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A revised northern European Turonian (Upper Cretaceous) dinoflagellate cyst biostratigraphy: Integrating palynology and carbon isotope events

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ABSTRACT

Organic walled dinoflagellate cyst (dinocyst) assemblage data are presented for a new Turonian regional reference core (Bch-1) drilled at Běchary in the Bohemian Cretaceous Basin, east-central Czech Republic. The detailed stratigraphic framework for the section is summarised based on calcareous nannofossil and macrofossil biostratigraphy, regional e-log correlation, sequence stratigraphy and carbon isotope chemostratigraphy. Dinocyst results obtained for 196 samples from the 405 m long core offer the highest resolution (~22 kyr) stratigraphically well-constrained data set available to date for the Turonian Stage, 93.9–89.8 Ma. A dinocyst biostratigraphic framework is presented based on the evolutionary first and last occurrence, first common occurrence, and acmes of key species. Published dinocyst data from English Turonian Chalk successions in East Sussex, Berkshire, Kent and Norfolk are reviewed within a stratigraphic framework provided by macrofossil records and carbon isotope event (CIE) chemostratigraphy. Critical analysis of existing published Turonian dinocyst zonation schemes shows them to be untenable. Correlation of the English Chalk data to Bch-1 provides a basis for defining a regional dinocyst event stratigraphy with 22 datum levels, and a revised dinocyst zonation scheme constrained within a chemostratigraphic framework of 10 major CIEs. The new zones consist of a Cenomanian *Litosphaeridium siphoniphorum* Zone, followed by the *Cauveridinium membraniphorum* Zone spanning the uppermost Cenomanian to Lower Coniacian. This is subdivided into: *Senoniasphaera turonica* (Lower–mid-Middle Turonian); and *Raetiaedinium truncigerum* (mid-Middle Turonian–mid-Lower Coniacian) subzones. The *Oligosphaeridium pulcherrimum* Zone (*Senonisphaera rotundata* Subzone) characterises the Lower Coniacian. The new stratigraphy offers a basis for improved correlation and dating of Upper Cretaceous successions.

1. Introduction

Over the last 40 years, a substantial amount of work has been undertaken on the biostratigraphy of Turonian organic walled dinoflagellate cysts (dinocysts) from the English and French Chalk and its correlatives in the Anglo-Paris Basin (Clarke and Verdier, 1967; Foucher, 1974, 1975, 1976a, 1980, 1981, 1983; Tocher, 1984; Tocher and Jarvis, 1987, 1994, 1995; Jarvis et al., 1987, 1988a,b; FitzPatrick, 1992, 1995, 1996; Pearce, 2000, 2010; Pearce et al., 2003, 2009; Prince et al., 2008; Lignum, 2009). However, to our knowledge, little has been published previously on the Turonian–Coniacian dinocyst biostratigraphy of Central Europe, notable exceptions being the work of Prössl (1990), Kirsch (1991) and Svobodová et al. (1998, 2002).

Here, new dinocyst data are presented from an expanded (>300 m thick) Turonian hemipelagic succession in a fully cored research borehole drilled recently in the Bohemian Cretaceous Basin at Běchary, east-central Czech Republic. Dinocyst records from four well-characterised English Chalk successions in East Sussex, Berkshire, Kent and Norfolk are reviewed and integrated using macrofossil biostratigraphy, lithostratigraphy and carbon isotope chemostratigraphy (Jarvis et al., 2006; Pearce et al., 2009) to provide a regional framework for comparison with results from the Czech Republic. Despite marked latitudinal provinciality that occurred in the Late Cretaceous (see Lentin and Williams, 1980; Costa and Davey, 1992), many of our marker taxa also occur to the north of the European Chalk province, well into the

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siliciclastic-prone facies of the Shetland Group. It is a particular strength of dinocysts to have a largely facies-independent preservation potential, exemplifying their use as a powerful biostratigraphic tool. In this paper, a revised dinocyst zonation for the northern European Turonian tied to the carbon isotope event (CIE) stratigraphy of Jarvis et al. (2006) is proposed, based on integrating the English Chalk data with new results from Bch-1.

2. Geological framework

The Bohemian Cretaceous Basin was an intra-continental basin formed during the Cenomanian–Santonian (100.5–83.6 Ma) as a seaway between the Boreal Sea and Alpine Ocean (Fig. 1). The basin originated by the reactivation of a fault system in the Variscan basement of the Bohemian Massif, and combined features of an epeiric sea formed during global transgression with those of a tectonically active setting that contains probably the highest proportion of siliciclastics of all the European Cretaceous basins north of the Alps (Uličný et al., 1997, 2009). During Turonian–Coniacian times, sedimentation in the Bohemian Basin was dominated by the repeated progradation of coarse-grained deltas and adjoining shorefaces, and was affected by redistribution of siliciclastics by strong along-shore tidal currents (Uličný, 2001). A maximum water depth of around 100 m is estimated for the basin interior (Mitchell et al., 2010).

During 2010, a 405 m research core, Bch-1, was drilled through a representative Lower Coniacian to Upper Cenomanian succession of offshore marine sediments in the Bohemian Cretaceous Basin, to investigate the responses of multiple proxies to sea-level change (Uličný et al., 2014). The Bch-1 site (50.31506°N 15.29497°E), located in the village of Běchary, east-central Czech Republic, is situated in the central basin between two depocentres (Fig. 1), one adjacent to the Most-Teplice High and Western Sudetic Island in the northwest, the other bordering the Bohemian Massif in the southeast. These source areas contributed varying amounts of sediment through the Turonian, but with the Western Sudetic Island being by far the most prominent source area.

The dominant lithofacies in the Bch-1 core consist of very dark grey marlstones and calcareous mudstones with a varying proportion of quartz silt (Fig. 2). The mean percentage of $CaCO_3$ through the core is ~35%, and carbonate is generally represented by a micritic component,

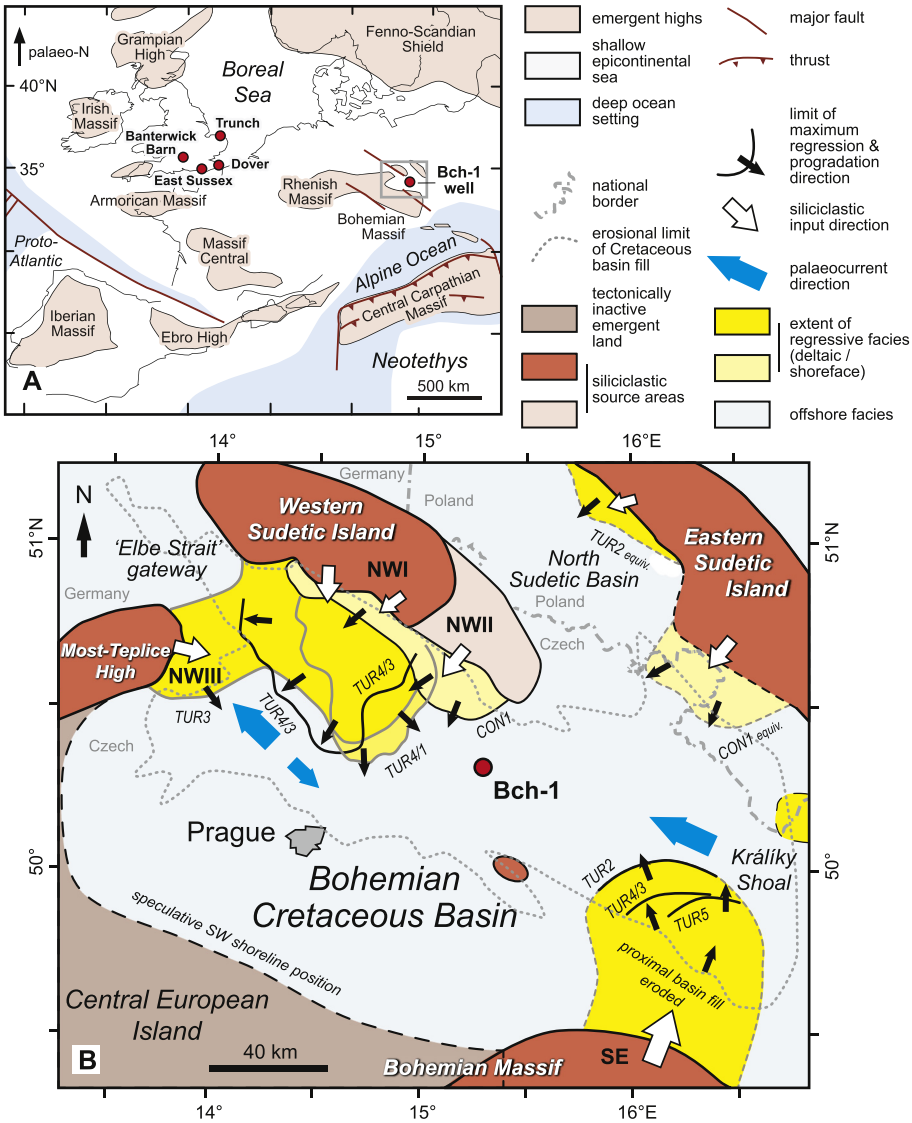


Fig. 1. Location and Turonian palaeogeography of the Bohemian Cretaceous Basin study section. (A) Simplified palaeogeography of the European epicontinental sea showing the location of the Bch-1 well. Adapted from Mitchell et al. (2010). (B) Detail of the Bohemian Cretaceous Basin, location shown by grey rectangle in A. Main siliciclastic source areas and sub-basins are shown: NW, Lužice-Jizera sub-basin; SE, Orlice-Ždár sub-basin. TUR2 — CON1 indicate regressive limits of nearshore strata in genetic sequences. Modified from Uličný et al. (2014).

