Palynology of the Cenomanian to lowermost Campanian (Upper Cretaceous) Chalk of the Trunch Borehole (Norfolk, UK) and a new dinoflagellate cyst bioevent stratigraphy for NW Europe

Martin A. Pearce ^{a,b,1}, Ian Jarvis ^b, Philip J. Ball ^c, Jiri Laurin ^d

^a Evolution Applied Limited, 2 A P Ellis Road, Upper Rissington, Cheltenham, Gloucestershire GL54 2QB, UK

^b Department of Geography, Geology and the Environment, Kingston University London, Penrhyn Road, Kingston-upon-Thames KT1 2EE, UK

^c Geography, Geology and the Environment, Faculty of Natural Sciences, Keele University, Newcastle ST5 5BG, UK

^d Institute of Geophysics, Academy of Sciences of the Czech Republic, Boční II/1401, Praha 4, Czech Republic

¹ Email: info@evolutionapplied.com

Abstract

A high-resolution palynological analysis of the Cenomanian to Lower Campanian in the Trunch borehole, Norfolk (southern North Sea basin) is documented. This constitutes the most detailed continuous record of organic-walled dinoflagellate cysts (dinocysts) from a single Upper Cretaceous section to date. A revised stratigraphic framework for the Trunch succession is presented, integrating regional marker bed lithostratigraphy, macrofossil biostratigraphy and carbon-isotope chemostratigraphy. Palynological events at Trunch are compared to published records with an emphasis on NW Europe, and a new stratigraphy comprising 65 dinocyst events is proposed. A geochronological age model based on radioisotopic and astrochronological ages of macrofossil biostratigraphic datum levels and global carbon-isotope events (CIEs) is used to revise the age calibration of the Upper Cretaceous $\delta^{13}\text{C}_{\text{carb}}$ carbonate reference curve for the English Chalk, and to calculate absolute ages for the palynological events with an accuracy judged to be ± 500 kyr. The palaeogeographic distribution of key taxa is presented based on records obtained from the Palynodata database and additional records, summarised to 212 sites world-wide. Endemic NW Europe, Northern Hemisphere wide and global species distributions are demonstrated. A taxonomic and detailed stratigraphic discussion is provided to determine the likelihood that the events may be considered as global first or last appearance datum levels, or are local to regional lowest and highest occurrences. Four global, 18 Northern Hemisphere and 43 NW Europe events are tabulated, including 28 inceptions or extinctions of marker species; an additional 37 events may be of regional significance.

Keywords:

Dinoflagellate cysts; Biostratigraphy; Carbon isotopes; Chemostratigraphy; Upper Cretaceous; Chalk.

1 Introduction

The Upper Cretaceous chalks of northwest Europe have been proven to be extremely rich in diversity and abundance of organic-walled dinoflagellate cysts; hereafter dinocysts (Clarke and Verdier, 1967; Kirsch, 1991; Prössl, 1992; Schiøler, 1992; FitzPatrick, 1995; Slimani, 2001a; Prince et al., 1999; 2008; Dodsworth, 2000, 2004a, b; Pearce et al., 2003, 2009; Surlyk et al., 2013; Olde et al., 2015a, b; 2016), which provide a means to potentially correlate successions to a very high resolution. The chalks of southern UK are particularly important as they were deposited in relatively shallow palaeo-water depths of 100 – 500 m (Hancock, 1975; Kennedy and Garrison, 1975; Mortimore et al., 2001) and have subsequently experienced minimal burial. Porosity – depth trends for normally compacted chalk from the North Sea (Mallon and Swarbrick, 2002), and fission track data and exhumation estimates (Japsen, 1997; Souque et al., 2019), suggest maximum burial depth of around 500 – 800 m in East Kent, up to approximately 1500 – 2000 m for the East Yorkshire Chalk (Welch, 2015). Tectonic deformation is limited and exposures generally exhibit only very minor faulting.

The Cenomanian to Campanian is widely accessible at outcrop, where the macrofossil biostratigraphy can also be employed, which has enabled detailed holostratigraphic studies (e.g. Jarvis et al., 1988a, b; Hampton et al., 2007; Thibault et al. 2016). The UK chalks also form the basis for the high-resolution (~1 m) Cenomanian – Lower Campanian carbonate $\delta^{13}\text{C}$ reference curve of Jarvis et al. (2006) that has been widely employed as a global standard for Late Cretaceous carbon isotope events (CIEs).

Due to the limited stratigraphic extent of exposed sections and deformation of the upper parts of the Chalk in Norfolk, the British Geological Survey (BGS; then known as the Institute of Geological Sciences) cored the Trunch borehole during 1974 – 1975 to recover the Chalk at its most complete development in Britain. Almost 641 m of Cenomanian – ?Lower Maastrichtian chalk (as originally defined by the BGS; since reinterpreted as uppermost Campanian, Voigt et al., 2012) was recovered and classified according to the zonal and lithostratigraphical scheme of Peake and Hancock (1961).

Palynological (quantitative and absolute abundance) and stable isotope (carbonate $\delta^{13}\text{C}$, $\delta^{18}\text{O}$) results for the Cenomanian to Lower Campanian at Trunch, calibrated using lithostratigraphic marker beds, macrofossil biostratigraphy and carbon isotope chemostratigraphy, are presented here. Abundant and diverse dinocyst assemblages

have been recovered, incorporating 184 species and subspecies. Biostratigraphic markers and other species displaying conspicuous events in the Trunch borehole will be discussed in detail. A new age model based on radioisotopic and astrochronological ages of macrofossil biostratigraphic datum levels and global CIEs, has been produced to determine absolute ages for the bioevents. The palaeogeographic extent of the marker taxa and their associated events will be assessed based on a comprehensive literature review, including taxonomic assessment of published data. A new palynological event stratigraphy for the Cenomanian to Lower Campanian is proposed.

1.1 Previous palynological studies of the UK Chalk

The first studies of Upper Cretaceous dinocysts from England (Reade, 1839; White 1842, 1844; Mantell, 1845, 1850; Deane, 1849; Wilkerson, 1849) were primarily taxonomic in nature and comprise descriptions of taxa observed in fragments of flint. Following a significant absence of published work, a rejuvenation of research occurred in the late 1960's, continuing to the present day.

Cookson and Hughes (1964) published the first account of the biostratigraphic distribution of dinocysts in the mid-Cretaceous of England. Their study of the Cambridge Greensand (Upper Albian – Cenomanian) included several new taxa as well as detailed stratigraphic information. This work was succeeded by Davey and Williams (1966a, b), Davey et al. (1966) and Davey (1969, 1970) in a series of essentially taxonomic studies of dinocysts, describing many new genera and species, including some stratigraphic details.

The first attempt to subdivide the Upper Cretaceous succession into a formal dinocyst biozonation scheme was made by Clarke and Verdier (1967) in a seminal paper on the Chalk of the Isle of Wight. Prince et al. (1999) showed that the original stratigraphic interpretation of Clarke and Verdier (1967) was flawed with respect to the position of the Santonian – Campanian boundary; nonetheless that work has remained the stratigraphically most comprehensive palynological analysis of the English Chalk, prior to the present work.

Following the pioneering research of Clarke and Verdier (1967), published palynological studies on other UK sections have been sparse. Although detailed in many cases, published studies have been based on sections with either a short stratigraphic range (Tocher and Jarvis, 1987, 1996; Jarvis et al., 1987, 1988a, b; FitzPatrick, 1995;

Dodsworth, 1996, 2000), and/or a significant palaeoenvironmental overprint (Prince et al., 1999, 2008; Pearce et al., 2003, 2009).

Finally, the English Chalk continues to yield new species. Recently, four new genera, twenty-seven new species and subspecies, and four new combinations of dinocysts were described from southern and eastern England by Prince et al. (1999, 2008), Pearce (2010, 2018), Pearce et al. (2011) and Pearce and Williams (2018).

2 Regional context of Trunch and the north Norfolk Chalk

It has been long recognised that the Chalk of northern and southern England displays significant lithological and faunal differences (e.g. Phillips, 1829; Mitchell, 1836; Barrois, 1876; Blake, 1878; Mortimer, 1878; Hill, 1898; Jukes-Browne and Hill, 1903, 1904; Rowe, 1904; Wright and Wright, 1942). In southern England the Chalk rests on Upper Greensand or Gault Clay, which is replaced by the Red Chalk (Hunstanton Formation) to the north (**Figs 1 – 2**). In general, the chalks of southern England are weakly lithified and readily yield well-preserved fossils (e.g. Smith and Batten, 2002), whereas northern chalks are typically cemented and exhibit prominent stylolites.

Around the Cenomanian – Turonian boundary, the Plenus Marls (**Fig. 2**) of southern England and northern France are replaced in Lincolnshire and Yorkshire by the Black Band and Variegated Beds (Jefferies, 1963; Wood and Mortimore, 1995; Hart, 2019). Flints typically appear in the Middle to Upper Turonian in the south and continue throughout the higher Chalk succession; they are absent from the mid-Santonian to Lower Campanian in northern England (Flamborough Chalk Formation). Flints types also differ between the two regions: in the south they consist predominantly of black-cored small nodular flints; successions in the north are dominated by grey-cored thick tabular flints (Mitchell, 1836; Mortimore and Wood, 1986).

The differences between southern and northern chalks have resulted in the development of discrete lithostratigraphic schemes for the two areas (Wood and Smith, 1978; Mortimore, 1986; Whitham, 1991, 1993; Bristow et al., 1997; Mortimore et al., 2001; Rawson et al., 2001; Hopson, 2005; Mitchell, 2019; **Figs 1 – 2**). By contrast, as first noted by Barrois (1876), much closer similarities exist between the Chalk of Yorkshire and that of northern Germany, and between the Chalk of southern England and that of the Paris Basin.

2.1 Chalk provinces

The different characteristics of the Chalk in southern and northern England has led to the concept of Southern and Northern Provinces with distinct lithological successions and fossil assemblages (Wood and Smith, 1978; Mortimore, 1983, 1986; Mortimore et al., 2001; Mortimore, 2014a), exemplified by those of Wiltshire, Hampshire, the Isle of Wight, Sussex, Surrey and Kent in the south, and of Lincolnshire and Yorkshire in the north (**Fig. 1**). Between these two regions lies a Transitional Province with mixed lithological and faunal characteristics that vary both geographically and stratigraphically. These changes are gradational and views concerning the placement and extent of the Transitional Province have varied widely. The southern boundary has been placed as far south as London (e.g. Hopson, 2005; Mortimore, 2014b), broadly following an east – west line immediately to the north of the Variscan Front (Busby and Smith, 2001), or as far north as Cambridgeshire and Suffolk (e.g. Mortimore and James, 2015). Similarly, the placement of the northern limit of the Transitional Province has ranged from southern Norfolk to offshore Lincolnshire (**Fig. 1**).

We follow recent interpretations of the extent of the Transitional Province (Mortimore and James, 2015; Mitchell, 2019) with the most significant facies shift occurring in south Cambridgeshire and Suffolk (**Fig. 1**) around the position of the WNW – ESE trending Ginton Thrust, a major basement structure in the underlying Anglo-Brabant Massif (Chadwick and Evans, 2005; Woods and Chacksfield, 2012). The distinct nature of the Chalk succession in Suffolk and wider East Anglia has resulted in the development of a regional stratigraphy of named marl and flint marker beds (Woods et al., 2012; **Fig. 2**). Based on recent offshore borehole evidence (Mortimore and James, 2015), the Transitional Province extends northwards across Norfolk into the southern North Sea (**Fig. 1**), where successions continue to show greater similarity to those in the Chilterns than to the Northern Province facies of Lincolnshire and Yorkshire.

2.2 Trunch borehole

The Trunch borehole was drilled by the Institute of Geological Sciences (now British Geological Survey) in September 1974 – February 1975 on the eastern edge of Trunch village (52.85953°N 1.40605°E), north Norfolk, eastern England (**Fig. 1**). The core site was located on an outcrop of the youngest preserved *in-situ* Chalk in the UK, close to the

rafted Maastrichtian coastal sections at Trimingham and Sidestrand (Peake and Hancock, 1970; Whittlesea, 1991; Peake and Hancock, 2000; Mortimore et al., 2001; Voigt et al., 2012). The aim was to provide a stratigraphic reference section for regional Upper Cretaceous stratigraphy, including correlation to the southern North Sea (Gallois and Morter, 1976). The borehole penetrated 469 m of top Campanian to Cenomanian Chalk, thin Lower Cretaceous and Lower Jurassic sections, and terminated in Triassic Mercia Mudstone Group (Keuper Marl) at 651 m depth. The core obtained represents the stratigraphically most extended Upper Cretaceous continuous onshore record in the UK.

The Chalk succession at Trunch lies within the Transitional Province, displaying a mixture of characteristics from both the Southern and Northern Provinces, together with some distinctive features such as the highly attenuated nature of the Cenomanian – Lower Turonian succession (Newell et al., 2018). The thinning is attributed to the presence of an underlying non-subsident Palaeozoic basement high that limited accommodation space across north Norfolk during the early Late Cretaceous. The lithofacies and marker bed stratigraphy of the Cenomanian – Coniacian interval at Trunch shows the greatest similarity to Northern Province successions (Wood et al. 1994; Fig 2). We therefore adopt the lithostratigraphic terminology of Wood and Smith (1978) for the studied interval in the borehole, while noting that the Santonian – Campanian interval shows increasing lithological divergence from both Southern and Northern Province Chalk successions.

3 Stratigraphic framework of the Trunch borehole

Detailed lithological logs and preliminary faunal records made during the drilling of the Trunch cored borehole in 1974 – 1975 (Morter et al., 1975; http://scans.bgs.ac.uk/sobi_scans/boreholes/517419/images/12114521.html) provided the basis for a summary stratigraphy published shortly thereafter by Gallois and Morter (1976). The interstitial fluid chemistry of core samples was later reported by Bath and Edmunds (1981). The Upper Cretaceous of the core was subsequently reassessed, with substantial additional macrofossil collecting, the results of which were presented by Wood et al. (1994). Their litho- and biostratigraphic analysis has provided the framework for all subsequent work on the borehole, including the present study. A new detailed stratigraphic log, that includes the positions of key

stratigraphically significant macrofaunal records and the named CIEs of Jarvis et al. (2006), is presented in **Figs 3 – 4**. Isotope curves that provide the basis for defining the chemostratigraphy at Trunch are plotted in **Fig. 5** and the numerical data are presented in **Supplementary Material Table 1**.

Previous stratigraphic studies on the Trunch core have included nannofossil (Burnett, 1988, 1990), ostracod (Pyne et al., 2003; Whatley et al., 2003) and dinocyst biostratigraphy (Pearce, 2010, 2018), sequence stratigraphy (Grant et al., 1999), and strontium (McArthur et al., 1993a; McArthur et al., 1993b) and carbon-isotope chemostratigraphy (Scholle and Arthur, 1980; Jenkyns et al., 1994; Jarvis et al., 2002, 2006; Linnert et al., 2018). Trunch core samples have been used to construct and test chemostratigraphic reference curves for Late Cretaceous carbon and oxygen stable-isotopes (Scholle and Arthur, 1980; Jenkyns et al., 1994; Jarvis et al., 2006) and strontium isotopes (McArthur et al., 1993b). The elemental stratigraphy has been described by Bath and Edmunds (1981) and Pearce (2000). The stable isotopic composition of carbonate-associated sulphur ($\delta^{34}\text{S}_{\text{CAS}}$) through the Middle Cenomanian – Middle Turonian interval (505 – 495 m) was presented by Owens et al. (2013).

3.1 Chemostratigraphy

3.1.1 Carbon and oxygen isotopes

The seminal paper by Scholle and Arthur (1980) that first demonstrated the application of carbon isotopes in Cretaceous pelagic limestones for stratigraphic correlation included filtered low-resolution carbonate carbon ($\delta^{13}\text{C}_{\text{carb}}$) and oxygen isotope ($\delta^{18}\text{O}$) curves from the Upper Cretaceous of “Norfolk” (i.e. the Trunch borehole). Bath and Edmunds (1981) published carbon and oxygen isotope data for 11 samples from Trunch, and low-resolution $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}$ profiles for the borehole were also illustrated by McArthur et al. (1993b fig. 4).

The Trunch $\delta^{13}\text{C}_{\text{carb}}$ curve of Scholle and Arthur (1980 fig. 2) clearly displays the key characteristics of the Cenomanian – Campanian carbon isotope stratigraphy: (1) a minimum in the Lower Cenomanian; (2) rising values with a positive excursion and maximum spanning the Cenomanian – Turonian boundary; (3) falling values to a pronounced minimum around the Turonian – Coniacian boundary; (4) rising values to a second lower-amplitude maximum around the Santonian – Campanian boundary; (5) falling values above, with a pronounced negative excursion in the Upper Campanian.

These trends were interpreted to represent synchronous changes in the global carbon cycle, and with the acquisition of multiple increasing high-resolution data sets worldwide, carbon stable-isotope chemostratigraphy has become generally accepted as a method for the regional to global correlation of Upper Cretaceous strata (Wendler 2013 and references therein). By contrast, the Trunch $\delta^{18}\text{O}$ curve displays less variation, with a general trend of rising values through the Upper Cretaceous and the highest values in the Upper Campanian (Scholle and Arthur, 1980 fig. 3).

The first detailed carbon and oxygen stable-isotope study of the English Chalk by Jenkyns et al. (1994) included data for the Campanian of the Trunch borehole. These data were used by Jarvis et al. (2002) to demonstrate a robust carbon isotope correlation of Campanian strata between the Tethyan (El Kef Tunisia; Bidart, France) and Boreal (Trunch) realms that has been confirmed by subsequent studies (e.g. Voigt et al., 2010; Linnert et al., 2018). This work was extended by Jarvis et al. (2006) who presented new carbonate carbon and oxygen isotope data for the Cenomanian – Santonian of Trunch (**Fig. 5**). These were integrated the $\delta^{13}\text{C}_{\text{carb}}$ results with the Campanian data of Jenkyns et al. (1994), together with published Upper Cretaceous records from East Kent, Culver Cliff Isle of Wight, Speeton North Yorkshire, Banterwick Barn Berkshire, Seaford Head and Eastbourne East Sussex. Using these data, Jarvis et al. (2006) constructed a composite age-calibrated carbon isotope reference curve and erected a formal CIE chemostratigraphy for the Late Cretaceous. The positions of the named CIEs in the Trunch core are indicated in **Figs 3 – 5**.

The carbon isotope reference curve for the Cenomanian – Campanian based on the English Chalk (Jarvis et al., 2006), which utilised data from Trunch for the Turonian – Coniacian boundary interval and the uppermost Santonian – Upper Campanian, has proved to provide a sound basis for the global correlation of Upper Cretaceous strata (e.g. Lamolda and Paul, 2007; Voigt et al., 2007; Sprovieri et al., 2013; Uramoto et al., 2013; Joo and Sageman, 2014; Jarvis et al., 2015; Thibault et al., 2016; Wohlwend et al., 2016; Jones et al., 2018; Linnert et al., 2018; Püttman et al., 2018; Razmjooei et al., 2018), including the improved definition of stage boundaries (Kennedy and Gale, 2006; Lamolda et al., 2014; Uličný et al., 2014; Thibault et al., 2016).

Work on the carbon isotope stratigraphy of the Campanian – Maastrichtian boundary succession on the north Norfolk coast, the Maastrichtian GSSP at Tercis les Bains France and sections at Gubbio Italy (Voigt et al., 2012) demonstrates that,

contrary to previous interpretations (Wood et al., 1994), the top of the Trunch core does not include the Maastrichtian (base Maastrichtian placed at the base of the *Belemnella obtusa* Zone, following Gradstein et al., 2012), but falls a short distance below the stage boundary. Nonetheless, the English $\delta^{13}\text{C}_{\text{carb}}$ record corresponds closely to profiles obtained from north Germany, Denmark, western France and central Italy, potentially enabling an extension of the Boreal Upper Cretaceous carbon-isotope reference curve to the Cretaceous – Paleogene boundary. Most recently, a high-resolution isotope study of the Late Campanian CIE (LCE) interval at Trunch (Linnert et al., 2018) confirmed the results of Scholle and Arthur (1980) and Jenkyns et al. (1994) that show a 0.7‰ negative $\delta^{13}\text{C}_{\text{carb}}$ anomaly at this level.

3.1.2 Strontium isotopes

The strontium isotope stratigraphy (SIS) of the Trunch borehole published by McArthur et al. (1993b) provided the first well-constrained $^{87}\text{Sr}/^{86}\text{Sr}$ reference curve for the Upper Cretaceous, particularly for the Coniacian – Campanian interval, which shows monotonic increasing isotope ratios. Data for the Cenomanian – Lower Campanian interval are plotted in **Fig. 5**. Results from the Trunch study have been compared to Upper Campanian data from Studland Bay Dorset (McArthur et al., 1993b), Campanian – Maastrichtian boundary values from Lägerdorf and Krons Moor northern Germany (McArthur et al., 1992), and to a radiometric age-calibrated strontium isotope reference curve for the Late Cretaceous of the US Western Interior (McArthur et al., 1994). The last of these contributes the main data for constructing a SIS global reference curve for the Late Cretaceous (Howarth and McArthur, 1997; McArthur et al., 2001, 2012).

Comparison between the Trunch and Western Interior $^{87}\text{Sr}/^{86}\text{Sr}$ data (McArthur et al., 1993b, 1994) shows good agreement for the Coniacian – Lower Campanian (**Fig. 5**), but values diverge significantly in the Upper Turonian below the Navigation Hardground ('Top Rock'). The Trunch $^{87}\text{Sr}/^{86}\text{Sr}$ values are anomalously high by up to 70×10^{-6} for 40 m below the hardground, with the greatest offset around the level of the 'Chalk Rock' (Hitch Wood CIE). Marine $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of around 0.7073 at this stratigraphic level are confirmed by isotope data from barite in ocean drilling cores (Mearon et al., 2003), compared to the measured value of 0.7074 at Trunch. Strontium isotope trends are again concordant for the mid-Turonian – Cenomanian portions of the

Trunch and Western Interior curves (**Fig. 5**), but with an offset to higher $^{87}\text{Sr}/^{86}\text{Sr}$ values at Trunch, particularly in the nodular chalk and hardground facies below 495 m.

Variable offsets to elevated $^{87}\text{Sr}/^{86}\text{Sr}$ values in the Upper Turonian at Trunch have been attributed to diagenesis (McArthur et al., 1993b; McArthur, 1994), possibly a result of the hardgrounds in this interval acting as permeability barriers that prevented the expulsion of ^{87}Sr -enriched compactional fluids, which precipitated isotopically anomalous cements in this part of the section. Present-day porewater profiles indicate mixing between meteoric water infiltrating the top of the Chalk and connate seawater trapped in pore spaces since deposition (Bath and Edmunds, 1981), but Chalk pore fluids typically display more radiogenic signatures than their accompanying matrix carbonate, due to the preferential release of Sr from the clay minerals during diagenesis and weathering (Shand et al., 2009). For comparison, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in vein-fill calcites in Coniacian – Campanian chalks from Northern Province chalks at Flamborough Head are also anomalously high, up to 0.7103, compared to matrix values of 0.7073 – 0.7076 (Faÿ-Gomord et al., 2018). Consequently, Trunch Upper Turonian Sr-isotope values are considered to be altered and cannot be used to derive accurate age data.

The Upper Santonian – uppermost Campanian $^{87}\text{Sr}/^{86}\text{Sr}$ profile at Trunch (**Fig. 5**) corresponds closely to that obtained from Lägerdorf – Krons Moor, north Germany (McArthur et al., 1993a), with the exception of a small interval below the level of the Trunch Hardgrounds in the upper Lower Campanian (Jarvis et al., 2002). However, more generally at Trunch, diagenetic alteration of the chalks (which are better cemented than their German equivalents), has increased $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the nanofossil matrix by 30×10^{-6} compared to values derived from macrofossils at the same stratigraphic level (McArthur et al., 1993b; **Fig. 5**). This diagenetic effect may be corrected by subtracting 30×10^{-6} from the $^{87}\text{Sr}/^{86}\text{Sr}$ values of the Norfolk nanofossil samples (McArthur et al., 1993a; McArthur, 1994).

The consistent monotonic increasing $^{87}\text{Sr}/^{86}\text{Sr}$ trend of both European Chalk sections brings into question the numerical age model for the Lower – Middle Campanian in the US Western Interior used to construct the 2012 Geological time scale (Gradstein et al., 2012), which generates a marked dog-leg pattern in the age-calibrated Sr-isotope profile (McArthur et al., 2016 fig. 3). This demonstrates how Sr-isotope data provide insights into stratigraphic completeness (McArthur et al., 2012, 2016) and, in

this case, raise an issue that will need to be addressed in future iterations of the geological timescale.

3.1.3 Sulphur isotopes

Carbonate associated sulphur isotopes ($\delta^{34}\text{S}_{\text{CAS}}$) have been studied from the Middle Cenomanian – basal Middle Turonian interval at Trunch and show a near-linear upwards increasing trend from 19 to 22‰ $\delta^{34}\text{S}_{\text{CAS}}$ between 505.0 and 495.0 m (Owens et al., 2013). This is consistent with data from northern and southern England (South Ferriby, Eastbourne), Italy (Gorgo Cerbara, Raia del Pedale), and the US Western Interior (USGS Portland No. 1 core) that indicate rising $\delta^{34}\text{S}_{\text{CAS}}$ in the Late Cenomanian and a maximum in the Turonian (Ohkouchi et al., 1999; Adams et al., 2010; Owens et al., 2013), several hundred thousand years after the maximum of >5 ‰ $\delta^{13}\text{C}_{\text{carb}}$ characterising the CTBE (e.g. Jarvis et al., 2011).

The $\delta^{34}\text{S}_{\text{CAS}}$ positive excursion may be attributed to increased deposition of isotopically light pyrite in expanded areas of oceanic seafloor euxinia during OAE2. The stratigraphic offset with respect to the positive carbon isotope excursion principally reflects the dramatically different residence times of C and S (<150 kyr and around 15 Myr, respectively; Walker, 1986; Lécuyer, 2016) in the oceans.

3.2 Lithostratigraphy, macrofossil biostratigraphy and carbon isotope stratigraphy

An independently derived and fully documented high-resolution stratigraphic framework is essential to constrain the palynological data. Here, we review the lithostratigraphy and macrofossil biostratigraphy of the core based on Wood et al. (1994), revised in the light of later work. These data are integrated with the carbon-isotope chemostratigraphy of Jarvis et al. (2006) to precisely place the dinocyst records presented herein. The stratigraphic framework is summarised in **Figs 3 – 5**.

3.2.1 Albion – Cenomanian boundary

The base of the Upper Cretaceous (Cenomanian) in the Trunch borehole is placed at the facies change to chalk at 512.22 m (**Fig. 3**), marking the base of the Ferriby Chalk Formation (Chalk Group) of Wood and Smith (1978). This occurs above a complex phosphatised hardground surface at the top of a highly condensed (63 cm) Lower

Albian Carstone Formation (oolitic ferruginous sandstone) to Upper Albian Hunstanton Formation (Red Chalk) succession (Gallois and Morter, 1976; Wood et al., 1994).

The Albian Red Chalk consists of red-brown coloured, quartz- and chert-rich pebbly intraclastic limestones with a microbially laminated upper surface (cf. Jeans, 1973, 1980; *Frutexitites*(?) Andrews et al., 2015) and common *Neohibolites* and *Inoceramus* fragments. In its type section at Hunstanton on the north Norfolk coast (**Fig. 1**), the top of the Red Chalk is considered to be of Late Albian *Callihoplites auritus* ammonite Subzone (top *Mortoniceras inflatum* Zone) age, with an overlying thin red marl that is possibly earliest Cenomanian (Owen, 1995; Mitchell, 2019). The uppermost Albian *Stoliczkaia dispar* ammonite Zone (*Mortoniceras* (*Subschloenbachia*) *rostratum* – *Pleurohoplites briacensis* Subzones) is absent, so significant stratigraphic gaps are indicated between the top of the Red Chalk and the marl and also between the marl and the overlying basal chalk (cf. Mitchell and Veltkamp, 1997; Andrews et al., 2015). The marl is absent in the more attenuated Trunch succession.

3.2.2 Cenomanian

Lower Cenomanian (512.22 – 506.30 m)

The basal unit of the Chalk at Trunch is the Paradoxica Bed (Peake and Hancock, 1961; Jeans, 1980), a hardground with a convolute mineralised surface at 511.91 m (**Fig. 3**). The bed consists of a well-cemented white to cream chalkstone (cf. Bromley and Gale, 1982) incorporating many small quartz and chert pebbles, and is highly fossiliferous throughout with abundant sponge remains, *Aucellina* and inoceramid bivalve fragments, and brachiopods. The surface is glauconitised, phosphatised and bored. This distinctive bed, characterised by abundant *Thalassinoides paradoxica* Woodward burrows (Kennedy, 1967), is well exposed at Hunstanton (**Fig. 1**) and likely corresponds to the lower *Neostlingoceras carcitanensis* ammonite Subzone of the Lower Cenomanian *Mantelliceras mantelli* Zone (Peake and Hancock, 1961, 1970; Jeans, 1980; Gale and Friedrich, 1989; Gallois, 1994; Mortimore et al., 2001).

The succession between the Paradoxica Bed hardground and an erosion surface at 509.80 m is assigned to the Lower Cenomanian *Mantelliceras mantelli* Zone, *N. carcitanensis* to *M. saxbii* Subzones (Wood et al., 1994). Within this interval, the basal bioclastic chalks rich in *Inoceramus crippei crippei* Mantell correspond to the First

(Lower) *Inoceramus* Bed of the Northern Province succession (Wiltshire, 1869; Hill, 1888; Peake and Hancock, 1961, 1970; Gaunt et al., 1992), which places these beds within the *Sharpeiceras schlueteri* Subzone of the mid-*M. mantelli* Zone (Mortimore et al., 2001; Wright and Kennedy, 2015; **Figs 2 – 3**). Our stratigraphically lowest productive palynology sample originates from the base of the First *Inoceramus* Bed.

Inoceramus ex gr. *virgatus* Schlüter is first recorded in the nodular chalks above the erosion surface at 509.80 m, and the species is abundant in the shell bed at 509.32 m, up to a planar hardground surface at 508.82 m (**Fig. 3**). This interval likely corresponds to the ubiquitous acme-occurrence of this species in the lower part of the uppermost Lower Cenomanian *Mantelliceras dixonii* Zone (Ernst et al., 1983; Gale, 1995; Mitchell et al., 1996; Mortimore et al., 2001; Jarvis et al., 2006; Wright and Kennedy, 2017). The omission/erosion surfaces at 509.80, 509.32 and 508.82 m correlate to marker horizons M4 – M6 of Gale (1989) at Folkestone, with M4 corresponding to the Sub-*dixonii* Erosion Surface of Wright and Kennedy (2017), and M6 with the Dixonii Limestone. The small minimum in the $\delta^{13}\text{C}_{\text{carb}}$ profile at this level correlates to the Virgatus Beds CIE (VBE, **Figs 3, 5**).

The above correlation is supported by records of *Orbirhynchia mantelliana* (J. de C. Sowerby) brachiopods at 508.40 and 508.43 m, a short distance above a planar hardground surface, indicating the position of the lowermost band of *O. mantelliana* (Om Band 1, cf. Gale, 1989). A small negative $\delta^{13}\text{C}_{\text{carb}}$ excursion at 508.0 m corresponds to the Mid-*dixonii* CIE (**Fig. 3**). Above this, in the absence of any definitive marker taxa, the fossiliferous bioturbated marly chalks, the dark marl between 507.05 and 507.12 m, and the hardground sediment below 506.30, are assigned to the upper *M. dixonii* Zone (**Figs 2 – 3**).

Middle Cenomanian (506.30 – 502.32 m)

A phosphatised hardground surface at 506.30 m is overlain by coarse-grained gritty and calcarenitic chalks with abundant fossil debris and black phosphatic pebbles; this facies continues upwards to 505.21 m (**Fig. 3**). These sediments are a development of the lower Middle Cenomanian Totternhoe Stone Member (Whitaker, 1865; Wood et al., 1994; Hopson, 2005), a distinctive unit in the Chiltern Hills of Berkshire and Hertfordshire, and in Cambridgeshire (= the Grey Bed of Hill, 1888, recognised in Lincolnshire and Yorkshire; also referred to locally as the Chilton Stone or Burwell

Rock). The Totternhoe Stone is considered to be broadly equivalent to the Cast Bed of southern England (Price, 1877; Gale, 1989; Mitchell et al., 1996; Mortimore et al., 2001), i.e. close to the base of the *Turrilites costatus* ammonite Subzone, *Acanthoceras rhotomagense* Zone (Wright and Kennedy, 2017), but some distance above the base of the Middle Cenomanian (*Cunningtoniceras inerme* Zone; **Fig. 2**).

The lithostratigraphic correlation is supported by the carbon isotope stratigraphy. A marked increase in the slope of the $\delta^{13}\text{C}_{\text{carb}}$ profile and a small positive excursion within the Totternhoe Stone at Trunch (**Fig. 5**) is correlated to Mid-Cenomanian Event I (MCEI). In the more expanded succession at Speeton (Yorkshire) this CIE is characterised by a double peak (Mitchell et al., 1996; Mitchell, 2019), one at the base of the Totternhoe Stone (MCEIa), the other in the marly interval at its top (MCEIb). The latter yields the belemnite *Praeactinocamax primus* (Plainville), indicating the position of the *P. primus* bed, a faunal event horizon that corresponds to the base of the Cast Bed (couplet C1) and the position of MCEIb in southern England (Gale, 1995; Mitchell et al., 1996; Wilmsen, 2003; Mitchell, 2005; Wilmsen et al., 2007). In the more condensed section at Hunstanton, *P. primus* occurs at the base of the Totternhoe Stone, demonstrating the presence of a hiatus at the base of the bed that cuts out older sediments representing MCEIa. Based on the similarities to the succession at Trunch it is likely that the small positive $\delta^{13}\text{C}_{\text{carb}}$ excursion here represents MCEIb of basal *A. rhotomagense* Zone age (**Fig. 5**), although higher resolution sampling is required to confirm this.

Elsewhere, the sub-Totternhoe Stone erosion surface locally cuts down into the underlying chalk, forming channels (Gallois, 1988; Bristow, 1990; Hopson, 1992; Wood, 1996) with sediment fills that may contain remanié fauna from multiple levels in the low Middle Cenomanian and from the uppermost Lower Cenomanian *M. dixonii* Zone (Wright and Kennedy, 2017). Comparable channels have been interpreted in seismic profiles from offshore north Norfolk (Mortimore and James, 2015). The basal Middle Cenomanian *Cunningtoniceras inerme* Zone, which includes the second of three *O. mantelliana* bands (*Om* Band 2), is likely missing at the hiatus on the sub-Totternhoe Stone erosion surface at Trunch.

The bed above the Totternhoe Stone was correlated by Wood et al. (1994) to the Ammonite Bed (Bed IV of Bower and Farmery, 1910) of the Northern Province succession (**Fig. 3**; Gaunt et al., 1992; Owen, 1992; Mortimore et al., 2001), and its

surface at 504.33 m to the P/B Break or “mid-Cenomanian non-sequence” of Carter and Hart (1977), characterised regionally by a sharp increase in the foraminifera planktic/benthic ratio and a flood of keeled planktonic species. This marker horizon occurs a short distance below the top of the *Turrilites costatus* Subzone in southern England (Wright and Kennedy, 2017). Upper *O. mantelliana* band sediments (*Om* Band 3), which immediately underlie the P/B break elsewhere, might be unpreserved or incorporated in the Ammonite Bed (cf. Gaunt et al., 1992). A $\delta^{13}\text{C}_{\text{carb}}$ minimum above the foraminifera change defines the P/B Break CIE (PBE in **Fig. 3**). This is correlated to the Ammonite Bed here, but sampling resolution is inadequate to place the event with high confidence.

The interval from 504.33 to 503.58 is rich in brachiopods, including *Concinnithyris* and *Terebratulina*, indicating a correlation with the lower part of the Lower Pink Band, lower *Turrilites acutus* Subzone, of the Northern Province Chalk stratigraphy (Bower and Farmery, 1910; Wright and Wright, 1942; Wood and Smith, 1978; Whitham, 1991; Gaunt et al., 1992; Wood et al., 1994). The nodular marly chinks above this terminate with a hardground surface at 502.32 m (**Fig. 3**), taken to mark the top of the *A. rhotomagense* Zone (Wood et al., 1994).

A 1 cm marl containing abundant small *Pycnodonte* spp. oysters overlying a hardground surface at 502.32m marks the base of the uppermost Middle Cenomanian, *Acanthoceras jukesbrownei* Zone. This bed equates to the Nettleton Pycnodonte Marl (Gaunt et al., 1992; Wood, 1992, = Gryphaea bed of Bower and Farmery, 1910), and the Pycnodonte Event of northern Germany (Ernst et al., 1983). The latter is characterised by rare *A. jukesbrownei* (Cpath) ammonites, while elsewhere in England the base of the *A. jukesbrownei* Zone yields common ‘*Inoceramus*’ ex gr. *atlanticus* (Heinz), a species that is known from the Pycnodonte Marl in northern England (Gaunt et al., 1992).

The 30 cm of hard nodular chalk immediately above the Pycnodonte Marl is interpreted to be a condensed development of the Nettleton Stone of the Northern Province (Gaunt et al., 1992), equivalent to Jukes-Browne Bed 7 (JB Bed VII; Jukes-Browne and Hill, 1903) at Dover and throughout southern England (Woods et al., 2012). The top of the Middle Cenomanian, defined by the last occurrence of *A. jukesbrownei*, is located a short distance above the top of JB Bed VII (Wright and Kennedy, 2017). A small negative $\delta^{13}\text{C}_{\text{carb}}$ shift occurs in the Pycnodonte Marl at Trunch and in more expanded form below the Nettleton Stone at Speeton. This is an expression of the MCEII

CIE, a characteristic *A. jukesbrownei* Zone marker (Mitchell et al., 1996; Jarvis et al., 2006; Mitchell, 2019).

Upper Cenomanian (502.32 – 500.07 m)

The base of the Upper Cenomanian *Calycoceras guerangeri* Zone is placed at the top of the Nettleton Stone at 502.00 m (**Fig. 3**). The overlying marly chalks correspond to the Upper Pink Band of the Northern Province stratigraphy (Bower and Farmery, 1910; Gaunt et al., 1992; Wood et al., 1994). A positive $\delta^{13}\text{C}_{\text{carb}}$ shift in this bed is correlated to the Jukes-Browne CIE (JBE in **Fig. 3**) that spans the *A. jukesbrownei* – *C. guerangeri* Zone boundary elsewhere (Jarvis et al., 2006). A glauconitised convolute hardground surface at 501.10 m caps a well-developed 25 cm thick stylolitic chalkstone. The negative $\delta^{13}\text{C}_{\text{carb}}$ excursion in this bed is equated to the Monument CIE (ME in **Fig. 3**). The interval between the glauconitised hardground surface and an unmineralised convolute hardground at 500.51 m was assigned to the *Metoicoceras geslinianum* ammonite Zone by Wood et al. (1994). A marly plexus from 501.02 to 500.96 m represents the thin, north Norfolk equivalent of the Plenus Marls (Jefferies, 1963 fig. 10; Wood et al., 1994; Voigt et al., 2006), and the glauconitised hardground, below, the sub-Plenus erosion surface and base of the Welton Chalk Formation of the Northern Province succession (Wood and Smith, 1978; Hart et al., 1991; Whitham, 1991; Dodsworth, 1996).

There is no development of organic-rich mudstones of Black Band facies (considered to be equivalent to uppermost Plenus Marls and Melbourn Rock of southern England) that characterise the basal Welton Chalk throughout the Northern Province and most of the North Sea Basin (Dakyns and Fox-Strangeways, 1886; Rowe, 1904; Jefferies, 1963; Wood and Smith, 1978; Jeans, 1980; Gaunt et al., 1992; Johnson and Lott, 1993; Wood and Mortimore, 1995; Dodsworth, 1996; Wood et al., 1997; Sumblar, 1999; Mitchell, 2000; Mortimore et al., 2001; Hart, 2019). The marly succession at the base of the Welton Chalk that incorporates the Black Band (the 'Variegated Beds' of Wood and Mortimore, 1995; Wood et al., 1997) was referred to the Flixton Member by Jeans (1980; Jeans et al., 1991) and Mitchell (2000, 2019). However, contrary to previous expectations, recent work has shown that the Transition Province Plenus Marls – Melbourn Rock facies seen at Trunch continues and expands offshore

north Norfolk, with ≥ 2 m of Plenus Marls observed in cores and seismic profiles (Mortimore and James, 2015; **Fig. 1**).

3.2.3 Cenomanian – Turonian boundary (CTB)

The base of the Turonian is placed at the surface of the planar hardground at 500.07 m, evidenced by the appearance of abundant *Mytiloides* spp. inoceramid bivalves in the overlying shelly chalks (Wood et al., 1994; cf. Kennedy et al., 2005; **Fig. 3**). The chalk below this, between the convolute hardground at 500.51 m and the planar hardground, was assigned by Wood et al. (1994) on general stratigraphic grounds to the uppermost Upper Cenomanian *Neocardioceras juddii* Zone, but there is no biostratigraphic evidence to support this interpretation.

Carbon isotope values attain a maximum for the core of 3.6‰ $\delta^{13}\text{C}_{\text{carb}}$ at 499.8 m, immediately above the planar hardground, the chalkstone from which yields a value of 3.2‰ (**Fig. 5**). Compared to the CTB Chalk reference section at Eastbourne and other Plenus Marls successions in southern England (Jarvis et al., 1988a, b, 2001, 2006, 2011; Jeans et al., 1991; Leary and Peryt, 1991; Gale et al., 1993, 2005; Jenkyns et al., 1994; Lamolda et al., 1994; Paul et al., 1999; Keller et al., 2001; Tsikos et al., 2004; Pearce et al., 2009) and the Black Band section at South Ferriby in Yorkshire (Schlanger et al., 1987; Hart et al., 1991), these relatively low maximum carbon isotope values suggest that sediments representing the stage boundary interval (upper *Metoicoceras geslinianum* – *Watinoceras devonensis* Zones), which typically yield values of $>4\text{‰}$ $\delta^{13}\text{C}_{\text{carb}}$ (i.e. the interval that includes CTBE peaks a – c of Jarvis et al., 2006, 2011), are absent at Trunch. It is concluded that a significant hiatus spanning the Cenomanian – Turonian boundary occurs at the planar hardground surface. Our dinocyst study cannot contribute further to the stratigraphic analysis because all samples spanning the stage boundary (*M. geslinianum* to basal *Mytiloides* zones) proved to be barren of palynomorphs (**Fig. 3, Supplementary Material Table 2**).

3.2.4 Turonian

Lower Turonian (500.07 – 496.0 m)

A concentration of stylolites and thin marly partings from 495.9 – 496.0 m is interpreted to represent the Chalk Hill Marls (**Fig. 3**), which mark the boundary

between flintless and overlying flinty portions of the Welton Chalk of the Northern Province (Wood and Smith, 1978; Gaunt et al., 1992; Wood, 1992; Wood et al., 1994; Mitchell, 2000). In the Trunch succession, and generally in the Northern Province (Mitchell, 2000), the marls coincide with a facies transition from grey gritty calcarenitic and nodular chalks rich in *Mytiloides*, below (with 'Melbourn Rock' facies at the base; Jukes-Browne, 1880; Hill and Jukes-Browne, 1886; Jukes-Browne and Hill, 1903; Jeans, 1980), to finer grained whiter less nodular chalks, above (**Fig. 3**). Mitchell (2000, 2019) referred the unit of calcarenitic chalks of the Lower Turonian to the Buckton Member, and the overlying flinty chalks to the Bempton Member. He placed the base of the Middle Turonian at the level of the first flint, immediately above the Chalk Hill Marls, albeit with little biostratigraphic control.

A well-defined minimum in the $\delta^{13}\text{C}_{\text{carb}}$ profile at 497.5 m in the Trunch core (**Fig. 5**) is equated to the Lulworth CIE (=Tu5 of Voigt et al., 2007) of the upper Lower Turonian (Jarvis et al., 2006). However, sampling resolution is inadequate to identify the finer scale $\delta^{13}\text{C}_{\text{carb}}$ isotope events of the Lower Turonian (Tu1 – Tu4; Voigt et al., 2007; Jarvis et al., 2015).

Middle Turonian (496.0 – 475.0 m)

The record of a fragmentary *Collignonicerias?* at 495.40 m (Wood et al., 1994) is indicative of the Middle Turonian *Collignonicerias woollgari* (Mantell) – *Mytiloides subhercynicus* (Seitz) – *Conulus subrotundatus* Mantell association that characterises the basal New Pit Chalk in southern England (Mortimore et al., 2001; base Middle Turonian *C. woollgari* Zone), and marks the base of the Middle Turonian in Germany (Ernst et al., 1983). The presence of darker grey semi-silicified nodules around this level (**Fig. 3**) may indicate a correlation with the First Main Flint of the Northern Province succession (Wood and Smith, 1978; Wood, 1992). The Lower – Middle Turonian boundary is provisionally placed at the Chalk Hill Marls.

The base of the *Terebratulina lata* Zone was placed at the thin 2 mm grey-green marl and a stylolitized surface at 493.97 m by Wood et al. (1994), although the lowest *T. lata* (R. Etheridge) was recorded much higher, at 489.32 m, immediately above the *Conulus* bed and just below a facies change to marlier chalks (**Fig. 3**). However, *Inoceramus* ex gr. *cuvieri* (J. de C. Sowerby) – *I.* ex gr. *lamarcki* Parkinson first appear around 493.0 m, indicating these beds lie within the *T. lata* Zone as recognised in the

Southern Province (Mortimore et al., 2001). *Terebratulina lata* is recorded sporadically in the Welton Chalk elsewhere and is uncommon in the lower beds of its index zone (Rowe, 1904; Mitchell, 2019).

A trend of rising $\delta^{13}\text{C}_{\text{carb}}$ values from the Lulworth CIE upwards to 493.0 m is followed by sharply falling values above (**Fig. 5**). The break point in the isotope profile is equated to the low-woolgari CIE (Tu10) and an underlying single point peak at 495.0 m to the Round Down CIE (Tu8), both prominent markers in the lower Middle Turonian (Voigt et al., 2007; Jarvis et al., 2015). The carbon isotope correlation to Dover (Jarvis et al., 2006) places the bottom of the *T. lata* Zone below the Round Down CIE, around the level of the Chalk Hill Marls (**Fig. 3**).

A succession of named marker marls typical of the Northern Province Middle Turonian [(Wood and Smith, 1978; Whitham, 1991; Caunt et al., 1992; Sumbler, 1999; Mitchell, 2000, 2019; Rawson and Whitham, 2000); East Anglian named equivalents are indicated in parentheses (Woods et al., 2012)], and highly characteristic of the Welton Chalk Formation, has been identified at Trunch (Wood et al., 1994; **Fig. 3**). These include beds that have been identified as bentonites based on their geochemical signatures (Wray and Wood, 1998; Wray, 1999; designated B1 – B5 in this paper). Middle – basal Upper Turonian markers (**Fig. 3**) are the: (1) Grasby Marl (Methwold Marl), a 2 cm grey-green laminated marl with its base at 487.59 m; (2) Barton Marls 1 – 4, the lowest of which (Barton Marl 1, Lower Marl; B1 bentonite) is a grey-green 1 cm laminated marl with chalk lenses and its base at 483.66 m; Barton Marl 2 (Pilgrims' Walk Marl), a 5 mm grey-green laminated bed with irregular top and bottom stylolitized surfaces and its base at 482.71 m; Barton Marls 3 – 4 constitute thin marly partings; (3) Melton Ross Marl (Mount Ephraim Marl; B2 bentonite), a prominent 8 cm greyish green marl with its base at 478.03 m; (4) Riby Marl, a 1 cm grey-green laminated stylolitized marl with its base at 475.44 m; (5) Deepdale Lower Marl (Twin Marls; B3 bentonite), a 2 cm grey-green laminated marl with a relatively planar top, irregular stylolitic base at 471.72 m, and enclosed lenses of chalk.

The declining $\delta^{13}\text{C}_{\text{carb}}$ trend above the low-woolgari CIE changes to a plateau interval with erratic values at the facies change from nodular to marly chalks at 489.0 m up to 480.0 m (**Fig. 3**), above which the long-term decline resumes (**Fig. 5**). The peak and breakpoint at the top of the plateau interval can be confidently correlated to the 'Pewsey' CIE (Jarvis et al., 2006), but a lack of stratigraphic resolution and erratic values

in the plateau interval make the identification of other CIEs uncertain. The Glynde negative CIE is placed at the level of Barton Marl 1 that correlates to Glynde Marl 1 of the Southern Province, the B1 bentonite (**Figs 2 – 3**).

Upper Turonian (475.0 – 429.9 m)

The base of the Upper Turonian in northern Europe is generally defined by the lowest occurrence (LO) of *Subprionocyclus neptuni* (Geinitz) (Bengtson, 1996; Ogg et al., 2004), which is approximately coincident with the LO *Inoceramus perplexus* Whitfield (= '*Inoceramus costellatus*' as widely applied in Europe; Walaszczyk and Wood, 1998). These index taxa have not been recorded at Trunch. These LO datum levels lie below the Southerham Marl 1 (B2 bentonite) in southern England (Gale, 1996; Jarvis et al., 2006) and its correlative, the Melton Ross Marl of the Northern Province (Mortimore et al., 2001), and are located between the Lower and Upper Southerham CIEs (Jarvis et al., 2006, 2015).

A long-term carbon isotope minimum occurs between 478.0 – 480.0 m at Trunch (**Fig. 5**), within which there are a number of rather poorly resolved peaks and troughs. A marked negative excursion immediately above the Deepdale Lower Marl (=Caburn Marl equivalent; B3 bentonite) may be assigned to the Bridgewick CIE, and the immediately underlying positive excursion to the Caburn CIE (Cb in **Fig. 3**). The Lower and Upper Southerham CIEs are less easily placed. Assuming the marl succession described above correctly identifies the positions of the key marker marls, the Lower Southerham CIE should lie below the Melton Ross Marl at 478.03 m. A positive excursion is not seen here. The Upper Southerham CIE should lie between the Melton Ross and Deepdale Lower Marls but is not well resolved. Higher resolution data are needed to address this problem but, in the meantime, the base of the Upper Turonian is provisionally placed above the Riby Marl, at 475.0 m.

A 9 cm semitabular flint (Deepdale Flint) and *Conulus* horizon at 472.50 m is overlain by a 8 cm nodular flint at 472.25 m (**Fig. 3**; Wood et al., 1994). It is notable that these, together with a 6 cm nodular flint at 486.46 m, are the only flints in the Welton Chalk at Trunch. This contrasts to the more generally flinty nature of the Formation in the Northern Province (Wood and Smith, 1978; Whitham, 1991; Gaunt et al., 1992; Mitchell, 2000, 2019; Mortimore et al., 2001), referred to the Bempton Member by Mitchell (2000). A horizon of stylolitic marly partings at 469.32 m corresponds to the

base of the Burnham Chalk Formation, characterised by a facies change from stylolitic, nodular and relatively massively bedded chalks of the Welton Formation, to marlier thin-bedded 'laminated' chalks with marl seams, and abundant tabular and semitabular flints in the Burnham Formation (Wood and Smith, 1978; Gaunt et al., 1992; Wood et al., 1994; Mitchell, 2019).

Notable fossil records in the higher Welton Chalk at Trunch include a bed with abundant *Orbirhynchia*, inoceramids and *Terebratulina* below 480.75 m, and a bed with "*Offaster sphaericus*" (Morter et al., 1975), common inoceramids, *Terebratulina* and *Orbirhynchia* at 476.60 m. The Welton Chalk at Trunch proved to be almost entirely barren of palynomorphs (**Fig. 3, Supplementary Material Table 2**), but these reappear in abundance at the base of the Burnham Chalk and are present in all samples studied above.

The basal beds of the Burnham Chalk in the Northern Province contain a succession of named tabular and semitabular flints and marls (Wood and Smith, 1978; Whitham, 1991; Mitchell, 2019) that can be recognised at Trunch (**Fig. 3**; Wood et al., 1994): (1) Ravensdale Flint, a 9 cm semitabular at 468.03 m with a 2 cm pseudobreccia marl 50 cm above that is normally silicified and locally fused to the top of the flint in northern England; (2) Triple Tabular Flints (Rough and Smooth Black flints, in part), a 10 cm tabular at 466.37 m, 14 cm tabular at 465.47 m, and a 5 cm semitabular at 464.97, with common *P. (S.) plana* above; (3), North Ormsby Marl (Grimes Grave Marl), a 4 cm grey-green laminated marl with its base at 462.74 m, overlain by fossiliferous chalks yielding oysters, inoceramids, brachiopods and echinoderms, and considered to represent the B4 bentonite; (4) Ludborough Flint (Floorstone Flint) a 30 cm tabular flint with its base at 460.30 m. The last of these is one of the most prominent marker beds in the Northern Province Chalk ('the white flint' of Rowe, 1929; Wood and Smith, 1978; Wood et al., 1994).

The Ravensdale Flint to Ludborough Flint succession represents a 'Northern Province Flint Maximum' (**Fig. 3**), that is equivalent to the 'Brandon Flint Series' in the Transitional Province of central and southern East Anglia (Skertchly, 1879; Hewitt, 1935; Mortimore and Wood, 1986; Bristow, 1990; Hildreth, 2019). The latter was mined extensively in prehistoric times for the production of flint tools and subsequently for gun flints, continuing into the mid-20th century (Clark and Piggott, 1933; Clarke, 1935). Other notable features in this interval (**Fig. 3**) are: a 2 cm medium grey marl

with associated chalk pebble 'pseudobreccia' at 468.35 m, overlain by echinoid-rich chalks at 468.28 m; beds yielding abundant *Infulaster* from 468.30 – 467.00 m; a band of *Plesiocorys* (*Sternotaxis*) *plana* (Mantell) at 464.82 – 464.70 m. Omission surfaces, with cemented nodular chalks below, occur at 463.82, 461.23 and 460.90 m.

The next major regional marker bed recognised in the succession is the Ulceby Marl (West Tofts Marl), a 5 cm grey-green crinoidal marl with its base at 442.81, overlain at 442.00 – 441.50 m by the Ulceby Oyster Bed (**Fig. 3**), with common pycnodonteine oysters, *Plesiocorys*, brachiopods and other fossils (Gallois and Morter, 1976). The abundance of small crinoid columnals in the Ulceby Marl makes this bed particularly distinctive (Wood and Smith, 1978; Gaunt et al., 1992). This supports its correlation to the Lewes Marl of the Southern Province (**Fig. 2**) that is also rich in crinoid debris and is interpreted as bentonite B5 (Wray and Wood, 1998). Between the Ludborough Flint and the Ulceby Marl are a pair of 2 – 3 cm marls with their bases at 459.57 and 458.90 m (**Fig. 3**), the grey-brown colour of the lower marl, contrasting to the grey-green colour of the upper marl. The brown colour suggests that the former is equivalent to the Thornton Curtis Marl of the Northern Province (Wood and Smith, 1978). A 2 cm grey-green laminated marl at 453.93 m likely correlates to Wootton Marl 2, the more persistent of a marl pair elsewhere in the Northern Province. The flinty chalks between the Thornton Curtis Marl and Wootton Marl 2 contain a number of marly intervals and omission surfaces (**Fig. 3**).

Between Wootton Marl 2 and the Ulceby Marl there is a complex of nodular chalks and hardgrounds overlain by a succession of well-developed semitabular and tabular flints (**Fig. 3**). This interval is correlative to the 'Vale House Flints Member' of the Northern Province (Hildreth, 2013; Green, 2019), although the hardground complex at Trunch equates to a flinty chalk succession lacking hardgrounds in Lincolnshire and east Yorkshire. No hardgrounds have been identified in the Burnham Chalk of the Northern Province (Gaunt et al., 1992), but a hardground succession comparable to that at Trunch continues in the Transitional Province facies developed offshore north Norfolk (Mortimore and James, 2015 fig. 11).

Two major hardgrounds occur in the Vale House Flints Member equivalent interval at Trunch, the lower with a convolute surface at 452.19 m, and the upper, better cemented hardground, with a pinkish ?phosphatised surface at 449.89 m (Gallois and Morter, 1976). The convolute hardground consists of fossiliferous yellow-stained chalk

with prominent marl-filled *Thalassinoides* burrows, and represents the top of a closely spaced flinty hardground complex with a second planar surface below, at 452.42 m, and three further cemented omission surfaces at 452.65, 452.90, 453.10 m (**Fig. 3**). An additional minor hardground surface occurs above the convolute hardground, at 451.70 m. The hardground at 449.89 m is the strongest developed in the Vale House Flints Member interval. It displays variegated mineralisation, pebble – cobble chalk intraclasts, grey chalk filled *T. paradoxica* burrows, and abundant dark grey sponge remains, bivalves, and brachiopods (Gallois and Morter, 1976). The ‘lamine’ chinks between the two main hardground intervals are highly fossiliferous with inoceramids, brachiopods, oysters, bryozoans, crinoids and echinoids. The hardground succession was referred to the ‘Chalk Rock’ by Gallois and Morter (1976).

The Chalk Rock hardground succession at Trunch coincides with a well-defined medium-term maximum and peak in the $\delta^{13}\text{C}_{\text{carb}}$ profile that is assigned to the Hitch Wood CIE (**Fig. 5**), one of the most clearly defined events in the Upper Cretaceous carbonate carbon isotope chemostratigraphy (Gale, 1996; Jarvis et al., 2006, 2015). This CIE lies within the lower Upper Turonian *P. (S.) plana* echinoid Zone (mid-*Subprionocyclus neptuni* ammonite Zone), immediately above the *Hyphantoceras* faunal Event. The ‘*Hyphantoceras* Event’ represents an important stratigraphic marker in the Upper Turonian of Western Europe (Viesse et al., 2004; Jarvis et al., 2015), being widely recognized in southern England, northern Spain, parts of France, Germany, the Czech Republic, Poland, and Kazakhstan, and potentially northern Algeria (Kaplan and Kennedy, 1996).

It is likely that the strongly developed mineralised hardground at the top of the Chalk Rock beds at Trunch (**Fig. 3**) equates to the Hitch Wood Hardground of the main Transitional Province Chalk Rock Member succession (Bromley and Gale, 1982; Gale, 1996; Mortimore et al., 2001). This hardground is known for its preservation of an aragonitic molluscan ‘*reussianum* fauna’ (Woods, 1896; Wright, 1979), characterised by the presence of the heteromorph ammonite *Hyphantoceras* (*Hyphantoceras*) *reussianum* (d’Orbigny). A *reussianum* fauna has not been recorded at Trunch, but the sediments above the Hitch Wood Hardground are gritty and calcarenitic at their base and are very fossiliferous, with brachiopods, bryozoans, inoceramids and echinoid debris being particularly abundant. This interval been referred to as the ‘Santon Downham Fossil Bed’ (Gallois and Morter, 1976; Hildreth, 2013). An equivalent level above the Chalk

Rock at Mundford, southern Norfolk, has yielded an abundant '*reussianum* fauna' (Gallois, 2016), also documented around Santon Downham, north Suffolk (Hewitt, 1924), 6 km to the south of Mundford. However, specimens of *H. (H.) reussianum* have also been recorded from just below and above the Wootton Marls in the Northern Province (Mortimore and Wood, 1986; Whitham, 1991; Gaunt et al., 1992; Green, 2019), which would place the onset of the *Hyphantoceras* Event before the $\delta^{13}\text{C}_{\text{carb}}$ maximum of the Hitch Wood CIE, as seen elsewhere in England and mainland Europe (Jarvis et al., 2015).

The higher beds of the Vale House Flints Member, up to the Ulceby Marl (B5 bentonite) at 442.81 m, consist of a succession of marly chalks containing two prominent tabular and one nodular flint (**Fig. 3**), and include a 'fossil bed' rich in bryozoans, serpulids, small brachiopods and inoceramids at 444.00 – 443.75 m (Gallois and Morter, 1976). A minor positive $\delta^{13}\text{C}_{\text{carb}}$ excursion at 447 m is correlated to the i1 peak of Jarvis et al. (2006). This was termed Hitch Wood 2 (HW2) by Jarvis et al. (2015) to reflect differences in the carbonate carbon and organic carbon isotope profiles around the Hitch Wood CIE documented in the Bohemian Cretaceous Basin (Uličný et al., 2014; Jarvis et al., 2015). There, high resolution paired carbon-isotope curves from the Běchary Bch-1 borehole show an offset in the position of the Upper Turonian $\delta^{13}\text{C}$ maxima. For $\delta^{13}\text{C}_{\text{carb}}$ this is situated immediately above the *Hyphantoceras* Event at the level of the Hitch Wood (HW1) CIE, but maximum values for $\delta^{13}\text{C}_{\text{org}}$ occur 20 m higher at the level of HW2 (base *M. scammii* Zone; Jarvis et al., 2015 fig. 5).

