The Cenomanian–Turonian boundary at Eastbourne (Sussex, UK): a proposed European reference section

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Abstract

The Cenomanian–Turonian boundary (CTB) section at Eastbourne, Sussex, England is the thickest at outcrop in the Anglo–Paris Basin, is rhythmic throughout, rich in macro-, micro- and nanno-fossils, and shows less diagenetic alteration than other sections in NW Europe. Geochemical and biostratigraphic data are all related to detailed (rhythmic) lithostratigraphy, allowing correlation with the global boundary stratotype section to within 20,000 years and accurate estimates of rates of changes. Very detailed stable isotope curves for oxygen and carbon are presented and show that the build-up phase of the CTB carbon excursion had two portions separated by a trough. Patterns of occurrence of coarse-fraction benthic foraminifera (>250 μm) show two peaks of extinction corresponding to the two build-up phases of the carbon excursion. Benthic and planktic foraminifera, ostracods and calcareous nannofossils all show declines in diversity and abundance across the CTB. Foraminifera also decline significantly in size. Key biomarker events for the CTB include: first occurrences of the ammonites Fagesia catinus and Mammites nodosoides, the bivalve Mytiloides, the planktic foraminifera Helvetoglobotruncana praehelvetica and Marginotruncana renzi, and the calcareous nannofossils Quadrum intermedium, Q. gartneri and Eproolithus octopetalus; and last occurrences of the ammonite Sciponoceras, the planktic foraminifera Rotalipora greenhornensis and R. cushmani, the calcareous nannofossils Corolithion kennedyi, Axopodorhabdus albianus, Lithraphidites acutus, Rhaugodiscus asper and Microstaurus chiastius. Cyclostratigraphy allows very precise correlation of isotopic and bioevents with other sections in Europe and North America. Eastbourne is recommended as a NW European standard section. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: biostratigraphy; lithostratigraphy; Cenomanian–Turonian boundary; stable isotopes; foraminifera; ostracods; calcareous nannofossils; Chalk; NW Europe

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1. Introduction

The Plenus Marls and the lower part of the White Chalk Formation represent the local expression of the Cenomanian–Turonian boundary event (CTBE) in southern England. The CTBE is here estimated to have lasted between 400,000 and 500,000 years and was an important episode in the Earth’s history. Among other things it was associated with: a significant mass extinction (Sepkoski, 1986); the widespread burial of organic carbon (Jenkyns, 1980; Herbin et al., 1986; Schlanger et al., 1987); the presence of a large, positive carbon stable isotope excursion (Scholle and Arthur, 1980); and the drowning of carbonate platforms (Philippe and Airaud-Crumière, 1991). Furthermore, it may have represented a turning point in the development of Mesozoic climates (Jenkyns et al., 1994). Previous studies of the Plenus Marls have concentrated on the relatively condensed succession at Dover in SE England (e.g., Jarvis et al., 1988; Jeans et al., 1991; Lamolda et al., 1994), which is thin and has significant diagenetic overprinting (Mitchell et al., 1997). Here, we present a detailed, integrated study of the thick Plenus Marls succession at Eastbourne, Sussex (Fig. 1), the thickest CTB succession exposed at outcrop in the Anglo–Paris Basin. We consider the lithological succession, stable isotopes of carbon and oxygen, macrofossils, foraminifera, ostracoda and calcareous nannofossils. This sequence is particularly significant because it contains an expanded Cenomanian–Turonian boundary succession which is rhythmic before, during and after the CTBE, allowing very precise correlation with the global boundary stratotype section, and which preserves ammonites, inoceramids and planktic foraminifera, as well as a stable carbon isotope signature with relatively little diagenetic overprint (Mitchell et al., 1997). Consequently, it represents an ideal reference section for the Cenomanian–Turonian boundary in NW Europe.

2. History of study

The term Plenus Marls (as ‘Actinocamax plenus marls’) was first used by Rowe (1900, p. 317) for the marly unit at the top of the Lower Chalk that had usually been called the belemnite marl ever since Whitaker (1872) reported the presence of the belemnite Actinocamx (formerly Belemnitella and now Praeactinocamx) plenus Blainville. Subsequently, the Plenus Marls have been accepted as a formation in their own right near the top of the Lower Chalk (e.g., Robinson, 1986) and have always been accepted as lying close to the Cenomanian–Turonian boundary.

In the 1980s, two new lithostratigraphic schemes for the Chalk Group of southern England were introduced (Mortimore, 1986; Robinson, 1986), and both schemes have been used subsequently in their type
areas: the South Downs (Mortimore, 1986) and the North Downs (Robinson, 1986). Gale et al. (1987) and Gale (1996) attempted a revision of the lithostratigraphic nomenclature of the English Chalk of Turonian age, and proposed a set of new terms. We use a slightly modified lithostratigraphic scheme similar to that of Gale (1996) for consistency rather than full endorsement. Following Gale et al. (1993) and Gale (1996) we place the Cenomanian–Turonian boundary at 10 cm above Meads Marl 4, where ammonites typical of the Neocardioceras juddii Zone (Thomelites serotinus Wright and Kennedy and Sciponoceras bohemicus anterius Wright and Kennedy) are last recorded. This level correlates with bed 86 (of Cobban and Scott, 1972) in the Global Boundary Stratotype section at Pueblo, Colorado (Bengtson, 1996). The end of the plateau phase of the carbon isotope curve occurs immediately above bed 86 at Pueblo, and in Meads Marl 6 at Eastbourne, strengthening this correlation.

3. Lithology

Sections at Gun Gardens, Beachy Head (National Grid Reference TV 588953; Grey Chalk, Plenus Marls and lower Ballard Cliff Member) and Holywell Steps (TV 600968; upper Ballard Cliff Member) were logged in detail to produce a composite section for the Cenomanian–Turonian boundary at Eastbourne (Figs. 1 and 2). The section at Beachy Head was especially chosen since it provides an expanded succession through the lower part of the Plenus Marls (Jefferies, 1962, 1963; Gale et al., 1993).

The succession consists of alternations of clay-rich carbonates (calcareous mudrocks, usually called marls) and clay-poor carbonates (calcisphere-, coccolith- and inoceramid-rich limestones, usually called chalks). Boundaries between beds are invariably bioturbated. The succession can be divided into three distinct units: the sub-Plenus Marls chalks (Grey Chalk Member of the Lower Chalk Formation), the Plenus Marls Formation, and the lower part of the White Chalk Formation. Cyclostratigraphic schemes for the Cenomanian and Turonian stages have been introduced by Gale (1995, 1996) for sections in NW Europe, and these schemes are used here with minor modification.

3.1. Lower Chalk Formation (Grey Chalk Member)

The top of the Lower Chalk Formation is represented by well developed, relatively pure chalks, and thin marls. The marls show extensive signs of pressure solution including numerous marl flasers resulting from the compaction of burrows. Each marl–chalk couplet has been numbered by Gale (1995) and we consider couplets D44 to D49 in this study. The uppermost couplet is 1.8 m thick and may represent a set of amalgamated couplets.

3.2. Plenus Marls Formation

The Plenus Marls Formation represents a clay-rich interval between the carbonate-rich Lower Chalk and White Chalk formations. The lower part of the Plenus Marls is represented by grey marls and poorly defined chalks. In the upper part of the Plenus Marls the chalks become purer and more clearly defined and the marls become thinner and riddled with marl flasers, indicating extensive pressure solution. Jeffries (1962, 1963) introduced a numbering system for the beds in the Plenus Marls based on both lithology and faunal content. He recognised eight beds (numbered 1–8) which have been universally used subsequently, although some authors also recognise a bed 9 (e.g., Jeans et al., 1991; Lamolda et al., 1994; Paul et al., 1994a). Gale (1995, fig. 14) introduced a couplet numbering scheme for the Plenus Marls and recognised nine couplets (E1–E9). E1 to E3 were represented by Jeffries’ bed 1, E4 by Jeffries’ beds 2–3, E5 by Jeffries’ beds 4–5, E6 by Jeffries’ beds 6–7, and E7–E9 by Jeffries’ bed 8. We have some doubts that Jeffries’ bed 8 at Eastbourne really represents three couplets, but maintain this usage for consistency. (By the same reasoning used by Gale, 1996, the extra chalk bed present in Jeffries’ bed 4 could be considered to represent a separate couplet.)

