PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Orbital tuning of Cenomanian marly chalk successions: towards a Milankovitch time-scale for the Late Cretaceous

A. S. Gale, J. R. Young, N. J. Shackleton, S. J. Crowhurst and D. S. Wray

*Phil. Trans. R. Soc. Lond. A* 1999 **357**, 1815-1829
doi: 10.1098/rsta.1999.0402

THE ROYAL SOCIETY

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Orbital tuning of Cenomanian marly chalk successions: towards a Milankovitch time-scale for the Late Cretaceous

By A. S. Gale[1,2], J. R. Young[2], N. J. Shackleton[3], S. J. Crowhurst[3] and D. S. Wray[1]

[1] *School of Earth and Environmental Science, Medway Campus, University of Greenwich, Chatham ME4 4AW, UK*
[2] *Department of Palaeontology, Natural History Museum, Cromwell Road, London SW7 5BD, UK*
[3] *Godwin Laboratory, University of Cambridge, Pembroke Street, Cambridge CB2 3SA, UK*

Outcrops of Cenomanian marly chalks in the Crimea (Ukraine) and SE England (UK), 2600 km apart, display conspicuous decimetre-scale rhythmicity and can be correlated by using 12 biostratigraphical events. Closely spaced samples from the two sections were used to generate long time-series of digitally captured grey-scale reflectance data. Spectral analysis of these data demonstrates that if the rhythmicity is assumed to be driven by precession (bedding cycles; mode at 20 ka), it is seen to be modulated by the short eccentricity cycle (100 ka bundles). The latter signal is expressed in the sediments by the occurrence of dark marls at precession minima occurring at eccentricity maxima. Although identified in the spectra, tilt (38 ka) and the long eccentricity cycle (400 ka) are not strongly expressed. Comparison of age-modelled, unfiltered grey-scale data between the two sections reveals strikingly similar patterns, and enables the identification of an 80 ka hiatus in the UK chalks.

**Keywords: Cenomanian; marly; chalk; Milankovitch; Europe; time-scale**

## 1. Introduction

The Cenomanian Stage (*ca.* 100–96.5 Ma) is widely developed as rhythmically bedded marly chalk in basinal settings across Europe. This mid-latitude facies belt extends from southeast England, through Germany and France east to the Dagestan Caucasus, a distance of some 3000 km (figure 1). The Cenomanian lends itself to high-resolution stratigraphical study because correlation is provided by a number of independent parameters including ammonite, inoceramid and planktic foraminiferan biostratigraphy, a $\delta^{13}$C curve (Jenkyns *et al*. 1994; Gale *et al*. 1993) and sequence stratigraphy (Robaszynski *et al*. 1998). Together, these form the basis of an integrated stratigraphy with a time resolution of *ca.* 250 ka (figure 2).

Gale (1989*a*, 1995) established a cyclostratigraphy for the Cenomanian marly chalks in western Europe (UK, France, Germany) which was based on the counting and correlation of decimetre thick rhythmic couplets within biostratigraphically constrained intervals. The couplets were believed to be precession cycles, bundled by 100 ka eccentricity cycles, which were used together as the basis of a time-scale;




PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

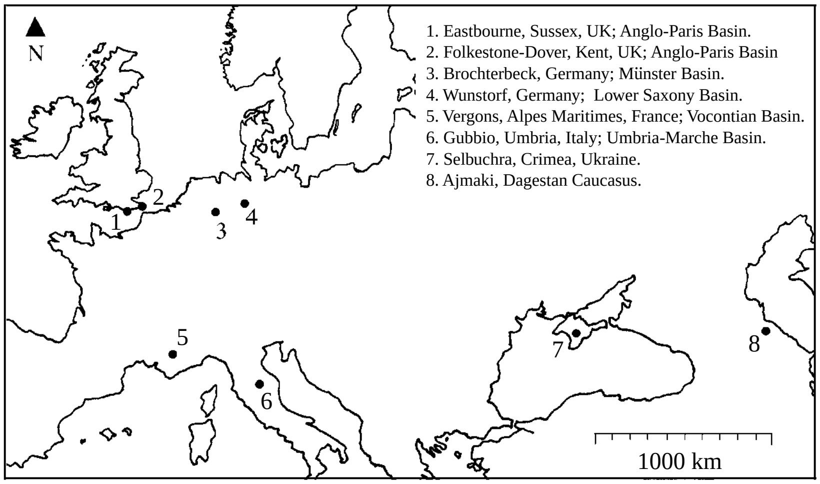


Figure 1. Map of Europe which shows the geographical positions of the sections studied (Folkestone–Eastbourne, Selbuchra, Crimea) and mentioned in the text, and other important Cenomanian sections in Europe.

couplets were numbered sequentially within units A–E (figure 2). This field-based study demonstrated that correlation of couplets is possible on an interbasinal scale. However, construction of the time-scale by cycle counting involved making numerous assumptions and lacked statistical rigour. We therefore decided to apply to the Cenomanian some of the methods of astronomical tuning developed in Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) studies of core which have proved successful in the development of a Neogene time-scale (e.g. Shackleton *et al*. 1990, 1995). This cannot be fully achieved for the Cretaceous because of uncertainties in the astronomical computations (Laskar, this issue).

The first stage of this work was to generate high-resolution depth series through appropriate Cenomanian successions. Few cores through Cenomanian chalks are available, and we therefore had to rely on sampling exposures. Because the basal part of the Lower Cenomanian is greatly condensed across much of Europe (Gale *et al*. 1996), we concentrated on the Middle and Upper Cenomanian, which are relatively expanded and complete. We chose two widely spaced localities which span the entire Middle and Upper Cenomanian: Selbuchra in the Crimea (Ukraine), and a composite section in southeast England (Folkestone–Dover and Eastbourne) (figures 1 and 2).