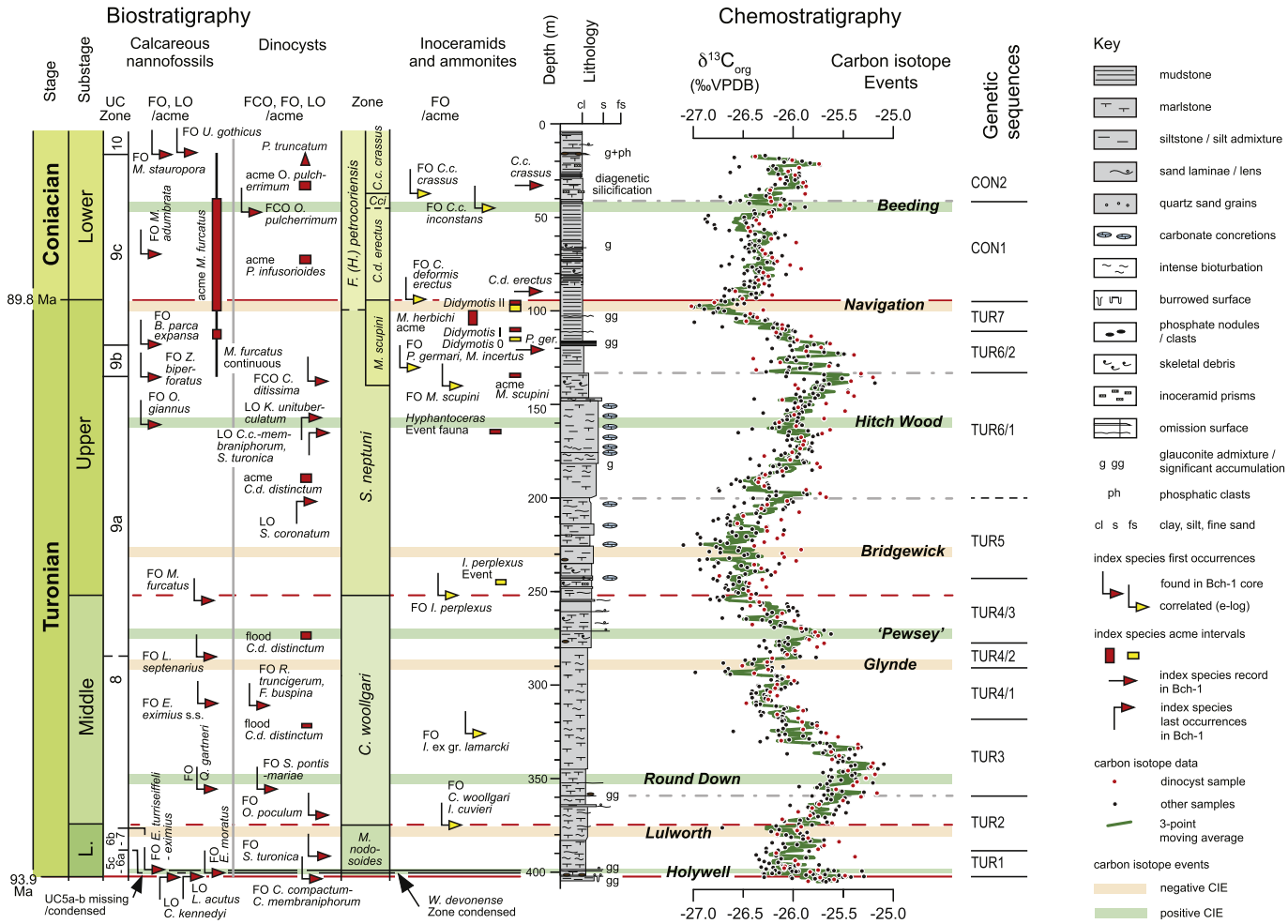


Fig. 2. Biostratigraphy and carbon isotope chemostratigraphy of the Bch-1 well. Calcareous nannofossil, dinocyst, inoceramid bivalve and ammonite datum levels are plotted against lithology and carbon isotope ratios of bulk organic matter ($\delta^{13}C_{org}$), and regional genetic sequences. Dinocyst datum levels from this study; other data from Uličný et al. (2014). Upper Cretaceous (UC) calcareous nannofossil zones after Burnett et al. (1998). Carbon isotope events (CIE) of Jarvis et al. (2006) are identified following Uličný et al. (2014). Minor revision of datum levels, genetic sequences and the placement of CIEs incorporates results from new unpublished stratigraphic work. Abbreviations used here and in text: FO = first occurrence; LO = last occurrence; FCO = first common occurrence; LCO = last common occurrence; RO = reappearance datum level. *Cci* = *Cremnoceramus crassus inconstans*.

some mm-scale bioclasts, and calcite spar in horizons with concretionary cement. Total organic carbon contents (TOC) average 0.42%. Turonian lithofacies show abundant bioturbation throughout the core, dominated by a distal *Cruziana* ichnofacies (sensu MacEachern et al., 2010).

3. Stratigraphic framework

Deposition in the Bohemian Cretaceous Basin has been split into a number of genetic sequences, termed TUR1–TUR7, CON1 and CON2 (Fig. 2), which were detailed by Uličný et al. (2009). The sequences are based on the analysis of a basin-scale correlation grid, developed using well-log data (gamma-ray, resistivity, neutron porosity logs) from >700 boreholes, in most cases supplemented by outcrop and core data. These genetic sequences, bounded by maximum transgressive surfaces, form a hierarchy of nested, composite sequences, interpreted to record a response to relative sea-level changes. The sequences record major cycles of regression and subsequent transgression, within which smaller scale cycles also occur. Correlation of the sequence boundaries to Bch-1, as presented here, has been modified from Uličný et al. (2014) in the light of new stratigraphic data.

The macrofossil and calcareous nannofossil biostratigraphy, along with carbon isotope data for the Bch-1 core, were published by Uličný et al. (2014). Key biostratigraphic datum levels are plotted here against a lithological log and the carbon isotope profile for the core in Fig. 2.

3.1. Litho- and biostratigraphy

Sediments from the bottom of the Bch-1 core (404.6–402.4 m) yield a Cenomanian nannofossil assemblage, including *Lithraphidites acutus* Verbeek & Manivit and *Corollithion kennedyi* Crux. The base of the Turonian (Sequence TUR1) is marked by a burrowed omission surface at 402.35 m, overlain by a 70 cm thick zone of glauconite-rich marlstone with phosphate concretions, interpreted as a hiatus, followed by condensed deposition (Valečka and Skoček, 1991; Uličný et al., 1993; Čech et al., 2005). A second, less prominent, omission surface at 398.2 m, is overlain by a 20 cm thick, glauconite-rich, greenish-grey marlstone (Fig. 2). Calcareous nannofossil zones UC 5a–b (Burnett et al., 1998; correlative to the uppermost Cenomanian upper *Metoicoceras geslinianum* and *Neocardioceras juddii* ammonite zones) are absent, confirming the interpretation of Uličný et al. (1993) of a major hiatus at this time in the central part of the basin. The first occurrence (FO) of *Eprolithus moratus* (Stover) at 400.0 m depth indicates that at least nannofossil zones UC 5c–6a are contained in the lowermost 2.35 m of the Turonian succession in Bch-1. The prominent earliest Turonian condensation event is attributed to the major flooding near the Cenomanian–Turonian boundary (CTB) that established

hemipelagic conditions over most of the basin (Klein et al., 1979; Uličný et al., 1997).

The first occurrence (FO) of the ammonite *Collignoceras woollgari* (Mantell), which marks the base of the Middle Turonian, appears regionally together with *Inoceramus cuvieri* (Sowerby) in the middle of Sequence TUR2. This datum level is placed at 374 m in Bch-1 (Fig. 2; Uličný et al., 2014), based on lithostratigraphic and e-log correlation to adjacent sections. An acme of *Inoceramus perplexus* Whitfield occurs at the base of Sequence TUR5. This level is distinctive due to a regional abundance of inoceramid prisms, identified at 246 m in the core, and correlates to the "*costellatus-plana* Event" in NW Germany (Richardt and Wilmsen, 2012). The base of the Upper Turonian, marked by the FO *I. perplexus*, is correlated to the upper part of Sequence TUR4/3, at 252 m depth, immediately above the first (rare) occurrence of the nannofossil *Marthasterites furcatus* (Deflandre) at 255 m. An ammonite fauna typical of the *Subprionocyclus neptuni* Zone is recorded in the middle of TUR6, at 165 m. This level is interpreted to represent the *Hyphantoceras* Event, a mid-Upper Turonian datum level that can be recognised in England, parts of France, Germany, Poland and the Czech Republic (e.g. Wiese et al., 2004).

The Upper Turonian–Lower Coniacian succession at Bch-1 is well constrained by inoceramid bivalve and ammonite records from the core (Fig. 2), supplemented by e-log correlation of FO datum levels from adjacent cores and outcrops. The uppermost Turonian index taxon *Mytiloides scupini* (Heinz) is recorded at 134 m, while the position of its true FO datum level is correlated to 140 m. *Prionocyclus germari* (Reuss) occurs at 121 m, with a correlated FO at 130 m. The latest Turonian succession of three bivalve acme occurrences, *Didymotis* Events 0, I and II (Wood et al., 1984, 2004; Čech, 1989; Walaszczyk and Wood, 1998; Wiese, 1999; Walaszczyk et al., 2010) is placed between 115 and 95 m; Events I and II are recorded directly in the core and the position of Event 0 is inferred by correlation. An acme of *Mytiloides herbichi* (Atabekjan) occurs from 108–99 m depth, between *Didymotis* Events I and II, as seen also on northern Germany (Wood et al., 2004).

The base of the Coniacian is placed at the correlated first occurrence of *Cremnoceramus deformis erectus* (Meek) at 94 m (cf. Walaszczyk et al., 2010), at the bottom of Sequence CON1 and immediately above the top of *Didymotis* Event 2; *C. d. erectus* was recovered from 89 m in the core (Fig. 2). An acme of *Marthasterites furcatus* spans the Turonian–Coniacian boundary interval.

The correlated FOs of *Cremnoceramus crassus inconstans* (Woods) at 45 m and *Cremnoceramus crassus crassus* (Petrascheck) at 37 m depth, and records of the latter species from the core at 33 m, enable the placement of the standard European Lower Coniacian inoceramid zones (Walaszczyk and Wood, 1998) in the core. The base of the Middle Coniacian is tentatively placed at the FO *Micula stauropora* (nannofossil Zone UC10), at 16 m depth, a short distance above the highest dinocyst sample at 17.5 m.

3.2. Carbon isotope chemostratigraphy

Turonian sediments display consistent secular variation in carbon isotope profiles throughout northern and southern Europe (Jarvis et al., 2006; Voigt et al., 2007, 2008; Richardt et al., 2013; Sprovieri et al., 2013), and remarkably similar trends have been documented from as far afield as Tibet and North America (e.g. Wendler, 2013; Joo and Sageman, 2014). The Cenomanian–Coniacian carbonate carbon isotope ($\delta^{13}C_{carb}$) reference curve for the English Chalk (Jarvis et al., 2006) and high-resolution $\delta^{13}C_{carb}$ curves from Liencres, northern Spain (Wiese, 1999) and Saltzgitter-Salder (Voigt and Hilbrecht, 1997), Oerlinghausen and Halle (Voigt et al., 2007) in northern Germany, have been correlated to the organic carbon isotope profile ($\delta^{13}C_{org}$) for Bch-1 by Uličný et al. (2014). A $\delta^{13}C_{org}$ profile was favoured for Bch-1 due to concerns over possible diagenetic alteration in carbonate-carbon profiles generated from relatively low-carbonate mudrocks. Consistent relationships were demonstrated between trends in the isotope profiles and the positions of key macrofossil datum levels in the different sections (Uličný et al., 2014 Fig. 3). A total of 20 peaks and troughs in the profile from Bch-1 were correlated between the various sections, including the major named CIEs of Jarvis et al. (2006).

The carbon isotope stratigraphy is consistent with an incomplete and attenuated Cenomanian – Turonian boundary succession at Bch-1, and the occurrence of an expanded Upper Turonian to Lower Coniacian section. The positions of the 9 most significant CIEs are shown for the Bch-1 section in Fig. 2, together with the primary $\delta^{13}C_{org}$ isotope data and a smoothed chemostratigraphic profile. Placement of the CIEs follows Uličný et al. (2014), with minor revision following the acquisition of new stratigraphic data.

4. Sampling and analysis

The 404.86 m Bch-1 core was drilled as a new Turonian regional reference section. Samples of approximately 50 g were taken every 2 m for elemental, isotopic and palynological analysis (196 samples). Based on an average compacted sedimentation rate for the Middle and Upper Turonian of 9 cm/kyr (Uličný et al., 2014), sampling resolution was on the order of 22 kyr. Additionally, smaller samples (20 g, total 610) were obtained at 0.5 m (5.6 kyr resolution) intervals for carbon stable-isotope analysis of the organic fraction ($\delta^{13}C_{org}$). Samples were cleaned, chipped to <3 mm, and homogenised. Subsamples for isotopic and elemental analysis were prepared and analysed following the methods described in Uličný et al. (2014).

It was necessary to process 10 g splits of chipped samples to yield representative assemblages of palynomorphs for quantitative analysis. Palynomorphs >15 μm were concentrated by a commercial processing company (PLS Ltd, Holyhead, UK) using the HF-HCl method of Lignum (2009) modified from Lignum et al. (2008, 'Company B' methodology). All samples were spiked with tablets containing the modern spore *Lycopodium* to allow statistically valid quantitative analysis of abundances (palynomorphs per gramme, ppg). Palynomorph identification and counting were undertaken using a light microscope with a 400× objective. Three hundred dinocysts were identified per sample. Broken or partial specimens were added to the count only if there was more than half of the specimen present; unidentifiable specimens were recorded as 'indeterminate' and were not included in the count of 300. Following this count, the remainder of the slide was scanned to identify any additional species, which were marked as 'present', but in abundances too low to be recorded among the 300.