3.3. White Chalk Formation

Mortimore (1986) introduced a lithostratigraphic scheme for the White Chalk of Sussex, and recognised three groups of beds, successively the Melbourn Rock, Holywell, and New Pit beds within his Ranscombe Chalk Member. He retained the use of the term Melbourn Rock, as originally applied
to hard nodular chalks in Cambridgeshire (Penning and Jukes-Browne, 1881), for the succession at Eastbourne. Gale (1996) pointed out that the distinctive characteristics of the Melbourn Rock are not shown by the lower part of the White Chalk Formation at Eastbourne, and introduced a modified lithostratigraphic scheme for the lower part of the White Chalk Formation. He recognised three members, from base upwards, the Ballard Cliff Member, the Holywell Member and the New Pit Member (after Mortimore, 1986). While we concur with the abandonment of the use of the term Melbourn Rock Beds at Eastbourne, we do not entirely agree with the boundaries of the lower two members in the White Chalk Formation. As noted by Gale (1996), the lower part of the White Chalk Formation is represented by two units: a lower unit consisting of hard chalks, locally nodular with thin faser marls, and an upper unit of gritty chalks separated by gritty faser-riddled marls. We consider that this lithological difference would have been a better criterion for defining members. However, in a wish not to confuse the lithostratigraphic nomenclature further, we use Gale’s new members in this paper. A succession of named marls is present within the Ballard Cliff and Holywell members. Those we discuss here are, in ascending order: Meads Marls 1±6 (Mortimore, 1986), Holywell Marls 1±7 (Mortimore, 1986; Gale, 1996), the Compton Pebble Marl (Gale, 1996), Gun Gardens Marls 1±2 (Mortimore, 1986), and the Lulworth Marl (Gale, 1996). Note that our highest sample is in the Lulworth Marl which lies nearly 18 m (and 20 rhythms) above Gun Gardens Marl 2 at Eastbourne. There is a very substantial gap above the top of the section shown in Fig. 2.

4. Biostratigraphy

Gale (1995, 1996) has discussed the macrofossil succession and biostratigraphy across the Cenomanian–Turonian boundary. Here we summarize only the most important points concerning the ammonite zones, the inoceramid zones, and pulse faunas.

4.1. Ammonites

4.1.1. Upper Cenomanian ammonite biostratigraphy

Three zones are recognised in the upper Cenomanian, the *Calycoceras guerangeri*, *Metoicoceras geslinianum* and *Neocardioceras juddii* zones. The section studied ranges from the top five metres of the *C. guerangeri* Zone, into the Turonian. According to Gale (1995, fig. 14; Gale, 1996, p. 181) the *M. geslinianum* Zone corresponds to Plenus Marls beds 1–9 (couplets E1–E10 inclusive) and the *N. juddii* Zone to the interval from the top of bed 9 to 10 cm above Meads Marl 4, where the last examples of *Sciponoceras* occur (couplets E11 just into E18).

4.1.2. Lower Turonian ammonite biostratigraphy

The section studied runs through the *Watinoceras devonense* and *Fagesia catinus* zones into the basal *Mammites nodosoides* Zone. The appearance of *Watinoceras devonense* Wright and Kennedy is used to define the base of the Turonian Stage (Kennedy and Cobban, 1991; Bengtson, 1996). This ammonite has not been found at Eastbourne and the zone is provisionally taken as the interval between the last occurrence of *N. juddii* Zone ammonites (*Thomelites serotinus* Wright and Kennedy, *Sciponoceras gracile* (Shumard) and *S. bohemicum anterius* Wright and Kennedy) and the first appearance of *Fagesia catinus* (Mantell). These events occur 10 cm above Meads Marl 4 and at the level of Holywell Marl 2 (couplets E18–E22 inclusive), according to Gale (1996, fig. 4).

The *Fagesia catinus* Zone is a new zone defined by Gale (1996, p. 181) as the total range of the nominate ammonite, which at Eastbourne is the interval from Holywell Marl 2 up to the Compton Pebble Marl (couplets E23–E27 inclusive). It is equivalent to both the *Pseudaspидoceras flexuosum* and *Vascosceras birch-
Fig. 3. Occurrence of pulse faunal species in the Plenus Marls at Eastbourne: SPES = sub-plenum erosion surface; S4ES = sub bed 4 erosion surface.
byi zones of the Western Interior Basin of the United States (Gale, 1996). Mammites nodosoides (Schlüter) first appears in the Compton Pebble Marl, defining the base of the eponymous zone.

4.2. Inoceramids

According to Gale (1995) the interval we have studied covers the upper Inoceramus pictus Zone and the zone of Mytiloides gr. opalinus. The first appearance of Mytiloides has been recognized as one of the key bioevents associated with the Cenomanian–Turonian boundary (e.g., Birkelund et al., 1984). Gale (1996, pp. 183–184) has added more detail concerning the occurrences of Mytiloides spp. in the early Turonian at Eastbourne. The first specimens of Mytiloides occur at the level of Holywell Marl 1, approximately 3 m (and three rhythms) above the last occurrences of Sciponoceras spp., which Gale accepted as the base of the Turonian. The assemblage includes M. cf. hattini Elder, M. columbianus Heinz, M. gr. mytiloides (Mantell) and Inoceramus gr. apicalis Woods. Just above Gun Gardens Marl 2 (couplet E34) abundant M. mytiloides occur accompanied by rarer M. labiatus (Schlotheim) and I. gr. apicalis.

4.3. Pulse faunas

The term pulse fauna was introduced by Jeans (1968) for recurring assemblages, or abnormal abundances, of calcitic macrofossils (principally belemnites, bivalves and brachiopods) in the Lower Chalk of England. The term has subsequently been used by Gale (1990) and Paul et al. (1994b). Key pulse faunal events at Eastbourne (Fig. 3) are the occurrences in the Plenus Marls of: (1) the brachiopod Orbirhynchia multicostata Pettitt in the top of bed 1a and bed 1b (couplet E3), (2) the bivalve Syncyclonema membranacea (Nilsson) in bed 2 (couplet E4), (3–5) the belemnite Praeactinocamax plenus (Blainville) and the bivalves Lyropecten (Aequipecten) arlesiensis (Woods) and Oxytoma seminuda (Dames) in beds 3–6 (couplets E4–E6), and (6) the brachiopod Orbirhynchia wiesti (Quenstedt) in bed 7 (couplet E6). Other noteworthy macrofaunal events within our section include the occurrence of the microcrinoid, Roveacrinus communis Douglas in abundance between Holywell Marls 2 and 3 (couplet E23) and the abundant occurrence of the epifaunal serpulid worm tube Filograna avita (J. Sowerby) encrusting Mytiloides shells in couplet E40 and nowhere else (see Gale, 1996).

5. Methods

5.1. Stable isotopes

Samples (about 50 g) for carbon and oxygen stable isotope analysis were taken at intervals of between 5 and 10 cm and recorded directly onto the logged sections (Fig. 2). Samples were labelled P1–P75, Q1–Q85 and R1–R120, depending on the local section from which they were taken. Samples Q26–Q27 and R1–R9 were duplicates and none of them was used. Samples for nannofloral analyses were a subset of the isotope samples.

All samples were dried overnight in an oven before further preparation. They were then ground to powder. Approximately 3 mg of the powders were used to determine stable isotope values of carbon and oxygen in the Liverpool University Stable Isotope Laboratory. All samples were calibrated using NBS 19 and are expressed as per mil (‰) variation relative to the VPDB (Vienna Pee Dee Belemnite) standard. Sample reproducibilities are better than ±0.1‰ for both oxygen and carbon isotopic values.

5.2. Foraminifera

At the same time as the nannofossil and stable isotope samples were collected, larger samples (ca. 500 g) were taken at pre-determined intervals to investigate the microfauna in the Eastbourne succession. Microfossil samples were labelled 1–47 (Fig. 2). In the Grey Chalk and Plenus Marls, samples were taken
from both chalk and marl facies, but above the Plenus Marls samples were taken exclusively from marl beds because the chalks are too strongly cemented to disaggregate except by methods that destroy microfossils (paraffin technique, hydrogen peroxide technique). In all cases samples were located on the detailed logs so that results can be compared directly.

In the laboratory, approximately 100 g of dried sediment was weighed out and dissociated by repeated freezing and thawing in a supersaturated solution of Na₂SO₄. Usually only one to three freeze-thaw cycles were necessary to dissociate the sediment. When thoroughly dissociated, samples were washed through a 63-μm sieve and dried overnight in an oven. Residues were then size sorted through a nest of sieves at 1/2 phi intervals from 500 down to 63 μm. Coarse (>250 μm) and fine (63–90 μm) fractions were analysed separately using a method which allowed estimates to be determined for each taxon of both total numbers of specimens per 100 g sediment, and percentages of the total fauna. This consisted of scattering residue on a picking tray, removing and identifying at least 300 specimens of microfossils, and keeping the picked and unpicked residues separate. The ratio of the weight of picked sediment that yielded approximately 300 specimens to the weight of unpicked sediment allows calculation of an estimate of total numbers in the entire residue. All foraminifera were identified to specific level where possible. Results are expressed as total numbers of specimens and as percentage abundance within each sample. Complete-linkage cluster analysis was performed on the coarse fraction benthic assemblage to detect faunal associations.