### (*a*) *SE England (Folkestone–Dover, Eastbourne), UK*

The cliff and foreshore sections between Folkestone and Dover in Kent, UK (Grid reference TR 271385–TR 308398), provide one of the best sections available for study of the Cenomanian Lower Chalk Formation in southeast England. The stratigraphy of this locality has been described by Kennedy (1969), Gale (1989*b*), Gale, in Jenkyns *et al*. (1994), and Gale (1995). The Lower and Middle Cenomanian successions are expanded and relatively complete here, and marly chalks at this locality are more weakly cemented than those elsewhere in SE England, and yield good stable isotope

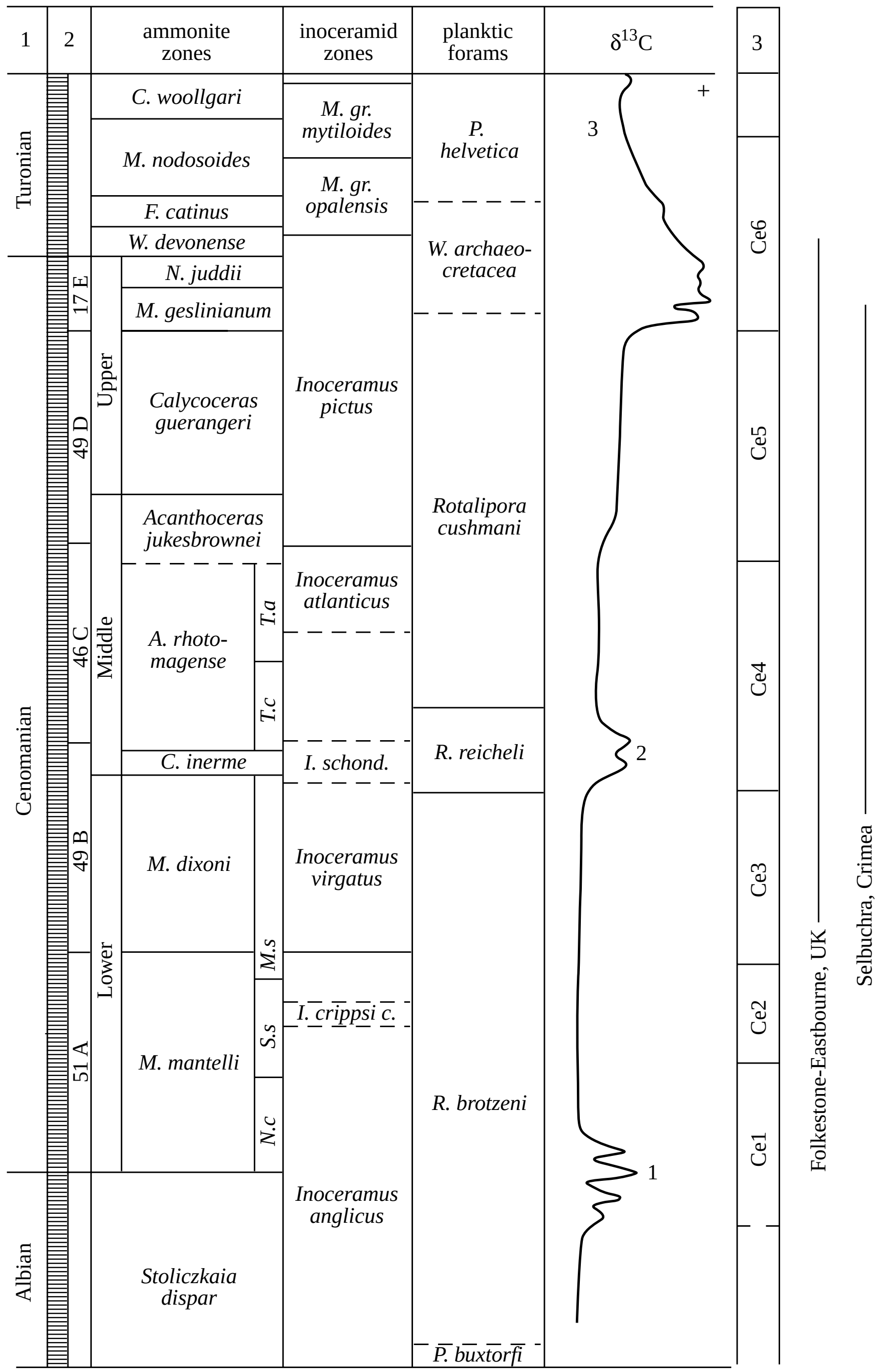


Figure 2. Outline stratigraphy of Cenomanian Stage to show subdivisions and positions of sections studied, after Gale (1995). Column 1 shows stages, column 2 shows cyclostratigraphical classification of Gale (1995). Column 3 shows sequences modified after Robaszynski *et al*. (1998). The $\delta^{13}$C curve includes three events with complex variance (1–3).

data (Ditchfield & Marshall 1989). A minor hiatus of *ca.* 40 ka is known to exist in the basal *A. rhotomagense* Zone (missing couplets B44–5) at Folkestone (Gale 1995), but there are no other known gaps in the succession. Rhythmicity is, however, only weakly developed or lost completely in the thin Upper Cenomanian part of the Folkestone–Dover succession, and we have therefore used the expanded and conspicuously rhythmic section exposed in sea-cliffs at Beachy Head, east of Eastbourne, Sussex (Grid reference TV 588964) for the Upper Cenomanian–basal Turonian part of the succession (Kennedy 1969; Jefferies 1962, 1963). The two sections have been correlated precisely using the couplets C40–C45 and D1–D10 (Gale 1995, fig. 12), supported by lithological and faunal data. Although Gale (1995) presumed that the successions in SE England are relatively complete, Robaszynski *et al.* (1998) predicted that small hiatuses might exist at the levels of sequence boundaries.

### (*b*) *Selbuchra, Crimea, Ukraine*

The southern slope of Selbuchra Hill, in the Crimean Highland, provides the best currently available section through the Cenomanian in the Crimea, which comprises natural exposures in gullies cut by ephemeral streams. The Middle and Upper Cenomanian succession is developed as marly chalks which are conspicuously rhythmic on a decimetre scale, and show 'bundling' of couplets into groups of four to six, which are defined by dark thin marl beds (figure 3). These marls probably represent the extreme precession minima that occur at eccentricity maxima, analogous with sapropels in the Plio-Pleistocene of the eastern Mediterranean (e.g. Hilgen 1991; Hilgen *et al.* 1995).

The succession in the Crimean Highland has been described by Naidin & Alekseev (1981), who identified a non-sequence between the Lower and Middle Cenomanian, recognized by Gale *et al.* (1999) as the sequence boundary/transgressive surface, which occurs widely at this level. The latest Cenomanian and Early Turonian at Selbuchra is represented by redeposited chalk debris flows and was not sampled. Gale *et al.* (1999) have established a detailed biostratigraphical and event-correlation between Selbuchra and the succession in southern England.

## 2. Biostratigraphical and event correlation

Although ammonites provide the most detailed stratigraphical subdivision of the Cenomanian Stage into eight zones and five subzones, they are relatively uncommon and stratigraphically restricted in the chalk facies. Planktic foraminiferans are widely used to subdivide the Cenomanian of Tethyan regions in particular (e.g. Premoli-Silva & Sliter 1995), but the zonation is rather coarse, and there is significant latitudinal diachroneity. In the marly chalk facies of northern Europe, acme occurrences of calcitic macrofossils such as oysters, brachiopods and inoceramid bivalves provide accurate correlations which can be extended eastwards to the Crimea (Gale *et al.* 1999). Ernst *et al.* (1983) called distinctive lithological and faunal horizons within the Cenomanian 'Events', and correlated these across northern Germany and into the UK. Some of the 'Events' can also be identified in the Crimea.