5. Dinocyst biostratigraphy of the Bch-1 core

All samples yielded abundant and generally well-preserved dinoflagellate cysts, averaging ~4000 dinocysts per gramme (~7000 dpg when corrected for carbonate-dilution, cf. Pearce et al., 2009). The occurrence and ranges of 76 common dinocyst species identified in the Bch-1 core are plotted in Fig. 3, and the relative abundances of dominant species are shown in Fig. 4. A complete list of taxa (92 species) is provided in Appendix A.

Dinocyst biostratigraphic datum levels identified at Bch-1 include the sequential first occurrences (FOs) of *Cyclonephelium compactum–Cauveridinium membraniphorum* in the uppermost Cenomanian, of *Senoniasphaera turonica* in the Lower Turonian, and of *Oligosphaeridium poculum*, *Subtilisphaera pontis-mariae*, *Raetiaedinium truncigerum* and *Florentinia buspina* in the Middle Turonian (Figs. 2, 3; Plate I). The last occurrences (LOs) of *Stephodinium coronatum*, *S. turonica*, *C. compactum–C. membraniphorum* and *Kiokansium unituberculatum* occur in the Upper Turonian. The first common occurrence (FCO) of *Chatangiella ditissima* and the FO of *Surculosphaeridium belowii* occur towards the top of the stage. The FO of *Cribroperidinium wilsonii* in the lowermost Coniacian is followed by the FCO of *Oligosphaeridium pulcherrimum*, above. With

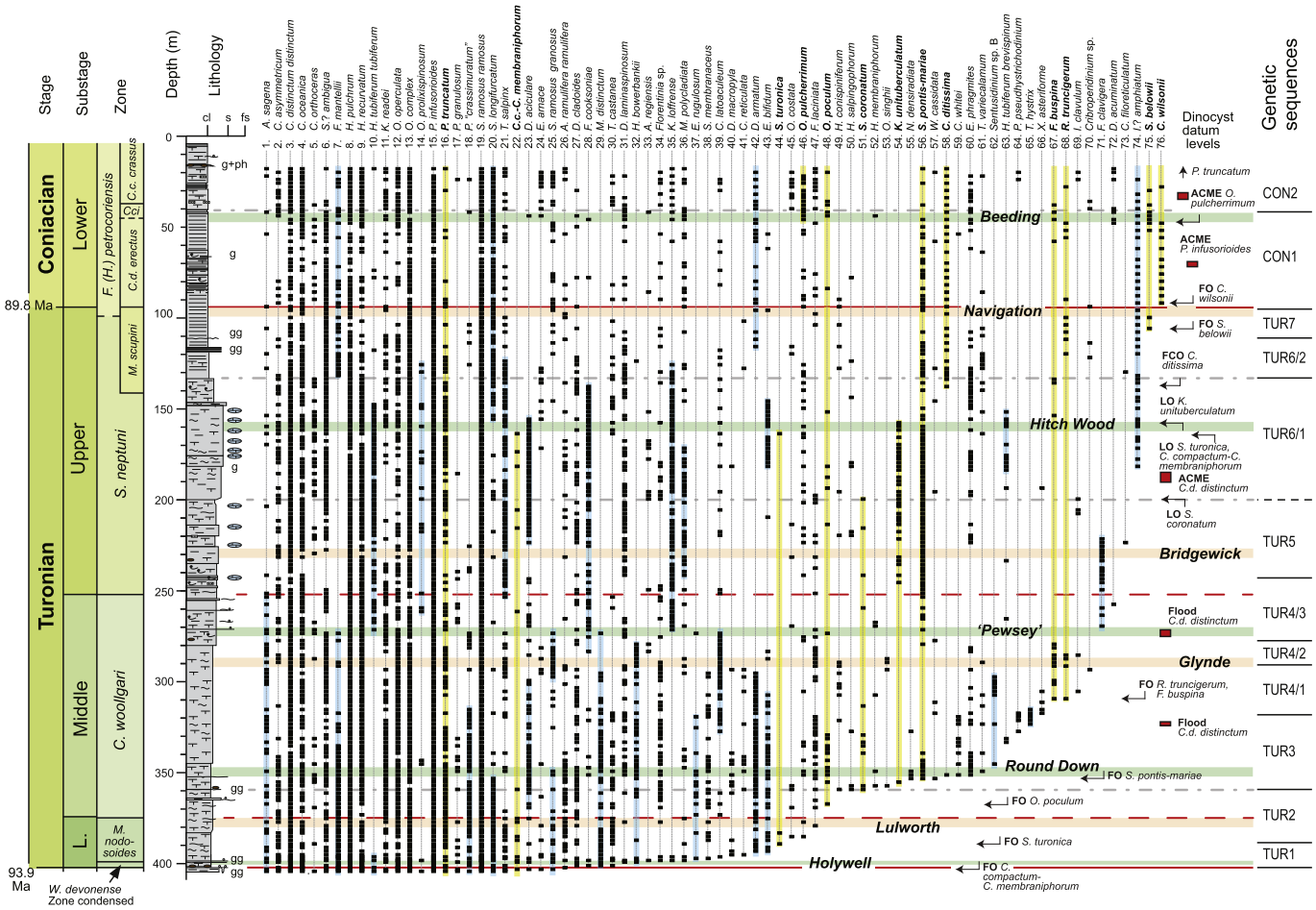


Fig. 3. Dinocyst ranges and datum levels plotted against the macrofossil biostratigraphy and lithology of the Bch-1 well. 'Floods' are short-term abundance spikes; 'acmes' are medium- to long-term abundance maxima. The positions of major CIEs and the location of regional genetic sequences are shown. A complete list of species identified and their taxonomic assignments is provided in Appendix A. The ranges of biostratigraphically significant species (in bold) are emphasised by the vertical yellow bars; examples of these are illustrated in Plate I. Species displaying intervals of consistent common occurrence that may be of palaeoenvironmental or local biostratigraphic significance are highlighted by the vertical blue bars. See Fig. 2 for biostratigraphy and lithological key.

the exceptions of *K. unituberculatum*, *S. pontis-mariae* and *C. ditissima*, most of these taxa occur sporadically (Fig. 3) and in low numbers (<1% of assemblage), limiting stratigraphic resolution. The last common occurrence (LCO) and reoccurrence (RO) datum levels of some species are also considered to have stratigraphic potential (discussed further in Section 6, below).

A number of distinctive dinocysts' range patterns are observed in the Bch-1 data (Figs. 3, 4). A generally inverse relationship between the relative abundance curves of *Palaeohystrichophora infusorioides* and *Spiniferites ramosus ramosus,* with a marked minimum of the former and an acme of the latter in Upper Turonian Sequences TUR5 — 6/1 (Fig. 4), reflects the numerical dominance of these two taxa in the assemblages. A well-defined acme of *Circulodinium distinctum distinctum* occurs from 185–190 m in mid-Upper Turonian Sequence TUR6/1, with lesser floods of the species below, in the Middle Turonian at 323.5 m (TUR3) and 271.5 m (TUR4/3).

Lower Turonian to basal Middle Turonian assemblages (Sequences TUR1 — 2) include relatively high proportions of *Hystrichosphaeridium pulchrum* and *Surculosphaeridium longifurcatum* (Fig. 4). *Downiesphaeridium armatum* is most common in Middle Turonian Sequences TUR3 — 4/1 and an acme of *Circulodinium latoaculeum* occurs in TUR4/3. Other notable events include the LO *Microdinium distinctum* and LCOs of *Hystrichospheridium bowerbankii* and *Achomosphaera sagena* towards the top of the Middle Turonian (Sequence TUR4/3).

A number of dinocyst species are more common within the regressive Upper Turonian package of Sequences TUR5 — 6/1 (cf. Uličný et al., 2014), notably *Downiesphaeridium aciculare*, *Oligosphaeridium prolixispinosum*, *Florentinia cooksoniae*, *Hystrichosphaeridium tubiferum brevispinum*, *Kleithriasphaeridium loffrense*, *Kiokansium unituberculatum*, *Subtilisphaera pontis-mariae*, *Tanyosphaeridium salpinx* (Figs. 3, 4). Common species that temporarily disappear within this interval are *Florentinia mantellii* and *Downiesphaeridium armatum*. The mutual exclusivity of a number of key taxa, points to palaeoenvironmental factors limiting their stratigraphic distribution in the Bohemian Cretaceous Basin.

Several well-defined FOs of common species are apparent in the section (Figs. 3, 4), notably, *Florentinia clavigera* towards the top of the Middle Turonian, and *Isabelidinium amphiatum* in the mid-Upper Turonian. *Surculosphaeridium belowii* and *Cribroperidinium wilsonii* first occur within the Turonian–Coniacian boundary interval, which from the upper half part of Sequence TUR6/1 to mid-Sequence CON1, is characterised by assemblages containing abundant *Sepispinula*? *ambigua*.

6. Turonian dinocyst biostratigraphy: review

Comparisons between dinocyst records from four key English Turonian Chalk sites (Fig. 1) and those obtained here from the Bohemian Cretaceous Basin (Figs. 3, 4) are illustrated in Fig. 5, based on

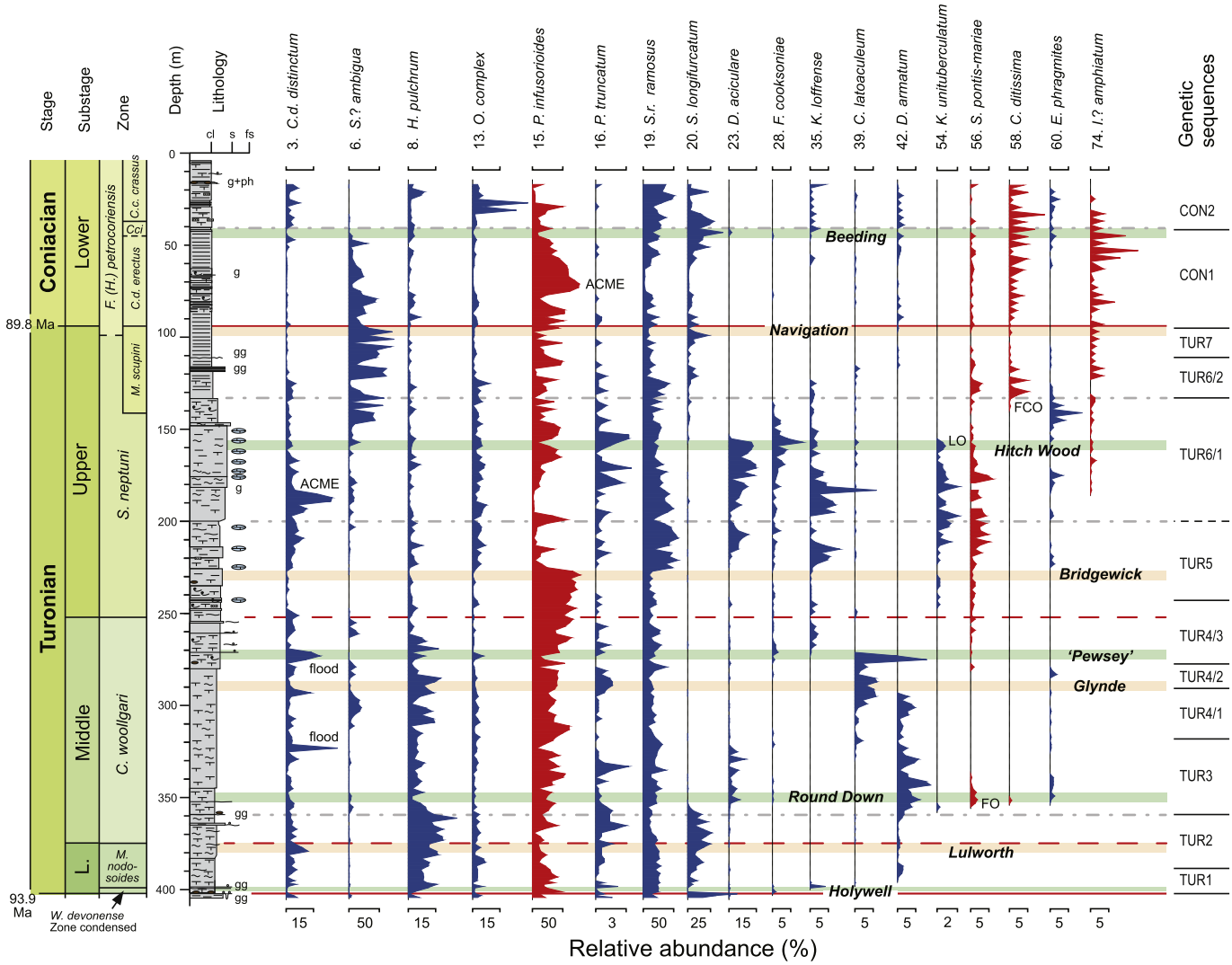


Fig. 4. Relative abundance of common dinocyst species in the Bch-1 well. Values derived from counts of 300 identified dinocysts per sample. Note the different scales used to enhance stratigraphic trends. Red fills indicate peridinioid (P-cysts) and blue fills gonyaulacoid (G-cysts) species. Assemblages are dominated by *P. infusorioides* and *S. ramosus ramosus*, and in the Turonian–Coniacian boundary interval, *S. ambigua*. See Fig. 2 for biostratigraphy and lithological key.