5.3. Ostracods

Ostracods were picked from the same residues as the foraminifera. The same technique was used to estimate both absolute numbers and percentage frequency per sample for each species, although counts are of valves, not individuals. Ostracods were also grouped as podocopids and platycopids and the percentage of platycopids calculated.

5.4. Calcareous nannofossils

For quantitative analysis of calcareous nannofossils we used a modified version of the preparation technique described by Flores (1985). This consists of (1) gently dispersing about 0.02 g of sample, (2) adding 10 ml distilled water and repeatedly agitating the suspension, (3) extracting 0.2 ml of suspension with a pipette and spreading it over a slide to cover a standard area (6.94 cm²), (4) leaving to dry on a hot-plate and sealing with Canada Balsam. Nannoflora were analysed using a petrological microscope at ×1000 magnification by identifying and counting 500 nannofossils per sample observed in randomly chosen fields of view (FoV). This gives a 99% level of confidence of not overlooking any taxon present at 1% or more of the total population (Dennison and Hay, 1967). All numerical data presented here relate to these standard counts per sample. Exactly the same technique was used on material from Dover and Menoyo, Spain (Lamolda et al., 1994; Paul et al., 1994a) to estimate nannofossil abundances and determine stratigraphic ranges. Results from all three localities should be comparable.

6. Results

6.1. Stable isotopes

6.1.1. Carbon stable isotopes

Stable isotope values for carbon show a major positive excursion through the Plenus Marls and lower part of the White Chalk (Fig. 4). Five main phases can be recognised (Lamolda et al., 1994), as follows: pre-exursion background, build-up, plateau, recovery and post-exursion background. The pre-excur-
sion phase occurs in the top of the Grey Chalk where $\delta^{13}C$ values start at around $2.7\%_{eVPDB}$ and increase very slightly to about $2.85\%_{eVPDB}$. Immediately after the facies change at the sub-plenus erosion surface (Jefferies, 1963), values begin to increase significantly up to a major peak of $5.3\%_{eVPDB}$ in bed 8 of the Plenus Marls. This is the build-up phase, which in the thick Plenus Marls succession at Eastbourne can be further subdivided. In the initial build-up phase $\delta^{13}C$ values increase to around $4.75\%_{eVPDB}$ in bed 3. Values then decline to a trough in the middle of bed 4, where they remain lower at around $4.1\%_{eVPDB}$ through the middle part of bed 4, before increasing again in the second build-up phase to the maximum in bed 8. Values then decline slightly to around $4.8\%_{eVPDB}$ but remain high up to Meads Marl 6. This is the plateau phase. The recovery phase lasts from Meads Marl 6 up to around the level of Holywell Marl 3, during which interval $\delta^{13}C$ values decline consistently and initially fairly rapidly to $3.7\%_{eVPDB}$. Thereafter they continue to decline but more gradually all the way up to Gun Gardens Marl 2, where a $\delta^{13}C$ value of $3.45\%_{eVPDB}$ is recorded. The more gradual decline in values between Holywell marls 3 and 7 makes it rather arbitrary where the recover phase ends and the post-excursion phase begins.

6.1.2. Oxygen stable isotopes

Oxygen isotope values fluctuate more than carbon values. However, the top Grey Chalk shows no real trend with $\delta^{18}O$ values averaging about $-3.0\%_{eVPDB}$ ($\pm0.25\%$). In bed 1 of the Plenus Marls there appears to be a weak trend to more negative values, especially in the middle of the bed. Overall values average about $-3.2\%_{eVPDB}$ ($\pm0.2\%$). Through beds 2–4 there is a reverse trend, with the least negative values in the middle averaging around $-2.7\%_{eVPDB}$. Through beds 5–8 there appears to be a significant decline in values to a new level of around $-3.8\%_{eVPDB}$, but also a new phenomenon of $\delta^{18}O$ values correlating very well with lithology. Marl values are around 1.0 to 1.5$\%$ less negative than adjacent chalk values. Values appear to increase through Meads Marls 2–6 and then decline again to $-3.9\%_{eVPDB}$ between Holywell Marls 1 and 2. They remain low up to Holywell Marl 7, after which values increase again to around $-3.5\%_{eVPDB}$.

6.2. Foraminifera

It is convenient to describe foraminifera by size fraction, with the benthic and planktic assemblages considered separately. The percentage of planktic foraminifera in the total assemblage of the coarse fraction (P %) is also significant.

6.2.1. Benthic foraminifera of the coarse fraction (>250 $\mu$m)

6.2.1.1 Composition. A total fauna of 68 specific level taxa has been identified and their stratigraphic occurrence is shown in Fig. 5. Of these 29 (42.6%) are textulariines, 2 (2.9%) are miliolines, and 37 (54.4%) are rotaliines.

Complete linkage cluster analysis resulted in the identification of five assemblages among the coarse-fraction benthic foraminiferal fauna. These assemblages occur in stratigraphic succession, and are labelled A to E (Fig. 5). Assemblage A is dominated by Lenticulina spp., Gavelinella balthica Brotzen, G. cenomanica (Brotzen) and Tritaxia spp. It is confined to the Grey Chalk and has a high proportion of minor elements (white in Fig. 6), reflecting the highly diverse initial fauna. In assemblage B these four taxa remain important but Lingulogavelinella involuta Owen, Gavelinella berthelini (Keller), and G. reussi (Khan) join them as increasingly important elements of the assemblage. Assemblage C these four taxa remain important but Lingulogavelinella globosa (Brotzen), G. berthelini and G. reussi. Assemblage C occurs through beds 2–9 of the Plenus Marls. In assemblage C the most important taxa are Textularia chapmani (Lalicker), Gaudryina austinana Cushman, Lingulogavelinella globosa (Brotzen), G. berthelini and G. reussi. Assemblage C occurs through beds 2–9 of the Plenus Marls. Assemblage D is dominated by Marssonella spp., G. berthelini, G. reussi, L. globosa and Tritaxia tricarinata Reuss. It occurs through all samples above bed 9 except the very topmost, which has assemblage E. The last assemblage is similar to assemblage D except that Lenticulina spp. and Arenobelimumina spp. join the five dominant taxa of assemblage D. Minor constituents are still collectively important through assemblages B and C, but minimal in assemblages D and E, reflecting the significant decline in diversity through the succession (see below).
Fig. 5. Occurrence of benthic foraminifera in the coarse fraction (＞250 μm) across the Cenomanian–Turonian boundary at Eastbourne. Note the two concentrations of last records, in bed 1 and across beds 4–8 of the Plenus Marls.
Fig. 6. Proportions (percentages) of dominant benthic foraminifera from the coarse fraction (>250 μm) and percentage epifaunal taxa (based on morphotype analysis, Koutsoukos and Hart, 1990) across the Cenomanian–Turonian boundary at Eastbourne.
Fig. 7. Total numbers per 100 g sample of coarse (>250 μm) benthic and planktic foraminifera, and of ostracods across the Cenomanian–Turonian boundary at Eastbourne.
6.2.1.2 Specific diversity. The number of specific level taxa recorded (diversity) changes significantly through the section and, in general, declines rapidly after the top of the Grey Chalk. Fifty-five species are recorded from the Grey Chalk. Of these, seven are confined to the Grey Chalk, although five of these are known from just one sample. Diversity declines in bed 1 of the Plenus Marls, which has a total recorded fauna of 47 specific level taxa, plus six Lazarus taxa known from below and above, but not actually in, bed 1. Five specific taxa occur for the first time, but seventeen are recorded for the last time, so that by the top of bed 4 diversity remains approximately the same: 36 species are recorded, plus three Lazarus taxa. Two new species appear, but two more occur for the last time, so that at the end of this interval diversity is still 36 taxa (including three Lazarus taxa not recorded in this interval, one of which is common to bed 1). The second significant decline in diversity occurs from the middle of bed 4 up to the marl above bed 9. Thirty-five species are recorded from this interval, plus one Lazarus taxon. However, no new species appear, but nineteen occur for the last time, so that diversity at the end of this interval is reduced to seventeen species (including one Lazarus taxon). Thereafter, diversity remains low. Samples from the Meads Marls have a total recorded fauna of thirteen species, plus four Lazarus taxa, one common to the interval below. No new species occur, but three more species are recorded for the last time so that diversity is down to fourteen species, including the four Lazarus taxa, by Meads Marl 6. Through the Holywell Marl diversity remains low. Sixteen species are recorded, plus one Lazarus taxon also absent from the Meads Marls (Textularia sp. B of Mitchell and Carr, 1998).