We have selected 12 biostratigraphical and event markers which can be correlated very widely in the European Cenomanian, 10 of which are present in both the Folkestone–Eastbourne composite section and in Selbuchra. We do not claim

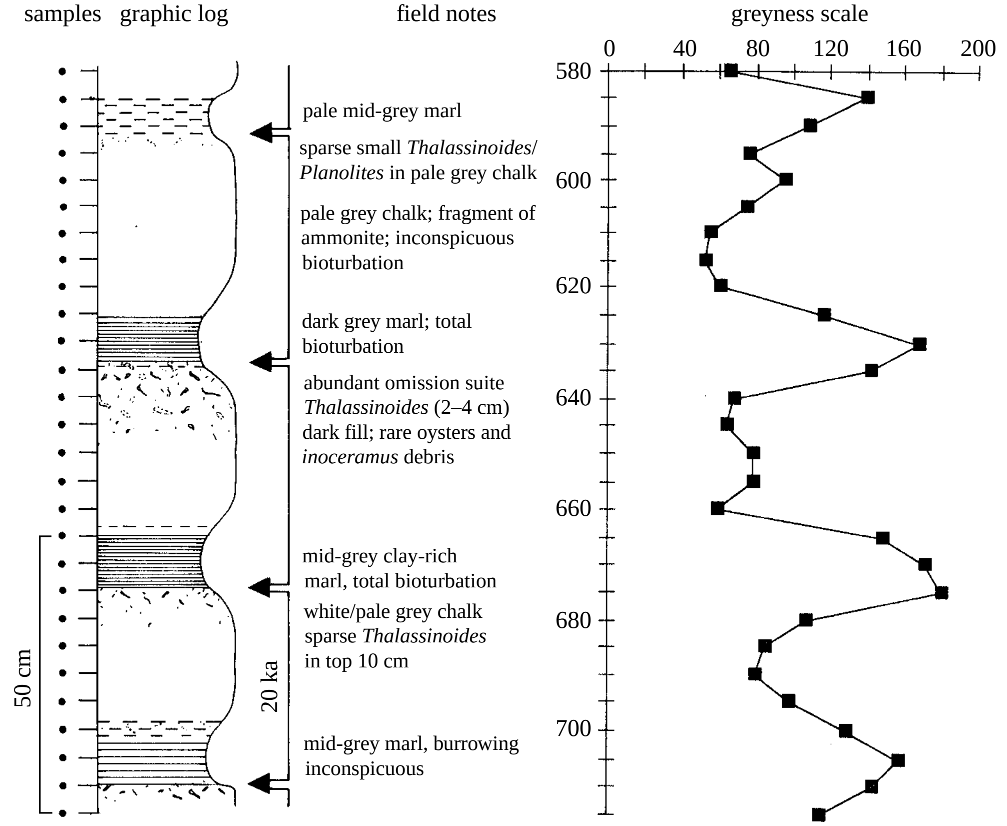


Figure 3. Detail of Crimean Section to show relationships of field data to grey-scale reflectance. The upper boundaries of the precession couplets (20 ka) were used to tune the age model.

that these are all precisely contemporaneous, but they provide the best available correlations; they are listed in ascending sequence below.

1. The base of the Middle Cenomanian *Cunningtoniceras inerme* Zone is taken at the first occurrence of the zonal species in couplet B37 at Folkestone and Southerham in Sussex (Paul *et al*. 1994). This event is included within the major hiatus between Lower and Middle Cenomanian sediments which exists across the Crimea.

2. The base of the Middle Cenomanian *Acanthoceras rhotomangense* Zone is taken at the first appearance of the zone fossil in couplet B43 at Folkestone and Southerham (Gale 1995), which is also included within the hiatus in the Crimea.

3. The third and highest acme of the rhynchonellid brachiopod *Orbirhynchia mantelliana* (d'Orbigny) within the *Turrilites costatus* Subzone which has been traced across northern England, southern England (Kennedy 1969; Gale 1995), northern Germany (Meyer 1990) and the Crimea (Gale *et al*. 1999). The acme extends from couplet C6–C10 (Gale 1995), but the species is most abundant in C9–10.

4. An acme of the baculitid ammonite *Sciponoceras baculoides*, also in the higher part of the *T. costatus* Subzone, is present in southern England (Kennedy 1969, 1971; Gale 1995; couplets C8–C12), northern Germany (Meyer 1990) southeast France (Gale 1995) and in limestone 5 of Naidin & Alekseev (1981) in the Crimea (Marcinowski 1980).

5. First occurrence of planktic foraminiferan *Rotalipora cushmani* (Morrow) is recorded very widely. In southern England, this falls in couplet C11 (Paul *et al*. 1994), somewhat earlier in northern Germany (Meyer 1990). In the Crimea this species first occurs 50 cm above the major hiatus (Kopaevitch, personal communication).

6. An acme of the bivalve *Inoceramus atlanticus* Heinz is present in the basal part (1–2 m) of the *Acanthoceras jukesbrownei* Zone in southern England, northern Germany (Meyer 1990; Ernst & Rehfeld 1997) and the Crimea (Gale *et al*. 1999). This species is short ranging (Tröger 1989).

7. An association of abundant oysters of the genus *Pycnodonte* and three thin dark marls characterizes the Oyster or Pycnodonte Event in northern Germany (Ernst *et al*. 1983; Ernst & Rehfeld 1997); this is present in southern England (Gale 1995; couplets D1–3) and the Crimea (Gale *et al*. 1999).

8. Immediately above the Pycnodonte Event is a massive, calcisphere-rich limestone representing the partial fusion of 5–8 couplets (Jukes Brown Bed VII in southern England; Pycnodonte Limestone in northern Germany). This bed is the transgressive systems tract of sequence Ce5 of Robaszynski *et al*. (1998), and is represented in the Crimea (Gale *et al*. 1999).

9. A lower acme of the oyster *Amphidonte* is identified in southern England, northern Germany (Ernst & Rehfeld 1997) and the Crimea (Gale *et al*. 1999).

10. A higher acme of *Amphidonte* is recognized in the same regions.

11. A marked erosional break at the base of the *M. geslinianum* Zone. The sharp lithological break from grey-white chalk to marls, which occurs at the base of the Plenus Marls in the Anglo-Paris Basin, has been interpreted as a sequence boundary generated by a rapid sea-level fall (Robaszynski *et al*. 1998). An equivalent break is present in northern Germany (*Fazieswechsel*; Ernst *et al*. 1983) and can be identified in the Selbuchra Section (Gale *et al*. 1999). Although the surface itself represents a correlative event, the age of the under- and overlying beds probably varies slightly regionally as the surface cuts erosively into the underlying *C. guerangeri* Zone Chalks.