macrofossil biostratigraphic correlation and further constrained by key CIEs. Carbon isotope data (Jarvis et al., 2006) are available to more precisely place the stratigraphic levels of dinocyst records (FitzPatrick, 1995; Pearce, 2000, 2010; Pearce et al., 2003; Prince et al., 2008) from Berkshire (Banterwick Barn borehole), Kent (Dover composite section) and Norfolk (Trunch borehole), but limited carbon isotope data are available for the Turonian of East Sussex. Here, the positions of the CIEs have been placed using bio- and lithostratigraphic criteria derived from other southern English Chalk sections where isotope data are available (Jenkyns et al., 1994; Pearce et al., 2003; Jarvis et al., 2006).

6.1. Cenomanian–Turonian boundary interval

No Cenomanian dinocyst marker species were recognised in the Bch-1 core. For example, *Adnatosphaeridium tutulosum* and *Litosphaeridium siphoniphorum*, which have last occurrences in the Upper Cenomanian *Metoicoceras geslinianum–Neocardioceras juddii* zones (Foucher, 1980, 1981; Courtinat et al., 1991; Costa and Davey, 1992; Dodsworth, 2000; Pearce, 2000; Lignum, 2009; Pearce et al., 2009), are absent. However, calcareous nannofossil records place the base Turonian at 402 m, indicated by the FO *Eprolithus octopetalus* at 401.2 m and the LOs of Upper Cenomanian species *Lithraphidites acutus* at 402.4 m and *Corollithion kennedyi* at 402.8.

Cauveridinium (formerly *Cyclonephelium) membraniphorum* and the *Cyclonephelium compactum–C. membraniphorum* 'complex' are important uppermost Cenomanian and Turonian dinocyst markers in NW Europe (e.g. Clarke and Verdier, 1967; Marshall and Batten, 1988; Pearce, 2000). The latter is found infrequently in Bch-1. The taxon first occurs in the Upper Cenomanian near the core base at 403.6 m (Fig. 3), and is recorded sporadically through the Lower and Middle Turonian, with a LO in the mid-Upper Turonian *Subprionocyclus neptuni* Zone. Elsewhere, the LCO of *C. membraniphorum* is generally recorded at or near the Turonian–Coniacian boundary (Prössl, 1990; Costa and Davey, 1992; Pearce, 2000; Pearce et al., 2003; Prince et al., 2008).

Cauveridinium membraniphorum ranges down into the Middle Albian (Foucher, 1981), and has been recorded as high as the Santonian and Campanian (Foucher, 1979; Ioannides, 1986; Harker et al., 1990), but it is generally only a common component of assemblages in the top Cenomanian and Turonian. An acme of *C. membraniphorum* has been identified as a useful dinocyst marker in the uppermost Cenomanian (Dodsworth, 2000; Lignum, 2009), but this acme is absent at Bch-1 and likely correlates to a hiatus in the section. The species has a LO or LCO near the top of the Upper Turonian in most English Chalk

sections (Fig. 5), and is rare in post-Turonian sediments. Prince et al. (1999) suggested that many non-figured specimens attributed by previous workers to *C. membraniphorum* in Santonian or younger sediments might be *Cyclonephelium filoreticulatum*, leaving a probable true LO of *C. membraniphorum* in the Lower Coniacian (Pearce, 2000; Pearce et al., 2003; Prince et al., 2008). The relatively low LO of the species in Bch-1 in the mid-Upper Turonian, reflects the low abundance of the species in the core.

Heterosphaeridium difficile and *Florentinia buspina* are biostratigraphic marker species that have Lower Turonian bases in NW Europe (Davey and Verdier, 1976; Foucher, 1980, 1981; Tocher and Jarvis, 1987; Jarvis et al., 1988a; Costa and Davey, 1992; FitzPatrick, 1995; Pearce et al., 2009). In the high northern latitudes, *H. difficile* has been recorded in the Cenomanian (Bell and Selnes, 1997; Bloch et al., 1999) suggesting that it is a cold water tolerant species that migrated southward with the predominant Late Cretaceous cooling. *Heterosphaeridium difficile* is absent at Bch-1, and *F. buspina* first appears in the Middle Turonian (Fig. 3). A mid-Turonian FO or FCO of *F. buspina* is also noted in most English Chalk sections (Fig. 5), although the exact stratigraphic position is variable, and sporadic occurrences range down into the Cenomanian (FitzPatrick, 1995; Pearce, 2000; Pearce et al., 2009).

6.2. Senoniasphaera bioevents

The first occurrence of *Senoniasphaera rotundata*, originally described by Clarke and Verdier (1967), has been widely regarded as being a marker for the Lower Turonian (Foucher, 1980, 1981; Tocher and Jarvis, 1987, 1994, 1995; Jarvis et al., 1988a,b; FitzPatrick, 1995; Lamolda and Mao, 1999; Dodsworth, 2000; Pearce, 2000; Pearce et al., 2003, 2011). Recent taxonomic revisions (Pearce et al., 2003, 2011), however, differentiate two main species of *Senoniasphaera* in the Turonian: *Senoniasphaera turonica* (= *S. rotundata alveolata* of Pearce et al., 2003, 2009; Prince et al., 2008); and *S. rotundata* (= *S. rotundata rotundata*). *Senoniasphaera* spp. are uncommon (Fig. 3) in Bch-1, but *S. turonica* first occurs within the *Mammites nodosoides* Zone, between the Holywell and Lulworth CIEs.

Published FOs of *Senoniasphaera* '*rotundata*' (interpreted here to be records of *Senoniasphaera turonica*; see Pearce et al., 2011 for discussion) occur in the lower part of the Lower Turonian *Mytiloides labiatus* Zone (equivalent to the *Watinoceras devonense–Mammites nodosoides* zones) in SE Devon (Jarvis et al., 1988b) and East Sussex (FitzPatrick, 1995; Pearce et al., 2009), at the top of the zone in Berkshire (Pearce et al., 2003), at the base of the Middle Turonian *Terebratulina lata* Zone (= *Collignoceras woollgari* Zone) in Kent (FitzPatrick, 1995), and towards the top of that zone in Norfolk (Pearce, 2000), where the Lower to basal Middle Turonian is barren of dinocysts (Fig. 5). The observed diachroneity of the FO *S. turonica* is likely facies controlled, dinocysts being less abundant in, and the index species absent from, coarser-grained condensed nodular chalk facies that characterise the Lower Turonian in many areas.

The Lower Turonian in Bch-1 yielded abundant dinocysts throughout, but *Senoniasphaera turonica* was recorded in only two samples (Fig. 3). Its FO in the lower *Mammites nodosoides* Zone is consistent with published lowest records of the species in the English Chalk (e.g. Tocher and Jarvis, 1987; Pearce et al., 2009). However, this cannot be regarded as being definitive. Sporadic occurrences of *S. turonica* consistently range down into the Middle Cenomanian, upper *Acanthoceras rhotomagense* Zone, at Culver Cliff, Isle of Wight England, at Wunstorf Quarry, northern Germany, and at Vergons, SE France, indicating that this is the true FO of the species (Lignum, 2009; Pearce et al., 2011). The FCO of *S. turonica*, however, typically lies towards the base of the Lower Turonian (Pearce et al., 2011).

Senoniasphaera abundances vary considerably between sections, but an acme of *Senoniasphaera turonica* occurs consistently in the Upper Turonian (*Sternotaxis plana* Zone; *Subprionocyclus neptuni* Zone) of the English Chalk successions (Fig. 5). *Senoniasphaera rotundata* s.s. first appears in the Upper Turonian, with a FCO around the stage boundary and an acme in the Lower Coniacian (*Micraster cortestudinarium* Zone). *Senoniasphaera rotundata* was not recorded from Bch-1. However, the LO *S. turonica* occurs in the lower *S. neptuni* Zone, above the Hitch Wood CIE, which is correlative with the uppermost acme of the species elsewhere (Fig. 5).