To summarize, specific diversity starts high with 55 species recorded from the Grey Chalk. It declines in two major steps which correspond to the two build-up phases of the carbon isotope curve; bed 1 where seventeen species are recorded for the last time and beds 4–9 where a further nineteen species have their last records. Above the Plenus Marls specific diversity remains low at about a quarter the initial value despite a small amount of faunal turnover.

6.2.1.3 Abundance. Abundance is expressed as total number of specimens per 100 g sediment sample (Fig. 7). In the coarse fraction, foraminiferal abundance apparently falls into two broad groupings. In the Grey Chalk and Plenus Marls abundance is variable (700–2700 specimens per 100 g), but can generally be classified as high. Variation does not seem to correlate with sediment type (marl versus chalk) and the abundance averages about 1500 specimens per 100 g. Above the Plenus Marls abundance is significantly lower, it averages about 750 specimens per 100 g, and is less variable in absolute terms (range 216–953). Proportionately, there is more variation in the upper samples, with the richest 4.41 times as rich as the poorest (as opposed to 3.86 times as rich for the lower samples).

6.2.2. Planktic foraminifera from the coarse fraction (>250 μm)

6.2.2.1 Composition. The planktic assemblage from the coarse fraction is far less diverse than the benthic assemblage. A total of only eighteen species has been recorded (Fig. 8). Of these, three species are rotaliporids, six are dicarinellids=praeglobotruncanids, seven are hedbergellids=whiteinellids, and the remaining two are Helvetoglobotruncana praelvetica (Trujillo) and Marginotruncana renzi (Gandolfi).

6.2.2.2 Morphotype groups. The largest, single-keeled, planktic foraminifera, the rotaliporids, disappear progressively in the lower Plenus Marls after a brief increase in abundance and diversity in bed 1: R. deeckeii (Franke) is confined to this bed (samples 10 and 12). As elsewhere in southern England, R. greenhornensis (Morrow) goes in bed 1b (sample 14) before R. cashmani (Morrow), which lingers on to the middle of bed 4 at Eastbourne (sample 22), a little higher than its last recorded occurrence else-
Fig. 8. Occurrence of planktic foraminifera in the coarse fraction (>250 μm) across the Cenomanian–Turonian boundary at Eastbourne.
where in the Anglo–Paris Basin (e.g., Jarvis et al., 1988; Lamolda et al., 1994). Smaller, double-keeled morphotypes (Dicarinella and Praeglobotruncana) are very minor constituents of the fauna in the Grey Chalk and lower Plenus Marls, but dominate the fauna through beds 4 to 6 (samples 21 to 25), before becoming very inconspicuous again from bed 7 up to the topmost sample. Small, simple, unkeeled hedbergellids and whiteinellids dominate this interval (bed 7 to Gun Gardens Marl 2), usually representing over 95% of the total fauna. A recovery occurs in the Lulworth Marl, where double-keeled morphotypes form over 40% of the planktic fauna.

6.2.2.3 Specific diversity. Changes in the pattern of diversity differ from those of the benthic foraminifera, largely because there is more overlap between outgoing and incoming species during the second build-up phase of the carbon isotope excursion. As a result, this interval has the highest recorded diversity (thirteen species). However, significant extinctions, particularly of the species of Rotalipora, occur during both build-up phases of the carbon excursion. Ten species are recorded from the Grey Chalk and none is confined to this interval. Ten species are recorded from bed 1 of the Plenus Marls, including R. deeckeii, which is confined to bed 1. In addition, a single Lazarus taxon, Dicarinella imbricata (Mornod), is recorded from below and above bed 1. Two species, R. deeckeii and R. greenhornensis, are recorded for the last time, so that at the top of bed 1 diversity has declined slightly to nine species (including the one Lazarus taxon). Between the base of bed 2 and the lower part of bed 4, ten species are recorded including one, Hedbergella planispira (Tappan), for the first time. There are no last occurrences in this interval, so diversity has increased to ten species by the middle of bed 4. During the second build-up phase of the carbon excursion, from the middle of bed 4 to the marl above bed 9, thirteen species are recorded, four for the last time, including R. cushmani the last species of Rotalipora and Praeglobotruncana gibba Klaus, which is confined to this interval. Two other species occur for the first time, H. praehelvetica and Whiteinella baltica Douglas and Rankin. Again diversity declines slightly to nine species by the end of this interval. Through the Meads Marls eight species are recorded and there is one Lazarus taxon. A single last occurrence is cancelled by one new appearance, so diversity remains unchanged. There are no changes through the Holywell Marls except that W. brittonensis (Loeblich and Tappan) and H. simplex (Morrow) are apparently recorded for the last time in Holywell Marl 7 (but see comments on the fine fraction). In the post-excursion phase of the carbon excursion diversity remains the same. Two species are apparently recorded for the last time, but they are replaced by M. renzi and Praeglobotruncana sp A. Thus, while there is considerable change in the composition of the fauna, there is little change in diversity throughout the section and the maximum occurs during the second build-up phase of the carbon excursion. However, the pattern of extinction appears similar to that of coarse-fraction benthic foraminifera, despite the small numbers of species involved, with two species of Rotalipora going in bed 1 and four more species, including R. cushmani, going between the middle of bed 4 and bed 9.

6.2.2.4 Abundance. Total number of specimens of coarser planktic foraminifera shows a broadly similar, but stronger, pattern to that of coarser benthic foraminifera. Numbers fluctuate considerably but are significantly higher through the Grey Chalk and Plenus Marls. Peak numbers (4670 per 100 g) are recorded at the top of bed 1 of the Plenus Marls, but otherwise numbers are around 2000 per 100 g. Above bed 9 abundance declines significantly and ranges from 83 to 628 specimens per 100 g.

6.2.2.5 Percentage coarse planktic foraminifera (P %). The percentage of planktic foraminifera in the coarse fraction (often erroneously referred to as the P/B ratio) is significant in determining palaeoenvironmental conditions, especially water depth. Broadly P % shows a similar pattern to abundance, except that the decline occurs a little higher in the section (Fig. 9). Values fluctuate considerably, but are generally high (around 50%) and reach a peak (>90%) at the top of bed 1 of the Plenus Marls. They remain high up to Meads Marl 4, after which they rarely exceed 30% and are lowest through Holywell Marls 1–3.
6.2.3. Benthic foraminifera from the fine fraction (63–90 μm)

6.2.3.1 Composition. The benthic foraminiferal fauna from the fine fraction is restricted and consists of just eleven species in total (Fig. 10). Three taxa, Pleurostomella sp. A, Praebulimina sp. A and Osangularia sp. A, are unknown in the coarse fraction. Pleurostomella sp. A is confined to beds 1–3 of the Plenus Marls (samples 8–20). The other two species range throughout the section and, together with Gyroidinoides sp. A, dominate the fauna, being commonly present as more than 10% of each sample. Spiroplectammina praelonga (Reuss), Gyroidinoides sp. A and Ramulina aculeata Wright are known from both coarse and fine fractions, but have different stratigraphic ranges. In all three cases small examples from the fine fraction range higher than large examples from the coarse fraction. Large S. praelonga are last recorded from the topmost Grey Chalk (sample 7); small examples first occur in, and range to the top of, bed 1a of the Plenus Marls (samples 8 and 13). Large Gyroidinoides sp. A are last recorded from bed 8 of the Plenus Marls (sample 30). Small examples form more than 10% of the fine fraction up to Meads Marl 2 (sample 37), occur rarely (<1%) in Meads Marl 5 (sample 40), are absent through the Holywell Marls, but reappear at <1% of the fine fraction in Gun Gardens Marl 2 and the Lulworth Marl (samples 46 and 47). Finally, large R. aculeata are last recorded from Meads Marl 4 (sample 39), while small R. aculeata first occur in Meads Marl 5 (sample 40) and range up to the Lulworth Marl where they form >5% of the fine fraction. In two of the three cases small forms are first recorded immediately after large forms are last recorded.

6.2.3.2 Diversity. Diversity apparently starts low, with only the commonest three taxa (accompanied by Eggerellina sp. in one sample) recorded from the Grey Chalk. Diversity is maximum in bed 1 of the Plenus Marls where nine of the eleven species occur. In the fine fraction S. praelonga is confined to bed 1 and Eggerellina sp. is last recorded from a single

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Fig. 9. Planktic percentage (P %) in the coarse fraction (>250 μm) across the Cenomanian–Turonian boundary at Eastbourne.
Fig. 10. Occurrence of benthic and planktic foraminifera in the fine fraction (>63–90 μm) across the Cenomanian–Turonian boundary at Eastbourne.
sample (16) in bed 2. Diversity declines through the Plenus Marls and Meads Marl 2. Allowing for Lazarus taxa, diversity remains low, at five species, through the remainder of the section.