The succession up to 40 m above the Ulceby Marl consists of flinty, marly and shelly chalks containing numerous omission surfaces, nodular chalks and thin hardgrounds. This facies contrasts to the more massive white chalks with abundant nodular, semitabular and tabular flints that characterise the equivalent interval in the Northern Province (Gaunt et al., 1992; Mitchell, 2019), which prevents the recognition of the key named marker beds that define the stratigraphy in that region. Of note at Trunch are a 50 cm fossiliferous bed with its base at 442.00 m yielding *Pycnodonte* oysters, correlated to the Ulceby Oyster Bed (Wood et al., 1994). A positive $\delta^{13}\text{C}_{\text{carb}}$ excursion spanning the Ulceby Marl and Ulceby Oyster Bed interval (**Fig. 3**) corresponds to the i2 peak of Jarvis et al. (2006), termed Hitch Wood 3 (HW3) by Uličný et al. (2014) and Jarvis et al. (2015).

Beds yielding *Pycnodonte* occur at 440.05 – 439.90, and above a hardground surface at 439.05 m. A band of common *Plesiocorys* occurs at 435.10 – 434.52 m.

3.2.5 Turonian – Coniacian boundary

A prominent pink variegated mineralised convolute hardground surface with yellow sponge-rich nodular chalks below, cut by dark grey to black marly chalk filled *Thalassinoides*, *Planolites* and *Zoophycos* burrows, is developed at 432.03 m. Small *Cremnoceramus waltersdorfensis waltersdorfensis* (Andert) and *Cremnoceramus rotundatus* (Fiege) occur with *Didymotis* sp. in the chalk immediately above the hardground between 431 and 432 m (**Fig. 3**), and *Inoceramus costellatus* Woods is recorded at 435.5 m (Wood et al., 1994). These faunal records demonstrate that the sediments immediately above the hardground are topmost Upper Turonian *C. waltersdorfensis* inoceramid Zone (lowest *Forresteria* (*Harleites*) *petrocoriensis* ammonite Zone), and correlate to the Navigation Hardgrounds and Navigation Marls complex of the Southern Province (Bailey et al., 1984; Mortimore, 1986; Wood et al., 1994; Mortimore et al., 2001), and broadly to the Top Rock of the Transitional Province in Suffolk (Bristow, 1990; Woods et al., 2012; Gallois, 2016). The surface of the Navigation Hardground at 432.03 m is taken to mark the top of the *P. (S.) plana* Zone. Nodular chalks and hardground are absent from equivalent Northern Province successions; there, the inoceramid-*Didymotis* association occurs 0.15 m beneath the middle of the three Kiplingcotes Marls (Gaunt et al., 1992), the highest of which is represented at Trunch by the marl seam at 430.15 m (Wood et al., 1994).

Following the recommendations of the Coniacian Working Group of the Subcommittee on Cretaceous Stratigraphy (Kauffman et al., 1996; Walaszczyk and Wood, 1998), the base of the Coniacian is placed at the lowest occurrence (LO) of *Cremnoceramus deformis erectus* (Meek), previously referred to *Cremnoceramus rotundatus* (*sensu* Tröger, *non* Fiege) (Walaszczyk et al., 2010; Ogg and Hinnov, 2012), which is coeval with the LO *Scaphites preventricosus* Cobban in the US Western Interior Basin (Walaszczyk and Cobban, 2000; Cobban et al., 2006). *Cremnoceramus d. erectus* has not been identified at Trunch, but in addition to the uppermost Turonian *C. w. waltersdorfensis* – *Didymotis* association recorded from immediately above the Navigation Hardground, specimens of *Cremnoceramus waltersdorfensis hannovrensis* (Heinz) are common with *Cremnoceramus rotundatus* (Fiege) at 427.88, and large *C. w.*

hannovrensis (Heinz) occur at 426.96 m (**Fig. 3**), indicative of the Lower Coniacian *C. hannoverensis* inoceramid Zone.

The LO of *C. d. erectus* in the candidate Coniacian stratotype section of Salzgitter-Salder (northern Germany) is coincident with the minimum $\delta^{13}\text{C}_{\text{carb}}$ value at the top of a broader trough defining the Navigation CIE (Voigt and Hilbrecht, 1997; Walaszczyk and Wood, 1998; Jarvis et al., 2006, 2015; Walaszczyk et al., 2010). This is ~1 m above the LO of *C. w. waltersdorfensis* and a flood of *Didymotis* (*Didymotis* Event II of Wood et al., 1984); the LO of *C. w. hannovrensis* occurs several metres higher in the section. An identical relationship between the isotope profile and the inoceramid - *Didymotis* succession is observed in sections in SE England and in the Czech Republic (Jarvis et al., 2006, 2015; Uličný et al., 2014). A distinctive sharp $\delta^{13}\text{C}_{\text{carb}}$ peak immediately preceding the Navigation CIE, around 433 m at Trunch (**Fig. 3**), is observed in other northern European carbon-isotope profiles (Jarvis et al., 2015), and is referred to an i5 peak here. The Turonian – Coniacian boundary at Trunch is placed at the $\delta^{13}\text{C}_{\text{carb}}$ minimum at 429.9 m, immediately above Kiplingcote Marl 3.

3.2.6 Coniacian

Lower Coniacian (429.9 – 411.6 m)

The Lower Coniacian (*Micraster cortestudinarium* echinoid Zone) is identified as the succession from 429.9 m to an interval of core loss at 411.63 m, which was considered by Wood et al. (1994) to represent the position of a marl seam equivalent to the East Cliff Marl 2 / Shoreham Marl 2 of the Southern Province, at the base of the *Micraster coranguinum* Zone (**Fig. 2**). This interpretation for the placement of the base of the Middle Coniacian is supported by records of *Cremnoceramus crassus crassus* Petrascheck (*C. schloenbachi* (Böhm) of earlier literature; Walaszczyk and Wood, 1998) around 420 m, indicative of the mid-Lower Coniacian *C. c. crassus* Zone (Walaszczyk, 2000; Walaszczyk and, Wood 2018), and of *Volvicceramus koeneni* (Müller), the basal Middle Coniacian marker (*V. koeneni* Zone), at 406.78 m. *Volvicceramus koeneni* is restricted to a few metres of section between Shoreham Marl 1 and Belle Tout 1 Lower Marl in southern England (Mortimore et al., 2001), and occurs at a similar position above the Little Weighton Marls, in the low Lower *Hagenowia rostrata* Zone of the Northern Province (Whitham, 1991).

The succession of marly chalks, nodular chalks and hardgrounds with abundant nodular, semitabular and tabular flints that characterise the Lower Coniacian at Trunch differs from the typical lithological successions of both the Southern and Northern Provinces, and individual beds cannot be correlated to other areas with any confidence. Notable features include thick 13 – 14 cm semitabular – tabular flints at 427.06, 425.76 and 422.68 m, a 3 cm grey-green laminated marl with a sharp top and irregular base containing small inoceramid chips and chalk pebbles at 423.00 m, and a series of yellow nodular chalks and weak hardgrounds, including two with well-developed surfaces at 423.82 and 420.26 m (**Fig. 3**).

The bed yielding common *Cremnoceramus* at 427.88 m likely marks the position of the *C. w. hannovrensis* Event recognized in northern Germany (Walaszczyk et al., 2010). A record of *C. w. hannovrensis* within an interval of nodular chalks at 426.96 m coincides with positive excursion in the $\delta^{13}\text{C}_{\text{carb}}$ profile that is correlated to the Beeding CIE (**Figs 3, 5**). An increased in $\delta^{13}\text{C}_{\text{carb}}$ values at 420.0 m in a bed yielding *C. crassus crassus*, immediately above a pair of hardgrounds (Light Point Hardgrounds?) is indicative of the mid-Lower Coniacian *C. c. crassus* Zone and the identification of the positive isotope excursion as the Light Point CIE.

Middle Coniacian (411.6 – 378.0 m)

Beds of yellow-stained nodular chalk continue through the Middle Coniacian up to 402.70 m. The record of *V. koeneni* at 406.78 m occurs at the base of a significant shift in the medium-term $\delta^{13}\text{C}_{\text{carb}}$ profile, from relatively constant values above the Light Point CIE to sharply increasing values between 408.0 – 406.0 m. This can be confidently identified as the East Cliff CIE, which not only has a distinctive isotope signature but coincides elsewhere to an acme of *V. koeneni* (Jarvis et al., 2006).

Volvicceramus aff. *involutus* (J. de C. Sowerby) is recorded at 402.62 m, and *Platyceramus mantelli* (Barrois) at 401.65 m (Wood et al., 1994; **Fig. 3**). These taxa are typical of the *Volvicceramus*-rich beds that characterise the basal *M. coranguinum* Zone (mid- to upper Middle Coniacian) in the Southern Province (Mortimore et al., 2001), and the basal part of the lower *H. rostrata* Zone in the Northern Province (Whitham, 1991); *V. involutus* is the index species of the upper Middle Coniacian *V. involutus* Zone. A further shift in the medium-term $\delta^{13}\text{C}_{\text{carb}}$ profile occurs at 401.0 m, from rising values below, to a plateau with considerable short-term variation above. The peak developed

at the base of this change of trend is assigned to the White Fall CIE, which coincides with the LO *V. involutus* elsewhere (Jarvis et al., 2006).

Wood et al. (1994) suggested that a prominent 9 cm tabular flint at 400.00 m is equivalent to the East Cliff Semitabular (Gale and Smith, 1982) and Seven Sisters Flint (Mortimore, 1986) of the Southern Province. This is not consistent with the carbon isotope correlation (Jarvis et al., 2006). However, a 9 cm massive nodular flint at 391.41 m in the Trunch core overlies a bed of *V. involutus* at 392.05 m and an oyster bed at 392.32 m (**Fig. 3**). Beds of *V. involutus* characteristically underlie the East Cliff Semitabular Flint in Kent (Bailey et al., 1984; Robinson, 1986), the Seven Sisters Flint in Sussex (Mortimore, 1986; Mortimore et al., 2001), and the Fingleworth Flint in the Northern Province (Wood and Smith, 1978; Whitham, 1991; Caunt et al., 1992), indicating the equivalence of these regional marker beds to the identified Trunch flint.

An interval of poor core recovery between 395.72 and 396.86 m includes a massive 8 cm flint, and Gallois and Morter (1976) indicated the presence of a marl around 395 m based on their interpretation of the geophysical data. A 19 m thick succession of fossiliferous flinty white chalks with occasional intervals displaying stylolitic marly partings characterise the succession above the East Cliff Flint at Trunch (**Fig. 3**).

Upper Coniacian (378.0 – 372.5 m)

The base of the Upper Coniacian is very poorly constrained in England. The substage boundary is defined by the LO of the inoceramid bivalve *Magadiceramus subquadratus* (Schlüter) (Knauth et al., 1996; Ogg and Hinnov, 2012), and is marked also by the appearance of common sphenoceramids (Walaszczyk and Wood, 2018), including *Sphenoceramus subcardissoides* (Schlüter). No definitive Upper Coniacian fossil markers have been identified at Trunch, and equivalent strata throughout the Southern and Northern Provinces are also poorly dated ('barren beds' of Mortimore et al., 2001). A number of peaks and troughs characterise the $\delta^{13}\text{C}_{\text{carb}}$ plateau interval of the Middle – Upper Coniacian (e.g. **Fig. 5**) but the unambiguous correlation of these is hampered by the low sampling resolution of published carbon isotope curves. Nonetheless, a weakly defined $\delta^{13}\text{C}$ maximum in the middle of the plateau interval, in the assumed Middle Coniacian, was designated as the Kingsdown CIE by Jarvis et al. (2006).

The base of the Upper Coniacian in the Southern Province is somewhat arbitrarily placed at the base of the 'barren beds', a short distance below the Cuckmere Sponge Bed (Mortimore et al., 2001). Higher resolution $\delta^{13}\text{C}_{\text{carb}}$ data for the Coniacian of Seaford Head, East Sussex indicate that this corresponds to the bottom of an unnamed positive isotope excursion that occurs above the peak defining the Kingsdown CIE (Thibault et al., 2016). Correlation to Trunch places the equivalent level at approximately 378 m depth.

3.2.7 Coniacian – Santonian boundary

The base of the Santonian stage (Lamolda et al., 2014) is defined by the lowest occurrence (LO) of *Cladoceras* (*Platyceras*) *undulatoaplicatus* (Roemer). A possible *C. undulatoaplicatus* was recorded by Wood et al. (1994) at 365.80 m at Trunch, just above a 9 cm flint at 366.50 m (**Fig. 4**). *Cladoceras undulatoaplicatus* occurs in flood abundance at two levels in the basal Santonian (Bailey et al., 1984; Lamolda et al., 2014), the upper and most prolific of which coincides with the Bedwell's Columnar Flint (Bedwell, 1874; Rowe, 1900) in southern England (Bailey et al., 1983, 1984; Mortimore, 1986; Mortimore et al., 2001).

The correspondence between *Cladoceras* records and carbon isotope stratigraphy has been considered by a number of authors (Jarvis et al., 2006; Gale et al., 2007; Paul and Lamolda, 2009; Lamolda et al., 2014; Thibault et al., 2016). A series of low amplitude peaks and troughs occur superimposed on a trend of long-term upwards-falling $\delta^{13}\text{C}_{\text{carb}}$ values by -0.5‰ between the Middle Coniacian Kingsdown positive CIE and the Middle Santonian $\delta^{13}\text{C}_{\text{carb}}$ minimum and Haven Brow negative CIE (**Fig. 5**). Small $\delta^{13}\text{C}_{\text{carb}}$ peaks occur around the levels of both the lower and the upper *C. undulatoaplicatus* bands – the Michel Dean and Bedwell CIEs, respectively (Jarvis et al., 2006).

Biostratigraphic and $\delta^{13}\text{C}_{\text{carb}}$ chemostratigraphic correlation of SE England sections with Ten Mile Creek, Texas and the Santonian GSSP at Olazagutia, Spain (Paul and Lamolda, 2009) confirms that the *C. undulatoaplicatus* record at Trunch corresponds best to the Bedwell CIE. Consequently, the Coniacian – Santonian boundary is placed lower, at 372.5 m, at the bottom of a marked 0.3‰ $\delta^{13}\text{C}_{\text{carb}}$ peak (**Figs 4 – 5**). This implies that the 40 cm nodular flint at 372.60 m, a short distance above a 'Middleton' sponge bed (cf.

Wright and Wright, 1942; Gallois and Morter, 1976) at 373.10 m, corresponds to the Michel Dean Flint (Mortimore, 1986) of southern England.

3.2.8 Santonian

Lower Santonian (372.5 – 359.0 m)

Regularly spaced large nodular and semitabular flints continue upwards through the Trunch succession from Bedwell's Columnar Flint to 350.61 m, above which there is a notable decrease in the abundance and thickness of flint bands (**Fig. 4**). This is taken to mark the top of the Burnham Chalk Formation.

The Santonian – Lower Campanian of the Northern Province consists of flint-free chalks of the Flamborough Formation (Wood and Smith, 1978; Mitchell, 2019), which is characterised not only by the absence of flint (rare large pale-coloured masses of chert occur in some sections; Mitchell, 1995), but also by the presence of numerous marl seams spaced at approximately 1-m intervals (Whitham, 1993). The base of the formation is located immediately above the highest significant flint (High Stacks Flint; Whitham, 1991) in the onshore Northern Province succession (top Burnham Chalk), and represents a sharp lithostratigraphic boundary. It falls within the mid-*Cordiceramus cordiformis* Zone in the Middle Santonian (Mortimore et al., 2001). The Flamborough Formation cannot be applied as a lithostratigraphic unit in the Trunch succession.

The equivalent interval in the Southern Province is represented by the Seaford Chalk (below) and Newhaven Chalk (above) formations (Rawson et al., 2001; **Fig. 2**). The former consists of pure soft white chalks with conspicuous bands of large flint, the latter by firm marly chalks with numerous marls seams and regular but fewer flint bands; in parts of east Kent (Thanet), the Seaford Chalk is overlain by very soft, nearly flint-free chalk of the Margate Chalk Formation (Mortimore and Wood, 1986; Bristow et al., 1997; Mortimore et al., 2001). The base of the Newhaven Chalk is Buckle Marl 1, which coincides with the base of the Upper Santonian *Uintacrinus socialis* crinoid Zone. A comparable lithological succession is not developed at Trunch, so the Southern Province lithostratigraphy cannot be used for the core.

Recognising the atypical character of the Trunch succession, we apply the term “Flamborough Chalk equivalent” to the upper part of our study section (**Fig. 4**). The

base of the formation is placed at the top of the last major consistent flint in the succession at 350.61 m, although this is some degree arbitrary since nodular flints remain common up to the core gap at 345.21 m. The chosen boundary is some distance above a transition to marlier chalks from around 362 m, expressed by an increase in aluminium oxide (Al_2O_3) and falling calcium carbonate (CaCO_3) contents (**Supplementary Material Table 1**), and by total insoluble residues that rise from ~1 to >2 wt% (Bath and Edmunds, 1981). Lower purity chalks characterise the remainder of the Santonian, but carbonate contents increase again from the base of the Campanian.

Middle Santonian (359.0 – 336.8 m)

The stratigraphic extent of the Lower Santonian, defined by the total range of *C. undulaticus* (Lamolda and Hancock, 1996), cannot be determined at Trunch due to a lack of adequate faunal records. *Cordiceramus cordiformis* (J. de C. Sowerby), a guide to the base of the Middle Santonian, is recorded at 355.98 m. The $\delta^{13}\text{C}_{\text{carb}}$ minimum marking the low Middle Santonian Haven Brow CIE occur immediately above at 354.0 m. The occurrence of *Conulus* at 354.01 m and *Sphenoceras* ex gr. *pachti* (Arkhangelsky) – *cardissoides* (Goldfuss) at 352.33 and 353.54 m confirm a Santonian age.

Throughout southern England the base of the Middle Santonian lies approximately mid-way between the Bedwell and Haven Brow CIEs, between two small $\delta^{13}\text{C}_{\text{carb}}$ peaks informally designated I1 and I2 by Jarvis et al. (2006). Correlation of the Trunch carbon isotope profile (**Fig. 5**) to those elsewhere (Jarvis et al., 2006; Thibault et al., 2016) places the base Middle Santonian at approximately 359 m in the core, around the facies change to marlier chalks (**Fig. 4**). A prominent 5 cm thick flint at 352.50 m has been correlated to Whitaker's 3-inch Flint based on the carbon-isotope stratigraphy (Jarvis et al., 2006).

Carbon isotope values increase upwards from the Haven Brow CIE and reach a maximum in the last sample immediately below a coring gap from 345.21 – 342.34 m, above which a medium-term $\delta^{13}\text{C}_{\text{carb}}$ fall is recorded. This $\delta^{13}\text{C}_{\text{carb}}$ maximum, which is not fully resolved at Trunch due to the missing section, can be ascribed to the Horseshoe Bay CIE, a prominent high Middle Santonian marker in the Upper Cretaceous carbon-isotope stratigraphy (Jarvis et al., 2006; Thibault et al., 2016).

Upper Santonian (336.8 – 306.72 m)

The lowest definite record of *Uintacrinus socialis* Grinnel, marking the base of the Upper Santonian (Lamolda and Hancock, 1996), is at 335.26 m, above a stylolitic marly plexus at 335.56 m (**Fig. 4**), and the index species is common in the overlying 10 m of section. The marly plexus coincides with a well-defined minimum in the carbon isotope profile indicative of the basal Upper Santonian Buckle CIE that is a prominent feature of northern European and Tethys isotope records (Jarvis et al., 2006; Thibault et al., 2016). A previously unidentified crinoid brachial at 336.8 m (Wood et al., 1994) is interpreted to be *U. socialis* since this level coincides with the base of the Buckle CIE (**Figs 4 – 5**), which lies in the lowest *U. socialis* Zone elsewhere (Jarvis et al., 2006; Thibault et al., 2016).

The marly plexus at 335.56 m is correlated to the Buckle Marls, which correspond to the base of the *U. socialis* Zone in the Southern Province (Mortimore et al., 2001), and match the position of the West Nook Marls in the Northern Province (Mitchell, 2019). A burrow flint at 339.77 m may be an equivalent of the Exceat Flint of southern England. A bed with oysters, inoceramids and echinoderm debris occurs above an omission surface at 330.15 m. The highest definitive *Uintacrinus* is recorded at 324.91 m, although unidentified crinoid brachials occur at 322.93 – 323.00 and 324.20 m (Wood et al., 1994). The lowest *Marsupites*, defining the uppermost Santonian *Marsupites* crinoid Zone (Hancock and Gale, 1996), is recorded at 319.54 m (Wood et al., 1994).

The carbon isotope profile displays long-term rising values from a minimum at the Buckle CIE to a maximum at the top of the Santonian (**Fig. 5**). Superimposed on the somewhat erratic rising trend of the low-resolution Trunch profile are a number of poorly resolved low-amplitude $\delta^{13}\text{C}_{\text{carb}}$ peaks and troughs. Correlation to the southern England stratigraphy indicates that this corresponds to the Hawks Brow CIE (Jarvis et al., 2006; Thibault et al., 2016). A massive 8 cm burrow flint at 321.95 m, 2 m below the base of the *Marsupites* Zone, is correlated to the Hawks Brow Flint. A minor negative $\delta^{13}\text{C}_{\text{carb}}$ excursion at 316 – 315 m coincident with a marl seam at 314.96 m and a shift to rising $\delta^{13}\text{C}_{\text{carb}}$ values above, corresponds in the stratigraphic position of the Foreness negative CIE and the Brighton 'Five' marls in southern England (Jarvis et al., 2006; Thibault et al., 2016).

The smooth ornamentation of the *Marsupites* plates recovered at 319.54 m are indicative of the species *M. laevigatus* Forbes that characterises the lower half of the

Marsupites Zone (Gale et al., 2008). The highest *Marsupites*, with ornamented plates [= *M. testudinarius* (Schlotheim)], occurs at 307.35 m. The LO of *M. testudinarius* occurs above the Brighton Marl in the Southern Province, a short distance above the Brighton 'Five' Marls (e.g. Thibault et al., 2016 fig. S1). Giant *Porosphaera* recovered at 306.80 m and 307.05 m are good secondary indicators of the *Marsupites* Zone.

3.2.9 Santonian – Campanian boundary

The highest occurrence of *Marsupites* has been proposed as the boundary marker for the base Campanian (Gale et al., 1995; Hancock and Gale, 1996; Gale et al., 2008), although a stage boundary definition and a GSSP remain to be agreed. Following Wood et al. (1994) and Jarvis et al. (2006), the base Campanian at Trunch is placed at the surface of the omission surface at 306.72 m which is overlain by shelly chalks with abundant inoceramid and oyster debris and common *Gonioteuthis* belemnites. Shelly chalks extend around 2 m below the omission surface. This lithological change is similar to that developed around the stage boundary at Lägerdorf in northern Germany, the "Grobkreide" facies (Ernst, 1963; Schulz et al., 1984). The facies spans the uppermost *Marsupites* Zone to lower *Gonioteuthis granulataquadrata* Zone (*O. pillula* Zone equivalent) in Yorkshire (Mitchell, 1995, 2019 fig. 12), and characterises the lower part of the *Echinocorys scutata* for *depressula* Subzone of the *Offaster pillula* Zone of southern England (Mortimore et al., 2001), and Northern Ireland (Creggan Chalk Formation, Ulster White Limestone Group; Fletcher, 1977; Hopson, 2005)

Placement of the stage boundary at the omission surface is consistent with the carbon isotope stratigraphy, since this coincides with the lower $\delta^{13}\text{C}_{\text{carb}}$ peak of a double excursion spanning the stage boundary interval (Santonian – Campanian Boundary Event, SCBE; Jarvis et al., 2002, 2006; Thibault et al., 2016; Deville de Periere et al., 2019). It is possible that there is a non-sequence at the omission surface, since the sculpture of the *Marsupites* calyx plate at 307.35 m suggests a horizon below the top of the zone. A significant hiatus at this level has been described at Whitecliff, Isle of Wight, in southern England (Jarvis et al., 2006).

Uintacrinus anglicus Rasmussen, the index taxon of the *U. anglicus* Zone that underlies the *Offaster pillula* Zone in the lowest Campanian (Rawson et al., 1978; Bailey et al., 1983, 1984; Mitchell, 1994, 1995; Wood et al., 1994; Mortimore et al., 2001; Gale et al., 2008) has not been identified at Trunch, although the thickest known *U. anglicus*

Zone in Europe is developed at Flamborough Head in Yorkshire (Mitchell, 1995, 2019; Deville de Periere et al., 2019). The relatively expanded nature of the positive $\delta^{13}\text{C}_{\text{carb}}$ excursion spanning the stage boundary at Trunch (cf. Jarvis et al., 2002, 2006; Thibault et al., 2016; Deville de Periere et al., 2019) suggests that sediments of this age are likely present.

3.2.10 Campanian

Lower Campanian (pars; 306.72 – 270.00 m)

Campanian sediments consist predominantly of moderately lithified grey-white fossiliferous (inoceramids and calcitic bivalves, echinoids, crinoids, brachiopods, bryozoans, serpulids, belemnites, fish debris), locally calcarenitic, chalk (Morter et al., 1975). Beds commonly display complex pale- and medium-grey marly fills of *Zoophycos*, *Thalassinoides* and *Chondrites* burrows. Thin marly partings, some showing stylolitic textures, occur at some levels (Fig. 4). Black centred, thalassinoid burrow flints and occasional thin secondary tabular flints are present. Beds of pyritic blue-grey lithistid and hexactinellid sponge remains occur at many levels.

The lowest probable *Offaster* and *Echinocorys scutata* Leske form *depressula* Brydone, characterising the Lower Campanian lower *O. pillula* Zone, are recorded in fossiliferous chalk at 296.94 m (Morter et al., 1975). A prominent 6 cm laminated silty green-grey marl at 286.55 m is identified as the Wells Marl of the north Norfolk coast, correlative to the Old North Marl in southern England, and the M1 marl at Lägerdorf, northern Germany (Wood et al., 1994). This approximates to the boundary between the *E. scutata depressula* Subzone and the overlying Abundant *O. pillula* Subzone (Brydone, 1912, 1914). The subzone boundary is placed approximately 1 m below the marl at 287.78 m, at the base of a bed yielding *Offaster* (Fig. 4). Records of *Offaster pillula* (Lamarck) at 284.51 and 283.68 m, the latter overlaid by an inoceramid bed at 283.61 m, probably represent the lower of two belts of *O. pillula* recognized in the Southern Province (Wood and Mortimore, 1988; Mortimore et al., 2001).

A trend of falling $\delta^{13}\text{C}_{\text{carb}}$ values above the SCBE positive excursions reaches a minimum immediately above the lower *Offaster* belt, above which a modest erratic rise occurs (Fig. 5). This carbon isotope minimum corresponds to the Pillula CIE, a

prominent feature of the Lower Campanian isotope stratigraphy in Germany, England, Italy and Iran (Thibault et al., 2016; Razmjooei et al., 2018).

The highest occurrence of *Hypoxytoma tenuiscostata* (Roemer) at 279.91 m and *Sphenoceras* at 275 m (Wood et al., 1994) are consistent with the Abundant *O. pillula* Subzone. A bed of medium-sized *O. pillula* in a burrowed marly interval between 272.5 – 273.5 m is inferred to be equivalent of the *planoconvexus* horizon with *O. pillula* form *planatus* Brydone that occurs at the top of the *O. pillula* Zone in southern England (Brydone, 1939; Mortimore et al., 2001). The base of the *Gonioteuthis quadrata* Zone is placed immediately above this horizon, at 272.50 m, 2.5 m below the top of our study interval. A further 227 m of Campanian *Belemnitella mucronata* and *B. lanceolata* Zone chalks are represented in the core, below an unconformity with Quaternary glacial deposits at 45.70 m depth (Gallois and Morter, 1976; Wood et al., 1994; Voigt et al., 2012).

4 Material and methods

A total of 267 chalk samples were obtained from the BGS Keyworth core store, Nottingham, UK (https://www.bgs.ac.uk/collections/corestore_kw.html). Chalk samples were taken at an average of 1 m spacing (**Figs 3 – 4; Supplementary Material Table 2**); no flints (cherts) were collected. Higher resolution sampling was undertaken through the Cenomanian and across the Turonian – Coniacian boundary due to the condensed nature of these intervals.

Core material available consisted principally of chippings of 10 cm composite intervals. Sample depths are thus reported to one decimal place; values represent the base of each 10 cm interval. Additionally, four samples were collected from specific marker horizons: 512.43 m, Hunstanton Formation (Red Chalk); 500.63 m, *M. geslinianum* Zone convolute hardground; 478.03 m, Melton Ross Marl (B2); 286.55 m, Wells Marl (Old Nore Marl equivalent). Where possible, 200 g of material was taken for palynological analysis, and an additional 50 g for elemental and stable-isotope geochemical analysis.

4.1 Palynological methods

All samples from the Trunch borehole were processed by Palynological Laboratory Services (PLS, Anglesey, UK) using a methodology based on the modified procedure of

Batten and Morrison (1983) as described by Pearce et al. (2003). In summary, ca. 200 g (dry weight) of weighed disaggregated material, spiked with *Lycopodium* spore tablets, was treated with concentrated (12M) HCl, concentrated (29M) HF and sieved with a 15 µm nylon sieve. Losses of dinocysts are known if a sieve size of greater than 15 µm is used (Lignum et al., 2008, Mertens et al., 2009). Oxidation was not employed due to known problems with assemblage bias (Schrunk, 1988; Dodsworth, 2000; Mertens, et al., 2009).

Where possible, 300 identified dinocysts (excluding pollen/spores, acritarchs and unidentified specimens) were recorded. A dinocyst specimen was recorded if over 50% of an individual was observed. Operculae and loisthocyst (cysts with no attached operculum; Sarjeant et al., 1987) fragments were recorded but only used to indicate the presence of a species if the loisthocyst was not included in the count. Although this procedure improves the description of the assemblage it should be noted that not all operculae or loisthocyst fragments are diagnostic to species level, and therefore, this procedure is not completely reliable. The species list and full taxonomic citations are provided in **Appendix A**. Counted abundances shown on the summary range chart (**Fig. 6**) are grouped into nine classes: present but outside of the main count (“+” <1/300); rare (1 – 4); frequent (5 – 9); very frequent (10 – 19); common (20 – 39); very common (40 – 59); abundant (60 – 99); very abundant (100 – 139); dominant (>139); reworked specimens are indicated (rw)

The calculation of absolute abundances (palynomorphs per gram; ppg) follows Pearce et al. (2003). Values are reported with and without a correction for carbonate dilution (Pross et al. 2006; Pearce et al., 2009); results are shown in **Fig. 7**. Values are reported below as the bulk lithology abundance, with the carbonate-corrected values in parentheses (when available). Species richness (number of observed species) and the Shannon diversity index (H , calculated using PAST software, Hammer et al., 2001; <https://folk.uio.no/ohammer/past/>) are plotted in **Fig. 7**. Values are reported below as species richness, with the Shannon diversity in parentheses. Palynological count data are provided in **Supplementary Material Table 2**.

4.2 Geochemical methods

Stable isotope analysis ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$ of the carbonate phase) were undertaken at the stable isotope laboratory, Department of Earth Sciences, University of Oxford, UK.

Subsamples of around 50 g were crushed to <3 mm chips in clean thick-walled plastic bags, using a metal plate and hammer. The chips were hand ground to a fine powder in an agate pestle and mortar. Carbon and oxygen stable-isotope analyses of the bulk carbonate fraction ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) in 250 μg of powdered samples, using a VG Isogas Prism II mass spectrometer with an online VG Isocarb common acid bath preparation system. Samples were first cleaned using hydrogen peroxide and acetone and dried at 60°C for at least 30 min. In the instrument they were reacted with purified phosphoric acid at 90°C. Calibration to the Vienna Pee Dee belemnite (VPDB) standard via NBS-19 was made daily using the Oxford in-house (NOCZ) Carrara marble standard. Data are reported in delta (δ) notation as per mil (‰) relative to the VPDB standard (**Fig. 5**). Reproducibility of replicate standards was better than 0.1‰ for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$. Trunch carbon-isotope data were plotted by Jarvis et al. (2005; numerical values were not provided); $\delta^{13}\text{C}_{\text{carb}}$ and corresponding $\delta^{18}\text{O}$ values are reported for the first time here (**Supplementary Material Table 1**).

For elemental analysis, samples were ground to fine powders in an agate ball mill, and dried at 60°C; subsamples were fused with LiBO_2 , and the melts dissolved in 0.5 M HNO_3 (Jarvis, 2003). Calcium determinations were performed by inductively coupled plasma - atomic emission spectroscopy (ICP-AES) employing a JY Ultima 2C spectrometer at Kingston University London. The instrument was calibrated using a range of sedimentary rock reference materials. The analytical protocol follows Olde et al. (2015). CaCO_3 values were calculated from bulk sediment Ca contents assuming that Ca resides only in the carbonate fraction. Aluminium contents are expressed as weight percent oxide. By reference to international reference materials run with samples, accuracy and precision were judged to be <3%. CaCO_3 and Al_2O_3 data are reported in **Supplementary Material Table 1**.

4.3 Palynological database

Most of the data on the spatial and temporal distribution of the selected stratigraphically important species were taken from the PALYNODATA database (Palynodata Inc and White, 2008), compiled over the last 25 years under the auspices of several major oil companies and the Geological Survey of Canada. The database is freely available and stores taxonomic, bibliographic, geographic and biostratigraphic information from all known pre-Quaternary palynological publications up to 2006

(https://gcmd.nasa.gov/records/CANADA-CGDI_Canada_GSC_PalyLit.html). For completeness, the taxonomy of all species discussed is reviewed, and synonyms are included in the database interrogation. Over 5000 entries for the species considered in this study exist, and their geographic locations are here condensed to 212 localities, including DSDP and ODP sites. Species records were supplemented by data from references missing in PALYNODATA, plus personal observations.

Every effort was made to check all cited references, to confirm species identifications where possible, and to determine the most likely spatial and temporal range of each species. To distinguish between chronostratigraphic position and age, we refer to the stratigraphically lowest and highest occurrence in individual sections as the LO (lowest occurrence) and HO (highest occurrence). If these events appear to represent the maximal range or the recognised inception or extinction of the species, the terms FAD (first appearance datum) or LAD (last appearance datum) are used.

4.4 Palaeogeographic mapping

Dinocyst distribution data were taken from Palynodata Inc and White (2008) with additional information from: Wilson (1974); Marshall and Batten (1988); Prössl (1990); Schiøler (1992); Dodsworth (2004a, b, 2016), Lebedeva (2006, 2008, 2010); McPherson et al. (2006); Wagreich et al. (2005); Zitt et al. (2006); Gedl (2007); Bubík et al. (2008); Calis and Drummond (2008); Lignum (2008); Nicolas (2008); Nikitenko et al. (2008); Skupien and Mohammed (2008); Soliman et al. (2008, 2009); Masure and Vrielynck (2009); Moradin and Allameli (2010); Peyrot et al. (2011); Mohamed et al. (2012); Nøhr-Hansen (2012), Da-Cama et al. (2014); Nøhr-Hansen et al. (2018); Dodsworth and Eldrett (2019); Eldrett et al. (2019) and personal observations. A summary table of the geographic localities is shown in **Supplementary Material Table 3**.

GPlates 2.1 (www.gplates.org) was employed to rotate the data points back to their original palaeogeographic positions. GPlates is an open-source, plate tectonic geographic information system that allows the manipulation of plate-tectonic reconstructions through geological time (Matthews et al., 2016; Müller et al., 2018). The geomagnetic rotations were updated from Gee and Kent (2007) to the GTS2016 timescale (Ogg et al., 2016). Within the relevant age interval, the GTS2016 model modifies the ages of the Late Cretaceous isochrones slightly from those used by Gee and Kent (2007), placing the young end of magnetic polarity chron M0r at 125.95 Ma rather

than at 120.6 – 121 Ma. In addition, C33n, C33o and C34n ages are modified respectively from 73.6, 79.1, 83.0 Ma to 74.3, 79.9 and 84.2 Ma. The resulting differences are marginal and likely within the error. Similarly, no significant differences to the GTS2016-calibrated plots were observed when adopting the new age model presented here, or the proposed GTS2020 time scale (see **Section 4.5**).

The palaeogeographic maps presented here, based on Cao et al. (2017), employ the palaeomagnetic reference frame to construct an ‘absolute’ plate motion model that may be used for palaeolatitude analysis through time-correcting the plates palaeo-positions relative to the spin axis of the Earth (Torsvik et al., 2012; Matthews et al., 2016). Data points were rotated from their present-day geographic coordinates (latitude/longitude WGS1984) using GPlates 2.1. The maps are projected using the World Geodetic Position WGS 1984 geographic coordinate system.

Key species are discussed (see also **Figs 11, 14, 16, 18, 21**) with respect to their palaeogeographic distributions plotted on **Figs 10, 12, 15, 17, 19 – 20**). With the exception of India and to a lesser extent Australia the majority of plates experience dominantly E – W motion during the Late Cretaceous and, therefore, only minor differences exist in their palaeolatitude position. Given errors inherent in the calculation of palaeolatitudes, an average value for the five time-slices is provided in the text. Five palaeogeographic maps derived from the reconstructions of Cao et al. (2017) are produced for the earliest: Cenomanian; Turonian; Coniacian; Santonian; and Campanian. The age of the geographic configuration closest to the species event under discussion is used to illustrate the species spatial distribution. Particular effort was made to check outliers or spurious occurrences of dinocyst taxa.

Palaeoclimate zones for the latest Early Cretaceous (Late Albian) and mid-Late Cretaceous (Early Campanian), compiled by Scotese et al. (2014), are plotted on the palaeogeographic maps to assess whether a species is confined to specific palaeoclimate belts. Only a limited range of palaeoclimate maps were provided by Scotese et al. (2014): Late Albian climate belts are plotted on the Cenomanian maps; Early Campanian climate belts are used for the other time slices.

4.5 Age model

Age constraints for the Cenomanian through Campanian interval at Trunch are provided by radioisotopic and astrochronological ages of macrofossil biostratigraphic

datum levels, global carbon-isotope excursions, and the base Chron C32 geomagnetic reversal, interpreted in previous studies (Sageman et al., 2006, 2014; Voigt and Schönfeld, 2010; Husson et al., 2011; Voigt et al., 2012; Meyers et al., 2012; Ogg and Hinnov, 2012; Ma et al., 2014; Laurin et al., 2014; Thibault et al., 2016; Gambacorta et al., 2019). A total of 30 age-control points is applied to the Upper Cretaceous at Trunch (**Fig. 8, Table 1**). The age-depth relationships between these points are estimated using piecewise cubic Hermite interpolating polynomial function (pchip) in the Matlab R2018b Curve Fitting Toolbox. The individual age-control points are equipped with uncertainties related to stratigraphic correlation, sampling resolution, and those inherent in the radioisotopic measurements and astrochronological interpretations. Between the age-control points, the uncertainties are linearly interpolated.

Recently published chronological constraints (see above) make it possible to update the age calibration of the English Chalk carbon-isotope reference curve of Jarvis et al. (2006). The composite profile is constructed using data from five sections: Dover; Eastbourne; Culver; Trunch; and Speeton (**Fig. 9**). Each section is tied to a series of age control points (**Supplementary Material Tables 4 – 7**), and an age-depth model is constructed using shape-preserving piecewise cubic interpolation. Because the interpolated ages are sensitive to local variations in sedimentation rates, it was necessary to introduce a series of secondary age control points at the junctions of the composite carbon-isotope plot. Age estimates at these levels are obtained as an arithmetic mean of interpolated ages between the primary age control points. An exception is the base Middle Coniacian in the Trunch and Culver data series, which is tuned to the Trunch reference section.

The international geologic timescale of Ogg et al. (2016), updated from GTS2012 of Gradstein et al. (2012), is currently in revision. The forthcoming publication, GTS2020, currently adopts the following ages for Late Cretaceous stage bases (F. Gradstein pers. comm., September 2019): Cenomanian 100.5 ± 0.1 Ma; Turonian 93.9 ± 0.2 Ma; Coniacian 89.4 ± 0.2 Ma; Santonian 85.7 ± 0.1 ; Campanian 83.6 ± 0.1 ; Maastrichtian 72.2 ± 0.2 . The justification of these age assignments has yet to be published, and there remains a possibility that some changes may be made. However, in addition to the ages calculated using the model presented in this paper, we have recalibrated the age-depth model for Trunch and the English Chalk $\delta^{13}\text{C}_{\text{carb}}$ reference curve (Jarvis et al., 2006) using the unpublished GTS2020 ages with a view to offering compatibility for future

workers adopting that time scale. The alternative ages of the bioevents are listed in Appendix B.

5 Carbon and oxygen stable-isotope stratigraphy

Carbon isotope data (Jenkyns et al., 1994; Jarvis et al., 2006) and established CIEs (Jarvis et al., 2006; Uličný et al., 2014; Thibault et al., 2016), integrated with lithostratigraphic marker bed correlation and macrofossil biostratigraphy (**Figs 3 – 4**), were employed to constrain the chronostratigraphy of the Trunch succession (**Section 3.2**), as summarised in **Fig. 5**. Identified CIEs provide significant calibration points for deriving an age model for the section (**Section 4.5**). The carbon isotope data are not considered further here.

Cretaceous pelagic and hemipelagic carbonate bulk sediment and carbonate fine-fraction oxygen isotopes commonly preserve consistent stratigraphic trends that have been used to interpret variation in past sea-surface temperatures (Ditchfield and Marshall, 1989; Jenkyns et al., 1994; Schrag et al., 1995; Clarke and Jenkyns, 1999; Stoll and Schrag, 2000; Pearce et al., 2009; Jarvis et al., 2015). The suitability of $\delta^{18}\text{O}$ trends derived from bulk-sediment analyses of chalks as a palaeo-environmental proxy, is supported by compatible $\delta^{18}\text{O}$ data obtained from pristine brachiopod shells (Voigt, 2000; Voigt et al., 2004, 2006) and planktonic foraminifera (Voigt et al., 2010) enclosed in the same sediments, and from coincident changes in macrofossil assemblages (Jarvis et al., 2011, 2015).

The oxygen isotope record at Trunch fluctuates on a sample-by-sample basis to a greater extent than that of carbon (**Fig. 5**). Detailed analysis of the $\delta^{18}\text{O}$ trends is beyond the scope of this paper but a number of features warrant comment. A generally rising $\delta^{18}\text{O}$ trend through the Cenomanian at Trunch with a large trough in the Middle Cenomanian is contrary to generally falling $\delta^{18}\text{O}$ values recorded elsewhere (Jenkyns et al., 1994; Clarke and Jenkyns, 1999; Voigt et al., 2004). The latter are interpreted to reflect the global warming of surface waters from the latest Aptian (O'Brien et al., 2017), towards the development of peak super-greenhouse climate conditions in the Early Turonian. Anomalous high $\delta^{18}\text{O}$ values in Upper Cenomanian at Trunch do not follow this trend.

The Albian – Lower Turonian section at Trunch is highly condensed, displays numerous erosion surfaces, beds of variable bioclastic debris, and has undergone

extensive early diagenesis associated with the development of nodular chalks and lithification and mineralisation of multiple hardgrounds (**Figs 3, 5**). Nonetheless, the range of isotope values for this section, between -1.8 and -3.2 $\delta^{18}\text{O}$, lies within the range of values typically recorded from shallow buried chalks of this age in NW Europe (e.g. Jenkyns et al., 1994; Wilmsen, 2007). Oxygen isotope values remain uncharacteristically high through the Lower and Middle Turonian at Trunch, by comparison to other European sections (Voigt and Hilbrecht, 1997; Stoll and Schrag, 2000; Voigt and Wiese, 2000; Voigt et al., 2007; Jarvis et al., 2015), but then step down to lower values in the high Middle Turonian, above the ‘Pewsey’ CIE. The reason for the anomalous $\delta^{18}\text{O}$ trend in the Cenomanian – Middle Turonian is unclear.

A series of $\delta^{18}\text{O}$ peaks and intervening troughs in the Upper Turonian compare well to the positions of similar peaks elsewhere in Europe. Maxima around the ‘Pewsey’, Caburn, and Hitch Wood CIEs (**Fig. 5**) have been interpreted to represent episodes of stepped cooling during the Late Turonian (intervals I – III), associated with influxes of north Boreal ‘cool water’ macrofaunal taxa into northern and central Europe (as discussed by Jarvis et al., 2015). The *Hoplanceras* Event that immediately precedes the Hitch Wood CIE (**Figs 3, 5 interval IV**), is an example of one of these cool-water pulse faunas. Low $\delta^{18}\text{O}$ values in the uppermost Turonian at Trunch, rising to a peak around the Beeding CIE, is a trend observed elsewhere (Jarvis et al., 2015).

A medium term $\delta^{18}\text{O}$ minimum in the low Middle Coniacian, around the level of the White Fall CIE (**Fig. 5**), is followed by generally rising values through the remainder of the section, as also seen at Dover in SE England (Jenkyns et al., 1994). This is interpreted to represent the onset of a period of accelerating long-term cooling that characterised the remainder of the Late Cretaceous (O’Brien et al., 2017). More detailed analysis of the $\delta^{18}\text{O}$ profile is compromised by a lack of stratigraphically well-constrained oxygen isotope records from comparable NW European sections.

6 Palynological results

A total of 267 samples were analysed from 512.43 – 270.0 m (Albian – Lower Campanian). The single sample from Albian Hunstanton Formation ‘Red Chalk’ at 512.43 m was barren and will not be discussed further. Twenty-six samples were taken from the condensed Cenomanian, 84 samples from the Turonian, 54 samples from the

Coniacian, 64 samples from the Santonian and the remaining 38 samples from the low Lower Campanian.

A summary relative abundance range chart of selected taxa is presented in **Fig. 6**; the entire data set is provided in **Supplementary Material Table 2**. The absolute abundance and specific diversity profiles are presented in **Fig. 7**. Taxa grouped as undifferentiated species (i.e. *Alterbidinium* spp.) are included in the sum of species richness. For simplicity, the genera *Alisogymnium* and *Dinogymnium* are included as dinocysts although they probably represent the ecdysal pellicles of dinoflagellates.

The palynoflora is dominated by 184 species and subspecies of dinocysts (particularly, *Spiniferites ramosus* subsp. *ramosus*, and significant numbers of *Palaeohystrichophora infusorioides* and *Achomosphaera ramulifera* throughout). Acritarchs (*Fromea* spp., *Palaeostomocystis reticulata*, *Paralecaniella indentata*, *Veryhachium* spp.), undifferentiated microforaminiferal-test-linings and scolecodonts, prasinophytes (*Cymatiosphaera* spp., *Pterospermella* spp., *Tarsisphaeridium geminiporatum*), spores and pollen (including hispidate gymnosperm pollen) and the colonial marine alga *Palambages morulosus* are also present. Conspicuous changes in the palynomorph assemblages and notable species influxes are described below. Significant species events are described in **Section 7**.

6.1 Cenomanian (Ferriby Chalk)

A distinct decrease in the proportion of *Palaeohystrichophora infusorioides* and *Spiniferites ramosus* subsp. *ramosus* occurs from the lower *Mantelliceras mantelli* Zone to the upper *Mantelliceras dixonii* Zone and is broadly mirrored by an increase in the proportion of *Pterodinium cingulatum* subsp. *cingulatum*, *Sepispinula? ambigua* and *Spiniferites twistringiensis*. The opposite trend is observed up to the mid-*Acanthoceras rhotomagense* Zone. *Achomosphaera ramulifera*, *Downiesphaeridium armatum* and *Tenua colliveri* are generally more numerous in the Lower Cenomanian, and an increase in numbers of *Litosphaeridium siphoniphorum* subsp. *siphoniphorum* and *Oligosphaeridium complex* is observed from the mid-*M. dixonii* Zone to the mid-*A. rhotomagense* Zone. A major collapse in recovery is observed in the Middle Cenomanian at 503.3 m (mid-*A. rhotomagense* Zone), marking the base of an interval of poor recovery (generally barren) that extends to the base of the Upper Turonian. For simplicity, this interval is referred to as the ‘barren’ beds.

Dinocyst species richness and diversity are high below the 'barren' beds, with an average of 49 species (H 3.06), and generally higher in the Early Cenomanian with 57 (3.3) at 507.9 m in the mid-*M. dixonii* Zone (**Fig. 7**). Absolute palynomorph abundances per gram (ppg) broadly increase through the Lower and Middle Cenomanian to a maximum of 2921 (113,076 carbonate-corrected) ppg at 505.8 m, prior to the upper *A. rhotomagensis* recovery collapse (**Figs 7, 11**). Above 503.8 m to 501.3 m (mid-*A. rhotomagensis* to upper *Calycoceras guerangeri* zone) recovery is extremely poor, and from 501.0 – 500.1 m (*Metoicoceras geslinianum* Zone) no specimens were recorded.

6.2 Turonian (Welton Chalk – lower Burnham Chalk)

A temporary recovery of palynomorphs occurs at 474.2 m and 473.6 m in the Upper Turonian, uppermost *Terebratulina lata* Zone (**Figs 6 – 7**); however, the base of the main recovery interval occurs at 469.0 m. *Achomosphaera ramulifera*, *Downiesphaeridium armatum* and *Tenua colliveri* broadly increase in number upwards through the *Plesiocorys (Sternotaxis) plana* Zone, whereas *Achomosphaera regiensis* and *Pterodinium cingulatum* subsp. *cingulatum* broadly decrease in number. A bimodal distribution of *P. infusorioides* is conspicuous with highest numbers in the lower mid- and upper *P. (S.) plana* Zone. Between these maxima, an increase in the proportion of *Achomosphaera ramulifera*, *Isabeldiniina cooksoniae*, *S. ramosus* subsp. *ramosus* and *S. twistringiensis* is observed.

Above the 'barren' beds dinocyst species richness and diversity broadly increase from 42 (2.95) at 469.0 m, to 56 (3.26) at 437.0 m prior to declining to 48 (3.00) at 430.0 m, with an average diversity of 47 (3.00; **Fig. 7**). Excluding the interval from 439.0 – 433.3 m where relatively low absolute abundances appear to be related to an increase in density of nodular chalk (and therefore, possibly lowered due to current winnowing), values broadly increase through the Upper Turonian (with a maximum of 1,072,107 ppg at 446.0 m, ~4 m above the 'Chalk Rock' beds; **Figs 7, 14**).

Two phases of Cenomanian reworking occur in the Upper Turonian from 469.0 – 461.0 m (base *P. (S.) plana* Zone), and particularly from 436.0 – 433.0 m (uppermost *P. (S.) plana* Zone; 'i5' CIE, immediately below the Navigation Hardground).

6.3 Coniacian (Burnham Chalk)

The Lower Coniacian (*Micraster cortestudinarium* Zone) is marked by a significant influx of *Palaeohystrichophora infusorioides* with an acme at 426.0 m, the remainder of the stage displays little change. Conspicuous influxes of *Canningia glomerata* and *Spiniferites ramosus* subsp. *aquilus* are observed in the upper *M. cortestudinarium* Zone, and *Heterosphaeridium verdieri* in the Middle Coniacian (*Micraster coranguinum* Zone).

Palynomorph species richness and diversity have averages of 43 (2.71) and broadly decline upsection, although maxima of 52 (3.15) and 50 (2.83) occur at 411.0 m and 393.0 m in the basal Middle and mid-Middle Coniacian (*M. coranguinum* Zone), respectively (**Fig. 7**). A minimum of 32 (2.61) dinocyst taxa are recorded at 377.0 m in the mid-Upper Coniacian (*M. coranguinum* Zone). Three intervals of increasing absolute abundances occur through the Coniacian, two in the Lower Coniacian (*M. cortestudinarium* Zone) and the third spanning the Middle and Upper Coniacian (**Figs 7, 16**). The lowermost phase is a continuation of rising values from the Upper Turonian to a maximum of 5333 (624,539) ppg at 425.0 m, the second phase rises from 843 (110,198) at 424.0 m to 11859 (1,517,372) at 411.0 m and the third from 1791 (183,981) at 411.0 m to 5255 (451,025) at 373.0 m. Minor Cenomanian reworking is noted at 379.0 m.

6.4 Santonian (upper Burnham Chalk and Flamborough Chalk equivalent)

A number of influxes characterise the Santonian. In the Lower Santonian (*M. coranguinum* Zone), common to very abundant *Spinidinium echinoideum* is recorded from 367.0 – 362.0 m (acme at 364.0 m, where it comprises almost 40% of the sample). In the Middle Santonian (*M. coranguinum* Zone), *Palaeoperidinium pyrophorum* has an influx in the lower part (356.0 – 351.0 m), and *Isabelidinium cooksoniae* in the upper part (346.0 – 336.0 m). In the Upper Santonian (*Uintacrinus socialis* Zone), *Chatangiella eminens* is particularly prominent from 334.0 – 326.0 m.

Species richness and diversity generally decrease up section from 50 (2.92) at 372.0 m to 40 (2.45) at 307.0 m, with an average of 43 taxa per sample (**Fig. 7**). Numbers are relatively consistent through the Lower and Middle Santonian (*M. coranguinum* Zone) with an average of 45 (2.74), decline into the Upper Santonian (*U. socialis* Zone) with an average of 40 (2.44), and increase through the remaining *Marsupites* Zone with an average of 44 (2.64). This reduction of species richness in the *U. socialis* Zone is associated with marked trough in Shannon diversity. Absolute dinocyst abundances

decline steadily upsection from 5394 (419,056) ppg at 372.0 m to 597 (41,699) ppg at 307.0 m (**Figs 7, 18**).

As with the Upper Turonian, sporadic Cenomanian reworking occurs in the Santonian, particularly at the base, over the Lower – Middle stage boundary and in the Upper Santonian (*Marsupites* Zone).

6.5 Lower Campanian (Flamborough chalk equivalent)

For the Lower Campanian, only the *Offaster pillula* and lowermost *Goniatites quadrata* zones are included in the present study. Notable compositional changes include influxes of *Rhynchodiniopsis saliorum* at 302.0 m, *Spinidinium echinoideum* at 295.0 m, and *Tenua colliveri* at 281.0 m where it dominated the assemblage. *Palaeohystrichophora infusorioides* and *Spinidinium echinoideum* decrease in numbers upsection, in direct contrast to *Senoniasphaera procressa*.

A broad upsection increase in species richness and diversity is observed from 41 (2.36) at 306.0 m to 48 (2.63) at 270.0 m (**Fig. 7**). Absolute dinocyst abundances remain relatively low from the Santonian with an average value of 931 (47,886) ppg to 288.0 m to the mid-*O. pillula* Zone. From this level, values increase steadily to the top of the studied section at 270.0 m, with a value of 9877 (828,938) ppg (**Figs 7, 21**). Cenomanian reworking is observed at 305.0 m and 279.0 m.

7 Palynological bioevents and palaeogeographic distribution of marker taxa

The temporal and spatial distribution of key taxa (including their synonymies) have been reviewed to determine whether the dinocyst events recorded here represent regional stratigraphic distributions (lowest occurrence, LO; highest occurrence, HO) or the full stratigraphic range of species (first appearance datum FAD, inception, to last appearance datum LAD, extinction), and how geographically widespread the events may be. The accurate determination of a species FAD and LAD is dependent on the availability of a geographically and stratigraphically widely distributed database. Accordingly, where LO and HO events coincide with the known maximum range, we take these as probable LAD and FAD events. Where dinocyst events are documented to occur within a limit portion of accepted ranges, or there is minimal available supporting data regarding the wider significance of the datum levels, we refer to LO and HO events.

Forty-eight taxa from the Trunch borehole are considered to have 65 significant events (see **Appendix B**), which are compared with available literature. The dinocyst events are plotted against the $\delta^{13}\text{C}_{\text{carb}}$ profile and CIE stratigraphy of the Trunch borehole and correlated to the recalibrated English Chalk carbon-isotope reference curve of Jarvis et al. (2006; **Fig. 9**) in **Figs 11, 14, 16, 18, 21**. The age vs. depth model for the Trunch borehole illustrated in **Fig. 8**, provides the basis for dating individual palynological events. This plot demonstrates a wide variation in sediment accumulation rates (uncorrected for compaction) ranging from a minimum of 0.25 cm kyr^{-1} in the Cenomanian to a maximum of 7.35 cm kyr^{-1} for the Upper Turonian, the interval of the Northern Province Flint Maximum. Maximum biostratigraphic resolution is provided by palynological events in the Late Turonian, around the Turonian – Coniacian boundary, and in the Santonian – earliest Campanian (**Fig. 8**). Ages calculated for the palynological events are considered in the discussion below (**Sections 7.1 – 7.5**).

Species distributions plotted on palaeogeographic maps derived from the reconstructions of Cao et al. (2017) are provided in **Figs 10, 13, 15, 17, 19 – 20**, with the climate zones of Scotese et al. (2014) included for a comparison. Dinocyst events are summarised in **Appendix B** and in **Section 8**, below.

Significant differences have long been recognised between the clastic-prone Upper Cretaceous sequences of the Northern and Norwegian–Greenland Sea (Shetland Group) to those of the more southerly chalk-prone sequences (Chalk Group). Notable absences of many Shetland Group marker species (e.g. *Chatangiella islae*, *Heterosphaeridium bellii*, *Trithyrodinium zakaii*) are apparent at Trunch; however, a number of important marker species are common between these two areas (e.g. *Alterbidinium ioannideii*, *Cyclonephelium membraniphorum*, *Epelidosphaeidia spinosa*, *Rhynchodiniopsis saliorum*, *Sindridinium borealis*, *Stephodinium coronatum*, *Surculosphaerium longifurcatum*). As pointed out by Costa and Davey (1992), a substantial number of undescribed or inadequately known species from onshore and offshore UK are known, and many of these have now been dealt with in Prince et al. (1999, 2008) and Pearce (2011, 2018). New data from Late Cretaceous outcrop material of Greenland (Nøhr-Hansen et al., 2019) is helping to improve our understanding of the northerly clastic-prone sequence palynology, while we consider our data here, to be the most detailed record from the (southern) Chalk Group.

7.1 Cenomanian

Ten species with 12 selected events are discussed: (1) LO and (2) HO of persistent *Sindridinium borealis*; (3) LAD of *Disphaeria munda*; (4) LAD of *Sidridinium borealis*; (5) LAD of *Hapsocysta peridictya*; (6) LAD and HO of common *Epelidosphaeridia spinosa*; (7) HO of persistent *Cribroperidinium? edwardsii*; (8) HO of persistent / common *Litosphaeridium siphoniphorum*; (9) HO of common *Sepispinula ambigua*; (10) LAD of *Pterodinium crassimuratum*; (11) LAD of *Wrevittia cassidata*; (12) LAD of *Carpodinium obliquicostatum*.

7.1.1 LO persistent, HO persistent and LAD of *Sindridinium borealis* (NW Europe)

Taxonomy and geographic distribution

Sindridinium borealis (Plate V, 11 – 12) has only recently been described by Nøhr-Hansen et al. (2018), but it has long been recognised by the hydrocarbon exploration industry as an important marker species for the Lower Cenomanian. The form is typically referred to as “*Sidridinium boreali*” [sic] in unpublished biostratigraphic reports, but has been recorded as *Ovoidinium? sp.1* from NE Greenland (Nøhr-Hansen, 1993) and offshore NW Norway (Radmacher, 2014). Care must be taken in assigning all records of *Ovoidinium? sp.1* of Nøhr-Hansen 1993 to *S. borealis* as the former taxon includes hypocauste forms that are now referred to as *Sindridinium anaanae* Nøhr-Hansen et al., 2018; these were not observed in the present study. *Sindridinium borealis* has also been observed from the Troms and Hammerfest basins, offshore north-west Norway by Costa (1985) and occurs extensively through the Norwegian Sea and northern North Sea (Pearce pers. obs.; Fig. 10a) as a ‘Boreal warm’ species. The occurrence of the taxon in the Trunch borehole is currently the most southerly occurrence known.

Stratigraphy

The probable FAD of *Sindridinium borealis* occurs in the Upper Albian (Nøhr-Hansen et al., 2018), but common occurrences are only known from the Lower Cenomanian. The highest occurrence of *S. borealis* (*Sbo*) in the Trunch borehole at 506.4 m (Figs 6, 10 – 11) appears to represent the LAD of the species, with a calculated age here of 96.42 (± 0.5) Ma. Frequently recorded specimens from 507.3 – 509.3 m

(restricted to the *M. mantellii* Zone) appear to approximate the range of commonly recorded specimens by Nøhr-Hansen et al. (2018) with a calculated age range here of 96.77 (± 0.51) – 97.58 (± 0.53) Ma.

7.1.2 LAD of *Disphaeria munda* (NW Europe)

Taxonomy and geographic distribution

Disphaeria munda (**Plate II, 6**) was first described as *Thalassiphora munda* by Davey and Verdier (1973) from the Albian and Cenomanian of France. It was considered by Yun (1981) to be a junior synonym of *T. dynamica* (Morgenroth 1966) Stover and Evitt, 1978 (originally described from the Lower Eocene of Germany). However, Lentin and Williams (1985) retained *T. munda*. Although there is a striking morphological similarity between these species, the probable Early Cenomanian LAD of *T. munda* (see below), suggests that these species are distinct (unless *T. dynamica* is based on a reworked specimen of *T. munda*), but a detailed analysis of both holotypes is required to be conclusive. *Disphaeria munda* is restricted to the Northern Hemisphere in a narrow latitudinal band from $\sim 66^\circ\text{N}$ (offshore mid-Norway, pers. obs.) to $\sim 39^\circ\text{N}$ (Colorado: Courtinat, 1993) and is found in North America, North Atlantic and western Europe.

