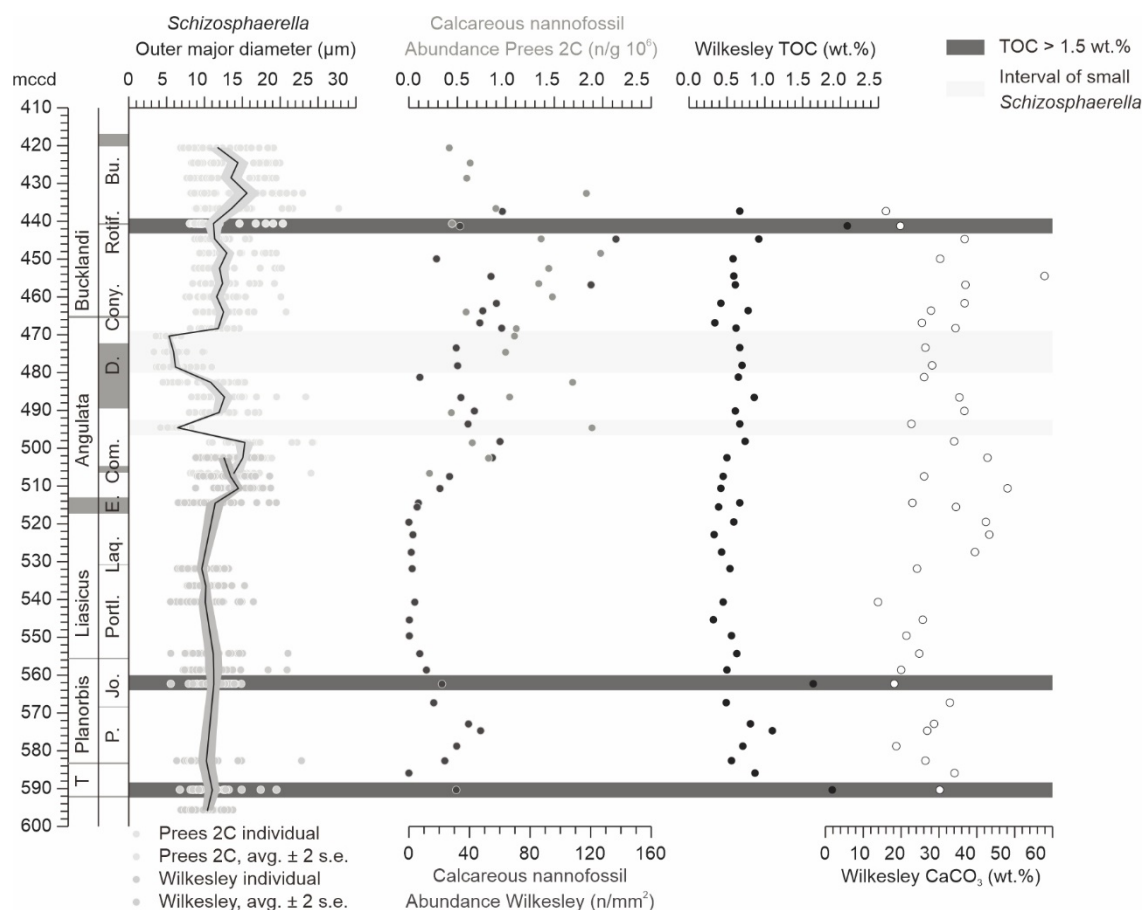


Figure 7. Individual size measurements and average with 2 s.e. confidence band for *Schizosphaerella* spp. measured in the Wilkesley and Prees 2C cores. Semi-quantitative (Wilkesley core) and absolute abundances (Prees 2C core) of calcareous nannofossils. TOC (bulk) and CaCO_3 data are shown for the Wilkesley core samples for which nannofossil abundance measurements were obtained. Dark grey bands denote samples with TOC > 1.5 wt.%. Light grey bands highlight the interval where *Schizosphaerella* spp. size is markedly reduced.

Mesozoic sequences, correlation of cores or boreholes on the basis of physical or geochemical properties is not unusual either (e.g., Evans et al., 1993; Penn, 1987), even though these are typically on multi-km scales. The use of drill core or outcrop records to improve the stratigraphic subdivision and robustness of zonal boundaries in key drill cores is still unusual for the Jurassic, likely because integrated stratigraphic schemes for this period are not yet fully developed. Furthermore, the principal subdivision of Jurassic strata below the stage level is based on ammonites (e.g., Hesselbo et al., 2020a; Hillebrandt et al., 2013; Bloos and Page, 2002), macrofossils that are not typically abundant in most core records. Few drill cores exist that have yielded (1) important chemostratigraphic records, (2) are complemented with highly resolved geophysical and geochemical data, (3) are sufficiently stratigraphically complete, and (4) are situated close to outcrop successions or other key drill cores to allow for improvements of their ammonite biostratigraphic constraints. The Llanbedr (Mochras Farm) core from the Cardigan Bay Basin (UK), for example, has been critical for Early Jurassic Earth system understanding (Fendley et al., 2024; Ullmann et al., 2022; Storm et al., 2020; Xu et al., 2018; Ruhl et al., 2016), but no local

Jurassic outcrop is available to further improve the biostratigraphy of this core. For other Early Jurassic basins in the UK, very few if any chemostratigraphic core records exist to supplement high quality information obtained from outcrop (Bristol Channel Basin, Xu et al., 2017; Hüsing et al., 2014; Ruhl et al., 2010; Wessex Basin, Schöllhorn et al., 2020). Conversely, published core records lack adjacent equally highly resolved records for outcrops to allow meaningful amendments of biostratigraphic schemes (Cleveland Basin, Beith et al., 2021, Larne Basin, Boomer et al., 2021).