6.3. Middle Turonian dinocyst events

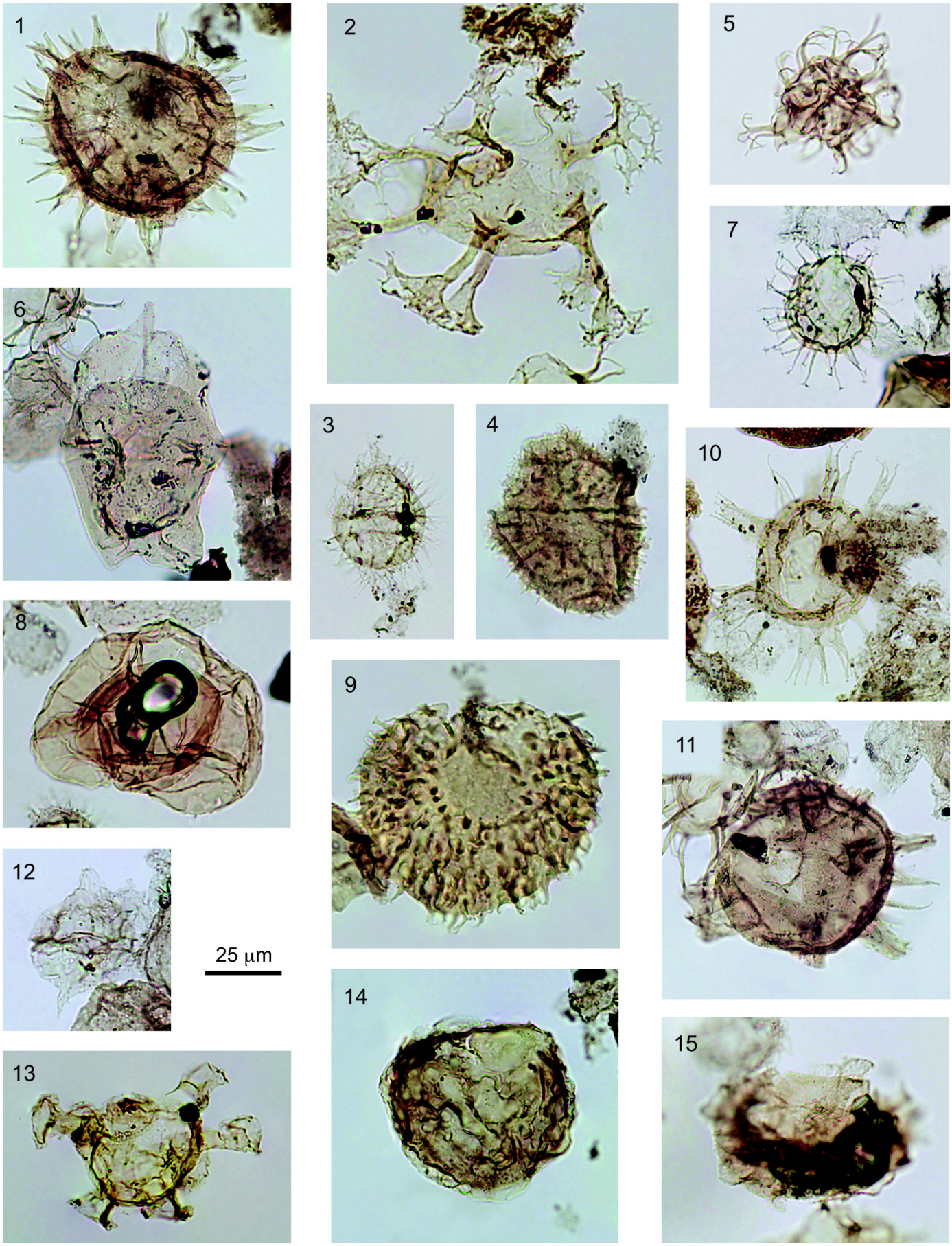
Oligosphaeridium poculum first occurs towards the base of the *Collignoceras woollgari* Zone at Bch-1 (Fig. 3). Its FO is recorded at a similar stratigraphic level in Berkshire and Kent (FitzPatrick, 1995; Pearce et al., 2003), but occurs lower in East Sussex, at the base of the *Mammites nodosoides* Zone (Pearce et al., 2009). The FO of *O. poculum* in the Trunch borehole of eastern England (see Pearce, 2010 for locality details) lies within the basal Coniacian, albeit based on only two records from the core (Pearce, 2000), and these may not be in situ as that interval shows evidence of intermittent sediment reworking. The datum level appears to be a consistent Turonian marker, although the species has been recorded from the Hauterivian of Germany (Prössl, 1990) and the Barremian–Albian, of Greenland, England and India (Jain, 1977; Lister and Batten, 1988; Nøhr-Hansen, 1993), so the Turonian FO is in truth a reoccurrence (RO) datum level, as indicated by Pearce et al. (2009, Fig. 3).

The FO *Subtilisphaera pontis-mariae* is found within the lower *Collignoceras woollgari* zone in Bch-1, marginally higher than the upper Lower Turonian placement of Hardenbol et al. (1998) for the Tethyan realm. However, the species has a long stratigraphic range, from at least Upper Albian (Davey, 1970; Lignum, 2009) to Lower Campanian (Prince et al., 1999; Pearce, 2000), so its stratigraphic utility is limited.

The FO *Raetiaedinium truncigerum* lies in the mid-*Collignoceras woollgari* Zone at Bch-1, slightly below the Glynde CIE. The FO of *R. truncigerum* has been previously recorded also from the upper Middle Turonian by Prössl (1990), or slightly higher in the Upper Turonian (Foucher, 1976a; Marshall, 1983; Williams and Bujak, 1985; Williams et al., 1993; Hardenbol et al., 1998) or Lower Coniacian (Kirsch, 1991), and so the FO appears to be a potential Middle Turonian marker. The species ranges into the Campanian in England and Germany (Kirsch, 1991; Williams et al., 1993; Prince et al., 1999; and by our personal observations).

Florentinia buspina also first occurs in the mid-*Collignoceras woollgari* Zone at Bch-1 (Fig. 3). A mid-Turonian FO or FCO of *F. buspina* is noted in most English Chalk sections (Fig. 5), although the exact stratigraphic position is variable. This is again a RO, since the species extends down into the Lower Cenomanian at Trunch (Pearce, 2000), at Culver Cliff Isle of Wight, and at Vergons SE France (Lignum, 2009). The species ranges upwards into the Campanian in Germany (Davey and Verdier, 1976; Kirsch, 1991; Pearce, 2000).

FitzPatrick (1995), Pearce (2000) and Pearce et al. (2003) recognised 'acmes' of *Circulodinium distinctum* within the Middle Turonian *Terebratulina lata* Zone of the English Chalk. Three main peaks of *C. distinctum* are found in the Bch-1 core (Figs. 4, 5): the first, in the mid-*Collignoceras woollgari* Zone, between the Round Down and Glynde CIEs, is the highest amplitude peak but is confined to a single sample; the second broader peak is towards the top of the *C. woollgari* Zone, at the level of the 'Pewsey' CIE; the third peak is located in the mid-*Subprionocyclus neptuni* Zone mid-way between the Bridgewick and the Hitch Wood CIEs. The first and second peaks correspond stratigraphically to floods and acme intervals of *C. distinctum* found in the English Chalk (Fig. 5). The final higher peak in the Upper Turonian may be of local significance, or may not have been recognised (or preserved) in the lower resolution sampling of the more attenuated, potentially less complete, English Chalk Upper Turonian successions (e.g. see discussion in Uličný et al., 2014).


1
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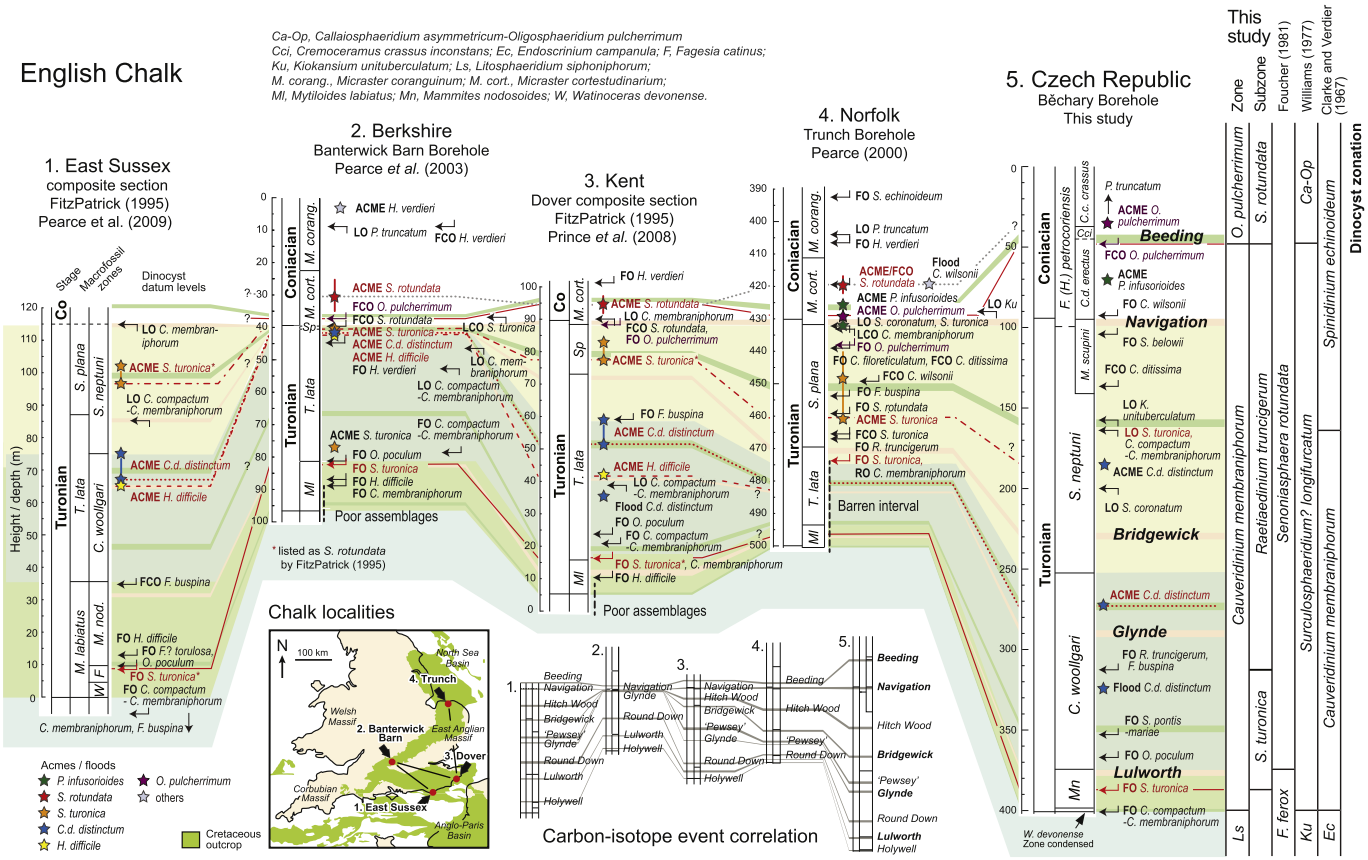

Fig. 5. Biostratigraphic and chemostratigraphic correlation of Bch-1 with English Chalk Turonian sections, showing key dinocyst datum levels. Inset map (modified from Rawson, 1992) shows locations of English sections. Traditional Chalk macrofossil zones based on inoceramid bivalves, brachiopods and irregular echinoids; ammonite zones are also shown for the East Sussex composite section. Carbon isotope events in East Sussex based on interpretation of lithostratigraphic and biostratigraphic data (Mortimore, 1986; FitzPatrick, 1995; Gale, 1996; Mortimore et al., 2001; Jarvis et al., 2006), and Pearce et al. (2009) for the Cenomanian–Turonian boundary interval.

6.4. Upper Turonian dinocyst events

The Upper Turonian at Bch-1 is marked by a series of last occurrence datum levels (Figs. 3, 5). The LO of *Stephodinium coronatum* occurs in the lower *Subprionocyclus neptuni* Zone at Bch-1. The LO of the species has been recorded marginally higher elsewhere in the area, in the *Mytiloides scupini* Zone of the Úpohlavy section, located 25 km NNW of Prague (Svobodová et al., 2002). This level correlates to a position just below the FO of *Prionocyclus germari* in other Bohemian Cretaceous Basin sections (cf. Fig. 2). This compares favourably to a top Upper Turonian LO of *S. coronatum* at Trunch (Pearce, 2000). The LO *S. coronatum* has also been recorded from the Turonian–Coniacian boundary interval elsewhere (Foucher, 1976b; Costa and Davey, 1992; Williams et al., 1993).

Bujak and Williams (1978) and Williams and Bujak (1985) stated that *Stephodinium coronatum* occurs in the Santonian, but without distribution data it is unknown whether this observation might be based on reworked specimens; Ioannides (1986) also recorded *S. coronatum* from Santonian to ?Maastrichtian sediments, but in samples that clearly contained reworked taxa. We therefore discount these records in the light of overwhelming evidence, at least for NW Europe, that the LO of *S. coronatum* occurs in the uppermost Turonian, close to the Turonian–Coniacian boundary.

The coincident LOs of *Senoniasphaera turonica* and *Cyclonephelium compactum–Cauveridinium membraniphorum* occur in the mid-*Subprionocyclus neptuni* Zone, below the Hitch Wood CIE; the former is somewhat lower than the last occurrence of *S. turonica* in the English Chalk (Fig. 5). The FCO of *Chatangiella ditissima* occurs towards the base

Plate I. Biostratigraphic marker species identified in the Turonian–Coniacian of the Bch-1 core.

1. *Pervosphaeridium truncatum* (Davey, 1969) Below 1982, sample 335.5 m
2. *Oligosphaeridium pulcherrimum* (Deflandre and Cookson 1955) Davey and Williams 1966, sample 33.5 m
3. *Palaeohystrichophora infusorioides* Deflandre 1935, sample 351.5 m
4. *Cribroperidinium wilsonii* (Yun Hyesu 1981) Poulsen 1996, sample 57.5 m
5. *Surculosphaeridium belowii* Yun Hyesu 1981, sample 51.5 m
6. *Chatangiella ditissima* (McIntyre, 1975) Lentin and Williams 1976, sample 33.5 m
7. *Kiokansium unituberculatum* (Tasch in Tasch et al. 1964) Stover & Evitt 1978, sample 197.5 m
8. *Stephodinium coronatum* Deflandre 1936, sample 215.5 m
9. *Circulodinium distinctum distinctum* (Deflandre and Cookson 1955) Jansonius, 1986, sample 187.5 m
10. *Florentinia buspina* (Davey and Verdier, 1976) Duxbury 1980, sample 285.5 m
11. *Raetiaedinium truncigerum* (Deflandre 1937) Kirsch, 1991, sample 55.5 m
12. *Subtilisphaera pontis-mariae* (Deflandre 1936) Lentin and Williams 1976, sample 219.5 m
13. *Oligosphaeridium poculum* Jain, 1977, sample 43.5 m
14. *Senoniasphaera turonica* (Prössl, 1990 ex Prössl, 1992) Pearce et al., 2011, sample 389.5 m
15. *Cyclonephelium compactum* complex of Marshall and Batten, 1988, sample 398.6 m.

of the *Mytiloides scupini* Zone at Bch-1. The FO of *C. ditissima* has been previously recorded from the lowermost Turonian (Costa and Davey, 1992), the Upper Turonian (Sweet and McIntyre, 1988; Prössl, 1990; Scott, 2014) and the Lower Coniacian (Williams et al., 1993). However, a high Upper Turonian (high *Sternotaxis plana* Zone) FCO was recorded at Trunch (Fig. 5) by Pearce (2000), at a comparable level to Bch-1, with lower sporadic occurrences in the Lower Cenomanian. The FCO of the species offers, therefore, a potential biostratigraphic datum level. *Chatangiella ditissima* is a common component of Santonian–Campanian assemblages in many areas (e.g. McIntyre, 1975; Ioannides, 1986; Costa and Davey, 1992; Skupien et al., 2009; Radmacher et al., 2014), with a likely LO in the Maastrichtian (Kirsch, 1991; Williams et al., 1993; Lebedeva, 2006; Lebedeva et al., 2013).

6.5. Turonian–Coniacian dinocyst boundary events

The Turonian–Coniacian boundary interval is marked by a series of benthic macrofossil events, particularly affecting the inoceramid bivalves (Walaszczyk, 2000), that enable the development of a refined biostratigraphy at Bch-1 (Fig. 5). A number of dinocyst events are also apparent. The FO of *Surculosphaeridium belowii* occurs immediately below the stage boundary and the Navigation CIE at Bch-1 (Fig. 3). This species has been recorded previously largely from Coniacian–Maastrichtian sediments in England, Germany and Austria (Yun, 1981; Kirsch, 1991; Pearce, 2000; Soliman et al., 2009; Mohamed and Wagreich, 2013), but it has also been identified from the Barremian of the Slovak Carpathians (Skupien, 2003); however, its Turonian reoccurrence (RO) datum level may be of stratigraphic value.

The FO *Cribroperidinium wilsonii* occurs immediately above the base Coniacian and the Navigation CIE at Bch-1 (Figs. 3, 5). A Turonian–Coniacian FO is consistent with records from Germany and Denmark (Kirsch, 1991; Schiøler, 1992), although the species ranges from Upper Albian–Campanian in southern England (Prince et al., 1999, 2008; Pearce, 2000; Lignum, 2009). However, the FCO of *C. wilsonii* is observed in the high Upper Turonian mid-*Sternotaxis plana* Zone above the Hitch Wood CIE at Trunch (Fig. 5), and here it becomes increasingly common through the mid- to Upper Coniacian, confirming its importance as a significant component of Coniacian dinocyst assemblages. Although *Palaeohystrichophora infusorioides* is a major component of the dinocyst assemblages through most of the succession at Bch-1, a prominent acme occurs in the lowest Coniacian *Cremnoceramus deformis erectus* Zone (Figs. 4, 5). A similar acme is recorded in the lowest Coniacian at Trunch (Pearce, 2000), though it has not been identified in other Chalk sections studied to date.

The first common and consistent occurrence of *Oligosphaeridium pulcherrimum* occurs at the top of the *Cremnoceramus deformis erectus* Zone at Bch-1, at the base of the Beeding CIE; an acme of the species occurs a short distance above, at the base of the *Cremnoceramus crassus crassus* Zone. The FO of persistently occurring specimens, FCO and/or acme of the species are observed around the Turonian/Coniacian boundary in Chalk sections throughout southern England (Fig. 5). The oldest record of *O. pulcherrimum* is from the Upper Jurassic (Brideaux, 1977), and it is a common component in the Lower Cretaceous (Prössl, 1990). However, the species has been noted previously as becoming more common in the Coniacian (Foucher, 1980; Pearce et al., 2003); in the zonation schemes of Williams (1975, 1977), *O. pulcherrimum* is an important indicator species for the Coniacian *O. pulcherrimum* Zone.

Pervosphaeridium truncatum ranges through the Cenomanian–Coniacian succession sampled at Bch-1. The species has a LO in the *Micraster coranguinum* Zone in Berkshire and Norfolk (Marshall, 1983; Pearce et al., 2003), southern England (Fig. 5), indicating that the top of Bch-1 probably lies below that stratigraphic level. However, records of the species from the Campanian–Maastrichtian in Germany and Canada (Harker et al., 1990; Kirsch, 1991) may point to a younger true LO.

The FO *Heterosphaeridium verdieri* was proposed as a high Lower Coniacian marker by Prince et al. (2008), based on records from Kent and the Isle of Wight. The species had previously been reported from Santonian deposits in Germany (Yun, 1981; Kirsch, 1991). The species has been recorded from the high-Middle Turonian in Berkshire (Pearce et al., 2003) and as a very rare component (possibly misidentified?) from the Upper Cenomanian of East Sussex (Pearce et al., 2009), but it has a FCO and acme in the low Middle Coniacian (Fig. 5). The absence of *H. verdieri* and *Spinidinium echinoideum* (another Middle Coniacian marker) at Bch-1 is consistent with the Early Coniacian age of the sampled section top indicated by macrofossil and nannofossil records (*Cremnoceramus crassus crassus* Zone, base UC10; Fig. 2).

7. Turonian dinocyst zonation

No generally accepted dinocyst zonation scheme exists for the Turonian Stage. Here, previously published zonations are critically reviewed in the light of recent studies, including the new data obtained from the Bch-1 core. The viability of individual zones is considered and, following revision, a new composite scheme is proposed.

7.1. Clarke and Verdier (1967) zonation

The *Hystrichosphaeridium* (now *Litosphaeridium*) *siphoniphorum* Zone was created by Clarke and Verdier (1967) to approximate the Cenomanian, from the stage base to a position within the Plenus Marl of southern England, which at the time, was considered to be questionably Turonian (cf. Jefferies, 1963). The stage boundary is now placed higher, within the overlying Ballard Cliff Member (Gale et al., 2005; Pearce et al., 2009). *Litosphaeridium siphoniphorum* tends to be common between its range base in the Upper Albian and the Upper Cenomanian. The LCO of *L. siphoniphorum* occurs consistently within the Upper Cenomanian (*Metoicoceras geslinianum* Zone) throughout Europe and in North America, although rare occurrences extend into the Lower Turonian (Davey, 1969; Foucher, 1979, 1980, 1982; Marshall and Batten, 1988; Courtinat et al., 1991; Huan and Habib, 1996; Hardenbol et al., 1998; Lamolda and Mao, 1999; Dodsworth, 2000; Pearce, 2000; Lignum, 2009; Pearce et al., 2009). The absence of *L. siphoniphorum* at Bch-1 is consistent with an absence of low *M. geslinianum* Zone and older Cenomanian sediments within the sampled interval.

Clarke and Verdier (1967) erected a *Scriniodinium* (previously *Endoscrinium*) *campanula* Zone to represent the uppermost Cenomanian to the lower Turonian interval (Fig. 5), which was characterised by the presence of *Xiphophoridium alatum* (now *Dinopterygium alatum*), *Cometodinium obscurum* and *Cyclonephelium hughesii*. The base was defined by the top of the *Litosphaeridium siphoniphorum* Zone, and the top by the LO of *S. campanula*. At Bch-1, *S. campanula* was recorded only in two Lower Coniacian samples, and is absent from the Turonian. The taxon occurs sporadically throughout the Cenomanian–Santonian at Trunch, with a LO here and at Culver Cliff in the Upper Santonian, mid-*Uintacrinus socialis* Zone (Prince et al., 1999, 2008; Pearce, 2000), and it is never a common component of the assemblage. Furthermore, *D. alatum* occurs through the Cenomanian to Upper Turonian (*Sternotaxis plana* Zone), and *C. obscurum* is only commonly recorded from the Upper Turonian (*S. plana* Zone), so the *S. campanula* Zone as defined previously is not viable.

Cauveridinium membraniphorum is a very distinctive component of uppermost Cenomanian and Turonian dinocyst assemblages throughout Europe (Section 6.1, above). A *Cyclonephelium* (now *Cauveridinium*) *membraniphorum* Zone, of Turonian to Coniacian/Santonian age, was erected by Clarke and Verdier (1967) based on limited sampling from the Isle of Wight. The base of the zone was defined by the LO of *Scriniodinium campanula*, and its top by the LO of *C. membraniphorum* (Fig. 5). Subsequent records extending the range of *S. campanula* into the Upper Santonian make the LO of this species untenable as a basal

marker for a largely Turonian zone. Accordingly, it is proposed here to redefine the base of the *C. membraniphorum* Zone by the LCO of *Litosphaeridium siphoniphorum*.

Clarke and Verdier (1967) erected a *Deflandrea echinoidea* (now *Spinidinium echinoideum*) Zone to represent the ?lower–mid-Santonian, defined as the interval immediately following the LO of *Cauveridinium membraniphorum*, to immediately below the FO of *Hystrichosphaeropsis ovum*, *Dinogymnium albertii* and *Dinogymnium heterocostatum*. The FO of *S. echinoideum* occurs in the Coniacian (Williams and Bujak, 1985); at Trunch and in Kent (Pearce, 2000; Prince et al., 2008) its FO is in the mid-Coniacian, low *Micraster coranguinum* Zone (Fig. 5). The index species has commonly low and varying abundance through the Coniacian–Campanian in different sections, but it generally shows a FCO around the base Santonian, making it a good Santonian marker (Foucher, 1976a; Heine, 1991; Kirsch, 1991; Prince et al., 1999; Pearce, 2000).

Using the original definition of Clarke and Verdier (1967), beds above the LO of *C. membraniphorum* at Bch-1 technically fall within their *S. echinoideum* Zone (Fig. 5). However, in reality the FO of the zonal index species falls stratigraphically above the interval represented in the Bch-1 core, and the zone is not considered to be relevant to the current study.

7.2. Williams (1977) zonation

Williams (1977) 'global' Upper Cretaceous dinocyst zonation scheme, based largely on assemblage data from southern England (Clarke and Verdier, 1967; Davey, 1969, 1970) and offshore eastern Canada, employed *Kiokansium unituberculatum* (then referred to as *Cleistosphaeridium polypes*) as a Cenomanian index species (Fig. 5). Subsequently, the LO of *K. unituberculatum* has been recorded as Lower Turonian (Foucher, 1981), and sporadic occurrences extend into the basal Lower Coniacian at Trunch (Pearce, 2000) but in an interval with significant Cenomanian reworking, so this latter record may be unreliable.