12. Last occurrence of *Rotalipora cushmani*. The last record of this species in Selbuchra has been provided by Kopaevitch (personal communication). In southeast England the species last occurs in the top of Bed 3 of the Plenus Marls (Jarvis *et al*. 1988). The last occurrence of this species has been widely used as a datum.

## 3. Methodology

The main sampling problem encountered was ensuring the precise correspondance of the evenly spaced sample intervals to the sedimentological log. To ensure compatability, the chosen field sections (Folkestone–Dover, Eastbourne, Selbuchra) were initially marked up with a metre rule at 5 cm (0.05 m) intervals prior to sampling. The sample positions were then recorded in a lined notebook at a scale of 8 mm:5 cm, and detailed sedimentological information (composition, colour, bioturbation, fauna, etc.) was recorded, with particular attention to critical boundaries between marls and chalks (figure 3). Small samples were then removed using a hammer and a fine cold chisel to ensure precision. Although simple, this methodology proved to be an accurate means of obtaining a continuous record of the chalk successions, and is readily repeatable. It is necessary to avoid weathered parts of the section in which the grey iron pyrites have oxidized to yellows and browns.

The main variable shown by the marly chalk samples is the ratio of carbonate to clay. Accurate measurement of this parameter is possible by various geochemical methods, or by measuring the amount of acid-insoluble residue. Increasingly, however, workers use digital capture of grey-scale reflectance as a proxy for carbonate:clay values in cores first used by Herbert & Fischer (1986). We therefore developed a rapid method to obtain grey-scale reflectance from samples (Young *et al*. 1999). This involves placing cut, dried chalk samples on an ordinary flat-bed scanner. For one sample suite from the Crimea, we cross-plotted values of $Al_2O_3$ (directly related to clay content) against grey-scale reflectance data (figure 4). They show strong covariance, and a regression line passes through the origin.

## 4. Development of the age model

Both successions show a conspicuous high-frequency variance in grey-scale reflectance, which is clearly apparent in the field as bedding couplets which are 20–50 cm in thickness (e.g. figures 3 and 5). The structure of these couplets has been described briefly by Destombes & Shepherd-Thorn (1971) and Ditchfield & Marshall (1989). The couplets comprise alternations of lighter calcisphere–foraminiferal wackestones containing 5–15% clay, and darker marly wackestones containing 10–30% clay. The top surface of each lighter, more carbonate-rich unit, is an omission surface (*sensu* Bromley 1975) which is strongly burrowed; the burrows are infilled by the darker overlying marly sediment and contrast conspicuously with the surrounding sediment. There is no trace of primary lamination and complex bioturbation (*Thalassinoides*, *Chondrites*, *Planolites*) is pervasive throughout the succession. Total organic carbon (TOC) values are very low, at 0.05–0.2%.

Gale (1989*a*, 1995) has argued that the high-frequency rhythmicity which is displayed by Cenomanian marly chalks is an expression of the precession cycle. He based this upon two pieces of evidence. Firstly, the duration of the Mid- and Late Cenomanian interval based upon Ar/Ar dates (2.2 Ma; Obradovitch 1994) is remarkably close to the duration obtained by taking a cycle duration of 20 ka and multiplying by the number of couplets (109) which gives 2.18 Ma. Secondly, 'bundling' of the cycles in groups of five (Gale 1989*a*) is suggestive of modulation of the precessional signal by the short (100 ka) eccentricity cycle (e.g. Fischer *et al*. 1991; Herbert & Fischer 1986). We therefore established initial age-models on the assumption that the decimetre-scale couplets each represent 20 ka (average value of Cretaceous precession,

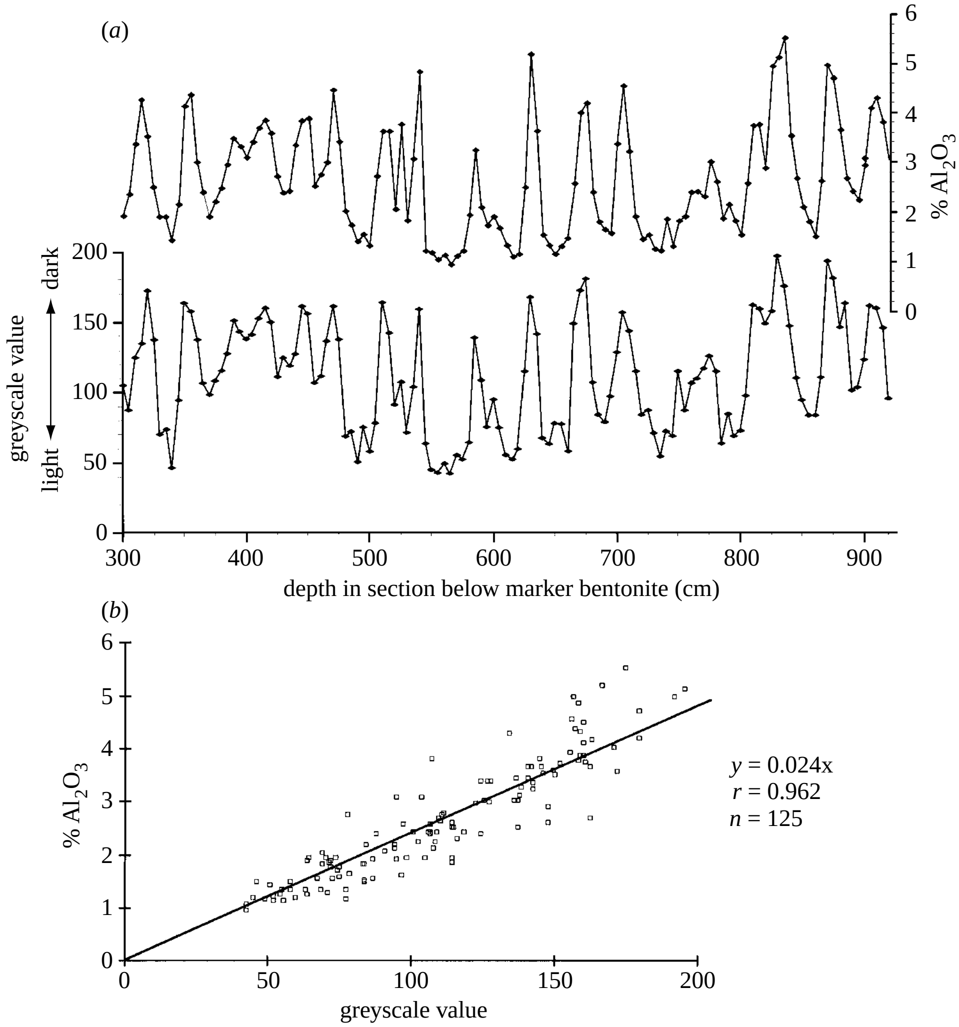


Figure 4. Relationship between grey-scale reflectance and $Al_2O_3$ content in Crimean Mid-Cenomanian chalks. (*a*) Comparison between grey-scale and $Al_2O_3$ curves based on 5 cm sample intervals. (*b*) Cross-plot to show strong covariance between the two parameters with regression line passing through the origin.

from Berger *et al*. 1989), and took the frequently conspicuous contacts between the tops of chalk beds and the bases of overlying marls as boundaries between successive 20 ka units (figure 3).