The Cheshire Basin suffers from a lack of abundant surface exposure of Jurassic rocks, but the rich ammonite record of the Wilkesley drill core (Bloos and Page, 2000; Donovan, 1966) provides a valuable opportunity to refine the ammonite biozonation scheme of Prees 2C and the impact of its chemostratigraphic data. Using only chemo- and lithostratigraphic means to correlate between the two cores allowed us to import the ammonite record into the Prees 2C depth scale at the resolution at which core materials of the Wilkesley core were retained, i.e. nominally ~30 cm. Whilst the depth of ammonite specimens is known at greater precision as these were recorded with exact depth in feet and inches, the less ro-

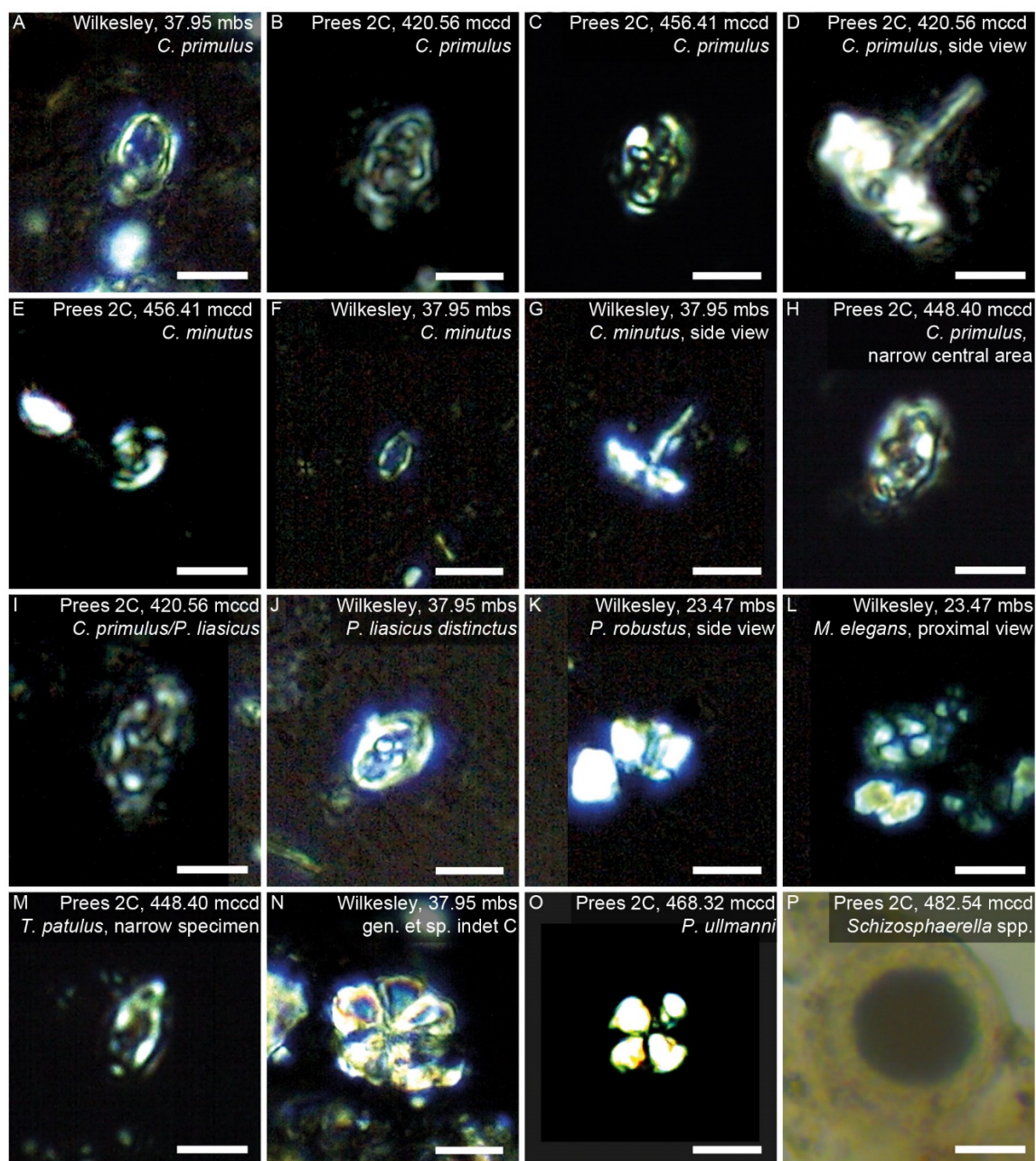


Figure 8. Various calcareous nannofossils as observed in the Wilkesley and Prees 2C cores. Scale bar is 5 µm. A–O: crossed polars; P: parallel polars, specimen filled with pyrite.

bust knowledge about the depth of chemostratigraphic tie points limits the resolution of this correlation. The combination of ammonite records from both cores more than doubles the number of specimens upon which the Cheshire Basin ammonite biozonation is erected (188 specimens up to 400 mccd at Prees 2C) with the addition of 293 Wilkesley registered ammonite specimens (Table 1). Improvement in the precision of zonal boundaries for Prees is especially prominent for the Liasicus–Angulata zonal boundary, for which the uncertainty of 519.70–508.37 mccd (11.33 m) could be narrowed to 517.28–512.98 mccd (4.30 m). A similar improvement in precision was achieved for the Conybeare–Rotiforme subzonal boundary from 440.96–432.26 mccd (8.70 m) to 440.96–

440.48 mccd (0.48 m) and the Portlocki–Laqueus subzonal boundary from 530.86–524.79 mccd (6.07 m) to 530.86–530.67 mccd (0.19 m). Whilst the majority of boundary positions in the studied interval is now constrained to within 1 m for Prees 2C, the boundary between the Complanata and Depressa subzones remains highly uncertain (17.24 m interval) because also the Wilkesley ammonite record is poor here.