Williams (1977) Turonian zonal index, *Surculosphaeridium*? *longifurcatum* (Fig. 5), is a long-ranging species, from Upper Barremian (Prössl, 1990) to Campanian (Williams and Bujak, 1985; Kirsch, 1991; Williams et al., 1993; Pearce, 2000). It is abundant in the Lower Turonian to basal Middle Turonian and in the Lower Coniacian at Bch-1, but its abundance records show little consistency between Chalk sections and it is considered to be of little biostratigraphic value.

Williams (1977) recognised a *Callaiosphaeridium asymmetricum*–*Oligiosphaeridium pulcherrimum* Zone within the Coniacian–Lower Santonian (Fig. 5). The first species is long ranging, from Hauterivian (Davey and Williams, 1966a,b; Warren, 1967) to Campanian (Foucher, 1979; Kirsch, 1991). By contrast, *O. pulcherrimum* has a consistent FCO in the Lower Coniacian (Pearce, 2000; Pearce et al., 2003; Prince et al., 2008), and it is proposed here as a Coniacian zonal index species (Fig. 5).

7.3. Foucher (1981) zonation

Foucher (1981) erected a *Senonisphaera rotundata* Zone, defined by the FO *S. rotundata*, for the Turonian (top not considered), with an Upper Cenomanian–Lower Turonian *Silicisphaera* (now *Florentinia*) *ferox* Zone, below (Fig. 5). The latter is long-ranging, Hauterivian (Gocht, 1959) to Maastrichtian (Clarke and Verdier, 1967; Foucher, 1975, 1976a; Foucher and Robaszynski, 1977; Kirsch, 1991), and is therefore of limited stratigraphic value. By contrast, *S. rotundata* sensu lato has proved to be a good biostratigraphic marker (Section 5.2). The genus is used here to define a new Lower to Middle Turonian *Senoniasphaera turonica* Subzone (*C. membraniphorum* Zone; Fig. 5) and a Lower Coniacian *S. rotundata* sensu stricto Subzone (*Oligosphaeridium pulcherrimum* Zone).

7.4. FitzPatrick (1995) zonation

A palynological zonation scheme for the uppermost Cenomanian to Turonian of the southern English Chalk was proposed by FitzPatrick (1995). Three zones were erected: Palynozones I to III. Palynozone I was considered to represent the Lower Turonian, with a base defined by the FO of *Heterosphaeridium difficile*, *Senoniasphaera rotundata* sensu lato, and *Florentinia buspina*. Another species thought to be an important index taxon was *Litosphaeridium* sp. A of Marshall and Batten (1988), which was recorded as having a LO in the lowest Turonian of East Sussex, immediately below the base of the *Mammites nodosoides* Zone.

Palynozone II was considered to represent the mid-Turonian (*Terebratulina lata* Zone), and was defined by the FO of *Florentinia*? *torulosa* to the LO of *Scriniodinium campanula*. Acmes of *Heterosphaeridium difficile* and *Circulodinium distinctum* characterise the middle part of the zone. *Florentinia*? *torulosa* is absent in the Turonian of Bch-1, and rare to absent in most English Chalk sections, so it is a rather poor index species. More importantly, the LO of *S. campanula* is Santonian (Foucher, 1976a; Kirsch, 1991; Costa and Davey, 1992; Prince et al., 1999; Pearce, 2000), so this zone cannot be employed as a Turonian marker.

Palynozone III was erected to represent the Upper Turonian, and was defined as lying directly above Palynozone II (i.e. above the LO of *Scriniodinium campanula*); the top of the zone was not defined. An acme of *Senoniasphaera* '*rotundata*' (considered here to be records of *Senoniasphaera turonica*) occurring in the lower part of the zone was considered to be of correlative value. In the light of the proven extended stratigraphic range of *S. campanula* in the English Chalk and elsewhere, Palynozone III would represent uppermost Santonian or Campanian, not Turonian strata. The Turonian palynozonation scheme of FitzPatrick (1995) is therefore fundamentally flawed.

7.5. A revised Turonian zonation

Here, we propose a single *Cauveridinium membraniphorum* Interval Zone spanning the top Cenomanian to basal Coniacian (Fig. 5). The base of the *C. membraniphorum* Zone is marked by the LCO of *Litosphaeridium siphoniphorum* (top *L. siphoniphorum* Zone). The *C. membraniphorum* Zone is subdivided into: *Senoniasphaera turonica* (Lower–Middle Turonian) and *Raetiaedinium truncigerum* (Middle Turonian–basal Coniacian) subzones. The top of the *C. membraniphorum* Zone is defined by the FCO *Oligosphaeridium pulcherrimum* (*S. rotundata* Subzone; base *O. pulcherrimum Zone*).

The FO of *Senoniasphaera turonica* is lower Middle Cenomanian *Acanthoceras rhotomagense* Zone in southern England, northern Germany and SE France (Pearce et al., 2011), but in northern Europe the species is rare at its FO and it is commonly absent from the Upper Cenomanian. However, it shows a widespread RO and FCO in the Lower Turonian (Foucher, 1980; Tocher and Jarvis, 1987; Jarvis et al., 1988a; Lamolda and Mao, 1999; Pearce et al., 2003, 2009). The FCO/RO of *S. turonica* defines the base of our *S. turonica* Subzone; its top is placed at the FO of *Raetiaedinium truncigerum*.

The FO of *Raetiaedinium truncigerum* in Bch-1 occurs within the Middle Turonian *Collignoceras woollgari* Zone, below the Glynde CIE, consistent with records of its lowest FO elsewhere (Section 5.3). It defines the base of the *R. truncigerum* Subzone.

Despite ranging down into the Hauterivian, *Oligosphaeridium pulcherrimum* shows a FCO and acme in the basal Coniacian (*Cremnoceramus deformis erectus* Zone; Beeding CIE) of Bch-1, which is consistent with records from the basal Coniacian of the English Chalk (Fig. 5). The FCO (in reality, a reoccurrence datum level; Section 5.5) is used here to mark the base of the *O. pulcherrimum* Zone, the lower part of which includes the FCO and an acme of *Senoniasphaera rotundata*, constituting the *S. rotundata* Subzone (top not defined).

8. Conclusions

An expanded Turonian cored succession (Bch-1) from Běchary in the Bohemian Cretaceous Basin has yielded abundant and diverse assemblages of well-preserved dinocysts throughout the Turonian–Lower Coniacian. Dinocyst records are constrained by calcareous nannofossil, macrofossil and sequence stratigraphic data (Uličný et al., 2014). A high-resolution (5.6 kyr) carbon isotope ($\delta^{13}C_{org}$) profile obtained from the core provides the basis for identifying the Turonian carbon isotope events (CIEs) of Jarvis et al. (2006) in the succession, and placing dinocyst datum levels directly within the CIE stratigraphy. To our knowledge, these records offer the highest resolution, fully stratigraphically constrained, Turonian dinocyst dataset published to date.

A succession of 18 dinocyst datum levels, considered to be of potential regional biostratigraphic significance, are recognised in Bch-1. From bottom to top, these are (Fig. 5): FOs of *Cyclonephelium compactum–Cauveridinium membraniphorum* and then *Senoniasphaera turonica* in the Lower Turonian; FOs of *Oligosphaeridium poculum*, *Subtilisphaera pontis-mariae*, a flood of *Circulodinium distinctum distinctum*, the FOs of *Raetiaedinium truncigerum* and *Florentinia buspina*, and a second flood of *C. d. distinctum* in the Middle Turonian; LO *S. coronatum*, a *C. d. distinctum* acme, the LOs *C. compactum–C. membraniphorum*, *S. turonica* and *Kiokansium unituberculatum*, the FCO *C. ditissima* and FO *Surculosphaeridium belowii* in the Upper Turonian; FO *Cribroperidinium wilsonii* coincides with the base Coniacian, followed by an acme of *Palaeohystrichophora infusorioides*, the FCO and then an acme of *Oligosphaeridium pulcherrimum*. *Pervosphaeridium trunctatum* ranges to the top of the sampled section (high Lower Coniacian).

A review of published Turonian records from English Chalk sections in East Sussex, Berkshire, Kent and Norfolk demonstrates the presence of several consistent dinocysts datum levels. However, detailed stratigraphic comparison is hampered by lateral thickness variation, by differences in sampling resolution and stratigraphic completeness, and by the presence of barren intervals and poor recovery in some sections. Consistent Chalk datum levels are provided by the FO *Senoniasphaera turonica* low in the Lower Turonian, an acme of *Circulodinium distinctum distinctum* in the high Middle Turonian, an acme of *S. turonica* in the mid-Upper Turonian with the FO *Oligosphaeridium pulcherrimum* towards the top of the substage. The Lower Coniacian is marked by the FCO or an acme of *O. pulcherrimum*, followed by an acme/FCO *Senonisphaera rotundata*.

Critical review of published Turonian dinocyst zonation schemes shows them to be untenable. A revised dinocyst zonation for the Turonian based on our review of the English Chalk data and new results from Bch-1, tied to the carbon isotope event stratigraphy of Jarvis et al. (2006), has been presented that is judged to be of likely wider geographic significance. Correlation of the English Chalk data to Bch-1 provides a basis for defining a regional dinocyst event stratigraphy with 22 datum levels, and a revised dinocyst zonation scheme constrained within a chemostratigraphic framework of 10 major CIEs.

The proposed new dinocyst zones consist of a Cenomanian *Litosphaeridium siphoniphorum* Zone, followed by the *Cauveridinium membraniphorum* Zone spanning the uppermost Cenomanian to Lower Coniacian. This is subdivided into: *Senoniasphaera turonica* (Lower–mid-Middle Turonian); and *Raetiaedinium truncigerum* (mid-Middle Turonian–mid-Lower Coniacian) subzones. The *Oligosphaeridium pulcherrimum* Zone (*Senonisphaera rotundata* Subzone) characterises the Lower Coniacian.

Key regional datum levels are (Fig. 6):

(1) within the Cenomanian–Turonian boundary CIE: LCOs *Litosphaeridium siphoniphorum* and *Wrevittia cassidata* (Upper Cenomanian, *Metoicoceras geslinianum* Zone), defining the base of the *Cauveridinium membraniphorum* Zone;

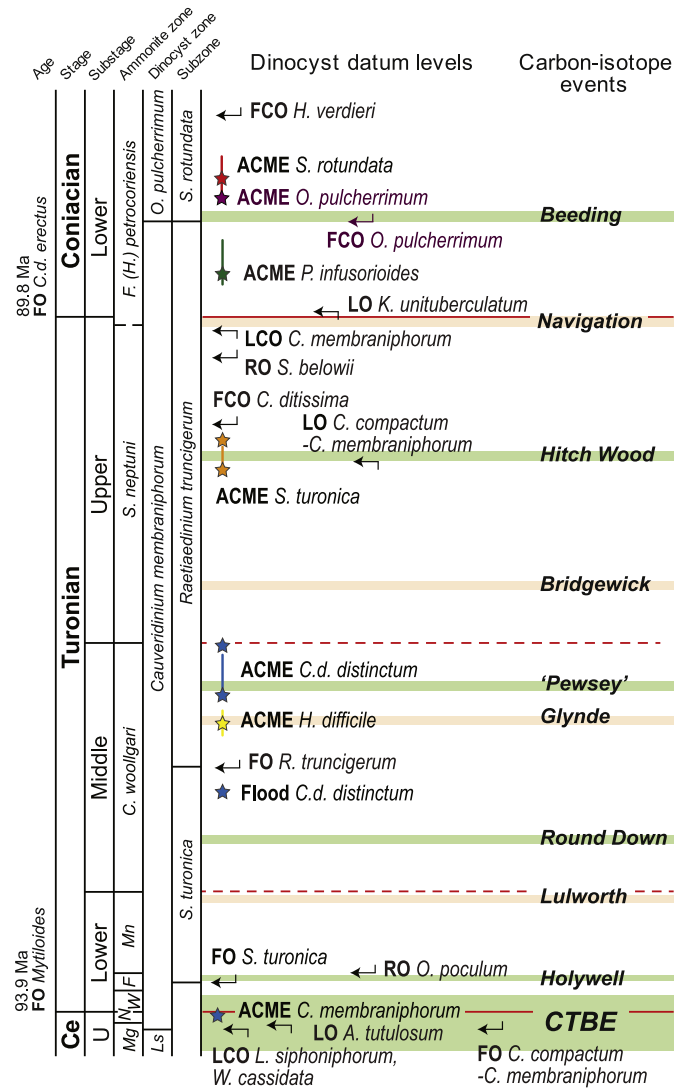

Fig. 6. Revised dinocyst zonation for the Turonian Stage, key dinocyst biostratigraphic markers, and their correlation to major carbon isotope events. Symbols as in Fig. 5. CTBE = Cenomanian–Turonian Boundary Event.

(2) FO *Cyclonephelium compactum–Cauveridinium membraniphorum* and LO *Adnatosphaeridium tutulosum* followed by an acme of *C. membraniphorum* in the uppermost Cenomanian (*Neocardioceras juddii* Zone);
(3) FO *Senoniasphaera turonica* below the Holywell CIE (Lower Turonian, *Fagesia catinus* Zone), defining the base of the *S. turonica* Subzone;
(4) RO *Oligosphaeridium poculum* above the Holywell CIE;
(5) flood of *Circulodinium distinctum distinctum* in the mid-Middle Turonian *Collignoceras woollgari* Zone;
(6) FO *Raetiaedinium truncigerum* between the Round Down and Glynde CIEs (Middle Turonian, *Collignoceras woollgari* Zone), defining the base of the *R. truncigerum* Subzone;
(7) acme of *Heterosphaeridium difficile* coincident with the Glynde CIE;
(8) an acme interval of *Circulodinium distinctum distinctum* at the summit of the Middle Turonian *Collignoceras woollgari* Zone, spanning the 'Pewsey' CIE;
(9) acme interval of *Senoniasphaera turonica* spanning the Hitch Wood CIE *Subprionocyclus neptuni* Zone, following the LO *Cyclonephelium compactum–Cauveridinium membraniphorum*;
(10) FCO *Chatangiella ditissima* in the higher Upper Turonian;

(11) RO *S. belowii*, then LCO *Cauveridinium membraniphorum* immediately below the Navigation CIE in the uppermost Turonian, with the LO *Kiokansium unituberculatum* immediately above in the base Coniacian;
(12) acme of *Palaeohystrichophora infusorioides* in the Lower Coniacian between the Navigation and Beeding CIEs;
(13) FCO *Oligosphaeridium pulcherrimum* below the Beeding CIE (Lower Coniacian, *Forresteria* (*Harleites*) *petrocoriensis* Zone), defining the bases of the *O. pulcherrimum* Zone and *Senonisphaera rotundata* Subzone.
(14) acmes of *Oligosphaeridium pulcherrimum* and then *Senonisphaera rotundata* in the mid-Lower Coniacian, with the FCO *Heterosphaeridium verdieri* towards the top of the substage.

The new stratigraphy offers potential for improved correlation and dating of Upper Cretaceous successions. However, additional high-resolution dinocyst datasets from multiple sections are required to test and further refine the Turonian biostratigraphy.

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Appendix A. Species list

Complete list of dinoflagellate cyst species recorded in the Bch-1 core. Numbers correspond to the order of species plotted in Fig. 3. Other taxa, found less commonly, are also listed along with the genetic sequence(s) from which they have been identified (i.e. TUR1-7, CON1-2, Figs. 2, 3). Taxonomic references are given in Fensome et al. (2008) and Pearce et al. (2011).

26	*Achomosphaera ramulifera ramulifera* (Deflandre 1937) Evitt 1963
33	*Achomosphaera regiensis* Corradini 1973
1	*Achomosphaera sagena* Davey and Williams, 1966
2	*Callaiosphaeridium asymmetricum* (Deflandre and Courteville 1939) Davey and Williams, 1966
41	*Cassiculosphaeridia reticulata* Davey, 1969
22	*Cauveridinium membraniphorum–Cyclonephelium compactum* Complex of Marshall and Batten, 1988
58	*Chatangiella ditissima* (McIntyre, 1975) Lentin and Williams 1976
3	*Circulodinium distinctum distinctum* (Deflandre and Cookson 1955) Jansonius 1986
39	*Circulodinium latoaculeum* (Yun Hyesu 1981) Islam 1993
TUR3	*Cometodinium obscurum* Deflandre and Courteville 1939
59	*Cometodinium whitei* (Deflandre and Courteville 1939) Stover and Evitt 1978
CON1, 2	*Conosphaeridium* Cookson and Eisenack 1969
CON1	*Conosphaeridium striatoconum* (Deflandre and Cookson 1955) Cookson and Eisenack 1969
4	*Coronifera oceanica* Cookson and Eisenack 1958
5	*Cribroperidinium orthoceras* (Eisenack 1958) Davey, 1969
70	*Cribroperidinium* sp. Neale and Sarjeant 1962
76	*Cribroperidinium wilsonii* (Yun Hyesu 1981) Poulsen 1996
74	*Cyclonephelium filoreticulatum* (Slimani 1994) Prince et al., 1999
TUR6/1, CON2	*Cyclonephelium hughesii* Clarke and Verdier, 1967
31	*Dapsilidinium laminaspinosum* (Davey and Williams 1966) Lentin and Williams 1981
72	*Dinogymnium acuminatum* Evitt et al. 1967
27	*Dinopterygium cladoides* Deflandre 1935
40	*Disphaeria macropyla* Eisenack and Cookson 1960
23	*Downiesphaeridium aciculare* (Davey, 1969) Islam 1993
42	*Downiesphaeridium armatum* (Deflandre 1937) Islam 1993
37	*Ellipsodinium rugulosum* Clarke and Verdier, 1967
24	*Exochosphaeridium arnace* Davey and Verdier 1973
43	*Exochosphaeridium bifidum* (Clarke and Verdier, 1967) Clarke et al. 1968
60	*Exochosphaeridium phragmites* Davey et al. 1966
67	*Florentinia buspina* (Davey and Verdier, 1976) Duxbury 1980
71	*Florentinia clavigera* (Deflandre 1937) Davey and Verdier 1973
28	*Florentinia cooksoniae* (Singh 1971) Duxbury 1980
47	*Florentinia laciniata* Davey and Verdier 1973
7	*Florentinia mantellii* (Davey and Williams, 1966) Davey and Verdier 1973
34	*Florentinia* sp. Davey and Verdier 1973
8	*Hystrichodinium pulchrum* Deflandre 1935
TUR4/1	*Hystrichosphaeridium* sp. Deflandre 1937
32	*Hystrichosphaeridium bowerbankii* Davey and Williams 1966
49	*Hystrichosphaeridium conispiniferum* Yun Hyesu 1981
9	*Hystrichosphaeridium recurvatum* (White 1842) Lejeune-Carpentier, 1940
50	*Hystrichosphaeridium salpingophorum* Deflandre 1935
10	*Hystrichosphaeridium tubiferum tubiferum* (Ehrenberg 1838) Deflandre 1937
63	*Hystrichosphaeridium tubiferum brevispinum* (Davey and Williams, 1966) Lentin and Williams 1993
52	*Hystrichostrogylon membraniphorum* Agelopoulos 1964
69	*Impletosphaeridum clavulum* (Davey, 1969) Islam 1993
74	*Isabelidinium*? *amphiatum* (McIntyre, 1975) Lentin and Williams 1977
TUR4/1	*Kallosphaeridium*? *ringnesiorum* (Manum and Cookson 1964) Helby 1987
54	*Kiokansium unituberculatum* (Tasch in Tasch et al. 1964) Stover & Evitt 1978
35	*Kleithriasphaeridium loffrense* Davey and Verdier, 1976
11	*Kleithriasphaeridium readei* (Davey and Williams, 1966) Davey and Verdier, 1976
TUR6/1, CON2	*Litosphaeridium arundum* (Eisenack and Cookson 1960) Davey 1979; emend. Lucas-Clark 1984
36	*Membranilarnacia polycladiata* Cookson and Eisenack in Eisenack 1963
29	*Microdinium distinctum* Davey, 1969
55	*Nematosphaeropsis denseradiata* (Cookson and Eisenack 1962) Stover and Evitt 1978
45	*Odontochitina costata* Alberti 1961; emend. Clarke and Verdier, 1967
12	*Odontochitina operculata* (Wetzel 1933a) Deflandre and Cookson 1955
53	*Odontochitina singhii* Morgan 1980
TUR4/1	*Odontochitinopsis molesta* (Deflandre 1937) Eisenack 1961
13	*Oligosphaeridium complex* (White 1842) Davey and Williams, 1966
48	*Oligosphaeridium poculum* Jain, 1977
14	*Oligosphaeridium prolixispinosum* Davey and Williams 1966
46	*Oligosphaeridium pulcherrimum* (Deflandre and Cookson 1955) Davey and Williams 1966
15	*Palaeohystrichophora infusorioides* Deflandre 1935
CON1	*Pareodinia ceratophora* Deflandre 1947
TUR2	*Pervosphaeridium* sp. Yun Hyesu 1981
TUR2 — 4/1, 4/3	*Pervosphaeridium cenomaniense* (Norvick 1976) Below 1982

TUR3 — 4/1, CON1 *Pervosphaeridium monasteriense* Yun Hyesu 1981
64 *Pervosphaeridium pseudhystrichodinium* (Deflandre 1937) Yun Hyesu 1981
16 *Pervosphaeridium truncatum* (Davey, 1969) Below 1982
17 *Prolixosphaeridium granulosum* (Deflandre 1937) Davey et al. 1966
18 *Pterodinium* "*crassimuratum*" (Davey and Williams, 1966) Thurow et al. 1988
68 *Raetiaedinium truncigerum* (Deflandre 1937) Kirsch, 1991
CON1 *Scriniodinium campanula* Gocht, 1959
44 *Senoniasphaera turonica* (Prössl, 1990 ex Prössl, 1992) Pearce et al., 2011
62 *Sentusidinium* sp. Sarjeant and Stover 1978
6 *Sepispinula*? *ambigua* (Deflandre 1937) Masure in Fauconnier and Masure 2004
38 *Spiniferites membranaceus* (Rossignol 1964) Sarjeant 1970
25 *Spiniferites ramosus granosus* (Davey and Williams, 1966) Lentin and Williams 1973
19 *Spiniferites ramosus ramosus* (Ehrenberg 1838) Mantell 1854
51 *Stephodinium coronatum* Deflandre 1936
56 *Subtilisphaera pontis-mariae* (Deflandre 1936) Lentin and Williams 1976
TUR3, 4/1 *Surculosphaeridium*? *basifurcatum* Yun Hyesu 1981
75 *Surculosphaeridium belowii* Yun Hyesu 1981
20 *Surculosphaeridium longifurcatum* (Firtion 1952) Davey et al. 1966
21 *Tanyosphaeridium salpinx* Norvick 1976
61 *Tanyosphaeridium variecalamum* Davey and Williams 1966
65 *Tenua hystrix* Eisenack 1958
30 *Trichodinium castanea* Deflandre 1935
57 *Wrevittia cassidata* (Eisenack and Cookson 1960) Helenes and Lucas-Clark 1997
TUR4/1 *Wrevittia helicoidea* (Eisenack and Cookson 1960) Helenes and Lucas-Clark 1997
TUR4/3 — 6/2 *Xenascus ceratioides* (Deflandre 1937) Lentin and Williams 1973
66 *Xiphophoridium asteriforme* Yun Hyesu 1981

Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.revpalbo.2014.10.006. These data include Google maps of the most important areas described in this article.

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