6.2.3.3 Abundance. Abundance of small benthic foraminifera (Fig. 11) is variable. It is highest in bed 1 and generally high in the marl beds of the Plenus Marls as well as in Meads Marl 5 (sample 40). Otherwise it is low and is not significantly lower in the Grey Chalk than in the Holywell Member.

6.2.4. Planktic foraminifera from the fine fraction (63–90 μm)

6.2.4.1 Composition and diversity. Planktic foraminifera from the fine fraction are even less diverse than the benthic fauna, with only eight species recorded from the samples analysed (Fig. 10). As with the fine-fraction benthic fauna, some taxa are confined to the fine fraction, whereas three species of Hedbergella occur in both fractions. Of the five taxa confined to the fine fraction, Schackoina cenomana (Schacko) is recorded at <1% from sample 7 only (topmost Grey Chalk). Globigerinelloides bentonensis (Morrow) is consistently common (>5–10%) up to bed 4 of the Plenus Marls (sample 22) and is last recorded from bed 8 (sample 30). Guembeliotria cenomana Keller is consistently common (>5–10%) up to Meads Marl 2 (sample 37), after which it is unrecorded until it reappears in the Lulworth Marl. Heterohelix moremani (Cushman) is consistently common throughout the section, whereas Schackoina sp. A (of Mitchell and Veltkamp, 1997) first appears in Meads Marl 3 (sample 40) and ranges up to the Lulworth Marl.

Of the three species of Hedbergella common to both fractions, two, H. planispira and H. simplex, range higher in the fine than the coarse fraction, whereas the third, H. delrioensis (Carsey), is abundant throughout the fine and the coarse fraction but first appears in the fine fraction in Meads Marl 5 (sample 40) and generally increases its proportion of the fine fraction up to the Lulworth Marl. Large H. simplex are last recorded from Meads Marl 2 (sample 37); small specimens range up to the Lulworth Marl. Large H. planispira are last recorded from Holywell Marl 7 (sample 44); small specimens are very common up to the Lulworth Marl.

6.2.4.2 Abundance. Abundance of fine planktic foraminifera (Fig. 11) is generally high in the Grey Chalk and Plenus Marls, but declines significantly in bed 6 of the Plenus Marls (sample 25) and remains low thereafter.

6.3. Ostracods

6.3.1. Composition

A fairly diverse fauna of ostracods has been recognized with 32 species recorded in all. In general, both occurrences and relative abundances within samples are more variable than for foraminifera, but an overall pattern of declining diversity is apparent (Fig. 12). A total of 27 species is recorded from the Grey Chalk, of which four species are confined to this level and recorded from two samples at most. Twenty species are recorded from bed 1 of the Plenus Marls and four Lazarus taxa range through this interval. Two species, Oertliella alata Weaver and Neoicythere kayei Weaver, have their highest occurrences, and Phodacythere cuneiformis Weaver appears, in bed 1. Twenty-four species occur in Plenus Marls beds 2 to 9 and one Lazarus taxon ranges through this interval. Dolocytheridea sp. A and P. cuneiformis are recorded from single samples, while seven other species have their highest occurrences in beds 4–9. Four more species are recorded for the last time in the interval from the top of bed 9 to Meads Marl 4, so that diversity has declined to eleven species by the Holywell Marls. Two highest occurrences are recorded in Holywell Marls 1 and 3, and one more before Gun Gardens Marl 2, where another five species are recorded for the last time. This leaves just three taxa known from the Lulworth Marl.

6.3.2. Diversity

The pattern of declining diversity of ostracods is more extended and less clearly stepped than that for benthic foraminifera, but this may be at least partly due to the difficulty in recovering ostracods from samples above the Plenus Marls.

Fig. 11. Estimates of total numbers per 100 g sample of fine (>63–90 μm) benthic and planktic foraminifera across the Cenomanian–Turonian boundary at Eastbourne.
Fig. 12. Occurrence of ostracods across the Cenomanian–Turonian boundary at Eastbourne.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Pre excursion</th>
<th>1st build-up</th>
<th>Trough</th>
<th>2nd Plateau</th>
<th>Recovery</th>
<th>Post excursion</th>
</tr>
</thead>
</table>

- *Gephyris dorensis*
- *Gephyrida murchisoni*
- *Cytheridella murchisoni*
- *Gephyria major* (inacutus)
- *Dolobathocythere sp. A*
- *Palaeocythereinae* (inacutus)
- *Gephyrida major* (dorensis)
- *Gephyria major* (dorensis)
- *Pseudocythere amherstiae*
- *Pseudocythere fisheri*
- *Macrocythere elipsa*
- *Cytherellidae* (inacutus)
- *Rhoicosytherea* (inacutus)
- *Pseudocythere dolius*
- *Pseudocytherea* (inacutus)
- *Cytherellidae* (inacutus)
- *Cytherellidae* (inacutus)
- *Ichthyocythere* (inacutus)
- *Bacupiocythere* (inacutus)
- *Cytherella* (inacutus)
- *Rhoicosytherea* (inacutus)
- *Rhoicosytherea* (inacutus)
- *Cytherella* (inacutus)
- *Cytherella* sp. A
- *Bacupiocythere* (inacutus)
- *Cytherella* sp. A
- *Mousseliocythere* sp. A
6.3.3. Abundance

Abundance of ostracods is variable, but generally higher in the Grey Chalk and lower Plenus Marls (Fig. 7). It falls by the top of bed 4 of the Plenus Marls and remains low thereafter. The proportion of platycopes is variable but generally low in the Grey Chalk and Plenus Marls, with a peak in bed 1. It increases through the Ballard Cliff Member and remains high (around 90%) throughout the Holywell Member (Fig. 13). The absolute numbers of platycopes do not vary that much; the increase in platycope percentage is due to a drastic reduction in numbers of podocopes (Fig. 13).

6.4. Calcareous nannofossils

6.4.1. Composition

The association is dominated by two taxa, Watznaueria barnesae (Black) and Eprolithus oralis (Stradner). Of these, the first is present in very high proportions, just as at Shakespeare Cliff, Dover, occurring in all populations above 46% (average 65%), whereas E. oralis does not exceed 15% in any sample. The remainder of the association (Fig. 14) is formed by a series of nannofossils normally present in proportions between 1 and 5%, such as Rhagodiscus achlyostaurion (Hill), Watznaueria biporta Bukry, Glaucolithus compactus (Bukry), Zeugrhabdotes elegans (Gartner), Z. embergeri (Noël), Tranolithus phacelosus Stover, Retecapsa spp. and Eiffellithus turriseiffelii (Deflandre). The rest are rare species (<1%).

6.4.2. Diversity

Perusal of Fig. 15 shows that the number of species identified per sample is notably lower towards the upper part of the section, especially in the lower samples from the Ballard Cliff Member (Q73–R42), with a moderate recovery at the top (R62–R104). The phenomenon manifests itself in the disappearance from the section of a large number of taxa, despite some having a much longer stratigraphic distribution recorded in the literature. This is the case with species such as Biscutum spp., Broinsonia enormis (Shumenko), B. signata (Noël), Loxolithus armilla (Black) and Helicolithus sp., some of which, such as Biscutum spp. and Broinsonia spp. (B. signata + B. enormis) occur in the lower part of the section in percentages up to 9 and 7%, respectively (Fig. 16).

6.4.3. Abundance

Abundance averages two nannofossils per field of view (minimum 0.5, maximum 6.4) and they are generally poorly preserved.

6.4.4. Patterns of occurrence

Important last occurrences in the section studied are those of Corolithion kennedyi Crux (sample P32, bed 1a of the Plenus Marls), Axopodorhabdus albianus (Black) (P54, topmost bed 1b), Lithraphidites acutus Verbeek and Manivit (Q22, bed 5), Rhagodiscus asper (Stradner) (Q50, bed 9) and Microstaurus chiasitus (Worsley) (Q57, first bed of the Ballard Cliff Member). Significant first occurrences are, in chronological order, those of Quadrum intermedium Varol (R32, between Meads Marl 4 and 5), Q. gartneri Prins and Perch-Nielsen (R37, in Meads Marl 5), the last used as a zonal marker, and that of Eprolithus octopetalus Varol (R42, in Meads Marl 6). It is also significant that Nannoconus elongatus Brönnimann is only present in the highest part of the section (sample R104, Holywell Marl 4), just as it occurs in Shakespeare Cliff, Dover, despite having a much wider stratigraphic range (Barremian–Campanian) elsewhere. Especially interesting are the variations in the abundance of E. oralis (Fig. 17). This species has alternating maxima and minima, with the majority of the maxima in samples taken from the marls.

7. Discussion

7.1. Lithology

Gale (1990, 1995, 1996) has outlined the evidence suggesting that marl–chalk rhythms in the Cenomanian and Turonian of the Anglo–Paris Basin are orbitally forced and can be used for very detailed correlation. They can also be used to estimate durations of events and rates of processes, provided one is reasonably sure which orbital cycle controlled the observed rhythms. Here we accept as a fundamental assumption that the marl–chalk rhythms reflect the precession cycle, which Berger and Loutre (1989) suggest
Fig. 13. Proportions of significant ostracod groups and total numbers per 100 g sample of podocope and platycope ostracods across the Cenomanian–Turonian boundary at Eastbourne. The platycope signal corresponds very closely to the proportions of *Cytherella* spp.
Fig. 14. Occurrence of calcareous nannofossils across the Cenomanian–Turonian boundary at Eastbourne.
had a periodicity of approximately 20,000 years in the Cretaceous. Many sections in western Europe reveal a decreasing content of siliciclastic material up through the Cenomanian, reflecting the progressive Cenomanian transgression. We presume that the rise in eustatic sea level buried land sources and reduced siliciclastic supply to sedimentary basins. In many sections this happened to such an extent that detecting rhythms in the uppermost Grey Chalk or its equivalents is impossible. At Shakespeare Cliff, Dover, for example, the uppermost five metres of the Grey Chalk reveal no trace of primary sedimentary bedding. It is thus impossible to correlate this interval precisely with other sections, or to estimate rates of sedimentation, or to gain any idea of the amount of erosion at the sub-plenus erosion surface, for example. One reason for using Eastbourne as a reference section is that rhythms are preserved in the uppermost Grey Chalk. Furthermore, differences in thickness of bed 1 of the Plenus Marls between Beachy Head, where our section was logged, and Holywell Steps, where it is only about 30 cm thick, indicate that there was considerable topography on the sub-Plenus erosion surface. Preserved rhythms potentially allow estimates of the amount of chalk removed before the Plenus Marls were deposited. In addition, the succession is considerably thicker than elsewhere in the Anglo–Paris Basin, and the sediments are weakly cemented and easy to process for microfossils compared with many sections outside the Anglo–Paris Basin. All these points suggest that Eastbourne provides an ideal reference section.
7.2. Stable isotopes

Much debate has centred on the amount of diagenetic alteration that has affected the stable isotopic composition of whole-rock carbonates. Hudson (1977) suggested that for unlithified chalks, with a composition similar to that of modern-day carbonate oozes, the oxygen isotopic composition was probably partially affected by diagenesis, whereas the carbon isotopic composition was probably unaltered. Thierstein and Roth (1991) undertook a study of deeply buried, organic carbon-rich, rhythmic carbonates from the Lower Cretaceous. They demonstrated that the stable isotopic oscillations correlated with the preservation of skeletal carbonate and attributed such oscillations to diagenesis. Mitchell et al. (1997) demonstrated that rhythmic oscillations in whole-rock samples and foraminifera from the Chalk were extensively controlled by the presence of cements located within large pores, such as foraminiferal tests and calcispheres. In the light of these studies we use cross-plots and deconvolution using inferred cement compositions to separate the diagenetic and palaeoceanographic signatures.

Fig. 18 shows a cross-plot of selected results from the Eastbourne data. Three groups of data are plotted: samples P1–P29 from the flat pre-excursion δ13C curve before the excursion begins (initial background of Paul and Mitchell, 1994), samples R10–R50 in the plateau phase of the excursion (sensu Paul and Mitchell, 1994), and samples R80–R120 in the flat part of the curve above the excursion (the post-excitation phase of Paul and Mitchell, 1994). Each data set plots on an interpreted mixing line between the primary oceanographic values and the inferred cement composition (estimated at δ13C = +3.5, δ18O
D/NUL 6.0½). In each case, chalk samples plot closer to the inferred cement composition than marl samples, and this results in cyclical oscillations of the stable isotopic values with lithology. Note, however, that because the carbon isotopic composition of the cement is midway between the lower and upper limits of δ13C measured at Eastbourne, chalks have more positive δ13C values than marls where δ13C values are low (e.g., in the Grey Chalk), but more negative values where the δ13C values are high (in the plateau phase of the excursion). The chalk beds represent more open diagenetic systems with larger numbers of pore spaces (calcispheres and planktic foraminifera) than the relatively closed diagenetic systems in the marl beds. Consequently cement is preferentially concentrated in the chalks, and the marls retain a larger component of the original palaeoceanographic isotopic signal. The cement functions to smooth out primary oceanographic δ13C peaks and troughs because the cement composition is generally defined by the overall bulk carbonate δ13C, whereas differential cementation produces oscillations in phase with lithology.

We believe that much of the detail visible in the δ13C signal is due to differential cementation. We recognize the following features which we believe represent the primary oceanographic signal. The initial base level had a δ13C value of about 2.8%e. There was then a steady climb in δ13C values up to a peak in bed 3 of the Plenus Marls of at least 4.75%e. Above this δ13C values fell to a trough in beds 4 to 6 of the Plenus Marls of 4.1%e, before rising again to the highest peaks of about 5.3%e in bed 8 of the Plenus Marls. δ13C values then remained constant or declined very slightly to about 4.8%e up to Meads Marl 6. Above this there was a fairly rapid decline to a new base level of 3.7%e at about the level of Holywell Marl 3.

Oxygen stable isotopic values are much more difficult to interpret in the light of the significantly negative values of the inferred cement composition and the clear diagenetic signal. However, considering the least altered values on the mixing lines in Fig. 18, we would suggest a palaeoceanographic value of about −2%e throughout. We feel that further interpretation of the δ18O signatures in the light of the significant cementation is pointless.

Gale et al. (1993) suggested that the δ13C excursion at Eastbourne could be characterized by three peaks. Their data were based on half-metre spaced samples and do not take into account any diagenesis of the Eastbourne section. While we agree that there is a distinct peak in bed 3 and that the plateau phase of the excursion begins in bed 8 of the Plenus Marls, we think that the plateau phase is essentially level. The additional peak that Gale et al. recognize at the level of Meads Marls 5 and 6 may well be due to a sample collected from weakly cemented sediments. The δ13C excursion at Eastbourne appears to be relatively simple with an initial peak, a trough, another increase followed by a longer plateau phase. This morphology is modified in the thinner succession at Dover (Lamolda et al., 1994; Paul and Mitchell, 1994) due to significant diagenesis (Mitchell et al., 1997). The first build-up phase is modified by troughs in beds 1b and 3 and the plateau phase is much more variable in the Dover section. This is due to the strong correlation between δ13C values and lithology caused by more intense cementation of the chalk beds. The bed 3 peak is visible in records from organic carbon at Pueblo, Colorado (Pratt and Threlkeld, 1984), and the plateau phase can be recognized. However, the entire curve is based on 23 values so the details of the Eastbourne curve are not recognizable.

Jenkyns et al. (1994) suggested that the Plenus Marls represented a maximum temperature optimum in the Cretaceous on the basis of δ18O values spaced at 1-m intervals throughout the Chalk. However, since they sampled chalk beds which we have shown are more subject to diagenesis than marls, we suspect that this inferred climatic optimum is more apparent than real.

7.3. Microfauna

In general, yields of microfossils are high and so stratigraphic ranges should be established fairly accurately. It follows that first and last occurrences are likely to be close to real local range terminations. However, it should be noted that in a few cases we know that size decrease means that last occurrences of foraminifera in the coarse fraction occur below local range terminations. We also know that last occurrences of some species are higher in the section at other localities. For example, last occurrences of Gavelinella baltica, G. cenomanica and Ataxophrag-
nium depressum (Perner) at Eastbourne occur in bed 1 of the Plenus Marls, but they are recorded from Bed 2 at Westbury, Wiltshire (Vaziri, 1997). Nevertheless, the general pattern of occurrences established at Eastbourne is accurate and requires some discussion. Benthic and planktic foraminifera and ostracods all suffered a drastic reduction in diversity, beginning with the onset of increasing δ¹³C values and not recovering until long after the return to a new background δ¹³C level. Further details are discussed below.

7.3.1. Benthic foraminifera

Benthic foraminifera suffered proportionately more extinctions than planktic foraminifera, with diversity reduced by 76% and 36%, respectively, by Gun Gardens Marl 2 (couplet E34). Benthic foraminiferal diversity was reduced in two main stages: in bed 1 (couplets E1–E3), and from bed 4 to bed 8 (couplets E5–E9), of the Plenus Marls, although further reduction occurred above the Plenus Marls. The pattern in both main extinction levels, whereby rarer species which occur sporadically go first, whereas consistent and common species go last, suggests that both patterns are seriously modified by the ‘Signor–Lipps effect’. Signor and Lipps (1982) argued that a combination of the incompleteness of the record and variations in sample size would distribute last occurrences below true extinction levels. Quantitative analysis of the Signor–Lipps effect suggests that it alone will account for the decline in diversity seen at both levels (Paul, unpublished data). This being so, we believe these extinctions were genuinely sudden and occurred at the tops of beds 1 (couplet E3) and 8 (couplet E9) of the Plenus Marls. If this interpretation is correct, the two events were separated by 80,000–120,000 years (depending on how many couplets bed 8 represents).

Benthic extinctions also frequently involved a pattern where larger species succumbed before smaller congeners. For example, Tritaxia macfadyeni and T. pyramidata go before the smaller T. tricarinata. Similarly, Lingulogavelinella involuta is replaced in the Plenus Marls by the smaller L. globosa, which in turn is replaced by the even smaller L. aumalensis in the early Turonian. Furthermore, some species which do survive show size reduction through the Cenomanian–Turonian boundary event (CTBE). Specimens of T. tricarinata from the Plenus Marls are consistently smaller than those from the Grey Chalk, or the early Turonian form T. tricarinata var. jongmansi. In addition, three species disappear from the coarse fraction significantly below their highest records in the fine fraction. In two of the three cases the species first appear in the fine fraction in the next sample above their highest record in the coarse fraction. Selection for size reduction in benthic foraminifera was apparently intense across the CTBE.

Abundance of specimens decreases across the Plenus Marls–Ballard Cliff Member boundary. Some surviving species, notably Marssonella spp., increase in absolute abundance across this boundary, the overall pattern cannot be entirely due to changes in lithology and the difficulty of extracting microfossils from the more indurated White Chalk. In summary, diversity, size and abundance of benthic foraminifera all decrease across the CTBE. Diversity reduction, and to a lesser extent size reduction, correlate well with the two intervals of rapid increase in δ¹³C values. Decline in abundance coincides with the onset of the plateau phase of the δ¹³C excursion.

7.3.2. Planktic foraminifera

Biostratigraphically significant last occurrences include those of Rotalipora decehei and R. greenhornensis in bed 1, and of R. cushmani in bed 4, of the Plenus Marls, the last slightly higher than previous records in bed 3. Biostratigraphically significant first occurrences include those of Helvetoglobotruncana praehelvetica in sample 29 from bed 8 of the Plenus Marls (couplet E7), although it does not become common until Holywell Marl 1 and is recorded from only four samples, and of Marginotruncana renzi in the Compton Pebble Marl (sample 45) and Schackoina sp. A (of Mitchell and Veltkamp, 1997) in Gun Gardens Marl 2 (sample 46). The last occurrence of R. cushmani defines the base of the W. archaeocretacea Zone.

Diversity, size and abundance all decrease through the CTBE, though less markedly than for benthic foraminifera. Maximum diversity of coarse planktic foraminifera (eleven species) occurs in bed 1 of the Plenus Marls, minimum diversity (seven species) in Gun Gardens Marl 2 and the Lulworth Marl. Size reduction involves both early loss of larger species (the rotaliporids in beds 1 and 4 of the Plenus
Marls) and size reduction within species. _Hedbergella simplex_ and _H. planispira_ range to the Lulworth Marl in the fine fraction, but disappear much earlier in the coarse fraction. Abundance drops very dramatically in bed 6 of the Plenus Marls and may partly reflect the greater induration of the sediments above this level.

Cross-plots of stable isotope data from the lower part of the Plenus Marls at Dover (data in Jeans et al., 1991 and Mitchell et al., 1997) show different gradients in their trend lines which can be used to infer depth in the water column. Basically the largest species (rotaliporids) lived deeper in the water column than either double-keeled or unkeeled morphotypes (dicarinellids + hedbergellids), contrary to the arguments of Corfield et al. (1990), who took no account of diagenetic overprinting of the isotopic signal. Thus it would seem that the original interpretation (e.g., Jarvis et al., 1988) that deeper dwelling planktic foraminifera succumbed whereas shallower taxa survived, is correct.

7.3.3. Ostracods

Ostracods occur more sporadically and inconsistently than either benthic or planktic foraminifera. Nevertheless they too suffered significant declines in diversity and abundance. Specific diversity declined by 70% at Gun Gardens Marl 2, almost as much as with benthic foraminifera. The pattern of reduction appears to be more gradual than for benthic foraminifera; certainly two distinct steps cannot be detected. As with planktic foraminifera, the dramatic reduction in abundance above the Plenus Marls may partly reflect the difficulty of processing more indurated White Chalk sediments.

The percentage of platoctopes, the so-called platycope signal, is interpreted as an indication of oxygen levels in the water column: high proportions of platytopes indicate low oxygen levels (Whatley, 1991). At Eastbourne the percentage of platytopes increases substantially from a minimum of about 10% in basal bed 3 of the Plenus Marls, to a maximum of over 90% in Meads Marl 3, and it remains above 85% thereafter. Absolute numbers of platytopes remain reasonably constant, but podocopids become very rare above the Plenus Marls. The reduction in podocopids is unlikely to result from loss of more delicate species above the Plenus Marls. Sporadic occurrences in this interval are mainly of platycope species, whereas if the podocopids had survived, one would have expected at least the occasional example to be discovered.

7.3.4. Summary of microfossil changes

In summary, both benthic and planktic foraminifera, and ostracods decline in diversity and abundance, and both groups of foraminifera decline in size across the CTBE. Coarse-fraction benthic foraminifera seem to be the most seriously affected with a 76% reduction in diversity by Gun Gardens Marl 2, as opposed to 36% for planktic foraminifera and 70% for ostracods. Size reduction occurs both by larger species succumbing before smaller congeners, and by reduction in size within specific taxa. Again benthic foraminifera display this pattern at least as much as planktic foraminifera. Any explanation of the causes of the CTBE must account for these phenomena. The platycope signal (Whatley, 1991), together with the known occurrence of sediments highly enriched in organic carbon (e.g., Herbin et al., 1986), together suggest reduced dissolved oxygen levels. The reduction in both size and abundance of benthic and planktic foraminifera is also consistent with reduced oxygen levels. Reduction in benthic diversity occurred in two main stages (top bed 1 and top bed 8 of the Plenus Marls) separated by 80,000 to 120,000 years. Key biostratigraphic events include the last occurrences of _Rotalipora greenhornensis_ (bed 1) and _R. cushmani_ (bed 4), and the first occurrence of _Helvetoglobotruncana praehelvetica_ (bed 8).

7.4. Calcareous nannofossils

7.4.1. Patterns of occurrence

The existence of differences in ranges at two neighbouring sections, which can occur in either order, i.e. earlier disappearances at Eastbourne compared with those at Dover, such as _C. kennedyi, A. albianus_ and _M. chiastius_, or later disappearances at Eastbourne, e.g. _L. acutus_ and _R. asper_, are likely to be due to chance in our opinion, the more so if one considers that these species become rare as they approach their highest recorded occurrences. Something similar, and attributable to the same cause, has been detected in the first appearances of _Quadrum intermedium_ and...
Q. gartneri, in that both forms appear in slightly older samples than one would expect by comparison with the Dover section, and in the presence at Dover of *Eprolithus eptapetalus*, a species not recognized at Eastbourne, even though its ancestor, *E. octopetalus*, occurs at Eastbourne but not at Dover.

7.4.2. State of preservation
The state of preservation of the association is poor. Microscopic observation of the specimens demonstrates the effects of dissolution and/or overgrowth: lost central areas, denticulate margins, isolated fragments, etc. Equally, examination of the percentages of *W. barnesae* leads to the same conclusion. This species is present in all samples in proportions greater than 46% (Fig. 15). According to Roth and Krumbach (1986), the occurrence of high percentages of this taxon (>40%) indicates samples which have suffered intense dissolution. Following the same authors, we have tried to establish the existence of an inverse linear correlation between the percentage of *W. barnesae* and the number of species identified per sample and obtain a correlation coefficient of \( r = 0.628 \) (\( p < 0.0001 \)).

7.4.3. Biostratigraphy
The association of calcareous nannofossils recognized in the section allows recognition of two biozones, the zone of *Effellithus turriseiffelii* Thierstein (1971) emend. Crux (1982) and the zone of *Quadrum gartneri* Cepek and Hay (1969) emend. Manivit et al. (1977). The presence of the species *Lithraphidites acutus*, even in the lowest samples from the section (with the exception of the first), indicates the upper part of the zone of *E. turriseiffelii*, and we consider its absence in the oldest sample as due to chance in that this taxon is rare in this section. Similarly, *Microrhabdulus decoratus*, the first occurrence of which has been used by Crux (1982) as defining the eponymous and highest subzone of the zone of *E. turriseiffelii*, has been found in the lowest part of the section, even if only in two samples. Nannofossil data indicate that the samples from the lower and middle parts of the section (up to sample R32, between Meads Marl 4 and 5) are of late Cenomanian age. Moreover this interpretation can be confirmed by the successive disappearances of five taxa whose biostratigraphic significance has been repeatedly confirmed by diverse authors: Crux (1982), Bralower (1988), Jarvis et al. (1988), Lamolda et al. (1994), Lamolda et al. (1997). These taxa are: *C. kennedyi* (sample P32, bed 1a), *A. albianus* (P54, bed 1b), *L. acutus* (Q22, bed 5), *R. asper* (Q50, bed 9) and *M. chiastius* (Q57, the first bed of the Ballard Cliff Member).

The first occurrence of *Q. gartneri* in sample R37, preceded by *Q. intermedium* (recorded as *Quadrum* sp. in the section at Dover, Lamolda et al., 1994), allows us to recognize the base of the eponymous zone. This event was recommended as an index of the lower Turonian by Birkelund et al. (1984), but see also Bengtson (1996).

The next species to appear is *Eprolithus eptapetalus* (sample R42, Meads Marl 6), which was not detected at Dover, whereas *E. eptapetalus* has not been identified at Eastbourne. Both species are rare in the two English sections studied, except at their first appearances, and were described by Varol (1992). Varol established an evolutionary trend in the genus *Eprolithus* in which there is a reduction in the number of petal elements in each circle from forms such as *E. floralis* (nine elements) to *E. octopetalus* (eight elements), *E. eptapetalus* (seven elements) and thus successively to forms with only five elements. The stratigraphic distribution of these taxa is in agreement with Varol’s morphological series, with *E. octopetalus* ranging from upper Cenomanian to basal Turonian and *E. eptapetalus* ranging from upper Cenomanian to lower Coniacian. Therefore, the presence of *E. octopetalus* in the highest part of the section provides another confirmation of the age of the samples studied.

Qualitatively speaking the association recognized in this section is practically identical to that described from the section at Dover (Lamolda et al., 1994). It is not possible to say the same about the quantitative data: on the one hand the abundance of calcareous nannofossils is notably lower, average twelve nannofossils/Field of view (nan/FoV) at Dover as opposed to two at Eastbourne (Fig. 15). Even though this difference could be largely due to the effects of dilution, which differs considerably in its strength between the two sections, another factor to consider is diagenesis. Both sections have a poorly preserved flora, but with marked differences as indicated by the percentages of *W. barnesae*, which
average 53% in all samples from Dover and 65% at Eastbourne.

7.4.4. *Eprolithus floralis*

This species exhibits significant variations in its proportions throughout the section. In Fig. 17 the percentages of *E. floralis* of the fraction without *W. barnesae* in different samples are shown. The alternations of maxima and minima, which also occur at Dover (Lamolda et al., 1994), coincide quite well with alternate beds of marl and chalk, respectively. Some of the maxima indicated, for example sample P45 (bed 1 of the Plenus marls), Q18 (upper part of bed 4) and Q29 (bed 6), could be equivalent to the corresponding peaks identified at Dover. It is difficult to obtain a perfect correspondence (maximum with maximum, minimum with minimum) in the details of the curves for each section when the sampling interval differs in the two sections. For example, nine samples were studied at Dover from the Plenus Marls where the alternations occur, whereas at Eastbourne eighteen examples have been examined. Equally the effects of dilution, as well as the chance of precisely where samples were taken in the field, will affect these variations.

Enrichment in *E. floralis* has been described previously by authors such as Roth and Krumbach (1986) or Bralower (1988), who recognised maxima in the proportions of this taxon in various Cenomanian–Turonian boundary sections in England, Germany and North America, and interpreted them as a consequence of a lowering of sea-water temperature. Later, Lamolda et al. (1994) also recognized these increases in samples from the section at Dover, but their utilization of a fine sampling interval allowed recognition of alternations of maxima and minima in successive beds of marl and chalk, respectively. The maxima in the marl beds coincide with less negative δ¹⁸O values, which were interpreted as
representing periods of lowered temperature of sea water, thus confirming the arguments of Roth and Krumbach (1986) and Bralower (1988). At that time the effects of diagenetic cements were thought to be minimal at Dover. The relatively good correspondence between the data from Dover and Eastbourne (except as already outlined) leads us to emphasize the potential value of *E. floralis* as an indicator of palaeotemperature variations. Lamolda and Gorostidi (1996) have found a similar correspondence in lower Turonian sediments of northern Spain, where higher values of *E. floralis* are recorded with an ingress of temperate fauna into the region.

7.4.5. *Broinsonia* spp. and *Biscutum* spp.

Finally, we point out that the behaviour of taxa such as *Broinsonia* spp. (*B. signata + B. enormis*) and *Biscutum* spp. is very similar in both sections, presenting maxima in the Grey Chalk (Fig. 16), much lower values in the Plenus Marls and declining drastically, including total absence, in the Ballard Cliff and Holywell members. This behaviour has no simple explanation. According to Roth (1981) *Biscutum* is a genus whose abundance indicates high productivity or zones of upwelling, whereas *Broinsonia* was regarded as a nannofossil characteristic of neritic areas by Roth and Krumbach (1986) who, moreover, indicated that it was encountered in very high proportions in the chalk of SE Europe, Texas and the south of France. Bralower (1988), who also recognized maxima in the proportions of this genus in upper Cenomanian samples from England, Germany and N. America, gave a more complete interpretation and suggested that the high proportions of this nannofossil could be an indication of different environmental factors, such as shallow water, reduced salinity or elevated fertility. Supporting the last possibility, if one compares the percentages of *Biscutum* spp. with those of *Broinsonia* spp. one obtains a significant correlation coefficient (*r* = 0.70, *p* < 0.0001; Fig. 19), which indicates to us that the factor (or factors) which controlled the distributions of both taxa were the same (or similar). In our opinion, one of these factors could have been productivity. In fact the correlations between abundance of nannofossils and the percentages of both *Broinsonia* spp. and *Biscutum* spp. are significant (*r* = 0.38, *p* < 0.05; *r* = 0.463, *p* < 0.005, respectively; Fig. 20). Patterns of abundance of both *Biscutum* spp. and *Broinsonia* spp. also support Roth and Krumbach’s and Bralower’s proposals about water depth, as their proportions decrease upward (Fig. 16) through the transgression during latest Cenomanian to early Turonian times (Lamolda et al., 1994).

8. Conclusions

The section through the Cenomanian–Turonian boundary event (CTBE) at Eastbourne is recommended as a reference section for Northwest Europe on the following grounds.

1. The section is the thickest at outcrop in the Anglo–Paris Basin, preserves rhythmic sediments below, in and above the Plenus Marls Formation, has suffered relatively minor diagenetic alteration and yields significant macro-, and abundant micro- and nanno-fossils.

2. The rhythmic succession enables rates of processes and durations of events across the CTBE to be calculated to within 20,000 years and enables very precise correlation with other sections.

3. A very precise stable isotope stratigraphy has established the most detailed δ¹³C curve available, which can be related to both lithostratigraphy and biostratigraphy. This curve consists of: a pre-excursion background, a build-up in two phases of rapid increase in δ¹³C values separated by a trough in bed 4 of the Plenus Marls, a plateau phase from bed 8 of the Plenus Marls to Meads Marl 6, a recovery phase from Meads Marl 6 to Holywell Marl 3, and a new post-excursion background thereafter.

4. Key macrofossil bioevents can be recognized and related to the detailed lithostratigraphy, including all NW European late Cenomanian and early Turonian ammonite zones, the incoming of inoceramid bivalves of the genus *Mytiloides*, and several pulse faunal events.

5. Boundaries of planktic foraminiferal and calcareous nannofossil zones can be plotted equally accurately on the lithostratigraphy and related to boundaries of macrofossil biozones.

6. The pattern of extinction of benthic foraminifera shows two significant periods of simultaneous extinctions, which coincide with the two peaks in the build-up phase of the δ¹³C curve.
(7) Planktic and benthic foraminifera, ostracods and calcareous nannofossils all show significant decrease in diversity and abundance across the CTBE at Eastbourne. Planktic and benthic foraminifera show significant size decrease as well.

(8) Key nannofossil bioevents associated with the CTBE can all be located precisely, including range terminations and changes in relative abundances.

(9) We correlate the base of the Turonian (that is the equivalent of the base of bed 86 in the global boundary stratotype section at Pueblo, Colorado) as the chalk bed between Meads marls 4 and 5.

The most significant events are summarized in Fig. 21. Together they establish the importance of the section at Eastbourne, not only for international correlation, but also for providing critical evidence concerning interpretation of the causes of the CTBE.

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References


Jeans, C.V., 1968. The origin of montmorillonite of European


Thierstein, H.R., Roth, P.H., 1991. Stable isotopic and carbonate