The palaeolatitudinal range of $\sim 57^\circ\text{N}$ (offshore mid-Norway, pers. obs.) to $\sim 32^\circ\text{N}$ (northern Spain: Lamolda and Mao, 1999; **Fig. 10b**) indicates that this species was a ‘Boreal tropical’ to ‘Boreal warm’ species

Stratigraphy

The majority of records indicate that *D. munda* occurs persistently to the top of the Lower Cenomanian (Davey, 1979; Fauconnier, 1979; Foucher, 1980, 1981; Tocher and Jarvis, 1996), or within the Middle Cenomanian (lower *A. jukesbrownei* Zone; Marshall, 1983), but rare specimens have been recorded from the uppermost Cenomanian (Pearce et al., 2009) and lowermost Turonian from southern UK (Tocher, 1984), and Colorado (USA; Courtinat 1993). Assuming that uppermost Cenomanian and Turonian occurrences are based on reworked specimens, the LAD of *D. munda* is suggested to occur in the Early Cenomanian. The HO of *D. munda* (*Dmu*) at 507.3 m in the Lower Cenomanian (*M. dixonii* Zone; **Figs 6, 11**) of the Trunch borehole is consistent with the

majority of published records and appears to approximate the LAD with a calculated age here of 96.77 (± 0.51) Ma.

7.1.3 LAD of *Hapsocysta peridictya* (worldwide)

Taxonomy and geographic distribution

Hapsocysta peridictya (**Plate II, 11**) was recognised as new and described from the Aptian to Cenomanian from the Canarvon Basin of Western Australia by Eisenack and Cookson (1960; as *Cannosphaeropsis peridictya*) after being originally attributed to *Cannosphaeropsis fenestrata* (now *Aiora fenestrata*) by Cookson and Eisenack (1958). Its generic status was questioned by Stover and Evitt (1978) and the species was subsequently transferred to *Hapsocysta* by Davey (1979). It is recorded from both hemispheres: from $\sim 66^\circ\text{N}$ (offshore mid-Norway, pers. obs.) to $\sim 11^\circ\text{N}$ (Tamil Nadu India: Jain, 1977; Venkatachala and Kumar, 1980) in the Northern Hemisphere; and from $\sim 6^\circ\text{S}$ (Papua New Guinea: Davey, 1988) to 71°S (ODP 692 and 693, Weddell Sea, Antarctica: Mohr, 1990) and is distributed through the North America, North Sea, North and South Atlantic, Antarctica, Indian Ocean and Australia as a sub-tropical to warm temperate species.

The palaeolatitudinal range of $\sim 66^\circ\text{N}$ (offshore mid-Norway, pers. obs.) to $\sim 21^\circ\text{N}$ (North Atlantic, DSDP 418: Hognun and Kelts, 1979) in the Northern Hemisphere and $\sim 28^\circ\text{S}$ (Campos Basin, Brazil: Arai and Masure, 1997) to $\sim 69^\circ\text{S}$ (ODP 692, 693, Weddell Sea, Antarctica: Mohr 1990) indicates that this species was adapted to both 'arid' and 'Boreal warm' climate belts (**Fig. 10c**).

Stratigraphy

Numerous records place *Hapsocysta peridictya* in the Aptian and Albian. However, Eisenack and Cookson (1960), Verdier (1970), Masure (1984), Mohr et al. (2002) and Shipboard Scientific Party (2004) indicate that the HO occurs in the Cenomanian. The HO of *Hapsocysta peridictya* (*Hpe*) at 504.8 m in the Middle Cenomanian (*A. rhotomagense* Zone) at Trunch may therefore correspond to the LAD of the species, with a calculated age of 95.84 (± 0.44) Ma (**Figs 6, 11**).

7.1.4 LAD and HO of common *Epelidosphaeridia spinosa* (N. Hemisphere)

Taxonomy and geographic distribution

Epelidosphaeridia spinosa (**Plate II, 9**) was originally (and invalidly — see Williams et al., 2017) described as *Palaeoperidinium spinosum* by Cookson and Hughes (1964) from the ?Lower Cenomanian of SE England. It was validly referred to as *Epelidosphaeridia spinosa* by Davey (1969). The species has been recorded from India (Venkatachala and Kumar, 1980) but on examining the plates, we feel the illustrated specimen is too dissimilar to the holotype to be counted. Two additional records from India (Jain and Taugourdeau-Lantz, 1973; Mehrotra et al., 2012) have not been checked and are tentatively included as geographic outliers. The remaining records indicate that it is restricted to the Northern Hemisphere from ~74°N (eastern Greenland: Nøhr-Hansen, 1991, 1993) to ~25°N (ODP 635, The Bahamas: Masure, 1988) and is found in North America, western and southeast Europe and North Africa.

The palaeolatitudinal range of ~81°N (northern Alaska: Witmer et al., 1981) to ~22°N (northeast Algeria: Foucher et al., 1994; **Fig. 10a**) indicates that this species was restricted to the north 'arid' and north 'Boreal warm' climate belts.

Stratigraphy

The bulk of the literature clearly places the highest occurrence of *Epelidosphaeridia spinosa* in the Cenomanian. As one of the earliest studies on the stratigraphic distribution of the species the work of Clarke and Verdier (1967) at Culver Cliff, Isle of Wight (southern UK) is particularly useful as it also provided quantitative data that can now be directly compared to the $\delta^{13}\text{C}_{\text{carb}}$ record (**Fig. 12**; Jarvis et al., 2001, 2006). Clarke and Verdier (1967) recorded the highest occurrence of *E. spinosa* in sample 11 (reported as within the lower Grey Chalk) and the highest frequent occurrence (where it reaches 5% of the total assemblage) in sample 8 (reported as within the upper Chalk Marl). Clarke and Verdier (1967) equated the top of the Chalk Marl with the top of the traditional *Schloenbachia varians* ammonite Zone. Their measured section corresponds closely to that presented by Jukes-Browne and Hill (1903). However, the *S. varians* Zone includes both the Chalk Marl and the lower part of the Grey Chalk (Jukes-Browne and Hill, 1903).

The main lithological break at the base of the Grey Chalk at Culver Cliff (cf. Gale et al., 1999 fig 2; Jarvis et al., 2001, 2006) occurs at 23.0 m above the base of the Cenomanian on Clarke and Verdier's (1967 text-fig. 2) measured section at Culver Cliff, and not at 36.7 m as indicated on their log. This is significant because their samples 6 – 9 thus all fall within the lower Grey Chalk (Middle Cenomanian, *A. jukesbrownei* Zone) rather than in the Chalk Marl as interpreted by them. The sample positions and dinocyst records of Clarke and Verdier (1967) are replotted against the stratigraphic log of Jarvis et al. (2001, 2006) in **Fig. 12**, and we determine samples 8 and 11 to be located in the Middle Cenomanian (mid-*A. rhotomagensis* Zone) and lower Upper Cenomanian (lower *C. guerangeri* Zone), respectively.

Other studies also place the highest occurrence of *E. spinosa* in the low Upper Cenomanian. Davey (1969, p.143) described *E. spinosa* to be rare to common in the “lower and middle horizons of the Cenomanian”, but did not provide quantitative data. From his account of where the species is absent, it appears that the species has a highest occurrence in the lower *H. subglobosus* Zone in southern England and the mid-*H. subglobosus* Zone in northern France. In the type Turonian area, Robaszynski et al. (1982) recorded very common *E. spinosa* in their lowermost sample (low Upper Cenomanian), no Middle Cenomanian material was studied. In the absence of a complete Cenomanian dataset, the significance of this sample cannot be adequately assessed. Prössl (1990) also recorded the highest occurrence (with commonly occurring specimens) in the low Upper Cenomanian. However, Prössl's study (1990) lacked independent biostratigraphic evidence and instead subdivided the Cenomanian section on an interpretation of sonic and resistance logs. How this was achieved was not explained, and as such we cannot consider the substage assignments as definitive.

It should be noted that Mao and Lamolda (1998) described *E. spinosa* as having a regular distribution of rare and occasionally common specimens in the Upper Cenomanian. Lamolda and Mao (1999) illustrated the species occurring persistently through the Upper Cenomanian in the majority of samples, suggesting that such occurrences are *in situ*. It is therefore possible that *E. spinosa* has a diachronous HO between southern UK (low Upper Cenomanian: Davey, 1969; Clarke and Verdier, 1976), northern France (mid-Upper Cenomanian: Davey, 1969) and northern Spain (high Upper Cenomanian; Lamolda and Mao (1999). In the absence of high-resolution data from well-correlated sections, this is speculative, and will require testing.

Consistent records of a Middle Cenomanian HO are also apparent. Foucher (1979, 1981) placed the highest occurrence of *E. spinosa* in the *A. rhotomagensis* Zone, where specimens were reported to be particularly common (Foucher, 1981). Costa and Davey (1992) and Wilkinson et al. (1993) placed the HO of *E. spinosa* in the *A. jukesbrownei* Zone, and these have been taken as standard references by biostratigraphers working in NW Europe. Costa and Davey (1992) did not provide supporting references, while Wilkinson et al. (1993) cited Foucher (1979, 1981). Marshall (1983; unpublished PhD thesis) placed the highest occurrence in the upper *A. jukesbrownei* Zone. Williams and Bujak (1985) recorded the species from the Middle Cenomanian but placed the highest occurrence in the early Turonian (see below).

Paul et al. (1994) also consistently recorded *E. spinosa* through the Cenomanian to their section top in the *A. rhotomagensis* Zone. Tocher and Jarvis (1994a, 1996) recorded a highest persistent occurrence of *E. spinosa* in the *A. rhotomagensis* Zone but found the species to be particularly common in the Lower Cenomanian. Tocher and Jarvis (1995) mentioned that the last common occurrence of *E. spinosa* is generally regarded as indicative of the top of the Middle Cenomanian but considered rare specimens in the Upper Cenomanian (*C. guerangeri* Zone) to be *in situ*. Pearce et al. (2009) found rare specimens of *E. spinosa* in the Upper Cenomanian (*M. geslinianum* Zone) and, in the absence of obvious reworking, considered the species to have a LAD within the Late Cenomanian. Finally, Dodsworth (2004b) recorded *E. spinosa* persistently in the Upper Cenomanian of Crimea.

Some studies have reported post-Cenomanian occurrences, but these can be discounted. For example, in their study of multiple wells from the Scotian Shelf and Grand Banks, Bujak and Williams (1978) stated that *E. spinosa* ranges from the Albian to the Cenomanian (where it become particularly common) and into the Turonian (together with *L. siphoniphorum*), but in greatly reduced numbers. No count data were provided and therefore, based on the apparent reduction of observed numbers in the Turonian, we presume these specimens to be reworked. Azéma et al. (1981) recorded rare *E. spinosa* in the Upper Santonian of Vendée France but as an outlier, is most likely based on reworked specimens. Williams and Bujak (1985) provided a stratigraphic range for *E. spinosa* from the uppermost Albian to the Lower Turonian, but subsequent syntheses (Williams et al., 1993, 2004) placed the LAD within the Late Cenomanian. Herbin et al. (1987) recorded *E. spinosa* in 4 samples spanning the Lower Cenomanian

to Santonian interval from the west North Atlantic. Reference was made to the species as a key marker for the Upper Albian to Lower Cenomanian, but no discussion was provided for the stratigraphically higher samples. Li and Habb (1996) recorded very rare *Epelidosphaeridia* cf. *spinosa* through the Cenomanian to the lowermost Turonian from the Western Interior of USA. They did not illustrate a specimen and given the implied difference from the type specimen, their data are also excluded.

In conclusion, we recommend the LAD of *Epelidosphaeridia spinosa* to be in the Late Cenomanian, with a significant increase in relative numbers in the Middle Cenomanian. In Spain (Lamolda and Mao, 1999) the HO of the species occurs ~2 m above the HO of *Litosphaeridium siphoniphorum*, and we arbitrarily place the species together on **Fig. 11**, with an estimated age here of ~94.2 Ma. In the UK, the highest occurrence (Clarke and Verdier, 1967) occurs immediately below CIE b1 with an estimated age here of ~95.15 Ma (**Fig. 11**). The highest frequent/common occurrence of *E. spinosa* of Clarke and Verdier (1967) in the Middle Cenomanian (upper *A. jukesbrownei* Zone) is suggested to be a useful event that occurs immediately below the Jukes-Browne CIE, with an estimated age here of ~95.35 Ma. In the Trunch borehole the HO of *Epelidosphaeridia spinosa* (*Esp*) occurs at 504.3 m (mid-*r. homagense* Zone; **Figs 6, 11**), with a calculated age here of 95.68 (± 0.41) Ma. It is rare, but nonetheless is a good marker for Cenomanian strata.

7.1.5 LO of persistent *Cribroperidinium? edwardsii* (NW Europe)

Taxonomy and geographic distribution

Cribroperidinium? edwardsii (**Plate I, 12**) was originally described as *Gonyaulax edwardsii* by Cookson and Eisenack (1958) from the Albian to Lower Turonian of western Australia. It has subsequently been transferred to *Gonyaulacysta* and finally to *Cribroperidinium* (see Williams et al., 2017). It can be easily mistaken for *C? orthoceras* and *C? muderongense*, complicating the review of its stratigraphic range; indeed Helenes (1984) considers these species (and *C? intricatum*) to be part of a morphological series. Available information suggests that *C? edwardsii* is distributed from ~79°N (Svalbard: Smelror et al., 1998) to ~64°N (Antarctic peninsula: Dettmann and Thomson, 1987; Olivero and Palamarczuk, 1987; Wrenn and Hart, 1988; Riding et al., 1998) and is cosmopolitan.

The palaeolatitudinal range is ~81°N (National Petroleum Reserve, Alaska: Witmer et al., 1981; North Slope of Alaska, as *C. aff. edwardsii*: Kimyai, 2000; northeast Alaska: Vandergon, 1986) to ~72°S (central South Island, New Zealand: Wilson 1982; **Fig. 10e**).

Stratigraphy

Cribroperidinium? edwardsii is typically recorded from the Lower Cretaceous (Smelror et al., 1998; Aguirre-Urreta et al., 1999; Duxbury, 2001; Fiet and Masure, 2001) and Upper Cenomanian (Clarke and Verdier, 1967; Norvick and Burger, 1976; Foucher, 1980; Costa and Davey, 1992; Prössl, 1990; Mohr and Gee, 1992; Pearce et al., 2009). Post-Cenomanian occurrences have been recorded (Cenomanian: Corradini, 1973; undifferentiated Turonian – lower Maastrichtian: Davey, 1978; Santonian – Maastrichtian: Ioannides, 1986) but the chronostratigraphic control is questionable. *In situ* occurrences have also been suggested in the Santonian (Yun, 1981), Campanian (Foucher, 1979; Tocher, 1987; Siegl-Farkas, 1997) and Maastrichtian (Roncaglia et al., 1999; although Brinkhuis and Schiøler, 1996 consider these occurrences to be reworked), but these records appear to be neither consistent nor common. Therefore, we interpret the LAD of *C? edwardsii* to lie in the Upper Cenomanian worldwide.

In the Trunch borehole, the highest occurrence of *C? edwardsii* occurs at 506.4 m at the top of the Lower Cenomanian (*M. juxonii* Zone) and therefore, prior to the disappearance of palynomorphs in the Middle Cenomanian, so this appears to be a true event (**Figs 6, 11**). A similar non-persistent occurrence was recorded by Marshall (1983) in the mid-*T. arcuatus* / *T. costatus* Zone (equivalent to the mid-*A. rhotomagense* Zone) from the lower Middle Cenomanian of Germany, and Clarke and Verdier (1967; **Fig. 12**) showed the highest persistent occurrence in the Upper Cenomanian, mid-*C. guerangeri* Zone, below CIE b2. An absence of specimens in the upper Upper Cenomanian is also apparent in the study of Pearce et al. (2009) from the upper *C. guerangeri* – *M. nodosoides* zones of southern UK, where *C? edwardsii* occurred only in a single sample. The scarcity of the species in the Upper Cenomanian was corroborated by Lignum (2008, also from southern England) who recorded the top of consistent *C? edwardsii* in the Middle Cenomanian (intra-*A. rhotomagense* Zone). Based on data from the North Sea, Costa and Davey (1992) placed the HO of *C? edwardsii* at the Cenomanian / Turonian boundary, but significantly, placed the top of persistently occurring specimens in the Middle Cenomanian (mid-*A. jukesbrownei* Zone). It is uncertain how

precisely calibrated the material in Costa and Davey (1992) was, but the range is nevertheless comparable with the results discussed here.

We suggest that the highest persistent occurrence of *C? edwardsii* occurs in the Upper Cenomanian (mid-*C. guerangeri* Zone), below CIE b2 in NW Europe, with an estimated age of ~94.95 Ma. The HO of persistent *C? edwardsii* (*C?ed*) in the Trunch borehole occurs at the first sample below the Lower / Middle Cenomanian boundary with a calculated age here of 96.42 (± 0.5) Ma, and therefore, slightly below the expected highest persistent occurrence event (**Fig. 11**).

7.1.6 HO of persistent / common *Litosphaeridium siphoniphorum* (worldwide)

Taxonomy and geographic distribution

Litosphaeridium siphoniphorum (**Plate III, 9**) was first described as *Hystriosphæridium siphoniphorum* by Cookson and Eisenack (1958) from the Albian and Cenomanian of Western Australia. Masrue and Vrielynck (2009) have previously shown that it has a bi-hemispheric distribution in the Albian, being largely absent from equatorial regions (an exception being from the Demarera Rise, Eldrett et al., 2017), and high latitudes. Our distribution map (**Fig. 10f**) confirms this distribution with a range of ~79°N (Axel Heiberg Island, Canadian Archipelago, as *Litosphaeridium siphoniphorum* subsp. *glabrum*: Núñez-Betelu et al., 1992) to ~6°N (Demarera Rise; Eldrett et al., 2017) in the Northern Hemisphere and ~12°S (DSDP 364: Morgan, 1978; Bathurst Island, Australia: Norvick and Burger, 1976; northern Madagascar: Herngreen et al., 1982) to ~64°S (Antarctic peninsula: Keating et al., 1992).

The palaeolatitudinal range of ~73°N (Axel Heiberg Island, Canadian Archipelago, as *L. siphoniphorum* subsp. *glabrum*: Núñez-Betelu et al., 1992) to ~0°N (Demarera Rise; Eldrett et al., 2017) and ~26°S (DSDP 364: Morgan, 1978) to ~68°S (North island, New Zealand: Crampton et al., 2001). This suggests that the species was widely adapted to Boreal and arid zone environments and was rare from the warmest Tropical waters.

Stratigraphy

The consensus of available literature suggests that the highest occurrence of *Litosphaeridium siphoniphorum* occurs in the Lower Turonian (Norvick and Burger, 1976; Decommer, 1982; Foucher, 1982; Robaszynski et al., 1982; Williams and Bujak,

1985; Herbin et al., 1987; Williams et al., 1993; Caron et al., 1999; Shipboard Scientific Party, 2004; Fensome et al., 2008) worldwide, possibly in the lowermost part of the substage (Habib and Drugg, 1987; Costa and Davey, 1992; Dodsworth, 2000). Post-Turonian occurrences have been documented but are considered here to be unreliable due to: (1) very low-resolution sampling (Coniacian: Foucher, 1979; Senonian: Corradini, 1973); (2) comparative rarity (Maastrichtian: Hoek et al., 1996); (3) being based on morphologically questionable specimens (Maastrichtian: Schrank and Ibrahim, 1995); or (4) occurring in samples with clearly reworked species (Coniacian: Foucher, 1979; Early Santonian: Yun, 1981; Campanian: Harker et al., 1990).

Detailed studies suggest that *L. siphoniphorum* has a highest common occurrence in the Upper Cenomanian (Bujak and Williams, 1978; Foucher, 1980; Marshall and Batten, 1988; Prössl, 1990), and specifically within the upper *M. aslinianum* Zone in southern England (Dodsworth, 2000; Pearce et al., 2009). Both Dodsworth (2000) and Pearce et al. (2009) found the highest persistent / common occurrence of *L. siphoniphorum* to occur in Plenus Marls Bed 6 of southern UK, which Dodsworth (2000) demonstrated to be correlative to Bed 73 in the Cenomanian – Turonian boundary stratotype at Pueblo (Colorado, USA).

The LAD of *L. siphoniphorum* is considered here to lie in the Lower Turonian worldwide, but with a highest persistent / common occurrence in the Upper Cenomanian in the Northern Hemisphere. Plenus Marls Bed 6 occurs mid-way between CTBE event ‘a’ and ‘b’ of Pearce et al. (2009 fig. 3) with an estimated age here of ~94.2 Ma. This is slightly younger than the age derived by Dodsworth and Eldrett (2019), based on an astronomical (obliquity) age model for the Iona-1 core in Texas: 94.56 Ma (top consistent) to 94.62 Ma (top common). However, those authors derived a base Turonian age of 94.12 Ma (cf. Eldrett et al., 2015) rather than the 93.90 Ma age adopted herein, and provisionally by GTS2020 (F. Gradstein pers. comm., 2019).

In the Trunch borehole, where the Upper Cenomanian – Lower Turonian succession is largely barren of palynomorphs, the highest common occurrence of *L. siphoniphorum* (*Lsi*) occurs at 504.3 m around CIE a1 of Jarvis et al. (2006) (**Figs 6, 11**) in the Middle Cenomanian (mid-*A. rhotomagense* Zone; calculated here as 95.68 ($\pm$ 0.41 Ma), and is therefore, not the same event, but is nevertheless a good marker for strata no older than Cenomanian.

7.1.7 HO of common *Sepispinula ambigua* (NW Europe)

Taxonomy and geographic distribution

The species *Micrhystridium ambiguum* was described by Deflandre (1937), and it has subsequently been combined with *Cleistosphaeridium*, *Polysphaeridium*, *Chlamydophorella*, *Dapsilidium*, and *Gorgonisphaeridium*, prior to the current questionable combination with *Sepispinula* (see Williams et al., 2017). From our inspection of the drawings/images of the holotypes, we consider *S. ambigua* to be the senior synonym of both *S. ancorifera* (previously combined with *Hystrichosphaeridium* and *Cleistosphaeridium*) and *S? huguoniotii* (previously combined with *Hystrichosphaeridium*, subsequently *Baltisphaeridium*, *Cleistosphaeridium*, and *Chlamydophorella*; see Williams et al., 2017), and therefore to be the valid type species of *Sepispinula*. We therefore, consider it a confident combination. A full taxonomic justification for this will be presented elsewhere.

Sepispinula ambigua (**Plate V, 10**) appears to have a bi-hemispherical distribution being recorded from ~74°N (eastern Greenland: Nøhr-Hansen, 1993) to ~11°N (Tamil Nadu, India: Garg et al., 1988; Khowaja Ateequzzaman and Jain, 1992) in the Northern Hemisphere and ~13°S (offshore north Western Australia: McMinn, 1988) to ~58°S (ODP 748: Mao and Mohr, 1992) in the south (**Fig. 10g**).

The palaeolatitudinal range of ~81°N (North Slope, Alaska; May and Stein, 1979) to ~10°N (Israel: Brenner, 1974), and ~40°S (western Madagascar: Chen, 1978) to ~69°S (North Island, New Zealand: Wilson, 1989) suggests that it was adapted to arid and Boreal climate zones.

Stratigraphy

Excluding infrequent records from the Cenozoic (Jiabo, 1978; Sun, 1994; Xu et al., 1997; Richards and Hillier, 2000), the vast majority of published ranges restrict *S. ambigua* to the Cretaceous. Limited long-range quantitative data for *S. ambigua* exists, but according to Clarke and Verdier (1967; **Fig. 12**, as *Sepispinula huguoniotii* that we consider to be a junior synonym of *S. ambigua*), Tocher (1984), Prössl (1990), Tocher and Jarvis (1996), Dodsworth (2000) and Pearce et al. (2009), *S. ambigua* appears to be particularly common in the Upper Cenomanian of NW Europe, from where a significant up-section reduction (or absence) into the Turonian occurs. According to Dodsworth

(2000) and Pearce et al. (2009) the highest common occurrence occurs in the middle / upper *M. geslinianum* Zone (Plenus Marls Bed 6), estimated here as ~94.2 Ma. In the Trunch borehole, *Sepispinula ambigua* (*S?am*) is common up to 504.8 m (**Figs 6, 11**); being infrequent and rare in the two samples above, in the Middle Cenomanian (mid-*A. rhotomagense* Zone). Its HO coincides with that of *Hapsocysta peridictya*, dated above as 95.84 (± 0.44) Ma, although the significance of this is uncertain due to the absence of palynomorphs in the higher Cenomanian. In strata younger than Cenomanian, it only occurs in intervals with the conspicuous reworking of Cenomanian species.

7.1.8 LAD of *Pterodinium crassimuratum* (NW Europe)

Taxonomy and geographic distribution

Pterodinium crassimuratum (**Plate IV, 7**) was originally described as *Hystriosphæra crassimurata* by Davey and Williams (1966a) from the Cenomanian of southern England. We reject the view of Kjellström (1973) and Pavlishina (1990) that it is a junior synonym of *P? pterotum*. The species appears to be restricted to the Northern Hemisphere from ~66°N (offshore mid-Norway, pers. obs.) to ~15°N (Senegal: Jain and Millepied, 1975; but note that their figured specimen is not clearly comparable with the holotype and is only questionably included here), and is distributed through North America, North Atlantic, Europe (and possibly West Africa, if the Senegalese occurrence is accepted).

The palaeolatitude range of ~56°N (offshore mid-Norway, pers. obs.) to potentially ~8°N (Senegal: Jain and Millepied, 1975), but with a principally northern mid-latitude distribution (**Fig. 10h**), suggests that *Pterodinium crassimuratum* was adapted to Boreal warm conditions.

Stratigraphy

Clarke and Verdier (1967) and Foucher (1979) recorded the highest occurrence of *Pterodinium crassimuratum* in the Lower and Upper Turonian, respectively; and Jain and Millepied (1975) in the Maastrichtian. We have applied a corrected stratigraphy to the records of Clarke and Verdier (1967), and find the highest occurrence to be in the Upper Cenomanian, Ballard Cliff Member (**Fig. 12**). A similar situation occurs with the stratigraphy used by Marshall (1983) who recorded the highest occurrence in his

lowermost Turonian sample (*M. labiatus* Zone); however, the underlying bed is ascribed to the *M. geslinianum* Zone (thereby missing the uppermost Cenomanian *N. juddii* Zone), so the reliability of the lowermost Turonian assignment is uncertain. Foucher (1979) also recorded *P. crassimuratum* in the lower Turonian with a significant absence until the uppermost Turonian. Since sea-level fluctuations over the Turonian / Coniacian boundary have been shown to cause significant reworking (e.g. see **Fig. 6**), the highest record of Foucher (1979) is considered to be of reworked specimens.

The majority of records for the highest occurrence of *P. crassimuratum* suggest that the LAD occurs in the Late Cenomanian in NW Europe (i.e. Clarke and Verdier, 1967; Davey, 1969; Fauconnier, 1979; Paul et al., 1994; Marshall, 1993) and specifically in the upper *M. geslinianum* Zone (uppermost Plenus Marls Bed c; Pearce et al., 2009 from southern UK), estimated here as ~94.1 Ma. In the Trunch borehole, the highest occurrence of *P. crassimuratus* (*Pcr*) occurs at 503.5 m in the Middle Cenomanian (mid-*A. rhotomagensis* Zone; **Figs 6, 11**), with a calculated age here of 95.53 (± 0.39) Ma. This does not coincide with the LAD, but the HC is nevertheless a good indicator for strata no younger than Cenomanian.

7.1.9 LAD of *Wrevittia cassidata* (NH Hemisphere)

Taxonomy and geographic distribution

Wrevittia cassidata (**Plate VI, 12**) was originally described as *Gonyaulax helicoidea* subsp. *cassidata* by Eisenack and Cookson (1960) from the Aptian to Cenomanian of Southern Australia. It was subsequently raised to species level and transferred to *Gonyaulacysta* and then to *Wrevittia* (see Williams et al., 2017). It has been recorded in both hemispheres, from ~79°N (Axel Heiberg Island, Canadian Archipelago: Núñez-Betelu et al., 1992) to ~11°N (Tamil Nadu, India: Khowaja-Ateequzzaman and Jain, 1992), and from ~6°S (Papua New Guinea: Davey, 1988) to ~37°S (offshore southeast South Australia: Stoian, 2002). As well as being conspicuously absent from the equatorial region, it is also not known from the southern proto-South Atlantic, central USSR, or the NW proto-Pacific margin. Baltes (1967a, b) figured specimens from Romania, but on inspection these appear to be more comparable to *Psaliogonyaulax deflandrei*, emphasizing the morphological similarity of the species.

The palaeolatitudinal range of $\sim 73^{\circ}\text{N}$ (Axel Heiberg Island, Canadian Archipelago: Núñez-Betelu et al., 1992) to $\sim 23^{\circ}\text{N}$ (DSDP 101: Hollister et al., 1972) and $\sim 26^{\circ}\text{S}$ (DSDP 364: Morgan, 1978) to $\sim 66^{\circ}\text{S}$ (offshore southeast South Australia: Stoian, 2002), suggests that *Wrevittia cassidata* favoured arid and Boreal warm conditions (**Fig. 13a**).

Stratigraphy

The highest stratigraphic occurrences of *Wrevittia cassidata* from Europe are consistently recorded in the Upper Cenomanian (Clarke and Verdier, 1967; Herengreen, 1978; Foucher, 1980; Marshall and Batten, 1988; Louwye, 1992; Dodsworth, 2000, 2004b; Pearce et al., 2009), although FitzPatrick (1995) recorded the species from the Turonian of southern England. Yun (1981) recorded *W. cassidata* from the Santonian of Germany, but no range chart was provided and he also figured other taxa typical of the Lower Cretaceous or Cenomanian (i.e. *Litosphaeridium siphoniphorum*, *Oligosphaeridium asterigerum*, *Polystephanophorus schindewolfii*, *Sepispinula ambigua*). The observation of *W. cassidata* by FitzPatrick (1995) comes from Langdon Stairs (Dover, UK), where it is rare and sporadic in the upper *Terebratulina lata* Zone and occasionally common in the *Plesiocorys (Sternotaxis) plana* Zone (Upper Turonian). The occurrences in the *P. (S.) plana* Zone are clearly associated with the Lighthouse Down Hardgrounds (see Jarvis et al. 2006) where reworking might be expected (as also observed at Trunch at the same approximate level). FitzPatrick (1995) did not record *W. cassidata* from any of her other five coeval sections. We therefore, consider these Turonian observations as being based on reworked specimens, and a Late Cenomanian LAD is likely.

Pearce et al. (2009) recorded the HO of *W. cassidata* in the *M. geslinianum* Zone (Plenus Marls Bed 6) together with the HO of common *S. ambigua* which, as discussed above, has an estimated age of ~ 94.2 Ma. Dodsworth (2000) recorded *W. cassidata* in the stratotype Cenomanian / Turonian boundary interval at Pueblo (Colorado, USA) in a single sample from upper Bed 78 (lower *N. juddii* Zone). Assuming that this is not based on a reworked specimen, it suggests that the HO of persistent *W. cassidata* can be raised to an estimated age here of at least ~ 94.1 Ma. The highest occurrence of *W. cassidata* (*Wca*) in the Trunch borehole occurs at 504.3 m (**Figs 6, 11**), at a break in the carbon isotope gradient between CIEs a1 and a2, with a calculated age here of $95.68 (\pm 0.41)$.

7.1.10 LAD of *Carpodinium obliquicostatum* (NW Europe)

Taxonomy and geographic distribution

Carpodinium obliquicostatum (**Plate I, 6**) was described by Cookson and Hughes (1964) from the Upper Albian to Lower Cenomanian of England. It is a particularly distinctive species that can be identified easily from fragments due to its unique ornamentation. It is restricted to the Northern Hemisphere in a narrow latitudinal band from ~66°N (offshore mid-Norway, pers. obs.) to ~39°N (Colorado, USA; Dodsworth, 2000) and is distributed throughout North America, North Atlantic and Europe. Hedlund and Norris (1968) recorded *C. cf. obliquicostatum* from Oklahoma, but on inspection, their illustrated specimen is sufficiently dissimilar to the holotype to be discounted here.

The palaeolatitudinal range of ~56°N (offshore mid-Norway, pers. obs.) to ~36°N (North Atlantic, ODP 1276; Shipboard Scientific Party 2004) suggests that *Carpodinium obliquicostatum* was a Boreal warm species (**Fig. 13b**).

Stratigraphy

Carpodinium obliquicostatum is typically recorded no higher than the Upper Cenomanian (Davey, 1969; Fouchet, 1930, 1981; Marshall and Batten, 1988; Prössl, 1990; Dodsworth, 2000, 2004a,b; Pearce et al., 2009), an exception being Williams and Bujak (1985) who placed this event in the lowermost Turonian. However, it was not stated what this record is based on and it is therefore excluded here. Marshall and Batten (1988) recorded the HO of *C. obliquicostatum* from the mid-*N. juddii* Zone in Germany. This has subsequently been demonstrated by Dodsworth (2000) to have a near synchronous transatlantic HO in Colorado (lower Bed 78, uppermost *M. geslinianum* / *S. gracile* Zone) and southern UK (single sample from the *N. juddii* Zone). An estimated age here of ~94.0 Ma for the mid-*N. juddii* Zone is therefore, suggested to be the LAD of the species. The highest occurrence of *C. obliquicostatum* (*Cob*) in the Trunch borehole at 503.8 m (Middle Cenomanian; *A. rhotomagense* Zone; **Figs 6, 11**), calculated here as 95.53 (± 0.39) Ma is therefore earlier than the LAD but is nonetheless a good indicator for strata no younger than Cenomanian.

7.2 Turonian

Thirteen species and fourteen events are discussed: (1) LO of *Heterosphaeridium difficile* (USA and UK); (2) LAD of *Hapsocysta dictyota*; (3) LAD of *Pervosphaeridium cenomaniense*; (4) FAD of *Canningia glomerata*; (5) LO of common *S. turonica*; (6) LO of common *Sentusidinium devonense*; (7) FAD and (8) LO of persistent *Raetiaedinium truncigerum*; (9) FAD of *Senoniasphaera filoreticulata*; (10) reappearance of *Oligosphaeridium pulcherrimum*; (11) HO of persistent *Cyclonephelium membraniphorum*; (12) LAD *Stephodinium coronatum*; (13) HO of persistent *Senoniasphaera turonica*; (14) HO of *Sentusidinium devonense*.

7.2.1 LO of *Heterosphaeridium difficile* (southern N. Hemisphere)

Taxonomy and geographic distribution

Heterosphaeridium difficile (**Plate II, 12; Plate III, 1**) was originally described by Manum and Cookson (1964) as a species of *Hystriospheridium* from the Cenomanian of Arctic Canada. It has been questionably (but invalidly) combined with *Cordosphaeridium*, and finally with *Heterosphaeridium* (see Williams et al., 2017). The species is recorded widely in the Northern Hemisphere from ~80°N (Mount Bridgeman, Canada: Núñez-Betelu et al., 1994) to ~33°N (northern Pakistan: Köthe et al., 1988 based on reworked specimens), with additional sporadic records from Colombia (~4°N: Jaramillo et al., 1994, based on questionable specimens), Australia (Bathhurst Island, ~12°S: Norvick and Burger, 1976), SE Brazilian continental shelf (~26°S: Arai, 1994), Antarctic Peninsula (~64°S: Keating, 1992) and New Zealand (~72°S: Hasegawa et al. 2013).

Excluding sporadic records (and that from Pakistan, since it is uncertain if the study area of Köthe et al., 1988 lay on the northern or southern Tethyan margin), the palaeolatitudinal range of ~81°N (North Alaska: Witmer et al., 1991) to ~37°N (Grand Banks and Scotian Shelf: Barss et al., 1979) suggests that *Heterosphaeridium difficile* favoured the north Boreal climate zone (**Fig. 13c**).

Stratigraphy

The oldest confident placement of the LO of *H. difficile* lies in the Cenomanian from high latitudes (i.e. Australia: Norvick and Burger, 1976; Barents Sea: Bell and Selnes, 1997; Alberta, Canada: Bloch et al., 1999). Both Manum and Cookson (1964) and Davey

(1969) recorded the species in the Albian but their chronostratigraphies are not adequately demonstrated.

Consistent LOs in the Lower Turonian from more southerly Northern Hemisphere sites are typical (Colorado, USA: Dodsworth, 2000; Czech Republic: Žítt et al., 1997; England: Pearce et al., 2003; North Sea: Costa and Davey, 1992; eastern Greenland: Nøhr-Hansen et al., in press; west Greenland: Pedersen and Nøhr-Hansen, 2014). FitzPatrick (1995) recorded rare *H. difficile* immediately above the Melbourne Rock beds in Sussex (2 km from the Gun Gardens section studied by Pearce et al., 2009) and by inference therefore, in the Upper Cenomanian *N. juddii* Zone (cf. Gale et al., 2005). In her text, FitzPatrick (1995) stated that *H. difficile* has a lowest occurrence in the Turonian, and excluded the spurious Upper Cenomanian occurrence that is documented by her data. In the Trunch borehole, the LO of *H. difficile* (*H. dif*) occurs at 462.00 m with the reappearance of palynomorphs in the Upper Turonian (*P. (S.) plana* Zone), which is a considerable distance above the regional LO.

Dodsworth (2000) recorded a solitary specimen of *H. difficile* from the Turonian stratotype section at Pueblo (Colorado, USA) in Bed 95 (Lower Turonian, mid-*Watinoceras coloradoense* Zone (within the *Pseudaspidoceras flexuosum* Zone of Kennedy et al., 2005), midway between the *N. juddii* and *M. nodosoides* zones), with an estimated age here of ~93.6 Ma (Fig. 14). The species was found to be persistent in the Middle Turonian (*C. woolgari* Ammonite Zone) by Dodsworth and Eldrett 2019. Jarvis et al. (1988a) and Pearce et al. (2003) recorded the LO of *H. difficile* stratigraphically slightly higher in the Lower Turonian (upper Holywell Member, upper *N. nodosoides* Zone) in southern England. The LO recorded by Jarvis et al. (1988a) occurs at the lower limit of the Lulworth CIE (Jarvis et al., 2006 figs 7, 16); the LO of Pearce et al. (2003) is slightly lower, immediately above CIE c2 (Tu3 of Voigt et al., 2007; Fig. 14), with an estimated age here of ~93.05 Ma. *Heterosphaeridium difficile* was not recorded in the Cenomanian / Turonian boundary interval by Pearce et al. (2009) from southern England, but their study did not include the entire *M. nodosoides* Zone, so the level of the LO of *H. difficile* was not sampled.

7.2.2 LAD of *Pervosphaeridium cenomaniense* (worldwide)

Taxonomy and geographic distribution

This species was originally described as *Exochosphaeridium cenomaniense* by Norvick in Norvick and Burger (1976) from the Cenomanian of Australia. It is widely reported throughout the Northern Hemisphere south of $\sim 66^{\circ}\text{N}$ (offshore mid-Norway, pers. obs.) to $\sim 9^{\circ}\text{N}$ (western Venezuela; Helenes et al., 1998) and from $\sim 12^{\circ}\text{S}$ (Bathurst Island, Australia: Norvick and Burger 1976; northern Madagascar: Herngreen et al., 1982) to $\sim 71^{\circ}\text{S}$ (ODP 962: Masure et al., 1998). It is distributed through North and South America, the North Atlantic and northern South Atlantic, Europe, North, West and south-eastern Africa, south-western Asia and northern Australia.

The palaeolatitudinal range of $\sim 63^{\circ}\text{N}$ (Alberta, Canada; Leckie et al., 1992) to $\sim 4^{\circ}\text{N}$ (western Venezuela; Helenes et al., 1998) and $\sim 28^{\circ}\text{S}$ (Campos Basin, offshore Brazil; Arai and Masure, 1997) to $\sim 68^{\circ}\text{S}$ (ODP 962; Masure et al., 1998), suggests that *Pervosphaeridium cenomaniense* (**Plate IV, 3**) was insensitive to climate variation but absent from high latitudes (**Fig. 13d**).

Stratigraphy

The LAD of *P. cenomaniense* appears to occur no higher than Lower Turonian (Norvick and Burger, 1976; Helenes et al., 1998; Lamolda and Mao, 1999), and specifically according to Pearce et al. (2009) within the lower *M. nodosoides* Zone, between the Compton Pebble Marl and Gun Gardens Marl 1 in southern England, with an estimated age here of ~ 3.4 Ma (**Fig. 14**).

In the German Konrad 101 borehole, Prössl (1990) indicated that the highest occurrence of *P. cenomaniense* lay in the lower Middle Turonian based on its occurrence in a single sample (otherwise with a top of persistent occurrences in the upper most Cenomanian). However, in the absence of a micro- or macrofossil calibration, his chronostratigraphic divisions are based on sonic and resistance logs (but it was not demonstrated how). It is therefore possible that this Turonian record is based on reworked specimen(s), so cannot confidently be used to raise the LAD up into the Middle Turonian. The HO of *P. cenomaniense* (*Pce*) at 507.9 m in the Lower Cenomanian (*M. dixonii* Zone; **Figs 6, 11**) in the Trunch borehole is therefore considerably below the suggested LAD, with a calculated age here of $97.01 (\pm 0.51)$ Ma.

7.2.3 FAD of *Canningia glomerata* (N. Hemisphere)

Taxonomy and geographic distribution

Clarke and Verdier (1967) described *Canningia glomerata* (as *Senoniasphaera rotundata*; **Plate I, 4**) from the Santonian – Campanian of southern England. It was transferred to *Canningia* by Fensome et al. (2019) and assigned the new species name on becoming a junior homonym. It has been recorded throughout North America, North Atlantic, eastern Greenland, Europe and south-western Asia from ~73°N (Kara Shelf, Russia: Lebedeva, 2006) to ~26°N (DSDP 138; Diederix et al., 1972). Given its wide temperate tolerance, it is somewhat surprising that *C. glomerata* is not recorded widespread in the Southern Hemisphere. According to Downing (1992) and Wood and Askin (1992) it occurs on Antarctica. However, only Wood and Askin (1992) provided an illustrated specimen and this appears to more closely resemble, *S. edenensis* Marshall 1990, and therefore, both Southern Hemisphere records are excluded here.

The palaeolatitude range of ~69°N (Kara Shelf, Russia; Lebedeva, 2006) to ~10°N (Israel; Eshet et al., 1994; Hoek et al., 1995; **Fig. 13e**) suggests the species was adapted to Boreal warm and arid climate belts.

Stratigraphy

In a study of multiple wells from the Norwegian Sea, Smelror et al. (1994) recorded *C. glomerata* from a sample within the Upper Albion – Lower Cenomanian. However, it appears to be an isolated case (and potentially caved), with the next record occurring well within the Turonian. No illustrated evidence was provided and in the light of available evidence this record is also excluded. Williams and Brideaux (1975) recorded *C. glomerata* from a single sample dated as Cenomanian – Turonian but which lacks stratigraphic resolution. Williams (1977) recorded rare *C. glomerata* from the eastern Atlantic Ocean from an interval dated as no younger than Middle – Upper Cenomanian, based on the presence of *D. alatum*. However, *D. alatum* is now considered to have a LAD in the mid-Early Campanian (**Section 7.5.3.**), furthermore *C. glomerata* was found to co-occur with *L. siphoniphorum* (**Section 7.1.6.**) that appears to have a LAD in the Early Turonian. Azéma et al. (1981) also recorded rare *Senoniasphaera* cf. *rotundata* in

a single sample from the ?Lower Cenomanian of western France but this is excluded here due to its questionable identification.

According to Foucher (1981), Jarvis et al. (1988a) and Pearce et al. (2003) the LO of *C. glomerata* lies in the lowest Middle Turonian; both Jarvis et al (1988a) and Pearce et al. (2003) record the event between CIEs d1 and d2. However, this LO can be extended down into the Lower Turonian based on data from Robaszynski et al. (1982), Tocher and Jarvis (1994b, 1995) and Lamolda and Mao (1999). Tocher and Jarvis (1994b) provided a dataset for the intra-Lower Turonian in western France, but the precise chronostratigraphic position of the LO of *C. glomerata* cannot be determined because the position of the substage boundaries is not known. It is similarly difficult to place the LO reported by Tocher and Jarvis (1995) since the top of the Lower Turonian was not reached in their study.

In northern Spain, Lamolda and Mao (1999) recorded the LO of *Canningia glomerata* ~2 m above the LO of *Mammites nodosoides* ~4 m above the LO of *Quadrum gartneri* and ~18 m below the LO of *Helvetotriton helvetica*. Robaszynski et al. (1982) recorded approximately the same proportional distribution of the LOs of *C. glomerata*, *Q. gartneri* and *H. helvetica* within the *M. nodosoides* Zone in western France, indicating a similar sequence of Lower Turonian events. FitzPatrick (1995) recorded the LO of *C. glomerata* ~8 m above the top of the Ballard Cliff member at Eastbourne (southern England), ~2 km from the CTBE study of Pearce et al. (2009). Recent observations from Dodsworth and Eldrett (2019) from Pueblo (Colorado USA), place the LO in the GSSP section Bed 113 (within the *M. nodosoides* Zone). This suggests that the LO lies close to the *H. catinus* / *M. nodosoides* zonal boundary (cf. Gale et al., 2005.) Therefore, until a more precise LO of the *C. glomerata* (*Cgl*) is available, the FAD is taken at the base of the *M. nodosoides* Zone, with an age of 93.35 Ma (**Fig. 14**).

In the Trunch borehole, *C. glomerata* has a LO at 459.0 m (*P. (S.) plana* Zone, Upper Turonian) with an age calculated here as 90.96 (± 0.5) Ma (**Figs 6, 14**), and although stratigraphically higher than expected due to the presence of an extended predominantly barren interval, it is nonetheless a useful indicator for strata no older than Turonian.

7.2.4 LO of common *Senoniasphaera turonica* (NW Europe)

Taxonomy and geographic distribution

Senoniasphaera turonica was originally described as *Craspedodinium turonicum* by Prössl (1990) later combined with *Senoniasphaera* by Pearce et al. (2011) who also considered it as the senior synonym of *Senoniasphaera rotundata* subsp. *alveolata* Pearce et al. (2003). Pearce et al. (2011) suggested that it is likely that some specimens of *S. rotundata* (now *Canningia glomerata*) recorded in the Turonian may be misidentified *S. turonica* (**Plate V, 6 – 7**).

Senoniasphaera turonica is recognised from ~55°N (northern North Sea, pers. obs.; Bornholm, Denmark; Schiøler, 1992 as *Senoniasphaera? sp. a*) to ~30°N (Texas, Dodsworth, 2016); through Denmark (Schiøler, 1992), southern England (Lignum, 2008; Pearce et al., 2009), France (Lignum, 2008) and Germany (Prössl, 1990; Lignum, 2008) and Colorado (USA; **Fig. 13f**).

The palaeolatitudinal range of ~46°N (northern North Sea, pers. obs.; Bornholm, Denmark, Schiøler, 1992) to ~32°N (Gr Texas, Dodsworth, 2016) suggests that *S. turonica* was restricted to the southern Boreal warm climate zone.

Stratigraphy

Although *S. turonica* has been recorded in the Cenomanian (Lignum, 2008), it becomes particularly common in the Lower Turonian (Pearce et al., 2003, 2009; Pearce, 2011), with the lowest common occurrence (Pearce et al., 2009; Olde et al., 2015) at the base of the *M. nodosoides* Zone (93.35 Ma; **Figs 6, 14**). This is consistent with the findings of Dodsworth and Eldrett (2019) who record the lowest occurrence at Pueblo (Colorado, USA) in the GSSP section, Bed 116 (*M. nodosoides* Zone). The lowest common occurrence of *S. turonica* is therefore, suggested to lie in the Lower Turonian in NW Europe, and possibly the Northern Hemisphere. In the Trunch borehole, *S. turonica* (*Stu*) has a LCO at 465.0 m (*Plesiocorys (S.) plana* Zone, lower Upper Turonian) with an age calculated here as 91.01 ($\pm$ 0.52) Ma; **Fig. 14**). The higher LCO is attributable to the presence of an extended ‘barren’ interval, but it is nonetheless a useful indicator for strata no older than Turonian.

7.2.5 LAD of *Hapsocysta dictyota* (N. Hemisphere)

Taxonomy and geographic distribution

Hapsocysta dictyota (**Plate II, 10**) was first recorded by Davey (1979) from the Albian of the Bay of Biscay, Atlantic Ocean. We concur with Masure and Vrielynck (2009) that it is restricted to the Northern Hemisphere, and recognise a range of south of $\sim 66^{\circ}\text{N}$ (offshore mid-Norway, pers. obs.) to $\sim 30^{\circ}\text{N}$ (northeast Libya; Unwins and Batten, 1989), through North America, North Atlantic, Europe, and North Africa. The palaeolatitudinal range of $\sim 56^{\circ}\text{N}$ (offshore mid-Norway, pers. obs.) to $\sim 12^{\circ}\text{N}$ (northeast Libya; Unwins and Batten, 1989), suggests that *H. dictyota* was adapted to arid and southern Boreal warm climate belts (**Fig. 13g**).

Stratigraphy

Hapsocysta dictyota is typically recorded from the Albian and Cenomanian (Davey, 1979; Below, 1984; Prössl, 1990), but the highest occurrences reported by Marshall and Batten (1988; who provided a range of Upper Cenomanian to Lower Turonian) and Dodsworth (2000), and from personal observations in the Norwegian Sea, suggest that the LAD occurs in the lowermost Turonian. Tocher (1984) recorded *H. dictyota* from the uppermost Turonian of southern England, but from a sample that also contained *Litosphaeridium siphoniphorum*. We consider this to be the result of reworking, with his highest *in situ* occurrence then lying in the uppermost Cenomanian.

Dodsworth (2000) recorded the HO of *H. dictyota* from the Turonian stratotype section at Pueblo (Colorado) from Bed 102 (lowermost *M. nodosoides* Zone) and slightly stratigraphically lower from southern UK in his highest sample from the lower *W. coloradoense* Zone. Dodsworth's observations from Pueblo are confirmed in Dodsworth and Eldrett (2019), where no stratigraphically higher samples yielded any further specimens of *H. dictyota*. Therefore, the LAD of *H. dictyota* is suggested to lie in the Early Turonian in the Northern Hemisphere. Due to the lack of age control on the age of Bed 102 at Pueblo, we approximate the LAD of *H. dictyota* to an estimated age of ~ 93.3 Ma (**Fig. 14**). In the Trunch borehole, the HO of *H. dictyota* (*Hdic*) occurs at 504.3 m in the Middle Cenomanian (mid-*A. rhotomagense* Zone; **Figs 6, 11**), lower than expected due to the existence of the largely barren interval above, with a calculated age of 95.68 (± 0.41) Ma.

7.2.6 LO of common *Sentusidinium devonense* (NW Europe)

Taxonomy and geographic distribution

Sentusidinium devonense (**Plate V, 8**) was originally recorded by Tocher (1984) in his PhD thesis as *Sentusidinium* sp. b, from the Lower Turonian of multiple sites in the western Anglo-Paris Basin. It was formally published by Pearce (2018) and is currently only known from NW Europe between $\sim 53^{\circ}\text{N}$ (Trunch borehole, this study) and $\sim 45^{\circ}\text{N}$ (southeast France: Lignum, 2008), with additional records from southern England (Tocher and Jarvis, 1987; Jarvis et al., 1988a; Fitzpatrick, 1995; Pearce et al., 2009), western France (Tocher, 1984) and northern Germany (Lignum, 2008).

The palaeolatitudinal range of $\sim 43^{\circ}\text{N}$ (this study; NW Germany: Lignum, 2008) to $\sim 36^{\circ}\text{N}$ (southeast France: Lignum, 2008) suggests that the taxon was a southern Boreal warm species (**Fig. 13h**).

Stratigraphy

Pearce et al. (2009) recorded the LO of *S. devonense* (as *Sentusidinium* sp. b of Tocher and Jarvis, 1987) in the mid-*M. geslinianum* Zone (Upper Cenomanian, Plenus Marls Bed 2/3) of southern England. Other documented LOs occur in the Lower Turonian (Tocher, 1984; Tocher and Jarvis, 1987; Jarvis et al., 1988a; FitzPatrick, 1995; Pearce, 2000). However, a significant increase in relative abundance has been noted in the lower Middle Turonian (FitzPatrick, 1995; Pearce, 2000) with an acme in the Middle Turonian. The position of the increase reported by Pearce (2000) occurs at the mid-point between CIEs d1 and d2 of Jarvis et al. (2006) with an estimated age of ~ 92.8 Ma (**Figs 6, 14**). The relative abundance increase noted by FitzPatrick (1995) occurs slightly higher around New Pit Marl 1 (above the Low-woollgari CIE). The lowest common occurrence of *S. devonense* (*Sde*; observed at 460 m depth in the Upper Turonian *Plesiocorys* (*S.*) *plana* Zone at Trunch) therefore, would be expected to occur within the 'barren' interval at Trunch and cannot be tested.

7.2.7 FAD and LO of persistent *Raetiaedinium truncigerum* (N. Hemisphere)

Taxonomy and geographic distribution

Raetiaedinium truncigerum (**Plate IV, 8**) was originally described as *Hystriosphæridium truncigerum* by Deflandre (1937) and has been subjected to numerous taxonomic revisions with combinations to *Cordosphaeridium*, *Exochosphaeridium*, *Florentinia*, *Litosphaeridium*, *Pervosphaeridium*, *Tityrosphaeridium*, and finally *Raetiaedinium* (see Williams et al., 2017). It is restricted to the Northern Hemisphere from ~66°N (offshore mid-Norway, pers. obs.) to ~30°N (central Texas, USA: Harker et al., 1990; northern Egypt: Schrank and Ibrahim, 1995) and is distributed through North America, North Atlantic, Europe, North Africa and south-western Asia (**Fig. 15a**). Davey (1978, plate 4 figs 12 – 13) recorded a taxon as *Exochosphaeridium truncigerum* from DSDP 361, offshore south-western Africa; however, it possesses significantly shorter processes than the holotype of *R. truncigerum* and is excluded here. The palaeolatitudinal range of ~56°N (offshore mid-Norway, pers. obs.) to ~10°N (Israel: Eshet et al., 1992, 1994; Hoek et al., 1996) suggests that *R. truncigerum* favoured southern warm Boreal and arid climate belts.

Stratigraphy

Despite records of *R. truncigerum* in the Late Jurassic (Riley and Sarjeant, 1972) and Lower Cretaceous (Below, 1982), the majority of detailed stratigraphic studies suggest the LO occurs in the Upper Cretaceous and particularly in the Coniacian (Bujak and Williams, 1978; Kirsch, 1981; Schiøler, 1992; Stover et al., 1996; Herngreen et al., 1996), or Upper Turonian (Foucher, 1974; Wilkinson and Halliwell, 1980; Williams and Bujak, 1985) in the Northern Hemisphere.

According to Prössl (1990) the LO occurs in the uppermost Middle Turonian of the Konrad 101 borehole (Germany); however, his chronostratigraphy is based on unspecified microfauna and elogs, so it is not known how accurate this placement is. Based on the first occurrence of *R. truncigerum* lying 20% from the top of the Middle Turonian (as estimated from his range chart) an age of ~91.6 Ma is possible for Prössl (1990), assuming the chronostratigraphy of the Konrad 101 borehole is accurate. Recent work by Olde et al. (2015) has identified the LO of *R. truncigerum* in the mid-Middle Turonian ~15 m below the Glynde CIE in borehole material from the Czech

Republic, followed by a conspicuous absence from immediately above the Glynde Event up to a reappearance towards the top of the Upper Turonian, mid-way between the Hitch Wood and Navigation CIEs. The lower occurrence has an estimated age here of ~91.9 Ma (**Fig. 14**) based on a $\delta^{13}\text{C}_{\text{carb}}$ correlation and supports the findings of Prössl (1990).

Raetiaedinium truncigerum (*Rtr*) has consistent distribution through the Trunch borehole, being present in over 78% of all samples studied (although rare) with a LO at 467.00m (above the reappearance of dinocysts in the Turonian) in the lowermost Upper Turonian (*P. (S.) plana* Zone). This event falls immediately above the h1 CIE with a calculated age of 91.04 (± 0.53) Ma and is taken as the lowest persistent occurrence (**Figs 6, 14**).

7.2.8 FAD of *Senoniasphaera filoreticulata* (NW Europe)

Taxonomy and geographic distribution

This species was originally described from the Campanian of the Netherlands as *Canningia filoreticulata* by Slimani (1994), transferred to *Cyclonephelium* by Prince et al. (1999) and finally *Senoniasphaera* by Fensome et al. 2019. Prince et al. (1999) considered it likely that this species may have previously been misidentified by others as *Cyclonephelium membraniphorum* due to its morphological similarity. Additional records from Belgium (Slimani, 1994), eastern Czech Republic (Skupien and Mohammed, 2008) and southern England (Pearce et al., 2003) restrict the species to NW Europe with a range of ~53 – 50°N. A tight palaeolatitudinal spread of ~43°N (Trunch borehole, this study) to ~41°N (eastern Czech Republic: Skupien and Mohammed, 2008) so far suggests that this species has a narrow ecological range in the southern Boreal warm climate belt (**Fig. 15b**).

Stratigraphy

According to Prince et al. (2008) the LO of *S. filoreticulata* (**Plate V, 4**) occurs in the Lower Coniacian (but note that they did not study the Turonian). The LO of *S. filoreticulata* (*Sfi*) in the Trunch borehole at 439.0 m (**Figs 6, 14**) extends the northern limit to ~47°N and the FAD into the latest Late Turonian (*P. (S.) plana* Zone). This event occurs at CIE i3 that has a calculated age of 90.16 (± 0.5) Ma (**Fig. 14**). Limited

published information restricts the usefulness of the species; however, the FAD is suggested to be a potentially useful indicator for the Late Turonian.

7.2.9 Reappearance of *Oligosphaeridium pulcherrimum* (NW Europe)

Taxonomy and geographic distribution

This species was originally described as *Hystriosphæridium pulcherrimum* from the Albian of Australia. It has subsequently been recorded from ~82°N (north Ellesmere Island, Canadian Archipelago: Nøhr-Hansen and McIntyre, 1998) to ~64°S (Antarctic peninsula: Palamarczuk et al., 1984; Dettmann and Thomson, 1987; Olivero and Palamarczuk, 1987; Wrenn and Hart, 1988; Askin et al., 1991; Cocozza and Clarke, 1992; Dolding, 1992; Keating, 1992; Keating et al., 1993; D'Almeida, 1996; Pirrie et al., 1997; Riding et al., 1998).

The palaeolatitudinal range of ~81°N (north Alaska: Witmer et al., 1981; Haga, 1990; Kimyai, 1992) to ~74°N (New Zealand: Raine, 1977) indicates that *O. pulcherrimum* (**Plate IV, 1**) was a truly cosmopolitan species (**fig. 15c**).

Stratigraphy

The inception of *Oligosphaeridium pulcherrimum* is well described from the uppermost Jurassic (Williams and Bajak, 1985; Riding and Thomas, 1988; Poulsen, 1993; Gitmez and Ertug, 1999). In their study of the Turonian and Coniacian of southern England, Pearce et al. (2003) recorded rare specimens of *O. pulcherrimum* in the Middle Turonian, with a persistent occurrence, potentially in the Upper Turonian (questionable, due to extreme condensation), and a significant increase in relative numbers through the Coniacian. Data from Schiøler (1992) supports the reappearance of the species in the uppermost Turonian. Robaszynski et al. (1982) recorded sporadic occurrences of rare specimens through the Turonian that increase to frequent in the Upper Turonian. Clarke and Verdier (1967) recorded very low numbers through the Turonian and Coniacian of southern England but showed an increase of relative numbers of *O. pulcherrimum* in the Lower Coniacian, which is supported by the data of Prince et al. (2008). Further evidence for a Coniacian reappearance is given by Williams and Brideaux (1975) who studied eight Upper Cretaceous cores from the western North Atlantic, and found *O. pulcherrimum* to have a range of Coniacian to Lower Santonian. A

Lower Coniacian reappearance may also be evident from the data presented by Kirsch (1991) and Nøhr-Hansen (1996) but is questionable due to a lack of stratigraphic control.

A temporary disappearance of the taxon has been reported by Prössl (1990) who recorded persistent *O. pulcherrimum* from the Upper Hauterivian to the Upper Albian of Germany, but from where there a prolonged absence up to the Upper Turonian. This is corroborated by Lignum (2008) who only recorded rare and sporadic occurrences of *O. pulcherrimum* through the Cenomanian and Lower Turonian of southern England, France and Germany. The absence of *Oligosphaeridium pulcherrimum* may be limited to NW Europe since it has been recorded continuously through the Turonian in northern Egypt (Foad and Lashin, 2012). In the Trunch borehole, the LO of *O. pulcherrimum* (*Opu*) occurs at 438.0 m in the uppermost Turonian (*P. (S) plana* Zone; **Figs 6, 14**) and is suggested to mark the regional reappearance of persistently occurring specimens. This event occurs immediately above CIE i3 with a calculated age here of 90.12 (± 0.49) Ma (**Fig. 14**).

7.2.10 HO of persistent *Cyclonephelium membraniphorum* (NW Europe)

Taxonomy and geographic distribution

Cyclonephelium membraniphorum was described by Deflandre and Cookson (1955) from the Albian – Cenomanian of Western Australia, and was subsequently associated with *Maghrebinia* and *Cauvri tinium* (see Williams et al., 2017) prior to be returned to *Cyclonephelium* by Fensholt et al. (2019). It is known from $\sim 74^\circ\text{N}$ (eastern Greenland: Nøhr-Hansen, in press) to $\sim 30^\circ\text{N}$ (northern Egypt: Schrank and Ibrahim, 1995) in the Northern Hemisphere and from $\sim 12^\circ\text{S}$ (Bathurst Island, Australia: Norvick and Burger, 1976) to $\sim 64^\circ\text{S}$ (Antarctic peninsula: Olivero and Palamarczuk, 1987).

The palaeolatitudinal range of $\sim 81^\circ\text{N}$ (northern Alaska: Witmer et al., 1981) to $\sim 12^\circ\text{N}$ (northern Egypt: Schrank and Ibrahim, 1995) and $\sim 31^\circ\text{S}$ (southeast Brazilian continental shelf: Arai, 1994) and $\sim 68^\circ\text{S}$ (northeast South Island, New Zealand: Wilson, 1982; Wilson and Morgans, 1989, both as questionable identifications) indicates that this species favoured Boreal warm climate belts in both hemispheres (**Fig. 15d**). Schiøler and Wilson (1998) recorded *Cyclonephelium* cf. *membraniphorum* farther to the south on the South Island of New Zealand, but on reviewing their figured specimen, we

agree with the implication that the specimen is sufficiently dissimilar to the holotype to be excluded.

Stratigraphy

The highest occurrence of *Cyclonephelium membraniphorum* (**Plate II, 2**) has been recorded from the Coniacian – Santonian of France (Foucher, 1979; based on a presence / absence data only, no distribution information given), lower Middle Santonian (herein, although immediately above a 15 m interval of reworking), Santonian – Campanian interval of Arctic Canada (Ioannides, 1986; presence only), Campanian of the USA (although rare and sporadic, Harker et al., 1990), and “post-Cretaceous” according to Foucher (1983).

The majority of records suggest that the LAD occurs close to or at the top of the Coniacian (Foucher, 1983, assuming his post-Cretaceous records are reworked; Williams and Bujak, 1985; Mohr and Gee, 1992; Schindler, 1992). Foucher (1971b; 1975a; 1976a, c as *Cyclonephelium cf. membraniphorum*; 1980), Costa and Davey (1992) and Prince et al. (2008) placed the HO at the top of the Turonian, which is coincident with the last persistent occurrence reported by Pearce et al. (2003). It is important to note that in a study of the Coniacian – Maastrichtian in Germany, Kirsch (1991) did not record *C. membraniphorum*, supporting the case that it is rare and sporadic post-Turonian. A conspicuous absence of *C. membraniphorum* may also have a wider geographical significance, where it was found to be absent above the Turonian in the USA by Scott et al. (2018) and Dodsworth and Eldrett (2019).

Therefore, the LAD of *C. membraniphorum* is suggested to lie in the Upper Coniacian, but with a highest persistent occurrence in the Upper Turonian, both events in the Northern Hemisphere. In the Trunch borehole, *C. membraniphorum* (*Cme*) is persistently recorded in productive samples (although generally rare) through the Cenomanian to Upper Turonian (to 433.3 m, *P. (S.) plana* Zone; **Figs 6, 14**), being notably sporadic above. This highest persistent occurrence is calculated here as 89.92 (± 0.47) Ma.

7.2.11 LAD of *Stephodinium coronatum* (N. Hemisphere)

Taxonomy and geographic distribution

Deflandre (1936a) described *Stephodinium coronatum* from the 'Senonian' (location uncertain), and with the exception of records from Australia (as *Stephodinium* cf. *coronatum*, Bathurst Island: Norvick and Burger, 1976; South Queensland: Burger, 1988; questionably from southwest Western Australia: Cookson and Eisenack, 1969) and the south-eastern Brazilian continental shelf (Arai, 1994) the species is dominantly a Northern Hemisphere form. The identification by Norvick and Burger (1976) may also be problematic as they considered *S. coronatum* to be synonymous with *S. australicum* and *S. europaicum*. The currently accepted view (Singh, 1983) is that *S. australicum* is not a junior synonym of *S. coronatum*.

Stephodinium coronatum has been recorded from ~77°N (Graham Island, Canadian archipelago, as *Stephodinium europaicum*: Manum and Cookson, 1964) and ~74°N (eastern Greenland: Nøhr-Hansen, in press) to ~24°N (DSDP 535, southeastern Gulf of Mexico: Riley and Fenton, 1984), and is distributed through North America, North Atlantic, Europe, North Africa and Asia.

The palaeolatitudinal range of ~81°N (northern Alaska: Witmer et al., 1981) to ~19°N (Tunisia: Caron et al., 1999) suggests that *Stephodinium coronatum* (**Plate VI, 7**) principally favoured north Boreal warm to Boreal tropical climate belts (**Fig. 15e**).

Stratigraphy

Bujak and Williams (1978) and Williams and Bujak (1985) referred to the highest occurrence of *S. coronatum* in the Santonian but provided no distribution data, so it is not possible to determine how persistently specimens were recorded in that range. Ioannides (1986) also recorded *S. coronatum* in the Santonian to ?Maastrichtian but in samples with prominent reworking of taxa. The bulk of available data suggests that *S. coronatum* has a highest occurrence (at least in the Northern Hemisphere) in the uppermost Turonian (i.e. Williams and Brideaux, 1975; Foucher, 1975a, 1976a; Marshall, 1983; Tocher, 1984; Costa and Davey, 1992; Williams et al., 1993) or confidently to the top of the Turonian, and questionably in the Lower Coniacian or Lower Santonian (Foucher 1979, 1983 - but the latter possibly attributed to *S. pellucidum*). Schiøler (1992) recorded the highest occurrence of *S. coronatum*

immediately below the highest common occurrence of his *Senoniasphaera?* sp. a (synonymous with *Senoniasphaera turonica*; **Section 7.2.4.**) taken here as a marker for the Upper Turonian (**Section 7.2.12.**). Prince et al. (2008) recorded *S. coronatum* in the Lower and lowest Middle Coniacian of southern UK, but on re-examination their material appears to more closely resemble *Disphaeria macropyla*.

Therefore, the LAD of *S. coronatum* is suggested to lie in the uppermost Turonian in the Northern Hemisphere. The highest occurrence of *S. coronatum* (Sco) in the Trunch borehole occurs at 432.4 m in the uppermost Turonian (*P. (S.) plana* Zone; **Figs 6, 14**), and is therefore, taken to correspond to the LAD. The event occurs in the lower part of the Navigation CIE with a calculated age here of 89.88 (± 0.47), Ma.

7.2.12 LO of persistent *Senoniasphaera turonica* (NW Europe)

Section 7.2.4. provides a brief taxonomic and geographic discussion for *Senoniasphaera turonica*.

Stratigraphy

With the exception of Prince et al. (2008, as *Senoniasphaera rotundata* subsp. *alveolata*), the highest persistent occurrence of *S. turonica* has been reported in the Upper Turonian (in Germany: Prössl, 1990; and southern England: Pearce et al., 2003). Marshall (1983) recorded a very similar form from Germany as *Senoniasphaera* sp. a that also has a highest occurrence in the Upper Turonian, which was subsequently listed as *Canningia* sp. a by Marshall and Batten (1988) and considered to be synonymous with *S. turonica* by Pearce et al. (2011). Prince et al. (2008) consistently recorded the species from the Upper Coniacian well into the Santonian (but presented no Turonian data), and although Pearce et al. (2003) recorded it into the Lower Coniacian, they found it to be only persistently present into the lowermost Coniacian (they included no Upper Coniacian data).

It appears likely that two intervals of persistent occurrence exist in NW Europe, with tops at the Turonian/Coniacian boundary and the top Middle Santonian. In the Trunch borehole, *Senoniasphaera turonica* (*Stu*) is persistently recorded to 432.2 m, and has a highest occurrence at 414.0 m in the upper Lower Coniacian (*M. cortestudinarium* Zone). Therefore, only the lower of the two top persistent occurrences described appears to be present in the southern North Sea basin, particularly as the species was

not recorded by Kirsch (1991) in his study of the Coniacian – Maastrichtian chalks of Germany. At Trunch, the event occurs within the lower part of the Navigation CIE at the Turonian/Coniacian boundary with a calculated age here of 89.87 (± 0.46) Ma (**Fig. 14**).

7.2.13 LAD of *Sentusidinium devonense* (NW Europe)

Section 7.2.6. provides a brief taxonomic and geographic discussion for *Sentusidinium devonense*.

Stratigraphy

The highest occurrence of *Sentusidinium devonense* has been recorded from the Banterwick Barn borehole in southern England and from the Trunch borehole (Pearce 2018; herein. In his PhD thesis, Pearce (2000) consistently recorded it as relatively common to abundant through the Turonian at Banterwick Barn (data was not made available in Pearce et al., 2003) with a highest occurrence questionably in the Upper Turonian (the Upper Turonian is extremely condensed). In the Trunch borehole, the highest occurrence occurs at 430.0 m at the Turonian/Coniacian boundary (lower *M. cortestudinarium* Zone; **Fig. 14**), which is consistent with the results of FitzPatrick (1995) from southern and southeast England. The apparent lack of any species of *Sentusidinium* above the Turonian in the Chalk of NW Europe (the genus was not recorded by Marshall, 1983; Kirsch, 1991; Schiøler, 1992; or Prince et al., 1999, 2008) confirms that *Sentusidinium devonense* (*Sde*) has its LAD in the Turonian. The event at Trunch occurs at the maximum negative excursion of the Navigation CIE at the Turonian/Coniacian boundary with a calculated age here of 89.76 (± 0.43) Ma (**Fig. 14**).

7.3 Coniacian

Five events in the Trunch borehole are discussed: (1) LO of persistent *Heterosphaeridium verdieri*; (2) HO of persistent *Callaiosphaeridium asymmetricum*; (3) LO of frequent *Senoniasphaera filoreticulata*; (4) FAD of *Spinidinium echinoideum*, (5) LO of persistent *Raphidodinium fucatum*.

7.3.1 LO of persistent *Heterosphaeridium verdieri* (NW Europe)

Taxonomy and geographic distribution

Heterosphaeridium verdieri was described by Yun (1981) from the Lower Santonian of Germany. It is restricted to the Northern Hemisphere from ~80°N (Mount Bridgeman, Ellesmere Island, Canadian Archipelago, as *H. cf. verdieri*: Núñez-Betelu et al., 1994) or confidently from ~66°N (offshore mid-Norway, pers. obs.) to ~49°N (SE Germany: Kirsch, 1991) with additional records from southern England (Pearce et al., 2003).

The palaeolatitudinal range of ~70°N (Mount Bridgeman, Ellesmere Island, Canadian Archipelago, Núñez-Betelu et al., 1994) or ~56°N (offshore mid-Norway, pers. obs.) to ~40°N (SE Germany: Kirsch, 1991) suggests that *Heterosphaeridium verdieri* (**Plate III, 2**) was confined to southern North Boreal warm environments (**Fig. 15f**).

Stratigraphy

Pearce et al. (2003) recorded the lowest occurrence of *Heterosphaeridium verdieri* in the Middle Turonian but specimens remain rare until a significant influx in the Middle Coniacian (mid-White Fall CIE). Prince et al. (2008) also found the species to be rare in the Lower Coniacian, with more persistent occurrences or increased relative numbers in the Middle Coniacian. In the Trunch borehole the LO is recorded at 406.0 m immediately above the East Cliff CIE in the mid-Middle Coniacian (*M. coranguinum* Zone, from where it is persistently recorded; **Figs 6, 16**). This is consistent with the findings of Prince et al. (2008) and Pearce et al. (2003). The lowest persistent occurrence of *H. verdieri* (*Hve*) therefore appears to be a good marker for the intra-Middle Coniacian in NW Europe, with a calculated age here of 87.99 (± 0.52) Ma (**Fig. 16**).

7.3.2 HO of persistent *Callaiosphaeridium asymmetricum* (NW Europe)

Taxonomy and geographic distribution

Callaiosphaeridium asymmetricum (**Plate I, 3**) was originally described as a species of *Hystrichosphaeridium* by Deflandre and Courtville (1939) from the 'Senonian' of France. It has been associated with the now invalid *Hexasphaera* (see Williams et al., 2017). The species has a present-day distribution from ~82°N (north Ellesmere Island, Canadian Archipelago: Nøhr-Hansen and McIntyre, 1998) to ~64°S (Antarctic

peninsula: Dettmann and Thomson, 1987; Keating, 1992; Keating et al., 1992). It is well distributed through North and southern South America, North Atlantic, NW Europe, North Africa and Australia, and sparsely recorded in Asia, southern South America, southern Africa, and Antarctic Peninsula.

Given the palaeogeography of the Early Coniacian (**Fig. 15g**), the species is notably absent from the equatorial region with a distribution of $\sim 81^{\circ}\text{N}$ (north Alaska, USA: May and Stein, 1979; Timmcke, 1981; Witmer et al., 1981; Kimyai, 2000) to $\sim 11^{\circ}\text{N}$ (Israel: Eshet et al., 1992), and $\sim 32^{\circ}\text{S}$ (Papua: Fraser et al., 1993) to $\sim 71^{\circ}\text{S}$ (northeast South Island, New Zealand: Schiøler and Wilson, 1998), which suggests that *C. asymmetricum* was restricted to the Boreal warm and arid climate zones. The record of the species as *?Callaiosphaeridium asymmetricum* by Lawal (1982) from NE Nigeria is excluded as we find the illustrated specimen too dissimilar to the holotype.

Stratigraphy

Callaiosphaeridium asymmetricum has been recorded from the Maastrichtian (Kjellström, 1973) but occurs sporadically and in low numbers, and is possibly based on reworked specimens. The bulk of available literature suggests that the highest occurrence of *C. asymmetricum* occurs in the Campanian, where it is typically rare and sporadic in the upper part (Robaszewski et al., 1985; Habib and Miller, 1989; Kirsch, 1991; Nøhr-Hansen, 1996), but the species is recorded consistently in the Lower Campanian (Foucher, 1975a, 1976a, c, 1979; Aurisano 1989; Mao and Mohr, 1992; Prince, 1997; Schiøler and Wilson, 1998; Fensome et al., 2008). Numerous stratigraphic studies indicate that the HC occurs at the Lower/Upper Campanian boundary (Williams and Bujak, 1985, in the mid-Campanian; Costa and Davey, 1992; Williams et al., 1993; Stover et al., 1996; Williams et al., 2004; pers. obs. from the Norwegian Sea). Fensome et al. (2008) provided an age of 79.8 Ma (Gradstein et al. 2004, Middle Campanian; out of range for the present study) for the LAD of *C. asymmetricum*.

In the Trunch borehole, the highest occurrence of *C. asymmetricum* (*Cas*) occurs at 350.0 m in the Middle Santonian (*M. coranguinum* Zone; **Figs 6, 18**), which does not coincide with the LAD of the species, and is taken as a local event. This event occurs immediately above the m2 CIE and is calculated here as $85.3 (\pm 0.55)$ Ma. The highest persistent occurrence occurs at 397.0 m at the j1 CIE in the Middle Coniacian (*M. coranguinum* Zone). This is consistent with the results of Foucher (1975a, 1976a, 1979)

from the Paris Basin, who recorded a conspicuous absence of *C. asymmetricum* through the Santonian prior to its reappearance in the Lower Campanian. The HO of persistent *C. asymmetricum* in the Middle Coniacian is interpreted to represent a local event with a calculated age here of 87.32 (± 0.54) Ma (**Fig. 16**).

7.3.3 LO of frequent *Senonasphaera filoreticulata* (NW Europe)

A brief taxonomic and geographic discussion of *Senonasphaera filoreticulata* is presented in **Section 7.2.8**.

Stratigraphy

At Trunch a minor influx (lowest frequent occurrence) of *S. filoreticulata* (*Sfi*) occurs at 388.0 m in the mid-Middle Coniacian (*M. coronguinum* Zone; **Figs 6, 16**) immediately below the Kingsdown CIE, with a calculated age here of 86.76 (± 0.55) Ma. This appears to be broadly synchronous with data from East Kent (SE England; Prince et al., 2008). Farther to the south, on the Isle of Wight, Prince et al. (2008) showed that this influx occurs slightly lower (but still mid-Middle Coniacian) below the j1 CIE and immediately above the Anvil Hardgrounds, with an estimated age here of 87.23 Ma (**Fig. 16**). Pearce et al. (2003) recorded the LO of *S. filoreticulata* in the Banterwick Barn borehole (Berkshire) at a position between the Light Point and East Cliff CIEs (Lower Coniacian) but crucially found relative numbers to be low. The top of the Banterwick Barn core lies within the negative $\delta^{13}\text{C}_{\text{carb}}$ excursion above the White Fall CIE but below the j1 CIE, and therefore below the influx noted at Trunch and on the Isle of Wight.

7.3.4 FAD of *Spinidinium echinoideum* (N. Hemisphere)

Taxonomy and geographic distribution

This small peridinioid species was originally described as *Deflandrea echinoidea* by Cookson and Eisenack (1960) from the Santonian and Campanian of Australia. It has subsequently been associated with *Vozzhennikovia* prior to *Spinidinium* (see Williams et al., 2017). It has a near-cosmopolitan distribution questionably from $\sim 75^\circ\text{N}$ (Canadian Arctic Archipelago, Byam Martin Island: Kerr, 1974) or confidently from $\sim 73^\circ\text{N}$ (Kara Sea shelf: Lebedeva, 2006) to $\sim 64^\circ\text{S}$ (Antarctic peninsula: Keating, 1992) but is absent

from ~4°N (Colombia: Dueñas-Jimenez, 1990) to ~13°S (offshore north Western Australia: McMinn, 1988).

The palaeolatitudinal range of ~82°N (northern Alaska: Witmer et al., 1981) to questionably ~69°S (Chatham Islands: Wilson, 1976; Mildenhall, 1977) or ~67°S (northeast South Island, New Zealand: Schiøler and Wilson, 1998; Rongaglia et al., 1999; southeast Tasmania: Harris et al., 1999) suggests that *S. echinoideum* (**Plate VI, 1**) favoured a broad range of Boreal warm environments in both hemispheres. (**Fig. 15h**).

Stratigraphy

Numerous studies have recorded *S. echinoideum* from the upper Lower Cretaceous (e.g. Davey, 1970, but which more resemble *Chichaouadinium vestitum*; and Ogg 1994, but which are infrequently present). Questionable Turonian first occurrences were reported by Foucher (1979; as *Spinidinium* cf. *echinoideum*), Azéma et al. (1981; but the chronostratigraphy is poorly constrained) and Courtillot (1993; the species is recorded from only one sample and no illustration was provided) and these records are excluded here.

The majority of records suggest that the lowest occurrence of *S. echinoideum* lies in the Coniacian (Fauconnier, 1984; Williams and Bujak, 1985; Kirsch, 1991 as *Spinidinium* cf. *echinoideum*; Schiøler, 1992; Nøhr-Hansen, 1994, 1996). Dam et al. (1998, following the zonation scheme of Nøhr-Hansen, 1996) recorded *S. echinoideum* in their Upper Turonian – Lower Coniacian interval of the Umiivik-1 borehole from West Greenland. This interval is characterised by the consistent presence of *Raphidodinium fucatum* (**Section 7.3.5.**) and as a result may be considered to be no older than Middle Coniacian based on our stratigraphical review. It should be mentioned that Pedersen and Nøhr-Hansen (2014) state that the ammonite zone index fossil *Scaphites preventricosus* was found to be *in situ* above specimens of *S. echinoideum* in the Umiivik-1 borehole, suggesting the FAD may occur at least as early as Early Coniacian. Azéma et al. (1981) recorded a bloom of *S. echinoideum* in their ‘Senonian’ section from western France, between the top of the Turonian and the FO of *S. protrusa* (**Section 7.4.8.**). This corresponds to middle of the Coniacian – mid-Middle Santonian interval, and lies potentially, therefore, in the Upper Coniacian.

The FAD of *S. echinoideum* is consequently suggested to lie in the Coniacian in the Northern Hemisphere, and until the material from the Umiivik-1 borehole be

investigated further, we choose to accept an Early Coniacian FAD for the species (following Pedersen and Nøhr-Hansen, 2014). The first occurrence of *S. echinoideum* (*Sec*) in the Trunch borehole occurs at 393.0 m in the mid-Middle Coniacian (*M. coranguinum* Zone; **Figs 6, 16**), and appears to be synchronous with that recorded by Prince et al. (2008; although it is extremely rare) in southern England. It is notable that neither Marshall (1983) nor Tocher (1984) recorded *S. echinoideum* from the Turonian to Lower Coniacian (their section tops) of Germany and France, respectively. Therefore, the lowest occurrence at Trunch (and other localities in Europe) is taken as a useful event for the species that occurs midway between the j1 and j2 CIEs, with a calculated age here of 87.05 (± 0.54) Ma (**Fig. 16**).

7.3.5 LO of persistent *Raphidodinium fucatum* (NW Europe)

Taxonomy and geographic distribution

Raphidodinium fucatum was described from the (presumed) 'Senonian' of France by Deflandre (1936b). It has subsequently been found to be restricted to the Northern Hemisphere from $\sim 71^\circ\text{N}$ (west Greenland: Nøhr-Hansen, 1996; Dam et al., 1998, 2000) to $\sim 36^\circ\text{N}$ (northern Iran: Moradin and Allameh, 2010) and is distributed through western Greenland, NW Europe and the Middle East.

The palaeolatitudinal range of $\sim 59^\circ\text{N}$ (west Greenland: Nøhr-Hansen, 1996; Dam et al., 1998, 2000) to $\sim 30^\circ\text{N}$ (northern Iran: Moradin and Allameh, 2010 as *Raphidodinium fucatum* [SIC]) indicates that *R. fucatum* was predominantly a North Boreal warm climate taxon (**Fig. 17a**).

Stratigraphy

There appears to be a latitudinal temperate affect controlling the distribution of the species. In Europe, according to Foucher (1975a, 1976b, 1979) the lowest occurrence of *R. fucatum* (**Plate IV, 9**) occurs at the top of the Turonian in France, although he did not provide detailed range data. That being said, Tocher (1984) did not record the species in his study of French Albion to Lower Coniacian chalks. The species is also unrecorded from the Santonian of southern England and only rare specimens occur in the Lower Campanian (Prince, 1997). Furthermore, a notable absence of *R. fucatum* is apparent in Germany since it was not recorded by either Marshall (1983) or Kirsch

(1991) in their Cenomanian – Coniacian and Coniacian – Maastrichtian studies, respectively.

In the higher latitudes, Costa and Davey (1992) indicated that in the North Sea the lowest occurrence occurs in the mid-Middle Turonian. As pointed out by Nøhr-Hansen (in press; see references therein), other middle Turonian lowest occurrences of *R. fucatum* in the middle Turonian have been recorded from the North Sea area, Norwegian Sea and west Greenland, while an upper Coniacian LO was reported by Nøhr-Hansen (2012) from the Sorgenfri Formation at Kangerlussuaq, eastern Greenland.

In the Trunch borehole, the lowest occurrence of *R. fucatum* (*Rfu*) occurs at 392.0 m in the upper Middle Coniacian (*M. coranguinum* Zone; **Figs 6–16**), and it continues to be reasonably persistently into the Campanian. Therefore, although the FAD of *R. fucatum* possibly lies in the Middle Turonian, the lowest persistent occurrence is suggested to lie in the Coniacian in NW Europe. The event in the Trunch borehole corresponds to the maximum negative $\delta^{13}\text{C}_{\text{carb}}$ excursion between j1 and j2 CIEs, with a calculated age here of 86.99 (± 0.54) Ma (**Fig. 16**).

7.4 Santonian

Twenty-five lowest (LO) and highest occurrence (HO) events in the Trunch borehole are discussed to assess their relationship to first (FAD) and last appearance datum (LAD) levels. These are, in stratigraphic order (base up): (1) FAD of *Spiniferites ramosus* subsp. *maeandriiformis*; (2) LO of common *Spinidinium echinoideum*; (3) temporary HO of *Senoniasphaera filoreticulata*; (4) HO of persistent *Psaligonyaulax deflandrei*; (5) LO of *Renidinium rigidum*; (6) FAD of *Chatangiella manumii*; (7) FAD of *Senoniasphaera protrusa*; (8) FAD of *Cannosphaeropsis utinensis*; (9) LAD of *Spiniferites porosus*; (10) LO of *Chatangiella eminens*; (11) HO of *Renidinium rigidum*; (12) FAD of *Pervosphaeridium intervalum*; (13) reappearance of *Coronifera striolata*; (14) FAD of *Dimidium striatum*; (15) LO of *Spiniferites jarvisii*; (16) FAD of *Odontochitina diducta*; (17) LO of common *Chatangiella eminens*; (18) LO of *Trimuridinium whitenessense*; (19) LO of *Odontochitina porifera*; (20) LAD of *Heterosphaeridium difficile*; (21) HCO of *Chatangiella eminens*; (22) LO of *Cordosphaeridium catherineae*; (23) LAD of *Scriniodinium campanula*; (24) FAD of *Rhynchodiniopsis saliorum*; (25) LAD of *Kleithriasphaeridium readei*.

7.4.1 FAD of *Spiniferites ramosus* subsp. *maendriformis* (NW Europe)

Taxonomy and geographic distribution

Corradini (1973) described *Spiniferites ramosus* var. *maendriformis* (Plate VI, 5) from the 'Senonian' of northwest Italy $\sim 46^{\circ}\text{N}$. Additional published records are sparse and come from offshore mid-Norway (the most northerly site at $\sim 66^{\circ}\text{N}$, pers. obs.) and the Norwegian North Sea (pers. obs.), Denmark and southern Sweden (Hultberg, 1985), Belgium and the Netherlands (Slimani, 2001a), and southern England (Prince et al., 1999).

The palaeolatitudinal range of $\sim 56^{\circ}\text{N}$ (offshore mid-Norway, pers. obs.) to $\sim 30^{\circ}\text{N}$ (northwest Italy: Corradini, 1973) restricts the species principally to the north European warm Boreal area (Fig. 17b).

Stratigraphy

The large sample spacing and uncertain chronostratigraphy in Corradini (1973) renders a stratigraphic comparison impractical, but according to Prince (1997) the lowest occurrence of *S. r. maendriformis* lies in the Upper Santonian at CIE o3. An excellent record of *S. r. maendriformis* (3rm) at Trunch extends the inception of the species to the lowermost Santonian where it is first recorded at 371.0 m (*M. coranguinum* Zone; Figs 6, 14, 18). At Trunch, the LO lies in the upper part of the Michel Dean CIE calculated here as $86.1 (\pm 0.52)$ Ma and therefore appears to be a marker for the earliest Santonian; this is suggested to be the FAD of the species. The first persistent occurrence lies in the Lower Campanian, dated here as $84.00 (\pm 0.50)$ Ma (Figs 18, 21).

7.4.2 LO of common *Spindinium echinoideum* (NW Europe)

Section 7.3.4. provides a brief taxonomic and geographic discussion for *Spindinium echinoideum*.

Stratigraphy

The FAD of *S. echinoideum* (Sec) likely occurs in the mid-Middle Coniacian. However, a significant influx of the species is recorded in the Trunch borehole with a lowest common occurrence at 370.0 m in the Lower Santonian (*M. coranguinum* Zone;

Figs 6, 16, 18). A similar influx is apparent in the Paris Basin (Foucher 1976b, 1979) and the proto-Atlantic Basin (Azéma et al., 1981 - although less convincing due to a lack of stratigraphic control). Interestingly, Foucher (1976b, 1979) recorded the highest occurrence of frequent specimens across the Santonian/Campanian boundary (SCB), with very rare specimens in the Upper Santonian. This same distribution is evident in the Trunch borehole, with a second influx of frequent to common *S. echinoideum* across the SCB.

Dam et al. (1998) recorded *S. echinoideum* in the Coniacian of West Greenland. These occur relatively abundantly (although no values were stated) in their Upper Turonian – Lower Coniacian interval (but which is considered here to be no lower than upper Middle Coniacian; **Section 7.3.4**). This may be an equivalent event, but the precise correlation is uncertain. The LO of common *S. echinoideum* in the Trunch borehole lies immediately above the Michel Dean CIE with a calculated age here of 86.06 (± 0.52) Ma (**Fig. 18**).

7.4.3 Temporary HO of *Senoniasphaera filoreticulata* (NW Europe)

A brief taxonomic and geographic discussion of *Senoniasphaera filoreticulata* is provided in **Section 7.3.3**.

Stratigraphy

Senoniasphaera filoreticulata was originally described from the Upper Campanian (lower *B. mucronata* Zone) of Belgium by Slimani (1994), with a highest occurrence in the upper Upper Campanian (*B. mucronata minor* Zone). A similar distribution has been observed in southern England (Iain Prince, pers. comm.), where it is often abundant to occasionally superabundant in the Upper Campanian. Upper Campanian material was not included in the present study. However, the temporary disappearance of persistently occurring *S. filoreticulata* (*Sfi*) within the Lower Santonian (Prince et al., 1999, 2008) is also apparent in the Trunch borehole at 368.0 m (**Figs 6, 16, 18**), and is suggested to be a locally significant event. In Kent and at Culver Cliff (Prince et al., 2008) the temporary disappearance of consistent *S. filoreticulata* occurs within the interval of the Michel Dean CIE (basal Santonian). At Trunch, the event falls slightly higher, midway between the Michel Dean and Bedwell CIEs, with a calculated age here of 85.99 (± 0.52) Ma (**Fig. 18**).

7.4.4 HO of persistent *Psaligonyaulax deflandrei* (NW Europe?)

Taxonomy and geographic distribution

Psaligonyaulax deflandrei was described by Sarjeant (1966) from the Cenomanian of southeast England; it has also been associated with *Gonyaulacysta* (see Williams et al., 2017). We follow Clarke et al. (1968) by considering it a senior synonym of *Gonyaulacysta extensa* Clarke and Verdier 1967). It is recorded from both hemispheres from ~66°N (offshore mid-Norway, pers. obs.) to ~64°S (Antarctic peninsula: Keating et al., 1992) but is conspicuously absent from equatorial areas from ~16°N (Andra Pradesh, India: Mehrotra et al., 2002) to ~12°S (South Atlantic DSDP 364: Morgan, 1978; Bathurst Island, Australia: Norvick and Burger, 1976). It is distributed through North America, North Atlantic, NW Europe, West Africa, south and southeastern Asia, south Indian Ocean, Australia and Antarctica.

The palaeolatitudinal range of ~56°N (offshore mid-Norway, pers. obs.) to ~20°N (southwest Morocco: Below, 1981) and ~20°S (South Atlantic, DSDP 364: Morgan, 1978) to ~64°S (offshore southeast South Australia: Stoian, 2002) suggests that *Psaligonyaulax deflandrei* (**Plate IV, 6**) favoured areas of arid to Boreal warm climate (**Fig. 17c**).

Stratigraphy

Highest occurrences of *P. deflandrei* have been recorded in the Santonian (Stoian, 2002) or Campanian (Foucher, 1975a, 1976a, 1979) but are typically sporadic or questionable. The highest occurrence or highest persistent occurrence has also been drawn at the top of the Coniacian (Foucher, 1976a; Costa and Davey, 1992) in NW Europe, or mid-Coniacian (Williams and Brideaux, 1975, as *G. extensa*) or lowermost Santonian (Foucher, 1975a; 1979 - questionable specimens were recorded in the basal Lower Campanian) in the Northern Hemisphere.

In the Trunch borehole, the highest occurrence of *P. deflandrei* (*Pde*) occurs at 328.0 m in the Upper Santonian (*U. socialis* Zone), but the highest occurrence of persistent specimens occurs at 367.0 m in the low Lower Santonian (*M. coranguinum* Zone; **Figs 6, 16, 18**), which is comparable with the HO recorded by Foucher (1975a, 1979).

However, it was not recorded by Kirsch (1991) or Prince et al. (1999, 2008) from the

Coniacian to Campanian of Germany and southern England, respectively, which apparently limits the usefulness of the event. In the Trunch borehole, the highest persistent occurrence occurs immediately below the Bedwell CIE with a calculated age here of 85.95 (± 0.52) Ma (**Fig. 18**).

7.4.5 LO of *Renidinium rigidum* (NW Europe?)

Taxonomy and geographic distribution

Renidinium rigidum (**Plate IV, 10 – 11**) was relatively recently described by Prince et al. (1999) from the Middle Santonian of southern England. It was subsequently recorded from four additional southeastern England sites by Prince et al. (2008) where the LO was extended into the Lower Santonian. Records of this species outside of the English Chalk are unknown and as such, it currently has a range of $\sim 53 - 50^\circ\text{N}$, with a palaeolatitudinal range of $\sim 43 - 41^\circ\text{N}$ (**Fig. 17d**).

Stratigraphy

At Culver Cliff and in East Kent (Prince et al., 2008) and in the Trunch borehole (at 361.0 m) the LO of *R. rigidum* (*Rri*) occurs consistently at the l1 CIE in the upper Lower Santonian (*Micraster coranguinum* Zone; **Fig. 6**) with a calculated age here of 85.77 (± 0.52) Ma (**Fig. 18**).

7.4.6 FAD of *Chatangiella manumii* (N. Hemisphere)

Taxonomy and geographic distribution

Chatangiella manumii (**Plate I, 9**) was originally described as *Cooksoniella manumii* by Vozzhennikova (1967) from the Upper Cretaceous of Russia. It appears to be restricted to the Northern Hemisphere, from $\sim 76^\circ\text{N}$ (Taymyr, Russia: Khomentovskii et al., 1999) to northern $\sim 30^\circ\text{N}$ (northern Egypt: Abdel-Kireem et al., 1996; Schrank and Ibrahim, 1995) and distributed through North America, North Atlantic, Europe (questionably in France), North Africa and Asia.

The palaeolatitudinal range of $\sim 75^\circ\text{N}$ (Taymyr, Russia: Khomentovskii et al., 1999) to $\sim 12^\circ\text{N}$ (northern Egypt: Abdel-Kireem et al., 1996; Schrank and Ibrahim, 1995) suggests that *C. manumii* was principally a north Boreal warm to Boreal tropical species (**Fig. 17e**).

Stratigraphy

The lowest stratigraphic level at which *C. manumii* has been recorded is Santonian (Herbin et al., 1987; Schrank and Ibrahim, 1995), although Campanian LOs are typical (Aurisano, 1989; Lentin and Vozzhennikova, 1990; Ilyina et al., 1994; Lebedeva, 2006). The LO of *C. manumii* (*Cma*) in the Trunch borehole occurs at 351.0 m in the Middle Santonian (*M. coranguinum* Zone; **Figs 6, 18**), but it is not persistently recorded until 279.0 m (where the relative abundance also increases) in the Lower Campanian (*O. pillula* Zone). The lowest occurrence at Trunch is taken as the FAD of the species and together with the LO of persistent specimens, are both taken as potentially useful bioevents in the Northern Hemisphere. The FAD occurs at the m2 CIE and the LO of persistent specimens above the pillula CIE with calculated ages of 85.37 (± 0.54) Ma and 83.48 (± 0.5) Ma, respectively (**Fig. 18**).

7.4.7 FAD of *Cannosphaeropsis utinensis* (N. Hemisphere)

Taxonomy and geographic distribution

Cannosphaeropsis utinensis (**Plate 1, 14**) was described by Wetzel (1933) from the 'Senonian' of the southern Baltic region. Numerous Miocene occurrences have been recorded but these are now attributed to *C. passio* de Verteuil and Norris 1996. Williams and Bujak (1985), Williams et al. (1993) and Williams et al. (2004) place the LAD of *C. utinensis* in the Maastrichtian. Therefore, Cenozoic occurrences (if not clearly reworked) have been omitted here. *Cannosphaeropsis utinensis* is recorded from ~57°N (southern Sweden: Kjellström, 1973, Hultberg, 1985) and ~56°N (Denmark: Wetzel, 1933, 1940; Wilson, 1971; Hansen, 1979a, b; Hultberg, 1985) to ~49°S (Santa Cruz, Argentina: Barreda and Palamarczuk, 2000).

The palaeolatitudinal range of ~52°N (Hokkaido Island, Japan: Kurita and Obuse, 1994) to ~59°S (southwest Western Australia: Cookson and Eisenack, 1962) suggests that *C. utinensis* was a low-latitude Boreal warm to tropical taxon (**Fig. 17f**).

Stratigraphy

The majority of records clearly suggest a LO of *C. utinensis* in the Santonian, either somewhere in the Middle Santonian (Foucher 1975a, b, 1976a, b, 1979, 1983), mid-Middle Santonian based on the contemporaneous appearance of *Senoniasphaera*

protrusa (Azéma et al., 1981), or Upper Santonian (Williams and Bujak, 1985; Stover et al., 1996; Prince et al., 1999). The FAD of *C. utinensis* is therefore suggested to lie in the Middle Santonian in the Northern Hemisphere with an estimated age of ~85.25 Ma (i.e. coincident with that of *S. protrusa*, see **Section 7.4.8.**). The lowest occurrence of *C. utinensis* (*Cut*) provided by Prince et al. (1999) occurs between CIEs o1 and o2 (**Figs 6, 18**) and is estimated to have an age of ~84.72 Ma. In the Trunch borehole the LO occurs at 310.0 m in the Upper Santonian (*M. testudinarius* Zone) with a calculated age of 84.30 (± 0.44) Ma (**Fig. 18**).

7.4.8 FAD of *Senoniasphaera protrusa* (N. Hemisphere)

Taxonomy and geographic distribution

Senoniasphaera protrusa (**Plate V, 5**) was described by Clarke and Verdier (1967) from the Santonian of southern England. Prince (1997) noted that not all specimens of *S. protrusa* possess antapical horns on the endocyst (such specimens are now *S. congrensa* (Prince et al., 2008) Fensome et al., 2019), as in the type species. In order to find new criteria to separate these species, Prince et al. (1999) made detailed measurements of the autocysts and ectocysts of *S. protrusa* and *Canningia glomerata* (as *S. rotundata*) and emended the species descriptions accordingly. Therefore, prior to 1999 and depending on the species concept used, these species names may not have been assigned correctly in the literature. For example, in Williams and Brideaux (1975 plate 1 fig. 9) their specimen of *S. protrusa* appears to be *Canningia glomerata*, while their *S. rotundata* (plate 1 fig. 10) appears to be *S. congrensa* following the emended descriptions of Prince et al. (1999).

Senoniasphaera protrusa is typically recorded from the Northern Hemisphere from ~71°N (west Greenland: as *Senoniasphaera* aff. *protrusa*, Nøhr-Hansen, 1996; Ust-Yenisei region, Russia: Lebedeva, 2006) to ~32°N (northern Texas, USA: Harker et al., 1990) and is distributed through North America, North Atlantic, Europe, North Africa and western Asia. Two conspicuously isolated additional occurrences have been recorded from the offshore Ivory Coast (~4°N: Tea-Yassia et al., 1999) and the Antarctic peninsula (~64°S: Dolding, 1992; no specimen was illustrated). Excluding the isolated occurrences, the palaeolatitudinal range of ~68°N (Ust-Yenisei region, Russia: Lebedeva

2006) to $\sim 21^{\circ}\text{N}$ (northeast Algeria: Foucher et al., 1994) suggests the species is principally a southern to mid- Boreal warm climate taxon (**Fig. 17g**).

Stratigraphy

The stratigraphically oldest records of *S. protrusa* occur from the Turonian (Williams, 1975; Bujak and Williams, 1978; Barss et al., 1979; Haq et al., 1987; Pearce et al., 2003). However, as discussed above, it is likely that these are specimens of *Canningia glomerata* following the emended description of Prince et al. (1999), which is certain in the case of Pearce et al. (2003). Stover et al. (1996) placed the LO of *S. protrusa* at the base of the Santonian, and Williams and Bujak (1985) in the intra-Lower? Santonian. However, the bulk of the literature suggests that the LO occurs in the mid-Santonian (Louwye, 1992), Middle Santonian (Foucher, 1975a, 1976a, b, 1979, 1983; Williams and Brideaux, 1975; Foucher and Robaczynski, 1977; Costa and Davey, 1992; Louwye, 1992) or, more precisely, in the upper Middle Santonian (Prince et al., 1999, 2008). Therefore, the FAD of *S. protrusa* is suggested to lie in the Middle Santonian in the Northern Hemisphere.

In East Kent and at Culver Cliff (Prince et al., 2008), the LO of *S. protrusa* occurs in the Middle Santonian above the Baldois Sponge Bed and within the Horseshoe Bay CIE, respectively. In the Trunch borehole, the LO of *S. protrusa* (*Spr*) at 339.0 m also lies in the upper Middle Santonian (*M. coranguinum* Zone; **Figs 6, 18**), but slightly higher stratigraphically than in southern England. The stratigraphically lower record in Kent is estimated to have an age of ~ 85.25 Ma, and this is suggested to be the FAD. The LO of *S. protrusa* in the Trunch borehole occurs slightly higher at isotope event n2, with a calculated age of $84.90 (\pm 0.50)$ Ma (**Fig. 18**).

7.4.9 LAD of *Spiniferites porosus* (N. Hemisphere)

Taxonomy and geographic distribution

Spiniferites porosus was originally described as a species of *Hystrichosphaera* by Manum and Cookson (1964) from the Upper Cretaceous of Arctic Canada. It is restricted to the Northern Hemisphere mid- and high latitudes from $\sim 77^{\circ}\text{N}$ (Graham Island, Canadian Archipelago: Manum and Cookson, 1964; Felix and Burbridge, 1976) to

~36°N (northern Iran: Moradin and Allameh, 2010) and is distributed through North America, NW Europe, and central Asia.

The palaeolatitudinal range of ~70°N (Graham Island, Canadian Archipelago: Manum and Cookson, 1964; Felix and Burbridge, 1976) to ~30°N (northern Iran: Moradin and Allameh, 2010) suggests the species was well suited to north Boreal warm and Boreal tropical climate belts (**Fig. 17h**).

Stratigraphy

Hansen (1977) recorded *Spiniferites porosus* (**Plate VI, 4**) in the Upper Maastrichtian but found it restricted to “certain localities”; it is unclear if these specimens were *in situ*. According to Williams and Bujak (1985), the highest occurrence occurs in the mid-Santonian, which is consistent with the findings here with an HO at Trunch of 349.0 m (*M. coranguinum* Zone; **Figs 6, 18**). Smelror et al. (1994) recorded *S. porosus* through the Turonian – Santonian interval in the Norwegian Sea, but the LO is likely to occur in the post-Turonian since the LO lies above the reappearance of consistent *O. pulcherrimum* specimens (**Section 7.2.9.**) that is taken as a Lower Coniacian marker. Therefore, the LAD of *S. porosus* (*Spo*) is suggested to lie in the mid-Santonian in the Northern Hemisphere following Williams and Bujak (1985). In the Trunch borehole, the event coincides with the isotope peak immediately above the m2 CIE, with a calculated age of 85.23 (± 0.56) Ma.

7.4.10 LO and LO of common *Chatangiella eminens* (NW Europe?)

Taxonomy and geographic distribution

Prince (1997) first recorded *Chatangiella eminens* as *Arvalidinium “spinosum”* from the upper Middle Santonian to Lower Campanian of Culver Cliff, southern England (but it was excluded from the species list of Prince et al., 1999). It was formally described by Pearce (2010) from the Trunch borehole as *Chatangiella eminens* (**Plate I, 8**). It has subsequently been recorded from offshore mid-Norway and questionably from Poland (pers. obs.). It therefore has a geographic range of ~66 – 51°N, with a palaeolatitudinal range of ~56 – 41°N within the southern North Boreal warm climate zone (**Fig. 19a**).

Stratigraphy

The LO of *Chatangiella eminens* (*Cem*) occurs in the upper Middle Santonian at the level of the n1 CIE in southern England (Prince, 1997) and at 346.0 m in the Trunch borehole (*M. coranguinum* Zone; lower part of the Horseshoe Bay CIE; **Figs 6, 18**). A significant up-section influx is noted in the Upper Santonian (Prince, 1997; at Buckle Marl 5, CIE o1) and this is also recognized at Trunch at 334.0 m (*U. socialis* Zone; between the Buckle Event and CIE o1; **Figs 6, 18**); the influx and acme appears to be a potentially correlatable event that warrant further testing. Both the LO and lowest common occurrence at Trunch are stratigraphically marginally lower than in southern England with calculated ages of 85.06 (± 0.59) Ma and 84.81 (± 0.5) Ma, respectively (**Fig. 18**).

7.4.11 HO of *Renidinium rigidum* (NW Europe?)

Section 7.4.5. provides a brief taxonomic and geographic discussion of *Renidinium rigidum*.

Stratigraphy

According to Prince et al. (1999; 2008) the LAD of *Renidinium rigidum* occurs in the Middle Santonian, immediately below Barrois Sponge Bed, midway between CIE m2 and the Horseshoe Bay CIE. In the Trunch borehole, the HO of *R. rigidum* (*Rri*) at 345.3 m also occurs in the mid-Middle Santonian (*Micraster coranguinum* Zone) but slightly higher, within the lower limit of the Horseshoe Bay CIE, with a calculated age of 85.03 (± 0.6) Ma (**Fig. 18**). Despite its limited known geographical range, *R. rigidum* appears to be an excellent biostratigraphic marker species, which may have been missed in previous studies due to its short stratigraphic range.

7.4.12 Reappearance of *Coronifera striolata* (NW Europe?)

Taxonomy and geographic distribution

Coronifera striolata (**Plate I, 11**) was originally described as *Hystriosphæridium striolatum* by Deflandre (1937) from the Upper Cretaceous of France, and has subsequently been transferred to *Baltisphaeridium* and *Exochosphaeridium* prior to *Coronifera* (see Williams et al., 2017). *Coronifera striolata* is recorded from both

hemispheres from ~80°N (Mount Bridgeman, Ellesmere Island, Canadian Archipelago: Núñez-Betelu et al., 1994) to ~24°N (DSDP 535, Gulf of Mexico: Riley and Fenton, 1984) in the Northern Hemisphere and from ~19°S (offshore northwest Western Australia: Stover and Helby, 1987a) to ~64°S (Antarctic peninsula: Dettmann and Thomson, 1987), and is well distributed through North America, North Atlantic, northwest Europe, southern and southeast Asia, southern Indian Ocean, Australia and Antarctica.

The palaeolatitudinal range of ~70°N (Mount Bridgeman, Ellesmere Island, Canadian Archipelago: Núñez-Betelu et al., 1994) to ~24°N (DSDP 535, Gulf of Mexico: Riley and Fenton, 1984; ODP 635, The Bahamas: Masure, 1988) and ~47°S (offshore northwest Western Australia: Stover and Helby, 1987a; Queensland, Australia: Burger, 1982) to ~74°S (DSDP 275, offshore southwest New Zealand: Wilson, 1975) suggests *C. striolata* was a mid- to high latitude Boreal warm taxon (Fig. 19b).

Stratigraphy

The LO of *C. striolata* (*Cst*) occurs at 342.7 m in the Trunch borehole (mid-Middle Santonian; Figs 6, 18) which is consistent with the lowest persistent occurrence reported by Prince et al. (1999, rare specimens were also recorded in the Lower Coniacian by Prince et al. 2008). In spite of other supporting studies (Foucher and Robaszynski, 1977; Bujak and Williams, 1978; Herbin et al., 1987) this contrasts to other published work that suggests a much lower LO.

Coronifera striolata was recorded from the Lower Cretaceous ('Neocomian') by Gocht (1959, as *Hystrichosphaeridium* cf. *striolatum*), Morgan (1980, as *Exochosphaeridium striolatum*), and Stover and Helby (1987a). However, the illustrated specimen provided by Gocht (1959) lacks the distinctive antapical process and that by Morgan (1980) appears to be *Pervosphaeridium truncatum* (known earlier as *Exochosphaeridium striolatum* subsp. *truncatum*); these records are discounted here. An example of *C. striolata* was not illustrated by Stover and Helby (1987a) and the record cannot, therefore, be verified.

Numerous studies suggest the LO of *C. striolata* occurs in the Albian (Cookson and Eisenack, 1971 as ?*Exosphaeridium* [sic] affinity *striolatum*; Steinkraus, 1980 but not illustrated), either in the Lower Albian (Prössl, 1990; Kennedy et al., 2000; not illustrated by either study), or in the Upper Albian (Foucher, 1979, 1980 - neither with illustrated specimens; Masure, 1988; Costa and Davey, 1992 - not illustrated, and based

on oil well data from the North Sea, so the presence of caved specimens cannot be discounted). Clarke and Verdier (1967) and Robaszynski et al. (1982) recorded *C. striolatum* from the base of their study sections, in the Cenomanian. Additional studies by Riley and Fenton (1984) and Dodsworth (2000), confirm the presence of the species in the Cenomanian. Excluding the majority of the studies lacking illustrated specimens, those of Clarke and Verdier (1967) and Masure (1988) suggest that an Upper Albian LO is likely, and this is taken as the FAD here.

Studies documenting *in situ* Turonian (Foucher, 1975a, 1976a, 1976b; Núñez-Betelu et al., 1994; Tocher and Jarvis, 1987) and Coniacian (Foucher, 1971a; Williams and Brideaux, 1975; Schiøler, 1992; Prince et al., 2008) occurrences of *C. striolata* corroborate a FAD that lies stratigraphically lower than the LO at Trunch.

In his upper Turonian – lower Campanian study of Culter Cliff, Prince (1997) recorded the LO of *C. striolata* from the upper Middle Santonian, falling between CIEs n1 and n2. This is equivalent to the LO at Trunch and has a calculated age of 84.96 (± 0.54) Ma (**Fig. 18**). In a follow up paper of the Coniacian – Campanian from a composite section in Kent, Prince et al. (2008) also found *C. striolata* to be more persistently recorded upwards from the Lower Santonian. Therefore, in NW Europe, the reappearance of persistent *C. striolata* is suggested to be a potentially useful marker of the Middle Santonian, but this requires testing.

7.4.13 FAD *Pervosphaeridium intervalum* (NW Europe)

Taxonomy and geographic distribution

Pervosphaeridium intervalum (**Plate IV, 4**) was described by Kirsch (1991) from the Campanian of Germany. *Pervosphaeridium septatum* Slimani 2001b from the Campanian of Belgium and the Netherlands appears to be very similar to *P. intervalum*. A morphological comparison of the holotypes (not provided by Slimani, 2001b) is required to confirm the validity of *P. septatum*.

Pervosphaeridium intervalum appears to be restricted to NW Europe from $\sim 55^{\circ}\text{N}$ (northern North Sea, pers. obs.) to $\sim 36^{\circ}\text{N}$ (northern Iran: Moradin and Allameh, 2010), with a palaeolatitudinal range of $\sim 45^{\circ}\text{N}$ (northern North Sea, pers. obs.) to $\sim 30^{\circ}\text{N}$ (northern Italy: Roncaglia, 2002; Roncaglia and Corradini, 1997; northern Iran: Moradin

and Allameh, 2010) restricting the species largely within the southern North Boreal warm climate belt (**Fig. 19c**).

Stratigraphy

Pervosphaeridium intervalum is restricted to the Upper Cretaceous with the lowest published records from the Upper Santonian (Prince et al., 1999, 2008). The LO of *P. intervalum* (Pint) at Trunch at 342.3 m in the upper Middle Santonian (*M. coranguinum* Zone; **Figs 6, 18**) lowers the inception of the species, and this is tentatively suggested to be the FAD. In the Trunch borehole the event occurs at the negative excursion between the Horseshoe Bay and n2 CIEs with a calculated age of 84.93 (± 0.54) Ma (**Fig. 18**).

7.4.14 FAD of *Dimidium striatum* (NW Europe)

Taxonomy and geographic distribution

This species was originally described as *Gonyaulacysta striata* by Clarke and Verdier (1967) from the Santonian of southern England, and subsequently associated with *Gonyaulacysta*, *Leptodinium*, *Impagidinium*, *Pterodinium* (See Williams et al., 2017) prior to *Dimidium* (Pearce, 2010). Confirmed records indicate that it is restricted to the Northern Hemisphere from $\sim 64^{\circ}\text{N}$ (southwest Greenland, Kangerdlugssuaq: Soper et al., 1976, as *Leptodinium striata*) to $\sim 35^{\circ}\text{N}$ (southwest Korea: Yun et al., 2000) with additional records from southern England (Davey et al., 1969; Prince et al., 1999) and NW Germany (Yun 1981 and Sarjeant, 1985). Williams and Brideaux (1975) recorded *Dimidium striatum* (as *Gonyaulacysta striata*; **Plate II, 3**) from western North Atlantic but on inspection their illustrated specimen possesses an apical horn and is therefore, a mis-identification, and is discounted here.

The narrow palaeolatitudinal range of $\sim 51^{\circ}\text{N}$ (SW Greenland, Kangerdlugssuaq: Soper et al., 1976) to $\sim 41^{\circ}\text{N}$ (southern England: Clarke and Verdier, 1967; southwest Korea: Yun et al., 2000) suggests *D. striatum* was principally associated with Boreal warm climates (**Fig. 19d**).

Stratigraphy

According to Pearce (2010), *Heslertonia rugula* Yun 1981 is a taxonomic junior synonym of *D. striatum* which were found to co-occur in the Santonian of Germany. Prince et al. (1999) also recorded the species as *Pterodinium? striatum* from the upper

Middle Santonian of southern England, which is consistent with our findings from the Trunch borehole where the LO of *D. striatum* (*Dst*) occurs at 336.0 m in the uppermost Middle Santonian (uppermost *M. coranguinum* Zone; mid-Buckle CIE) with a calculated age of 84.85 (± 0.5) Ma. The stratigraphically lower record by Prince et al. (1999) from Culver Cliff is tentatively taken to represent the FAD of the species. This occurs midway between CIEs n1 and n2 with an estimated age of ~ 84.94 Ma.

7.4.15 LO of *Spiniferites jarvisii* (NW Europe?)

Spiniferites jarvisii (Plate VI, 2) was described by Pearce (2010) from the Santonian of the Trunch borehole with a LO at 337.0 m in the uppermost Middle Santonian (uppermost *M. coranguinum* Zone; Figs 6, 18, *Sja*). Due to its distinctive morphology, the first occurrence of this species is suggested to be a potential useful marker for the Middle/Upper Santonian boundary. It has been observed from the Santonian of the Norwegian North Sea and Poland (pers. obs.; Fig. 19c), but more records are required to establish the geographic distribution and likely FAD. At Trunch the event falls immediately below the Buckle CIE with a calculated age of 84.87 (± 0.5) Ma (Fig. 18).

7.4.16 FAD of *Odontochitina diducta* (NW Europe?)

Taxonomy and geographic distribution

Odontochitina diducta (Plate III, 10) was described by Pearce (2010) from the high *Offaster pillula* Zone (mid-lower Campanian) in the Trunch borehole, and an emended description of the species was provided by Pearce (2018) to broaden the morphological variability in the type material. It is restricted to NW Europe from $\sim 66^\circ\text{N}$ (offshore mid-Norway, pers. obs.) to $\sim 51^\circ\text{N}$ (southern England: as *Odontochitina* sp. a, Prince et al., 2008) with additional records from the Norwegian North Sea ($\sim 61^\circ\text{N}$, pers. obs.) and the North Sea ($\sim 55^\circ\text{N}$, as *Odontochitina* sp. a, Costa and Davey, 1992, but without description; and pers. obs.). Keating (1992) recorded a very similar form (as *Odontochitina* sp. II) but which differs by apparently possessing a particularly thick periphragm; however, no diagnosis was provided so this record is not included. Prince (1997; as *O.* sp. a Costa and Davey 1992) discriminated this species by the presence of “widely diverging [presumably the lateral from antapical] horns” but did not provide

measurements, but which were later suggested by Pearce (2010) to be equal to or greater than 80°.

The palaeolatitudinal range of from ~56°N (offshore mid-Norway, pers. obs.) to ~41°N (southern England: Prince et al., 2008) indicates that *O. diducta* was associated with areas of Boreal warm climate (**Fig. 19f**).

Stratigraphy

Prince et al. (2008) recorded rare and sporadic specimens of *O. sp. a* from the lower Coniacian (*M. cortestudinarium* Zone), and from the upper Santonian (*M. testudinarius* Zone; isotope event o3 of Jarvis et al. 2006 fig. 11) from southern England. The first occurrence in the Trunch borehole occurs at 336.0 m in the uppermost middle Santonian (uppermost *M. coranguinum* Zone; mid-Buckle Event; **Figs 6, 18, Odi**) and appears to be comparable with the lowest Santonian record of Prince et al. (2008) with a calculated age of 84.85 (± 0.5) Ma (**Fig. 18**). Given the unknown angle separating the horns in the specimens recorded in the Coniacian these records are excluded.

7.4.17 LO of *Odontochitina porifera* (NW Europe)

Taxonomy and geographic distribution

Odontochitina porifera (**Plate II, 11**) was described by Cookson (1956) from the 'Senonian' of Australia. It has a cosmopolitan distribution from ~74°N (eastern Greenland: Nøhr-Hansen, 2012) to ~66°S (ODP 1167, East Antarctica: Macphail and Truswell, 2004).

The palaeolatitudinal range is ~61°N (Alberta, Canada: Fensome and Norris, 1982) to ~69°S (ODP 1167, east Antarctica: Macphail and Truswell, 2004; **Fig. 19g**). The precise temporal and special distribution of this species may be complicated due to its similarity to *O. cribropoda* and *O. striatoperforata* (junior synonym of *O. costata*), that also possesses perforated horns.

Stratigraphy

In the type material from Australia, Cookson (1956) also described additional new species as *Gymnodinium* (now *Dinogymnium*) *nelsonense* and *Deflandrea* (now *Manumiella*) *cretacea*. According to Helby et al. (1987) the range of these species is considered to be Santonian to Lower Maastrichtian and mid-Santonian to Lower

Maastrichtian, respectively, indicating that *O. porifera* exists in post-Coniacian sediments. Helby et al. (1987) considered the range of *O. porifera* to be from the base of the Santonian to Lower Campanian. Additional ranges for *O. porifera* have been given as spanning the Santonian and Campanian (Keating 1992) and ?Upper Santonian to uppermost Campanian (Wilson, 1984). Askin (1988), Dolding (1992), Wood and Askin (1992) and Schiøler and Wilson (1998) recorded *O. porifera* within the Campanian, while Smith (1992) indicated that the upper range may lie in the Maastrichtian. More recent studies from the Southern Hemisphere, calibrated by magnetostratigraphy (Crampton et al., 2000), place the base of the *O. porifera* Zone of Schiøler and Wilson (1998, defined by the LO of *O. porifera*) in New Zealand, within the mid-Lower Santonian.

In the Northern Hemisphere, Prince et al. (1999) recorded the LO of the species from the macrobiostratigraphically calibrated lower Upper Santonian (*U. socialis* Zone) and well into the Lower Campanian of southern England, and Sigal-Farkas (1997) recorded the species (as *O. porifera-striatopora*) from the uppermost Santonian well into the mid-Campanian of Hungary. Moreover, Campanian occurrences of *O. porifera* from the Northern Hemisphere are further corroborated by Kirsch (1991) from Germany, and Antonescu et al. (2001b) and Schiøler and Wilson (2001) from France. Nøhr-Hansen et al. (in press) describe the LO of *O. porifera* to occur in the middle part of their *Chatangiella* “*spinosa*” (now *Cnatangiella islae* Zone that spans the middle Coniacian to middle Santonian and place the event at the base of the Santonian. These data suggest that a near globally synchronous appearance of *O. porifera* occurred in the Early Santonian, and with respect to Nøhr-Hansen et al. (in press) consider our LO of *O. porifera* in the Upper Santonian to be a NW European event, until a precise mid- to high northern hemisphere correlation can be achieved.

At Trunch and in East Kent (Prince et al., 2008), the LO occurs between the o3 and the Hawks Brow CIEs with a calculated age of 84.59 (± 0.50) Ma (**Figs 6, 18, Opo**). At Culver Cliff (Prince et al., 1999) the LO of *O. porifera* has been recorded slightly lower, between CIEs o1 and o2, giving an estimated age of ~84.73 Ma (**Fig. 18**); this is considered to be the age of the LO in the NW Europe.

Discrepancy with Canadian data

Based on palynological data from offshore southeastern Canada, Williams (1975) defined 11 zones for the Cretaceous, but whose chronostratigraphies were stated to be tentative due to a lack of macrofossil calibration. The lowest occurrence of *O. porifera* was found in his *Oligosphaeridium pulcherrimum* Zone that was believed to be of Coniacian age, and was defined as the interval from the latest (stratigraphically highest) common occurrence of *Surculosphaeridium longifurcatum* at the base, to the latest occurrence of *Oligosphaeridium pulcherrimum* at the top. Additional events within the zone include the LO of *R. truncigerum* and the HOs of *Callaiosphaeridium asymmetricum* and *Scriniodinium campanula*.

In the Trunch borehole, the highest common occurrence of *S. longifurcatum* occurs at the base of the Upper Santonian (*U. socialis* Zone) and the highest occurrence of *O. pulcherrimum* occurs in the Lower Campanian (*O. billula* Zone). Furthermore, the HOs of *Callaiosphaeridium asymmetricum* and *Scriniodinium campanula* (see **Sections 7.3.2.** and **7.4.23.**; **Fig. 6**) occur in the Middle and Upper Santonian, respectively, with the LO of *O. porifera* occurring in-between at ~250 m in the lower Upper Santonian (mid-*U. socialis* Zone). This suggests a miscalibration of the chronostratigraphy of the offshore SE Canadian wells or a difference in taxonomic concept for *O. porifera*.

The FAD of *O. porifera* in the Coniacian was assumed by Williams and Brideaux (1975), Bujak and Williams (1978), Williams and Bujak (1985), Haq et al. (1987; but presumably based on Williams and Bujak, 1985). The same assumption was made by Williams et al. (1993, based on Williams and Bujak, 1985) who included new references but provided no update for the Coniacian to Campanian. Similarly, Stover et al. (1996, presumably following Williams et al., 1993 but stated to be based on European data), and Schrank and Ibrahim (1995, but based on Williams et al., 1993) assumed a Coniacian FAD. All these studies place the highest occurrence of *O. porifera* in the Middle Santonian with the LAD dated to be 84.70 Ma by Fensome et al. (2008), i.e. actually below the lowest occurrence at Trunch. Prince et al. (2008) recorded a single specimen of *O. porifera* from the mid-Middle Coniacian of Whitecliff (Isle of Wight, southern England), but with the next appearance of specimens in the Upper Santonian (upper *U. socialis* Zone).

In summary, the FAD of *O. porifera* remains unclear and it may either occur in the Early Coniacian (Canadian Atlantic) or Early Santonian (Southern Hemisphere and

Europe), although the bulk of calibrated data suggest the latter. Since the lowest occurrence in NW Europe is slightly higher than in the Southern Hemisphere, it represents a LO rather than FAD; an age of 84.73 Ma for the LO of *O. porifera* is given for NW Europe only. The LAD lies in the Campanian or questionably Maastrichtian; the LAD reported by Fensome et al. (2008) is a local HO only.

7.4.18 LO of *Trimuridinium whitenessense* (NW Europe?)

Taxonomy and geographic distribution

Trimuridinium whitenessense (**Plate VI, 10**) was originally described as *Senoniasphaera whitenessii* by Prince et al. (2008) from the Upper Santonian of southern England, and transferred to *Trimuridinium* with the correct species epithet of “*ense*” (after the type area of White Ness, East Kent) by Fensome et al. (2019). It has only been documented from the English Chalk (an additional record was provided by Prince, 1997 as *Senoniasphaera* sp. a), but its scarcity is likely due to the recent discovery of the species. The known palaeolatitude range is ~43°N (Trunch borehole, this study) to ~41°N (southern England: Prince, 1997; Prince et al., 2008) in an area of Boreal warm climate (**Fig. 17d**).

Stratigraphy

The lowest occurrence *T. whitenessense* (*Twh*) in the Trunch borehole occurs at 301 m in the Lower Campanian (*O. faster pillula* Zone; **Figs 6, 18**), with a calculated age of 84.07 (± 0.5) Ma. The event occurs stratigraphically lower in East Kent (Prince et al., 2008), where the LO occurs between CIEs o1 and o2, with an estimated age of ~84.73 Ma (**Fig. 18**).

7.4.19 HO of common *Chatangiella eminens* (NW Europe?)

A brief taxonomic and geographic discussion for *Chatangiella eminens* is provided in **Section 7.4.10**.

Stratigraphy

In the Trunch borehole, the HO of common *C. eminens* (*Cem*) occurs at 326.0 m in the lower Upper Santonian (mid-*U. socialis* Zone) immediately above the o3 CIE (**Figs 6, 18**). At Culver Cliff, the HO of common *C. eminens* (as *Chatangiella “spinosa”*; Prince,

1997) occurs at precisely the same horizon, but the species extends infrequently to a final HO in the Lower Campanian. The HO of common *C. eminens* is, therefore, taken to represent potentially useful event for the Upper Santonian with a calculated age of 84.61 (± 0.5) Ma (**Fig. 18**).

7.4.20 LAD of *Heterosphaeridium difficile* (worldwide)

A brief taxonomic and geographic discussion for *Heterosphaeridium difficile* is presented in **Section 7.2.1**.

Stratigraphy

Brideaux and Myhr (1976) recorded *Hystrichosphaeridium* sp. cf. *H. difficile* sensu McIntyre (1974) well in the lower to mid-Campanian of an exploration well in Arctic Canada. However, this form (illustrated in McIntyre 1974) appears to more closely resemble *Hystrichosphaeridium paracostatum* Cookson and Eisenack 1974, and this record is discounted. McIntyre (1974) illustrated a similar form as *Hystrichosphaeridium* sp. 3 (cf. *H. difficile*) from an undifferentiated Santonian – Campanian interval, but we do not consider this sufficiently similar to the holotype of *Heterosphaeridium difficile* to be considered either.

Stratigraphic studies in West Greenland indicates that the LAD of *H. difficile* occurs in the Santonian. Nøhr-Hansen (1994) recorded the HO near the top of his undifferentiated Coniacian – Upper Santonian interval, and Nøhr-Hansen (1996) reported the HO at the base of an undifferentiated Upper Santonian – Lower Campanian interval. Núñez-Betelu et al. (1994) recorded persistently occurring specimens of *H. difficile* with a HO well before the top of the Kanguk Formation in Arctic Canada (dated as Late Turonian to Early Campanian by Núñez-Betelu et al., 1992). Costa and Davey (1992) placed the HO at the Lower / Upper Santonian boundary, which is consistent with Williams and Bujak (1985), Williams et al. (1993), and Stover et al. (1996). Nøhr-Hansen et al. (2016) place the HO of *H. difficile* at the top of the Lower Santonian, and Fensome et al. (2008) placed the HO in the middle of an undifferentiated Santonian interval.

In his study of the Upper Cretaceous of Culver Cliff, southern England, Prince (1997; not shown in Prince et al., 1999) place the HO in the lower Upper Santonian (mid-*U. socialis* Zone) above CIE o2. Therefore, the LAD of *H. difficile* is suggested to lie in the

Late Santonian worldwide. This is supported by the Santonian HO reported by Keating (1992) for the Southern Hemisphere. In the Trunch borehole the HO of *H. difficile* (*Hdif*) occurs at 326.0 m in the lower Upper Santonian (mid-*U. socialis* Zone; **Figs 6, 18**), immediately above CIE o3 and this is taken to represent the LAD of the species, with a calculated age of 84.61 (± 0.50) Ma.

7.4.21 LO of *Cordosphaeridium catherineae* (NW Europe?)

Cordosphaeridium catherineae (**Plate I, 10**) was described by Pearce (2010) from the Santonian of the Trunch borehole. It has also been observed from southern England (Iain Prince pers. comm., but was not mentioned in his published studies of the area), and from the Upper Santonian of Poland (pers. obs.; **Fig. 12b**). In the Trunch borehole, the lowest occurrence at 323.0 m in the mid-Upper Santonian (upper *U. socialis* Zone; **Figs 6, 18**) is included here as a potential bioevent due to its easily recognizable form. The event occurs immediately below the Hawks Brown CIE with a calculated age of 84.55 (± 0.5) Ma (**Fig. 18, Cca**). More records are necessary to determine if this age represents the FAD of the species.

7.4.22 FAD of *Rhynchodiniopsis saliorum* (NW Europe)

Taxonomy and geographic distribution

This species has commonly been referred to as *Spongodinium "cristatum"* or a species of *Cribooperidinium*, with particularly well-developed crests, in unpublished biostratigraphic consultant reports on the Upper Santonian and Lower Campanian of the NW Europe. It was formally described as *Rhynchodiniopsis saliorum* (**Plate V, 1**) by Louwye (1995) from the Lower Campanian of Belgium, where its lowest occurrence was recorded in the lowermost Campanian. Prince (1997 unpublished, as *Rhynchodiniopsis* sp. a) recorded a consistent lowest occurrence in the mid-Upper Santonian (base *M. testudinarius* Zone) of two southern England sites (where it occurs sporadically), but the species was omitted from the published lists of Prince et al. (1999, 2008). Slimani (2001a) also recorded the species from Belgium and southern Netherlands.

The palaeolatitudinal range of $\sim 56^{\circ}\text{N}$ (offshore mid-Norway, pers. obs.) to $\sim 41^{\circ}\text{N}$ (Belgium: Louwye, 1995; Slimani, 2001a; southern England: Prince, 1997) suggests that the species was restricted to an area of southern North Boreal warm climate (**Fig. 20a**).

Stratigraphy

Personal observations from the Barents Sea and Norwegian Sea suggest that the species has a consistent lowest occurrence within the Upper Santonian, although the precise position is unclear. The LO of *R. saliorum* (*Rsa*) in the Trunch borehole occurs at 312.0 m in the high Upper Santonian (mid-*M. testudinarius* Zone: **Figs 6, 18**) immediately above CIE q1 with a calculated age of $84.37 (\pm 0.46)$ Ma. Records from southern England indicate a stratigraphically lower LO, within the interval of the Hawks Brow CIE (summit of the *U. socialis* Zone; coincident with the LAD of *Scriniodinium campanula*), dated here as $84.53 (\pm 0.50)$ Ma (**Fig. 18**).

7.4.23 LAD of *Scriniodinium campanula* (Northern hemisphere)

Taxonomy and geographic distribution

Scriniodinium campanula (**Plate V, 3**) was described by Gocht (1959) from the Hauterivian of northwestern Germany. It has been associated with *Endoscrinium* (see Williams et al., 2017). We agree with Harker and Sarjeant (1975) and Brideaux and McIntyre (1975) that it is a senior synonym of *Gonyaulacysta fragosa* Brideaux 1971.

Scriniodinium campanula has been recorded in both hemispheres from $\sim 82^{\circ}\text{N}$ (northern Ellesmere Island, Canadian Archipelago: Nøhr-Hansen and McIntyre, 1998) to $\sim 38^{\circ}\text{S}$ (west North Island, New Zealand; Helby et al., 1988), but is conspicuously absent from $\sim 24^{\circ}\text{N}$ (DSDP 99, Caribbean: Hollister et al., 1972; ODP 535, southeast Gulf of Mexico: Riley and Fenton, 1984) to $\sim 6^{\circ}\text{S}$ (Papua New Guinea: Davey, 1988). It is distributed through North America, North Atlantic, NW Europe, NW Africa, Asia, eastern Indian Ocean and Australia, (**Fig. 20b**). It is conspicuously absent from the South Atlantic Ocean.

The palaeolatitudinal range of $\sim 83^{\circ}\text{N}$ (north Alaska: May, 1979; Witmer et al., 1981) to $\sim 11^{\circ}\text{N}$ (central Iraq: Al-Ameri et al., 2001) and from $\sim 32^{\circ}\text{S}$ (Papua New Guinea: Davey, 1988) to $\sim 62^{\circ}\text{S}$ (west North Island, New Zealand: Helby et al., 1988) suggests

that the species was widespread in arid, Boreal warm and Boreal tropical climate zones but was intolerant of fully tropical conditions (**Fig. 20b**).

Stratigraphy

Scriniodinium campanula has a LAD in the Santonian, either in the upper (Williams and Bujak, 1985) or lower (assuming a bipartite division; Costa and Davey, 1992) portion of the stage. Supporting, but poorly calibrated, stratigraphic evidence for an Upper Santonian LAD is provided by Ioannides (1986 - HO in the lower part of an undifferentiated Santonian – Campanian interval), Kirsch (1991 - in the upper part of the Upper Santonian), and Núñez-Betelu et al. (1994) who recorded persistently occurring specimens that have a HO well below the top of Kanguk Formation (referred to the Upper Turonian to Lower Campanian by Núñez-Betelu et al., 1992). Evidence for a Lower Santonian HO is provided by Foucher (1976a, 1976b, 1979), Williams and Brideaux (1975) and Nøhr-Hansen (1994, 1996 - both from a single sample in an undifferentiated Coniacian – Lower Santonian interval).

In his macrofossil-calibrated study, Priole et al. (1999) recorded the HO of *S. campanula* (*Sca*) in the mid-Upper Santonian (with a tripartite subdivision; upper *U. socialis* Zone), which is consistent with our records from the Trunch borehole (HO recorded at 322.0 m; **Figs 6, 18**). Therefore, the LAD of *S. campanula* is suggested to lie in the mid-Upper Santonian in the Northern Hemisphere. At Culver Cliff, the HO of *S. campanula* occurs at the first positive isotope peak below the Hawks Brow CIE; the event occurs slightly higher at Trunch within the interval of the Hawks Brow CIE. This isotope event is consequently taken to represent the LAD of the species with a calculated age of 84.53 (± 0.50) Ma (**Fig. 18**).

7.4.24 LAD of *Kleithriasphaeridium readei* (N. Hemisphere)

Taxonomy and geographic distribution

This species was originally described as *Hystrichosphaeridium readei* by Davey and Williams (1966b) from the Cenomanian of SE England. It has been recorded from both hemispheres from $\sim 73^\circ\text{N}$ (Barents Sea: Århus, 1991) to $\sim 26^\circ\text{S}$ (southeast Brazilian continental shelf: Arai, 1994) and through North America, South America, North Atlantic, NW Europe, NE Africa, southeast Asia and Australia. No occurrences have been

reported between $\sim 30^{\circ}\text{N}$ (northern Egypt: El-Beialy, 1995) to $\sim 4^{\circ}\text{S}$ (Papua: Fraser et al., 1993).

The palaeolatitudinal range of $\sim 63^{\circ}\text{N}$ (Barents Sea: Århus, 1991) to $\sim 12^{\circ}\text{N}$ (northern Egypt: El-Beialy 1995) and $\sim 32^{\circ}\text{S}$ (southeast Brazilian continental shelf: Arai, 1994) to $\sim 51^{\circ}\text{N}$ (west Western Australia: Backhouse, 2003) indicates the species favoured arid and mid-latitude Boreal warm climate zones (**Fig. 20c**).

Stratigraphy

According to Davey and Verdier (1976) the HO of *Kleithriasphaeridium readei* (**Plate III, 6**) lies in the 'Senonian'; possibly, due to either questionable specimens (Foucher and Robaszynski, 1977) or uncertain stratigraphy (Bujak and Williams, 1978), within the Santonian. Other studies point to a Coniacian HO, either at the top (Foucher, 1979; Williams and Bujak, 1985) or in the lowermost part of the stage (Foucher, 1976a, b). The species has not been observed in many studies that focus on the stratigraphic range of the species, and it is conspicuously unrecorded in key papers on the Cenomanian to Campanian chalks of southern England (Clarke and Verdier, 1967; Prince et al., 1999, 2008; Pearce et al., 2003) and from the Upper Cenomanian to Maastrichtian chalks of Germany (Frössl, 1990; Kirsch, 1991).

In the Trunch borehole, the HO of *K. readei* (*Kre*) occurs at 321.0 m in the mid-Upper Santonian (upper *U. socialis* Zone; **Figs 6, 18**); however, although its occurrence is never particularly consistent, the species is more typical of the Coniacian. The LAD is suggested to lie in the Late Santonian, in support of Foucher and Robaszynski (1977) and Bujak and Williams (1978). However, the top of consistently occurring specimens may be in the Coniacian although it is unclear where in the stage this lies. The LAD in the Santonian is placed immediately above the Hawks Brow CIE, with a calculated age of $84.52 (\pm 0.50)$ Ma (**Fig. 18**).

7.5 Lower Campanian

Four lowest occurrence events are discussed here: (1) LO of persistent *Whitecliffia spinosa*; (2) LO of *Alterbidinium ioannidesii*; (3) FAD of *Dinopterygium alatum*; (4) LO of *Spiniferites multispinulus*.

7.5.1 LO of persistent *Whitecliffia spinosa* (NW Europe?)

Taxonomy and geographic distribution

Whitecliffia spinosa (**Plate VI, 11**) was originally described as *Pterospermopsis spinosa* by Clarke and Verdier (1967) from the Santonian of southern England. It has subsequently been combined with *Pterospermella*, questionably with *Thalassiphora* (see Williams et al., 2017) and finally with *Whitecliffia* by Pearce (2010) as the type species. It is typical of the Northern Hemisphere from ~55°N (Norwegian Sea; pers. obs.) to ~44°N (Scotian Shelf: Barss et al., 1979) and is distributed through the North Atlantic, and NW Europe. Sarkar and Prasad (2000) recorded *W. spinosa* from the Paleogene of northern India (~16°N) but this is omitted from our records due to its isolated occurrence and because its position falls outside the accepted palaeolatitudinal (estimated as ~5°N) and temporal range of the species (see below).

The narrow palaeolatitudinal range of *W. spinosa* from ~45°N (Norwegian Sea; pers. obs.) to ~37°N (western France: Masurov, 1983; Scotian Shelf: Barss et al., 1979), places the species tightly towards the southern limit of the North Boreal warm climate belt (**Fig. 20d**).

Stratigraphy

According to Bujak and Williams (1978) and Barss et al. (1979), the lowest occurrence of *W. spinosa* occurs in the Coniacian. Foucher (1979) also placed the LO of *W. spinosa* in the ?Lower Coniacian but stated that this was based on data from Clarke and Verdier (1967); this is incorrect since Clarke and Verdier (1967) recorded the lowest occurrence in the Upper Santonian, *M. testudinarius* Zone. Prince et al. (1999, 2008) recorded rare specimens of *W. spinosa* in a few samples from Upper Santonian chalks, but a lowest persistent occurrence is apparent within the Lower Campanian (Prince et al., 1999 fig. 2). This lowest persistent occurrence lies in the middle of the Santonian / Campanian Boundary Event CIE, above the FAD of *Uintacrinus anglicus*, with an estimated age of ~84.15 Ma. The LO of *W. spinosa* was recorded in the lowermost Lower Campanian of Belgium by Louwye (1992). However, Foucher (1979) placed the LO at the Coniacian/Santonian boundary; this requires high-resolution testing before it can be used to confidently extend the range of the species downwards. The LO of *W. spinosa* (*Wsp*) in the Trunch borehole at 292.0 m, in the Lower Campanian

(*Offaster pillula* Zone; **Figs 6, 21**), is comparable with the lowest persistent occurrence of Prince et al. (1999) and the LO of Louwye (1992), and has a calculated age of 83.91 ($\pm$ 0.50) Ma.

7.5.2 LO of *Alterbidinium ioannidesii* (N. Hemisphere)

Alterbidinium ioannidesii was figured by Ioannides (1986) as Dinoflagellate sp. E (without a description), from $\sim 73^\circ\text{N}$ (Bylot Island, Canadian Archipelago), questionably from Maastrichtian strata. It was formally described as *Alterbidinium ioannidesii* (**Plate I, 1**) by Pearce (2010) from the Trunch borehole (the most southerly known locality at $\sim 53^\circ\text{N}$). The species has been recovered from the Western Interior Seaway (Da Gama et al., 2014), and exploration well material from the Davies Strait (Nøhr-Hansen et al., 2016), and the North Sea, Norwegian North Sea, Norwegian sea and offshore mid-Norway (pers. obs.) from the Upper Santonian? – Lower Campanian sediments, where it can often constitute a common or even abundant proportion of the palynoflora. It should be noted that the precise chronostratigraphic calibration has not been demonstrated. The palaeolatitudinal range of $\sim 67^\circ\text{N}$ (Bylot Island, Canadian Archipelago: Ioannides, 1986) to $\sim 43^\circ\text{N}$ (Trunch borehole, this study) suggests the species is restricted to North Boreal warm mid-latitudes (**Fig. 20e**).

The LO of *A. ioannidesii* (*Aio*) in the Trunch borehole at 299.0 m in the Lower Campanian (basal *Offaster pillula* Zone) is taken to represent the LO of the species from its most southerly distribution limit at $\sim 42^\circ\text{N}$, with a calculated age of 84.05 ($\pm$ 0.5) Ma (**Fig. 21**).

7.5.3 LAD of *Dinopterygium alatum* (N. Hemisphere)

Taxonomy and geographic distribution

Dinopterygium alatum (**Plate II, 5**) was originally described as *Hystrichodinium alatum* from the Albian – Cenomanian of Australia by Cookson and Eisenack (1962). It has subsequently been associated with *Pyramidium*, *Oodnadattia* and *Xiphophoridinium* (see Williams et al., 2017) prior to *Dinopterygium* by Fensome et al. (2009). It has a cosmopolitan distribution from $\sim 74^\circ\text{N}$ (NE Greenland: Nøhr-Hansen, 1993) to $\sim 44^\circ\text{N}$ (Chatham Islands, New Zealand: Mildenhall and Wilson, 1976), with a remarkably wide

palaeolatitudinal range of ~83°N (north Alaska: Witmer et al., 1981) to ~68°S (Chatham Islands, New Zealand: Mildenhall and Wilson, 1976; **Fig. 20f**).

Stratigraphy

In their study of the Belgium chinks, Foucher and Robaszynski (1977) recorded *Dinopterygium alatum* from the Lower Maastrichtian, corroborated by Foucher (1979). Robaszynski et al. (1985) recorded rare *D. alatum* in a single sample from the Lower Maastrichtian of the Stage type area (Early Maastrichtian occurrences were considered to be reworked by Nøhr-Hansen, 1996), but found rare *D. cf. alatum* to be generally restricted to the Lower Campanian. This is supported by Kirsch (1991) who recorded *D. alatum* from several samples in the (presumably) Lower Campanian of Germany. An HO in the mid-Lower Campanian was suggested by Prince et al. (1999) who recorded *D. alatum* reasonably consistently into the mid-*O. pillula* Zone, but the species was absent from the remainder of the Campanian (Prince, unpublished data). A Lower Campanian HO is apparent in the Southern Hemisphere. Schiøler and Wilson (1998) recorded *D. alatum* ranging into the Lower Campanian (their section top) of New Zealand, but it was only recorded twice (presumably reworked) in seventy-eight samples from five Campanian sections by Roncaglia et al. (1999). Marshall (1990) listed the species from offshore southern eastern Australia from a dredge sample dated as Campanian; however, it was not recorded from a nearby exploration well and therefore, cannot be confirmed to be *in situ*.

In the Trunch borehole the HO of *D. alatum* (*Dal*) is recorded at 329.0 m in the lower Upper Santonian (mid-*U. socialis* Zone; **Figs 6, 18**) and therefore, stratigraphically lower than the studies discussed above. Numerous other work supports a HO in the Santonian: *Dinopterygium alatum* has not been recorded in several detailed stratigraphic studies of the Campanian (Harker et al., 1990; Heine, 1991; Antonescu et al., 2001a) or Maastrichtian (Marheinecke, 1992; Antonescu et al., 2001a). The HO has been reported variously in the Upper (Foucher 1975a, 1976a, b, 1979; Williams and Bujak, 1985; Williams et al., 1993; Stover et al., 1996), Middle (Costa and Davey 1992; Masure et al., 1998; Fensome et al., 2008) or Lower Santonian (Williams and Brideaux, 1975). Considering all the evidence, the LAD of *D. alatum* is suggested to lie in the earliest Early Campanian, but Upper Santonian HOs in the Northern Hemisphere are typical.

In the Trunch borehole, the HO of *D. alatum* occurs between CIEs o2 and o3 with a calculated age of 84.68 ($\pm$ 0.5) Ma, which is in close agreement with that of Fensome et al. (2008). However, the HO provided by Prince et al. (1999) occurs approximately three-quarters of the way through the *O. pillula* Zone (their top sample was ~3 m below top of the Zone). This yields a slightly younger estimated age of ~83.45 Ma (**Fig. 21**, *Smu*).

7.5.4 LO of *Spiniferites multispinulus* (NW Europe?)

Spiniferites multispinulus (**Plate VI, 3**) was described by Pearce (2010) and is currently only known from the Lower Campanian of the Trunch borehole. The temporal and spatial distribution remains to be determined due to its recent discovery, but it may have been overlooked in the literature due to its similarity to *S. ramosus* subsp. *gracilis* (Davey and Williams 1966a) Lentin and Williams 1973 (see Pearce 2010 for comparison). In addition, given its relatively short range, it is unlikely to be found without tight sampling. However, as a distinctive species, it is included here as a potential bioevent for the Lower Campanian, with a lowest occurrence at 277.0 m (upper *Offaster pillula* Zone) with a calculated age of 83.40 ($\pm$ 0.49) Ma (**Fig. 21**).

8 Conclusion

A new organic walled dinoflagellate cyst (dinocyst) event stratigraphy has been developed for the Cenomanian to the Early Campanian based on a high-resolution palynological study of the Trunch borehole, together with the critical review of >5000 species records in the published literature.

The stratigraphic positions of the palynological event horizons at Trunch are precisely defined based on an integrated high-resolution framework of regional lithostratigraphic marker beds (including 5 bentonitic marls), macrofossil biostratigraphy, and carbon-isotope event (CIE) chemostratigraphy. This framework provides a basis for comparison with literature records, the majority of which lack comparable stratigraphic resolution. A total of 66 dinocyst bioevents from 49 species, and 1 bisaccate pollen bioevent are defined. These are judged to be of regional (NW Europe), Northern Hemisphere wide or, in four cases, of global stratigraphic significance.

Absolute ages for the palynological events have been derived from a chronostratigraphic model based on radioisotopic and astrochronological ages of macrofossil biostratigraphic datum levels, global CIEs and a geomagnetic reversal. Individual dinocyst events, summarised in **Fig. 22**, are dated with a resolution of 10 – 100 kyr, but the accuracy of these ages is typically judged to be around ± 500 kyr due principally to uncertainties in the geological timescale.

Plots of the palaeogeographic distribution of key species, and critical appraisal of literature records, have allowed an assessment of the geographic extent of the dinocyst species and their associated events. Significant palaeolatitudinal patterns are apparent, with many species restricted to the Northern Hemisphere or to specific climate belts; others are found to be cosmopolitan (**Fig. 23**). Some apparently endemic taxa are newly described species, the geographic extent of which will become more apparent as further studies are conducted.

The 65 palynological events defined here (**Fig. 22, Appendix B**), including those interpreted to represent evolutionary first appearance and last appearance datum levels (FAD, LAD), together with ages derived for lowest and highest occurrences (LO, HO) in regional sections, are (from oldest to youngest):

1. **Early Cenomanian** (4 events): **(1) 97.58 Ma** LO frequent *Sindridinium borealis* (NW Europe); **(2) 96.77 Ma** LAD *Lisphaeria munda* (NW Europe); **(3) 96.77 Ma** HO frequent *Sindridinium borealis* (NW Europe); **(4) 96.42 Ma** LAD *Sindridinium borealis* (NW Europe).
2. **Middle Cenomanian** (4 events): **(5) 95.84 Ma** LAD *Hapsocysta peridictya* (worldwide); **(6) 95.25 Ma** HO common *Epelidosphaeridia spinosa* (N Hemisphere); **(7) 95.15 Ma** HO *Epelidosphaeridia spinosa* (UK) (N Hemisphere); **(8) 94.95 Ma** HO persistent *Cribooperidinium? edwardsii* (NW Europe).
3. **Late Cenomanian** (6 events): **(9) 94.20 Ma** LAD *Epelidosphaeridia spinosa* (N Hemisphere); **(10) 94.20 Ma** HO persistent/common *Litosphaeridium siphoniphorum* (worldwide); **(11) 94.20 Ma** HO common *Sepispinula ambigua* (NW Europe); **(12) 94.10 Ma** LAD *Pterodinium crassimuratum* (NW Europe); **(13) 94.10 Ma** LAD *Wrevittia cassidata* (N Hemisphere); **(14) 94.00 Ma** LAD *Carpodinium obliquicostatum* (NW Europe);
4. **Early Turonian** (6 events): **(15) 93.60 Ma** LO *Heterosphaeridium difficile* (USA) (southern N Hemisphere); **(16) 93.40 Ma** LAD *Pervosphaeridium cenomaniense*

- (worldwide); **(17) 93.35 Ma** FAD *Canningia glomerata* (N Hemisphere); **(18) 93.35 Ma** LO common *Senoniasphaera turonica* (NW Europe); **(19) 93.30 Ma** LAD *Hapsocysta dictyota* (N Hemisphere); **(20) 93.05 Ma** LO *Heterosphaeridium difficile* (UK) (NW Europe);
5. **Middle Turonian** (2 events): **(21) 92.80 Ma** LO common *Sentusidinium devonense* (NW Europe); **(22) 91.90 Ma** FAD *Raetiaedinium truncigerum* (N Hemisphere).
  6. **Late Turonian** (7 events): **(23) 91.04 Ma** LO persistent *Raetiaedinium truncigerum* (N Hemisphere); **(24) 90.16 Ma** FAD *Senoniasphaera filoreticulata* (NW Europe); **(25) 90.12 Ma** reappearance *Oligosphaeridium pulcherrimum* (N Hemisphere); **(26) 89.92 Ma** HO persistent *Cyclonephelium membraniferum* (NW Europe); **(27) 89.88 Ma** LAD *Stephodinium coronatum* (N Hemisphere); **(28) 89.87 Ma** HO persistent *Senoniasphaera turonica* (NW Europe); **(29) 89.76 Ma** LAD *Sentusidinium devonense* (NW Europe).
  7. **Middle Coniacian** (5 events): **(30) 87.99 Ma** LO persistent *Heterosphaeridium verdieri* (NW Europe); **(31) 87.32 Ma** HO persistent *Callaiosphaeridium asymmetricum* (NW Europe); **(32) 87.25 Ma** LO frequent *Senoniasphaera filoreticulata* (NW Europe); **(33) 87.45 Ma** FAD *Spinidinium echinoideum* (N Hemisphere); **(34) 86.99 Ma** LO persistent *Raphidodinium fucatum* (NW Europe)
  8. **Early Santonian** (5 events): **(35) 86.10 Ma** FAD *Spiniferites ramosus* subsp. *maeandriiformis* (NW Europe); **(36) 86.06 Ma** LO common *Spinidinium echinoideum* (NW Europe); **(37) 85.99 Ma** temporary HO *Senoniasphaera filoreticulata* (NW Europe); **(38) 85.95 Ma** HO persistent *Psaligonyaulax deflandrei* (NW Europe?); **(39) 85.77 Ma** LO *Renidinium rigidum* (NW Europe?).
  9. **Middle Santonian** (10 events): **(40) 85.37 Ma** FAD *Chatangiella manumii* (N Hemisphere); **(41) 85.25 Ma** FAD *Cannosphaeropsis utinensis* (N Hemisphere); **(42) 85.25 Ma** FAD *Senoniasphaera protrusa* (N Hemisphere); **(43) 85.23 Ma** LAD *Spiniferites porosus* (N Hemisphere); **(44) 85.06 Ma** LO *Chatangiella eminens* (NW Europe?); **(45) 85.03 Ma** HO *Renidinium rigidum* (NW Europe?); **(46) 84.96 Ma** reappearance *Coronifera striolata* (NW Europe?); **(47) 84.96 Ma** FAD *Pervosphaeridium intervalum* (NW Europe); **(48) 84.94 Ma** FAD *Dimidium striatum* (NW Europe); **(49) 84.87 Ma** LO *Spiniferites jarvisii* (NW Europe?).
  10. **Late Santonian** (10 events): **(50) 84.85 Ma** FAD *Odontochitina diducta* (NW Europe?); **(51) 84.81 Ma** LO common *Chatangiella eminens* (NW Europe?); **(52)**

- 84.73 Ma** LO *Odontochitina porifera* (NW Europe); **(53) 84.73 Ma** LO *Trimuridinium whitenessense* (NW Europe?); **(54) 84.61 Ma** HO common *Chatangiella eminens* (NW Europe?); **(55) 84.61 Ma** LAD *Heterosphaeridium difficile* (worldwide); **(56) 84.55 Ma** LO *Cordosphaeridium catherineae* (NW Europe?); **(57) 84.53 Ma** FAD *Rhynchodiniopsis saliorum* (NW Europe); **(58) 84.53 Ma** LAD *Scriniodinium campanula* (N Hemisphere); **(59) 84.52 Ma** LAD *Kleithriasphaeridium readei* (N Hemisphere).
11. **Early Campanian** (6 events): **(60) 84.15 Ma** LO persistent *Whitecliffia spinosa* (NW Europe?); **(61) 84.05 Ma** FAD *Alterbidinium ioannidesii* (N Hemisphere); **(62) 84.00 Ma** LO persistent *Spiniferites ramosus* subsp. *maeandriiformis* (NW Europe); **(63) 83.48 Ma** LO persistent *Chatangiella manumii* (N Hemisphere); **(64) 83.45 Ma** LAD *Dinopterygium alatum* (N Hemisphere); **(65) 83.40 Ma** LO *Spiniferites multispinulus* (NW Europe?).

Highest stratigraphic resolution (**Fig. 22**) is achieved for the Late Cenomanian – Early Turonian, Late Turonian, Middle Coniacian and Santonian. Significant short- and long-term fluctuations in absolute dinoflagellate abundance, species richness and diversity in the Trunch succession correspond well to stage and macrofossil zonal boundaries. It is anticipated that a series of abundance ‘events’ may be characterised upon further testing to form the basis of an additional biostratigraphic tool.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

9 Acknowledgments

The manuscript benefitted from the insightful reviews of Dr Paul Dodsworth (Stratasolve Ltd) and Dr Henrik Nøhr-Hansen (GEUS Geological Survey of Denmark and Greenland) for which we are very grateful. Malcolm Jones (Palynological Laboratory Services, PLS) is thanked for the preparation of the palynological samples. This study was supported, in part, by a PhD studentship grant to MAP from Equinor Energy AS (previously Statoil ASA), and subsequent funding to IJ (contracts 4500867860; 4501936147; 4502299156; 4502311303).

10 Appendices

10.1 Appendix A. List of palynological taxa

A complete list of organic walled dinoflagellate cyst taxa and associated palynomorphs recorded from the Cenomanian – Lower Campanian of the Trunch borehole is provided below. The classification of Fensome et al. (1993) is followed here, with references cited therein. The taxonomy of Williams et al. (2017) is employed (and cited as they appear in that work), with new combinations of Wood et al. (2016), Fensome et al. (2019) and Pearce and Williams (2018), and new species of Pearce (2018). Species marked with an asterisk (*) are illustrated on the range chart, **Fig. 6**. Stratigraphically significant species and selected other taxa are illustrated in **Plates 1 – 6**.

DIVISION DINOFLAGELLATA (Bütschli 1885) Fensome et al. 1993

SUBDIVISION DINOKARYOTA Fensome et al. 1993

CLASS DINOPHYCEAE Pascher 1914

SUBCLASS GYMNODINIPHYCEAE

ORDER PTYCHODISCALES

FAMILY PTYCHODISCACEAE

SUBFAMILY DINOGYMNIOIDEAE

Alisogymnium euclaense (Cookson and Eisenack 1970a) Lentin and Vozzhennikova 1990

Dinogymnium acuminatum Evitt et al. 1967 (**Plate II, 4**)

Dinogymnium denticulatum (Alberti 1961) Evitt et al. 1967

SUBCLASS PERIDINIPHYCEAE Fensome et al. 1993

ORDER GONYAULACALES Taylor 1980

SUBORDER CLADOPYXIIINEAE Fensome et al. 1993

Histiocysta palla Davey 1969

Microdinium bensonii subsp. *pilatum* Slimani 1994

Microdinium? *crinitum* Davey 1969

Microdinium distinctum Davey 1969

Microdinium ornatum Cookson and Eisenack 1960

Microdinium reticulatum Vozzhennikova 1967

Microdinium? *sincfalensis* Louwye 1995

Microdinium spp. Cookson and Eisenack 1960

FAMILY PAREODINIACEAE

SUBFAMILY PAREODINIOIDEAE

Pareodinia ceratophora Deflandre 1947

FAMILY UNCERTAIN

Rhptocorys veligera (Deflandre 1937) Lejeune-Carpentier and Sarjeant 1983 (**Plate IV, 12**)

SUBORDER GONYAULACINEAE (Autonym)

FAMILY GONYAULACACEAE

SUBFAMILY LEPTODINIOIDEAE Fensome et al. 1993

* *Carpodinium obliquicostatum* Cookson and Hughes 1964 (**Section 7.1.10.; Plate I, 6**)

Conosphaeridium norfolkense Pearce 2018

* *Kleithriasphaeridium readei* (Davey and Williams 1966b) Davey and Verdier 1976 (**Section 7.2.24.; Plate III, 6**)

Leptodinium cancellatum Brideaux and McIntyre 1975

* *Litosphaeridium siphoniphorum* subsp. *glabrum* Lucas-Clark 1984 (**Section 7.1.6.**)

* *Litosphaeridium siphoniphorum* subsp. *siphoniphorum* (Cookson and Eisenack 1958) Davey and Williams 1966 (**Section 7.1.6.; Plate III, 9**)

Litosphaeridium spp. Davey and Williams 1966

Oligosphaeridium complex (White 1842) Davey and Williams 1966

Oligosphaeridium poculum Jain 1977

* *Oligosphaeridium pulcherrimum* (Deflandre and Cookson 1955) Davey and Williams 1966 (**Section 7.2.9.; Plate IV, 1**)

* *Rhynchodiniopsis saliorum* Louwye 1995 (**Section 7.4.22.; Plate V, 1**)

SUBFAMILY CRIBROPERIDINIOIDEAE Fensome et al. 1993

Apteodinium deflandrei (Clarke and Verdier 1967) Lucas-Clark 1987 (**Plate I, 2**)

* *Cordosphaeridium catherineae* Pearce 2010 (**Section 7.4.21.; Plate I, 10**)

Cribroperidinium cooksoniae Norvick 1976

* *Cribroperidinium? edwardsii* (Cookson and Eisenack 1958) Davey 1969 (**Section 7.1.5.; Plate I, 12**)

Cribroperidinium wilsonii (Yun 1981) Poulsen 1996 (**Plate II, 1**)

Cribroperidinium spp. Neale and Sarjeant 1962

Florentinia buspina (Davey and Verdier 1976) Duxbury 1980

Florentinia deanei (Davey and Williams 1966) Davey and Verdier 1973

Florentinia ferox (Deflandre 1937) Duxbury 1980

Florentinia radiculata (Davey and Williams 1966) Davey and Verdier 1973

Florentinia? torulosa (Davey and Verdier 1976) Lentin and Williams 1981

Florentinia spp. Davey and Verdier 1973

* *Hapsocysta dictyota* Davey 1979 (**Section 7.2.5.; Plate II, 10**)

* *Hapsocysta peridictya* (Eisenack and Cookson 1960) Davey 1979 (**Section 7.1.3.; Plate II, 11**)

Kallosphaeridium spp. De Coninck 1969

Spongodinium delitiense (Ehrenberg 1838) Deflandre 1936 (**Plate VI, 6**)

SUBFAMILY GONYAULACOIDEAE (Autonym)

Achomosphaera crassipellis (Deflandre and Cookson 1955) Stover and Evitt 1978

Achomosphaera cf. *granulata* Mao Shaozhi 1989

Achomosphaera ramulifera (Deflandre 1937) Evitt 1963

Achomosphaera regiensis Corradini 1973

Achomosphaera sagena Davey and Williams 1966

* *Cannosphaeropsis utinensis* Wetzel 1933 (**Section 7.4.7.; Plate I, 5**)

Hystrichosphaeropsis ovum Deflandre 1935 (**Plate III, 4**)

Hystrichosphaeropsis quasicrobata (Wetzel 1961) Gocht 1976 (**Plate III, 5**)

Hystrichostrogylon membranaceum Agelopoulos 1964

Hystrichostrogylon robustum Pearce 2010

* *Psaligonyaulax deflandreii* Sarjeant 1966 (**Section 7.4.4.; Plate IV, 6**)

Pterodinium cingulatum subsp. *cingulatum* (Wetzel 1933) Below 1981

Pterodinium cingulatum subsp. *granulatum* (Clarke and Verdier 1967) Lentin and Williams 1981

Pterodinium cingulatum subsp. *reticulatum* (Davey and Williams 1966) Lentin and Williams 1981

Pterodinium? cornutum Cookson and Eisenack 1962

* *Pterodinium crassimuratum* (Davey and Williams 1966) Thurow et al. 1988 (**Section 7.1.8.; Plate IV, 7**)

* *Spiniferites jarvisii* Pearce 2010 (**Section 7.4.15.; Plate VI, 2**)

Spiniferites membranaceus (Rossignol 1964) Sarjeant 1970

* *Spiniferites multispinulus* Pearce 2010 (**Section 7.5.4.; Plate VI, 3**)

* *Spiniferites porosus* (Manum and Cookson 1964) Harland 1973 (**Section 7.4.9.; Plate VI, 4**)

Spiniferites pseudofurcatus (Klumpp 1953) Sarjeant 1970

Spiniferites ramosus subsp. *aquilis* Pearce 2010

Spiniferites ramosus subsp. *ginakrogiae* Pearce 2018

Spiniferites ramosus subsp. *gracilis* (Davey and Williams 1966) Lentin and Williams 1973

Spiniferites ramosus subsp. *granomembranaceus* (Davey and Williams 1966) Lentin and Williams 1973

Spiniferites ramosus subsp. *granosus* (Davey and Williams 1966) Lentin and Williams 1973

* *Spiniferites ramosus* subsp. *maeandriiformis* (Corradini 1973) Lentin and Williams 1975 (**Section 7.4.1.; Plate VI, 5**)

* *Spiniferites ramosus* subsp. *ramosus* (Ehrenberg 1838) Mantell 1854

Spiniferites ramosus subsp. *reticulatus* (Davey and Williams 1966) Lentin and Williams 1973

Spiniferites twistringiensis (Maier 1959) Fensome et al. 1990

Unipontadinium grande (Davey 1975) Wrenn 1958

* *Wrevittia cassidata* (Eisenack and Cookson 1960) Helenes and Lucas-Clark 1997 (**Section 7.1.9.; Plate VI, 12**)

SUBFAMILY UNCERTAIN

* *Callaiosphaeridium asymmetricum* (Deflandre and Courteville 1939) Davey and Williams 1966 (**Section 7.3.2.; Plate I, 3**)

Cometodinium obscurum Deflandre and Courteville 1939

Cometodinium whitei (Deflandre and Courteville 1939) Stover and Evitt 1978

Coronifera oceanica Cookson and Eisenack 1958

* *Coronifera striolata* (Deflandre 1937) Stover and Evitt 1978 (**Section 7.4.12.; Plate I, 11**)

Hystrichodinium pulchrum Deflandre 1935 (**Plate III, 3**)

Kiokansium unituberculatum (Tasch in Tasch et al. 1964) Stover and Evitt 1978

* *Pervosphaeridium cenomaniense* (Norvick 1976) Below 1982 (**Section 7.2.2.; Plate IV, 3**)

* *Pervosphaeridium intervalum* Kirsch 1991 (**Section 7.4.13.; Plate IV, 4**)

Pervosphaeridium morgenrothii (Corradini 1973) Kirsch 1991

Pervosphaeridium pseudhystrichodinium (Deflandre 1937) Yun 1981 (**Plate IV, 5**)

Pervosphaeridium truncatum (Davey 1969) Below 1982

* *Scriniodinium campanula* Gocht 1959 (**Section 7.4.23.; Plate V, 3**)

Sentusidinium sp. a Tocher and Jarvis 1987

* *Sentusidinium devonense* Pearce 2018 (**Sections 7.2.6., 7.2.13.; Plate V, 8**)

Sentusidinium euteiches (Davey 1969a) Wood et al. 2016

Sentusidinium ringnesiorum (Manum and Cookson 1964) Wood et al. 2016 (**Plate V, 9**)

* *Stephodinium coronatum* Deflandre 1936 (**Section 7.2.11.; Plate VI, 7**)

Surculosphaeridium belowii Yun 1981

Surculosphaeridium? cassospinum Yun 1981

Surculosphaeridium longifurcatum (Firtion 1952) Davey et al. 1966

Trichodinium castanea Deflandre 1935 ex Clarke and Verdier 1967 (**Plate VI, 9**)

FAMILY AREOLIGERACEAE Evitt 1963

* *Canningia glomerata* (Clarke and Verdier 1967) Fensome et al. 2019 (**Section 7.2.3.; Plate I, 4**)

Canningia reticulata Cookson and Eisenack 1960

Circulodinium distinctum (Deflandre and Cookson 1955) Jansonius 1986

Cleistosphaeridium latoaculeum (Yun 1981) Fensome et al. 2019

* *Cyclonephelium membraniphorum* Cookson and Eisenack 1962 (**Section 7.2.10.; Plate II, 2**)

Palynodinium helveticum Kirsch 1931

* *Senoniasphaera filoreticulata* (Slanina 1994) Fensome et al. 2019 (**Sections 7.2.8., 7.3.3., 7.4.3.; Plate V, 4**)

* *Senoniasphaera protrusa* Clarke and Verdier 1967 (**Section 7.4.8.; Plate V, 5**)

* *Senoniasphaera turonica* (Prössl 1990 ex Prössl 1992) Pearce et al. 2011 (**Sections 7.2.4., 7.2.12; Plate V, 6 – 7**)

* *Renidinium rigidum* Prince et al. 1999 (**Sections 7.4.5., 7.4.11.; Plate IV, 10 – 11**)

Tenua colliveri (Cookson and Eisenack 1960) Helby 1987 (**Plate VI, 8**)

* *Trimuridinium whitenessense* (Prince et al. 2008) Fensome et al. 2019 (**Section 7.4.18.; Plate VI, 10**)

SUBORDER CERATIINEAE Fensome et al. 1993

FAMILY CERATIACEAE Willey and Hickson 1909

Odontochitina costata Alberti 1961

* *Odontochitina diducta* Pearce 2010 (**Section 7.4.16.; Plate III, 10**)

Odontochitina operculata (Wetzel 1933) Deflandre and Cookson 1955

* *Odontochitina porifera* Cookson 1956 (**Section 7.4.17.; Plate III, 11**)

Xenascus ceratioides (Deflandre 1937) Lentin and Williams 1973

Xenascus perforatus (Vozzhennikova 1967) Yun 1981

Xenascus yunii Prince et al. 2008

Xenascus spp. Cookson and Eisenack 1969

SUBORDER GONIODOMINEAE Fensome et al. 1993

FAMILY GONIODOMACEAE Lindemann 1928

SUBFAMILY PYRODINIOIDEAE Fensome et al. 1993

* *Dinopterygium alatum* Cookson and Eisenack 1962) Fensome et al. 2009 (**Section 7.5.3.; Plate II, 5**)

Dinopterygium cladoides Deflandre 1935

Dinopterygium cf. *cladoides* Deflandre 1935

Dinopterygium tuberculatum (Eisenack and Cookson 1962) Stover and Evitt 1978

Eisenackia crassitabulata Deflandre and Cookson 1965

Fetchamium prolixispinosum (Davey and Williams 1966) Pearce and Williams 2018

Hystrichosphaeridium? *paracostatum* Cookson and Eisenack 1974

Hystrichosphaeridium bowerbankii Davey and Williams 1966 / *recurvatum* (White 1842) Lejeune-Carpentier 1940

Hystrichosphaeridium tubiferum subsp. *brevispinum* (Davey and Williams 1966) Lentin and Williams 1973

Hystrichosphaeridium tubiferum subsp. *tubiferum* (Ehrenberg 1838) Deflandre 1937

SUBORDER UNCERTAIN

FAMILY UNCERTAIN

Atopodinium haromense Thomas and Cox 1988

Caligodinium cf. *aceras* (Manum and Cookson 1964) Lentin and Williams 1973

Cassiculosphaeridia alba Pearce 2010

Cassiculosphaeridia reticulata Davey 1969a

Chlamydophorella discreta Clarke and Verdier 1967

Chlamydophorella nyei Cookson and Eisenack 1958

Codoniella campanulata (Cookson and Eisenack 1960) Downie and Sarjeant 1965

Dapsilidinium laminaspinosum (Davey and Williams 1966) Lentin and Williams 1981

Dapsilidinium? *pumilum* (Davey and Williams 1966) Lentin and Williams 1981

Dapsilidinium spp. Bujak et al. 1980

* *Dimidium striatum* (Clarke and Verdier 1967) Pearce 2010 (**Section 7.4.14.; Plate II, 3**)

Ellipsodinium rugulosum Clarke and Verdier 1967 (**Plate II, 8**)

Exochosphaeridium arnace Davey and Verdier 1973

Exochosphaeridium majus (Clarke and Verdier 1967) Peyrot 2011

Exochosphaeridium majus (Clarke and Verdier 1967) Peyrot 2011 (robust type)

Exochosphaeridium phragmites Davey et al. 1966

Heterosphaeridium conjunctum Cookson and Eisenack 1968

* *Heterosphaeridium difficile* (Manum and Cookson 1964) Ioannides 1986 (7.2.1., 7.4.20.; **Plate II, 12, Plate III, 1**)

Heterosphaeridium heteracanthum (Deflandre and Cookson 1955) Eisenack and Kjellström 1972

Heterosphaeridium spinaconjunctum Yun 1981

* *Heterosphaeridium verdieri* Yun 1981 (**Section 7.3.1.; Plate IV, 2**)

Membranilarnacia polycladiata Cookson and Eisenack in Eisenack 1963

* *Membranilarnacia wilsonii* Pearce 2010

Montanarocysta aemiliana Corradini 1973

Neosphaerodictyon filiosum Slimani 2003

* *Raetiaedinium truncigerum* (Deflandre 1937) Kirsch 1991 (**Section 7.2.7.; Plate IV, 8**)

* *Raphidodinium fucatum* Deflandre 1936 (**Section 7.3.5.; Plate IV, 9**)

Tanyosphaeridium variecalamus Davey and Williams 1966

Trigonopyxidina ginella (Cookson and Eisenack 1960) Downie and Sarjeant 1965

Valensiella ovulum (Deflandre 1947) Eisenack 1963

Wallodinium anglicum (Cookson and Hughes 1964) Lentin and Williams 1973

* *Whitecliffia spinosa* (Clarke and Verdier 1967) Pearce 2010 (**Section 7.5.1.; Plate VI, 11**)

ORDER PERIDINIALES Haeckel 1894

SUBORDER PERIDINIACEAE (Autonym)

FAMILY PERIDINIACEAE Ehrenberg 1831

OVOIDINIOIDEAE (Norris 1978) Bujak and Davies 1983

* *Epelidosphaeridia spinosa* Davey 1969a (**Section 7.1.4.; Plate II, 9**)

* *Sindridinium borealis* Nøhr-Hansen et al. 2018 (**Section 7.1.1.; Plate V, 11 – 12**)

SUBFAMILY PALAEOPERIDINIOIDEAE (Vozzhennikovia 1961) Bujak and Davies 1983

* *Palaeohystrichophora infusorioides* Deflandre 1935

* *Palaeoperidinium pyrophorum* (Ehrenberg 1838) Sarjeant 1967b (**Plate IV, 2**)

Subtilisphaera pontis-mariae (Deflandre 1936) Lentin and Williams 1976

SUBFAMILY DEFLANDREOIDEAE Bujak and Davies 1983

* *Alterbidinium ioannidesii* Pearce 2010 (**Section 7.5.2.; Plate I, 1**)

Alterbidinium spp. Lentin and Williams 1985

Amphidiadema spp. Cookson and Eisenack 1960

Chatangiella ditissima (McIntyre 1975) Lentin and Williams 1976 (**Plate I, 7**)

* *Chatangiella eminens* Pearce 2010 (**Sections 7.4.10., 7.4.19.; Plate I, 8**)

* *Chatangiella manumii* (Vozzhennikova 1967) Lentin and Williams 1976 (**Section 7.4.6.; Plate I, 9**)

Isabelidinium acuminatum (Cookson and Eisenack 1958) Stover and Evitt 1978

Isabelidinium cooksoniae (Alberti 1959) Lentin and Williams 1977

Isabelidinium glabrum (Cookson and Eisenack 1969) Lentin and Williams 1977a

* *Spinidinium echinoideum* (Cookson and Eisenack 1956) Lentin and Williams 1976 (**Sections 7.3.4., 7.4.2.; Plate VI, 1**)

Trithyrodinium spp. Drugg 1967

SUBFAMILY OVOIDINIOIDEAE (Norris 1973) Bujak and Davies 1983

Leberidocysta chlamydata (Cookson and Eisenack 1962) Stover and Evitt 1978 (**Plate III, 7**)

Leberidocysta defloccata (Davey and Verdier 1973) Stover and Evitt 1978 (**Plate III, 8**)

SUBCLASS UNCERTAIN

ORDER UNCERTAIN

FAMILY UNCERTAIN

Prolixosphaeridium conium Davey 1969

CLASS UNCERTAIN

Disphaeria macropyla Cookson and Eisenack 1960

* *Disphaeria munda* (Davey and Verdier 1973) Norvick 1976 (**Section 7.1.2.; Plate II, 6**)

Downiesphaeridium? aciculare (Davey 1969) Islam 1993

Downiesphaeridium armatum (Deflandre 1937) Islam 1993 (**Plate II, 7**)

* *Impletosphaeridium banterwickense* Pearce 2018

* *Sepispinula ambigua* (Deflandre 1937) Masure in Fauconnier and Masure 2004 (**Section 7.1.7.; Plate V, 10**)

* *Sepispinula pertusa* (Davey 1969) Masure in Masure and Fauconnier 2004

Additional palynomorphs:

Cymatiosphaera spp. Wetzel 1933 (prasinophyte)

Fromea amphora Cookson and Eisenack 1958 (acritarch)

Fromea fragilis (Cookson and Eisenack 1962) Stover and Evitt 1978 (acritarch)

Microforaminiferal-test-lining

Palaeostomocystis reticulata Deflandre 1937 (acritarch)

Palambages morulosa Wetzel 1961 (colonial marine alga)

Paralecaniella indentata (Deflandre and Cookson 1955) Cookson and Eisenack 1970 (acritarch)

Pterospermella spp. Eisenack 1972 (prasinophyte)

* *Rugubivesiculites rugosus* Pierce 1961 (bisaccate pollen; Plate V, 2)

Scolecodont (polychaete annelid jaw element)

Tarsisphaeridium geminiporatum Riegel 1974 (prasinophyte)

Bisaccate gymnosperm pollen

Veryhachium spp. Denuff 1954 (acritarch)

10.2 Appendix B. Summary of species bioevents

Appendix B. Age and palaeogeographic extent of bioevents

Event	Abbreviation	Event name	Geographic range	Depth (m)	Transect borehole		Extended range explanation	Final age (Ma) this study	Final calibrated to provisionally GTS 2020*	Section	Substage
					Age (Ma) this study	Age (Ma) calibrated to provisionally GTS 2020*					
65	Smu	LO <i>Spiniferites multispinulus</i>	NW Europe?	27	83.4	82.8		83.40	82.82	7.5	
64	Dal	LAD <i>Dinopterygium alatum</i>	N Hemisphere	329	84.6	84.1	75% from the base of the pillula Zone (Prince et al., 1999)	83.45	82.86	7.5	
63	Cma (pers)	LO persistent <i>Chatangiella manumii</i>	N Hemisphere	279	83.4	82.9		83.48	82.90	7.4	

					50)	23)						
6	<i>Srm</i>	LO persistent	NW		84.0	83.4						
2	(pers)	<i>Spiniferites ramosus maeandriiformis</i>	Europe	29	0	1			84.	83.	7.	
				6	(±0.50)	(±0.21)			00	41	4.	1.
6	<i>Aio</i>	FAD <i>Alterbidinium ioannidesii</i>	N Hemisphere	29	5	6			84.	83.	7.	
1				9	(±0.50)	(±0.21)			05	46	5.	2.
6	<i>Wsp</i>	LO persistent	NW		83.9	83.3						
0	(pers)	<i>Whitecliffia spinosa</i>	Europe?	29	1	2	mid-Santonian / Campanian Boundary Event (Prince et al. 1999)		84.	83.	7.	Early Campanian
				2	(±0.50)	(±0.22)			15	56	5.	1.
5	<i>Kre</i>	LAD <i>Kleithrasphaeridium readei</i>	N Hemisphere	32	2	3			84.	83.	7.	
9				1	(±0.50)	(±0.22)			52	93	4.	
5	<i>Sca</i>	LAD <i>Scriniodinium campanula</i>	N Hemisphere	32	3	4			84.	83.	7.	
8				2	(±0.50)	(±0.22)			53	94	4.	
5	<i>Rsa</i>	FAD <i>Rhynchodiniopsis saliorum</i>	NW Europe	31	7	8	Hawke Bay CIE (Prince et al., 2008); occurring with <i>Scriniodinium campanula</i>		84.	83.	7.	
7				2	(±0.46)	(±0.18)			53	94	4.	
5	<i>Cca</i>	LO <i>Cordosphaeridium catherineae</i>	NW Europe?	32	5	6			84.	83.	7.	
6				3	(±0.50)	(±0.22)			55	96	4.	
5	<i>Hdif</i>	LAD <i>Heterosphaeridium difficile</i>	world wide	32	1	2			84.	84.	7.	
5				5	(±0.50)	(±0.27)			61	02	4.	
5	<i>Cem</i>	HO common <i>Chatangiella eminens</i>	NW Europe?	32	1	2			84.	84.	7.	
4	●			6	(±0.50)	(±0.27)			61	02	4.	
5	<i>Twh</i>	LO <i>Trimuradinium whitenessense</i>	NW Europe?	30	7	8	midway between o1 and o2 CIEs (Prince et al., 2008)		84.	84.	7.	
3				1	(±0.50)	(±0.22)			73	14	4.	
5	<i>Opo</i>	LO <i>Odontochitina porifera</i>	NW Europe	32	9	0	midway between o1 and o2 CIEs (Prince et al., 2008)		84.	84.	7.	
2				5	(±0.50)	(±0.22)			73	14	4.	
5	<i>Cem</i>	LO common <i>Chatangiella eminens</i>	NW Europe?	33	1	2			84.	84.	7.	
1	●			4	(±0.50)	(±0.22)			81	22	4.	
5	<i>Odi</i>	FAD <i>Odontochitina diducta</i>	NW Europe?	33	5	6			84.	84.	7.	earliest Late Santonian
0				6	(±0.50)	(±0.22)			85	26	4.	
4	<i>Sja</i>	LO <i>Spiniferites jarvisii</i>	NW Europe?	33	7	8			84.	84.	7.	
9				7	(±0.50)	(±0.22)			87	28	4.	

4 8	<i>Dst</i>	FAD <i>Dimidium striatum</i>	NW Europe	33 6	84.8 5 (± 0.50)	84.2 6 (± 0.22)	midway between n1 and n2 CIEs (Prince et al., 1999)	84. 94	84. 35	7. 4. 14
4 7	<i>Pint</i>	FAD <i>Pervosphaeridium intervalum</i>	NW Europe	34 2. 3	84.9 6 (± 0.54)	84.3 7 (± 0.26)		84. 96	84. 37	7. 4. 13
4 6	<i>Cst</i> (reapp)	reappearance <i>Coronifera striolata</i>	NW Europe?	34 2. 3	84.9 6 (± 0.54)	84.3 7 (± 0.26)		84. 96	84. 37	7. 4. 12
4 5	<i>Rri</i>	HO <i>Renidinium rigidum</i>	NW Europe?	34 5. 3	85.0 3 (± 0.60)	84.4 4 (± 0.32)		85. 03	84. 44	7. 4. 11
4 4	<i>Cem</i>	LO <i>Chatangiella eminens</i>	NW Europe?	34 6	85.0 6 (± 0.59)	84.4 7 (± 0.31)		85. 06	84. 47	7. 4. 10
4 3	<i>Spo</i>	LAD <i>Spiniferites porosus</i>	N Hemisphere	34 9	85.2 3 (± 0.56)	84.6 5 (± 0.28)		85. 23	84. 65	7. 4. 9
4 2	<i>Spr</i>	FAD <i>Senoniasphaera protrusa</i>	N Hemisphere	33 9	84.9 0 (± 0.50)	84.3 1 (± 0.22)	negative peak above m2 CIE (Prince et al., 2008)	85. 25	84. 66	7. 4. 8
4 1	<i>Cut</i>	FAD <i>Cannosphaeropsis utinensis</i>	N Hemisphere	31 0	84.3 0 (± 0.14)	83.7 1 (± 0.16)	with <i>Senoniasphaera protrusa</i> (Azéma et al., 1981)	85. 25	84. 66	7. 4. 7
4 0	<i>Cma</i>	FAD <i>Chatangiella manumii</i>	N Hemisphere	35 1	85.3 7 (± 0.54)	84.7 8 (± 0.26)		85. 37	84. 78	7. 4. 6
3 9	<i>Rri</i>	LO <i>Renidinium rigidum</i>	NW Europe	36 1	85.7 7 (± 0.52)	85.1 6 (± 0.25)		85. 77	85. 16	7. 4. 5
3 8	<i>Pde</i> (pers)	HO persistent <i>Psalignonyaulax deflandrei</i>	NW Europe?	36 7	85.9 5 (± 0.52)	85.3 7 (± 0.24)		85. 95	85. 37	7. 4. 4
3 7	<i>Sfi</i> (temp)	temporary HO <i>Senoniasphaera filoreticulata</i>	NW Europe	36 8	85.9 9 (± 0.52)	85.4 3 (± 0.22)		85. 99	85. 43	7. 4. 3
3 6	<i>Sec</i> ●	LO common <i>Spinidinium echinoideum</i>	NW Europe	37 0	86.0 6 (± 0.52)	85.5 6 (± 0.18)		86. 06	85. 56	7. 4. 2
3 5	<i>Srm</i>	FAD <i>Spiniferites ramosus maeandriiformis</i>	NW Europe	37 1	86.1 0 (± 0.52)	85.6 2 (± 0.16)		86. 10	85. 62	7. 4. 1
3 4	<i>Rfu</i> (pers)	LO persistent <i>Raphidodinium fucatum</i>	NW Europe	39 2	86.9 9 (± 0.54)	86.3 8 (± 0.29)		86. 99	86. 38	7. 3. 5

Middle
Santoni
anEarly
Santoni
an

33	Sec	FAD <i>Spinidinium echinoideum</i>	N Hemisphere	393	87.0 5 (± 0.54)	86.4 4 (± 0.29)		87.05	86.44	7.34	
32	Sfi O	LO frequent <i>Senoniasphaera filoreticulata</i>	NW Europe	388	86.7 6 (± 0.55)	86.1 6 (± 0.28)	immediately below j1 CIE (Prince et al., 2008)	87.23	86.63	7.33	
31	Cas (pers)	HO persistent <i>Callaiosphaeridium asymmetricum</i>	NW Europe	397	87.3 2 (± 0.54)	86.7 2 (± 0.29)		87.32	86.72	7.32	
30	Hve (pers)	LO persistent <i>Heterosphaeridium verdieri</i>	NW Europe	406	87.9 9 (± 0.52)	87.4 6 (± 0.30)		87.99	87.46	7.31	Middle Coniacian
29	Sde	LAD <i>Sentusidinium devonense</i>	NW Europe	430	89.7 6 (± 0.43)	89.4 1 (± 0.25)		89.76	89.41	7.213	latest Turonian
28	Stu (pers)	HO persistent <i>Senoniasphaera turonica</i>	NW Europe	432	89.8 7 (± 0.46)	89.5 2 (± 0.28)		89.87	89.52	7.212	
27	Sco	LAD <i>Stephodinium coronatum</i>	N Hemisphere	432	89.8 8 (± 0.47)	89.5 3 (± 0.25)		89.88	89.53	7.211	
26	Cme (pers)	HO persistent <i>Cyclonephelium membraniphorum</i>	NW Europe	433	89.9 2 (± 0.47)	89.5 1 (± 0.29)		89.92	89.57	7.210	
25	Opu (reapp)	reappearance <i>Oligosphaeridium pulcherrimum</i>	N Hemisphere	433	90.1 2 (± 0.49)	89.7 7 (± 0.30)		90.12	89.77	7.29	
24	Sfi	FAD <i>Senoniasphaera filoreticulata</i>	NW Europe	439	90.1 6 (± 0.50)	89.8 1 (± 0.30)		90.16	89.81	7.28	
23	Rtr (pers)	LO persistent <i>Raetiaedinium truncigerum</i>	N Hemisphere	467	91.0 4 (± 0.53)	90.6 9 (± 0.35)		91.04	90.69	7.27	Late Turonian
22	Rtr	FAD <i>Raetiaedinium truncigerum</i>	N Hemisphere	467	91.0 4 (± 0.53)	90.6 9 (± 0.35)	below the Glynde CIE in Czech Republic (Olde et al., 2015)	91.90	91.69	7.27	
21	Sde ●	LO common <i>Sentusidinium devonense</i>	NW Europe	460	90.9 7 (± 0.50)	90.6 2 (± 0.32)	midway between d1 and d2 CIEs (Pearce, 2000)	92.80	92.79	7.26	Middle Turonian
20	Hdif (UK)	LO <i>Heterosphaeridium difficile</i> (UK)	NW Europe	462	90.9 9 (± 0.51)	90.6 4 (± 0.33)	immediately above c2 CIE (UK; Pearce et al., 2003)	93.05	93.05	7.21	
19	Hdic	LAD <i>Hapsocysta dictyota</i>	N Hemisphere	504	95.6 8 (± 0.41)	95.6 2 (± 0.50)	Bed 103 (lowermost <i>M. nodosoides</i> Zone), Pueblo (USA; Dodsworth, 2000)	93.30	93.30	7.25	
1	Stu	LO common	NW	46	91.0	90.6	~base <i>M. nodosoides</i>	93.	93.	7.	

8	●	<i>Senoniasphaera turonica</i>	Europe	5	1 (±0.52)	6 (±0.34)	Zone (Pearce et al., 2009)	35	35	2.4.	
17	Cgl	FAD <i>Canningia glomerata</i>	N Hemisphere	459	6 (±0.50)	1 (±0.32)	~base <i>M. nodosoides</i> Zone (FitzPatrick, 1995)	93.35	93.35	7.2.3.	
16	Pce	LAD <i>Pervosphaeridium cenomaniense</i>	world wide	507.9	1 (±0.51)	2 (±0.56)	between the Compton Pebble Marl and Gun Gardens Marl 1 (UK; Pearce et al., 2009)	93.40	93.40	7.2.2.	
15	Hdif (US A)	LO <i>Heterosphaeridium difficile</i> (USA)	southern N Hemisphere				Bed 95, Pueblo (USA; Dodsworth, 2000)	93.60	93.60	7.2.1.	earliest Turonian
14	Cob	LAD <i>Carpodinium obliquicostatum</i>	NW Europe	503.8	95.53 (±0.39)	95.47 (±0.47)	mid-N. <i>juddii</i> Zone (Marshall and Latten, 1988)	94.00	94.00	7.1.10.	latest Cenomanian
13	Wca	LAD <i>Wrevittia cassidata</i>	N Hemisphere	504.3	95.68 (±0.41)	95.62 (±0.50)	Bed 78, Pueblo (USA; Dodsworth, 2000)	94.10	94.10	7.1.9.	
12	Pcr	LAD <i>Pterodinium crassimuratum</i>	NW Europe	503.8	95.53 (±0.39)	95.47 (±0.47)	uppermost Plenus Marl Bed 8 (Pearce et al., 2009)	94.10	94.10	7.1.8.	
11	Sam ●	HO common <i>Sepispinula ambigua</i>	NW Europe	504.8	95.84 (±0.4)	95.79 (±0.54)	Plenus Marl Bed 6 (Dodsworth, 2000; Pearce et al., 2009)	94.20	94.20	7.1.7.	
10	Lsi (pers) ●	HO persistent/common <i>Litosphaeridium siphoniphorum</i>	world wide	504.3	95.68 (±0.41)	95.62 (±0.50)	Plenus Marl Bed 6 (Pearce et al., 2009)	94.20	94.20	7.1.6.	
9	Esp	LAD <i>Epelidosphaeridia spinosa</i>	N Hemisphere				from Lamolda and Mao (1999)	94.20	94.20	7.1.4.	
8	C?e d (pers)	HO persistent <i>Cribroperidinium? edwardsii</i>	NW Europe	506.4	96.42 (±0.50)	96.48 (±0.60)	below b2 CIE (Figure 11)	94.95	94.95	7.1.5.	
7	Esp (UK)	HO <i>Epelidosphaeridia spinosa</i> (UK)	N Hemisphere	504.3	95.68 (±0.41)	95.62 (±0.50)	immediately below b1 CIE (Figure 11)	95.15	95.15	7.1.4.	Late Cenomanian
6	Esp O/ ●	HO common <i>Epelidosphaeridia spinosa</i>	N Hemisphere				immediately below Jukes-Brownei CIE (Figure 11)	95.35	95.35	7.1.4.	
5	Hpe	LAD <i>Hapsocysta peridictya</i>	world wide	504.8	95.84 (±0.44)	95.79 (±0.54)		95.84	95.79	7.1.3.	Middle Cenomanian
4	Sbo	LAD <i>Sindridinium borealis</i>	NW Europe	506.4	96.42 (±0.50)	96.48 (±0.60)		96.42	96.48	7.1.1.	
3	Dmu	LAD <i>Disphaeria munda</i>	NW Europe	507.3	96.77 (±0.51)	96.96 (±0.58)		96.77	96.96	7.1.2.	
2	Sbo O	HO frequent <i>Sindridinium borealis</i>	NW Europe	507.7	96.77	96.96		96.77	96.96	7.1.	

			e	3	(± 0.51)	(± 0.58)			1.	
1	Sbo O	LO frequent <i>Sindridinium borealis</i>	NW Europe	50 9. 3	97.5 9 (± 0.53)	98.2 3 (± 0.52)	97. 58	98. 23	7. 1. 1.	mid- Early Cenoma nian

pers = persistent; reapp = reappearance; LO = lowest occurrence; HO = highest occurrence;
FAD = first appearance datum; LAD = last appearance datum. Abundances: open circles =
frequent; filled circles = common

*The proposed GTS2020 adopts the following ages for Late Cretaceous stage bases (F. Gradstein pers. comm., September 2019): Cenomanian 100.5 ± 0.1 Ma; Turonian 93.9 ± 0.2 Ma; Coniacian 89.4 ± 0.2 Ma; Santonian 85.7 ± 0.1 ; Campanian 83.6 ± 0.1 ; Maastrichtian 72.2 ± 0.2 .

These ages have been substituted in our age model to derive the GTS2020-calibrated ages presented here. Age differences between values derived from the two models vary greatly, but all lie within error of each other.

11 References

- Abdel-Kireem, M.R., Schrank, E., Samir, A.M., Ibrahim, M.I.A., 1996. Cretaceous palaeoecology, palaeogeography and palaeoclimatology the northern Western Desert Egypt. *Journal of African Earth Sciences* 22, 93–112.
- Adams, D.D., Hurtgen, M.T., Sageman, B.B., 2010. Volcanic triggering of a biogeochemical cascade during Oceanic Anoxic Event 2. *Nature Geoscience* 3, 201–204.
- Aguirre-Urreta, M.B., Concheyro, A., Lorenzo, M., Ottone, E.G., Rawson, P.F., 1999. Advances in the biostratigraphy of the Agrio Formation (Lower Cretaceous) of the Neuquén Basin, Argentina: ammonites, palynomorphs and calcareous nannofossils. *Palaeogeography, Palaeoclimatology, Palaeoecology* 150, 33–47.
- Al-Ameri, T.K., Al-Najar, T.K., Batten, D.J., 2001. Palynostratigraphy and palynofacies indications of depositional environments and source potential for hydrocarbons: the Mid Cretaceous Nahr Umr and lower Maaddud Formations, Iraq. *Cretaceous Research* 22, 735–742.
- Andrews, J.E., Kendall, A.C., Hall, A., 2015. Microbial crust with *Frutexites*(?) and iron staining in chalks: Albion – Cenomanian boundary, Hunstanton, UK. *Geological Magazine* 152, 1–11.
- Antonescu, E., Foucher, J.-C., Odin, G.S., 2001a. Dinoflagellate cysts from the transition at Tercis les Bains (Landes, France). In: Odin, G.S. (Ed.), *The Campanian–Maastrichtian Stage Boundary: characterisation at Tercis les Bains (France): correlation with Europe and other continents*. IUGS Special Publication (Monograph) Series 36; Developments in Palaeontology and Stratigraphy Series 19, Amsterdam, pp. 235–252.
- Antonescu, E., Foucher, J.-C., Odin, G.S., Schiøler, P., Siegl-Farkas, A., Wilson, G.J., 2001b. Dinoflagellate cysts in the Campanian–Maastrichtian succession of Tercis les Bains (Landes, France), a synthesis. In: Odin, G.S. (Ed.), *The Campanian–Maastrichtian Stage Boundary: characterisation at Tercis les Bains (France): correlation with Europe and other continents*. IUGS Special Publication (Monograph) Series 36; Developments in Palaeontology and Stratigraphy Series 19, Amsterdam, pp. 253–264.
- Arai, M., 1994. Dinoflagellates of the Late Cretaceous (Turonian – Maastrichtian) Continental Shelf, Southeast Brazil. *Boletim do Simpósio Sobre o Cretáceo do Brasil* 3, 59–62.
- Arai, M., Masure, E., 1997. The dinoflagellates of the Vraconian of the Campos Basin, (Brasil), paper presented at Second Annual Conference of IGCP Project 381. (South Atlantic Mesozoic Correlations).
- Århus, N., 1991. Dinoflagellate cyst stratigraphy of some Aptian and sections from North Greenland, southeastern Spitsbergen and the Barents Sea. *Cretaceous Research* 12, 209–225.
- Askin, R.A., 1988. The Campanian – Paleocene palynological succession of Seymour and adjacent islands, northeastern Antarctic Peninsula In: Feldmann, R.M., Woodburne, M.O. (Ed.), *Geology and palaeontology of Seymour Island, Antarctic Peninsula*. Geological Society of America, Memoir 169, 131–153.

- Askin, R.A., Elliot, D.H., Stilwell, J.D., Zinsmeister, W.J., 1991. Stratigraphy and paleontology of Campanian and Eocene sediments, Cockburn Island, Antarctic Peninsula. *Journal of South American Earth Sciences* 4, 99–117.
- Aurisano, R.W., 1989. Upper Cretaceous dinoflagellate biostratigraphy of the subsurface Atlantic Coastal Plain of New Jersey and Delaware, U.S.A. *Palynology* 13, 143–179.
- Azéma, C., Fauconnier, D., Viaud, J.M., 1981. Microfossils from the Upper Cretaceous of Vendée (France). *Review of Palaeobotany and Palynology* 35, 237–281.
- Backhouse, J., 2003. Appendix 2: Palynology. In: Dixon, M., Haig, D.W., Mory, A.J., Backhouse, J., Ghorri, K.A.R., Howe, R., Morris, P.A., GSWA Edaggee 1 Well completion report, (interpretive) Gascoyne Platform, Southern Carnarvon Basin Western Australia.). Geological Survey of Western Australia. Record 2003, 43–49.
- Bailey, H.W., Gale, A.S., Mortimore, R.N., Swiecicki, A., Wood, C.J., 1983. The Coniacian–Maastrichtian stages of the United Kingdom, with particular reference to southern England. *Newsletters on Stratigraphy* 12, 29–42.
- Bailey, H.W., Gale, A.S., Mortimore, R.N., Swiecicki, A., Wood, C.J., 1984. Biostratigraphical criteria for the recognition of the Coniacian to Maastrichtian stage boundaries in the Chalk of North West Europe, with particular reference to southern England. *Bulletin of the Geological Society of Denmark* 33, 31–39.
- Baltes, N., 1967a. Microflora from Miocene salt-bearing formations of the Pre-Carpathian Depression (Rumania). *Review of Palaeobotany and Palynology* 2, 183–194.
- Baltes, N., 1967b. The microflora of the Miocene "Green Sands" in the Moesian Platform (Rumania). *Review of Palaeobotany and Palynology* 5, 183–197.
- Bardet, N., Mazin, J.-M., Azéma, C., Begouen, V., Masure, E., 1991. L'Ichthyosaure de Bedeille (Ariege, France) examen palynologique de la gangue et mise au point stratigraphique. *Bulletin de la Société Géologique de France*, 8e série 162, 897–903.
- Barreda, V.D., Palamarczuk, S., 2000. Continental and marine palynomorphs from the type area of the Monte Leon Formation, Santa Cruz Province, Argentina. *Ameghiniana* 37, 5–12.
- Barrois, C., 1876. Recherches sur le terrain Crétacé Supérieur de l'Angleterre et de l'Irlande. Lille: Imprimerie et Librairie Six-Horemans, 232pp.
- Barss, M.S., Bujak, J.P., Williams, G.L., 1979. A palynological zonation and correlation of sixty-seven wells. Geological Survey of Canada, Paper 78, 1–118.
- Bath, A.H., Edmunds, W.M., 1981. Identification of connate water in interstitial solution of chalk sediment. *Geochimica et Cosmochimica Acta* 45, 1449–1461.
- Batten, D.J., Morrison, L., 1983. Methods of palynological preparation for palaeoenvironmental, source potential and organic maturation studies. Norwegian Petroleum Directorate, Bulletin 2, 35–53.
- Bebout, J.W., 1981. An informal palynologic zonation for the Cretaceous System of the United States Mid-Atlantic, (Baltimore Canon Area), outer continental shelf. *Palynology* 5, 159–194.

- Bedwell, F.A., 1874. The Isle of Thanet. The ammonite zone, the depth of the Chalk in section, and the continuity of its flint floorings. *Geological Magazine*, New Series, Decade II 1, 16–22.
- Bell, D.G., Selnes, H., 1997. The first appearance datum (FAD) of *Heterosphaeridium difficile* (Manum and Cookson) dinoflagellate, in clastic deposits, offshore Norway. *Journal of Micropalaeontology* 16, 30.
- Below, R., 1981. Dinoflagellaten-zysten aus dem oberen Hauterive bis unteren Cenoman süd-West-Marokkos. *Paläontographica Abteilung B* 176, 1–145.
- Below, R., 1982. Scholochorate cysts of Gonyaulacaceae (Dinophyceae) from the Lower Cretaceous of Morocco. *Paläontographica Abteilung B* 182, 1–51.
- Below, R., 1984. Aptian to cenomanian dinoflagellate cysts from the mazagan plateau, Northwest Africa (sites 545 and 547, Deep Sea Drilling Project leg 79). In: Hinz, K., Winterer, E.L., et al. (Eds), *Initial Reports of the Deep Sea Drilling Project*, U.S. Government Printing Office, 79, Washington, pp. 621–649.
- Bengtson, P., 1996. The Turonian stage and substage boundaries. In: *Proceedings "Second International Symposium on Cretaceous Stage Boundaries"* Brussels 8 – 16 September 1995. l'Institut Royal des Sciences Naturelles de Belgique, pp. 69–79.
- Bettar, I., Meon, H., 2006. La palynoflore continentale de l'Albien du bassin d'Agadir-Essaouira (Maroc). *Revue de Paléobiologie* Genève 25, 593–631.
- Blake, J.F., 1878. On the chalk of Yorkshire. *Proceedings of the Geologists' Association* 5, 232–270.
- Bloch, J.D., Schroder-Adams, C.J., Leckie, D.A., Craig, J., McIntyre, D.J., 1999. Sedimentology, micropaleontology, geochemistry, and hydrocarbon potential of shale from the Cretaceous Lower Colorado Group in Western Canada. *Geological Survey of Canada, Bulletin* 531, 1–185.
- Bower, C.R., Farmery, J.R., 1910. Zones of the Lower Chalk of Lincolnshire. *Proceedings of the Geologists' Association* 21, 333–359.
- Brenner, G.J., 1974. Palynostratigraphy of the Lower Cretaceous Gevar'am and Talme Yafe Formations in the Gevar'am 2 well (Southern Coastal Plain, Israel). *Geological Survey of Israel, Bulletin* 59, 1–27.
- Brideaux, W.W., McIntyre, D.J., 1975. Miospores and microplankton from Aptian–Albian rocks along Horton River, District of MacKenzie. *Geological Survey of Canada, Bulletin*, 252 1–85.
- Brideaux, W.W., Myhr, D.W., 1976. Lithostratigraphy and dinoflagellate cyst succession in the Gulf Mobil Parsons N-10 Well, District of MacKenzie. *Geological Survey of Canada, Paper* 76, 235–249.
- Brinkhuis, H., Schiøler, P., 1996. Palynology of the Geulhemmerberg Cretaceous/Tertiary boundary section (Limburg, southeast Netherlands). *Geologie en Mijnbouw* 75, 193–213.
- Bristow, C.R., 1990. *Geology of the Country around Bury St Edmunds* HMSO, London.
- Bristow, C.R., Mortimore, R.N., Wood, C.J., 1997. Lithostratigraphy for mapping the Chalk of southern England. *Proceedings of the Geologists' Association* 108, 293–315.

- Bromley, R.G., Ekdale, A.A., 1987. Mass transport in European Cretaceous chalk; fabric criteria for its recognition. *Sedimentology* 34, 1079–1092.
- Bromley, R.G., Gale, A.S., 1982. The lithostratigraphy of the English Chalk Rock. *Cretaceous Research* 3, 273–306.
- Brydone, R.M., 1912. *The Stratigraphy of the Chalk of Hants* London: Dulau and Co. Ltd, 116 pp.
- Brydone, R.M., 1914. The zone of *Offaster pilula* in the south English Chalk. *Geological Magazine* 6, 359–369, 405–411, 449–457, 509–513.
- Brydone, R.M., 1939. *The Chalk zone of Offaster pilula* London: Dulau and Company 8 pp.
- Bubík, M., Skupien, P., Švábenická, L., 2008. Stratigrafie křídových pestrých oceánských vrstev karpatského flyše na Moravě. *Geologické výzkumy na Moravě a ve Slezsku v roce 2007*, Brno 2008, 46–52.
- Bujak, J.P., Williams, G.L., 1978. Cretaceous palynostratigraphy of offshore southeastern Canada. *Geological Survey of Canada, Bulletin* 297, 1–19.
- Burnett, J.A., 1988. North-west European Late Cretaceous Calcareous Nannofossils: Biostratigraphy and Selected Evolutionary Lineages. Unpublished PhD thesis. University College London.
- Burnett, J.A., 1990. A new nannofossil zonation scheme for the Boreal Campanian. *International Nannofossil Association Newsletter* 12, 67–70.
- Burger, D., 1982. Palynological examination of Late Mesozoic sediments in GSQ Hughenden 7, and notes on geological events in the northern Eromanga Basin. *Queensland Government Mining Journal* 83, 421–432.
- Burger, D., 1988. Early Cretaceous environments in the Eromanga Basin; palynological evidence from GSQ Wyandra-1 corehole. In: *Jell, P.A., Playford, G. (Eds), Palynological and Palaeobotanical Studies in Honour of Basil E. Balme. Association of Australasian Palaeontologists, Memoir* 5, 173–186.
- Busby, J.P., Smith, N.J.P., 2001. The nature of the Variscan basement in southeast England: evidence from integrated potential field modelling. *Geological Magazine* 138, 669–685.
- Calis, N., Drummond, D.J., 2008. Hydrogeologic data from six test wells in the Upper Patapsco and Lower Patapsco aquifers in Southern Maryland. *Maryland Geological Survey Basic Data Report* 22, 1–74.
- Cao, W.C., Zahirovic, S., Flament, N., Williams, S., Golonka, J., Muller, R.D., 2017. Improving global paleogeography since the late Paleozoic using paleobiology. *Biogeosciences* 14, 5425–5439.
- Caron, M., Robaszynski, F., Amédéo, F., Baudin, F., De Coninck, J., Hochuli, P., Salis-Perch Nielsen, K.V., Tribouillard, N.-P., 1999. Duration of the oceanic anoxic event at the Cenomanian – Turonian boundary cyclostratigraphic interpretation of the Bahloul Formation in Central Tunisia. *Bulletin de la Société Géologique de France, 8e série* 170, 145–160.
- Carter, D.J., Hart, M.B., 1977. Aspects of mid-Cretaceous stratigraphic micropalaeontology. *Bulletin of the British Museum of Natural History (Geology)* 29, 1–135.

- Chadwick, R.A., Evans, D.J., 2005. A seismic atlas of southern England: images of subsurface structure. Keyworth, Nottingham: British Geological Survey.
- Chen, Y.Y., 1978. Jurassic and Cretaceous palynostratigraphy in the Morondava Basin of Madagascar. PhD thesis, University of Arizona, Arizona, 264 pp.
- Clark, G., Piggott, S., 1933. The age of the British flint mines. *Antiquity*, 7, 166–183.
- Clarke, L.J., Jenkyns, H.C., 1999. New oxygen isotope evidence for long-term Cretaceous climatic change in the Southern Hemisphere. *Geology* 27, 699–702.
- Clarke, R., 1935. The flint-knapping industry at Brandon. *Antiquity* 9, 38–56.
- Clarke, R.F.A., Verdier, J.P., 1967. An investigation of microplankton assemblages from the chalk of the Isle of Wight, England. *Verhandelingen der Koninklijke Nederlandse Akademie van Wetenschappen, Afdeling Natuurkunde, Eerste Reeks* 24, 1–96.
- Clarke, R.F.A., Davey, R.J., Sarjeant, W.A.S., Verdier, J.P., 1968. A note on the nomenclature of some Upper Cretaceous and Eocene dinoflagellate taxa. *Taxon* 17, 181–183.
- Cobban, W.A., Walaszczyk, I., Obradovich, J.D., McKinney, R.C., 2006. A USGS Zonal Table for the Upper Cretaceous Middle Cenomanian–Maastrichtian of the Western Interior of the United States Based on Ammonites, Inoceramids, and Radiometric Ages. Reston, Virginia: USGS Open File Report 2006–1250, 46 pp.
- Cocozza, C.D., Clarke, C.M., 1992. Eocene microplankton from La Meseta Formation, northern Seymour Island. *Antarctic Science* 4, 355–362.
- Cookson, I.C., 1956. Additional microplankton from Australian Late Mesozoic and Tertiary sediments. *Australian Journal of Marine and Freshwater Research* 7, 183–191.
- Cookson, I.C., Eisenack, A., 1958. Microplankton from the Australian and New Guinea Upper Mesozoic sediments. *Proceedings of the Royal Society of Victoria* 74, 19–79.
- Cookson, I.C., Eisenack, A., 1960. Microplankton from Australian Cretaceous sediments. *Micropaleontology* 6, 1–18.
- Cookson, I.C., Eisenack, A., 1962. Additional microplankton from Australian Cretaceous sediments. *Micropaleontology* 8, 485–507.
- Cookson, I.C., Hughes, M.F., 1964. Microplankton from the Cambridge Greensand (Mid-Cretaceous). *Palaeontology* 7, 37–59.
- Cookson, I.C., Eisenack, A., 1969. Some microplankton from two bores at Balcatta, Western Australia. *Journal of the Royal Society of Western Australia* 52, 3–8.
- Cookson, I.C., Eisenack, A., 1971. Cretaceous microplankton from Eyre No.1 Bore core 20, Western Australia. *Proceedings of the Royal Society of Victoria* 84, 217–225.
- Cookson, I.C., Eisenack, A., 1974. Microplankton from Australian Mesozoic and Tertiary sediments. *Palaeontographica Abteilung B* 148, 44–93.
- Corradini, D., 1973. Non-calcareous microplankton from the Upper Cretaceous of the Northern Apennines. *Bollettino della Societa Paleontologica Italiana* 11, 119–197.

- Costa, L.I., 1985. The *Ascodinium* plexus in the latest Albian to earliest Cenomanian offshore Arctic Norway. In: Third International Conference on Modern and Fossil Dinoflagellates, Egham, August, 1985, Abstracts, unnumbered page.
- Costa, L.I., Davey, R.J., 1992. Dinoflagellate cysts of the Cretaceous System. In: Powell, A.J. (Ed.), A Stratigraphic Index of Dinoflagellate Cysts. Chapman and Hall, London, pp. 99–131.
- Courtinat, B., 1993. The significance of palynofacies fluctuations in the Greenhorn Formation (Cenomanian–Turonian) of the Western Interior Basin, USA. *Marine Micropaleontology* 21, 249–257.
- Courtinat, B., Crumière, J.-P., Méon, H., Schaaf, A., 1991. Les associations de kystes de dinoflagellés du Cénomanién–Turonien de Vergons (Bassin Vocontien France). *Geobios* 24, 649–666.
- Crampton, J., Mumme, T., Raine, I., Roncaglia, L., Schiøler, P., Strong, P., Turner, G., Wilson, G., 2000. Revision of the Piripauan and Haururian local stages and correlation of the Santonian–Maastrichtian (Late Cretaceous) in New Zealand. *New Zealand Journal of Geology and Geophysics* 43, 309–333.
- Crampton, J., Raine, I., Strong, P., Wilson, G., 2001. Integrated biostratigraphy of the Raukumara Series (Cenomanian–Coniacian) at Mangaotane Stream, Raukumara Peninsula, New Zealand. *New Zealand Journal of Geology and Geophysics* 44, 365–389.
- Da Gama, R.O.B.P., Lutz, B., Desjardins, P., Thompson, M., Prince, I.M., Espejo, I., 2014. Integrated paleoenvironmental analysis of the Niobrara Formation: Cretaceous Western Interior Seaway, northern Colorado. *Palaeogeography, Palaeoclimatology, Palaeoecology* 413, 66–80.
- Dakyns, J.R., Fox-Strangeways, C., 1880. The geology of the country around Driffeld. HMSO, London.
- Dam, G., Nøhr-Hansen, H., Christiansen, F.G., Bojesen-Koefoed, J.A., Laier, T., 1998. The oldest marine Cretaceous sediments in West Greenland (Umiivik-1 Borehole) — record of the Cenomanian–Turonian Anoxic Event? *Geology of Greenland Survey Bulletin* 180, 128–131.
- Dam, G., Nøhr-Hansen, H., Pedersen, K.R., Sønderholm, M., 2000. Sedimentary and structural evidence of a new Early Campanian rift phase in the Nuussuaq Basin, West Greenland. *Cretaceous Research* 21, 127–154.
- Davey, R.J., 1969. Non-calcareous microplankton from the Cenomanian of England, northern France and North America. Part 1. *British Museum (Natural History) Geology, Bulletin* 17, 103–180.
- Davey, R.J., 1970. Non-calcareous microplankton from the Cenomanian of England, Northern France and North America. Part 2. *British Museum (Natural History) Geology Bulletin* 18, 333–397.
- Davey, R.J., 1978. Marine Cretaceous palynology of Site 361, DSDP Leg 40, off Southwestern Africa. In: Bolli, H.M., Ryan, W.B.F., et al. (Eds), Initial Reports of the Deep Sea Drilling Project, U.S. Government Printing Office, 40, Washington, pp. 883–913.

- Davey, R.J., 1979. Marine Apto–Albian palynomorphs from Holes 400A and 402A, IPOD, Leg 48, Northern Bay of Biscay. In: Montadert, L., Roberts, D.G., et al. (Eds), Initial Reports of the Deep Sea Drilling Project, U.S. Government Printing Office, 48, Washington, pp. 547–577.
- Davey, R.J., 1988. Palynological zonation of the Lower Cretaceous, Upper and Uppermost Middle Jurassic in the northwestern Papuan Basin of Papua, New Guinea. Geological Survey of Papua New Guinea Memoir 13, 1–77.
- Davey, R.J., Williams, G.L., 1966a. IV. The genera *Hystrichosphaera* and *Achomosphaera*. In: Davey, R.J., Downie, C., Sarjeant, W.A.S., Williams, G.L., Studies on Mesozoic and Cainozoic dinoflagellate cysts. Bulletin of the British Museum (Natural History), Geology Supplement 3, London, pp. 28–52.
- Davey, R.J., Williams, G.L., 1966b. V. The genus *Hystrichosphaeridium* and its allies. In: Davey, R.J., Downie, C., Sarjeant, W.A.S., Williams, G.L., Studies on Mesozoic and Cainozoic dinoflagellate cysts. Bulletin of the British Museum (Natural History), Geology Supplement 3, London, pp. 53–106.
- Davey, R.J., Verdier, J.P., 1973. An investigation of microfakton assemblages from latest Albian (Vraconian) sediments. Revista Española de Micropaleontología 5, 173–212.
- Davey, R.J., Verdier, J.P., 1976. A review of certain non-tabulate Hystrichosphaerid dinocysts. Review of Palaeobotany and Palynology 22, 307–335.
- Davey, R.J., Downie, C., Sarjeant, W.A.S., Williams, G.L., 1966. Fossil dinoflagellate cysts attributed to *Baltisphaeridium*. In: Davey, R.J., Downie, C., Sarjeant, W.A.S., Williams, G.L., Studies on Mesozoic and Cainozoic Dinoflagellate Cysts. Bulletin of the British Museum (Natural History), Geology Supplement 3, London, pp. 157–175.
- de Verteuil, L., Norris, G., 1996. Part I. Dinoflagellate cyst zonation and allostratigraphy of the Chesapeake Group. In: Miocene dinoflagellate stratigraphy and systematics of Maryland and Virginia, Micropaleontology, Supplement 42, 1–82.
- Deane, H., 1849. On the occurrence of fossil *Xanthidia* and *Polythalamia* in Chalk. Transactions of the Microscopy Society, London 2, 77–79.
- Decommer, H., 1982. Palynological and sedimentological study of Jurassic and Cretaceous sediments from five boreholes from northern France. Annales de la Société Géologique du Nord 101, 161–176.
- Deflandre, G., 1936a. Les flagelles fossiles. Aperçu biologique et paleontologiques. Role geologique. Actualités scientifiques et industrielles 335, 1–97.
- Deflandre, G., 1936b. Microfossiles des silex Crétacés. Premier partie. Generalites. Flagelles. Annales de Paléontologie 25, 151–191.
- Deflandre, G., 1937. Microfossiles des silex Crétacés. Deuxième partie. Flagellés incertae sedis Hystrichosphaeridés. Sarcodinés. Organismes divers. Annales de Paléontologie 26, 51–103.
- Deflandre, G., Courteville, H., 1939. Note préliminaire sur les microfossiles des silex Crétacés du Cambréssis. Bulletin de la Société Française de Microscopie 8, 95–106.

- Deflandre, G., Cookson, I.C., 1955. Fossil microplankton from Australian Late Mesozoic and Tertiary sediments. *Australian Journal of Marine and Freshwater Research* 6, 242–313.
- Dettmann, M.E., Thomson, M.R.A., 1987. Cretaceous palynomorphs from the James Ross Island area, Antarctica. *Bulletin of the British Antarctic Survey* 77, 13–59.
- Deville de Periere, M., Pellenard, P., Thibault, N., 2019. The Santonian – Campanian Boundary Event (SCBE) In Boreal basins: New geochemical and mineralogical data from the Northern Chalk Province (East Yorkshire, UK). *Cretaceous Research* 95, 61–76.
- Diederix, D.O.J., de Haan, R., Tichler, W.O., 1972. Site 138. In: Hayes, D.E., Pimm, A.C., et al. (Eds), *Initial Reports of the Deep Sea Drilling Project*, U.S. Government Printing Office 14, Washington, p. 138.
- Ditchfield, P., Marshall, J.D., 1989. Isotopic variation in rhythmically bedded chalks: Paleotemperature variation in the Upper Cretaceous. *Geology* 17, 842–845.
- Dodsworth, P., 1996. Stratigraphy, microfossils and depositional environments of the lowermost part of the Welton Chalk Formation (Late Cenomanian to early Turonian, Cretaceous) in eastern England. *Proceedings of the Yorkshire Geological Society* 51, 45–64.
- Dodsworth, P., 2000. Trans-Atlantic dinoflagellate cyst stratigraphy across the Cenomanian – Turonian (Cretaceous) Stage boundary. *Journal of Micropalaeontology* 19, 69–84.
- Dodsworth, P., 2004a. The distribution of dinoflagellate cysts across a Late Cenomanian carbon isotope ($\delta^{13}\text{C}$) anomaly in the Pulawy borehole, central Poland. *Journal of Micropalaeontology* 23, 77–80.
- Dodsworth, P., 2004b. Palynology of the Cenomanian–Turonian (Cretaceous) boundary section at Aksudere, Crimea. *Palynology* 28, 129–141.
- Dodsworth, P., 2016. Palynostratigraphy and palaeoenvironments of the Eagle Ford Group (Upper Cretaceous) at the Lozier Canyon outcrop reference section, west Texas, USA. *Palynology* 40, 357–378.
- Dodsworth, P., Eldrett, J.S., 2019. A dinoflagellate cyst zonation of the Cenomanian and Turonian (Upper Cretaceous) in the Western Interior, United States. *Palynology* 43, 701–723.
- Dolding, P.J.D., 1992. Palynology of the Marambio Group (Upper Cretaceous) of northern Humps Island. *Antarctic Science* 4, 311–326.
- Duane, A.M., 1996. Palynology of Byers Group (Late Jurassic–Early Cretaceous) of Livingston and Snow Islands, Antarctic Peninsula: its biostratigraphical and palaeoenvironmental significance. *Review of Palaeobotany and Palynology* 91, 241–281.
- Dueñas-Jimenez, H., 1990. Dinoflagellates, a new tool for the biostratigraphic control of sediments from the Middle and Upper Cretaceous. *Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales* 17, 433–440.

- Duxbury, S., 2001. A palynological zonation scheme for the Lower Cretaceous: United Kingdom Sector, Central North Sea. *Neues Jahrbuch für Geologie und Paläontologie. Abhandlungen* 219, 95–137.
- Eisenack, A., Cookson, I.C., 1960. Microplankton from Australian Lower Cretaceous sediments. *Proceedings of the Royal Society of Victoria* 72, 1–11.
- El-Beialy, S.Y., 1993. Mid-Cretaceous palynomorphs from the Bardawil-1 borehole, North Sinai, Egypt. *Cretaceous Research* 14, 49–58.
- El-Beialy, S.Y., 1995. Campanian–Maestrichtian palynomorphs from the Duwi (Phosphate) Formation of the Hamrawein and Umm El-Hueitat Mines, Red Sea Coast, Egypt. *Review of Palaeobotany and Palynology* 85, 303–317.
- Eldrett, J.S., Ma, C., Bergman, S.C., Lutz, B., Gregory, F.J., Dodsworth, P., Phipps, M., Hardas, P., Minisini, D., Ozkan, A., Ramezani, J., Bowring, S.A., Kamo, S.L., Ferguson, K., Macaulay, C., Kelly, A.E., 2015. An astronomically calibrated stratigraphy of the Cenomanian, Turonian and earliest Coniacian from the Cretaceous Western Interior Seaway, USA: Implications for global chronostratigraphy. *Cretaceous Research* 56, 316–344.
- Ernst, G., 1963. Stratigraphische und gesteinschemische untersuchungen im Santon und Campan von Lägerdorf (SW-Holstein). *Mitteilungen aus dem Geologischen Staatsinstitut im Hamburg* 32, 72–127.
- Ernst, G., Schmid, F., Siebertz, E., 1983. Event stratigraphie im Cenoman und Turon von NW Deutschland. *Zitteliana* 10, 531–554.
- Eshet, Y., Moshkovitz, S., Habib, D., Benjamini, C., Magaritz, M., 1992. Calcareous nannofossil and dinoflagellate stratigraphy across the Cretaceous/Tertiary boundary at Hor Hahar, Israel. *Marine Micropaleontology* 18, 199–228.
- Eshet, Y., Hoek, R., Almogi-Labin, A., 1994. A new dinocyst-based biostratigraphic framework for Campanian–Maastrichtian organic rich-carbonate sequences in Israel. *Geological Survey of Israel, Report* 94, 1–24.
- Fauconnier, D., 1979. Les dinoflagelles de l'Albien et du Cenomanien inferieur du Bassin de Paris. *Documents du Bureau des Recherches Géologiques et Minières* 5, 1–146.
- Fauconnier, D., 1984. Marine Cretaceous palynology of Holes 549 and 550, Deep Sea Drilling Project Leg, 80, Northern Bay of Biscay. In: Graciansky, P.C. de, Poag, C.W., et al. (Eds), *Initial Reports of the Deep Sea Drilling Project*, U.S. Government Printing Office 80, Washington, pp. 653–662.
- Fauconnier, D., Masure, E., 2004. Les dinoflagellés fossile. Guide pratique de détermination. Les genres à processus et à archéopyle apical. 602 pp., BRGM Editions.
- Faÿ-Gomord, O., Allanic, C., Verbiest, M., Honlet, R., Champenois, F., Bonifacie, M., Chaduteau, C., Wouters, S., Muchez, P., Lasseur, E., Swennen, R., 2018. Understanding fluid flow during tectonic reactivation: an example from the Flamborough Head Chalk outcrop (UK). *Geofluids* 2018, doi.org/10.1155/2018/9352143.
- Felix, C.J., Burbridge, P.P., 1976. Age of microplankton studied by Manum and Cookson from Graham and Ellef Ringes Islands. *Geoscience and Man* 15, 83–86.

- Fensome, R.A., Norris, G., 1982. Palynostratigraphic comparison of Cretaceous of the Moose River Basin, Ontario, with marginal marine assemblages from the Scotian Shelf and Alberta. Ontario Geological Survey, Miscellaneous Paper 103, 37–42.
- Fensome, R.A., Taylor, F.J.R., Norris, G., Sarjeant, W.A.S., Wharton, D.I., Williams, G.L., 1993. A classification of living and fossil dinoflagellates. *Micropaleontology*, Special Publication Number 7, 1–351.
- Fensome, R.A., Crux, J.A., Gard, I.G., MacRae, R.A., Williams, G.L., Thomas, F.C., Fiorini, F., Wach, G., 2008. The last 100 million years on the Scotian Margin, offshore eastern Canada: an event-stratigraphic scheme emphasizing biostratigraphic data. *Atlantic Geology* 44, 93–126.
- Fensome, R.A., Williams, G.L., MacRae, R.A., 2009. Late Cretaceous and Cenozoic fossil dinoflagellates and other palynomorphs from the Scotian Margin, offshore eastern Canada. *Journal of Systematic Palaeontology* 7, 1–79.
- Fensome, R.A., Williams, G.L., Wood, S.E.L., Riding, J.B., 2019. A review of the areoligeracean dinoflagellate cyst *Cyclonephelium* and morphologically similar genera. *Palynology* 43, supplement 1, 1–71.
- Fiet, N., Masure, E., 2001. Albian dinoflagellates from the Umbria-Marche Basin (Italy); Proposed biozonation for the Tethys Domain. *Cretaceous Research* 22, 63–77.
- FitzPatrick, M.E.J., 1995. Dinoflagellate cyst biostratigraphy of the Turonian (Upper Cretaceous) of Southern England. *Cretaceous Research* 16, 757–791.
- Fletcher, T.P., 1977. Lithostratigraphy of the Chalk (Ulster White Limestone Formation) in Northern Ireland. HMSO, London.
- Foad, M.T., Lashin, G.M.A., 2012. Aptian–Turonian Palynomorphs From El-Waha-1 Well, Southwestern Part of the Western Desert, Egypt. *Journal of Applied Sciences Research* 8, 1870–1877.
- Foucher, J.-C., 1971a. Etude micropaléontologique des silex coniaciens du puits 19 de Lens-Lievin (Pas-de-Calais). *Bulletin du Museum National d'Histoire Naturelle, Sciences de la Terre* 5, 77–129.
- Foucher, J.-C., 1971b. Microfossiles des Silex Coniaciens de la falaise du Boise-de-Cise (Somme). *Cahiers de Micropaléontologie* 8, 1–13.
- Foucher, J.-C., 1974. Microfossiles des silex du Turonien Supérieur de Ruyalcourt (Pas-de-Calais). *Annales de Paléontologie* 60, 111–164.
- Foucher, J.-C., 1975a. Dinoflagellés et acritarches des silex Crétacés du bassin de Paris: une synthèse stratigraphique. *Annales Scientifiques de l'Université de Reims et de l'A.R.E.R.S. (Association régionale pour l'étude et la recherche scientifiques)* 13, 8–10.
- Foucher, J.-C., 1975b. Kystes de Dinoflagellés des Bassins de Mons et de Paris. In: Robaszyński, F. (Ed.), *Les faciès du Senonien (Maestrichtien–Mons–Lille). Livret-guide des excursions dans le Crétacé du Limbourg, de la région de Mons et du Nord de la France*. Groupe Français du Crétacé 13–16 Mai 1975, p. 21.
- Foucher, J.-C., 1976a. Les Dinoflagellés des Silex et la Stratigraphie du Crétacé Supérieur Français. *Revue de Micropaléontologie* 18, 213–220.

- Foucher, J.-C., 1976b. Microplancton des silex Crétacés du Beauvaisis. Cahiers de Micropaléontologie, Nouvelle série 2, 3–28.
- Foucher, J.-C., 1979. Distribution stratigraphique des kystes de Dinoflagellés et des acritarches dans le Crétacé Supérieur du Bassin de Paris et de l'Europe septentrionale. Paläontographica Abteilung B 169, 78–105.
- Foucher, J.-C., 1980. Dinoflagellés et Acritarches. In: Robaszynski, F., Amédéo, F., Foucher, J.-C., Gaspard, D., Magniez-Jannin, F., Manivit, H., Sornay, J. (Eds), Synthèse biostratigraphique de l'Aptien au Santonien du Boulonnais à partir de sept groupes paléontologiques (foraminifères, nannoplancton, dinoflagellés et microfaunes. Revue de Micropaléontologie 22, 288–297.
- Foucher, J.-C., 1981. Kystes de Dinoflagellés du Crétacé Moyen Européen: Proposition d'une échelle biostratigraphique pour le domaine nord-occidental. Cretaceous Research 2, 331–338.
- Foucher, J.-C., 1982. Dinoflagellés. Mémoires du Muséum National d'Histoire Naturelle. Nouvelle Série, Série C, Sciences de la Terre 49, 278–288.
- Foucher, J.-C., 1983. Distribution des Kystes de Dinoflagellés dans le Crétacé moyen et Supérieur du Bassin de Paris. Cahiers de Micropaléontologie, Nouvelle série 4, 23–41.
- Foucher, J.-C., Robaszynski, F., 1977. Microplancton des silex du Bassin de Mons (Belgique) (Dinoflagellés Crétacés et Paléogènes). Annales de Paléontologie 63, 19–58.
- Foucher, J.-C., Pons, D., Mami, L., Bellier, J.-P., 1994. Premier Inventaire de la microflore Crétacé (Dinokystes, Spores et pollen) du Sud-Est Constantinois (Algeria): Conséquences biostratigraphiques. Comptes Rendus de l'Académie des Sciences, Série II 318, 1563–1570.
- Fraser, T.H., Bon, J., Samuel, L., 1993. A new dynamic stratigraphy for the West Irian micro-continent, Indonesia, and its implications. Proceedings of the 22nd Annual Convention of the Indonesian Petroleum Association, pp. 707–761.
- Gale, A.S., 1989. Field meeting at Folkestone Warren, 29th November, 1987. Proceedings of the Geologists' Association 100, 73–82.
- Gale, A.S., 1995. Cyclostratigraphy and correlation of the Cenomanian stage in Western Europe. In: House, M.R., Gale, A.S. (Eds), Orbital Forcing Timescales and Cyclostratigraphy. Geological Society of London Special Publication 85, 177–197.
- Gale, A.S., 1996. Turonian correlation and sequence stratigraphy of the Chalk in southern England. In: Hesselbo, S.P., Parkinson, D.N. (Eds), Sequence Stratigraphy in British Geology. Geological Society of London Special Publication 103, 177–195.
- Gale, A.S., Smith, A.B., 1982. The palaeobiology of the irregular echinoids *Infulaster* and *Hagenowia*. Palaeontology 25, 11–42.
- Gale, A.S., Friedrich, S., 1989. Appendix. Occurrence of the ammonite genus *Sharpeiceras* in the Lower Cenomanian Chalk Marl of Folkestone. Field Meeting at Folkestone Warren, 29th November, 1987. Proceedings of the Geologists' Association 100, 80–82.

- Gale, A.S., Jenkyns, H.C., Kennedy, W.J., Corfield, R.M., 1993. Chemostratigraphy versus biostratigraphy: data from around the Cenomanian – Turonian boundary. *Journal of the Geological Society London* 150, 29–32.
- Gale, A.S., Montgomery, P., Kennedy, W.J., Hancock, J.M., Burnett, J.A., McArthur, J.M., 1995. Definition and global correlation of the Santonian–Campanian boundary. *Terra Nova* 7, 611–622.
- Gale, A.S., Hancock, J.M., Bristow, R., Mortimore, R.N., Wood, C.J., 1999. 'Lithostratigraphy for mapping the Chalk of southern England' by Bristow et al. (1997): Discussion. *Proceedings of the Geologists' Association* 110, 65–72.
- Gale, A.S., Kennedy, W.J., Voigt, S., Walaszczyk, I., 2005. Stratigraphy of the Upper Cenomanian–Lower Turonian Chalk succession at Eastbourne, Sussex, UK: ammonites, inoceramid bivalves and stable carbon isotopes. *Cretaceous Research* 26, 460–487.
- Gale, A.S., Kennedy, W.J., Lees, J.A., Petrizzo, M.R., Walaszczyk, I., 2007. An integrated study (inoceramid bivalves, ammonites, calcareous nannofossils, planktonic foraminifera, stable carbon isotopes) of the Ten Mile Creek section, Lancaster, Dallas County, north Texas, a candidate Global boundary Stratotype Section and Point for the base of the Santonian Stage. *Acta Geologica Polonica* 57, 113–160.
- Gale, A.S., Hancock, J.M., Kennedy, W.J., Petrizzo, M.R., Lees, J.A., Walaszczyk, I., Wray, D.S., 2008. An integrated study (geochemistry, stable oxygen and carbon isotopes, nannofossils, planktonic foraminifera, inoceramid bivalves, ammonites and crinoids) of the Waxahachie Dam Spillway section, north Texas: a possible boundary stratotype for the base of the Campanian Stage. *Cretaceous Research* 29, 131–167.
- Gallois, R.W., 1988. *Geology of the Country around Ely*. HMSO, London.
- Gallois, R.W., 1994. *Geology of the Country around King's Lynn and The Wash*. HMSO, London.
- Gallois, R.W., 2016. The stratigraphy of the Middle Chalk (Upper Cretaceous) succession at Mundford, Norfolk, UK. *Proceedings of the Geologists' Association* 127, 451–463.
- Gallois, R.W., Morter, A., 1976. Trunch Borehole, Mundesley (132) Sheet. In: *IGS Boreholes 1975*. London: Institute of Geological Sciences, pp. 8–10.
- Gambacorta, G., Malinverno, A., Erba, E., 2019. Orbital forcing of carbonate versus siliceous productivity in the late Albian–late Cenomanian (Umbria-Marche Basin, central Italy). *Newsletters on Stratigraphy* 52, 197–220.
- Garg, R., Khowaja-Ateequzzaman, Jain, K.P., 1988. Jurassic and Lower Cretaceous dinoflagellate cysts from India with some remarks on the concepts of Upper Gondwana. In: Venkatachala, B.S., Maheshwari, H.K. (Eds), *Concepts, limits and extension of the Indian Gondwana*. *The Palaeobotanist* 36, 254–267.
- Gaunt, G.D., Fletcher, T.P., Wood, C.J., 1992. *Geology of the Country around Kingston upon Hull and Brigg*. HMSO, London.
- Gedl, P., 2007. Dinocysts from Upper Cretaceous deep-water marine variegated facies (Malinowa Shale Formation), Pieniny Klippen Belt, Poland: example from the Potok Trawne creek. *Studia Geologica Polonica* 127, 139–152.

- Gee, J.S., Kent, D.V., 2007. Source of oceanic magnetic anomalies and the geomagnetic polarity timescale. In: Schubert, G. (Ed.), *Treatise on Geophysics*, 5. Geomagnetism. Elsevier, Amsterdam, pp. 455–507.
- Gitmez, G.U., Ertug, K., 1999. Dinoflagellate cysts and acritarchs from the Jurassic–Cretaceous boundary, Northwest Anatolia, Turkey. *Micropaleontology* 45, 69–98.
- Gocht, H., 1959. Microplankton from the northwest Germany Neocomian (Part II). *Paläontologische Zeitschrift* 33, 50–89.
- Gradstein, F.M., Williams, G.L., 1976. Biostratigraphy of the Labrador Shelf. Part 1. Geological Survey of Canada, Open File Report 349, 1–32.
- Gradstein, F.M., Ogg, J., Smith, A.G., 2004. *A geologic time scale 2004*. Cambridge University Press, Cambridge, 589 pp.
- Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M., 2012. *The Geologic Time Scale 2012*. Elsevier, Amsterdam, 1144 pp.
- Grant, S.F., Coe, A.L., Armstrong, H.A., 1999. Sequence stratigraphy of the Coniacian succession of the Anglo – Paris Basin. *Geological Magazine* 136, 17–38.
- Green, J.P., 2019. The macrofauna of the Vale House Flints Member (Burnham Chalk Formation, Upper Turonian, Late Cretaceous) of Lincolnshire and a palaeoenvironmental reconstruction. *Proceedings of the Yorkshire Geological Society* 62, 195–200.
- Habib, D., 1977. Comparison of Lower and Middle Cretaceous palynostratigraphic zonations in the Western North Atlantic. In: Swain, F.M. (Ed.), *Stratigraphic Micropaleontology of Atlantic Basin and Borderlands*. Elsevier Scientific Publication, Amsterdam, pp. 341–367.
- Habib, D., Drugg, W.S., 1987. Palynology of Sites 603 and 605. In: van Hinte, J.E., Wise, S.W. Jr, et al. (Eds), *Initial Reports of the Deep Sea Drilling Project*, U.S. Government Printing Office 93, Washington, pp. 751–775.
- Habib, D., Miller, J.A., 1989. Dinoflagellate species and organic facies evidence of marine transgression and regression in the Atlantic Coastal Plain. *Palaeogeography, Palaeoclimatology, Palaeoecology* 74, 23–47.
- Haga, H., 1990. Palynology report of outcrop samples from North Slope, Alaska. Alaska Division of Geological and Geophysical Surveys. Public-data File 90, 1–20.
- Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. PAST: Paleontological Statistics software package for education and data analysis. *Palaeontologica Electronica* 4, 9.
- Hampton, M.J., Bailey, H.W., Gallagher, L.T., Mortimore, R.N., Wood, C.J., 2007. The biostratigraphy of Seaford Head, Sussex, southern England; an international reference section for the basal boundaries for the Santonian and Campanian Stages in chalk facies. *Cretaceous Research* 28, 46–60.
- Hancock, J.M., 1975. The petrology of the Chalk. *Proceedings of the Geologists' Association* 86, 499–535.
- Hancock, J.M., Gale, A.S., 1996. The Campanian Stage. In: *Proceedings "Second International Symposium on Cretaceous Stage Boundaries"* Brussels 8 – 16 September 1995. l'Institut Royal des Sciences Naturelles de Belgique, pp. 103–109.

- Hansen, J.M., 1977. Dinoflagellate stratigraphy and echinoid distribution in Upper Maastrichtian and Danian deposits from Denmark. Geological Society of Denmark, Bulletin (Meddelelser Fra Dansk Geologisk Forening) 26, 1–26.
- Hansen, J.M., 1979a. Dinoflagellate zonation around the boundary. In: Christensen, W.K., Birkelund, T. (Eds), The Maastrichtian and Danian of Denmark. Cretaceous – Tertiary Boundary Events Symposium 18 – 24 September 1979. University of Copenhagen, pp. 136–141.
- Hansen, J.M., 1979b. A new dinoflagellate zone at the Maastrichtian/Danian Boundary in Denmark. Danmarks Geologiske Undersøgelse 1978, 131–140.
- Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. Science 235, 1156–1167.
- Harker, S.D., Sarjeant, W.A.S., 1975. The stratigraphic distribution of organic-walled dinoflagellate cysts in the Cretaceous and Tertiary. Review of Palaeobotany and Palynology 20, 217–315.
- Harker, S.D., Sarjeant, W.A.S., Caldwell, W.G.E., 1990. Late Cretaceous (Campanian) organic-walled microplankton from the interior plains of Canada, Wyoming and Texas; biostratigraphy, palaeontology and palaeoenvironmental interpretation. Paläeontographica Abteilung B 219, 1–243.
- Harris, P.T., O'Brien, P.E., Quilty, P., McMin, A., Moldway, D., Exon, N.F., Hill, P.J., Wilson, C.W., 1999. Sedimentation and Continental Slope processes in the vicinity of an ocean waste-disposal site, southern Tasmania. Australian Journal of Earth Sciences 46, 577–591.
- Hart, M.B., 2019. The 'Black Band': local expression of a global event. Proceedings of the Yorkshire Geological Society 62, 217–226.
- Hart, M.B., Dodsworth, P., Ditchfield, F.W., Duane, A.M., Orth, C.J., 1991. The Late Cenomanian event in eastern England. Historical Biology 5, 339–354.
- Hasegawa, T., Crampton, J., Schindler, P., Field, B., Fukushima, K., Kakizaki, Y., 2013. Carbon isotope stratigraphy and depositional oxia through Cenomanian/Turonian boundary sequences (Upper Cretaceous) in New Zealand. Cretaceous Research 40, 61–80.
- Heine, C.J., 1991. Late Santonian to Early Maastrichtian dinoflagellate cysts of northeast Texas. In: Thompson, L.B., Heine, C.J., Percival, S.F., Selznick, M.R., (Eds), Stratigraphy and micropalaeontology of the Campanian shelf in northeast Texas. Micropalaeontology, Special Publication 5, New York, pp. 117–147.
- Helby, R.J., Morgan, R., Partridge, A.D., 1987. A palynological zonation of the Australian Mesozoic. In: Jell, P.A., (Ed.), Studies in Australian Mesozoic Palynology. Memoir of the Association of Australasian Palaeontologists, Memoir 4, 1–94.
- Helby, R.J., Wilson, G.J., Grant-Mackie, J.A., 1988. A preliminary biostratigraphic study of Middle to Late Jurassic dinoflagellate assemblages from Kawhia, New Zealand. In: Jell, P.A., Playford, G. (Eds), Palynological and Palaeobotanical Studies in Honour of Basil E. Balme. Association of Australasian Palaeontologists, Memoir 5, pp. 125–166.

- Helden, B.G.T.V., 1977. Correlation of microplankton assemblages with ammonite faunas from the Jurassic Wilkie Point Formation, Prince Patrick Island, District of Franklin. Geological Survey of Canada, Paper 77, 163–171.
- Helenes, J., 1984. Morphological analysis of Mesozoic-Cenozoic *Cribroperidinium* (Dinophyceae), and taxonomic implications. *Palynology* 8, 107–137.
- Helenes, J., De Guerra, C., Vasquez, J., 1998. Palynology and chronostratigraphy of the Upper Cretaceous in the subsurface of the Barinas Area, Western Venezuela. *AAPG, Bulletin* 82, 1308–1328.
- Herbin, J.P., Masure, E., Roucache, J., 1987. Cretaceous formations from the lower continental rise off Cape Hatteras: Organic geochemistry, dinoflagellate cysts and the Cenomanian–Turonian boundary event at Sites 603, (Leg 93), and 105, (Leg 11). In: Hinte, J.E. van, Wise, S.W. Jr, et al. (Eds), Initial Reports of the Deep Sea Drilling Project, U.S. Government Printing Office 93, Washington, pp. 1139–1162.
- Herngreen, G.F.W., 1978. A preliminary dinoflagellate zonation of Aptian–Cenomanian in the Netherlands. *Palinologíá, Número extraordinario* 1, 273–281.
- Herngreen, G.F.W., Randrianasolo, A., Verbeek, J.W., 1982. Micropaleontology of Albian to Danian strata in Madagascar. *Micropaleontology* 28, 97–109.
- Herngreen, G.F.W., Eillebrecht, A.T.J.M., Gortemaker, J.E., Remmelts, G., Schuurman, H.A.H.M., Verbeek, J.W., 1996. Upper Cretaceous Chalk Group stratigraphy near the Isle of Texel, The Netherlands (a multidisciplinary approach). *Mededelingen Rijks Geologische Dienst, Nieuwe Serie* 50, 1–63.
- Hewitt, H.D., 1924. Notes on some Chalk sections in the district around Thetford, Norfolk *Proceedings of the Geologists' Association* 35, 220–244.
- Hewitt, H.D., 1935. Further notes on the Chalk of the Thetford District, Norfolk *Proceedings of the Geologists' Association* 46, 18–37.
- Hildreth, P.N., 2013. The Vale House Flints Member, a flint-rich unit of the Burnham Chalk Formation of the Northern Province, East Yorkshire and Lincolnshire, UK. *Proceedings of the Yorkshire Geological Society* 59, 177–186.
- Hildreth, P.N., 2019. The distribution and form of flint, with particular reference to the Chalk Group (Upper Cretaceous) of the Northern Province, UK. *Proceedings of the Yorkshire Geological Society* 62, 178–186.
- Hill, W., 1888. On the lower beds of the Upper Cretaceous Series in Lincolnshire and Yorkshire. *Quarterly Journal of the Geological Society of London* 44, 320–364.
- Hill, W., Jukes-Browne, A.J., 1886. The Melbourn Rock and zone of *Belemnitella plana* from Cambridge to the Chiltern Hills. *Quarterly Journal of the Geological Society of London* 42, 216–231.
- Hochuli, P., Kelts, K., 1979. Palynology of Middle Cretaceous black clay facies from Deep Sea Drilling Project sites 417 and 418 of the western North Atlantic. In: Donnelly, T., Francheteau, J., Bryan, W., Robinson, P., Flower, M., Salisbury, M., et al. (Eds), Initial Reports of the Deep Sea Drilling Project, U.S. Government Printing Office, 51–53, Washington pp. 897–935.
- Hoek, R.P., Eshet, Y., Almogi-Labin, A., 1996. Dinoflagellate cyst zonation of Campanian – Maestrichtian sequences in Israel. *Micropaleontology* 42, 125–150.