The Sebuchra section could be modelled in a straightforward manner; the assumption that each bed recognized represents 20 ka does not give rise to anomalous jumps in implied sedimentation rate (figure 6). The lowest part of the section could not be easily 'tuned'; the uppermost part was also not 'tuned' in detail because of the presence of a prominent bentonite in the section. The experiments described in the time-series analysis below were carried out on a 720 ka long 'tuned' interval (figures 5 and 6).

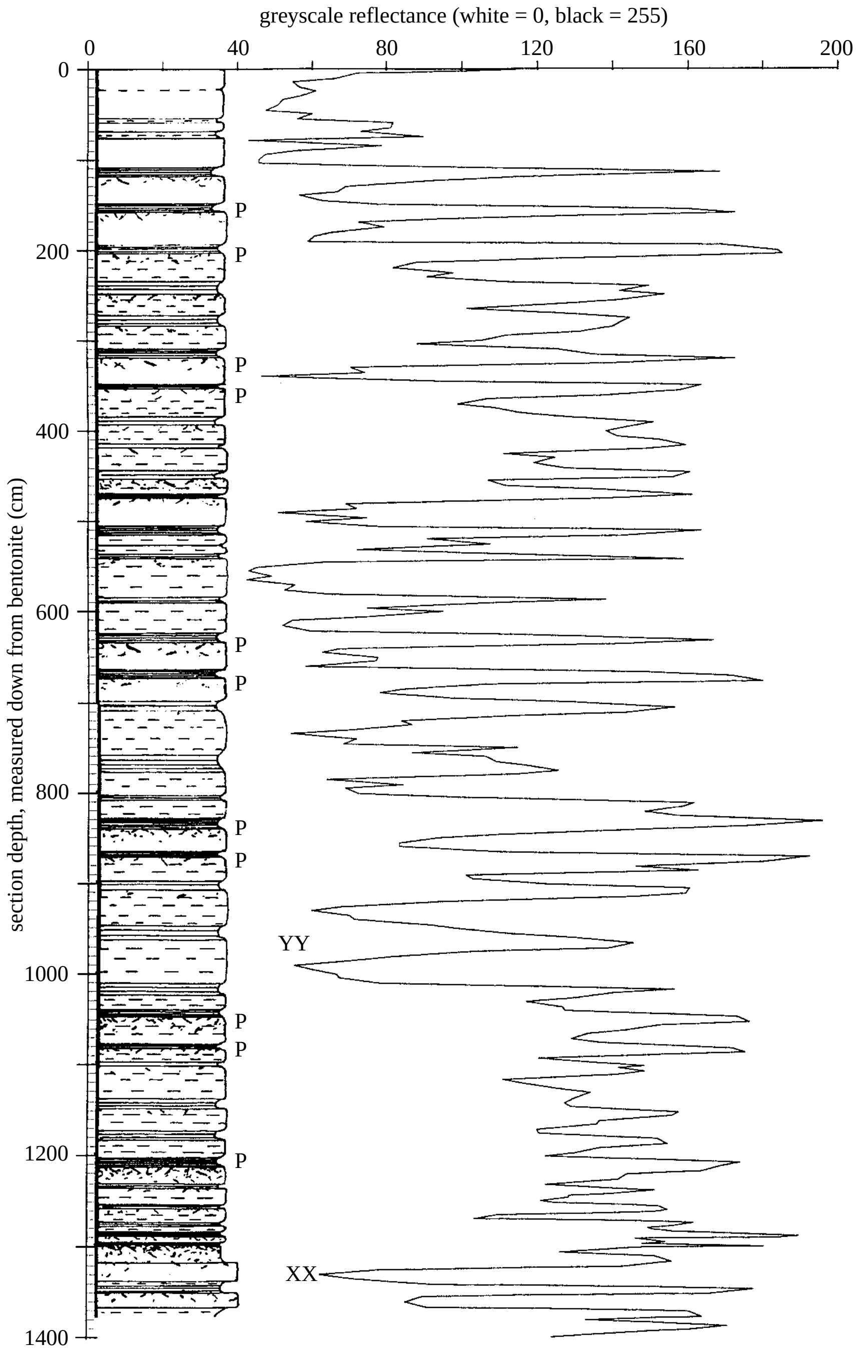


Figure 5. Subsection of Middle Cenomanian at Selbuchra, Crimea, to show field log and grey-scale reflectance data. The zero datum is a bentonite. These data were used for the spectral analysis shown in figure 8. Note paired dark marls interpreted as eccentricity maxima/precession minima (P).

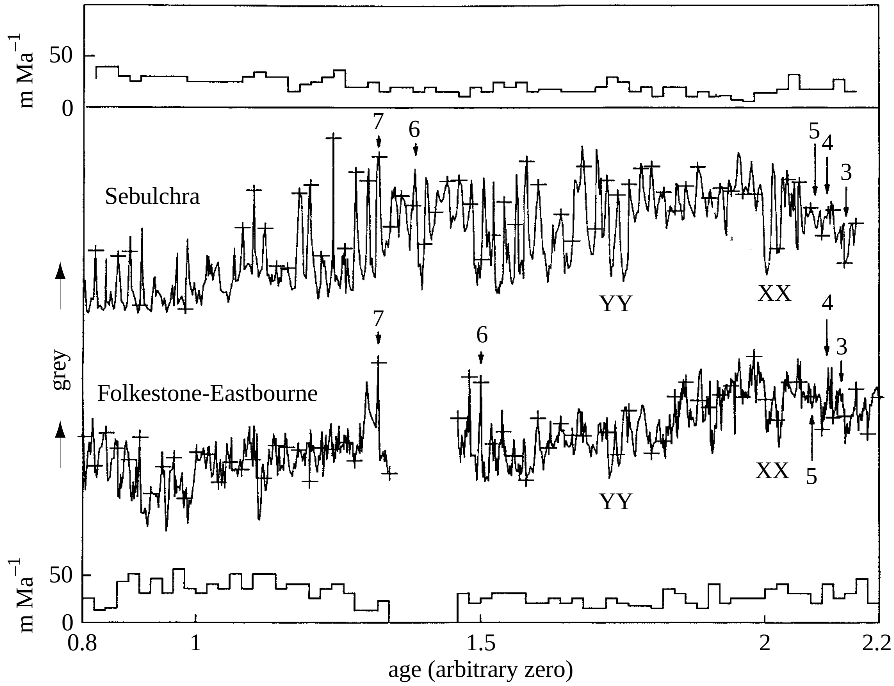


Figure 6. Match between Folkestone–Crimea grey-scale reflectance data, tuned to a 20 ka duration for couplets, to show matching in variance patterns in relation to biostratigraphical markers 3–7. Note inferred hiatus at Folkestone–Eastbourne between markers 6 and 7, and match of conspicuous paired light limestone beds (XX, YY).