One of the notable outcomes of this work is the revision of the biostratigraphic framework for the Wilkesley core to match current species concepts and a revised ammonite biozonation scheme (Table 1). When the ammonite fauna of Wilkesley was first assessed (Donovan, 1966), the Tilmanni Zone had not been defined, and two

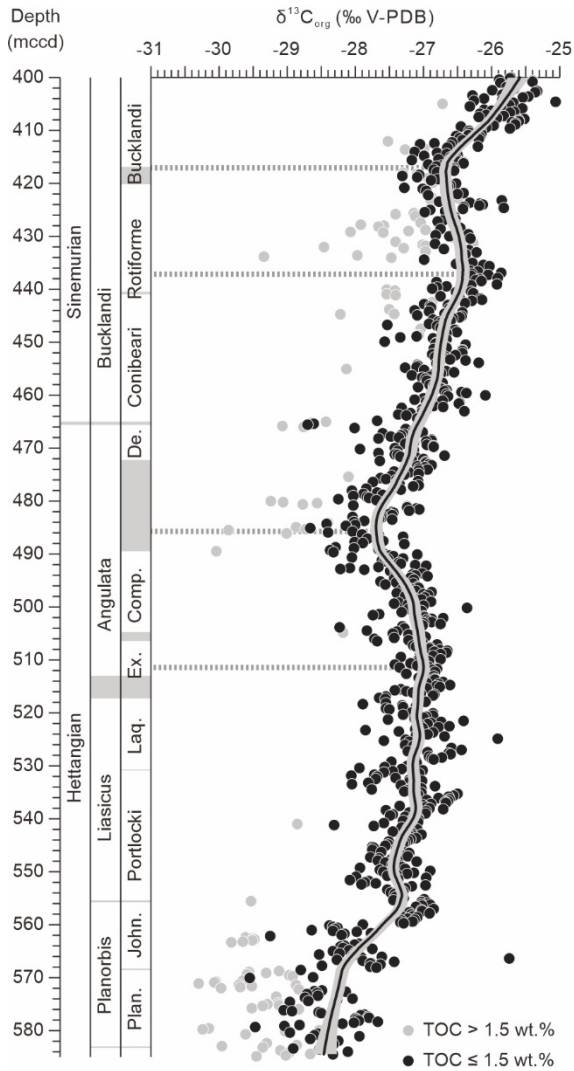


Figure 9. LOESS fit (0.1 smoothing factor) with 95% confidence band for organic carbon isotope ratios of Prees 2C samples in the depth range of 585 mccd (uppermost Tilmanni Zone) to 400 mccd (upper Bucklandi Zone), where TOC (of decarbonated material) is < 1.5 wt.%. Subtle, but significant swings in isotope ratios are present and inversions in isotope ratio trends discussed in the text are indicated with dotted lines. Raw data plotted as black dots were included in the fit and grey dots were excluded due to high TOC.

small ammonites (registered specimens AL128 and AL145) towards the top of the core had been tentatively assigned to *Euagassiceras* sp. This assignment implied the Sinemurian Semicostatum Zone, and therefore a very thin (upper) Bucklandi Zone in the core. Similar to Prees 2C, the Wilkesley ammonite zonation can also be improved based on the correlative ammonites from the other drill core, reducing uncertainties of some zonal boundaries markedly. Whilst nominally the Wilkesley core is less suitable for high resolution (chemo-)stratigraphic work than Prees 2C due to the lack of a retained archive half, this improvement in zonal boundary position is nevertheless meaningful. It is noteworthy that more than 700 registered specimens with depth information of inch precision exist for this core which could be utilized for further

comparative work.

Similar efforts could benefit existing legacy drill core material in UK and elsewhere, provided that chemostratigraphy for core and outcrops is available at sufficient resolution and geographic proximity (e.g. the Late Jurassic Kimmeridge Clay cores from the Dorset coast, UK; Morgans-Bell et al., 2001; Gallois, 2000).

4.2 *Schizosphaerella* Systematics in the Cheshire Basin

In line with previous findings from adjacent basins, *Schizosphaerella* spp. are present in the Wilkesley core even in the Earliest Jurassic sample from the Tilmanni Zone, and comprise the vast majority of nannofossils in the Hettangian (e.g., Paulsen and Thibault, 2023; Clémence et al., 2010). *Schizosphaerella* spp. is an enigmatic, rock-forming nannofossil which dominated the assemblages during the entire Early Jurassic. Recently, a striking morphological similarity between the Jurassic *Schizosphaerella* and the unicellular planktonic flagellates of the genus *Phacotus* (Chlorophyta, Chlamydomonadales) living in lakes of the temperate zone (Szeląg-Wasielewska et al., 2018) has been reported (Menini et al., 2021; Peti et al., 2021). The broader pattern of *Schizosphaerella* abundance shows very low values in the Liasicus Zone and a transient reduction in the upper Angulata Zone in the Cheshire Basin record (Figure 7).

A distinct reduction in size alongside a relative reduction in abundance is noted for *Schizosphaerella* in the middle to upper Angulata Zone in the Prees 2C core (Figure 8). *Schizosphaerella* size records for the Hettangian are not currently available from other areas, but a stratigraphically extended (Sinemurian to lower Toarcian) record for the Paris and Lusitanian Basins has been evaluated (Peti et al., 2021; Peti and Thibault, 2017; Suan et al., 2010). Size changes in *Schizosphaerella* in the Lusitanian and Paris Basins were interpreted largely as a consequence of temperature change, with small morphotypes of a size comparable to the smaller averages seen in the Angulata Zone of the Cheshire Basin linked to warmer temperatures and negative carbon isotope excursions (Peti et al., 2021; Suan et al., 2010).

Few quantitative paleotemperature data are available for the middle and upper Hettangian. However, if macrofossil $\delta^{18}\text{O}$ data from the Bristol Channel Basin are interpreted as indicative of temperature rather than salinity in the emergent Lurasian Seaway, they do not support a significant transient warming in the Angulata Zone (Hesselbo et al., 2020b). A loose connection with the negative $\delta^{13}\text{C}_{\text{org}}$ excursion observed in the Angulata Zone can be suggested, as the steepening of the descending limb of this excursion appears to be in close stratigraphic proximity to the size reduction in *Schizosphaerella* around 495 mccd. The peak of this excursion, however, evidences a recovery of *Schizosphaerella* size, and the stratigraphically more sustained size reduction between 480 and 470 mccd coincides with the increasing limb of the excursion.

