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THE ROYAL SOCIETY

Astronomical calibration of the Jurassic time-scale from cyclostratigraphy in British mudrock formations

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Three British Jurassic mudrock formations have been investigated, via time-series analysis, for evidence of sedimentary cyclicity related to orbital–climatic (Milankovitch) cyclicity: the Blue Lias, the Belemnite Marls and the Kimmeridge Clay Formation.

Magnetic-susceptibility measurements through the Blue Lias (uppermost Triassic to Sinemurian) were used to generate high-resolution time-series. The data indicate the presence of a regular sedimentary cycle that gradually varies in wavelength according to sedimentation rate. Tuning of this cycle to the 38 ka Jurassic obliquity cycle produces spectral evidence for two additional regular cycles of small amplitude. These correspond to the 95 ka component of orbital eccentricity and the 20 ka orbital–precession cycles. Cycle counting allowed the minimum duration of four ammonite zones to be estimated and the duration of the Hettangian stage is estimated to be at least 1.29 Ma. Calcium carbonate measurements through the Belemnite Marls (lower Pliensbachian) are characterized by two scales of cyclicity that can be firmly linked to orbital–precession (20 ka) and the 123 ka component of eccentricity. A time-scale has been developed from the precession-related sedimentary cycles, with cycle counts used to constrain the duration of two ammonite zones. In the Kimmeridge Clay Formation (Kimmeridgian–Tithonian), magnetic-susceptibility measurements made on exposures, core material and down boreholes can be correlated at the decimetre scale. Only measurements of magnetic susceptibility made below the Yellow Ledge Stone Band (midway through the formation) are suitable for analysis of the bedding-scale cyclicity. A large-amplitude sedimentary cycle detected in the lower part of the formation is probably related to the orbital–obliquity cycle (38 ka). In certain stratigraphic intervals, there is evidence for small-amplitude cycles related to orbital precession (20 ka).

This study of the British Jurassic shows that, in the Rhaetian–Sinemurian, the dominant cyclicity was related to obliquity. In the Pliensbachian this had shifted dominantly to precession, and in the Kimmeridgian obliquity again dominated. These shifts in cycle dominance presumably reflect changing local or global palaeoclimatic and/or palaeoceanographic conditions.

Keywords: cyclostratigraphy; interval dating; Jurassic, Milankovitch; palaeoclimatology; sedimentary cycles; time-series analysis

1. Introduction

British Jurassic strata are very well exposed and are some of the most intensively studied in the world. In particular, the coastlines of Dorset and Yorkshire provide structurally undeformed sections which are largely complete at the level of biostratigraphic zones and subzones. Ammonites are especially useful for correlation and relative dating of the British Jurassic, although alternative, lower-resolution microfossil-based schemes also exist (e.g. Ainsworth *et al*. 1998). Within the Boreal biogeographic province, there are 75 ammonite zones and well over 100 subzones (Cope *et al*. 1980*a*, *b*; Cope 1995). On the latest chronometric scale of Gradstein *et al*. (1994), the Jurassic is estimated to have lasted 61.5 Ma, implying a temporal resolution comparable with the microfossil zonation of the late Cenozoic.

However, despite the excellent biostratigraphic controls, chronometric dating remains problematic. This lack of chronometric precision arises from the rarity of volcanic rocks associated with marine sediments. A recently developed radiometric-dating technique, which uses the Re–Os isotope system, will potentially revolutionize numerical dating of Mesozoic–Recent organic-rich mudrocks (Cohen *et al*. 1999). However, currently, the estimated uncertainty in the ages of the stage boundaries ranges up to ± 4.0 Ma so that in some cases the uncertainty limits in successive stage boundaries overlap (Gradstein *et al*. 1994).

Here we describe the current status of attempts to improve this situation using cyclostratigraphy and time-series analysis as applied to British Jurassic mudrocks. Mudrocks are commonly suitable for investigations of sedimentary cyclicity because they tend to be much more stratigraphically complete than coarser-grained siliciclastic successions from shallow-shelf settings. Time-series analysis of mudrocks can be used to test for the presence of regular sedimentary cycles (i.e. regular in thickness and, by inference, regular in time) which are characteristic of orbital–climatic forcing (Fischer *et al*. 1990; Weedon 1993). In this paper we use 'time-series' to mean any sequential set of data, whether located with respect to rock thickness or time (Schwarzacher 1993, p. 49).

The Jurassic of Britain contains four marine mudrock units possessing a sedimentary cyclicity which has been attributed to orbital–climatic (or Milankovitch) cycles: the Blue Lias, Belemnite Marls, Oxford Clay Formation and Kimmeridge Clay Formation (figure 1). Currently, compositional data collected at sufficiently high stratigraphic resolution for time-series analysis have been obtained only from the Blue Lias (Rhaetian–Sinemurian), Belemnite Marls (Pliensbachian) and Kimmeridge Clay Formation (Kimmeridgian (*sensu gallico*)–Lower Tithonian). Natural gamma-ray and sonic-velocity downhole logs are available through the Oxford Clay Formation (Callovian–Lower Oxfordian; Whittaker *et al*. 1985; Penn *et al*. 1986). However, since the individual sedimentary cycles are just a few tens-of-centimetres

Figure 1. British Jurassic mudrocks showing clear bedding-scale cyclicity. The Jurassic Period lasted 61.5 Ma according to the time-scale of Gradstein *et al*. (1994). The British Jurassic mudrock units indicated cover a total of 27 out of 75 ammonite zones recognized in the Boreal palaeobiogeographic province (Cope 1995). Here the age of stage boundaries follows Gradstein *et al*. (1994), but each stage has been illustrated as though the component zones had equal durations. The limits of the mudrock units are located with respect to the ammonite zones. Ryaz. = Ryazanian, Pt = Portlandian. The base of the Tithonian is believed to correlate approximately with Blake's Bed 42 in the Kimmeridge Clay Formation. Kimmeridgian *sensu anglico* includes the Kimmeridgian *sensu gallico* (illustrated) plus the pre-Portlandian part of the Tithonian.

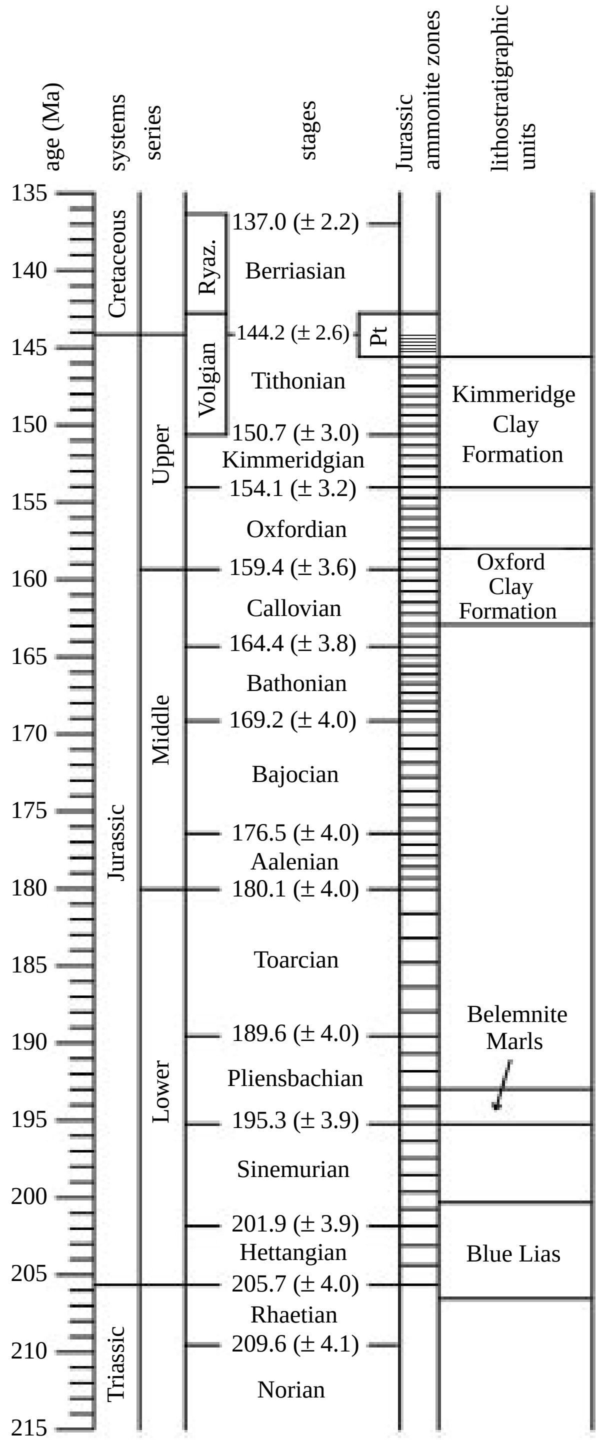

Figure 1. For description see opposite.

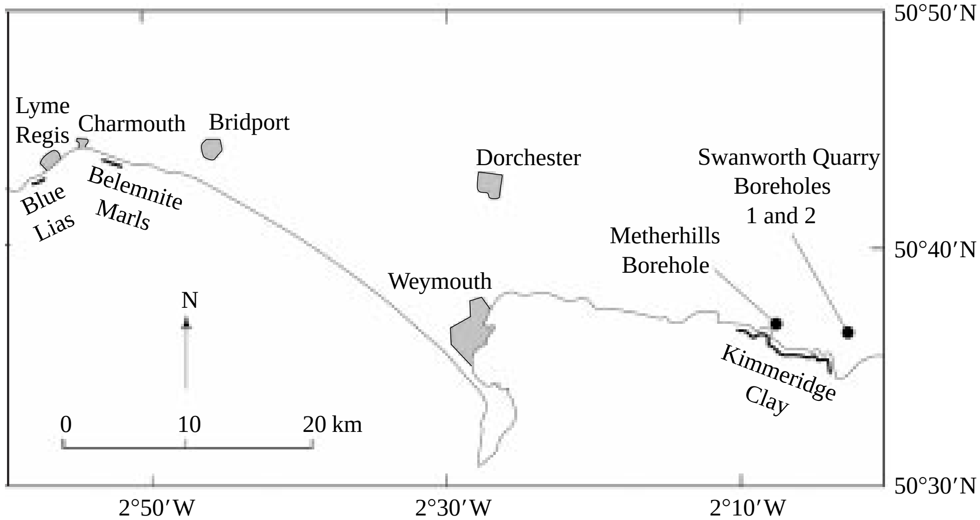

Figure 2. Locations of the exposures used (Blue Lias, Belemnite Marls, Kimmeridge Clay Formation) for generating the time-series described.

thick (Hudson & Martill 1994), these wireline log data lack the resolution required for time-series analysis. Some bulk compositional time-series have been obtained from the Oxford Clay (Kenig *et al*. 1994), but unfortunately the sampling interval is such that the signal is clearly aliased (cf. Priestley 1981).

The time-series described here have all been obtained so that the samples are uniformly spaced, using a sample interval that is much smaller than the thinnest beds. This prevents aliasing of the stratigraphic information (Priestley 1981). The spectral technique used is based on the discrete Fourier transform and confidence-limits procedures adopted by Weedon & Jenkyns (1999). In all cases the initial analysis has been performed using stratigraphic thickness rather than time. Factors such as variable sedimentation rates, undetected hiatuses, bioturbation and diagenesis affect the relationship between time and thickness (Weedon 1989; Herbert 1994). These distortions reduce the chances of detecting any original periodic or quasi-periodic phenomena. However, the presence of regular sedimentary cyclicity in the 'depth domain', combined with dating that suggests periods of tens of thousands of years, is taken to indicate orbital–climatic forcing of sedimentation.

All three formations considered have the same original components: clay minerals, coccolithic and other fine-grained skeletal carbonate, organic matter and minor macrofossils. The proportions of these components vary both within and between formations. Additionally, diagenesis has produced varying amounts of pyrite and secondary carbonate cement. Each of the formations described was deposited in the Wessex Basin, which formed due to rifting in the Triassic–Jurassic (Chadwick 1986; Jenkyns & Senior 1991; Hesselbo & Jenkyns 1995; Underhill 1998). Consequently, the thicknesses of the various formations vary across syn-sedimentary faults.

In the case of the Belemnite Marls, samples were collected in the field and analysed for weight percentage $CaCO_3$. For both the Blue Lias and Kimmeridge Clay, time-series were obtained by using measurements of magnetic susceptibility. Magnetic susceptibility relates to the proportions, and types, of magnetizable material in a sample: it does not indicate remnant magnetization. In organic-carbon-rich sediments, such as those discussed here, early diagenetic dissolution, by H_2S, of ferrimagnetic minerals such as magnetite leads to substantially smaller magnetic-susceptibility values compared with those encountered in modern deep-sea sediments (Lovely 1987; Robinson 1990). In such cases, magnetic susceptibility in mudrocks may be dominated by weakly magnetizable paramagnetic clay minerals (Hounslow 1985). Note that pyrite, as a byproduct of iron-oxide reduction (Canfield & Berner 1987), has a magnetic susceptibility which is virtually zero ($+0.837 \times 10^{-8}$ SI; Bleil & Petersen 1987). This means that pyrite has essentially no effect on measured susceptibility values in ancient organic carbon-rich mudrocks. Non-ferroan calcite is diamagnetic and also has a very low susceptibility (-0.48×10^{-8} SI; Collinson 1983), whereas ferroan calcite and dolomite can have fairly high susceptibilities. Here the precise origin of the magnetic susceptibility is not the issue, nor are the absolute values; the intention is to demonstrate the utility of the parameter as a tool for generating time-series in ancient mudrocks (cf. Robinson 1990).

2. The Blue Lias

(*a*) *Introduction*

The Blue Lias crops out in many parts of Britain but is best known from the coastal cliffs east and west of Lyme Regis, on the Dorset–Devon border (Lang 1924; figure 2). The formation consists of interbedded pale blue-grey limestones, light and dark blue-grey marls and black millimetre-laminated shales. The proportions of the various rock types vary through the formation (figure 3). At Lyme Regis, the beds are centimetres to decimetres in thickness and can be traced laterally for at least 4 km. Early discussions on the origin of the cyclicity are given by Lang *et al*. (1923), Kent (1936) and Shukri (1942). Hallam (1960) carried out the first modern sedimentological and palaeontological study. Sedimentological and oxygen- and carbon-isotope data indicate that the limestones formed, at least partly, via oxidation of organic carbon during sulphate reduction, prior to compaction (Hallam 1964; Campos & Hallam 1979; Weedon 1987*a*; Raiswell 1988; Bottrell & Raiswell 1989).

Hallam (1964) suggested that the diagenetic limestone formation was controlled by primary compositional factors. Weedon (1985) concurred with this view, arguing that the light-grey marls, dark-grey marls and laminated shales were deposited as distinct sediments on the sea floor. Subsequently, carbonate cementation of the light-grey marls produced a continuum from isolated limestone nodules through nodular limestone beds to laterally continuous limestone beds with planar contacts (i.e. fully cemented light-grey marl beds). Thus, according to the model developed by Weedon (1985), primary variations in the carbonate content of the lithologies were amplified by diagenetic processes. This interpretation was disputed by Hallam (1986; see discussion by Weedon (1987*b*)). Raiswell (1988) suggested that formation of early diagenetic limestones was linked to episodes of low accumulation rate.

The environment of deposition was certainly subject to substantial variations in bottom-water oxygenation, which influenced the occurrence of burrowing as well as benthic macrofaunal diversity (Hallam 1960; Weedon 1985). Well-oxygenated bottom waters were associated with relatively high carbonate, low clay-mineral and low organic-carbon contents. Episodes of anoxia were accompanied by deposition of black millimetre-laminated sediments with relatively low carbonate-, high clay-mineral and high organic-carbon contents.

It is very likely that the fluxes to the sea floor of clay minerals, carbonate mud and organic matter were influenced by climate. The beds with the highest contents of clay minerals and organic matter are laminated on a sub-millimetre scale. The association of organic matter with clay-rich sediments can be explained in two ways (Weedon 1985). Variations in run-off might have controlled the clay flux and development of density stratification in the water column and hence anoxia and increased organic-matter preservation. Alternatively, run-off might have controlled productivity via nutrient supply. Nutrient supply could have influenced the proportion of organic-walled plankton to coccolithophores (more organic-walled plankton during times of high nutrient levels) at the same time as controlling bottom-water oxygenation through the flux of organic matter. It is also possible that the cyclicity is the result of a combination of these two environmental controls.

Shukri (1942) specifically considered orbital–precession cycles as an explanation for the cyclicity in the Blue Lias. However, the variations in spatial separation of limestone beds led him to reject this model. House (1985) and Weedon (1985) revived the orbital–climatic model as an explanation for the primary cyclicity, the latter based on time-series analysis of digitized rock-type measurements. In that study it was assumed that sedimentation rates were essentially constant and that ammonite zones lasted *ca.* 1 Ma each. Both these assumptions have been abandoned for the present re-assessment of the cyclicity.

(*b*) *Measurements*

The cliff west of Lyme Regis (figure 2) was used for re-measuring the beds and determining magnetic susceptibility. Measurements were made on freshly broken rock faces at right angles to bedding. A Bartington Instruments MS2 meter and F-probe were employed to determine magnetic susceptibility at fixed 2 cm intervals. All measurements were made in duplicate and averaged. Instrumental drift, primarily caused by temperature variations, was established between each measurement point and corrected for by using measurements made in air more than 50 cm from all rock surfaces. The resulting time-series clearly shows that the limestones have lower susceptibility than the marls and laminated shales (figure 3). Indeed, magnetic susceptibility and carbonate are inversely related when determined using discrete samples, confirming previous observations (Hounslow 1985). The generally higher values of magnetic susceptibility in the limestones, marls and shales of the *liasicus*-Zone beds, compared with the older and younger strata, have been reproduced in measurements made on coeval strata in Somerset, 50 km to the NNW (Weedon & Jenkyns, unpublished data). The long-term variation in susceptibility must reflect stratigraphic variation in mineralogy.

(*c*) *Time-series analysis*

Before interpreting the spectra, it is worth discussing the influence of the isolated nodule beds. While measuring magnetic susceptibility, carbonate nodules were avoided unless they constituted more than 50% of a bed. It may appear that this strategy could have erroneously missed some important information. However, consider the effect on the spectra of making the measurements through the nodules in

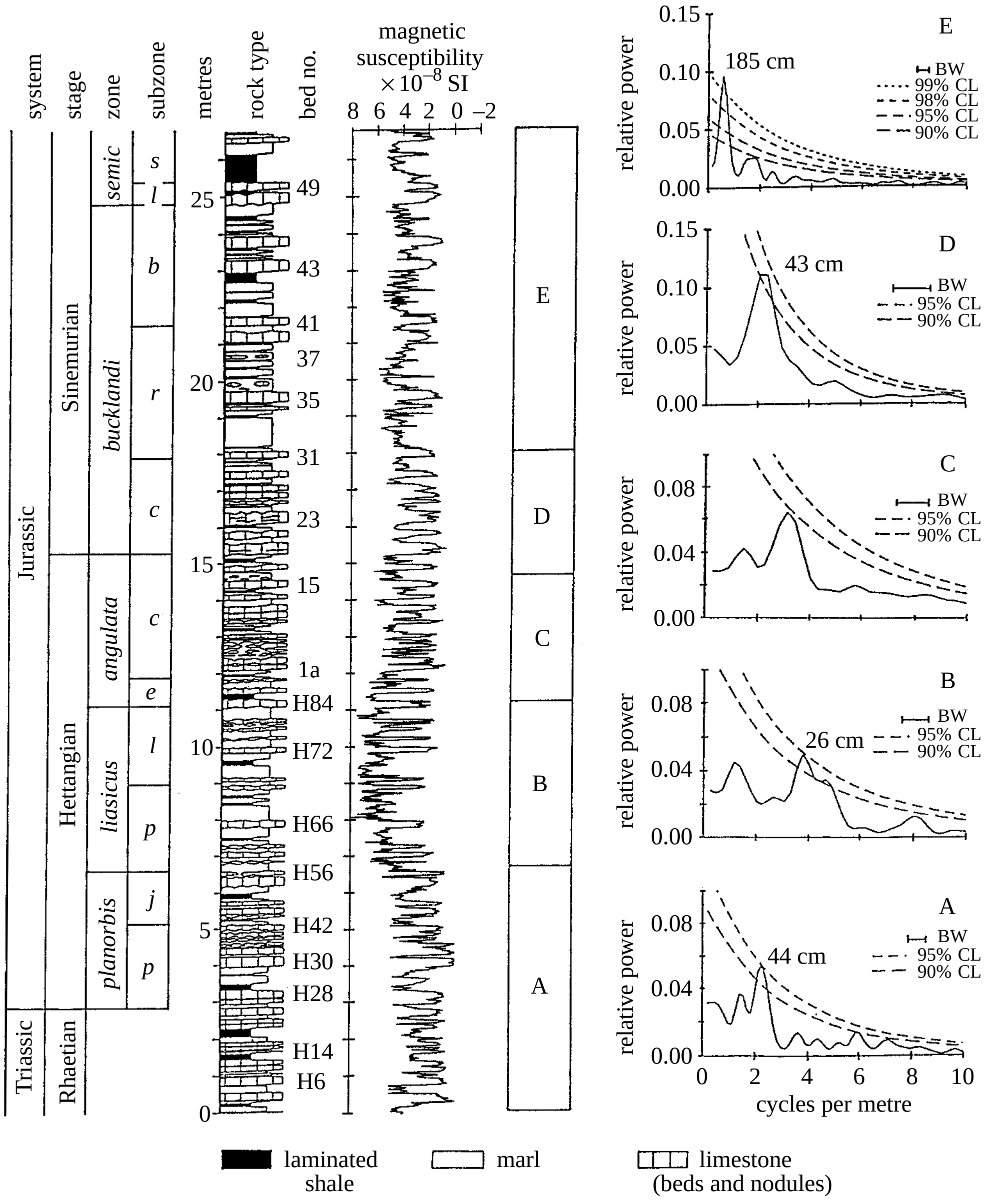

Figure 3. (Left) Time-series of magnetic susceptibility from the Blue Lias measured at 2 cm intervals west of Lyme Regis (figure 2). Bed numbers follow Lang (1924), biostratigraphy from Cope *et al*. (1980*a*) and Page (1992, 1995). The magnetic-susceptibility values have been plotted using a reversed scale so that limestone measurements (low values) project to the right. Note that in the *bucklandi* and *rotiforme* subzones of the *bucklandi* Zone, a few centimetre-scale horizons of beef calcite have susceptibility values as low as the limestone beds. *semic* = *semicostatum* Zone. Subzone letters denote subzone names: *planorbis* Zone—*planorbis* and *johnsoni* subzones; *liasicus* Zone—*portlocki* and *laqueus* subzones; *angulata* Zone—*extranodosa* and *complanata* subzones; *bucklandi* Zone—*conybeari*, *rotiforme* and *bucklandi* subzones. (Right) Power spectra from segments of the Blue Lias time-series. BW, bandwidth; CL, confidence level.

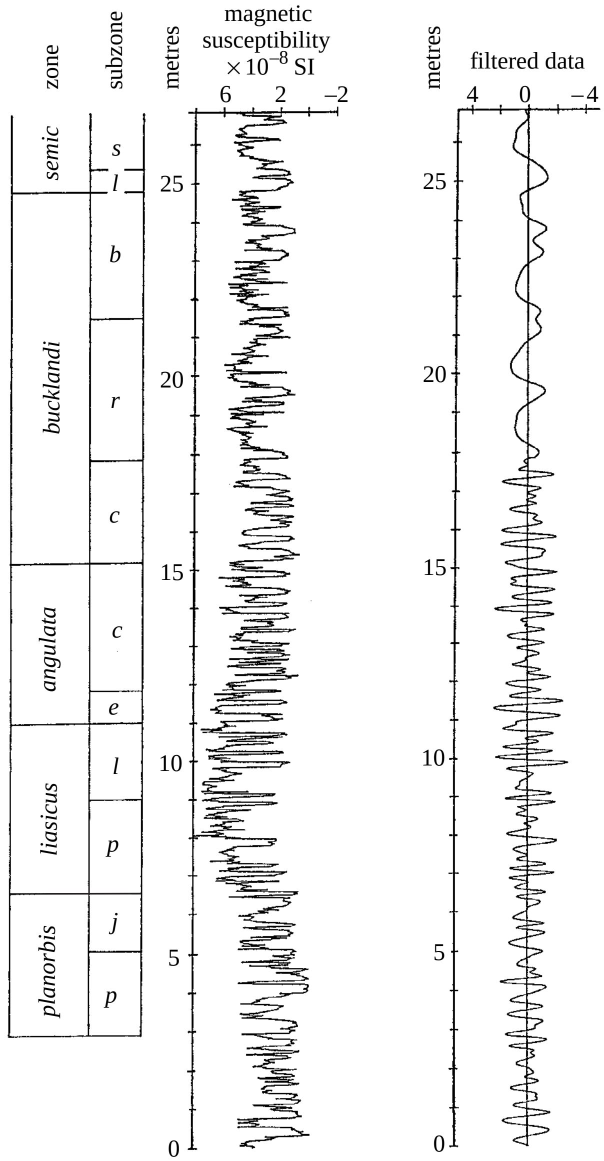

Figure 4. Results of bandpass filtering the Blue Lias magnetic-susceptibility time-series based on the spectral results of figure 3. For biostratigraphic nomenclature see caption to figure 3.

a few additional light-grey marl beds. Any spectral peaks will become reinforced where the extra limestones occur at the same spacing as the continuous limestone beds. On the other hand, if the extra limestones lay at some other spacing they would contribute power at positions away from the main spectral peaks, thereby slightly reducing the peak strength. Either way, because light-grey marl beds containing nodules form less than 5% of the total thickness of the Blue Lias at Lyme Regis, their inclusion or exclusion will have little effect on the spectra.

This study differs from that of Weedon (1985) in two important respects. Firstly,

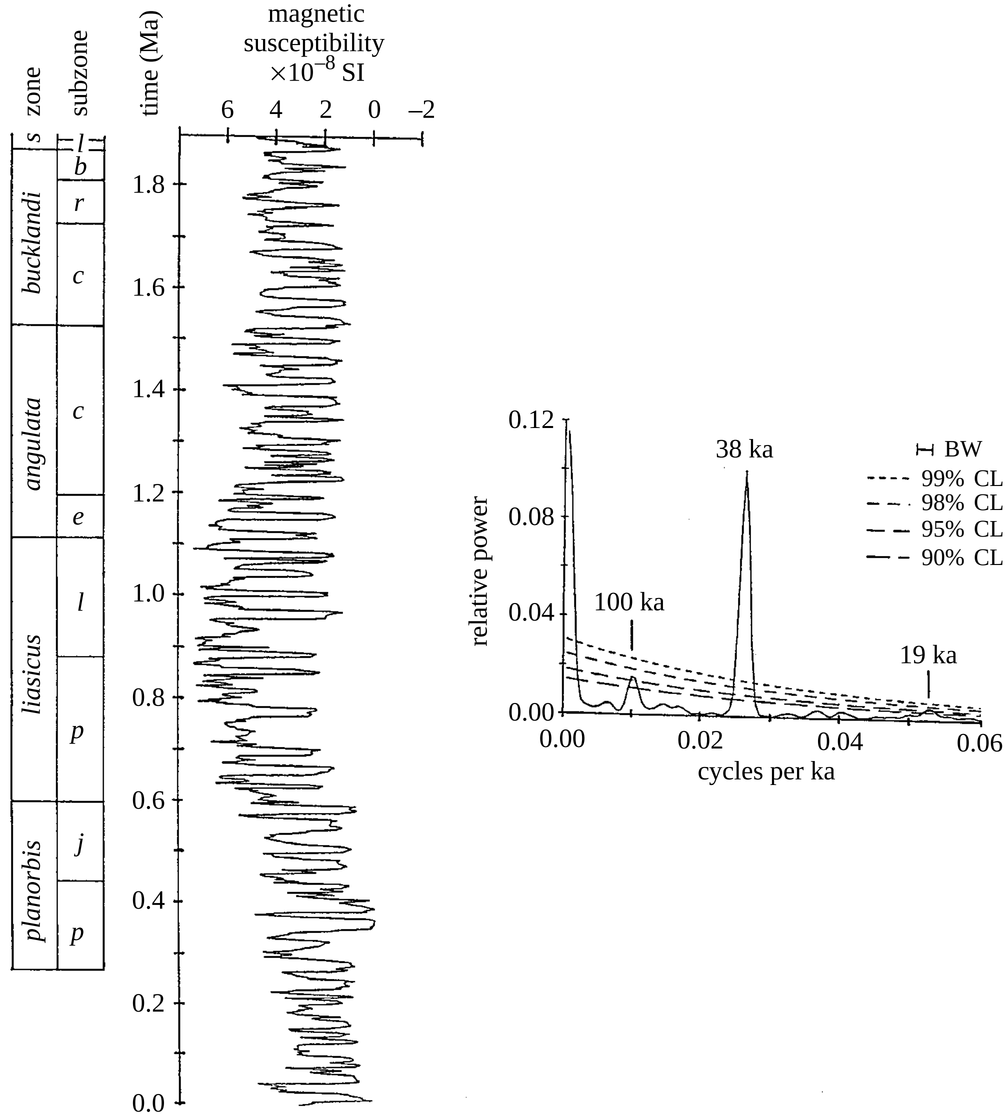

Figure 5. Tuned data from the Blue Lias and the corresponding power spectrum. Note that the size of the 38 ka spectral peak is partly a result of the tuning the cycles in figure 4 to this period. For biostratigraphic nomenclature see caption to figure 3.

the magnetic-susceptibility time-series relates (inversely) to carbonate contents only, without regard to the presence or absence of lamination in carbonate-poor lithologies. Secondly, since it is clear that the average separation of the limestones varies, the spectral analysis has been conducted using short segments which are considered 'stationary' (i.e. near-constant mean and standard deviation (Priestley 1981)). The spectra in figure 3 show that, in the five data segments, there is a single well-defined spectral peak, whose frequency position varies. We interpret this in terms of a single regular environmental cycle with variations in sedimentation rate causing the vari-

Table 1. *Minimum duration of ammonite zones and subzones based on counts of cycles in the Blue Lias*

(The durations are based on the inference that the cycles identified in figure 4 are related to the 38 ka obliquity cycle.)

subzone	minimum duration (ka)	zone	minimum duration (ka)	stage	minimum duration (Ma)
bucklandi	76				
rotiforme	76	*bucklandi*	342		
conybeari	190				
complanata	380	*angulata*	456		
extranodosa	76				
laqueus	228	*liasicus*	494	*Hettangian*	1.29
portlocki	266				
johnsoni	152	*planorbis*	342		
planorbis	190				

ations in cycle wavelength. We have used bandpass filtering to isolate this cycle in successive segments (figure 4).

In order to constrain the period of this sedimentary cyclicity we employ the current estimate for the duration of the Hettangian of 3.8 Ma (Gradstein *et al*. 1994). Using figure 4, there are 34 cycles in this stage at Lyme Regis implying an average duration of 112 ka. However, it is known that at Lyme Regis there are likely to be missing cycles at stratigraphic breaks (Weedon 1985; Smith 1989; Page 1992, 1995; Bessa & Hesselbo 1997). Therefore 112 ka represents a maximum period for the cyclicity. This implies that the sedimentary cycles could record the effects of the 95 ka eccentricity cycle or the obliquity cycle (38 ka in the Early Jurassic) or the precession cycle (20 ka in the Early Jurassic (Berger & Loutre 1994)).

Hallam (1960, 1964) showed that, in the *angulata* and *bucklandi* zones, the number of limestone–non-limestone alternations increases as a function of zonal thickness. He believed this could be explained via diagenetic processes (Hallam 1964). Weedon (1985, 1987*b*), however, argued that increased numbers of cycles are indicative of more complete sections. The situation is complex because in the Watchet Section in Somerset, in some biostratigraphic intervals, the much greater thicknesses compared with Lyme Regis are not associated with substantially increased numbers of limestone–non-limestone cycles (Weedon 1987*a*, *b*). The lithostratigraphic correlation of the Lyme Regis cycles with other sections awaits further work. Nevertheless, it appears possible that the cycles relate to obliquity or precession if the Lyme Regis section is incomplete at the tens of ka scale (Weedon 1985).

Further insight is provided by tuning the data. The filtering results in figure 4 were used to identify individual cycles and the maxima and minima were fixed at constant time-intervals. A spectrum of the new time-series revealed two new regular cycles that are both significant at the 95% level (figure 5). The wavelength ratios of the new cycles compared with the tuning cycles are 2.63 and 0.495. These ratios indicate that we can explain all three scales of cyclicity in terms of Milankovitch parameters if the tuning cycle had a period of 38 ka. Thus the other cycle periods become 100 ka and 19 ka, consistent with the 95 ka eccentricity and 20 ka precession cycles (figure 5). By counting the numbers of inferred 38 ka cycles in figure 4 we have determined the minimum duration of four ammonite zones (table 1). These results indicate a minimum duration of 1.29 Ma for the Hettangian.

3. The Belemnite Marls

(*a*) *Introduction*

The Belemnite Marls crops out on the coast east of Charmouth, Dorset (figure 2). The formation consists of interbedded light blue-grey and dark blue-grey marls with rare brown-black sub-millimetre-laminated shales. The beds are tens-of-centimetres thick and can be traced laterally along the coast for at least 2 km. There are many sedimentological similarities between the Blue Lias and Belemnite Marls (Sellwood 1970), but only two early diagenetic limestones occur as the stratigraphically lowest and highest beds of the latter unit. These limestones mark biostratigraphic gaps (Callomon & Cope 1995; Hesselbo & Jenkyns 1995) and may owe their origin to oxidation of organic matter and sulphate reduction as with the Blue Lias. Lang *et al*. (1928) provided the first detailed descriptions of the Belemnite Marls, and Sellwood (1970) carried out a sedimentological and palaeontological study. The primary nature of the regularly interbedded light- and dark-grey marls is shown clearly by the burrow-mottling at bed contacts, where light-coloured sediment is piped into dark and vice versa. The environment of deposition and models used to explain the cyclicity are very similar to that of the Blue Lias (Weedon & Jenkyns 1990, 1999).

(*b*) *Measurements*

Weedon & Jenkyns (1990, 1999) used high-resolution sampling and bulk geochemistry to produce time-series for the whole formation; their results are summarized here. Samples were obtained at fixed 3 cm intervals and analysed in duplicate for wt % $CaCO_3$. The time-series (figure 6) reveals pronounced decimetre-scale cycles associated with the light-grey marl–dark-grey marl bedding couplets. The couplets decrease in thickness considerably in the top third of the unit, probably due to a decrease in net sedimentation rate. The time-series generally reflects smoothly changing carbonate contents caused by bioturbation and sample homogenization. However, in the topmost 1.59 m, the carbonate values vary in a rather erratic, albeit reproducible, manner. This probably indicates aliasing (Priestley 1981) of the very thinnest beds by the 3 cm sampling interval. Consequently, data from the topmost 1.59 m were excluded from the time-series analysis. The couplets vary in terms of their average carbonate contents, producing metre-scale bundles of couplets that are visible in the field.

(*c*) *Time-series analysis*

Spectral analysis was performed using three segments of data (A–C in figure 6), because of the suspected variations in sedimentation rate. The spectra reveal that the couplets were very regular with wavelengths of *ca.* 37 cm in segments A and B. The bundle cycles had wavelengths of 3 m, although they do not form spectral peaks which can be distinguished statistically from the spectral background. In segment C,

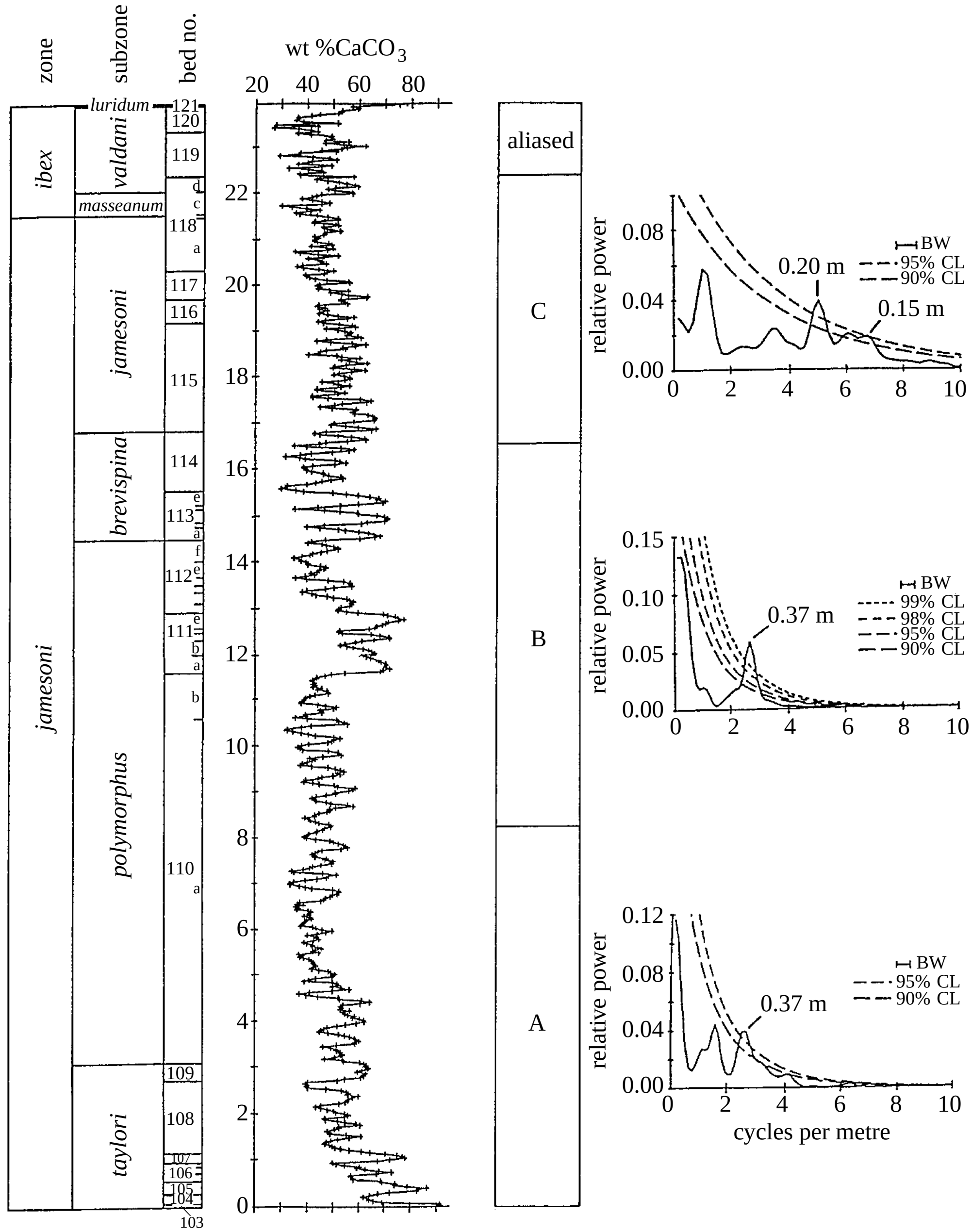

Figure 6. wt% $CaCO_3$ time-series and spectra for the Belemnite Marls. The time-series is based on samples collected at 3 cm intervals east of Charmouth (figure 2). Bed numbers follow Lang *et al*. (1928).

the couplets decreased in wavelength to 20 cm and then 15 cm, whereas the bundles reduced to cycles 1 m thick. In segments A and B, the regularity of the couplets suggests that they were probably produced by a periodic environmental cycle. As

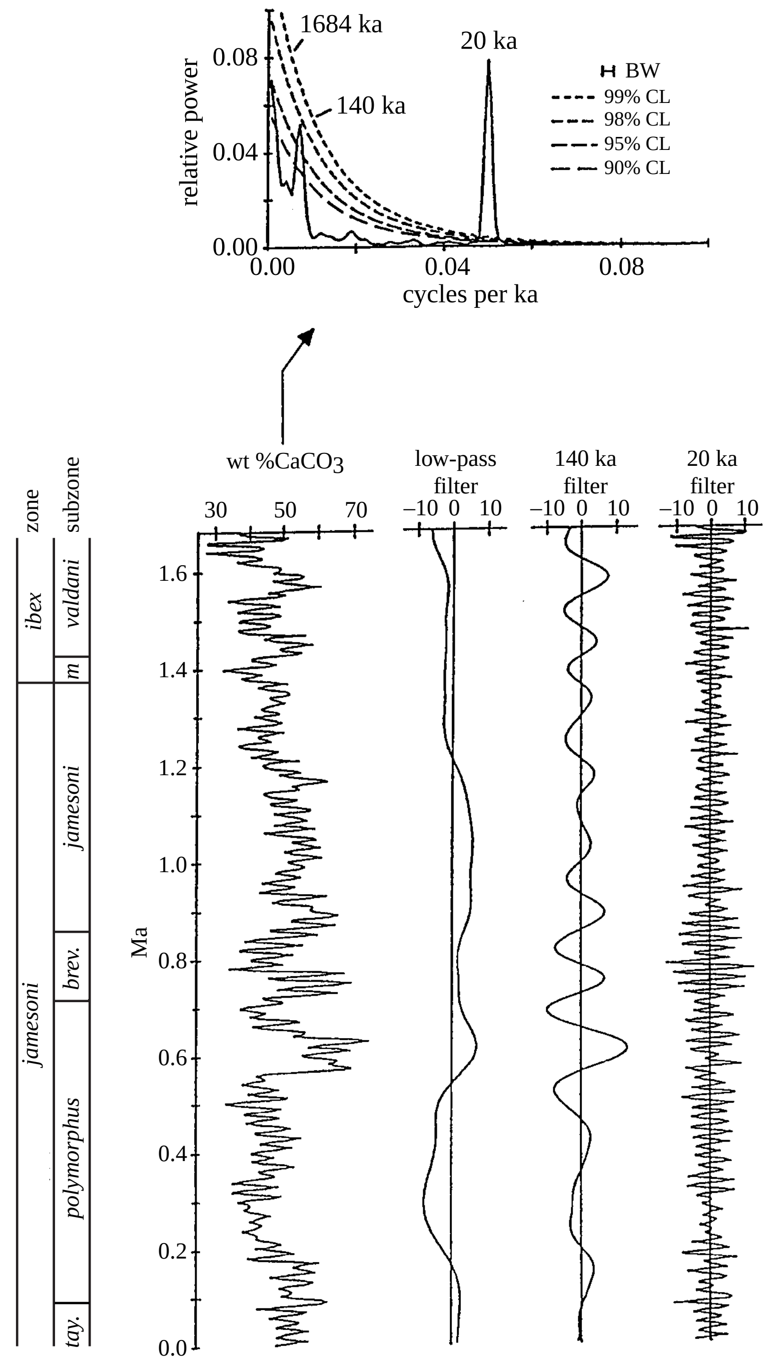

Figure 7. Time-scale for the Belemnite Marls developed by assuming each couplet represents 20 ka. The resulting time-series has spectral evidence for three scales of cyclicity. The spectral peak labelled with 140 ka probably corresponds to the 123 ka component of the eccentricity cycle (Weedon & Jenkyns 1999). For biostratigraphic nomenclature see figure 6.

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

the bundle cycles cannot be distinguished from the spectral background, it is unclear from the depth-domain analysis whether or not the bundle cycle reflects a periodic sedimentary phenomenon.

The time-scale, developed by Weedon & Jenkyns (1999) for those parts of the Belemnite Marls that appear to be complete (figure 7), was based on the inference that the couplets represent the precession cycle (20 ka). This is compatible with the figure for the duration of the Pliensbachian (5.7 Ma) computed from the Gradstein *et al*. (1994) time-scale: the stage contains 15 ammonite subzones, whose average duration was hence 0.38 Ma. The Belemnite Marls is divided into 7 subzones and contains 89 couplets (Weedon & Jenkyns 1999), giving a maximum couplet duration of *ca.* 30 ka.

A spectrum of the data plotted using the cyclostratigraphic time-scale indicates that the bundles were regular and had a period of *ca.* 140 ka (figure 7). This is consistent, within the uncertainty of the spectral analysis, with the 123 ka component of the eccentricity cycle (Berger 1977; Weedon & Jenkyns 1999). There were apparently longer-term oscillations present in addition, but these are too few to be able to judge whether or not they relate to the 413 ka and 1.3 Ma components of the orbital-eccentricity cycle (Berger 1977; Weedon & Jenkyns 1999).

Finally, Weedon & Jenkyns (1999) used the new cyclostratigraphic time-scale to estimate the minimum duration of the lower Pliensbachian ammonite subzones and zones. By combining this information with cycle counts from the Yorkshire coast and Switzerland they showed that the whole Pliensbachian lasted a minimum of 4.82 Ma. They also argued that strontium-isotope ratios decreased linearly in the Early Jurassic (Jones *et al*. 1994*a*, *b*; cf. Miller *et al*. 1991). The Belemnite Marls time-scale was used to establish that $^{87}Sr/^{86}Sr$ decreased at a rate of 0.000 042 Ma^{-1} and they estimated the minimum duration of the Hettangian, Sinemurian and Pliensbachian stages as 2.86, 7.62 and 6.67 Ma respectively. These values are, within error, consistent with the Gradstein *et al*. (1994) values (3.8, 6.6 and 5.7 Ma respectively).

4. The Kimmeridge Clay Formation

(*a*) *Introduction*

An extensive literature exists for the Kimmeridge Clay Formation, partly because it represents the principal source rock for North Sea oil. The formation has been correlated from Dorset to Yorkshire using distinctive marker beds (Cox & Gallois 1980; Penn *et al*. 1986). At the type section in Dorset, distinctive beds are named (e.g. the Blackstone, White Stone Band, Yellow Ledge Stone Band, etc.) and groups of beds and individual beds are numbered (Cox & Gallois 1980; Wignall 1990; Coe 1992). Similar facies are present over a wide area, but the total thickness and completeness varies (Gallois 1976; Cox & Gallois 1980; Melnyk *et al*. 1994). The main rock types are medium dark-grey marls, dark-grey shales, dark grey-black laminated shales, greyish brownish black mudstones, pale-grey coccolithic limestones, and grey to pale yellow limestones and dolostones (figure 8). There is an obvious cyclicity, picked up by the alternation of organic-rich and organic-poor sediments and this is clearly displayed in parts of the type section exposed in Kimmeridge Bay, Dorset (figure 8). The dolostones, typically ferroan, are diagenetic and were investigated isotopically by Irwin (1979, 1980), and by electron microscopy, X-ray microanalysis and X-ray diffraction by Feistner (1989).

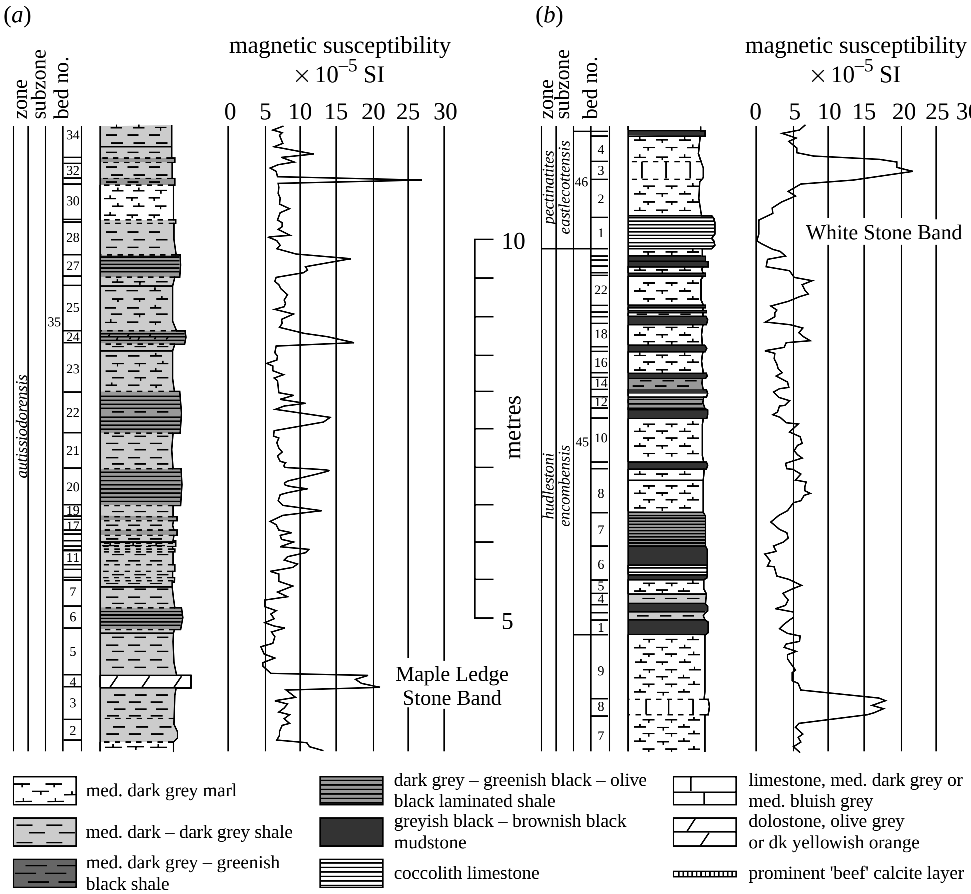

Figure 8. (*a*) and (*b*) Lithological logs and magnetic-susceptibility measurements through portions of the Kimmeridge Clay Formation as exposed in east Dorset (figure 2). Bed group numbers after Cox & Gallois (1980) and Coe (1992).

Gallois (1976) argued that coccolithophorid blooms caused reduced oxygen contents and anoxia, leading to enhanced organic-matter preservation, but Tyson *et al.* (1979) argued that water-column stratification was a key element in the process. Oschmann's (1988) sedimentological and palaeontological observations were used to argue for seasonal water stratification. Waterhouse (1995) used quantitative palynology to clarify the terrestrial and marine influences on the composition of the organic matter. Tyson (1996) employed organic geochemical and palynological data to show that substantial variations in organic-carbon richness are more likely to have been linked to dilution by inorganic components (clay minerals and coccoliths) than to variations in productivity.

Dunn (1974) carried out a pioneering time-series analysis of a 20 m section centred on the Blackstone (an extraordinarily carbon-rich unit of the Kimmeridge Clay Formation) and reasoned that the metre-scale cyclicity was linked to Milankovitch cycles. Hallam & Bradshaw (1979) and House (1985) also suggested that orbital–climatic cycles were involved in the deposition of the unit. Waterhouse (1995) argued

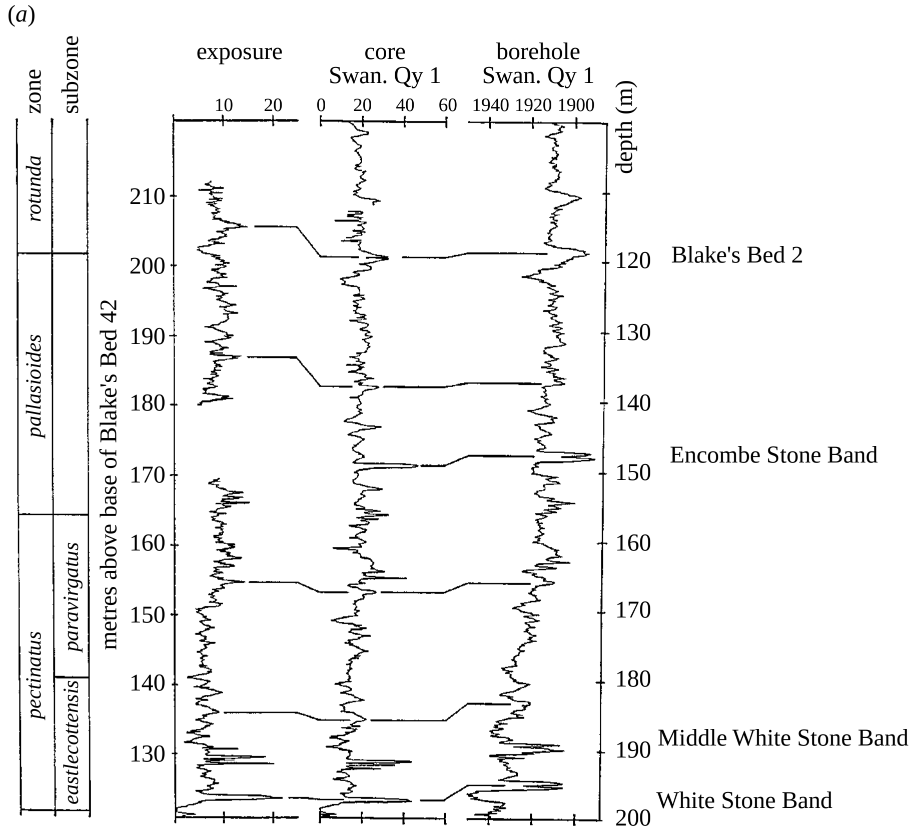

Figure 9. Magnetic-susceptibility measurements from the Kimmeridge Clay Formation type section exposure (at 10 cm), core (at 5 cm) and boreholes (at 5 cm). Note the strong degree of correlation at the metre scale of the magnetic-susceptibility signal from the exposure to core and boreholes. Note also that in the borehole logs single large magnetic-susceptibility peaks recorded in the exposure and core appear as double peaks due to a measurement artefact.

that obliquity cycles dominated the marine system with precession affecting the local terrestrial environment. Melnyk *et al*. (1994) used gamma-ray logs from across the Wessex Basin to investigate the cyclicity using time-series analysis at the tens-of-metres to metre scale. They were unable to resolve oscillations with wavelengths of less than 50 cm. Here we consider a much higher-resolution time-series based on magnetic susceptibility from exposures, as well as downhole logs and cores from dedicated boreholes through the Kimmeridge Clay.

(*b*) *Measurements*

Three boreholes were fully cored and wireline logged at the eastern and western ends of the Dorset type section (figure 2; Gallois 1998). The two boreholes at Swanworth Quarry penetrated the top of the formation, whereas the borehole at Metherhills overlapped with the base of one of the other boreholes (Swanworth Quarry 1) and penetrated to the base of the unit. As part of a complete suite of wireline logs, magnetic susceptibility was measured, at 5 cm intervals, in the Swanworth Quarry 2

(*b*)

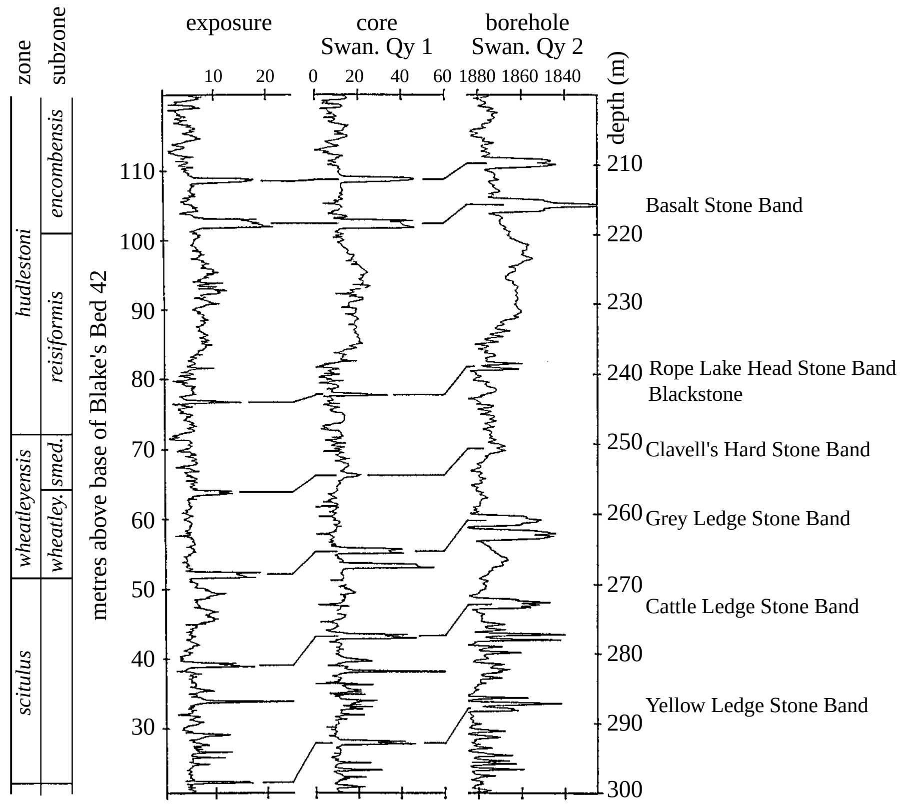

Figure 9. (*Cont.*)

and Metherhills boreholes. The core from Swanworth Quarry 1 and Metherhills was also measured at 5 cm in the laboratory using a Bartington Instruments loop sensor. Additionally, the exposure was redescribed and magnetic susceptibility determined on fresh rock faces at 10 cm intervals using the same procedures as in the Blue Lias study.

It is clear from the graphic logging in the field that the magnetic-susceptibility values are related to the lithology (figure 8). The ferroan dolostone beds give very high readings and the coccolithic limestones low readings. The remaining mudstones and shales have susceptibilities that vary according to lithology and stratigraphic position within the formation. Thus, below the Yellow Ledge Stone Band, the more organic-rich beds (laminated shales and greyish brownish black mudstones) usually produce much higher susceptibilities than the marls and medium dark-grey shales. Above this level, magnetic-susceptibility values are generally slightly higher in the marls and dark-grey shales than in the more organic-rich shales and mudstones (figure 8). The exact mineralogical origin of the magnetic-susceptibility signal and the reason for the change at the Yellow Ledge Stone Band awaits further investigations.

Parts of the various susceptibility time-series produced for this study are illustrated in figure 9. Generally, the magnetic-susceptibility signal is highly reproducible in the exposure, core and downhole logs. However, at many levels a single large magnetic-

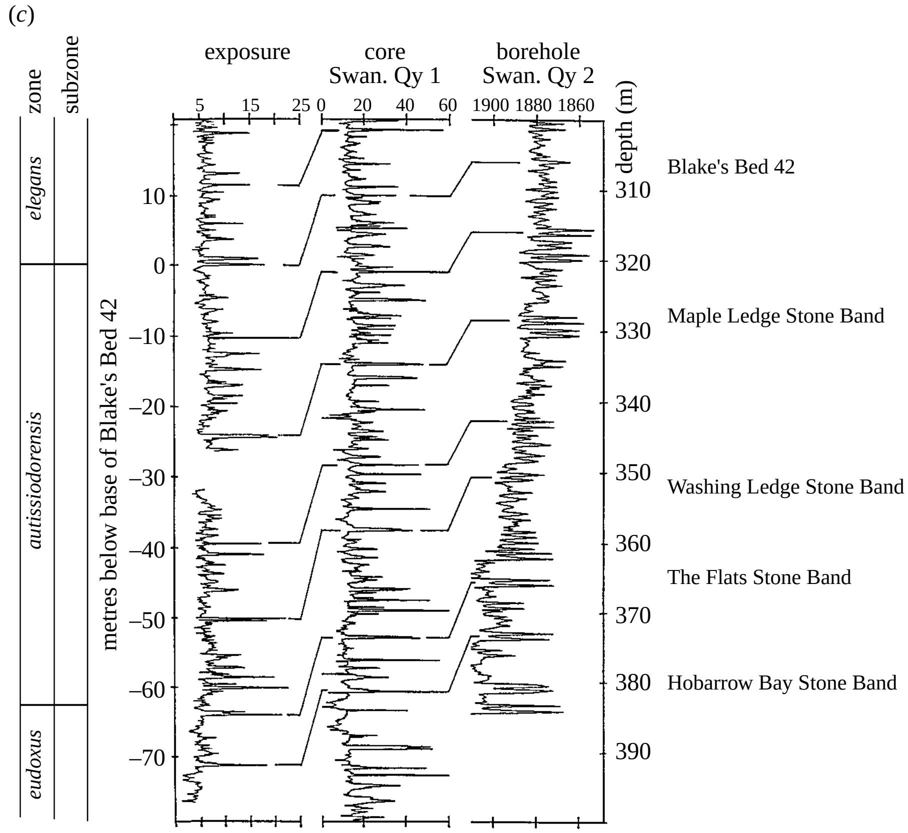

Figure 9. (*Cont.*)

susceptibility peak in the exposure and core measurements is represented as a double peak in the downhole logs. This appears to be an artefact of the downhole logging measurement. This means that the downhole data are not suitable for time-series analysis unless this artefact has been removed by some form of deconvolution.

(*c*) *Time-series analysis*

For time-series analysis we have used the laboratory measurements of the core from Swanworth Quarry 1. A spectrum for the whole data-set is dominated by very long wavelength (hundreds of metres in wavelength) oscillations. In order to study the bedding-scale cyclicity, the data were split into shorter segments. In some parts of the data, the spectra of small segments reveal a single significant spectral peak; elsewhere a secondary peak is present (figure 10). In intervals where a secondary peak was detected it is noticeable that the susceptibility oscillations are characterized by narrow peaks and flat troughs (a cuspate shape). This suggests that the secondary peaks relate to the harmonics of the main cyclicity and can thus be considered artefacts. However, distinct oscillations with small amplitude, but half the wavelength of the main cyclicity, are also present (figure 10*b*). Consequently, we believe the secondary peaks result both from the cuspate shape of the main oscillations and the presence of small-amplitude cycles with half the wavelength of the main cycles.

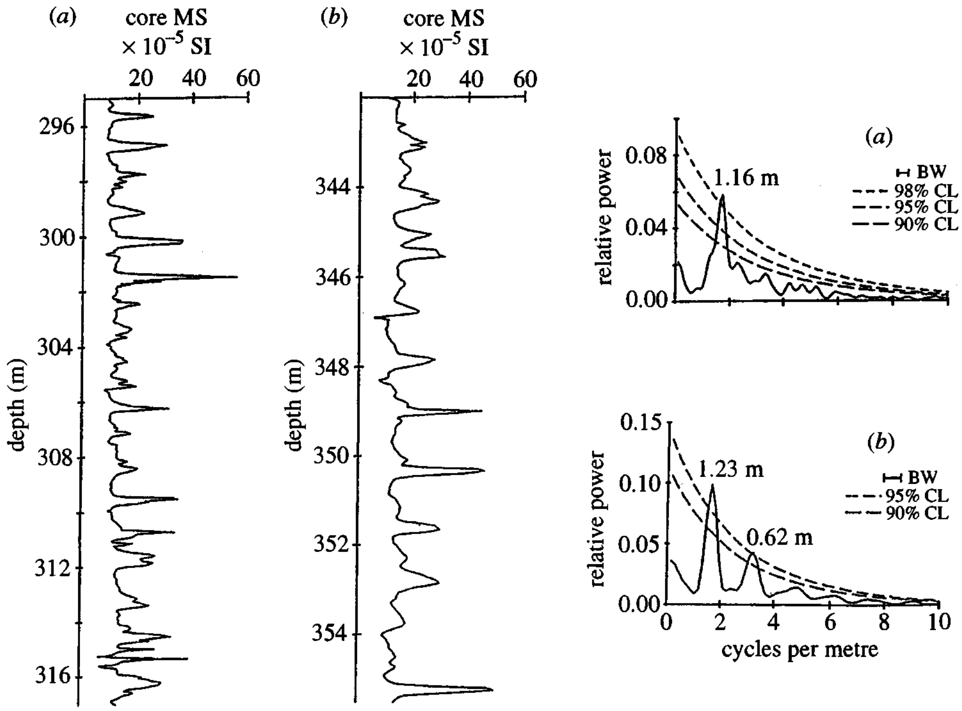

Figure 10. Time-series and corresponding power spectra from small segments of the magnetic-susceptibility data collected from Swanworth Quarry 1 cores.

In order to summarize the spectral results, we have used contoured evolutionary spectra (figure 11). These were based on spectra generated from 10 m data segments, using the multi-taper method and an algorithm from Pardo-Igúzquiza *et al.* (1994). The multi-taper method of spectral estimation has the advantage that the frequency resolution is higher than conventional methods (Thomson 1982, 1990). Successive data segments overlapped by 1.5 m and the resulting stack of spectra was then contoured in terms of relative power. Note that the ends of the contoured plot do not extend to the ends of the whole data-set, because each component spectrum used for contouring is located at the centre of its corresponding data segment.

Between the 190 m and 293 m levels in Swanworth Quarry 1, the evolutionary spectrum reveals power to be concentrated at very low frequencies, commonly at positions corresponding to wavelengths of 10 m or greater (figure 11). Thus, in the upper part of the formation the susceptibility signal is almost entirely dictated by the spacing of the dolomitic horizons (figure 9). Because the metre-scale lithological variations are not adequately reflected by the magnetic-susceptibility measurements in the upper part of the formation, we restrict analysis of the cyclicity to the record below the Yellow Ledge Stone Band in the *elegans*, *autissiodorensis* and upper *eudoxus* zones.

Below the 293 m level (corresponding to the Yellow Ledge Stone Band), there is a continuous ridge of power occurring between about 1 and 0.5 m cycles per metre (figure 11). This indicates the presence of a single cycle with a wavelength that varies from 1 to 2 m. Below the 293 m level, an additional ridge of power occurs intermittently at double the frequency of the main ridge. This corresponds to the second

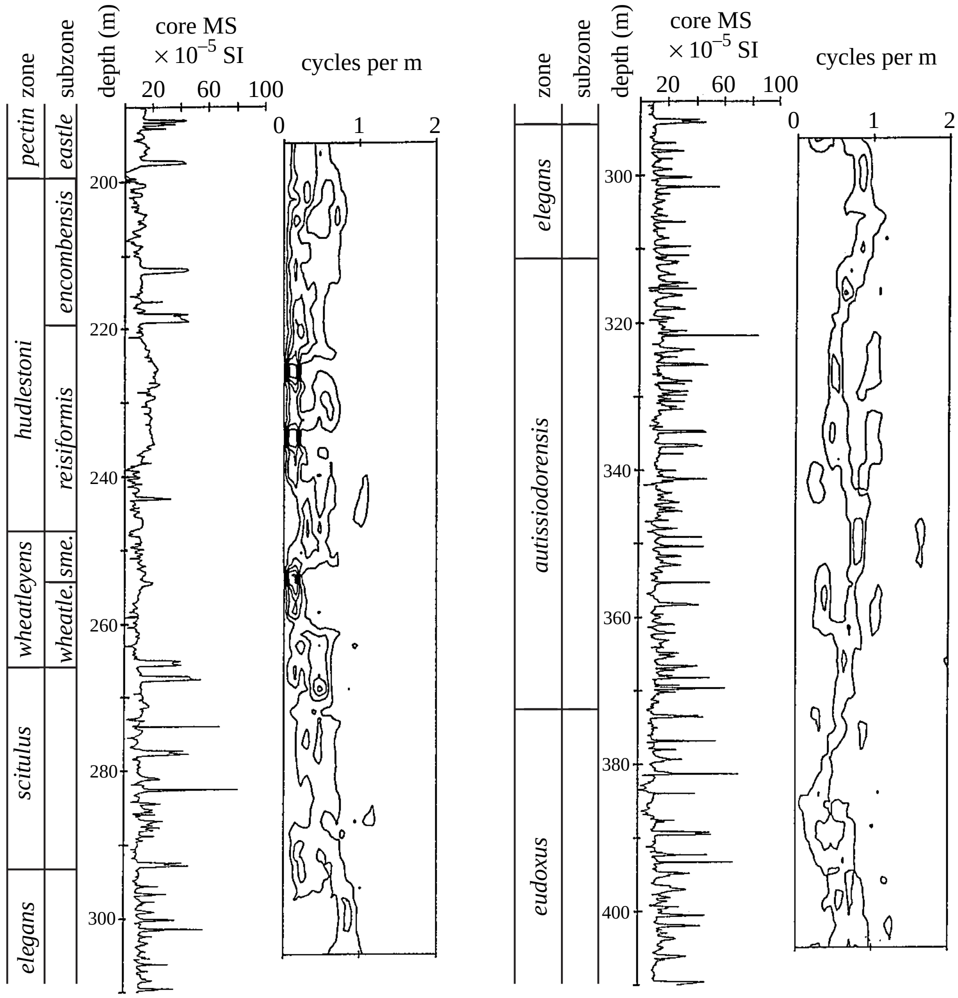

Figure 11. Evolutionary spectrum for the magnetic-susceptibility time-series from Swanworth Quarry 1 core. The contours indicate relative power. Note the pronounced change in the character of the time-series at around the 293 m level (corresponding to the Yellow Ledge Stone Band), which is reflected in the position of the main power concentrations in the evolutionary spectrum.

harmonic and/or the smaller-scale cyclicity. Bandpass filtering using a fairly wide pass-band allows the individual cycles of the dominant and subsidiary cyclicity to be picked out (figure 12). The variations in wavelength are pronounced and presumably result from variations in sedimentation rate.

The period of the cyclicity demonstrated here is difficult to assess directly. The time-series covers just two complete ammonite zones of the Kimmeridgian Stage. According to Gradstein *et al*. (1994), the *autissiodorensis* Zone (*autissiodorensis* and *irius* subzones) and *elegans* Zone (taken to be equivalent to the *gigas* and part of the *gravesiana* subzones) had a combined duration of *ca.* 2.0 Ma. Recent magnetostratigraphic results from France suggest that the *autissiodorensis* Zone may

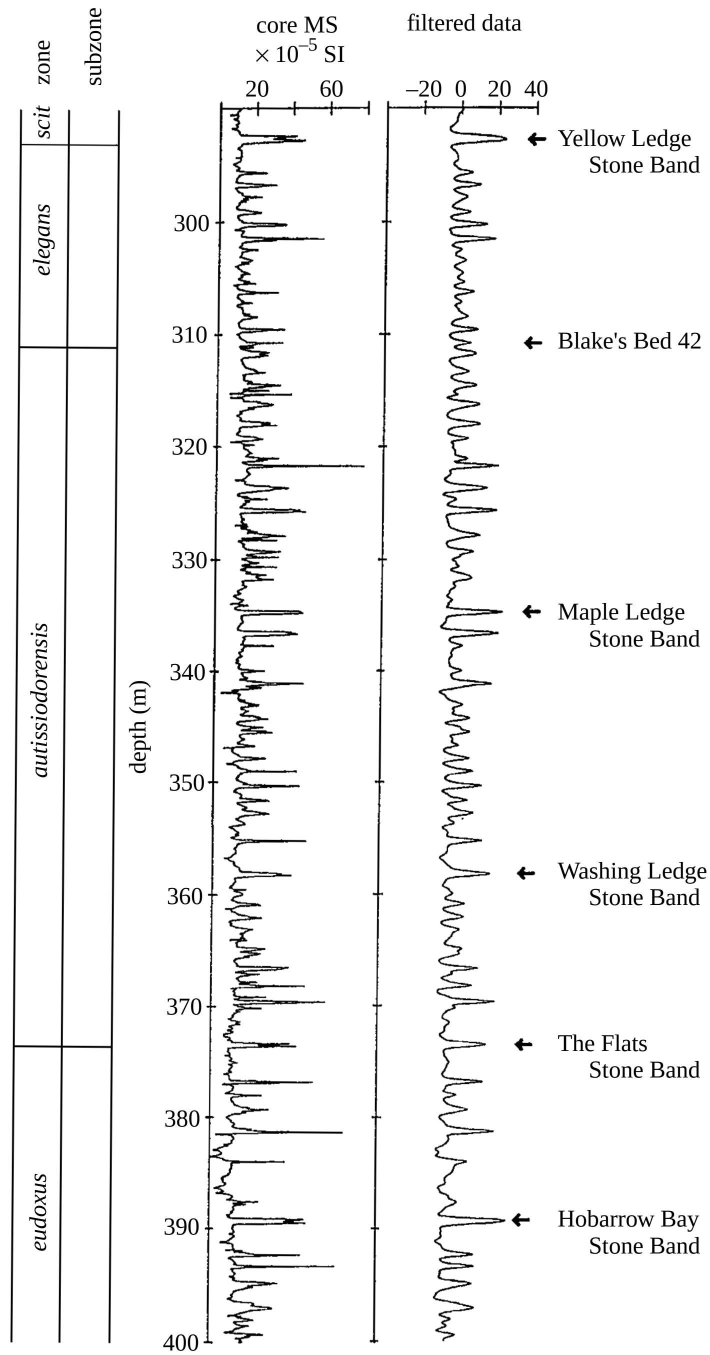

Figure 12. Bandpass filtering of the magnetic-susceptibility data from Swanworth Quarry 1 core, based on the evolutionary spectrum of figure 11. The filtered data reveal the gradual variation in wavelength of the oscillations caused by variations in sedimentation rate.

include most of polarity chron M23 (Ogg, personal communication) and is therefore much longer than indicated by Gradstein *et al*. (1994). For M25 to M19, the Gradstein *et al*. (1994) time-scale is based on matching the sea-floor record of magnetic anomalies to the magnetic polarity zones measured at exposures on land. However, these anomalies have not been tied directly to the ammonite zonal limits used at the type section in Dorset and consequently the implied durations of the zones are subject to uncertainties. Using figure 12, the number of large-amplitude, long-wavelength cycles in the *autissiodorensis* Zone is 35.5, whereas in the *elegans* Zone there are 14. Therefore, taking the total duration of these zones to be according to the published time-scale, the average duration of the large-amplitude cycles appears to be *ca.* 40 ka (2 Ma/49.5) or less. The two regular sedimentary cycles identified earlier have a wavelength ratio of 2.0. Consequently, we believe they record the relatively strong influence of the 38 ka obliquity cycle and a weaker influence of the 20 ka precession cycle. The 38 ka cycle was also invoked by House (1985), Melnyk *et al*. (1994) and Waterhouse (1995) to explain the sedimentary cyclicity.

The individual cycles identified in figure 12 from the filtering were used to develop a time-scale. This involved fixing successive peaks of the dominant cycles at 38 ka intervals (figure 13). The number of cycles present in the *autissiodorensis* Zone implies a minimum duration of 1.35 Ma, and a minimum duration of 0.53 Ma for the *elegans* Zone. An evolutionary spectrum of the data on the new time-scale (figure 13) shows that, as expected, there is a spectral power ridge related to a 38 ka cyclicity and associated second and third harmonic ridges (corresponding to periods of 19 ka and 12.7 ka). We believe the 19 ka power ridge incorporates information from some intervals of distinct small-scale (20 ka) precession-related cyclicity (e.g. at the 1.7–1.3 and 0.6–0.4 Ma levels). However, there is no evidence for additional spectral peaks at low frequencies that might correspond to the eccentricity-cycle periods. This differs from the cases of the Blue Lias and Belemnite Marls where tuning led to recognition of long-wavelength regular cycles.

5. Conclusions

All three units studied contain firm evidence for regular sedimentary cyclicity linked to Milankovitch cycles, but modulated by long-term (million year) variations in sedimentation rates. However, the different units show the varying influence of orbital–climatic cycles. Thus the Blue Lias exhibits 20 ka precession, dominant 38 ka obliquity and 95 ka eccentricity cycles, the Belemnite Marls shows dominant 20 ka precession and 123 ka eccentricity cycles and the Kimmeridge Clay Formation dominant 38 ka obliquity and, intermittently, 20 ka precession cycles. There is therefore a shift from dominant obliquity cycles in the Rhaetian–Sinemurian to dominant precession cycles in the Pliensbachian. Hinnov & Park (this issue) documented a transition from dominant precession to obliquity cycles in the Toarcian of the Tethyan region. Obliquity cycles dominated during the Kimmeridgian. This changing response to the orbital cycles is reminiscent of the late Cenozoic (e.g. Ruddiman *et al*. 1989). It remains to be determined whether the changes in the relative influence of the orbital cycles is related to local or global palaeoclimatic and/or palaeoceanographic factors.

In this study, magnetic susceptibility has been demonstrated to be useful for the generation of high-resolution time-series in ancient organic-rich mudrocks. However, it is clear that, even within the same lithological unit such as the Kimmeridge Clay

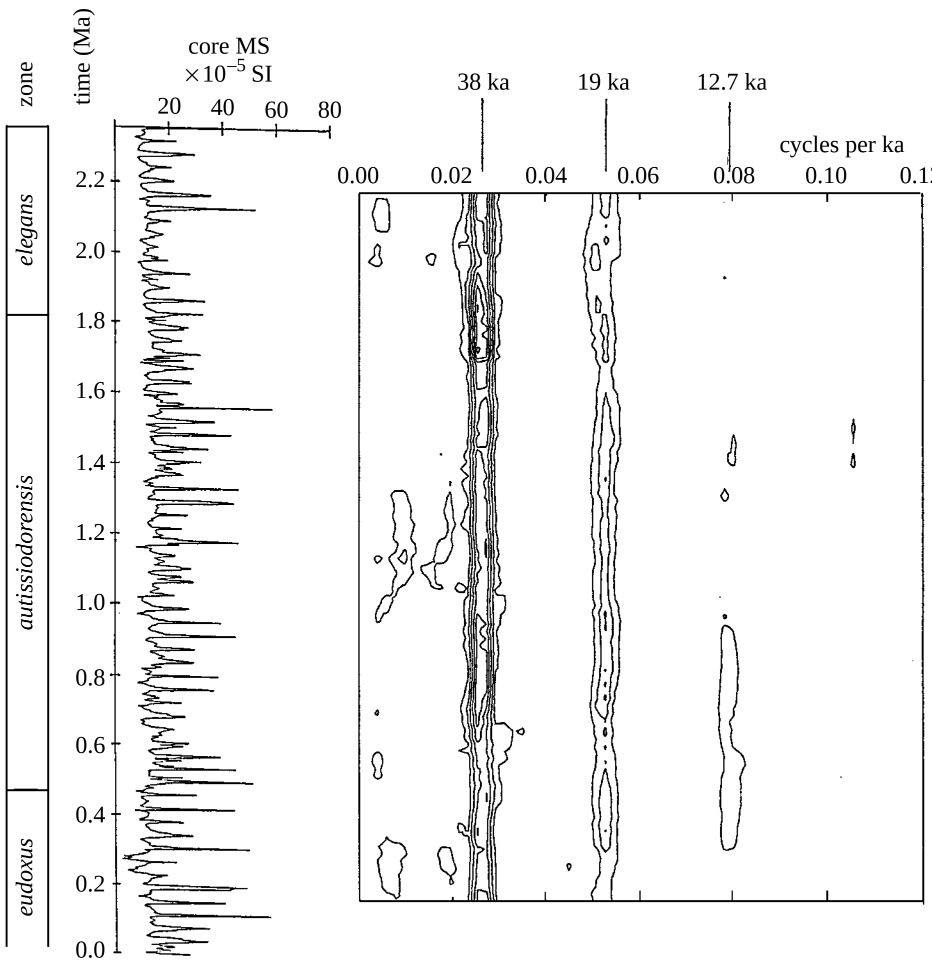

Figure 13. Data plotted assuming each large-amplitude cycle corresponds to 38 ka plus the corresponding evolutionary spectrum. Note that the new time-series was interpolated at constant 2 ka interval prior to spectral analysis, causing minor smoothing of the series. The evolutionary spectrum reveals the expected power ridge related to the 38 ka cyclicity plus a ridge at half the period (twice the frequency) that relates to small-scale cyclicity and a harmonic of the 38 ka cycles.

Formation, the character and exact mineralogical origin of the magnetic-susceptibility signal can change. This change reflects palaeoenvironmental and diagenetic factors. Further work on the upper part of the Kimmeridge Clay Formation and Oxford Clay Formation may well provide useful additional information on Milankovitch cyclicity. The use of strontium-isotope data combined with cyclostratigraphic data from the Belemnite Marls allowed estimation of the duration of the first three stages in the Jurassic (Weedon & Jenkyns 1999). Nevertheless, complete calibration of the Jurassic will require additional radiometric dates and improvements in absolute dating (Pálfy 1995; Pálfy *et al*. 1996; Cohen *et al*. 1999), cyclostratigraphic analysis of different (non-mudrock) facies and the use of improved biostratigraphic data.

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