The English sections show less variance and hence afford a less well resolved record. On the basis of biostratigraphical controls we started by assigning the boundary between two limestone beds (XX in figure 6) an age of 2.0 Ma. It was then relatively straightforward to correlate the record to the Selbuchra section from this point up to a higher pair of limestone beds (YY in figure 6). However, this correlation produces a misalignment of the higher biostratigraphical markers 6–8. If a hiatus of 80 ka is introduced into the Folkestone age model, both parts of the succession align well. This hiatus is associated with a strongly bioturbated omission surface, and probably corresponds with the sequence boundary at the junction of sequences Ce4–Ce5 (Robaszynski *et al.* 1998); its existence is thus supported by sedimentological evidence. The age-modelled data for the lower part of the Selbuchra section and the corresponding interval at Folkestone are shown in figure 6. The two sections show closely similar variance patterns from 1.0 to 1.5 Ma when aligned using event markers 3–5; note the exact correspondence of the two pairs of light beds (XX, YY), for example.

We also placed 'missing time' in the age model at points where we knew hiatuses exist from comparison with other sections, as at the B43–C1 boundary (Gale 1995) where two couplets are missing at Folkestone. We identified individual couplets which exceeded background sedimentation rate by a factor of two as representing two precession cycles. These include Beds 2–3 and 4–5 of the Plenus Marls. The massive 2 m chalk unit which immediately underlies the Plenus Marls at Eastbourne (Gale 1995)

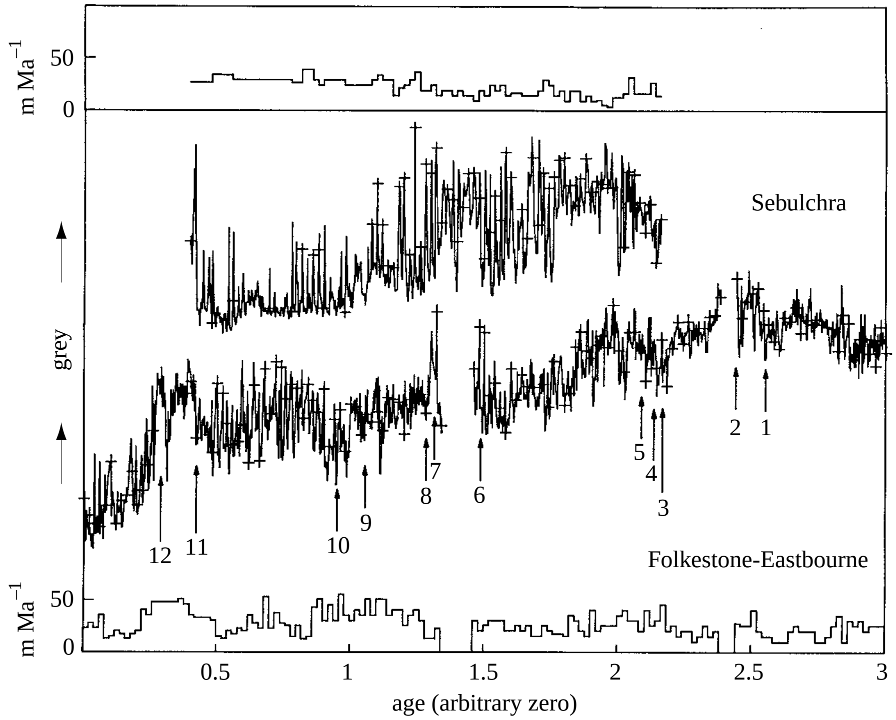


Figure 7. Full reflectance data-set, tuned to 20 ka boundaries, for Mid- and Late Cenomanian successions of Selbuchra (Crimea, Ukraine) and Folkestone–Eastbourne composite (SE UK). Hiatuses appear as gaps with zero accumulation. Accumulation rates are shown in metres per million years. Markers 1–12 are biostratigraphical events described in text.

was taken to represent three precession cycles. The full age-modelled data for both sections incorporating hiatuses are shown in figure 7.

## 5. Time-series analysis

To investigate the spectral character of the data we conducted two experiments based on the 0.72 Ma segment in the lower part of the Crimean Section mentioned above. Figure 8*a* shows a linear Blackman–Tukey spectral analysis as 'tuned' above (i.e. with control points at 20 ka intervals). This shows that there is significant variance at *ca.* 100 ka and 400 ka. There is very weak power in the region of 40 ka that may be related to obliquity variation but is clearly not strong enough to be used for time-scale development.

For the second experiment (figure 8*c*) we removed all age control points except the top and bottom, equivalent to a spectral analysis in the depth domain scaled to be comparable with figure 8*a*. This shows a generalized concentration of variance encompassing the precession and obliquity range of frequencies, very clearly separated from lower-frequency variance concentrations that are close to 100 ka and 400 ka. Clearly, the sedimentation rate is not sufficiently constant to rigorously prove precessional forcing by spectral analysis in the depth domain.