4.3 Carbon Isotope Stratigraphy across the Triassic–Jurassic Boundary

Carbon isotope stratigraphy has been one of the most useful means of correlating End-Triassic to Earliest Jurassic strata over long distances (see Korte et al. 2018 for a review). This is particularly the case, because the designated marker of the base Jurassic, the ammonite taxon *Psiloceras spelae tirolicum* (Hillebrandt et al., 2013), is not found outside sections in the European Alps and only approximated by *Psiloceras spelae spelae* in South American successions (Hillebrandt et al., 2013). The definition for the base of the Jurassic was adopted in keeping with the traditional and ongoing practise to define Jurassic GSSPs via the first occurrence datum of an ammonite (Hesselbo et al., 2020a) as a unique and definite marker. The Kuhjoch section was chosen in part also because of its rich marine faunas, microflora, and potential for chemostratigraphic correlation (Hillebrandt et al., 2013). Importantly, significant and characteristic shifts in carbon isotope ratios occur here (e.g., Ruhl et al., 2009). When interpreted together with ammonite biostratigraphy, palynological and lithostratigraphic markers, these shifts allow for comparatively confident long-range correlations (e.g., Jeram et al., 2021; Ruhl et al., 2020; Korte et al., 2018; Figure 10), even though alternative options of correlation persist (Jeram et al., 2021; Lindström et al., 2017).

Through the debate about the detailed correlation of strata based on $\delta^{13}\text{C}_{\text{org}}$, the successions of Somerset (St Audrie's Bay and East Quantoxhead, e.g., Xu et al., 2017; Hüsing et al., 2014; Ruhl et al., 2010; Hesselbo et al., 2002) have gained an informal reference status. These coastal outcrops have been cyclostratigraphically calibrated (Weedon et al., 2019, 2018; Hüsing et al., 2014; Ruhl et al., 2010), studied for numerous proxies of stratigraphic relevance through the Hettangian Stage (Hesselbo et al., 2020b, 2002; Hüsing et al., 2014; Clémence et al., 2010; Paris et al., 2010; Ruhl et al., 2010; Warrington et al., 1994), and host the GSSP for the base Sinemurian (Bloos and Page, 2002). Thus, composite sections from the Somerset coast provide long, relatively continuous, records of paleoenvironmental proxies with stratigraphic relevance.

The largely agreed correlation of C isotope events across the Triassic–Jurassic transition between the GSSP at Kuhjoch (Ruhl et al., 2009) and St Audrie's Bay (Hesselbo et al., 2002) links a sharp negative carbon isotope excursion in the uppermost Rhaetian (the “initial CIE”, or End-Triassic extinction CIE) at the base of the Tiefengraben Mb at Kuhjoch to a similarly distinct negative CIE commencing in the uppermost Cotham Mb of the Lillstock Fm in St Audrie's Bay (Ruhl et al., 2020; Korte et al., 2018). Following a transient recovery in organic $\delta^{13}\text{C}_{\text{org}}$, a second negative isotope excursion is observed in close proximity to the first occurrence of *P. spelae tirolicum* at Kuhjoch (Hesselbo et al., 2020a; Hillebrandt et al., 2013), which can tentatively be linked to a small negative isotope excursion marking the base of the Blue Lias Formation at St Audrie's Bay (Korte et al., 2009; Hesselbo et al., 2004,

2002). Organic carbon isotope ratios then rise briefly in the Lowermost Jurassic Tilmanni Zone, before another, stratigraphically more expanded, negative excursion that has become known as the “main excursion” (Hesselbo et al., 2002) commences approximately midway through the Tilmanni Zone. The establishment of isotope trends in the Austrian GSSP section in this interval is impacted by tectonic movement and accessibility of sections (e.g., Ruhl et al., 2020; Lindström et al., 2017), complicating correlations on the basis of organic carbon isotopes. Smooth, albeit high-magnitude isotopic changes matching the main correlative horizons of the Kuhjoch Section in St Audrie's Bay, however, allow for the main UK reference sections to be matched to each other (Figure 10).

Based on lithological characteristics, TOC, and organic $\delta^{13}\text{C}_{\text{org}}$, the following correlation between Prees 2C and St Audrie's Bay can be proposed. The initial CIE, commencing in St Audrie's Bay near the top of the Cotham Mb at c. 12.6 m (Hesselbo et al., 2002) starts at 593.98 mccd and peaks at 592.78 mccd. Following a recovery to higher $\delta^{13}\text{C}_{\text{org}}$ values and continuously low TOC, a minor negative CIE coincides with a distinct enrichment in TOC and marks the boundary of the Lillstock Fm with the Blue Lias Fm in St Audrie's Bay (ca. 14.4 m, Hesselbo et al., 2002). The same simultaneous rise in TOC and minor negative CIE is seen in Prees 2C, with the first TOC-rich sample occurring at 590.20 mccd and the negative CIE beginning at 589.98 mccd.

As a potentially complicating factor, an erosional surface has been described for both the nearby Platt Lane and Wilkesley drill cores at the top of the Rhaetian (Warrington et al., 1996; Poole and Whiteman, 1966). Indeed, the Latest Triassic Langport Mb is described as only 0.18 m thick in Prees 2C (Hesselbo et al., 2023), where elsewhere in the UK, it typically extends over several metres. Were the Langport Mb essentially cut out of the sequence at Prees 2C, a minor negative CIE—located at c. 592 mccd in the Prees 2C core—could then represent the “initial CIE” identified at the top of the Langport Mb in St Audrie's Bay. However, given the ubiquitous association of the peak of this negative isotope excursion with an increase in TOC (Figure 10), it may equally be surmised that the 3 m of strata overlying the Langport Mb at Prees are time-equivalent to the upper Langport Mb elsewhere in Somerset despite showing an unusual lithological expression, and any hiatus on the top of the Langport Mb in Prees 2C is minor. Such lateral facies changes in the Langport Member have previously been proposed for other locations in Southern England, notably between Somerset and Dorset (Korte et al., 2009; Hesselbo et al., 2004). We thus prefer this latter option, as the implication of the former would introduce further speculative differences in sedimentation and sediment preservation between the Bristol Channel and Cheshire Basin.

Overall, however, the organic carbon isotope curves of St Audrie's Bay and Prees 2C in the interval from the Cotham Mb to the top of the Tilmanni Zone are highly similar, with a slightly more expanded succession in

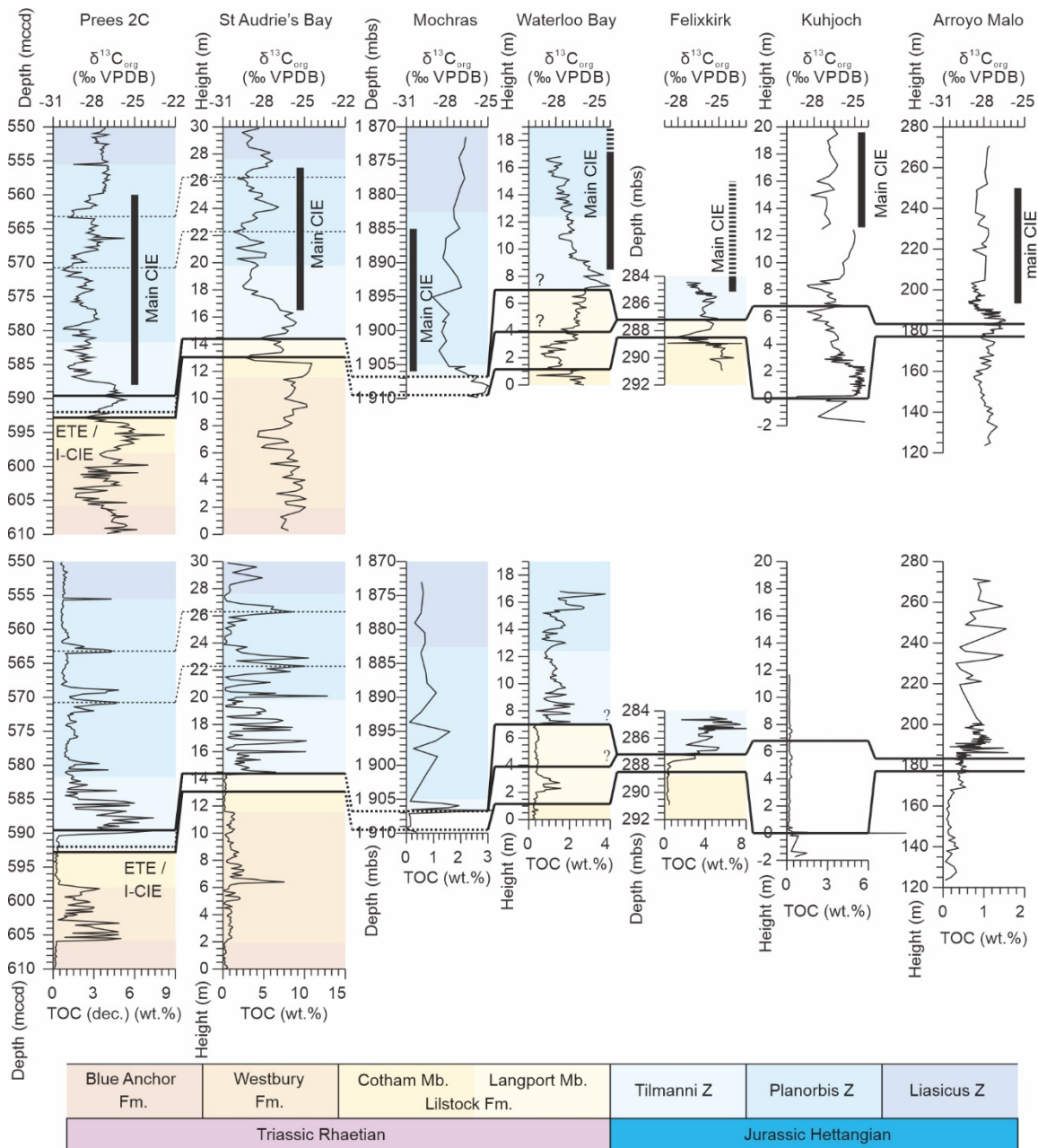


Figure 10. Detailed correlation of UK successions, the GSSP at Kuhjoch and the Argentinian Section at Arroyo Malo using $\delta^{13}\text{C}_{\text{org}}$ and TOC. Color code is based on lithostratigraphy for the Rhaetian part and ammonite biozonation for the Hettangian part in the UK successions. St Audrie's Bay, Somerset, UK: Ruhl et al. (2010), Hesselbo et al. (2002); Mochras core, Wales, UK: Storm et al. (2020); Waterloo Bay, Northern Ireland, UK: Jeram et al. (2021); Felixkirk core, Yorkshire, UK: Beith et al. (2021); Kuhjoch, Austria: Ruhl et al. (2009); Korte et al. (2018); Arroyo Malo, Argentina: Ruhl et al. (2020).

Prees 2C. This similarity supports that Prees 2C may be used as another reference section for this critical time interval, at least for (super-) regional correlation, even though some doubts have been voiced about the global significance of some of the carbon isotope trends across the Triassic–Jurassic boundary (Fox et al., 2020).

4.4 A New Carbon Isotope Reference for the Planorbis Zone

Cyclostratigraphic evaluation of the St Audrie's Bay—East Quantoxhead composite has been undertaken

based on the assumption that the coastal outcrops in Somerset represent essentially continuous sedimentation throughout the Hettangian (Hüsing et al., 2014; Ruhl et al., 2010). This assumption has since been challenged based on detailed ammonite assemblage comparison across southern UK outcrops, suggesting that substantial parts of the Planorbis Zone at St Audrie's Bay are in fact missing (Weedon et al., 2019). Indeed, the thickness of Planorbis strata at St Audrie's Bay is comparatively small, with less than 8 m assigned to this ammonite zone (Hesselbo et al., 2004), where in Prees 2C the Planorbis

zone is represented by a more than three times thicker interval of 26 m. Compared to this mismatch, the thicknesses of the Liasicus (30.2 m vs ca. 40 m) and Angulata (33.0 m vs ca. 50 m) zones are much more comparable between Somerset and Prees 2C, respectively. This highlights the convergence of sediment accumulation rates in the upper Hettangian, and lends support to the presence of more prominent gaps in the lower Hettangian successions of Somerset.

Distinct phases of organic matter enrichment coupled with negative spikes in $\delta^{13}\text{C}_{\text{org}}$ values occur both in Somerset and in the Cheshire Basin records of Wilkesley and Prees 2C (Figure 11).

Whether or not these isotopic and organic content features are of correlative value beyond individual basins is unclear, as they are more likely to reflect changes in the nature of organic matter and its preservation (e.g., Ruhl et al., 2020; Suan et al., 2015) than changes in $\delta^{13}\text{C}$ in the ocean-atmosphere system. However, the formation of metre-thick intervals of organic-rich mudstones suggests considerable perturbations in local depositional environments which conceivably may have affected adjacent basins in a similar fashion, especially if an orbital control on their occurrence is postulated (Storm et al., 2020; Xu et al., 2017; Ruhl et al., 2010).

According to ammonite assemblage comparisons, likely missing strata in the St Audrie's Bay record were assigned to the bottom, middle and top of the Planorbis Zone (Weedon et al., 2019). Tentatively, two intervals of organic matter enrichment in Prees 2C associated with negative CIEs culminating at 571 and 563 mcd can be matched to organic matter enrichment intervals with similar character at St Audrie's Bay, where negative CIEs are found at 22 and 26 m height (Figures 10 and 11). Based on these correlations, a substantial part of the lower and upper Planorbis Zone, and potentially between these two spikes, would indeed be missing in the Somerset outcrops. Following this argument, the much more carbonate-rich nature of the Planorbis Zone at St Audrie's Bay compared to the rest of the Hettangian in Somerset and the Planorbis zone in the Cheshire Basin (Figure 11) could also indicate a lack of detrital sediment deposition in this interval in Somerset.

If the Somerset record is indeed thus affected, the Prees 2C data allow gaps in this record to be filled, illustrating more confidently the extent of the main negative isotope excursion in organic carbon up to the middle of the Johnstoni Subzone of the Planorbis Zone and a return to less negative $\delta^{13}\text{C}_{\text{org}}$ values in the uppermost Planorbis Zone.

4.5 Hettangian Organic Carbon Isotope Stratigraphy, Local and Global Effects

4.5.1 A reliable $\delta^{13}\text{C}_{\text{org}}$ record representing a global signal

From the Planorbis Zone onwards, the Hettangian succession in Somerset is characterised by recurrent intervals of organic matter enrichment which coincide with

negative carbon isotope spikes. The close connection of TOC content with isotope ratios suggests that the associated carbon isotope spikes are not a meaningful reflection of changes in the carbon isotope ratios of the ocean-atmosphere system, but rather dominated by changes in the type of organic matter preserved in the strata (Ruhl et al., 2020; Suan et al., 2015). Given that marine organic matter in the Early Jurassic is depleted in ^{13}C compared to co-eval terrestrial organic matter (e.g., Suan et al., 2015; Hesselbo et al., 2007), discrete intervals of distinct organic matter enrichment are thus interpreted here to reflect an increased proportion of marine organic matter.

While such intervals of TOC enrichment are locally significant and important for understanding basinal processes, a global reference organic carbon isotope record for the Hettangian would ideally be devoid of such local overprints. At the same time, stratigraphic completeness, biostratigraphic control and resolution of available chemostratigraphic records are critical, and there currently is no published record superior to the Somerset coast with regard to all these latter criteria. The Cheshire Basin $\delta^{13}\text{C}_{\text{org}}$ has the potential to match and surpass the Somerset record in these aspects, with > 600 $\delta^{13}\text{C}_{\text{org}}$ data for the Hettangian interval, a thicker and potentially more complete sequence, and well-constrained biostratigraphy. Importantly, the Cheshire Basin also features only very few intervals in the Liasicus and Angulata zones where significant TOC enrichments are observed (Figures 3 and 11). Analogous to the Hettangian-Sinemurian strata in Somerset, these enrichments are interpreted here to be linked with a substantially higher proportion of marine organic matter with distinct isotopic composition. Excluding these intervals from consideration by limiting the isotope dataset to samples with TOC less than 1.5 wt.% (in decarbonated material) reveals subtle changes in carbon isotope ratios which may be of global relevance (Figure 9). By extension, these trends may enable valuable insights into the biotic recovery following on from the End-Triassic mass extinction.

4.5.2 Comparison of Cheshire Basin organic carbon ratios to carbonate records

Few coherent carbonate carbon isotope records exist for the Hettangian, but continuous records for the entire Hettangian have been generated for Val Adrara (Italy, van de Schootbrugge et al., 2008), the Carnduff 2 core (Northern Ireland, UK, Boomer et al., 2021) and the Mochras core (Wales, UK, Ullmann et al., 2022). Neither the Carnduff 2 nor the Mochras carbonate record are likely to have retained $\delta^{13}\text{C}_{\text{carb}}$ values without significant post-depositional modification (Ullmann et al., 2022), even though they feature clear isotopic perturbations that are of global significance. In Italy, absolute $\delta^{13}\text{C}_{\text{carb}}$ values in the lower Hettangian reach a maximum similar to that seen in oysters from Lavernock Point (South Wales, UK, Korte et al., 2009) and a protracted decline in carbonate carbon isotope ratios follows that is akin to that of oysters in the Bristol Channel Basin (Hesselbo et al., 2020b, Figure

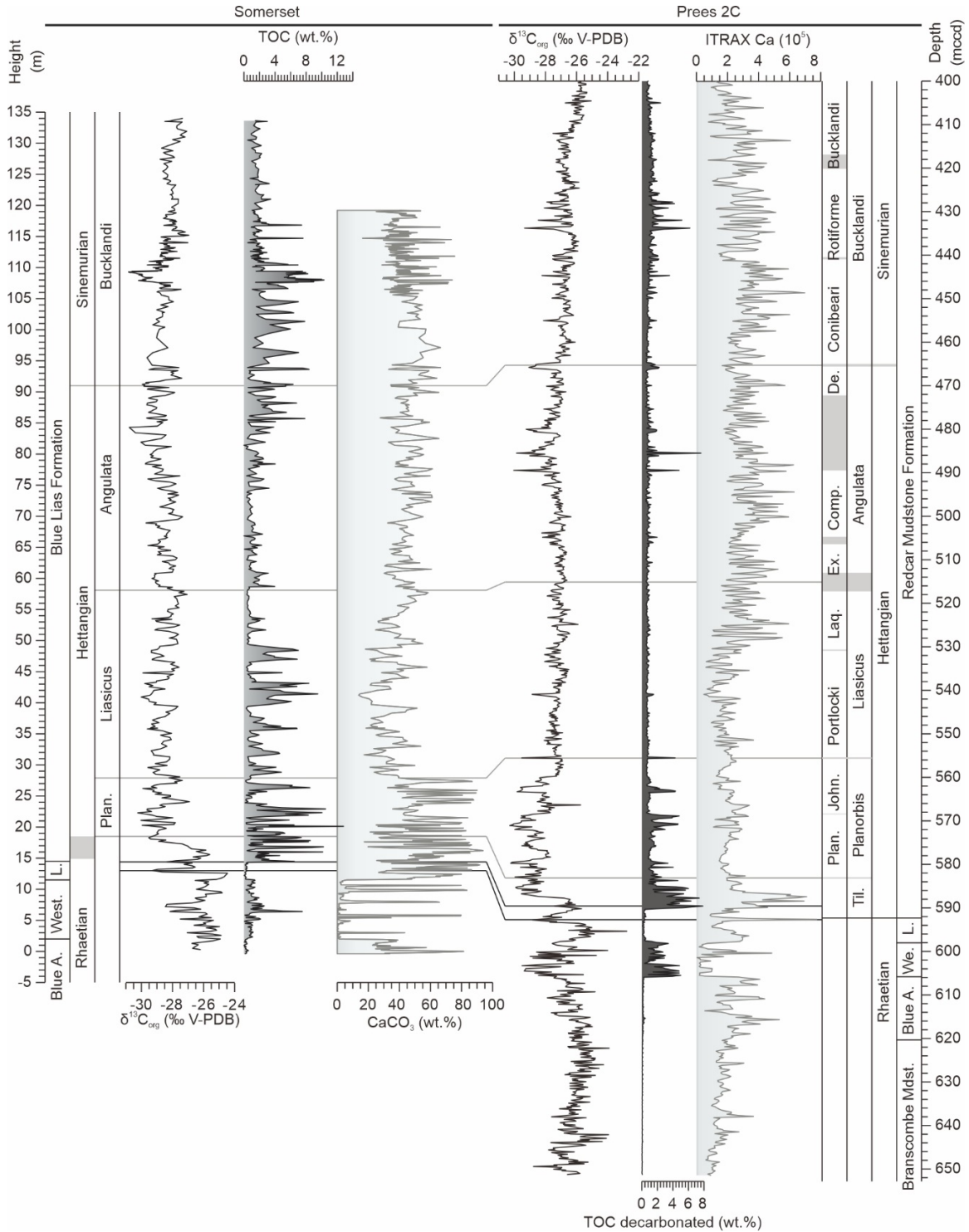


Figure 11. Comparison of organic carbon isotope ratios, TOC, and carbonate content in the Somerset outcrops (left, data from Xu et al. (2017); Hüsing et al. (2014); Ruhl et al. (2010); Hesselbo et al. (2002)) and Prees 2C (right). Grey correlation lines are drawn based on ammonite biostratigraphic constraints for zonal boundaries, black correlation lines near the TJ boundary on the basis of chemostratigraphic markers. The significantly thicker Planorbis Zone of Prees 2C shows a clear expression of the main negative CIE and much lower average carbonate content, pointing at lower chances of substantial gaps in deposition. The less prominent development of TOC enrichment intervals in Prees 2C as compared to Somerset above the Planorbis Zone is also evident.

12). However, shifts in isotopic ratios also align closely to changes in lithology in the Italian succession, and the rate of isotopic change is significantly different to the observed organic carbon isotope trends from the Cheshire

Basin even when taking into account that biostratigraphic control and variations in sedimentation rate are poorly constrained in shallow marine carbonate sections (Bachan et al., 2012).

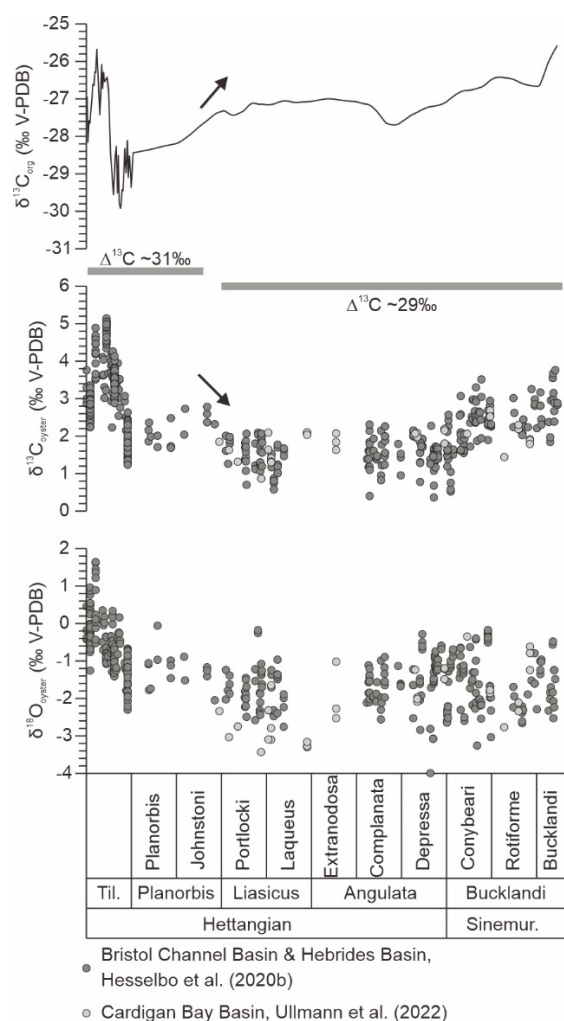


Figure 12. Prees 2C $\delta^{13}\text{C}_{\text{org}}$ data in comparison with coeval $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ data from the Bristol Channel Basin and Hebrides Basin (Hesselbo et al., 2020b), and the Cardigan Bay Basin (Ullmann et al., 2022), plotted against ammonite subzones of equal thickness. Prees 2C organic carbon data for the Tilmanni Zone are plotted as measured, while the LOESS fit is shown for the Planorbis to Bucklandi zones. Grey bars show approximate difference in carbon isotope ratios between organic matter and carbonate. Til. Tilmanni.

A more direct comparison of the Cheshire Basin record can be made through the published macrofossil carbon isotope record for the Hettangian of South Wales and Somerset (UK, Hesselbo et al., 2020b, Figure 12). This carbonate carbon isotope record supports key features of the organic carbon isotope trends seen in the Cheshire Basin. Particularly, both datasets share a positive excursion in the lower Tilmanni Zone followed by a large downward shift that is terminated in the Johnstoni Subzone of the Planorbis Zone. Comparatively little change is seen in the Liasicus and Angulata zones until a rise in carbon isotope ratios commences tentatively in the Depressa Subzone of the Angulata Zone that reaches into the upper Bucklandi Zone—transiently interrupted in the Rotiforme Subzone. The one major difference between the two records occurs at the end of the Johnstoni Subzone, where the organic carbon isotope record suggests the return

from negative carbon isotope ratios of the main carbon isotope excursion, while the carbonate record shows a further decline in $\delta^{13}\text{C}$. Tentatively, this opposing trend may be linked to a gradual reduction in atmospheric $p\text{CO}_2$ and therewith reduced fractionation of carbon between organic and inorganic carbon (Kump and Arthur, 1999). However, oxygen isotope ratios from macrofossils, if taken to reflect changes in paleotemperature rather than the isotopic composition of ambient water, do not support such an interpretation. Where the isotopic difference between carbonate and organic matter carbon isotope records decreases, a tentative warming reflected by decreasing carbonate $\delta^{18}\text{O}$ is observed (see also Hesselbo et al., 2020b). Given the unknown contributions of marine and terrestrial organic matter to the organic carbon record in the Cheshire Basin and other likely complicating factors affecting organic matter carbon isotope fractionation (e.g., Hinga et al., 1994), a combination of factors were likely at play generating the observed differences in $\delta^{13}\text{C}_{\text{org}}$ and $\delta^{13}\text{C}_{\text{fossil-calcite}}$ trends (Bachan et al., 2012).

5 CONCLUSIONS

Correlation of the core records of Wilkesley and Prees 2C allowed for the combination of biostratigraphic constraints from ammonites and calcareous nannofossils found in both cores, yielding a detailed ammonite biozonation scheme for the Cheshire Basin that is complete at the subzone level. The comparatively expanded Hettangian sequence in the Cheshire Basin of c. 127 m thickness in Prees 2C is thus found to be devoid of extended gaps in deposition at least at the resolution of this scheme.

Organic carbon in the Cheshire Basin shows episodic enrichments in the Hettangian and lower Sinemurian linked with enrichment of ^{12}C in organic matter, tentatively linked to phases of enhanced marine organic matter preservation. These TOC enrichments are akin to, but less pronounced than those in the Bristol Channel Basin, allowing for a more confident assessment of Hettangian carbon cycle changes based on organic matter chemostratigraphy.

A series of minor carbon isotope events are constrained, with a positive trend following the main isotope excursion of the Planorbis Zone lasting to the lowermost Angulata Zone, a c. 1 permil sized negative carbon isotope excursion in the middle Angulata Zone and a continuous rise for the remainder of the Hettangian. A continued rise in carbon isotope ratios until approximately the lowermost Rotiforme Subzone of the lower Sinemurian Bucklandi Zone is then interrupted by a transient, slight decrease in the Rotiforme Subzone, followed by a steeper rise in the lowermost Bucklandi Subzone of the Bucklandi Zone.

Calcareous nannofossils show a diversification event in the lower Sinemurian Bucklandi Zone, where also abundances increase. This might correspond to an evolutionary pulse following the extinction event at the Triassic-Jurassic boundary. The size of *Schizosphaerella*

spp., an enigmatic nannofossil very common in Lower Jurassic rocks, shows a drastic size reduction concomitant with the negative organic carbon isotope excursion observed in the Angulata Zone.

The successful merger of ammonite records from Wilkesley and Prees 2C underlines the potential for the construction of integrated stratigraphies from drill core records and supports the establishment of Prees 2C and therewith the Cheshire Basin as an additional, reliable reference of Hettangian chemostratigraphy.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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