- Hollister, C.D., Ewing, J.I., Habib, D., Hathaway, J.C., Lancelot, Y., Luterbacher, H., Paulus, F.J., Poag, C.W., Wilcoxon, J.A., Worstell, P., 1972. Site 101: Blake–Bahama Outer Ridge (Southern End). Initial reports of the Deep Sea Drilling Project, 14, Washington, pp. 105–110.
- Hopson, P.M., 1992. Geology of the Letchworth, north-west Hitchin and Holwell district, Hertfordshire Keyworth. British Geological Survey. Technical Report WA/92/42.
- Hopson, P.M., 2005. A stratigraphical framework for the Upper Cretaceous Chalk of England and Scotland with statements on the Chalk of Northern Ireland and the UK Offshore Sector. BG Survey. Research Report RR/05/01, 90 pp.
- Howarth, R.J., McArthur, J.M., 1997. Statistics for strontium isotope stratigraphy: A robust LOWESS fit to the marine Sr-isotope curve for 0 to 206 Ma, with look-up table for derivation of numeric age. *Journal of Geology* 105, 441–456.
- Hultberg, S.U., 1985. Dinoflagellate studies of the Upper Maastrichtian and Danian in southern Scandinavia. PhD thesis, University of Stockholm, Stockholm, 189 pp.
- Husson, D., Galbrun, B., Laskar, J., Hinnov, L.A., Thibault, N., Gardin, S., Locklair, R.E., 2011. Astronomical calibration of the Maastrichtian (Late Cretaceous). *Earth and Planetary Science Letters* 305, 328–340.
- Ilyina, V.I., Kulkova, I.A., Lebedeva, N.K., 1994. Microphytofossils and detail stratigraphy of marine Mesozoic and Cenozoic of Siberia. *Obedinennyi Institut Geologii Geoliziki i Mineralogii, (Novosibirsk)* 81, 1–192.
- Ioannides, N.S., 1986. Dinoflagellate cysts from Upper Cretaceous–Lower Tertiary sections, Bylot and Devon Islands, Arctic Archipelago. *Geological Survey of Canada, Bulletin* 371, 1–99.
- Islam, M.A., 1993. Review of the fossil dinoflagellate *Cleistosphaeridium*. *Revista Española de Micropaleontología* 25, 81–94.
- Jain, K.P., 1977. Additional dinoflagellates and acritarchs from Grey Shale Member of Dalmiapuram Formation, South India. *The Palaeobotanist* 24, 170–194.
- Jain, K.P., Taugourdeau-Lantz, J., 1973. Palynology of Dalmiapuram grey shale, Dalmiapuram Formation, District Trichinopoly, south India: Taxonomy. *Geophytology* 3, 52–68.
- Jain, K.P., Millepied, P., 1975. Cretaceous microplankton from Senegal Basin, West Africa. Part 2. Systematics and biostratigraphy. *Geophytology* 5, 126–171.
- Japsen, P., 1997. Regional Neogene exhumation of Britain and the western North Sea. *Journal of the Geological Society of London* 154, 239–247.
- Jaramillo, C., Amezquita, O.Y., 1994. Palinoestratigrafía del Grupo Olini (Coniaciano–Campaniano), Valle Superior del Magdalena, Colombia. *Estudios Geológicos del Valle Superior del Magdalena* 17, 1–18.
- Jarvis, I., 2003. Sample preparation for ICP-MS. In: Jarvis, K.E., Gray, A.L., Houk, R.S. (Eds), *Handbook of Inductively Coupled Plasma Mass Spectrometry*. Viridian, Woking 172–224.
- Jarvis, I., Woodroff, P.B., 1984. Stratigraphy of the Cenomanian and basal Turonian (Upper Cretaceous) between Branscombe and Seaton, SE Devon, England. *Proceedings of the Geologists' Association* 95, 193–215.

- Jarvis, I., Leary, P.N., Tocher, B.A., 1987. Mid-Cretaceous (Albian – Turonian) stratigraphy of Shapwick Grange Quarry, S.E. Devon, England. *Mesozoic Research* 1, 119–134.
- Jarvis, I., Carson, G.A., Cooper, M.K.E., Hart, M.B., Leary, P.N., Tocher, B.A., Horne, D., Rosenfeld, A., 1988a. Microfossil assemblages and the Cenomanian – Turonian (late Cretaceous) oceanic anoxic event. *Cretaceous Research* 9, 3–103.
- Jarvis, I., Carson, G.A., Hart, M.B., Leary, P.N., Tocher, B.A., 1988b. The Cenomanian – Turonian (late Cretaceous) anoxic event in SW England: evidence from Hooken Cliffs near Beer, SE Devon. *Newsletters on Stratigraphy* 18, 147–164.
- Jarvis, I., Murphy, A.M., Gale, A.S., 2001. Geochemistry of pelagic and hemipelagic carbonates: criteria for identifying systems tracts and sea-level change. *Journal of the Geological Society London* 158, 685–696.
- Jarvis, I., Mabrouk, A., Moody, R.T.J., De Cabrera, S.C., 2002. Late Cretaceous (Campanian) carbon isotope events, sea-level change and correlation of the Tethyan and Boreal realms. *Palaeogeography, Palaeoclimatology, Palaeoecology* 188, 215–248.
- Jarvis, I., Gale, A.S., Jenkyns, H.C., Pearce, M.A., 2006. Secular variation in Late Cretaceous carbon isotopes and sea-level change: evidence from a new $\delta^{13}\text{C}$ carbonate reference curve for the Cenomanian – Campanian (99.6 – 70.6 Ma). *Geological Magazine* 143, 561–608.
- Jarvis, I., Lignum, J.S., Gröcke, D.R., Jenkyns, H.C., Pearce, M.A., 2011. Black shale deposition, atmospheric CO_2 drawdown, and cooling during the Cenomanian – Turonian Oceanic Anoxic Event. *Paleoceanography* 26, 17 pp.
- Jarvis, I., Trabucho-Alexandre, J., Gröcke, D.R., Uličný, D., Laurin, J., 2015. Intercontinental correlation of organic carbon and carbonate stable isotope records: evidence of climate and sea-level change during the Turonian (Cretaceous). *The Depositional Record* 1, 53–90.
- Jeans, C.V., 1973. The Market Weighton Structure: tectonics, sedimentation and diagenesis during the Cretaceous. *Proceedings of the Yorkshire Geological Society* 39, 409–444.
- Jeans, C.V., 1980. Early submarine lithification in the Red Chalk and Lower Chalk of east England: a bacterial control model and its implications. *Proceedings of the Yorkshire Geological Society* 43, 81–157.
- Jeans, C.V., Long, D., Hall, M.A., Bland, D.J., Cornford, C., 1991. The geochemistry of the Plenus Marls at Dover, England: evidence of fluctuating oceanographic conditions and of glacial control during the development of the Cenomanian – Turonian $\delta^{13}\text{C}$ anomaly. *Geological Magazine* 128, 603–632.
- Jefferies, R.P.S., 1963. The stratigraphy of the *Actinocamax plenus* subzone (Turonian) in the Anglo-Paris Basin. *Proceedings of the Geologists' Association* 74, 1–34.
- Jenkyns, H.C., Gale, A.S., Corfield, R.M., 1994. Carbon- and oxygen-isotope stratigraphy of the English Chalk and Italian Scaglia and its palaeoclimatic significance. *Geological Magazine* 131, 1–34.
- Jiabo, 1978. On the Paleogene dinoflagellates and acritarchs from the Coastal Region of Bohai. Nanjing Institute of Geology and Palaeontology, Academia Sinica, Nanjing, China, 190 pp.

- Johnson, H., Lott, G.K., 1993. Cretaceous of the central and northern North Sea. Lithostratigraphic nomenclature of the UK North Sea. British Geological Survey, Keyworth pp. 94–115.
- Jones, M.M., Sageman, B., Meyers, S.R., 2018. Turonian sea level and paleoclimatic events in astronomically tuned records from the tropical North Atlantic and Western Interior Seaway. *Paleoceanography and Paleoclimatology* 33, 470–492.
- Joo, Y.J., Sageman, B.B., 2014. Cenomanian to Campanian carbon isotope chemostratigraphy from the Western Interior Basin, U.S.A. *Journal of Sedimentary Research* 84, 529–542.
- Jukes-Browne, A.J., 1880. The subdivisions of the Chalk. *Geological Magazine* 7, 248–257.
- Jukes-Browne, A.J., Hill, W., 1903. The Cretaceous rocks of Britain. Vol. II — The Lower and Middle Chalk of England London: His Majesty's Stationery Office.
- Jukes-Browne, A.J., Hill, W., 1904. The Cretaceous rocks of Britain. Vol. III — The Upper Chalk of England London: His Majesty's Stationery Office.
- Kaplan, U., Kennedy, W.J., 1996. Upper Turonian and Coniacian ammonite stratigraphy of Westphalia, NW Germany. *Acta Geologica Polonica* 46, 305–352.
- Kapoor, P.N., Prasad, B., Swamy, S.N., Shukla, M., 1999. Palynostratigraphy and hydrocarbon source potential of Cretaceous sediments in Krishna Sub-Basin, India. *Geoscience Journal* 20, 11–24.
- Kauffman, E.G., Kennedy, W.J., Wood, C.L., 1996. The Coniacian stage and substage boundaries. In: Proceedings "Second International Symposium on Cretaceous Stage Boundaries" Brussels 8 – 16 September 1995. l'Institut Royal des Sciences Naturelles de Belgique, pp. 81–94.
- Keating, J.M., 1992. Palynology of the Lachman Crags Member, Santa Marta Formation (Upper Cretaceous) of north-west James Ross Island. *Antarctic Science* 4, 293–304.
- Keating, J.M., Spencer-Jones, M., Newham, S., 1992. The stratigraphical palynology of the Kotick Point and Whiskey Bay Formation, Gustav Group (Cretaceous), James Ross Island. *Antarctic Science* 4, 279–292.
- Kjellström, G., 1973. Maastrichtian microplankton from the Höllviken Borehole No.1 in Scania, southern Sweden. *Sveriges Geologiska Undersökning, Serie C no. 688*, 67, 1–59.
- Keller, G., Han, Q., Adatte, T., Burns, S.J., 2001. Palaeoenvironment of the Cenomanian – Turonian transition at Eastbourne, England. *Cretaceous Research* 22, 391–422.
- Kennedy, W.J., 1967. Burrows and surface traces from the Lower Chalk of southern England. *Bulletin of the British Museum (Natural History) Geology* 15, 127–167.
- Kennedy, W.J., Garrison, R.E., 1975. Morphology and genesis of nodular chalks and hardgrounds in the Upper Cretaceous of southern England. *Sedimentology* 22, 311–386.
- Kennedy, W.J., Gale, A.S., 2006. The Cenomanian Stage. *Proceedings of the Geologists' Association* 117, 187–205.

- Kennedy, W.J., Gale, A.S., Bown, P.R., Caron, M., Davey, R.J., Gröcke, D.R., Wray, D.S., 2000. Integrated stratigraphy across the Aptian–Albian boundary in the Marnes Bleues, at the Col de Pré-Guittard, Arnayon (Drôme), and at Tartonne (Alpes-de-Haute-Provence), France: A candidate global boundary stratotype section and Boundary Point for the base of the Albian Stage. *Cretaceous Research* 21, 591–720.
- Kennedy, W.J., Walaszczyk, I., Cobban, W.A., 2005. The Global Boundary Stratotype Section and Point for the base of the Turonian Stage of the Cretaceous: Pueblo, Colorado, U.S.A. *Episodes* 28, 93–104.
- Kerr, J.W., 1974. Geology of Bathurst Island Group and Byam Martin Island, Arctic Canada. Geological Survey of Canada, Memoir 378, 1–152.
- Khomentovskii, O.V., Zakharov, V.A., Lebedeva, N.K., Vorobeva, O.I., 1999. Granitsa Santona i Kampana na Severe Sibiri. *Geologiya i Geofizika* 40, 512–529.
- Khowaja-Ateequzzaman, Jain, K.P., 1992. Hauterivian–Barremian dinoflagellate cyst assemblage from subsurface of Polar Basin, Southern India. *Geophytology* 22, 133–180.
- Kimyai, A., 1992. Palynological assemblages of the Cretaceous sediments in the Fish Creek test Well No.1, North Slope, Alaska. *Revista Española de Micropaleontología* 24, 27–42.
- Kimyai, A., 2000. Palynology and biostratigraphy of the Lower Cretaceous sediments in the South Barrow Test well no. 1, Point Barrow, Alaska. *Palynology* 24, 201–215.
- Kirsch, K.-H., 1991. Dinoflagellate cysts of the Upper Cretaceous of the Helvetic and Ultrahelvetic of the Upper Bavaria. *Munchener Geowissenschaftliche Abhandlungen Reihe A, Geologie und Palaeontologie* 22, 1–306.
- Kjellström, G., 1973. Maastrichtian microplankton from the Höllviken Borehole no.1 in Scania, southern Sweden. *Sveriges Geologiska Undersökning, Afhandlingar och Uppsatser* 67, 1–59.
- Koppelhus, E.B., Pedersen, C.K., 1993. A palynological and sedimentological study of Cretaceous floodplain deposits of the Atane Formation at Skansen and Igdlunguaq, Disko, West Greenland. *Cretaceous Research* 14, 707–734.
- Köthe, A., Khan, A.M., Ashraf, M., 1988. Biostratigraphy of the Surghar Range, Salt Range, Sulaiman Range and the Kohat area, Pakistan, according to Jurassic through Paleogene calcareous nannofossils and Paleogene dinoflagellates. *Geologisches Jahrbuch Reihe B* 71, 3–87.
- Kurita, H., Obuse, A., 1994. Paleogene dinoflagellate cysts and pollen from the Haboro Formation, northern Central Hokkaido, Japan and their chronostratigraphic and paleoenvironmental implication. *Journal of the Geological Society of Japan (Chishitsugaku Zasshi)* 100, 292–301.
- Lamolda, M.A., Hancock, J.M., 1996. The Santonian Stage and substages. In: *Proceedings "Second International Symposium on Cretaceous Stage Boundaries"* Brussels 8 - 16 September 1995. l'Institut Royal des Sciences Naturelles de Belgique, pp. 95–102.
- Lamolda, M.A., Mao, S., 1999. The Cenomanian – Turonian boundary event and dinocyst record at Ganuza (Northern Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology* 150, 65–82.

- Lamolda, M.A., Paul, C.R.C., 2007. Carbon and oxygen stable isotopes across the Coniacian/Santonian boundary at Olazagutia, northern Spain. *Cretaceous Research* 28, 37–45.
- Lamolda, M.A., Gorostidi, A., Paul, C.R.C., 1994. Quantitative estimates of calcareous nannofossil changes across the Plenus Marls (latest Cenomanian), Dover, England — implications for the generation of the Cenomanian – Turonian boundary event. *Cretaceous Research* 15, 143–164.
- Lamolda, M.A., Paul, C.R.C., Peryt, D., Pons, J.M., 2014. The Global Boundary Stratotype and Section Point (GSSP) for the base of the Santonian Stage, "Cantera de Margas", Olazagutia, northern Spain. *Episodes* 37, 2–13.
- Laurin, J., Čech, S., Uličný, D., Štaffen, Z., Svobodová, M., 2014. Astrochronology of the Late Turonian: Implications for the behavior of the carbon cycle at the demise of peak greenhouse, *Earth and Planetary Science Letters* 394, 254–269.
- Lawal, O., 1982. Palynological biostratigraphy and palaeoenvironment of Cretaceous formations of Upper Benue, North-East Nigeria, University of Nice, Nice, 199 pp.
- Leary, P.N., Peryt, D., 1991. The late Cenomanian oceanic anoxic event in the western Anglo-Paris Basin and southeast Danish-Polish Trough: survival strategies of and recolonisation by benthonic foraminifera. *Historical Biology* 5, 321–338.
- Lebedeva, N.K., 2006. Dinocyst biostratigraphy of the Upper Cretaceous of northern Siberia. *Paleontological Journal* 40, S604–S621.
- Lebedeva, N.K., 2008. ДИНОЦИСТЫ И БИОСТРАТИГРАФИЯ ВЕРХНЕМЕЛОВЫХ ОТЛОЖЕНИЙ СЕВЕРА СИБИРИ, Трофимука Сибирского отделения Российской Академии наук, 41 pp.
- Lebedeva, N.K., 2010. Palynofacies in Upper Cretaceous sediments of Northern Siberia. *Stratigrafiya. Geologicheskaya Korrelyatsiya* 18, 70–87.
- Leckie, D.A., Singh, C., Bloch, I.D., Wilson, M., Wall, J., 1992. An anoxic event at the Albian–Cenomanian boundary; The Fish Scale Marker Bed, northern Alberta, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* 92, 139–166.
- Lécuyer, C., 2016. Seawater residence times of some elements of geochemical interest and the salinity of the oceans. *Bulletin de la Société Géologique de France* 187, 245–259.
- Lentin, J.K., Williams, G.L., 1973. Fossil dinoflagellates: index to genera and species. Geological Survey of Canada, Paper 73, 1–176.
- Lentin, J.K., Williams, G.L., 1985. Fossil dinoflagellates: index to genera and species. Canadian Technical Report of Hydrography and Ocean Sciences 60, 1–451.
- Lentin, J.K., Vozzhennikova, T.F., 1990. Fossil dinoflagellates from the Jurassic, Cretaceous and Paleogene deposits of the USSR — a restudy. *American Association of Stratigraphic Palynologists, Contributions Series* 23, 1–221.
- Li, H., Habib, D., 1996. Dinoflagellate stratigraphy and its response to sea level change in Cenomanian – Turonian sections of the Western Interior of the United States. *Palaaios* 11, 15–30.
- Li, W., Liu, Z.-S., 1994. The Cretaceous palynofloras and their bearing on stratigraphic correlation in China. *Cretaceous Research* 15, 333–365.

- Lignum, J.S., 2008. Cenomanian (Upper Cretaceous) Palynology and Chemostratigraphy: Dinoflagellate Cysts as Indicators of Palaeoenvironmental and Sea-level Change. Unpublished PhD thesis, Kingston University, London, 579 pp.
- Lignum, J.S., Jarvis, I., Pearce, M.A., 2008. A critical assessment of standard processing methods for the preparation of palynological samples. *Review of Palaeobotany and Palynology* 149, 133–149.
- Linnert, C., Robinson, S.A., Lees, J.A., Perez-Rodriguez, I., Jenkyns, H.C., Petrizzo, M.R., Arz, J.A., Bown, P.R., Falzoni, F., 2018. Did Late Cretaceous cooling trigger the Campanian – Maastrichtian Boundary Event? *Newsletters on Stratigraphy* 51, 145–166.
- Louwye, S., 1992. Dinoflagellate cyst stratigraphy of the Upper Cretaceous of Western Belgium. *Bulletin de la Société Belge de Géologie, de Paléontologie et d'Hydrologie* 101, 255–275.
- Louwye, S., 1995. New dinoflagellate cyst species from Upper Cretaceous subsurface deposits of western Belgium. *Annales de la Société Géologique de Belgique* 118, 147–159.
- Ma, C., Meyers, S.R., Sageman, B.B., Singer, B.S., Jicha, P.K., 2014. Testing the astronomical time scale for oceanic anoxic event 2, and its extension into Cenomanian strata of the Western Interior Basin (USA). *Geological Society of America Bulletin* 126, 974–989.
- Macphail, M.K., Truswell, E.M., 2004. Palynology of Neogene slope and rise deposits from ODP Sites 1165 and 1167, East Antarctica. In: Cooper, A.K., O'Brien, P.E., Richter, C. (Eds), *Proceedings of the Ocean Drilling Program, Scientific Results* 188, College Station, Texas, pp. 1–20.
- Mallon, A.J., Swarbrick, R.E., 2002. A compaction trend for non-reservoir North Sea Chalk. *Marine and Petroleum Geology*, 19, 527–539.
- Mantell, G.A., 1845. Notes of a microscopical examination of the Chalk and Flint of southeast England, with remarks on the animalcules of certain Tertiary and modern deposits. *Annals and Magazine of Natural History* 16, 73–88.
- Mantell, G.A., 1850. *A Pictorial Atlas of Fossil Remains Consisting of Coloured Illustrations Selected from Parkinson's "Organic Remains of a Former World", and Artis's "Antediluvian Phytology"* xii+207 pp.; Henry G. Bohn, London, U.K.
- Manum, S.B., Cookson, I.C., 1964. Cretaceous microplankton in a sample from Graham Island, Arctic Canada, collected during the Second Fram Expedition (1898–1902). With notes on microplankton from the Hassel Formation, Elef Ringnes Island. *Norske Videnskaps-Akademi, 1. Matematisk-Naturvidenskapelig Klasse, Skrifter, Ny Serie*, 17, 1–36.
- Mao, S., Mohr, B.A.R., 1992. Late Cretaceous dinoflagellate cysts (?Santonian – Maastrichtian) from the Southern Indian Ocean (Hole 748C). In: Wise, S.W. Jr, Schlich, R., et al. (Eds), *Proceedings of the Ocean Drilling Program, Scientific Results* 120, College Station, pp. 307–341.
- Mao, S., Lamolda, M.A., 1998. Late Cenomanian and Early Turonian dinoflagellate cysts at Ganuza Navarr I. Systematic palaeontology. *Revista Española de Paleontología* 13, 261–286.

- Marheinecke, U., 1986. Dinoflagellaten des Maastrichtium der Grube Hemmoor (Niedersachsen). *Geologisches Jahrbuch*, Reihe A 93, 3–93.
- Marshall, K.L., 1983. Dinoflagellate cysts from the Cenomanian, Turonian and Coniacian of Germany and England. Unpublished PhD thesis, University of Aberdeen, Aberdeen, 211 pp.
- Marshall, K.L., Batten, D.J., 1988. Dinoflagellate cyst associations in Cenomanian–Turonian "Black Shale" sequences of northern Europe. *Review of Palaeobotany and Palynology* 54, 85–103.
- Marshall, N.G., 1990. Campanian dinoflagellates from southeastern Australia. *Alcheringa* 14, 1–38.
- Masure, E., 1983. Dinoflagellés. In: Neumann, M., Platel, J.P. (coord.), *Le Campanien stratotypique: étude lithologique and micropaléontologique*. *Géologie Méditerranéenne* 10, 51–52.
- Masure, E., 1984. L'indice de diversité et les dominances des "communautés" de kystes de dinoflagellés: marqueurs bathymétriques; forage 398 D, croisière 47 B. Palaeobathymetry data; Drill Site 398D, Leg 471. *Bulletin de la Société Géologique de France*, 7e série 26, 93–111.
- Masure, E., 1988. Albian–Cenomanian dinoflagellate cysts from Sites 627 and 635, Leg 101, Bahamas. In: Austin, J.A., Jr, Schlager, W., et al. (Eds), *Proceedings of the Ocean Drilling Program, Scientific Results 101*, College Station, pp. 121–138.
- Masure, E., Vrielynck, B., 2009. Late Albian dinoflagellate cyst paleobiogeography as indicator of asymmetric sea surface temperature gradient on both hemispheres with southern high latitudes warmer than northern ones. *Marine Micropaleontology* 70, 120–123.
- Masure, E., Rauscher, R., Dejax, J., Schuller, M., Ferré, B., 1998. Cretaceous – Paleocene palynology from the Côte d'Ivoire – Ghana transform margin, Sites 959, 960, 961 and 962. In: Mascle, J., Lohmann, G.P., Moullade, M. (Eds), *Proceedings of the Ocean Drilling Program, Scientific Results 159*, College Station, pp. 253–276.
- Matthews, K.J., Maloney, K.T., Zahirovic, S., Williams, S.E., Seton, M., Müller, R.D., 2016. Global plate boundary evolution and kinematics since the late Paleozoic: *Global and Planetary Change* 146, 226–250.
- May, F.E., Stein, J.A., 1979. Dinoflagellate and acritarch assemblages from the Grandstand Formation, (Middle to Upper Albian), of the Nanushuk Group, Simpon Core Test 25, National Petroleum Reserve in Alaska, northern Alaska. Alaska. Division of Geological Survey. Information Circular. Preliminary results, study of Nanushuk Group Rocks 794, 128–145.
- McArthur, J.M., 1994. Recent trends in strontium isotope stratigraphy. *Terra Nova* 6, 331–358.
- McArthur, J.M., Kennedy, W.J., Gale, A.S., Thirlwall, M.F., Chen, M., Burnett, J., Hancock, J.M., 1992. Strontium isotope stratigraphy in the Late Cretaceous — intercontinental correlation of the Campanian – Maastrichtian boundary. *Terra Nova* 4, 385–393.
- McArthur, J.M., Thirlwall, M.F., Chen, M., Gale, A.S., Kennedy, W.J., 1993a. Strontium isotope stratigraphy in the Late Cretaceous: numerical calibration of the Sr isotope

- curve and intercontinental correlation for the Campanian. *Paleoceanography* 8, 859–873.
- McArthur, J.M., Thirlwall, M.F., Gale, A.S., Kennedy, W.J., Burnett, J.A., Matthey, D., Lord, A.R., 1993b. Strontium isotope stratigraphy for the Late Cretaceous: a new curve, based on the English Chalk. In: Hailwood, E.A., Kidd, R.B., (Eds), *High Resolution Stratigraphy*. Geological Society of London Special Publication 70, 195–209.
- McArthur, J.M., Kennedy, W.J., Chen, M., Thirlwall, M.F., Gale, A.S., 1994. Strontium isotope stratigraphy for Late Cretaceous time — direct numerical calibration of the Sr isotope curve based on the United States Western Interior. *Palaeogeography, Palaeoclimatology, Palaeoecology* 108, 95–119.
- McArthur, J.M., Howarth, R.J., Bailey, T.R., 2001. Strontium isotope stratigraphy: LOWESS version 3: Best fit to the marine Sr-isotope curve for 0 – 509 Ma and accompanying look- up table for deriving numerical age. *Journal of Geology* 109, 155–170.
- McArthur, J.M., Howarth, R.J., Shields, G.A., 2012. Strontium isotope stratigraphy. In: Gradstein, F., Ogg, J.G., Schmitz, M., Ogg, G. (Eds) *The Geologic Time Scale 2012*. Amsterdam, Elsevier, pp. 127–144.
- McArthur, J.M., Steuber, T., Page, K.N., Landman, N.M., 2016. Sr-Isotope stratigraphy: assigning time in the Campanian, Pliensbachian, Toarcian, and Valanginian. *Journal of Geology* 124, 569–586.
- McIntyre, D.J., 1974. Palynology of an Upper Cretaceous section, Horton River, District of MacKenzie, N. W. T. Geological Survey of Canada, Paper 74, 1–57.
- McMinn, A., 1988. Outline of a Late Cretaceous dinoflagellate zonation of Northwestern Australia. *Alcheringa* 12, 137–150.
- McPherson, M.L., Currie, B.S., Pierson, J.S., 2006. Reservoir Characterization of the Cretaceous Cedar Mountain and Dakota Formations, Southern Uinta Basin: Year - One Report. Utah Geological Survey, Open-File Report 492, 1–99.
- Mearon, S., Paytan, A., Bralower, T.J., 2003. Cretaceous strontium isotope stratigraphy using marine barite. *Geology* 31, 15–18.
- Mehrotra, N.C., Venkateshala, B.S., Swamy, S.N., Kapoor, P.N., 2002. Krishna – Godavari Basin. In: *Palynology in Hydrocarbon Exploration (The Indian Scenario)*. Memoir of the Geological Society of India 48, 61–88.
- Mertens, K.N., Verhoeven, K., Verleye, T., Louwye, S., Amori, A., Ribeiro, S., Deaf, A.S., Harding, I.C., Schepper, S. de, González, C., Kodrans-Nsiah, M., Vernal, A. de, Henry, M., Radi, T., Dybkjær, K., Poulsen, N.E., Feist-Burkhardt, S., Chitolie, J., Heilmann-Clausen, C., Londeix, L., Turon, J.-L., Marret, F., Matthiessen, J., McCarthy, F.M.G., Prasad, V., Pospelova, V., Kyffin Hughes, J.E., Riding, J.B., Rochon, A., Sangiorgi, F., Welters, N., Sinclair, N., Thun, C., Soliman, A., Nieuwenhove, N. van, Vink, A., Young, M., 2009. Determining the absolute abundance of dinoflagellate cysts in recent marine sediments: The *Lycopodium* marker-grain method put to the test. *Review of Palaeobotany and Palynology* 157, 238–252.
- Meyers, S.R., Siewert, S.E., Singer, B.S., Sageman, B.B., Condon, D.J., Obradovich, J.D., Jicha, B.R., Sawyer, D.A., 2012. Intercalibration of radioisotopic and astrochronologic

- time scales for the Cenomanian – Turonian boundary interval, Western Interior Basin, USA. *Geology*, pp. 407–10.
- Mildenhall, D.C., 1977. Cretaceous palynomorphs from the Waihere Bay Group and Kahuitara Tuff, Chatham Islands, New Zealand. *New Zealand Journal of Geology and Geophysics* 20, 655–672.
- Mildenhall, D.C., Wilson, G.J., 1976. Cretaceous palynomorphs from the Sisters Islets, Chatham Islands, New Zealand. *New Zealand Journal of Geology and Geophysics* 19, 121–126.
- Millioud, M.E., 1969. Dinoflagellates and acritarchs from some western European Lower Cretaceous type localities, in *Proceedings of the 1st International Conference on Planktonic Microfossils, Geneva 1967*, edited, pp. 420–434, Leiden.
- Mitchell, J., 1836. On the chalk and flint of Yorkshire, as compared with the chalk and flint of the southern counties of England. *The Edinburgh New Philosophical Journal, Exhibiting a View of the Progressive Discoveries and Improvements in the Sciences and the Arts* 20, 68–74.
- Mitchell, S.F., 1994. New data on the biostratigraphy of the Flamborough Chalk Formation (Santonian, Upper Cretaceous) between South Landing and Danes Dyke, North Yorkshire. *Proceedings of the Yorkshire Geological Society* 50, 113–118.
- Mitchell, S.F., 1995a. Lithostratigraphy and biostratigraphy of the Hunstanton Formation (Red Chalk, Cretaceous) succession at Speeton, North Yorkshire, England. *Proceedings of the Yorkshire Geological Society* 50, 285–303.
- Mitchell, S.F., 1995b. *Uintacrinus anglicus* Kasmussen from the Upper Cretaceous Flamborough chalk formation of Yorkshire: Implications for the position of the Santonian – Campanian boundary. *Cretaceous Research* 16, 745–756.
- Mitchell, S.F., 2000. The Welton Formation (Chalk Group) at Speeton, NE England: implications for the late Cretaceous evolution of the Market Weighton Structure. *Proceedings of the Yorkshire Geological Society* 53, 17–24.
- Mitchell, S.F., 2005. Eight Belemnite biohorizons in the Cenomanian of northwest Europe and their importance. *Geological Journal* 40, 363–382.
- Mitchell, S.F., 2019. The Chalk Group (Upper Cretaceous) of the Northern Province, eastern England — a review. *Proceedings of the Yorkshire Geological Society* 62, 153–177.
- Mitchell, S.F., Veltkamp, C.J., 1997. *Schackoina moliniensis* Reichel from the Lower Cenomanian of north-east England and its stratigraphical significance. *Proceedings of the Yorkshire Geological Society* 51, 367–372.
- Mitchell, S.F., Paul, C.R.C., Gale, A.S., 1996. Carbon isotopes and sequence stratigraphy. In: Howell, J.A., Aitken, J.F. (Eds), *High Resolution Sequence Stratigraphy: Innovations and Applications*. The Geological Society of London Special Publication 104, 11–24.
- Mohamed, O., Piller, W.E., Egger, H., 2012. The dinocyst record across the Cretaceous/Palaeogene boundary of a bathyal mid-latitude Tethyan setting: Gosau Group, Gams Basin, Austria. *Cretaceous Research* 35, 143–168.

- Mohr, B.A.R., 1990. Early Cretaceous palynomorphs from ODP Sites 692 and 693, the Weddell Sea, Antarctica. In: Barker, P.F., Kennett, J.P., et al. (Eds), Proceedings of the Ocean Drilling Program, Scientific Results 113, College Station, pp. 449–464.
- Mohr, B.A.R., Gee, C.T., 1992. Late Cretaceous palynofloras, (sporomorphs and dinocysts) from the Kerguelen Plateau, Southern India Ocean (Sites 748 and 750). In: Wise, S.W. Jr, Schlich, R., et al. (Eds), Proceedings of the Ocean Drilling Program, Scientific Results 120, College Station, pp. 281–306.
- Mohr, B.A.R., Wähnert, V., Lazarus, D.B., 2002. Mid-Cretaceous paleobotany and palynology of the Central Kerguelen Plateau, Southern Indian Ocean (ODP Leg 183, Site 1138). In: Frey, F.A., Coffin, M.F., Wallace, P.J., Quilty, P.G. (Eds), Proceedings of the Ocean Drilling Program, Initial Reports 183, College Station, Texas, 1–39 pp.
- Moradian, F., Allameh, M., 2010. Palynology of the Abderaz Formation in Hamam Ghaleh in Kopet Dagh sedimentary basin, in The 1st International Applied Geological Congress, edited, pp. 920–924, Department of Geology, Islamic Azad University – Mashad Branch, Iran, 26–28 April 2010.
- Morgan, R., 1978. Albian to Senonian palynology of Site 262, Angola Basin. In: Bolli, H.M., Ryan, W.B.F., et al. (Eds), Initial Reports of the Deep Sea Drilling Project, U.S. Government Printing Office 40, Washington, pp. 915–951.
- Morgan, R., 1980. Palynostratigraphy of the Australian early and middle Cretaceous. Geological Survey of New South Wales, Palaeontology Memoir 18, 1–153.
- Morgenroth, P., 1966. Lower Eocene microfossils and concretions of Northwest Germany. *Paläeontographica Abhandlung B* 119, 1–53.
- Morter, A.A., Gallois, R.W., Clark, R.D., 1975. Record of the IGS Trunch borehole. London: IoG Sciences.
<http://scans.bgs.ac.uk/sobiscans/boreholes/517419/images/12114521.html>.
- Mortimer, R., 1878. On the flint of the Chalk of Yorkshire. *Proceedings of the Geologists' Association* 5, 344–354.
- Mortimore, R.N., 1983. The stratigraphy and sedimentation of the Turonian – Campanian in the Southern Province of England. *Zitteliana* 10, 27–41.
- Mortimore, R.N., 1986. Stratigraphy of the Upper Cretaceous White Chalk of Sussex. *Proceedings of the Geologists' Association* 97, 97–139.
- Mortimore, R.N., 2014a. *Logging the Chalk*. Dunbeath, Caithness. Whittles Publishing 53 pp.
- Mortimore, R.N., 2014b. A stratigraphic framework for the Chalk: Transitional Province (London Basin, Chiltern Hills and East Anglia). In: *Logging the Chalk*. Dunbeath, Caithness: Whittles Publishing, pp. 117–173.
- Mortimore, R.N., Wood, C.J., 1986. The distribution of flint in the English Chalk with particular reference to the "Brandon Flint Series" and the high Turonian flint maximum. In: *The Scientific Study of Flint and Chert*. Cambridge University Press, pp. 7–20.
- Mortimore, R.N., James, L., 2015. The search for onshore analogues for the offshore Upper Cretaceous Chalk of the North Sea. *Proceedings of the Geologists' Association* 126, 188–210.

- Mortimore, R.N., Wood, C.J., Gallois, R.W., 2001. *British Upper Cretaceous Stratigraphy* Peterborough: Joint Nature Conservation Committee, 558 pp.
- Müller, R.D., Cannon, J., Qin, X., Watson, R.J., Gurnis, M., Williams, S., Pfaffelmoser, T., Seton, M., Russell, S.H.J., Zahirovic, S., 2018. GPlates — Building a Virtual Earth Through Deep Time: *Geochemistry, Geophysics, Geosystems* 15, 30 pp.
- Newell, A.J., Woods, M.A., Farrant, A.R., Smith, H., Haslam, R.B., 2018. Chalk thickness trends and the role of tectonic processes in the Upper Cretaceous of southern England. *Proceedings of the Geologists' Association* 129, 610–628.
- Nicolas, M.P.B., 2008. Williston Basin Project (Targeted Geoscience Initiative II): Results of the biostratigraphic sampling program, southwestern Manitoba (NTS 62F, 62G4, 62K3). Manitoba Geological Survey, Geoscientific Paper GP2880-1, 1–28.
- Nikitenko, B.L., Pestchevitskaya, E.B., Lebedeva, N.K., Ilyina, V.I., 2008. Micropalaeontological and palynological analyses across the Jurassic–Cretaceous boundary on Nordvik Peninsula, Northeast Siberia. *New letters on Stratigraphy* 42, 181–222.
- Nøhr-Hansen, H., 1991. Dinoflagellate cyst zonation of Barremian to Albian deposits from East Greenland. *Palynology* 15, 248–249.
- Nøhr-Hansen, H., 1993. Dinoflagellate cyst stratigraphy of the Barremian to Albian, Lower Cretaceous, Northeast Greenland. *Grønlands Geologiske Undersøgelse, Bulletin* 166, 1–171.
- Nøhr-Hansen, H., 1994. Dinoflagellate cyst biostratigraphy of the Upper Cretaceous Black Mudstones on Svartenhuk Halvø, West Greenland. *Grønlands Geologiske Undersøgelse, Open File Series* 94, 1–25.
- Nøhr-Hansen, H., 1996. Upper Cretaceous dinoflagellate cyst stratigraphy, onshore West Greenland. *Grønlands Geologiske Undersøgelse, Bulletin* 170, 1–103.
- Nøhr-Hansen, H., 2012. Palynostratigraphy of the Cretaceous–lower Palaeogene sedimentary succession in the Kangerlussuaq Basin, southern East Greenland. *Review of Palaeobotany and Palynology* 178, 59–90.
- Nøhr-Hansen, H., McIntyre, D.J., 1998. Upper Barremian to Upper Albian (Lower Cretaceous) dinoflagellate cyst assemblages, Canadian Arctic Archipelago. *Palynology* 22, 147–166.
- Nøhr-Hansen, H., Williams, G.L., Fensome, R.A., 2016. Biostratigraphic correlation of the western and eastern margins of the Labrador–Baffin Seaway and implications for the regional geology. *Geological Survey of Denmark and Greenland, Bulletin* 37, 77 pp.
- Nøhr-Hansen, H., Costa, L.I., Pearce, M.A., Alsen, P., 2018. New Albian to Cenomanian (Cretaceous) dinoflagellate cyst taxa of ovoidinioid affinities from East Greenland, the Barents Sea and England. *Palynology* 42, 366–391.
- Norvick, M.S., Burger, D., 1976. Palynology of the Cenomanian of Bathurst Island, Northern Territory, Australia. *Bureau of Mineral Resources, Geology and Geophysics, Bulletin* 151, 1–169.
- Núñez-Betelu, L.K., MacRae, R.A., Hills, L.V., Muecke, G.K., 1992. Uppermost Albian–Campanian palynological biostratigraphy of Axel Heiberg and Ellesmere Islands

- (Canadian Arctic). United States Department of Interior, OCS Report, MMS. Stratigraphy and Paleogeography. 1992 Proceedings International Conference on Arctic Margins 94(40), 135–140.
- Núñez-Betelu, L.K., Hills, L.V., Krause, F.F., McIntyre, D.J., 1994. Upper Cretaceous paleoshorelines of the northeastern Sverdrup Basin, Ellesmere Island, Canadian Arctic Archipelago. Stratigraphy, Biostratigraphic Correlation and Paleogeography. 1994 Proceedings International Conference on Arctic Margins, pp. 43–49.
- O'Brien, C.L., Robinson, S.A., Pancost, R.D., Damste, J.S.S., Schouten, S., Lunt, D.J., Alsenz, H., Bomemann, A., Bottini, C., Brassell, S.C., Farnsworth, A., Forster, A., Huber, B.T., Inglis, G.N., Jenkyns, H.C., Linnert, C., Littler, K., Markwick, P., McAnena, A., Mutterlose, J., Naafs, B.D.A., Puttmann, W., Sluijs, A., van Helmond, N.A.G.M., Vellekoop, J., Wagner, T., Wrobel, N.E., 2017. Cretaceous sea-surface temperature evolution: Constraints from TEX86 and planktonic foraminiferal oxygen isotopes. *Earth-Science Reviews* 172, 224–247.
- Ogg, G., 1994. Dinoflagellate cysts of the Early Cretaceous North Atlantic Ocean. *Marine Micropaleontology* 23, 241–263.
- Ogg, J.G., Hinnov, L.A., 2012. Cretaceous. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds), *The Geological Time Scale 2012*. Elsevier, Amsterdam, pp. 793–853.
- Ogg, J.G., Agterberg, F.P., Gradstein, F.M., 2004. The Cretaceous Period. In: Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds), *A Geological Time Scale 2004*. Cambridge: Cambridge University Press, pp. 344–383.
- Ogg, J.G., Ogg, G., Gradstein, F., 2016. *A concise geologic time scale*. Amsterdam: Elsevier, 240 pp.
- Ohkouchi, N., Kawamura, K., Kajiwa, Y., Wada, E., Okada, M., Kanamatsu, T., Taira, A., 1999. Sulfur isotope records from Livello Bonarelli (northern Apennines, Italy) black shale at the Cenomanian – Turonian boundary. *Geology* 27, 535–538.
- Olde, K., Jarvis, I., Pearce, M., Uličný, D., Tocher, B., Trabucho-Alexandre, J., Gröcke, D., 2015. A revised northern European Turonian (Upper Cretaceous) dinoflagellate cyst biostratigraphy: integrating palynology and carbon isotope events. *Review of Palaeobotany and Palynology* 213, 1–16.
- Olde, K., Jarvis, I., Pearce, M.A., Walaszczyk, I., Tocher, B.A., 2016. Organic-walled dinoflagellate cyst records from a prospective Turonian – Coniacian (Upper Cretaceous) GSSP, Słupia Nadbrzeżna, Poland. *Cretaceous Research* 65, 17–24.
- Olivero, B., Palamarczuk, S., 1987. Cenomanian ammonites and dinoflagellates from James Ross Island, Antarctica. *Ameghiniana* 24, 35–49.
- Oltz, D.F., 1969. Numerical analyses of palynological data from Cretaceous and Early Tertiary sediments in East Central Montana. *Paläontographica Abteilung B* 128, 90–166.
- Owen, H.G., 1992. The Gault – Lower Greensand Junction Beds in the northern Weald (England) and Wissant (France), and their depositional environment. *Proceedings of the Geologists' Association* 103, 83–110.
- Owen, H.G., 1995. The upper part of the Carstone and the Hunstanton Red Chalk (Albian) of the Hunstanton Cliff, Norfolk. *Proceedings of the Geologists' Association* 106, 171–181.

- Owens, J.D., Gill, B.C., Jenkyns, H.C., Bates, S.M., Severmann, S., Kuypers, M.M.M., Woodfine, R.G., Lyons, T.W., 2013. Sulfur isotopes track the global extent and dynamics of euxinia during Cretaceous Oceanic Anoxic Event 2. *Proceedings of the National Academy of Sciences USA* 110, 18407–18412.
- Palamarczuk, S., Ambrosini, G., Villar, H., Medina, F., Martinez-Macchiavello, J.C., Rinaldi, C., 1984. The Lopez de Bertodano and Sobral Formations of Vicecomodora Marambio Island, Antarctica. *Congreso Geológico Argentino, Actas del Noveno* 1, 399–419.
- Palynodata Inc, White, J.M., 2008. Palynodata datafile: 2006 version. Geological Survey of Canada.
- Paul, C.R.C., Lamolda, M.A., 2009. Testing the precision of bioevents. *Geological Magazine* 146, 625–637.
- Paul, C.R.C., Mitchell, S.F., Marshall, J.D., Leary, P.N., Gale, A.S., Beane, A.M., Ditchfield, P.W., 1994. Palaeoceanographic events in the Middle Cenomanian of Northwest Europe. *Cretaceous Research* 15, 707–738.
- Paul, C.R.C., Lamolda, M.A., Mitchell, S.F., Vaziri, M.R., Forostidi, A., Marshall, J.D., 1999. The Cenomanian – Turonian boundary at Earlsbourne (Sussex, UK): a proposed European reference section. *Palaeogeography, Palaeoclimatology, Palaeoecology* 150, 83–121.
- Pavlishina, P., 1990. Early Cenomanian palynomorphs near the village of Sanadinovo, central north Bulgaria. *Review of the Bulgarian Geological Society* 51, 89–101.
- Peake, N.B., Hancock, J.M., 1961. The Upper Cretaceous of Norfolk. *Transactions of the Norfolk and Norwich Naturalists' Society* 19, 293–339.
- Peake, N.B., Hancock, J.M., 1970. The Upper Cretaceous of Norfolk. In: *The Geology of Norfolk*. Geological Society of Norfolk. Norwich, pp. 293–339.
- Peake, N.B., Hancock, J.M., 2000. The Chalk of Norfolk I 1961 – 2000. In: *The Geological Society of Norfolk 50th Anniversary Jubilee Volume*. Geological Society of Norfolk. Norwich, pp. 22–26.
- Pearce, M.A., 2000. Palynology and Chemostratigraphy of the Cenomanian to Lower Campanian Chalks of southern and Eastern England. Unpublished PhD thesis, Kingston University London, 432 pp.
- Pearce, M.A., 2010. New genera and species of organic-walled dinoflagellate cysts from the Cenomanian to lower Campanian of the Trunch borehole, southeast England. *Journal of Micropalaeontology* 29, 51–72.
- Pearce, M.A., 2018. Additional new organic-walled dinoflagellate cysts from two onshore UK Chalk boreholes. *Journal of Micropalaeontology* 37, 73–86.
- Pearce, M.A., Williams, G.L., 2018. *Fetchamium prolixispinosum* gen. et comb. nov. (division Dinoflagellata). *Journal of Micropalaeontology* 37, 17–20.
- Pearce, M.A., Jarvis, I., Swan, A.R.H., Murphy, A.M., Tocher, B.A., Edmunds, W.M., 2003. Integrating palynological and geochemical data in a new approach to palaeoecological studies: Upper Cretaceous of the Banterwick Barn Chalk borehole, Berkshire, UK. *Marine Micropaleontology* 47, 271–306.

- Pearce, M.A., Jarvis, I., Tocher, B.A., 2009. The Cenomanian–Turonian boundary event, OAE2 and palaeoenvironmental change in epicontinental seas: new insights from the dinocyst and geochemical records. *Palaeogeography, Palaeoclimatology, Palaeoecology* 280, 207–234.
- Pearce, M.A., Lignum, J.S., Jarvis, I., 2011. *Senoniasphaera turonica* (Prössl, 1990 ex Prössl, 1992) comb. nov., senior synonym of *Senoniasphaera rotundata alveolata* Pearce et al., 2003: an important dinocyst marker for the Lower Turonian chalk of NW Europe. *Journal of Micropalaeontology* 30, 91–93.
- Peyrot, P., Barroso-Barcenilla, F., Barrón, E., Comas-Rengifo, M.J., 2011. Palaeoenvironmental analysis of Cenomanian – Turonian dinocyst assemblages from the Castilian Platform (Northern – Central Spain). *Cretaceous Research* 32, 504–526.
- Phillips, J., 1829. Illustrations of the geology of Yorkshire or a description of the strata and organic remains of the Yorkshire coast: accompanied by a geological map, sections and plates of the fossil plants and animals. J. Phillips, York, 192 pp.
- Pierce, R.L., 1961. Lower Upper Cretaceous plant microfossils from Minnesota. *Minnesota Geological Survey, Bulletin* 42, 1–86.
- Pirrie, D., Crame, J.A., Lomas, S.A., Riding, J.B., 1997. Late Cretaceous stratigraphy of the Admiralty Sound Region, James Ross Basin, Antarctica. *Cretaceous Research* 18, 109–137.
- Poulsen, N.E., 1993. Dinoflagellate cyst biostratigraphy of the Oxfordian and Kimmeridgian of Poland. *Acta Geologica Polonica* 43, 251–272.
- Prasad, B., 1999. Palynological characterisation, biostratigraphy and depositional environment of Pre-Tertiary litho units of Krishna – Godavari Basin, India. *Geoscience Journal* 20, 143–164.
- Price, F.G.H., 1877. On the beds between the Gault and Upper Chalk near Folkestone. *Quarterly Journal of the Geological Society, London* 33, 431–448.
- Prince, I.M., 1997. Palynology of the Upper Turonian to Lower Campanian Chalks of Southern England. Unpublished PhD thesis, University of Wales, Aberystwyth, 334 pp.
- Prince, I.M., Jarvis, I., Tocher, B.A., 1999. High-resolution dinoflagellate cyst biostratigraphy of the Santonian: Basal Campanian (Upper Cretaceous): New data from Whitecliff, Isle of Wight, England. *Review of Palaeobotany and Palynology* 105, 143–169.
- Prince, I.M., Jarvis, I., Pearce, M.A., Tocher, B.A., 2008. Dinoflagellate cyst biostratigraphy of the Coniacian–Santonian (Upper Cretaceous): new data from the English Chalk. *Review of Palaeobotany and Palynology* 150, 59–96.
- Pross, J., Link, E., Ruf, M., Aigner, T., 2006. Delineating sequence stratigraphic patterns in deeper ramp carbonates: quantitative palynofacies data from the Upper Jurassic, Kimmeridgian) of Southwest Germany. *Journal of Sedimentary Research* 76, 524–538.
- Prössl, K.F., 1990. Dinoflagellates of the Cretaceous, (Early Hauterivian to Late Turonian), in the Niedersachsen Basin. *Stratigraphy and facies changes of the*

- Konrad 101 borehole, as well as several other boreholes from northwest Germany. *Paläeontographica Abteilung B* 218, 93–101.
- Püttman, T., Linnert, C., Dolling, B., Mutterlose, J., 2018. Deciphering Late Cretaceous (Cenomanian to Campanian) coastline dynamics in the southwestern Münsterland (northwest Germany) by using calcareous nannofossils: Eustasy vs local tectonics. *Cretaceous Research* 87, 174–184.
- Pyne, R.S., Whatley, R.C., Wilkinson, I.P., 2003. New species of Ostracoda from the Upper Cretaceous Chalk (Conician to Lower Maastrichtian) of East Anglia, U.K. *Revista Espanola de Micropaleontología* 35, 87–118.
- Radmacher, W., Tyszka, J., Mangerud, G., Pearce, M.A., 2014. Dinoflagellate cyst biostratigraphy of the Upper Albian to Lower Maastrichtian in the southwestern Barents Sea. *Marine and Petroleum Geology* 57, 109–121.
- Raine, J.I., 1977. Palynology of samples from Kawau-1A offshore well. In: Strong, C.P. (Ed.), *Biostratigraphy of the Kawau No. 1A offshore well*. New Zealand Geological Survey 18, 9–15.
- Rawson, P.F., 2018. Itinerary 12 Thornwick Bay and North Landing, Flamborough. In: Rawson, P.F., Wright, J.K., *Geology of the Yorkshire Coast* (4th edition), Geologists' Association Guide 34, 126–131.
- Rawson, P.F., Curry, D., Dilley, F.C., Hancock, J.M., Kennedy, W.J., Neale, J.W., Wood, C.J., Worssam, B.C., 1978. *A correlation of Cretaceous rocks in the British Isles*. Edinburgh. Scottish Academic Press, Geological Society of London, 70pp.
- Rawson, P.F., Allen, P., Gale, A.S., 2001. The Chalk Group — a revised lithostratigraphy. *Geoscientist*, 11, 21.
- Razmjooei, M.J., Thibault, N., Kani, A., Dinarès-Turell, J., Pucéat, E., Shahriari, S., Radmacher, W., Jamali, A.M., Ullmann, C.V., Voigt, S., Cocquerez, T., 2018. Integrated bio- and carbon-isotope stratigraphy of the Upper Cretaceous Gurpi Formation (Iran): A new reference for the eastern Tethys and its implications for large-scale correlation of stage boundaries. *Cretaceous Research* 91, 312–340.
- Reade, J.B., 1839. On some new organic remains in the flint of Chalk. *Annals of Natural History* 2, 191–192.
- Richards, B.C., Hillier, B.W., 2000. Post-drilling analysis of the North Falkland Basin: Part 1: Tectono stratigraphic framework. *Journal of Petroleum Geology* 23, 253–272.
- Riding, J.B., Thomas, J.E., 1988. Dinoflagellate cyst stratigraphy of the Kimmeridge Clay, (Upper Jurassic) from the Dorset Coast, southern England. *Palynology* 12, 65–88.
- Riding, J.B., Crame, J.A., Dettmann, M.E., Cantrill, D.J., 1998. The age of the Base of the Gustav Group in the James Ross Basin Antarctica. *Cretaceous Research* 19, 87–105.
- Riley, L.A., Sarjeant, W.A.S., 1972. Survey of the stratigraphical distribution of dinoflagellates, acritarchs and tasmanitids in the Jurassic. *Geophytology* 2, 1–11.
- Riley, L.A., Fenton, J.P.G., 1984. Palynostratigraphy of the Berriasian to Cenomanian sequence at Deep Sea Drilling Project Site 535, Leg 77, southeastern Gulf of Mexico. In: Buffler, R.T., Schlager, W., et al. (Eds), *Initial Reports of the Deep Sea Drilling Project*, U.S. Government Printing Office, 77, Washington, pp. 675–690.

- Robaszynski, F., Alcaydé, G., Amédéo, F., Badillet, G., Damotte, R., Foucher, J.-C., Jardiné, S., Legoux, O., Manivit, H., Monciardini, C., Sornay, J., 1982. Le Turonien de la région type: Saumurois et Touraine. Stratigraphie, biozonations, sédimentologie. Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine 6, 119–225.
- Robaszynski, F., Bless, M.J.M., Felder, P.J., Foucher, J.-C., Legoux, O., Manivit, H., Meessen, J.P.M.T., Tuuk, L.A. Van der., 1985. The Campanian–Maestrichtian boundary in the chalky facies close to the type-Maestrichtian area. Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine 9, 1–113.
- Robinson, N.D., 1986. Lithostratigraphy of the Chalk Group of the North Downs, southeast England. Proceedings of the Geologists' Association 97, 141–170.
- Roncaglia, L., 2002. Lower Maastrichtian dinoflagellates from the Viano Clay Formation at Viano, northern Apennines, Italy. Cretaceous Research 23, 65–76.
- Roncaglia, L., Corradini, D., 1997. Upper Campanian to Maastrichtian dinoflagellate zonation in the northern Apennines, Italy. Newsletters on Stratigraphy 35, 29–57.
- Roncaglia, L., Field, B.D., Raine, J.I., Schiøler, P., Wilson, G.J., 1999. Dinoflagellate biostratigraphy of Piripauan–Haumurian (Upper Cretaceous) sections from northeast South Island, New Zealand. Cretaceous Research 20, 271–314.
- Rowe, A.W., 1900. The zones of the White Chalk of the English coast I. Kent and Sussex. Proceedings of the Geologists' Association 16, 289–368.
- Rowe, A.W., 1904. The zones of the White Chalk of the English coast IV. Yorkshire. Proceedings of the Geologists' Association 18, 193–296.
- Rowe, A.W., 1929. The zones of the white Chalk of Lincolnshire. Naturalist 875, 411–439.
- Sageman, B.B., Meyers, S.R., Arthur, M.A., 2006. Orbital time scale and new C-isotope record for Cenomanian – Turonian boundary stratotype. Geology 34, 125–128.
- Sageman, B.B., Singer, B.S., Meyers, S.R., Seiwert, S.E., Walaszczyk, I., Condon, D.J., Jicha, B.R., Obradovich, D., Sawyer, D.A., 2014. Integrating $^{40}\text{Ar}/^{39}\text{Ar}$, U – Pb, and astronomical clocks in the Cretaceous Niobrara Formation, Western Interior Basin, USA, Geological Society of America Bulletin 126, 956–973.
- Sarjeant, W.A.S., 1966. Dinoflagellate cysts with *Gonyaulax*-type Tabulation. In: Davey, R.J., Downie, C., Sarjeant, W.A.S., Williams, G.L., Studies on Mesozoic and Cainozoic Dinoflagellate Cysts. Bulletin of the British Museum (Natural History), Geology, Supplement 3, London, pp. 107–157.
- Sarjeant, W.A.S., 1985. The German Aptian dinoflagellate cysts of Eisenack (1958): A restudy. Review of Palaeobotany and Palynology 45, 47–106.
- Sarjeant, W.A.S., Stancliffe, R.P.W., 1994. The *Micrhystridium* and *Veryhachium* complexes (Acanthomorpha: Acanthomorpha and Polygonomorpha): A taxonomic reconsideration. Micropaleontology 40, 1–77.
- Sarjeant, W.A.S., Lacalli, T., Gaines, G., 1987. The cysts and skeletal elements of dinoflagellates: speculations on the ecological causes for their morphology and development. Micropaleontology 33, 1–36.

- Sarkar, S., Prasad, B., 2000. Palaeoenvironmental significance of dinoflagellate cysts from the Subathu Formation (Late Ypresian–Middle Lutetian) of Koshalia Nala Section, Shimla Hills, India. *Himalayan Geology* 21, 167–176.
- Schiøler, P., 1992. Dinoflagellate cysts from the Arnager Limestone Formation (Coniacian, Late Cretaceous) Bornholm, Denmark. *Review of Palaeobotany and Palynology* 72, 1–25.
- Schiøler, P., Wilson, G.J., 1998. Dinoflagellate biostratigraphy of the Middle Coniacian–Lower Campanian (Upper Cretaceous) in South Marlborough, New Zealand. *Micropaleontology* 44, 313–349.
- Schiøler, P., Wilson, G.J., 2001. Dinoflagellate biostratigraphy around the Campanian–Maastrichtian boundary at Tercis les Bains, southwest France. In: Odin, G.S. (Ed), *The Campanian–Maastrichtian Stage Boundary: characterisation at Tercis les Bains (France): correlation with Europe and other Continents*. IUGS Special Publication (Monograph) Series 36; *Developments in Palaeontology and Stratigraphy* Series 19, Amsterdam, pp. 221–234.
- Schlanger, S.O., Arthur, M.A., Jenkyns, H.C., Scholle, P.A., 1987. The Cenomanian – Turonian Oceanic Anoxic event, I. Stratigraphy and distribution of organic carbon-rich beds and the marine $\delta^{13}\text{C}$ excursion. In: *Marine Petroleum Source Rocks*. Blackwell, Oxford, pp. 371–399.
- Scholle, P.A., Arthur, M.A., 1980. Carbon isotopic fluctuation in Cretaceous pelagic limestones: potential stratigraphic and petroleum exploration tool. *AAPG Bulletin* 64, 67–87.
- Schrag, D.P., Depaolo, D.J., Richter, F.M., 1995. Reconstructing past sea-surface temperatures - correcting for diagenesis of bulk marine carbonate. *Geochimica et Cosmochimica Acta* 59, 2265–2278.
- Schrank, E., 1988. Effects of chemical processing on the preservation of peridinioid dinoflagellates: a case from the Late Cretaceous of NE Africa. *Review of Palaeobotany and Palynology* 56, 123–140.
- Schrank, E., Ibrahim, M.I.A., 1995. Cretaceous (Aptian–Maastrichtian) palynology of foraminifera-dated wells (KRM-1, AG-18) in Northwestern Egypt. *Berliner Geowissenschaftliche Abhandlungen, Reihe A, Geologie und Paläontologie* 177, 1–44.
- Schulz, M.-G., Ernst, G., Ernst, H., Schmid, F., 1984. Coniacian to Maastrichtian stage boundaries in the standard sections for the Upper Cretaceous white chalk of N.W. Germany (Lägerdorf – Krons Moor – Hemmoor): Definitions and proposals. *Bulletin of the Geological Society of Denmark* 33, 203–215.
- Scotese, C.R., Boucot, A.J., Chen Xu, 2014. *Atlas of Phanerozoic Climatic Zones (Mollweide Projection)*, Volumes 1-6, PALEOMAP Project PaleoAtlas for ArcGIS, PALEOMAP Project, Evanston, IL.
- Scott, R.W., Oboh-Ikuenobe, F.E., Benson Jr., D.G., Holbrook, J.M., Alnahwi, A., 2018. Cenomanian-Turonian flooding cycles: U.S. Gulf Coast and Western Interior. *Cretaceous Research*, 89 191–210.

- Shand, P., Darbyshire, D.P.F., Love, A.J., Edmunds, W.M., 2009. Sr isotopes in natural waters: Applications to source characterisation and water-rock interaction in contrasting landscapes. *Applied Geochemistry* 24, 574–586.
- Shipboard Scientific Party, 2004. Site 1276. In: Tucholke, B.E., Sibuet, J.-C., Klaus, A., et al. (Eds), *Proceedings of the Ocean Drilling Project, Initial Reports. Ocean Drilling Program 210*, College Station, Texas, pp. 1–358.
- Siegl-Farkas, A., 1997. Dinoflagellate stratigraphy of the Senonian Formations of the Transdanubian range. *Acta Geologica Hungarica* 40, 73–100.
- Singh, C., 1983. Cenomanian microfloras of the Peace River area, northwestern Alberta. *Research Council of Alberta, Bulletin* 44, 322 pp.
- Skertchly, S.B.J., 1879. *On the Manufacture of Gun Flints*. HMSO, London, 80 pp.
- Skupien, P., Mohamed, O., 2008. Campanian to Maastrichtian palynofacies and dinoflagellate cysts of the Silesian Unit, Outer Western Carpathians, Czech Republic. *Bulletin of Geosciences* 83, 207–224.
- Slimani, H., 1994. Les dinokystes des Craies du Campanien au Danien à Halembye, Turnhout (Belgique) et à Beutenaken (Pays-Bas). *Mémoires pour servir à l'explication des cartes Géologiques et Minières de la Belgique* 37, 1–173.
- Slimani, H., 2001a. Les kystes de dinoflagellés du Campanien au Danien dans la région de Maastricht (Belgique, Pays-Bas) et Turnhout (Belgique): biozonation et corrélation avec d'autres régions en Europe occidentale. *Geologica et Palaeontologica* 35, 161–201.
- Slimani, H., 2001b. New species of dinoflagellate cysts from the Campanian–Danian Chalks at Halembye and Turnhout (Belgium) and at Beutenaken (The Netherlands). *Journal of Micropalaeontology* 20, 1–11.
- Smelror, M., Jacobsen, T., Rise, L., Skarbo, O., Verdenius, J., Vigran, J.O., 1994. Jurassic to Cretaceous stratigraphy of shallow cores on the More Basin Margin, Mid-Norway. *Norsk Geologisk Tidsskrift (Norwegian Journal of Geology)* 74, 89–107.
- Smelror, M., Mørk, A., Moncal, E., Rutledge, D., Leereveld, H., 1998. The Klippfisk Formation: A new lithostratigraphic unit of Lower Cretaceous platform carbonates on the western Barents Shelf. *Polar Research, New Series* 17, 181–202.
- Smith, A.B., Batten, D.J., 2002. *Fossils of the Chalk*. Second ed. London: The Palaeontological Association, 374 pp.
- Smith, S.W., 1992. Microplankton from the Cape Lamb Member, López de Bertodano Formation (Upper Cretaceous), Cape Lamb, Vega Island. *Antarctic Science* 4, 337–353.
- Soliman, A., Suttner, T.J., Lukeneder, A., Summesberger, H., 2008. Dinocysts and ammonoids of Upper Cretaceous sediments of the Pemberger Quarry (Krappfeld, Carinthia, Austria). *Berichte der Geologischen Bundesanstalt* 74, 100–101.
- Soliman, A., Suttner, T.J., Lukeneder, A., Summesberger, H., 2009. Dinoflagellate cysts and Ammonoids from Upper Cretaceous sediments of the Pemberger Formation (Krappfeld, Carinthia, Austria). *Ann. Naturhist. Mus. Wien* 110, 401–421.

- Song, Z.-C., Zheng, Y., Liu, J., 1995. Palynological assemblages across the Cretaceous/Tertiary boundary in northern Jiangsu, Eastern China. *Cretaceous Research* 16, 465–482.
- Soper, N.J., Downie, C., Higgins, A.C., Costa, L.I., 1976. Biostratigraphic ages of Tertiary Basalt on the East Greenland Continental Margin and their relationship to plate separation in the Northeast Atlantic. *Earth and Planetary Science Letters* 32, 149–157.
- Souque, C., Knipe, R.J., Davies, R.K., Jones, P., Welch, M.J., Lorenz, J., 2019. Fracture corridors and fault reactivation: Example from the Chalk, Isle of Thanet, Kent, England. *Journal of Structural Geology* 122, 11–26.
- Sprovieri, M., Sabatino, N., Pelosi, N., Batenburg, S.J., Coccioni, R., Iavarone, M., Mazzola, S., 2013. Late Cretaceous orbitally-paced carbon isotope stratigraphy from the Bottaccione Gorge (Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology* 379, 81–94.
- Steinkraus, W.E., 1980. Biostratigraphy. In: Amato, R.V., Behout, J.W. (Eds), *Geologic and Operational summary, Cost No. G-1 Well, Georges Bank area, North Atlantic OCS*. United States Geological Survey, Open-File Report 80, 39–52.
- Stoian, L.M., 2002. Late Cretaceous–Late Eocene palynofloras from drillhole Troas 1, offshore Otway Basin, South Australia. *Minerals and Energy Resources*. Government of South Australia. Report 300 : 2002, 1–21.
- Stoll, H.M., Schrag, D.P., 2000. High-resolution stable isotope records from the Upper Cretaceous rocks of Italy and Spain: Glacial episodes in a greenhouse planet? *GSA Bulletin* 112, 308–319.
- Stover, L.E., Evitt, W.R., 1978. Analyses of pre-Pleistocene organic-walled dinoflagellates. *Stanford University Publications, Geological Sciences* 15, 1–300.
- Stover, L.E., Helby, R.J., 1987a. Early Cretaceous dinoflagellates from the Vinck-1 Well, offshore Western Australia. In: *Jell, P.A. (Ed.), Studies in Australian Mesozoic Palynology, Association of Australasian Palaeontologists, Memoir 4, Sydney*, pp. 227–260.
- Stover, L.E., Helby, R.J., 1987b. Some Early Cretaceous dinoflagellates from the Houtman-1 Well, Western Australia. In: *Jell, P.A. (Ed.), Studies in Australian Mesozoic Palynology, Association of Australasian Palaeontologists, Memoir 4, Sydney*, pp. 261–295.
- Stover, L.E., Brinkhuis, H., Damassa, S.P., Versteil, L. de, Helby, R.J., Monteil, E., Partridge, A.D., Powell, A.J., Riding, J.B., Smelror, M., Williams, G.L., 1996. Mesozoic – Tertiary dinoflagellates, acritarchs and Prasinophytes. In: *Jansonius, J., McGregor, D.C. (Eds), Palynology: Principles and Applications. American Association of Stratigraphic Palynologists* 2, 641–750.
- Sumbler, M.G., 1999. *The Stratigraphy of the Chalk Group in Yorkshire and Lincolnshire*. British Geological Survey, Keyworth, Nottingham. Technical Report WN/99/02, 30 pp.
- Sun, X., 1994. Paleogene dinoflagellate cysts from the Liaohe Depression, North East China. *Palynology* 18, 67–86.

- Surlyk, F., Rasmussen, S.L., Boussaha, M., Schiøler, P., Schovsbo, N.H., Sheldon, E., Stemmerik, L., Thibault, N., 2013. Upper Campanian–Maastrichtian holostratigraphy of the eastern Danish Basin. *Cretaceous Research* 46, 232–256.
- Tea-Yassia, J., Digbeh, Z.B., Yaa, K.R., Glohia, B.V., 1999. Study of some Upper Cretaceous palynomorphs from the Côte d'Ivoire offshore basin: biostratigraphical and palaeoenvironmental implications. *Journal of African Earth Sciences* 29, 783–798.
- Thibault, N., Jarvis, I., Voigt, S., Gale, A.S., Attree, K., Jenkyns, H.C., 2016. Astronomical calibration and global correlation of the Santonian (Cretaceous) based on the marine carbon isotope record. *Paleoceanography* 31, 847–865.
- Thurrow, J., Moullade, M., Brumsack, H.-J., Masure, E., Taugourdeau-Lantz, J., Dunham, K., 1988. The Cenomanian–Turonian boundary event (CTBE) at Hole 641A, ODP Leg 103, (Compared with the CTBE interval at Site 398). In: Boillot, G., Winterer, E.L., et al. (Eds), *Proceedings of the Ocean Drilling Program, Scientific Results* 103, College Station, pp. 587–634.
- Timmcke, T.A., 1981. Palynology of the Lower Cretaceous Pebble Shale Unit, Point Barrow, Alaska. United States Geological Survey, Open-File Report 81, 2–115.
- Tocher, B.A., 1984. Palynostratigraphy of uppermost Albian to basal Coniacian (Cretaceous) sediments of the western Anglo–Paris Basin. Unpublished PhD thesis, City of London Polytechnic, London, 223 pp.
- Tocher, B.A., 1987. Campanian to Maastrichtian dinoflagellate cysts from the United States Atlantic margin, Deep Sea Drilling Project Site 612. In: Poag, C.W., Watts, A.B., et al. (Eds), *Initial Reports of the Deep Sea Drilling Project*, Washington, U.S. Government Printing Office 95, 419–428.
- Tocher, B.A., Jarvis, I., 1987. Dinoflagellate cysts and stratigraphy of the Turonian (Upper Cretaceous) chalk near Beer, southeast Devon, England. In: Hart, M.B. (Ed.), *Micropalaeontology of Carbonate Environments*. Special Publication of the British Micropalaeontological Society, pp. 138–175.
- Tocher, B.A., Jarvis, I., 1994a. Dinoflagellate cyst distribution and stratigraphy of the Lower – Middle Cenomanian (Upper Cretaceous) at Fumichon, Normandy, Northern France. *Revue de Micropaléontologie* 37, 223–232.
- Tocher, B.A., Jarvis, I., 1994b. Dinoflagellate cyst distribution from the Lower Turonian (Upper Cretaceous) of Ports, Indre-et-Loire. *Bulletin d'Information des Géologues du Bassin de Paris* 31, 13–23.
- Tocher, B.A., Jarvis, I., 1995. Dinocyst distributions and stratigraphy of two Cenomanian – Turonian boundary (Upper Cretaceous) sections from the Western Anglo-Paris Basin. *Journal of Micropalaeontology* 14, 97–105.
- Tocher, B.A., Jarvis, I., 1996. Dinoflagellate cyst distributions and the Albian–Cenomanian boundary (Mid-Cretaceous) at Cordebugle, northwest France and Lewes, Southern England. *Journal of Micropalaeontology* 15, 55–67.
- Torsvik, T.H., Van der Voo, R., Preeden, U., Mac Niocaill, C., Steinberger, B., Doubrovine, P.V., van Hinsbergen, D.J., Domeier, M., Gaina, C., Tohver, E., 2012. Phanerozoic polar wander, palaeogeography and dynamics. *Earth-Science Reviews* 114, 325–368.

- Tsikos, H., Jenkyns, H.C., Walsworth-Bell, B., Petrizzo, M.R., Forster, A., Kolonic, S., Erba, E., Premoli-Silva, I.P., Baas, M., Wagner, T., Sinninghe Damsté, J.S., 2004. Carbon-isotope stratigraphy recorded by the Cenomanian – Turonian Oceanic Anoxic Event: correlation and implications based on three key localities. *Journal of the Geological Society London* 161, 711–719.
- Uličný, D., Jarvis, I., Gröcke, D.R., Čech, S., Laurin, J., Olde, K., Trabucho-Alexandre, J., Švábenická, L., Pedenychouk, N., 2014. A high-resolution carbon-isotope record of the Turonian stage correlated to a siliciclastic basin fill: Implications for mid-Cretaceous sea-level change. *Palaeogeography, Palaeoclimatology, Palaeoecology* 405, 42–58.
- Unwins, P.J.R., Batten, D.J., 1989. Early to mid-Cretaceous palynology of northeast Libya. In: El-Arnauti, A., Owens, B., Thusu, B. (Eds), *Subsurface Palynostratigraphy of Northeast Libya*, pp. 215–257.
- Uramoto, G.-I., Tahara, R., Sekiya, T., Hirano, H., 2013. Carbon isotope stratigraphy of terrestrial organic matter for the Turonian (Upper Cretaceous) in northern Japan: Implications for ocean-atmosphere $\delta^{13}\text{C}$ trends during the mid-Cretaceous climatic optimum. *Geosphere* 9, 355–366.
- Vajda, V., 2001. Aalenian to Cenomanian terrestrial palynofloras of SW Scania, Sweden. *Acta Palaeontologica Polonica* 46, 403–426.
- Valensi, L., 1955. Sur quelques microorganismes des silex crétacés du Magdalénien de Saint-Amand (Cher). *Bulletin de la Société Géologique de France, 6e série* 5, 35–40.
- Vandergon, M.A., 1986. Microfossil correlation of Mesozoic and Cenozoic units Arctic National Wildlife Refuge, Northeastern Alaska. Alaska Division of Geological and Geophysical Surveys. Public-data File 86, 1–74.
- Venkatachala, B.S., Kumar, A., 1980. An assemblage of dinoflagellate cysts and acritarchs from Dalmiapuram Grey Sandstone, Cauvery Basin, Tamil Nadu, India. *Journal of the Palaeontological Society of India* 23, 92–109.
- Verdier, J.P., 1970. Addendum to the memoir of G. Deflandre and I.C. Cookson. Fossil microplankton from Upper Mesozoic and Tertiary sediments of Australia. *Cahiers de Micropaléontologie* 4, 1–54.
- Voigt, S., 2000. Stable oxygen and carbon isotopes from brachiopods of southern England and northwestern Germany: estimation of Upper Turonian palaeotemperatures. *Geological Magazine* 137, 687–703.
- Voigt, S., Hilbrecht, H., 1997. Late Cretaceous carbon isotope stratigraphy in Europe: correlation and relations with sea level and sediment stability. *Palaeogeography, Palaeoclimatology, Palaeoecology* 134, 39–59.
- Voigt, S., Wiese, F., 2000. Evidence for Late Cretaceous (Late Turonian) climate cooling from oxygen-isotope variations and palaeobiogeographic changes in Western and Central Europe. *Journal of the Geological Society London* 157, 737–743.
- Voigt, S., Schönfeld, J., 2010. Cyclostratigraphy of the reference section for the Cretaceous white chalk of northern Germany, Lagerdorf – Krons Moor: A late Campanian – early Maastrichtian orbital time scale. *Palaeogeography, Palaeoclimatology, Palaeoecology* 287, 67–80.

- Voigt, S., Gale, A.S., Flögel, S., 2004. Midlatitude shelf seas in the Cenomanian-Turonian greenhouse world: Temperature evolution and North Atlantic circulation. *Paleoceanography* 19, PA4020.
- Voigt, S., Gale, A.S., Voigt, T., 2006. Sea-level change, carbon cycling and palaeoclimate during the Late Cenomanian of northwest Europe; an integrated palaeoenvironmental analysis. *Cretaceous Research* 27, 836–858.
- Voigt, S., Aurag, A., Leis, F., Kaplan, U., 2007. Late Cenomanian to Middle Turonian high-resolution carbon isotope stratigraphy: New data from the Münsterland Cretaceous Basin, Germany. *Earth and Planetary Science Letters* 253, 196–210.
- Voigt, S., Friedrich, O., Norris, R.D., Schoenfeld, J., 2010. Campanian – Maastrichtian carbon isotope stratigraphy: shelf-ocean correlation between the European shelf sea and the tropical Pacific Ocean. *Newsletters on Stratigraphy* 44, 57–72.
- Voigt, S., Gale, A.S., Jung, C., Jenkyns, H.C., 2012. Global correlation of Upper Campanian – Maastrichtian successions using carbon-isotope stratigraphy: development of a new Maastrichtian timescale. *Newsletters on Stratigraphy* 45, 25–53.
- Vozzhennikova, T.F., 1967. *Iskopaemye peridinei Yur'skikh, Melovykh i Paleogenovykh otlozheniy SSSR*, Izdatelstvo Nauka, Moscow and S.R., 347 pp.
- Wagreich, M., Pavlishina, P., Malata, E., 2006. Biostratigraphy of the lower red shale interval in the Rhenodanubian Flysch Zone of Austria. *Cretaceous Research* 27, 743–753.
- Walaszczyk, I., 2000. Inoceramid bivalves at the Turonian/Coniacian boundary: biostratigraphy, events and diversity trend. *Acta Geologica Polonica* 50, 421–430.
- Walaszczyk, I., Wood, C.J., 1998. Inoceramids and biostratigraphy at the Turonian/Coniacian boundary based on the Salzgitter-Salder Quarry, Lower Saxony, Germany, and the Słupia Nadbrzeżna section, central Poland. *Acta Geologica Polonica* 48, 395–434.
- Walaszczyk, I., Cobban, W.A., 2000. Inoceramid faunas and biostratigraphy of the Upper Turonian – Lower Coniacian of the Western Interior of the United States. *Special Papers in Palaeontology* 64, 1–118.
- Walaszczyk, I., Wood, C.J., 2018. Inoceramid bivalves from the Coniacian (Upper Cretaceous) of the Staffhorst shaft (Lower Saxony, Germany) – Stratigraphical significance of a unique succession. *Cretaceous Research* 87, 226–240.
- Walaszczyk, I., Wood, C.J., Lees, J.A., Peryt, D., Voigt, S., Wiese, F., 2010. The Salzgitter-Salder Quarry (Lower Saxony, Germany) and Słupia Nadbrzeżna river cliff section (central Poland): a proposed candidate composite Global Boundary Stratotype Section and Point for the Coniacian Stage (Upper Cretaceous). *Acta Geologica Polonica* 60, 445–477.
- Walker, J.C.G., 1986. Global geochemical cycles of carbon, sulfur and oxygen. *Marine Geology* 70, 159–174.
- Welch, M.J., Souquet, C., Davies, R.K., Knipe, R.J., 2015. Using mechanical models to investigate the controls on fracture geometry and distribution in chalk. In: Agar, S.M., Geiger, S. (Eds), *Fundamental Controls on Fluid Flow in Carbonates: Current Workflows to Emerging Technologies*. Geological Society of London Special Publication 406, 281–309.

- Wendler, I., 2013. A critical evaluation of carbon isotope stratigraphy and biostratigraphic implications for Late Cretaceous global correlation. *Earth-Science Reviews* 126, 116–146.
- Wetzel, O., 1933. Die in organischer Substanz erhaltenen Mikrofossilien des baltischen Kreide-Feuersteins mit einem sediment-petrographischen und stratigraphischen Anhang. *Paläontographica Abteilung A* 78, 1–110.
- Wetzel, O., 1940. Mikropaläontologische Untersuchungen an der obersten Kreide von Stevns Klint-Kridtbrud auf der dänischen Insel Seeland und an ihrem Feuerstein in geschiebekundlicher Hinsicht. *Zeitschrift für Geschiebeforschung* 16, 118–165.
- Whatley, R.C., Pyne, R.S., Wilkinson, I.P., 2003. Ostracoda and palaeo-oxygen levels, with particular reference to the Upper Cretaceous of East Anglia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 194, 355–386.
- Wheeler, J.W., Sarjeant, W.A.S., 1990. Jurassic and Cretaceous palynomorphs from the Central Alborz Mountains, Iran; Their significance in biostratigraphy and palaeogeography. *Modern Geology* 14, 267–374.
- Whitaker, W., 1865. On the Chalk of Buckinghamshire and on the Totternhoe Stone. *Quarterly Journal of the Geological Society of London* 21, 398–400.
- White, H.H., 1842. On fossil *Xanthidia*. *Microscopical Journal*, London 11, 35–40.
- White, H.H., 1844. On a new species of fossil *Xanthidium*. *Transactions of the Microscopical Society of London* 1, 87.
- Whitham, F., 1991. The stratigraphy of the Upper Cretaceous Ferriby, Welton and Burnham formations north of the Humber, north-east England. *Proceedings of the Yorkshire Geological Society* 46, 227–254.
- Whitham, F., 1993. The stratigraphy of the Upper Cretaceous Flamborough Chalk Formation north of the Humber, north-east England. *Proceedings of the Yorkshire Geological Society* 49, 235–258.
- Whittlesea, P.S., 1991. The Maastrichtian in Norfolk. *Bulletin of the Geological Society of Norfolk* 40, 33–51.
- Wiese, F., Wood, C.J., Kaplan, U., 2004. 20 years of event stratigraphy in NW Germany; advances and open questions. *Acta Geologica Polonica* 54, 639–656.
- Wilkinson, I.P., Halliwell, G.P., 1980. Offshore micropalaeontological biostratigraphy of southern and western Britain. *Institute of Geological Sciences, Report* 79, 1–65.
- Wilkinson, I.P., Hine, N.M., Riding, J.B., 1993. Appendix: Cretaceous biostratigraphic biomarkers. In: Johnson, H., Lott, G.K. (Eds), *Cretaceous of the Central northern North Sea. Lithostratigraphic Nomenclature of the UK North Sea* 2, 187 pp.
- Wilkinson, S.J., 1849. Observations on *Xanthidium*, both fossil and recent. *Transactions of the Microscopical Society of London* 2, 89–92.
- Williams, G.L., 1975. Dinoflagellate and spore stratigraphy of the Mesozoic–Cenozoic, offshore eastern Canada. *Geological Survey of Canada, Paper* 75, 107–161.
- Williams, G.L., 1977. Palynological biostratigraphy, Deep Sea Drilling Project, Sites 367 and 370. In: Lancelot, Y., Seibold, E., et al. (Eds), *Deep Sea Drilling Project*,

- Washington, Initial Reports, U.S. Government Printing Office 38, Washington, pp. 783–798.
- Williams, G.L., Brideaux, W.W., 1975. Palynologic analyses of Upper Mesozoic and Cenozoic rocks of the Grand Banks, Atlantic Continental Margin. Geological Survey of Canada, Bulletin 236, 1–162.
- Williams, G.L., Bujak, J.P., 1985. Mesozoic and Cenozoic dinoflagellates. In: Bolli, H.M., Saunders, J.B., Perch-Nielsen, K. (Eds), *Plankton Stratigraphy*. Cambridge University Press, Cambridge pp. 847–964.
- Williams, G.L., Stover, L.E., Kidson, E.J., 1993. Morphology and stratigraphic range of selected Mesozoic–Cenozoic dinoflagellate taxa in the northern Hemisphere. Geological Survey of Canada, Paper 92, 1–137.
- Williams, G.L., Brinkhuis, H., Pearce, M.A., Fensome, R.A., Weegink, J.W., 2004. Southern Ocean and Global Dinoflagellate Cyst Events compared: Index events for the Late Cretaceous–Neogene. In: Exon, N.F., Kennett, J.P., Malone, M.J. (Eds), *Proceedings of the Ocean Drilling Program, Scientific Results 139*, 1–98.
- Williams, G.L., Fensome, R.A., MacRae, R.A., 2017. The Lennin and Williams Index of fossil dinoflagellates 2017 edition. American Association of Stratigraphic Palynologists Foundation, Contribution 48, 1097 pp.
- Wilmsen, M., 2003. Sequence stratigraphy and palaeoceanography of the Cenomanian Stage in northern Germany. *Cretaceous Research* 24, 525–568.
- Wilmsen, M., 2007. Integrated stratigraphy of the upper lower-lower Middle Cenomanian of northern Germany and southern England. *Acta Geologica Polonica* 57, 263–279.
- Wilmsen, M., Niebuhr, B., Wood, C.J., Zawischa, D., 2007. Fauna and palaeoecology of the Middle Cenomanian *Praeactinoptammax primus* Event at the type locality, Wunstorf quarry, northern Germany. *Cretaceous Research* 28, 428–460.
- Wilson, G.J., 1971. Observations on European Late Cretaceous dinoflagellate cysts. Part 1. In: Farinacci, A. (Ed.), *Proceedings of the 2nd Planktonic Conference, Rome, 1970*. Edizioni Tecnoscienza 2, Rome, pp. 1259–1275.
- Wilson, G.J., 1974. Upper Campanian and Maastrichtian Dinoflagellate Cysts from the Maastricht Region and Denmark. Unpublished PhD thesis, University of Nottingham, Nottingham, 601 pp.
- Wilson, G.J., 1975. Palynology of deep-sea cores from DSDP Site 275, Southeast Campbell Plateau. In: Kennett, J.P., Houtz, R.E., et al. (Eds), *Initial Reports of the Deep Sea Drilling Project*, U.S. Government Printing Office 29, Washington, pp. 1031–1035.
- Wilson, G.J., 1976. Late Cretaceous, (Senonian), dinoflagellate cysts from the Kahuitara Tuff, Chatham Islands. *New Zealand Journal of Geology and Geophysics* 19, 127–143.
- Wilson, G.J., 1982. Dinoflagellates from an ammonite-bearing float concretion, Tangaruhe Stream, Southern Hawkes Bay. *New Zealand Geological Survey* 52, 5.
- Wilson, G.J., 1984. New Zealand Late Jurassic to Eocene dinoflagellate biostratigraphy – A summary. *Newsletters on Stratigraphy* 13, 104–117.

- Wilson, G.J., 1989. Appendix 1: Dinoflagellate assemblages from the Urewera Group. In: Moore, P.R., et al. (Ed.), *Stratigraphy and Structure of Cretaceous (Neocomian – Maestrichtian) sedimentary rocks in the Anini-Okaura Stream area, Urewera National Park, New Zealand*. *New Zealand Journal of Geology and Geophysics* 32, 525–526.
- Wilson, G.J., Morgans, H.E.G., 1989. Cretaceous – Tertiary boundary at Tawanui Southern Hawkes Bay, New Zealand. *New Zealand Geological Survey, Record* 40, 29–40.
- Wiltshire, T., 1869. On the Red Chalk of Hunstanton. *Quarterly Journal of the Geological Society of London* 25, 185–192.
- Witmer, R.J., Mickey, M.B., Haga, H., 1981. Biostratigraphic correlation of selected test wells of National Petroleum Reserve in Alaska. *United States Geological Survey, Open-File Report* 81–1165, 1–92.
- Wohlwend, S., Hart, M., Weissert, H., 2016. Chemostratigraphy of the Upper Albian to mid-Turonian Natih Formation (Oman) — how authigenic carbonate changes a global pattern. *The Depositional Record* 2, 97–117.
- Wood, C.J., 1992. Upper Cretaceous (Chalk). In: *Geology of the Country around Kingston upon Hull and Brigg Memoir for 1:50 000 Geological Sheets 80 and 89 (England and Wales)*. HMSO, London, pp. 77–101.
- Wood, C.J., 1996. Upper Cretaceous: Chalk Group. In: *London and the Thames Valley*. 4th ed. HMSO, London, pp. 76–91.
- Wood, C.J., Smith, E.G., 1978. Lithostratigraphical classification of the Chalk in North Yorkshire, Humberside and Lincolnshire. *Proceedings of the Yorkshire Geological Society* 42, 263–287.
- Wood, C.J., Mortimore, R., 1988. Chalk biostratigraphy. In: *Geology of the country around Brighton and Worthing*. HMSO, London, pp. 58–64.
- Wood, C.J., Mortimore, R.N., 1995. An anomalous Black Band succession (Cenomanian – Turonian boundary interval) at Melton Ross, Lincolnshire, eastern England and its international significance. *Berlin Geowiss Abh Reihe E.16 Gundolf Ernst Festschrift*, pp. 277–287.
- Wood, C.J., Ernst, G., Rosemann, G., 1984. The Turonian – Coniacian stage boundary in Lower Saxony (Germany) and adjacent areas: the Salzgitter – Salder Quarry as a proposed international standard section. *Bulletin of the Geological Society of Denmark* 33, 225–238.
- Wood, C.J., Morter, A.A., Gallois, R.W., 1994. Appendix 1. Upper Cretaceous stratigraphy of the Trunch borehole. TG23SE8. In: *Geology of the Country around Great Yarmouth Memoir for 1:50,000 Sheet 162 (England and Wales) with an Appendix on the Trunch Borehole by Wood and Morter*. HMSO, London, pp. 105–110.
- Wood, C.J., Batten, D.J., Mortimore, R.N., Wray, D.S., 1997. The stratigraphy and correlation of the Cenomanian – Turonian boundary interval succession in Lincolnshire, northern England. *Freiberger Forschungshefte Reihe C* 468, 333–346.
- Wood, S.E., Askin, R.A., 1992. Dinoflagellate cysts from the Marambio Group, (Upper Cretaceous) of Humps Island. *Antarctic Science* 4, 327–336.

- Wood, S.E.L., Riding, J.B., Fensome, R.A., Williams, G.L., 2016. A review of the *Sentusidinium* complex of dinoflagellate cysts. *Review of Palaeobotany and Palynology* 234, 61–93.
- Woods, H., 1896. The Mollusca of the Chalk Rock: Part I. *Quarterly Journal of the Geological Society of London* 52, 68–98.
- Woods, M.A., Chacksfield, B.C., 2012. Revealing deep structural influences on the Upper Cretaceous Chalk of East Anglia (UK) through inter-regional geophysical log correlations. *Proceedings of the Geologists' Association* 123, 486–499.
- Woods, M.A., Mortimore, R.N., Wood, C.J., 2012. The Chalk of Suffolk. In: *A Celebration of Suffolk Geology: GeoSuffolk 10th Anniversary Volume*. GeoSuffolk, Ipswich, pp. 105–131.
- Wray, D.S., 1999. Identification and long-range correlation of bentonites in Turonian – Coniacian (Upper Cretaceous) chalks of northwest Europe. *Geological Magazine* 136, 361–371.
- Wray, D.S., Wood, C.J., 1998. Distinction between detrital and volcanogenic clay-rich beds in Turonian – Coniacian chalks of eastern England. *Proceedings of the Yorkshire Geological Society* 52, 95–105.
- Wrenn, J.H., Hart, G.F., 1988. Paleogene dinoflagellate cyst biostratigraphy of Seymour Island, Antarctica. In: Feldmann, R.M., Woodburne, M.O. (Eds), *Geology and Paleontology of Seymour Island, Antarctic Peninsula*. Geological Society of America, Memoir 169, 321–447.
- Wright, C.W., 1979. The ammonites of the English Chalk. *Bulletin of the British Museum Natural History (Geology)* 31, 281–332.
- Wright, C.W., Wright, E.V., 1942. The Chalk of the Yorkshire Wolds. *Proceedings of the Geologists' Association* 53, 111–127.
- Wright, C.W., Kennedy, W.J., 2015. The Ammonoidea of the Lower Chalk, Part 6. *Monograph of the Paleontographical Society London* 169, 404–460.
- Wright, C.W., Kennedy, W.J., 2017. The Ammonoidea of the Lower Chalk, Part 7. *Monograph of the Paleontographical Society London* 171, 461–561.
- Xu, J., Pan, Z., Yang, Y., Zhu, Y., Fan, N., 1997. On the Paleogene microphytoplankton from the Shengli oil-bearing region, Shandong, China, pp. 1–241.
- Yun, H.-S., 1981. Dinoflagellates of the Upper Cretaceous (Santonian), of Westfalen. *Paläeontographica Abteilung B* 177, 1–89.
- Yun, H.-S., Byun, H., Park, Y.A., 2000. Paleoenvironments interpretation based on microfossil assemblages from intertidal sediments of the Haenam Bay. *Journal of the Paleontological Society of Korea* 16, 123–144.
- Zinsmeister, W.J., Camacho, H.H., 1982. Late Eocene (to possibly Earliest Oligocene) molluscan fauna of the La Meseta Formation of Seymour Island, Antarctic Peninsula. In: Craddock, C. (Ed.), *Antarctic Geoscience*. International Union of Geological Sciences, Series B, pp. 299–304.
- Žítt, J., Nekvasilová, O., Bosák, P., Svobodová, M., Štemproková-Jírová, D., Štastný, M., 1997. Rocky coast facies of the Cenomanian–Turonian boundary interval at Velim,

(Bohemian Cretaceous Basin, Czech Republic). Second Part. Vestník Ceskeho Geologickeho Ústavu (Bulletin of the Czech Geological Survey) 72, 141–155.

Žítt, J., Vodrážka, R., Hradecká, L., Svobodová, M., Zágöršek, K., 2006. Late Cretaceous environments and communities as recorded at Chrtníky (Bohemian Cretaceous Basin, Czech Republic). Bulletin of Geosciences 81, 43–79.

List of Figures and Tables

Fig. 1. Chalk provinces and the geology of north Norfolk showing the location of the Trunch borehole. Geological map based on Peake and Hancock (1961, 1970), inset map modified from Mortimore and James (2015) and Mitchell (2019).

Fig. 2. Stratigraphic framework of the English Chalk with the key markers identified in the Trunch succession and their lateral equivalents in the Northern and Southern Provinces. Dark blue vertical bar indicates the stratigraphic extent of the study interval in the Trunch borehole. Named marker beds follow the Northern Province stratigraphy (Wood and Smith, 1978; Gaunt et al., 1992), with central East Anglia Transitional Province (Woods et al., 2012) and Southern Province (Mortimore, 1986; Mortimore et al., 2001) named equivalents indicated where appropriate. B1 – B5 are bentonitic marls (Wray and Wood, 1998; Wray, 1999). Not to scale. Alb = Albian, HFm = Hunstanton Formation. Modified from Woods et al. (2012).

Fig. 3. Cretaceous stratigraphy of the Trunch borehole I: Albian to Upper Coniacian 515 – 375 m depth. Lithology based on the detailed logs of Morter et al. (1975; http://scans.bgs.ac.uk/sobi_scans/boreholes/517419/images/12114521.html). Macrofossil records from Morter et al. (1975) and Wood et al. (1994). Named carbon stable-isotope events after Jarvis et al. (2006). B1 – B5 are bentonitic marls (Wray and Wood, 1998; Wray, 1999). Named marker beds follow the Northern Province stratigraphy (Wood and Smith, 1978; Gaunt et al., 1992), with central East Anglia Transitional Province (Woods et al., 2012) and Southern Province (Mortimore, 1986; Mortimore et al., 2001) named equivalents indicated where appropriate (**Fig. 2**). See text for further stratigraphic details. LJ = Lower Jurassic, A = Albian, Ce = Cenomanian, UCe = Upper Cenomanian, LTu = Lower Turonian, MCo = Middle Coniacian, Aj = *Acanthoceras jukes-brownei*, Cg = *Calycoceras guerangeri*, Mg = *Metoicoceras geslinianum*, Mcg = *Micraster coranguinum* Zone, Iv = *Inoceramus virgatus*. Green horizontal bands indicate extent of positive carbon isotope events (CIE), cream bands are negative CIEs (Jarvis et al., 2006): VBE = Virgatus Beds Event; MCEI = Mid-Cenomanian Event I; PBE = P/B Break Event; MCEII = Mid-Cenomanian Event II; JBE = Jukes-brownei Event; ME = Monument Event; CTBE = Cenomanian – Turonian

Boundary Event; Cb = Caburn Event; HW2 and HW3 are Hitch Wood Events 2 and 3 of Uličný et al. (2014). See **Fig. 4** for lithological key.

Fig. 4. Cretaceous stratigraphy of the Trunch borehole II: Upper Coniacian to Lower Campanian 375 – 270 m depth. See **Fig. 2** for sources of stratigraphic data and presentational information. Op = *Offaster pillula*, SCBEa = Santonian – Campanian Boundary Event peak a, SCBEb = peak b (following Thibault et al., 2016).

Fig. 5. Stratigraphic summary, carbonate $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ profiles, and carbon isotope events for the Cenomanian – Lower Campanian of the Trunch borehole. Age model after Table 1. Carbon (blue) and oxygen (red) isotope profiles and carbon isotope events (CIEs) after Jarvis et al. (2006); HW2 and HW3 CIEs following Uličný et al. (2014); SCBE and Pillula CIE from Thibault et al. (2016). Thin coloured lines join individual data points; underlying paler blue and red lines are 3-point moving averages. Strontium isotope data (filled circles with error bars) from McArthur et al. (1993b). Chalk Sr-isotope data (white filled circles) are corrected for diagenesis by subtracting 30×10^{-6} from the measured $^{87}\text{Sr}/^{86}\text{Sr}$ values (cf. McArthur et al., 1993a); fossil data (yellow filled circles) are uncorrected. Orange line connects individual data points. The thick yellow line indicates the primary Sr-isotope trend based on US Western Interior data (McArthur et al., 1994), which underpin the global Sr-isotope reference curve (McArthur et al., 2001, 2012). Deviation of the Trunch data from the reference curve in the Cenomanian and Turonian and is attributed to diagenesis (see text for discussion). Alb = Albian, Ce = Cenomanian, L = Lower, M = Middle, U = Upper, *Mm* = *Mantelliceras mantelli*, *Md* = *M. dixonii*, *Ar* = *Acanthoceras rhotomagense*, *M* = *Mytiloides labiatus*, B1 – B6 are regional bentonitic marl marker beds (Wray and Wood, 1998). Note the interval of poor palynological recovery spanning the Upper Cenomanian – lower Upper Turonian. See Table 1 for numerical age assignments.

Fig. 6. Cenomanian – Lower Campanian stratigraphy and selected dinoflagellate cyst ranges in the Trunch borehole. Vertical grey bars join the lowest and highest occurrences of stratigraphically important dinocyst taxa; these do not necessarily correspond to evolutionary inception or extinction levels (see text for discussion). The

staggered labelling of taxa, for clarity, does not imply more restricted ranges. Refer to **Figs 2 – 5** for stratigraphic assignments and abbreviations.

Fig. 7. Absolute organic walled dinoflagellate cyst abundance, species richness and diversity for the Cenomanian – Lower Campanian of the Trunch borehole. Intervals of peak abundance are indicated by the thick green lines. Carbonate-corrected abundance data are plotted for comparison but follow the same trend as the uncorrected curve. Shannon Index calculated using PAST software (Hammer et al., 2001). Refer to **Figs 2 – 5** for stratigraphic assignments and abbreviations.

Fig. 8. Depth vs. age plot for the Cenomanian – Lower Campanian of the Trunch borehole. The positions of dinocyst datum levels and estimated sediment accumulation rates are shown. Calibration was achieved using 36 age-control points for the Upper Cretaceous (**Table 1**) derived from radioisotopic and astrochronological ages of macrofossil biostratigraphic datum levels, global carbon-isotope excursions, and the base Chron C32 geomagnetic reversal (see **Section 4.5** for methodology).

Fig. 9. English Chalk $\delta^{13}\text{C}_{\text{carb}}$ reference curve and carbon-isotope event (CIE) stratigraphy of the Late Albian – Early Campanian. The curve and isotope stratigraphy of Jarvis et al. (2006) has been recalibrated against age using recently published chronological constraints (see **Section 4.5** for methodology).

Fig. 10a–h. Distribution map of **(a)** *Sindridinium borealis* (base Cenomanian map); **(b)** *Disphaeria munda* (base Cenomanian map); **(c)** *Hapsocysta peridictya* (base Turonian map); **(d)** *Epelidosphaeridia spinosa* (base Turonian map); **(e)** *Cribroperidinium? edwardsii* (base Turonian map); **(f)** *Litosphaeridium siphoniphorum* (base Turonian map); **(g)** *Sepispinula ambigua* (base Turonian map); **(h)** *Pterodinium crassimuratum* (base Turonian map). Site locations rotated from their present-day geographic coordinates using GPlates 2.1. Palaeogeography after Cao et al. (2017); palaeoclimate zones from Scotese et al. (2014). The tabulated summary is provided in Supplemental data 3, see Palynodata Inc and White (2008) for references.

Fig. 11. Summary of Cenomanian bioevents. *C?ed* = *Cribroperidinium? edwardsii*, *Cgl* = *Canningia glomerata*, *Cob* = *Carpodinium obliquicostatum*, *Dmu* = *Disphaeria munda*, *Esp* = *Epelidosphaeridia spinosa*, *Hdic* = *Hapsocysta dictyota*, *Hdif* = *Heterosphaeridium difficile*, *Hpe* = *Hapsocysta peridictya*, *Lsi* = *Litosphaeridium siphoniphorum*, *Pce* = *Pervosphaeridium cenomaniense*, *Pcr* = *Pterodinium crassimuratum*, *Sam* = *Sepispinula ambigua*, *Sbo* = *Sindridinium borealis*, *Sde* = *Sentusidinium devonense*, *Stu* = *Senoniasphaera turonica*, *Wca* = *Wrevittia cassidata*. Species events from the Trunch borehole that have been used as events on the English Chalk Reference $\delta^{13}\text{C}_{\text{carb}}$ curve are shown in bold and indicated by a red dashed line. Additional events on the English Chalk Reference $\delta^{13}\text{C}_{\text{carb}}$ curve are derived from other sources (see the text for details).

Fig. 12. Stratigraphic distribution and relative abundance of dinocyst species recorded by Clarke and Verdier (1967) in the Culver Cliff section with highest occurrences in the Cenomanian – basal Turonian, plotted against the $\delta^{13}\text{C}_{\text{carb}}$ isotope profile (Jarvis et al., 2001) and CIEs of Jarvis et al. (2006). Sample positions are based on correlation to a skeleton stratigraphy (Clarke and Verdier 1967 text-fig. 2). The taxonomy has been updated. Note that we reinterpret Clarke and Verdier's (op cit.) illustrated specimen of *Baltisphaeridium granulatum* (their plate 12 figs 7 – 8; now *Prolixosphaeridium granulatum*) to be *Prolixosphaeridium conulum*. See Fig. 2 for full zonal names. GM = Glauconitic Marl, MR = Melbourn Rock, PM = Plenus Marls, UG = Upper Greensand.

Fig. 13a–h. Distribution map of (a) *Wrevittia cassidata*; (b) *Carpodinium obliquicostatum*; (c) *Heterosphaeridium difficile*; (d) *Pervosphaeridium cenomaniense*; (e) *Canningia glomerata*; (f) *Senoniasphaera turonica*; (g) *Hapsocysta dictyota*; (h) *Sentusidinium devonense* (all base Turonian maps). Site locations rotated from their present-day geographic coordinates using GPlates 2.1. Palaeogeography after Cao et al. (2017); palaeoclimate zones from Scotese et al. (2014). The tabulated summary is provided in Supplemental data 3, see Palynodata Inc and White (2008) for references.

Fig. 14. Summary of Turonian bioevents. *Cgl* = *Canningia glomerata*, *Cme* = *Cauveridinium membranniphorum*, *Hdic* = *Hapsocysta dictyota*, *Hdif* = *Heterosphaeridium difficile*, *Opu* = *Oligosphaeridium pulcherrimum*, *Pce* = *Pervosphaeridium cenomaniense*, *Rtr* = *Raetiaedinium truncigerum*, *Sco* = *Stephodinium coronatum*, *Sde* = *Sentusidinium*

devonense, *Sfi* = *Senoniasphaera filoreticulata*, *Stu* = *Senoniasphaera turonica*. Species events from the Trunch borehole that have been used as events on the English Chalk Reference $\delta^{13}\text{C}_{\text{carb}}$ curve are shown in bold and indicated by a red dashed line.

Additional events on the English Chalk Reference $\delta^{13}\text{C}_{\text{carb}}$ curve are derived from other sources (see the text for details).

Fig. 15a–h. Distribution map of **(a)** *Raetiaedinium truncigerum* (base Turonian map); **(b)** *Senoniasphaera filoreticulata* (base Turonian map); **(c)** *Oligosphaeridium pulcherrimum* (base Coniacian map); **(d)** *Cyclonephelium membraniphorum* (base Coniacian map); **(e)** *Stephodinium coronatum* (base Coniacian map); **(f)** *Heterosphaeridium verdieri* (base Coniacian map); **(g)** *Callaiosphaeridium asymmetricum* (base Santonian map); **(h)** *Spinidinium echinoideum* (base Santonian map). Site locations rotated from their present-day geographic coordinates using GPlates 2.1. Palaeogeography after Cao et al. (2017); palaeoclimate zones from Scotese et al. (2014). The tabulated summary is provided in Supplemental data 3, see Palynodata Inc and White (2008) for references.

Fig. 16. Summary of Coniacian bioevents. *Cas* = *Callaiosphaeridium asymmetricum*, *Cgl* = *Canningia glomerata*, *Hve* = *Heterosphaeridium verdieri*, *Mwi* = *Membranilarnacia wilsonii*, *Pde* = *Psaligonyaulax deflandrei*, *Pin* = *Palaeohystrichophora infusorioides*, *Rfu* = *Raphidodinium fucatum*, *Sde* = *Sentusidinium devonense*, *Sec* = *Spinidinium echinoideum*, *Sfi* = *Senoniasphaera filoreticulata*, *Srm* = *Spiniferites ramosus* subsp. *maendriiformis*. Species events from the Trunch borehole that have been used as events on the English Chalk Reference $\delta^{13}\text{C}_{\text{carb}}$ curve are shown in bold and indicated by a red dashed line. Additional events on the English Chalk Reference $\delta^{13}\text{C}_{\text{carb}}$ curve are derived from other sources (see the text for details).

Fig. 17a–h. Distribution map of **(a)** *Raphidodinium fucatum*; **(b)** *Spiniferites ramosus* subsp. *maendriiformis*; **(c)** *Psaligonyaulax deflandrei*; **(d)** *Renidinium rigidum* and *Trimuridinium whitenessense*; **(e)** *Chatangiella manumii*; **(f)** *Cannosphaeropsis utinensis*; **(g)** *Senoniasphaera protrusa*; **(h)** *Spiniferites porosus* (all base Santonian map). Site locations rotated from their present-day geographic coordinates using GPlates 2.1. Palaeogeography after Cao et al. (2017); palaeoclimate zones from Scotese et al. (2014).

The tabulated summary is provided in Supplemental data 3, see Palynodata Inc and White (2008) for references.

Fig. 18. Summary of Santonian bioevents. *Aio* = *Alterbidinium ioannidesii*, *Cas* = *Callaiosphaeridium asymmetricum*, *Cca* = *Cordosphaeridium catherineae*, *Cem* = *Chatangiella eminens*, *Cma* = *Chatangiella manumii*, *Cst* = *Coronifera striolata*, *Cut* = *Cannosphaeropsis utinensis*, *Dal* = *Dinopterygium alatum*, *Dst* = *Dimidium striatum*, *Hdif* = *Heterosphaeridium difficile*, *Kre* = *Kleithriasphaeridium readei*, *Odi* = *Odontochitina diducta*, *Opo* = *Odontochitina porifera*, *Pde* = *Psaligonyaulax deflandrei*, *Pint* = *Pervosphaeridium intervalum*, *Rri* = *Renidinium rigidum*, *Rso* = *Rhynchodiniopsis saliorum*, *Sca* = *Scriniodinium campanula*, *Sec* = *Spinidinium scirrhosoides*, *Sfi* = *Senoniasphaera filoreticulata*, *Sja* = *Spiniferites jarvisii*, *Spo* = *Spiniferites porosus*, *Spr* = *Senoniasphaera protrusa*, *Srm* = *Spiniferites ramosus* subsp. *maendriiformis*, *Twh* = *Trimuridinium whitenessense*, *Wsp* = *Whitecliffia spinosa*. Species events from the Trunch borehole that have been used as events on the English Chalk Reference $\delta^{13}\text{C}_{\text{carb}}$ curve are shown in bold and indicated by a red dashed line. Additional events on the English Chalk Reference $\delta^{13}\text{C}_{\text{carb}}$ curve are derived from other sources (see the text for details).

Fig. 19a–h. Distribution map of (a) *Chatangiella eminens*; (b) *Coronifera striolata*; (c) *Pervosphaeridium intervalum*; (d) *Dimidium striatum*; (e) *Spiniferites jarvisii*; (f) *Odontochitina diducta*; (g) *Odontochitina porifera*; (h) *Cordosphaeridium catherineae* (all base Campanian map). Site locations rotated from their present-day geographic coordinates using GPlates 2.1. Palaeogeography after Cao et al. (2017); palaeoclimate zones from Scotese et al. (2014). The tabulated summary is provided in Supplemental data 3, see Palynodata Inc and White (2008) for references.

Fig. 20a–f. Distribution map of (a) *Rhynchodiniopsis saliorum*; (b) *Scriniodinium campanula*; (c) *Kleithriasphaeridium readei*; (d) *Whitecliffia spinosa*; (e) *Alterbidinium ioannidesii*; (f) *Dinopterygium alatum* (all base Campanian map). Site locations rotated from their present-day geographic coordinates using GPlates 2.1. Palaeogeography after Cao et al. (2017); palaeoclimate zones from Scotese et al. (2014). The tabulated

summary is provided in Supplemental data 3, see Palynodata Inc and White (2008) for references.

Fig. 21. Summary of Early Campanian bioevents. *Aio* = *Alterbidinium ioannidesii*, *Cma* = *Chatangiella manumii*, *Cut* = *Cannosphaeropsis utinensis*, *Kre* = *Kleithriasphaeridium readei*, *Rsa* = *Rhynchodiniopsis saliorum*, *Sca* = *Scriniodinium campanula*, *Smu* = *Spiniferites multispinulus*, *Srm* = *Spiniferites ramosus* subsp. *maendriformis*, *Twh* = *Trimuridinium whitenessense*, *Wsp* = *Whitecliffia spinosa*. Species events from the Trunch borehole that have been used as events on the English Chalk Reference $\delta^{13}\text{C}_{\text{carb}}$ curve are shown in bold and indicated by a red dashed line. Additional events on the English Chalk Reference $\delta^{13}\text{C}_{\text{carb}}$ curve are derived from other sources (see the text for details).

Fig. 22. Cenomanian – Campanian palynological datum levels for NW Europe: summary of ages and geographic extent. See text for derivation of age model (**Section 4.5**) and dating of individual events (**Sections 7.1 – 7.5**).

Fig. 23. Palaeogeographic distribution of palynological biostratigraphic marker species identified in the Trunch borehole. Sites represent concatenated data from multiple literature sources and adjacent field or core sections, where available. Site locations were rotated from their present-day geographic coordinates (latitude/longitude WGS1984) using GPlates 2.11 (see **Section 4.4**). Species are grouped into stage intervals based on the age closest to the species event(s) identified at Trunch; corresponding palaeogeographic distribution maps are shown in **Figs 10, 13, 15, 17, 19 – 20**. Cosmopolitan species placed to the left, more endemic species to the right. Lengths of histogram bars (see key) represent percentage of sites sampling that stage interval from which the species has been recorded. Note the greater number of sites recorded from mid-palaeolatitudes in both hemispheres.

Table 1. Age constraints for the Upper Cretaceous of the Trunch borehole.

Age control point	D e p t	Sa mp lin g	Sa mp lin g	Ag e an ch	An ch ore d	Age floatin g	Flo ati ng age	Ag e co m	Tot al un cer	References

	1		11	8	Campa	0	.4	9	(2016)
	4.				nian		5		
	9				+0.26				
	3				base				
	2				Campa		84		
Hawks Brow CIE	1.		0.0	0.3	nian	0.1	.5	0.5	Thibault et al.
	9	1.0	23	8	+0.34	0	3	0	(2016)
	3				base				
base Buckle CIE	3				Campa		84		
(LO <i>Uintacrinus</i>	5.		0.0	0.3	nian	0.1	.8	0.5	Thibault et al.
<i>socialis</i>)	9	1.0	17	8	+0.66	0	5	0	(2016)
	3				base				
	4				Campa		84		
Exceat Flint	0.		0.0	0.3	nian	0.1	.5	0.5	Thibault et al.
	0	1.0	21	8	+0.73	0	2	0	(2016)
	3				base				
	4				Campa		85		
Horseshoe Bay	5.		0.1	0.3	nian	0.1	.3	0.6	Thibault et al.
CIE	2	2.0	17	8	+0.81	0	0	0	(2016)
	3				base				
	5				Campa		85		
Haven Brow CIE	3.		0.0	0.3	nian	0.1	.6	0.5	Thibault et al.
	9	1.0	31	8	+1.35	0	7	1	(2016)
	3				base				
	6				Campa		85		
Bedwell CIE	5.		0.0	0.3	nian	0.1	.9	0.5	Thibault et al.
	9	1.0	37	8	+1.72	0	1	2	(2016)
	3				base				
	7				Campa		86		
base Santonian	2.		0.0	0.3	nian	0.1	.1	0.5	Thibault et al.
	6	1.0	38	8	+1.97	0	6	2	(2016)
	3				base				
	8				Campa		86		
Kingsdown CIE	5.		0.0	0.3	nian	0.1	.6	0.5	Thibault et al.
	9	1.0	71	8	+2.47	0	6	5	(2016)
	4								
Base Middle	1								
Coniacian (East	1.		0.0				88.	0.5	interpolated age;
Cliff Marl 2)	5	0.5	36				42	2	this study
	4				base				
base C.	2				Coniaci		89		
<i>schloenbachi</i>	6.		0.0	0.3	an -	0.0	.5	0.5	Laurin et al.
Zone	0	1.0	64	8	0.25	6	0	0	(2014)
	4								
	2			89			89		
base Coniacian	9.		0.0	.7	0.3		.7	0.4	Sageman et al.
	9	1.0	51	5	8		5	3	(2014)

	4				base				
	3				Coniaci		89		
	2.	0.0	0.3		an	0.0	.8	0.4	Laurin et al.
<i>Didymotis</i> I Event	6	1.0	43	8	+0.137	5	9	7	(2014)
	4				base				
	4				Coniaci		90		
base <i>M. scupini</i>	7.	0.0	0.3		an	0.0	.5	0.5	Laurin et al.
Zone	9	1.0	72	8	+0.795	5	5	0	(2014)
	4				base				
	5				Coniaci		90		
peak Hitch Wood	2.	0.0	0.3		an	0.0	.8	0.4	Laurin et al.
CIE	0	1.0	14	8	+1.091	8	4	7	(2014)
	4				base				
	7				Coniaci		91		
	0.	0.0	0.3		an	0.1	.3	0.5	Laurin et al.
Bridgewick CIE	9	0.5	24	8	+1.356	4	1	4	(2014)
	4				base				
	7				Coniaci		91		
base <i>I. perplexus</i>	5.	0.0	0.3		an	0.0	.3	0.5	Laurin et al.
Zone	0	1.0	73	8	+1.555	7	1	2	(2014)
	4								
	9						92		
base <i>C. woollgari</i>	7.	0.3	92	0.			.9	0.5	Ogg and Hinnov
Zone	0	1.0	26	.9			0	3	(2012)
	5								
	0.						93		
	0	0.1	33	0.1			.9	0.2	Meyers et al.
base Turonian	7	0.2	30	.9	5		0	8	(2012)
	5								Sageman et al.
	0		94				94		(2006), Meyers et
onset OAE2	0.	0.0	.4	0.1		0.0	.4	0.2	al. (2012), Ma et
positive CIE	9	0.2	71	4	5	2	4	4	al. (2014)
	5								
	0		96				96		
	5.	0.2	.1	0.2			.1	0.4	Gambacorta et al.
MCE I, peak "a"	8	0.5	06	9	8		9	9	(2018)
	5								
	1								
	2.		98				98		
	2	0.2	.8	0.3			.8	0.5	Gambacorta et al.
base Cenomanian	2	0.5	06	4	5		4	6	(2018)

placement of the base Maastrichtian and base Chron C32 are derived from carbon-isotope correlation between the borehole and adjacent coastal outcrop sections (Voigt et al., 2012 figs. 5, 6).

List of plates

Plate I. 1. *Alterbidinium ioannideii* Pearce 2010, 298 m. 2. *Apteodinium deflandrei* (Clarke and Verdier 1967) Lucas-Clark 1987, 364 m. 3. *Callaiosphaeridium asymmetricum* (Deflandre and Courteville 1939) Davey and Williams 1966b, 507.4 m. 4. *Canningia glomerata* (Clarke and Verdier 1967) Fensome et al., 2019, 420 m. 5. *Cannosphaeropsis utinensis* Wetzel 1933, 310 m. 6. *Carpodinium obliquicostatum* Cookson and Hughes 1964, 504.3 m. 7. *Chatangiella ditissima* (McIntyre 1975) Lentin and Williams 1976, 403.9 m. 8. *Chatangiella eminens* Pearce 2010, 332 m. 9. *Chatangiella manumii* (Vozzhennikova 1967) Lentin and Williams 1976, 278 m. 10. *Cordosphaeridium catherineae* Pearce 2010, 271 m. 11. *Coryphaena striolata* (Deflandre 1937) Stover and Evitt 1978, 270 m. 12. *Cribroperidinium? edwardsii* (Cookson and Eisenack 1958) Davey 1969a, 433.3 m. Scale bars are 10 µm.

Plate II. 1. *Cribroperidinium wilsonii* (Yun Hyesu 1981) Poulsen 1996, 397 m. 2. *Cyclonephelium membraniphorum* Cookson and Eisenack 1962b, 458 m. 3. *Dimidium striatum* (Clarke and Verdier 1967) Pearce 2010, 336 m. 4. *Dinogymnium acuminatum* Evitt et al. 1967, 280 m. 5. *Dinopterygium alatum* (Cookson and Eisenack 1962b) Fensome et al. 2009, 504.3 m. 6. *Lisphaeria munda* (Davey and Verdier 1973) Norvick 1976, 507.9 m. 7. *Downiesphaeridium armatum* (Deflandre 1937) Islam 1993, 397 m. 8. *Ellipsodinium rugulosum* Clarke and Verdier 1967, 504.3 m. 9. *Epelidosphaeridia spinosa* Cookson and Hughes 1964, 504.3 m. 10. *Hapsocysta dictyota* Davey 1979b, 508.8 m. 11. *Hapsocysta peridictya* (Eisenack and Cookson 1960) Davey 1979b, 504.8 m. 12. *Heterosphaeridium difficile* (Manum and Cookson 1964) Ioannides 1986, 406 m, apical view. Scale bars are 10 µm.

Plate III. 1. *Heterosphaeridium difficile* (Manum and Cookson 1964) Ioannides 1986, 406 m, operculum. 2. *Heterosphaeridium verdieri* Yun Hyesu 1981, 404 m. 3. *Hystrichodinium pulchrum* Deflandre 1935, 458 m. 4. *Hystrichosphaeropsis ovum* Deflandre 1935, 319 m. 5. *Hystrichosphaeropsis quasicribrata* (Wetzel 1961) Gocht 1976, 270 m. 6. *Kleithriasphaeridium readei* (Davey and Williams 1966b) Davey and Verdier 1976, 508.8 m. 7. *Leberidocysta chlamydata* (Cookson and Eisenack 1962b) Stover and Evitt 1978, 510.3 m. 8. *Leberidocysta defloccata* (Davey and Verdier 1973)

Stover and Evitt 1978, 510 m. 9. *Litosphaeridium siphoniphorum* (Cookson and Eisenack 1958) Davey and Williams 1966b, 507.9 m. 10. *Odontochitina diducta* Pearce 2010, 280 m. 11. *Odontochitina porifera* Cookson 1956, 315 m. Scale bars are 10 µm.

Plate IV. 1. *Oligosphaeridium pulcherrimum* (Deflandre and Cookson 1955) Davey and Williams 1966b, 431.3 m. 2. *Palaeoperidinium pyrophorum* (Ehrenberg 1838 ex Wetzel 1933a) Sarjeant 1967b, 424 m. 3. *Pervosphaeridium cenomaniense* (Norvick 1976) Below 1982c, 507.9 m. 4. *Pervosphaeridium intervalum* Kirsch 1991, 342.3 m. 5. *Pervosphaeridium pseudhystrichodinium* (Deflandre 1937) Yun Hyesu 1981, 507.9 m. 6. *Psalignonyaulax deflandrei* Sarjeant 1966b, 507.9 m. 7. *Pterodinium crassimuratum* (Davey and Williams 1966a) Thurow et al. 1988, 510.3 m. 8. *Laetiaedinium truncigerum* (Deflandre 1937) Kirsch 1991, 271 m. 9. *Raphidodinium fucatum* Deflandre 1936b, 312 m. 10–11. *Renidinium rigidum* Prince et al. 1999, 351 m, 11 ventral view, 12 dorsal view. 12. *Rhiptocorys veligera* (Deflandre 1937) Lejeune-Carpentier and Sarjeant 1983, 462 m. Scale bars are 10 µm.

Plate V. 1. *Rhynchodiniopsis saliorum* Le Bouwe 1997, 308 m. 2. *Rugubivesiculites rugosus* Pierce 1961, 510.3 m. 3. *Scriniodinium campanula* Gocht 1959, 465 m. 4. *Senoniasphaera filoreticulata* (Slinnani 1994) Fensome et al., 2019, 388 m. 5. *Senoniasphaera protrusa* Clarke and Verdier 1967, 317 m. 6–7. *Senoniasphaera turonica* (Prössl 1990 ex Prössl 1992b) Pearce et al. 2011, 466 m, 6 dorsal view, 7 ventral view. 8. *Sentusidinium devonense* Pearce 2018, 418 m. 9. *Sentusidinium ringnesiorum* (Manum and Cookson 1964) Wood et al. 2016, 510.3 m. 10. *Sepispinula ambigua* (Deflandre 1937) Masure in Fauchonier and Masure 2004, 506.4 m. 11–12. *Sindridinium borealis* Nøhr-Hansen et al. 2018, 507.9 m, 11 specimen with an attached operculum, 12 specimen with detached operculum. Scale bars are 10 µm.

Plate VI. 1. *Spinidinium echinoideum* (Cookson and Eisenack 1960a) Lentin and Williams 1976, 272 m. 2. *Spiniferites jarvisii* Pearce 2010, 299 m. 3. *Spiniferites multispinulus* Pearce 2010, 270 m. 4. *Spiniferites porosus* (Manum and Cookson 1964) Harland 1973, 451 m. 5. *Spiniferites ramosus* subsp. *maeandriiformis* (Corradini 1973) Lentin and Williams 1975, 400 m. 6. *Spongodinium delitiense* (Ehrenberg 1838) Deflandre 1936b, 288 m. 7. *Stephodinium coronatum* Deflandre 1936a, 451 m. 8. *Tenua*

colliveri (Cookson and Eisenack 1960b) Fensome et al. 2019, 511.3 m. 9. *Trichodinium castanea* Deflandre 1935, 458 m. 10. *Trimuridinium whitenessense* (Prince et al. 2008) Fensome et al., 2019, 301 m. 11. *Whitecliffia spinosa* (Clarke and Verdier 1967) Pearce 2010, 286.55 m. 12. *Wrevittia cassidata* (Eisenack and Cookson 1960) Helenes and Lucas-Clark 1997, 507.9 m. Scale bars are 10 μ m.

Supplementary data

Table 1. Stable isotopes and carbonate data for the Trunch borehole.

Table 2. Palynology count data for the Trunch borehole (512 - 272 m).

Table 3. Geographic location summary.

Table 4. Late Cretaceous age model: age constraints for the Culver Cliff outcrop section.

Table 5. Late Cretaceous age model: age constraints for the Dover outcrop section.

Table 6. Late Cretaceous age model: age constraints for the Eastbourne outcrop section.

Table 7. Late Cretaceous age model: age constraints for the Speeton outcrop section.

Highlights

- a detailed record of Cretaceous organic-walled dinoflagellate cysts is presented
- we propose a new stratigraphy comprising 65 dinocyst events
- absolute ages are assigned to palynological events with a 10 – 100 kyr resolution
- the palaeogeographic distributions of key dinocyst taxa are reviewed and mapped
- specific global, Northern Hemisphere and NW European bioevents are demonstrated

Figure 1

Figure 2

Figure 3

Figure 4

Trunch

Figure 5

Figure 6A

Figure 6B

Figure 8

Figure 9

Figure 10

Figure 11

Figure 13

Figure 15

Figure 17

Figure 19

Figure 20

Figure 21

Figure 22

Biostratigraphic marker species

Figure 23