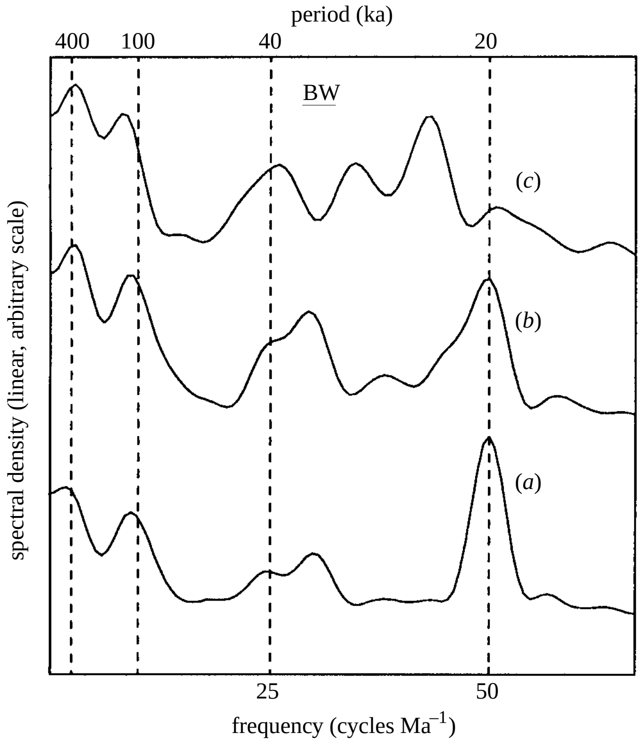


Figure 8. Linear Blackman–Tukey spectral analysis of a 720 ka section of Mid-Cenomanian time from Selbuchra (Crimea, Ukraine). (*a*) Time domain, tuned with control points at 20 ka intervals; note significant variance at 100 ka and 400 ka corresponding to eccentricity. (*b*) Time domain, tuned to 100 ka; note power in precession and (?) obliquity frequencies, and eccentricity (100 ka, 400 ka). (*c*) Depth domain, with only top and bottom depth control points; generalized concentration of variance around precession and obliquity frequencies, separated from concentrations close to 100 ka and 400 ka.

For the last experiment we eliminated the majority of the age control points, retaining only one per 100 ka, the short eccentricity signal. Figure 8*b* shows a linear spectrum of this time-series; again both the precession power and the weaker power that may be related to obliquity are evident, and the power at 100 ka and 400 ka is retained.

Finally, for the part of this interval that is represented in Folkestone (i.e. below the 80 ka hiatus mentioned above), we carried out cross-spectral analysis that shows coherency at both the 20 ka as well as generalized low-frequency coherence (figure 9). This supports the notion that 'tuning' the two sequences to the 20 ka couplet interval leads to a more or less correct overall correlation.

In an ancient precession-dominated record we are faced with the dilemma that the frequency of the strongest signal is poorly known because its value has changed slowly through time as a consequence of tidal friction, a factor that is not very well known and is dependent on the physics of the Earth rather than on gravitational interactions between the planets. The eccentricity periods (especially the 406 ka 'long eccentricity cycle'; Laskar, this issue) are better constrained astronomically but only become clearly apparent in the rock record after it has been linearized to time on

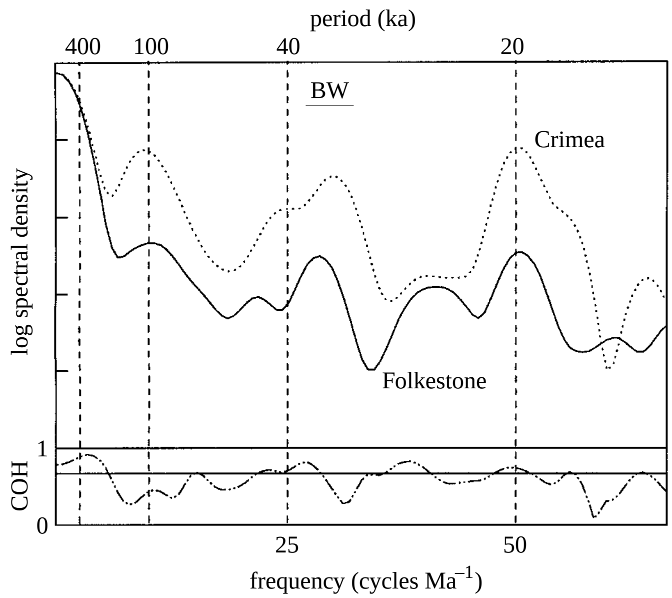


Figure 9. Cross-spectral analysis of segment of time (1.45–2.1 Ma; indicated in figure 6) between Folkestone and Selbuchra sections, to show coherency at 20 ka and more generalized low-frequency coherence. The coherency supports the age modelling to 20 ka couplet intervals used in this paper.

the basis of the precession cycles. The experiments described above show that by matching observed cyclicity in these two sections to a fixed-period 'precession', we reveal a clear response to eccentricity. As a longer spliced section is developed, it should become possible to tie this record to a real orbital eccentricity record and so to develop a real time-scale.

## 6. Conclusions

Time-series through Cenomanian marly chalks in northwest and eastern Europe were generated using grey-scale reflectance data from closely spaced samples. The data were age-modelled taking a value of 20 ka for the average duration of the precession-related cycles. Time-series analysis shows variance at *ca.* 100 ka and *ca.* 400 ka that probably arises from eccentricity variations, supporting the initial assumption that the most prominent cycle arises from precessional forcing. Power that may be related to obliquity is also present.

Comparison of the age-modelled time-series of Mid Cenomanian marls between Selbuchra in the Crimea and Folkestone, UK reveals closely similar patterns of variance in reflectance values. The mismatch of the patterns when constrained by biostratigraphical markers leads us to infer the presence of an 80 ka hiatus at Folkestone.

The approach used here can be applied to additional sections and may be expected to lead to a precise estimate of the duration of the Mid and Late Cenomanian which appears to be close to 3.0 Ma on the basis of the present data.

We thank Matteo Tazzi and Kirsten Muller for undertaking the laborious job of preparing and scanning thousands of chalk samples. We also thank Annie Dhondt for arranging the trip to the





PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Crimea which gave A.S.G. the opportunity to sample the Selbuchra Section, and the staff of Moscow University for their hospitality in the Crimea. Ruslan Gabadullan and other students from Moscow helped dig out the Selbuchra Section. N.J.S. is grateful to NERC grant GR3/11461 for support.

## References

Berger, A., Loutre, M. F. & Dehant, V. 1989 Pre-Quaternary Milankovitch frequencies. *Nature* **323**, 133.

Bromley, R. G. 1975 Trace fossils at omission sufaces. In *The study of trace fossils* (ed. R. W. Frey), pp. 399–428.

Destombes, J. P. & Shephard-Thorn, E. R. 1971 Geological results of the Channel Tunnel site investigation 1964–5. Institute of Geological Sciences Report no. 71/11.

Ditchfield, P. & Marshall, J. D. 1989 Isotopic variation in rhythmically bedded chalks: paleotemperature variation in the Upper Cretaceous. *Geology* **17**, 842–845.

Ernst, G. & Rehfeld, U. 1997 The transgressive development in the Lower and Middle Cenomanian of the Salzgitter area (N-Germany) recorded by sea-level controlled eco- and litho-events. *Freiberger Forschungsheft* **468**, 79–107.

Ernst, G., Schmid, F. & Seibertz, E. 1983 Event-Stratigraphie im Cenoman und Turon von NW-Deutschland. *Zitteliana* **10**, 531–554.

Fischer, A. G., Herbert, T. D., Napoleone, G., Premoli Silva, I. & Ripepe, M. 1991 Albian pelagic rhythms (Piobbico core). *J. Sediment. Petrol.* **61**, 1164–1172.

Gale, A. S. 1989*a* A Milankovitch scale for Cenomanian time. *Terra Nova* **1**, 420–425.

Gale, A. S. 1989*b* Field meeting in the Warren, Folkestone, Kent. *Proc. Geol. Ass.* **100**, 73–83.

Gale, A. S. 1995 Cyclostratigraphy and correlation of the Cenomanian of Europe. In *Orbital forcing timescales and cyclostratigraphy* (ed. M. R. House & A. S. Gale), pp. 177–197. Geological Society Special Publication no. 85.

Gale, A. S., Jenkyns, H. C., Kennedy, W. J. & Corfield, R. 1993 Chemostratigraphy versus lithostratigraphy—evidence from the Cenomanian–Turonian boundary. *J. Geol. Soc. Lond.* **150**, 29–32.

Gale, A. S., Kennedy, W. J., Burnett, J. A. & Caron, M. 1996 The Late Albian to Early Cenomanian succession at Mont Risou near Rosans (Drome, SE France): an integrated study (ammonites, inoceramids, nannofossils, planktonic foraminifera and carbon isotopes). *Cretaceous Res.* **17**, 515–606.

Gale, A. S., Hancock, J. M. & Kennedy, W. J. 1999 Biostratigraphical and sequence correlation of the Cenomanian successions of Mangyshlak (Kazakhstan), Crimea (Ukraine) and southern England. *Bull. Inst. R. Sci. Natur. Belgique.* (In the press.)

Herbert, T. D. & Fischer, A. G. 1986 Milankovitch climatic origin of Mid-Cretaceous black shale rhythms in central Italy. *Nature* **321**, 739–743.

Hilgen, F. J. 1991 Extension of the astronomically calculated (polarity) time scale to the Miocene/Pliocene boundary. *Earth Planet. Sci. Lett.* **107**, 349–368.

Hilgen, F. J., Krijgsman, W., Langereis, C. G., Lourens, L. J. & Zachariasse, W. J. 1995 Extending the astronomical (polarity) timescale into the Miocene. *Earth Planet. Sci. Lett.* **136**, 495–510.

Jarvis, I., Carson, G. A., Cooper, M. K. E., Hart, M. B., Leary, P. N., Tocher, B. A., Horne, D. & Rosenfeld, A. 1988 Microfossil assemblages and the Cenomanian–Turonian (Late Cretaceous) Oceanic Anoxic Event. *Cretaceous Res.* **9**, 3–103.

Jefferies, R. P. S. 1962 The palaeoecology of the *Actinocamax plenus* subzone (lowest Turonian) in the Anglo-Paris Basin. *Palaeontology* **4**, 609–647.

Jefferies, R. P. S. 1963 The stratigraphy of the *Actinocamax plenus* subzone (Turonian) in the Anglo-Paris Basin. *Proc. Geol. Ass.* **74**, 1–34.

Jenkyns, H. C., Gale, A. S. & Corfield, R. 1994 The stable oxygen and carbon isotope stratigraphy of the English Chalk and the Italian Scaglia. *Geol. Mag.* **13**, 1–34.

Kennedy, W. J. 1969 The correlation of the Lower Chalk of south-east England. *Proc. Geol. Ass.* **80**, 459–560.

Kennedy, W. J. 1971 Cenomanian ammonites from southern England. *Palaeontology* (Special Papers) **8**, 133 pp., 64 plates.

Marcinowski, R. 1980 Cenomanian ammonites from the German Demoratic Republic, Poland and the Soviet Union. *Acta Geologica Polonica* **30**, 215–325.

Meyer, T. 1990 Biostratigraphischeund Sedimentologische Untersuchungen in der Planer fazies des Cenoman von Nordwestdeutschland. *Mitt. Geol. Inst. Univ. Hannover* **30**, 1–114.

Naidin, D. P. & Alekseev, A. S. 1981 Importance of ocean drilling data for interpretation of sedimentation and life of fauna in the Cenomanian of the Crimean highlands. In *Evolution of organisms and biostratigraphy of the Mid-Cretaceous* (ed. V. Krassilov), pp. 7–21. Vladivostok.

Obradovitch, J. 1994 Cretaceous time scale. In *Evolution of the Western Interior Basin* (ed. W. G. E. Caldwell & E. G. Kauffman). *Geol. Ass. Canada* (Spec. Paper) **39**, 379–396.

Paul, C. R. C, Ditchfield, P., Gale, A. S., Learey, P. N., Mitchell, S. & Duane, A. 1994 Palaeoceanographic events in the Middle Cenomanian of north-west Europe. *Cretaceous Res.* **15**, 707–738.

Premoli-Silva, I. & Sliter, W. V. 1995 Cretaceous planktonic foraminiferal biostratigraphy and evolutionary trends from the Bottacione section, Gubbio, Italy. *Palaeontographica Italica* **82**, 1–89.

Robaszynski, F., Gale, A., Juignet, P., Amedro, F. & Hardenbol, J. 1998 Sequence stratigraphy in the Upper Cretaceous of the Anglo-Paris Basin, exemplified by the Cenomanian Stage. In *Mesozoic and Cenozoic Sequence stratigraphy of European Mesozoic Basins* (ed. J. Hardenbol, J. Thierry, M. B. Farley, Th. Jaquin, P.-C. De Graciansky & P. R. Vail). *SEPM Spec. Publ.* no. 60, pp. 363–386.

Shackleton, N. J., Berger, A. & Peltier, W. R. 1990 An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. *Trans. R. Soc. Edinb.* **81**, 251–261.

Shackleton, N. J., Crowhurst, S., Hagelberg, T., Pisias, N. G. & Schneider, D. A. 1995 A late Neogene time scale: application to leg 138 sites. In *Proc. ODP, Scientific Results* (ed. N. G. Pisias, L. A. Mayer, T. R. Janacek, A. Palmer-Julson & T. H. van Andel), vol. 138, pp. 73–101.

Tröger, K.-A. 1989 Problems of Upper Cretaceous inoceramid biostratigraphy and paleobiogeography in Europe and Western Asia. In *Cretaceous of the Western Tethys. Proc. 3rd Int. Cretaceous Symp., Tübingen 1987 Schweizerbart'sche, Stuttgart* (ed. J. Wiedmann), pp. 911–930.

Young, J., Gale, A. S., Geisen, M., Tazzi, M. & Wray, D. 1999 Flat bed scanning of outcrop samples, an effective and efficient method of obtaining time series data. *J. Sediment. Res.* (In the press.)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES