Thesis presented to the University of Oxford
for the Degree of Doctor of Philosophy.

PALAEOCLIMATIC SIGNIFICANCE OF OPEN-MARINE CYCLIC SEQUENCES.

VOLUME 2

GRAHAM PETER WEEDON  B.Sc., A.R.S.M.

Linacre College
and Department of Earth Sciences,
## CONTENTS OF VOLUME 2 - FIGURES

### Chapter 1

1.1A Location of the lithostratigraphic units listed in Table 1A.  
1.2A The nature of cyclic changes in orbital obliquity.  
1.2B The nature of cyclic changes in orbital eccentricity.  
1.2C The nature of cyclic changes in orbital precession.  

### Chapter 2

2.1A Map of basal Lias localities.  
2.1B Field photo of limestone nodule in Lang's bed 36, Lyme Regis.  
2.1C Field photo of limestone nodules in light marl bed passing laterally into a continuous limestone bed.  
2.1D Field photo illustrating the different rock types.  
2.1E Field photo illustrating the different rock types.  
2.1F Field photo of *Chondrites* burrow-mottles in a light marl and limestone bed.  
2.1G Field photo of *Diplocraterion* burrow-mottle in a limestone underneath a dark marl bed.  
2.1H Field photo of burrow-mottling in a dark marl and limestone bed.  
2.1I Field aspect of the basal Lias at Lyme Regis, Dorset.  
2.1J Field aspect of the basal Lias at Watchet, Somerset.  
2.1K Field photo of Palmer's beds C56-C82 near Blue Ben, Watchet.  
2.1L Field photo of Trueman's beds 9-33, Pre-planorbis beds - planorbis zone, Lavernock Point, Glamorgan.  
2.1M Field aspect of the basal Lias at Nash Point, Glamorgan.  
2.1N Field photo of Trueman's beds 1-7, conybeari subzone, bucklandi zone, Nash Point.  
2.1O Field photo of Clement's *et al.*'s beds 17k-23g, angulata zone, Long Itchington, Warwickshire.  
2.2A The Sutton Stone overlying the Carboniferous Limestone at Southerndown, Glamorgan.  
2.2B Close-up of the Southerndown beds at Southerndown, Glamorgan.  
2.2C The Brockley Down Stone overlying the Carboniferous Limestone at Lulsgate, Avon.  
2.2D Loose blocks of Brockley Down Stone at Lulsgate Quarry.  
2.2E Thin section photomicrograph of limestone.  
2.2F Thin section photomicrograph of limestone.  
2.2G Thin section photomicrograph of limestone.  
2.2H Thin section photomicrograph of limestone.  
2.2I Thin section photomicrograph of *Gryphaea*.  
2.2J Thin section photomicrograph of *Gryphaea*.  
2.2K Thin section photomicrograph of light marl.  
2.2L Thin section photomicrograph of light marl.  
2.2M Thin section photomicrograph of dark marl.  
2.2N Thin section photomicrograph of dark marl.
2.2O Thin section photomicrograph of laminated shale. 21
2.2P Thin section photomicrograph of laminated shale. 21
2.2Q Thin section photomicrograph of beef calcite. 22
2.2R Thin section photomicrograph of beef calcite. 22
2.2S Thin section photomicrograph of laminated limestone. 23
2.2T Thin section photomicrograph of laminated limestone. 23
2.3A XRD trace for laminated shale whole-rock powder. 24
2.4A SEM photomicrograph of limestone. 25
2.4B SEM photomicrograph of light marl. 25
2.4C SEM photomicrograph of light marl. 26
2.4D SEM photomicrograph of dark marl. 26
2.4E SEM photomicrograph of dark marl. 27
2.4F SEM photomicrograph of dark marl. 27
2.4G SEM photomicrograph of dark marl. 28
2.4H SEM photomicrograph of laminated shale. 28
2.4I SEM photomicrograph of laminated shale. 29
2.4J SEM photomicrograph of laminated limestone. 29
2.5A Relative thickness changes in the basal Lias studied. 30
2.5B Field photo of limestone surface dominated by Gryphaea. 31
2.5C Field photo of limestone containing limestone intraclasts. 31
2.5D Field photo of isolated dark marl burrow-mottles. 32
2.5E Photo of cut and polished block of limestone showing encrusted and bored surface. 33
2.5F Photo of cut and polished block of limestone showing encrusted and bored surface. 33
2.5G Negative prints of acetate peels from the encrusted and bored limestone surface. 34
2.5H Negative prints of acetate peels from the encrusted and bored limestone surface. 34
2.8A Stratigraphic variations in the average proportions of different rock types. 35
2.8B Stratigraphic variations in the average proportions of different rock types. 36
2.8C Correlation of %light marl/limestone with number of limestone beds and nodule horizons. 37
2.8D Correlation in the basal Lias. 38
2.8E Possible lithostratigraphic correlation for the lower part of the basal Lias. 39
2.8F Possible lithostratigraphic correlation for the upper part of the basal Lias. 40

Chapter 3

3.2A Lower Lias whole rock composition according to rock type. 41
3.2B TOC/\text{CaCO}_3 relationship at Watchet and Lyme Regis. 42
3.2C Clay/FeS\text{$_2$}CaCO\text{$_3$} relationship at Watchet and Lyme Regis. 43
3.3A Variations in whole rock composition at Watchet. 44
3.4A Detailed geochemical profiles through Lang's beds 13-20 45
Upper angulata zone, Seven Rock Point, Lyme Regis.
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4B</td>
<td>Field photo of Lang's beds 13-20, <em>angulata</em> zone, Seven Rock Point, Lyme Regis.</td>
<td>46</td>
</tr>
<tr>
<td>3.4C</td>
<td>Interpretation of S/DOP/Fe/TOC plots</td>
<td>47</td>
</tr>
<tr>
<td>3.4D</td>
<td>S/DOP/Fe/TOC relationships Upper <em>angulata</em> zone, Lyme Regis.</td>
<td>48</td>
</tr>
<tr>
<td>3.4E</td>
<td>Fe/S and S/TOC relationships at Watchet and Lyme Regis.</td>
<td>49</td>
</tr>
<tr>
<td>3.4F</td>
<td>Stable isotopes of carbonate from the <em>angulata-bucklandi</em> zone, Lyme Regis.</td>
<td>50</td>
</tr>
<tr>
<td>3.4G</td>
<td>Previously published stable isotopes from the Pre-<em>planorbis</em> beds-<em>semicostatum</em> zone, Lyme Regis.</td>
<td>51</td>
</tr>
<tr>
<td>3.4H</td>
<td>Stable isotopes in <em>Cryphaea arcuata</em> specimen BLG33.</td>
<td>52</td>
</tr>
<tr>
<td>3.4I</td>
<td>Stable isotopes in a limestone nodule from Lang's bed 37 <em>bucklandi</em> zone, Seven Rock Point, Lyme Regis.</td>
<td>53</td>
</tr>
</tbody>
</table>

**Chapter 4**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2A</td>
<td>Walsh power spectral estimates.</td>
<td>54</td>
</tr>
<tr>
<td>4.2B</td>
<td>The effect of hiatuses upon a perfectly regular time series.</td>
<td>55</td>
</tr>
<tr>
<td>4.2C</td>
<td>Time series: 16cm cycle plus 'random' gaps, for Fig 4.2B.</td>
<td>56</td>
</tr>
<tr>
<td>4.2D</td>
<td>Time series generated with random numbers.</td>
<td>57</td>
</tr>
<tr>
<td>4.2E</td>
<td>Spectrum of random time series.</td>
<td>58</td>
</tr>
<tr>
<td>4.2F</td>
<td>Time series generation.</td>
<td>59</td>
</tr>
<tr>
<td>4.2G</td>
<td>Choosing sample intervals.</td>
<td>60</td>
</tr>
<tr>
<td>4.2H</td>
<td>Testing the significance of spectral peaks.</td>
<td>61</td>
</tr>
<tr>
<td>4.2I</td>
<td>Harmonics.</td>
<td>62</td>
</tr>
<tr>
<td>4.3A</td>
<td>Basal Lias, Lyme Regis time series.</td>
<td>63</td>
</tr>
<tr>
<td>4.3B</td>
<td>Basal Lias, Lyme Regis power spectra.</td>
<td>64</td>
</tr>
<tr>
<td>4.3C</td>
<td>Basal Lias, Watchet time series.</td>
<td>65</td>
</tr>
<tr>
<td>4.3D</td>
<td>Basal Lias, Watchet time series.</td>
<td>66</td>
</tr>
<tr>
<td>4.3E</td>
<td>Basal Lias, Watchet time series.</td>
<td>67</td>
</tr>
<tr>
<td>4.3F</td>
<td>Basal Lias, Watchet power spectra.</td>
<td>68</td>
</tr>
<tr>
<td>4.3G</td>
<td>Basal Lias, Lavernock Point time series.</td>
<td>69</td>
</tr>
<tr>
<td>4.3H</td>
<td>Basal Lias, Lavernock Point power spectra.</td>
<td>70</td>
</tr>
<tr>
<td>4.3I</td>
<td>Basal Lias, Nash Point time series.</td>
<td>71</td>
</tr>
<tr>
<td>4.3J</td>
<td>Basal Lias, Nash Point power spectra.</td>
<td>72</td>
</tr>
<tr>
<td>4.3K</td>
<td>Basal Lias, Long Itchington time series.</td>
<td>73</td>
</tr>
<tr>
<td>4.3L</td>
<td>Basal Lias, Long Itchington power spectra.</td>
<td>74</td>
</tr>
</tbody>
</table>

**Chapter 5**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1A</td>
<td>Relationship between number of cemented horizons and zone thickness.</td>
<td>75</td>
</tr>
<tr>
<td>5.3A</td>
<td>Sea-level changes in the Early Jurassic in Britain.</td>
<td>76</td>
</tr>
<tr>
<td>5.4A</td>
<td>Productivity model.</td>
<td>77</td>
</tr>
<tr>
<td>5.4B</td>
<td>Stagnation model.</td>
<td>78</td>
</tr>
<tr>
<td>5.5A</td>
<td>General environmental model for the latest Triassic and earliest Jurassic in South Britain.</td>
<td>79</td>
</tr>
<tr>
<td>5.5B</td>
<td>Palaeogeography in the Hettangian and Early Sinemurian.</td>
<td>80</td>
</tr>
</tbody>
</table>
Chapter 6

6.2A Field aspect of the Boom Clay Formation, Terhagen, near Antwerp. 81
6.2B Boom Clay Formation time series. 82
6.2C Boom Clay Formation power spectra - using five codes. 83
6.2D Boom Clay Formation power spectra - using two codes. 84
6.3A Field aspect of the Upper Kimmeridge Clay Formation, near Freshwater Steps, Kimmeridge, Dorset. 85
6.3B Kimmeridge Clay Formation time series. 86
6.3C Kimmeridge Clay Formation upper section power spectra. 87
6.3D Kimmeridge Clay Formation lower section power spectra. 88
6.4A Measured sections within the stratigraphy of Breggia Gorge, Ticino, Switzerland. 89
6.4B Field aspect of the Toarcian section, Breggia Gorge. 90
6.4C Breggia Gorge Toarcian section time series. 91
6.4D Breggia Gorge Toarcian section power spectra. 92
6.4E Field aspect of the Upper Pliensbachian section Breggia Gorge. 93
6.4F Breggia Gorge Upper Pliensbachian section time series. 94
6.4G Breggia Gorge Upper Pliensbachian section power spectra. 95
6.4H Field aspect of the Middle Pliensbachian section Breggia Gorge. 96
6.4I Breggia Gorge Middle Pliensbachian section time series. 97
6.4J Breggia Gorge Middle Pliensbachian section power spectra. 98
6.5A Field aspect of the Belemnite Marls, Charmouth, Dorset. 99
6.5B Belemnite Marls time series. 100
6.5C Belemnite Marls power spectra. 101
6.6A Field aspect of the 'Siliceous Shales', Robin Hood's Bay, Yorkshire. 102
6.6B 'Siliceous Shales' time series. 103
6.6C 'Siliceous Shales' power spectra. 104
6.7A Field aspect of the Upper Birkhill Shales, Dob's Linn, Dumfries and Galloway. 105
6.7B Upper Birkhill Shales time series. 106
6.7C Upper Birkhill Shales power spectra. 107
CONTENTS OF VOLUME 2 - APPENDICES

For Chapter 2 - Stratigraphic logs for the basal Lias sections

Key to stratigraphic logs.
2.1 Stratigraphic log for the basal Lias at Lyme Regis. 108
2.2 Stratigraphic log for the basal Lias at Watchet. 115
2.3 Stratigraphic log for the basal Lias at Lavernock Point. 138
2.4 Stratigraphic log for the basal Lias at Nash Point. 145
2.5 Stratigraphic log for the basal Lias at Long Itchington. 149

For Chapter 3 - Geochemical methodology

3.1 Bulk sample preparation. 156
3.2 Gryphaea specimen preparation. 156
3.3 Determination of %CaCO₃, %TOC, and % FeS₂. 157
3.4 Determination of %Fe/R and DOP/R. 158
3.5 Determination of δ¹⁸O and δ¹³C. 160
3.6 Reproducibility. 161

For Chapter 4 - Computer Program for illustrating time series and generating Walsh power spectra

4.1 Listing of Program WPSPEC. 163

For Chapter 5 - Publications

5.1 Weedon 1985. 168
5.2 Weedon 1986. 169
5.3 Weedon 1987. 184

For Chapter 6 - Time series for various formations

6.1 Time series for the Boom Clay Formation. 186
6.2 Time series for the Upper Kimmeridge Clay Formation. 188
6.3 Time series for the Toarcian section at Breggia Gorge. 190
6.4 Time series for the Upper Pliensbachian section at Breggia Gorge. 193
6.5 Time series for the Middle Pliensbachian section at Breggia Gorge. 195
6.6 Time series for the Belemnite Marls. 196
6.7 Time series for the 'Siliceous Shales'. 197
6.8 Time series for the Upper Birkhill Shales. 198
A DOB'S LINN
B ROBIN HOOD'S BAY
C LONG ITCHINGTON
D LAVERNOCK POINT
E NASH POINT
F WATCHET
G LYME REGIS
H CHARMOUTH
I KIMMERIDGE BAY - CHAPMAN'S POOL
J ANTWERP AND FOUR PITS WITHIN 19km
K BREGGIA GORGE

FIG 1.1A LOCATION OF THE LITHOSTRATIGRAPHIC UNITS LISTED IN TABLE 1A
Fig 1.2A The Nature of Cyclic Changes in Orbital Obliquity (Tilt).

**OBLIQUITY:** Dominant Period = 41kyr, Minor Periods = 29kyr & 54kyr, Period on Power spectra = 41kyr.

**Oblique View of Orbit:**

a) Obliquity = Minimum

![Diagram showing obliquity at minimum]

b) Obliquity = Maximum

![Diagram showing obliquity at maximum]

**Radiation Levels - for 45°N with circular orbit:**

a) Less Seasonal

![Graph showing less seasonal radiation]

b) More Seasonal

![Graph showing more seasonal radiation]

**Climatic Effect:** Changes degree of seasonality. Nb. if Obliquity = 0° then there would be no seasons.

*(Diagrams are schematic. Based on data from Berger 1980 & 1984.)*
Fig 1.2B The Nature of Cyclic Changes in Orbital Eccentricity.

ECCENTRICITY: Dominant Periods = 95kyr, 100kyr, 120kyr & 410kyr. Periods on Power Spectra = 100kyr & 410kyr.

Plan View of Orbit:

a) Eccentricity = Minimum
\( (\epsilon = 0.0005) \)

b) Eccentricity = Maximum
\( (\epsilon = 0.0607) \)

Radiation Levels - for 45°N with no precession and constant obliquity

Climatic Effect:
Very small change in total insolation from year to year. Mainly controls the impact of precession upon climate (Fig 1.2C). Nb. if eccentricity = 0.0 (ie a circular orbit), then precession absent. Greater eccentricity leads to more important precession impact. Cause of asymmetry in the duration of summer compared to winter.

(Diagrams are schematic. Based on data from Berger 1980 & 1984.)
Fig 1.2C The Nature of Cyclic Changes in Orbital Precession.

PRECESSION: Dominant Periods = 19kyr & 23kyr,
Periods on Power Spectra = 19kyr & 23kyr or 21kyr only.

Oblique View of Orbit:
Nb. Summer occurs when the relevant hemisphere faces towards the Sun.

Radiation Levels - for 45°N, constant obliquity, $\epsilon$ = large

Radiation Levels - for 45°N, constant obliquity, $\epsilon$ = small

Climatic Effect:
Given season becomes alternately short & intense and long & weak. Size of impact controlled by eccentricity (Fig 1.2B). See Berger 1980 for a more precise description of precession.

(Diagrams are schematic. Based on data from Berger 1980 & 1984.)
Fig 2.1B

Limestone nodule in Lang's bed 36 at Lyme Regis. The nodule passes laterally into light marl. Nearby beds of laminated shale (brown), dark marl (dark blue/grey) and light marl (light blue grey) are compacted round the nodule. bucklandi zone, Lyme Regis. The hammer is 39cm long.

Fig 2.1C

Limestone nodules in a light marl passing laterally into a light marl bed. The nodules and continuous limestone bed can be seen just below Dr. H.C. Jenkyns waist and occur in Lang's bed 37, bucklandi zone, Lyme Regis.
Fig 2.1D

Illustration of different rock types. Laminated shale overlies light marl and dark marl. The light marl bed contains a limestone nodule. The light bed represents Lang's bed 15c, angulata zone, Lyme Regis. The lens cap is 5cm in diameter.

Fig 2.1E

Illustration of different rock types. A limestone bed overlies dark marl burrow mottles. Under this a light marl bed contains a limestone and at the base in a laminated shale bed with a burrowed top. Lang's beds 18 and 19, angulata zone, Lyme Regis. The lens cap is 5cm in diameter.
Fig 2.1F

Chondrites burrow-mottles in a light marl and limestone bed. The mottles pass down from a dark marl bed. Lang's beds 17 and 18, angulata zone, Lyme Regis. Notice that the light marl/dark marl contact is despite burrow-mottling. Lens cap is 5cm in diameter.

Fig 2.1G

Diplocraterion burrow-mottle in a limestone underneath a dark marl bed. The spreite are only poorly developed suggesting that most Arenicolites mottles observed were produced by the same organism which produced Diplocraterion. Lang's bed 19, angulata zone, Lyme Regis.
**Fig 2.1H**

Burrow-mottles in a dark marl and limestone bed. Notice that *Chondrites* burrow occur within an *Arenicolites* or *Thalassinoides* burrow-mottle. Lang's bed 19, *angulata* zone, Lyme Regis.

**Fig 2.1I**

Field aspect of the basal Lias at Lyme Regis, West Cliff, Dorset. The section illustrated represents Lang's beds 1-49 - about 13m thick.
Fig 2.1J

Field aspect of the basal Lias at St. Audrie's Cliff, Watchet, Somerset. The average proportion of limestones was used by Palmer (1972) to divide the basal Lias into divisions A-F. Illustrated here are division A, B and the lowermost part of C. The photograph illustrates Palmer's beds A17-C11 representing about 32m (Pre-planorbis beds - lowest angulata zone). Cope et al. 1980 suggested that Watchet above the second limestone bed in the section illustrated. The base of the Jurassic be defined at

---

Fig 2.1K

Palmer's beds C56-C82 below Blue Ben, angulata zone Watchet. Small normal fault displaces the beds at the right of the photograph. The hammer is 39cm long.
Fig 2.1L

Trueman's beds 9-33, Pre-planorbis beds - planorbis zone, Lavernock Point, Glamorgan. Many laminated limestone beds are enclosed by laminated shale (Appendix Section 2.3). The section represents 10m of the basal Lias.
Fig 2.1M

Field aspect of the basal Lias at Nash Point, Glamorgan. The section represents about 27m. Notice the exceptionally high proportion of limestone and the very nodular contacts.

Fig 2.1N

Trueman's beds 1-7, bucklandi zone, Nash Point. The hammer is 39cm long.
Clement's et al.'s (1975) beds 17k-23g, *angulata* zone, Long Itchington, Warwickshire. The section represents about 5m.
Fig 2.2A

The Sutton stone overlying the Carboniferous Limestone at Southerndown, Glamorgan. The hammer is 39cm long.

Fig 2.2B

Close-up of the Southerndown beds at Southerndown, Glamorgan. The lens cap (diameter 5cm) is leaning against a bed containing a relatively high proportion of clay and lithoclasts. Stylolites can be seen at the top of the section.
The Brockley Down Stone overlying the Carboniferous Limestone at Lulsgate, Avon. The Brockley Down Stone is about 14m thick in Lulsgate Quarry.

Loose blocks of Brockley Down Stone, Lulsgate Quarry, containing Carboniferous Limestone lithoclasts.
Fig 2.2E

Thin section photomicrograph of limestone. Plane polarized light. The section is partly stained. The matrix consists of microspar and clay and contains a small benthonic foraminifera filled by glauconite, lower right. The large bioclase on the left represents the wall of an ammonite chamber composed of neomorphic spar. Sample BL103, bucklandi zone, Lyme Regis. The width of the photo represents 3mm.

Fig 2.2F

Thin section photomicrograph of limestone. Crossed polars. The whole section is stained. Neomorphic spar forms the uncrushed walls of an ammonite chamber. The centre of one chamber is filled by cavity filling spar - the blue tinged part is ferroan calcite, the rest is non-ferroan calcite. The matrix of microspar and clay appears to be pelleted. Sample BL105, fallen block, Lyme Regis. The field of view is 3mm across.
Fig 2.2G

Thin section photomicrograph of limestone. Crossed polars. Part of an ammonite set in a clay and microspar matrix. The black dots are pyrite framboids. Sample BL103, bucklandi zone, Lyme Regis. Field of view 3mm across.

Fig 2.2H

Thin section photomicrograph of limestone. Cathodoluminescence. Zoning in the neomorphic spar appears to indicate two phases of growth. The bivalve fragment lower right is unaltered and therefore not luminescent although it is overgrown by luminescent cement. The matrix microspar is uniformly luminescent. Quartz silt grains luminesce blue. Same area as Fig 2.2G.
Fig 2.21

Thin section photomicrograph of Gryphaea. Crossed polars. The original foliated texture appears to have been preserved. Sample BLG28, angulata zone, Lyme Regis. Field of view 8.5mm across.

Fig 2.2J

Thin section photomicrograph of Gryphaea. Cathodoluminescence. The bulk of the shell is unaltered and not luminescent. (Nb. photo overexposed). Cleavage and twin planes appear to be filled with luminescent cement. Same area as Fig 2.21.
Fig 2.2K

Thin section photomicrograph of light marl. Plane polarized light. A large ostracod can be seen lower right. The matrix consists of intimately mixed microspar and clay with black patches representing pyrite. Sample BW44, angulata zone, Watchet. The width of the photo represents 1.5mm.

Fig 2.2L

Thin section photomicrograph of light marl. Cathodoluminescence. The microspar matrix is more or less uniformly luminescent with a few silt grade quartz grains (blue). Same area as Fig 2.2K.
Fig 2.2M

Thin section photomicrograph of dark marl. Plane polarized light. The matrix consists of clay and organic laminae with dispersed microspar 'blebs'. A bleb-rich horizon can be seen at the top of the photograph. A burrow is filled by light marl, lower left. Sample BL120, bucklandi zone, Lyme Regis. The width of the photo represents 3mm.

Fig 2.2N

Thin section photomicrograph of dark marl. Cathodoluminescence. The clay and organic matrix contains many small ostracods and some quartz silt grains. The microspar in the blebs luminesces yellow/orange whereas a few isolated microspar crystals (? microdolomite) are zoned and luminesce red/orange. A burrow-mottle, top right, is filled with light marl containing more ostracods. Sample BL120, bucklandi zone, Lyme Regis. Field of view 1.5mm across.
Fig 2.20

Thin section photomicrograph of laminated shale. Plane polarized light. The white material is calcite microspar often forming 'blebs'. Clay laminae are brown and organic laminae are black. Sample BL117, bucklandi zone, Lyme Regis. Field of view 4.5mm across.

Fig 2.2P

Thin section photomicrograph of laminated shale. Cathodoluminescence. Small ostracods are normally masked by clay and organic matter, but they can be picked out under cathodoluminescence. Notice the lamina of concentrated ostracods in the middle. Most carbonate appears to be ostracodal. A few isolated microspar crystals, eg. middle top and middle bottom, are zoned and euhedral - they may represent microdolomite. Silt grade quartz grains (blue) are scattered throughout. Sample BL117, bucklandi zone, Lyme Regis. Field of view 1mm across.
Fig 2.2Q

Thin section photomicrograph of beef calcite. Crossed polars. Laminated shale inclusions can be seen at the top. Crystal size increases away from the inclusion perhaps indicating growth from the inclusion upwards and downwards. Sample BL115, bucklandi zone, Lyme Regis. Field of view 1mm across.

Fig 2.2R

Thin section photomicrograph of beef calcite. Cathodoluminescence. Some zoning indicates some change in water chemistry or two or more stages of growth. Staining, however, shows that the ferroan-non-ferroan calcite contacts are bedding parallel and cut across the crystal boundaries. Same area as Fig 2.2Q.
Fig 2.2S

Thin section photomicrograph of laminated limestone. Plane polarized light. Lighter and darker horizons might represent cemented bleb-rich and bleb-poor horizons (Fig 2.2M). Black areas represent pyrite. Matrix mainly consists of microspar with disseminated clay. Spherical structures might be large (60μm diameter) Schizosphaerella Sample LA39, bed 33, planorbis zone, Lavernock Point. Field of view 1mm across.

Fig 2.2T

Thin section photomicrograph of laminated limestone. Cathodoluminescence. The non-luminescent pyrite appears to be concentrated in the lighter (? originally bleb-rich) horizons. Scattered quartz grains luminesce blue. Same areas as Fig 2.2S.
Fig. 23: XRD TRACE FOR LAMINATED SHALE WHOLE-ROCK POWDER, SAMPLE BL318.
Fig 2.4A

SEM photomicrograph of limestone. A matrix of fused calcite microspar contains an elongate ring which appears to be a corroded coccolith considering its size and shape. Sample BL103, Lang's bed 29, bucklandi zone, Lyme Regis. Field of view 19\(\mu\)m across.

Fig 2.4B

SEM photomicrograph of light marl. Clay and microspar surround what appears to be a partially overgrown coccolith. Sample BW71 Palmer's bed C85, angulata zone, Watchet. Field of view 25\(\mu\)m across.
The spheres are *Schizosphaerella punctulata* - probably representing the calcified walls of a dinoflagellate (Kälin and Bernoulli 1984). The walls of this fossil were originally very porous (Fig 2.4H), but these examples are partially cemented. Sample BW71, Palmer's bed C85, *angulata* zone, Watchet. Field of view 78μm across.

A single valve of *Schizosphaerella*. The walls have been internally cemented producing a smooth outer surface. Sample LI28, Clements et al.'s bed 20d, *angulata* zone, Long Itchington. Field of view 38μm across.
Fig 2.4E

SEM photomicrograph of dark marl. A coccolith aggregate can be seen surrounded by clay and organic matter. Sample BL120, Lang's bed 32, bucklandi zone, Lyme Regis. Field of view 124μm across.

Fig 2.4F

SEM photomicrograph of dark marl. Close-up of the top part of the coccolith aggregate in Fig 2.4E. Notice that a variety of sizes and species of coccoliths are present (see Hamilton 1980 for identifications). Most of the aggregates appear to be free of clay, but microspar crystals appear to be engulfing some coccoliths (eg. middle centre, middle top and lower left). Sample BL120 as Fig 2.4E. Field of view 64μm across.
Fig 2.4G  
SEM photomicrograph of dark marl. Part of a coccolith aggregate showing microspar overgrowths on coccoliths. Sample BL120, Lang's bed 32a, bucklandi zone, Lyme Regis. Field of view 45μm across.

Fig 2.4H  
SEM photomicrograph of laminated shale. A matrix of clay and organic matter contains a small coccolith aggregate (top left), Schizosphaerella puntulata (middle centre and middle right), and a euhedral microspar crystal. The calcite laths which make up the wall of Schizosphaerella can be seen in the left hand specimen, but they are larger and more fused than examples figured by Källin and Bernoulli (1984). Lower right is an area of fibrous clay - probably authigenic illite. Sample BL117, Lang's bed 32, bucklandi zone, Lyme Regis. Field of view 75μm across.
Fig 2.4I

SEM photomicrograph of laminated shale. Three specimens of *Schizosphaerella punctulata* can be seen. The left hand specimen is surrounded by lightly fused microspar crystals, whereas the right hand specimens are embedded in fused microspar. Notice that the specimens are not surrounded by fringes of radial calcite spar (cf. Kalin & Bernoulli 1984). Specimen BW83, Palmer's bed C94, angulata zone, Watchet. Field of view 75μm across.

Fig 2.4J

SEM photomicrograph of laminated limestone. A microspar matrix encloses a *Schizosphaerella* specimen with a slightly pitted surface the walls appear to have been almost totally cemented (compare with Fig 2.4H). Sample BW86, Palmer's bed C94, angulata zone, Watchet. Field of view 75μm across.
Fig 25A RELATIVE THICKNESS CHANGES IN THE BASAL LIAS STUDIED
Fig 2.5B

Limestone surface dominated by *Gryphaea*. Other types of body fossils are rare, limestone dominated by one body fossil were ascribed to biological processes rather than winnowing. The specimens associated are unbroken and of much lower density than would be expected for a winnowed horizon. On the other hand the density of bioclasts is higher than in most limestones and the combination of low diversity 'high' density biota implies a restricted environment (there is some evidence for less than normal oxygenation for light marl (limestone) deposition (Section 5.2.2)). Palmer's bed C93, angulata zone, Watchet. The hammer is 39cm long.

Fig 2.5C

Limestone containing intraclasts. The intraclasts represent limestone and laminated shale and some contain worn bioclasts. The matrix limestone is dominated by dispersed crinoid fragments. Loose block, Lyme Regis. The lens cap is 5 cm in diameter.
Fig 2.5D

Isolated dark marl burrow-mottles. In this limestone bed a continuous dark marl bed can usually be seen overlying the dark marl burrow-mottles (eg. Fig 2.1G and 2.1H). However, here the dark marl bed appears to have been removed by erosion, leaving the mottles, but not the sediment which filtered down into the originally open burrows. Lang's bed 19, \textit{angulata} zone, Lyme Regis.
Fig 2.5E

Cut and polished block of limestone showing encrusted and bored surface. At the base of the block are intraclasts of laminated shale. A dome shaped surface (left) is overlain by bioclastic packstone grading up into burrow-mottled carbonate mudstone. Lang's bed 25, conybeari subzone, bucklandi zone, Lyme Regis. Width of photo represents 25cm.

Fig 2.5F

Close-up of Fig 2.5E. The dome shaped surface is encrusted by Liostrea. At the centre bottom two sharp contacts between limestone of different colours appear to intersect. This suggests that the dome consists of limestone intraclasts. Just below the encrusted surface, centre right, is a truncated bioclast within what appears to be a triangular intraclast. Under the encrusted surface, top left, are a series of U-shaped Trypanites (?bivalve) borings. Width of photo represents 12cm.
Fig 2.5G

Negative print of acetate peel from encrusted and bored limestone surface. Close-up of the top centre of Fig 2.5F (note this print is reverse sense to Fig 2.5F). The *Liostrea* specimen has borings of *Talpina ramosa* (? phoronid) and encrusts a limestone surface which also has *Talpina* borings. Very small dots and thin lines within the left part of the *Liostrea* may represent algal or fungal borings (Kennedy pers. comm. 1985). At the right of the print, about 1mm of 'light' coloured limestone overlies the bored limestone and underlies the *Liostrea* specimen. The limestone with *Talpina* borings forms a layer about 3mm thick on top of a flat surface of 'lighter' coloured limestone which is interrupted by *Trypanites* borings elsewhere (Fig 2.5F). The *Liostrea* specimen is overlain by bioclastic packstone/wackestone with many small gastropods and benthonic foraminifera. Width of print represents 1.7cm.

Fig 2.5H

Negative print of acetate peel from encrusted and bored limestone surface. Close-up of the top left of Fig 2.5F. The bored limestone surface has been bored and encrusted several times. The top part of the *Trypanites* borings of Fig 2.5F can be seen at the lower left. Width of print represents 2.5cm.
Fig. 2-8A STRATIGRAPHIC VARIATION IN THE AVERAGE PROPORTIONS OF DIFFERENT ROCK TYPES

**WATCHET**

- Conybeari sz bucklandi zone
- Complanata sz
- Angulata zone
- Extranodosa sz
- Laqueus sz
- Liassicus zone
- Portlocki sz
- Johnstoni sz
- Planorbis zone
- Pre-planorbis Beds

**LYME REGIS**

- Reynesi sz Semicostatum z
- Bucklandi sz
- Rotiforme sz
- Conybeari sz
- Angulata zone
- Laqueus sz
- Liassicus zone
- Portlocki sz
- Johnstoni sz
- Planorbis zone
- Pre-planorbis Beds

- Light marl/Limestone beds
- Dark marl beds
- Laminated shale/Laminated limestone beds

% Thickness
Figure 28B: Stratigraphic variation in the average proportions of different rock types.

**Long Itchington**

- **Bucklandi zone**
- **Angulata zone**
- **Liasicus zone**

**Lavernock Point**

- **Angulata zone**
- **Liasicus zone**
- **Planorbis zone**
- **Pre-planorbis Beds**

Legend:
- Light marl/limestone beds
- Dark marl beds
- Laminated shale/laminated 1st beds
Fig 2.8C Correlation of %IM/I thickness with No. of L beds + nodule horizons
Many or most beds correlatable in literature.

Calcarea Bed horizon correlatable.

Correlation using laminated shale beds suggested here.

R Rugby
L1 Long Itchington
S Seamount (Southmouth)
SB Stout Bay
BC Bull Cliff
LP Lavernock Point
BK Brent Knoll
W Watchet
T Tolcis
LR Lyme Regis

Fig 2-8D CORRELATION IN THE BASAL LIAS
Fig 2B: POSSIBLE LITHOSTRATIGRAPHIC CORRELATION FOR THE LOWER PART OF BASAL LIAS
Fig 2.8F: POSSIBLE LITHOSTRATIGRAPHIC CORRELATION FOR THE UPPER PART OF BASAL LIAS.
Fig. 32a Lower Lias whole rock composition according to rock type

LIMESTONE

LIGHT MARL

DARK MARL

DARK, LAMINATED SHALE

LAMINATED LIMESTONE

□ LYME REGIS

□ WATCHET
Fig 3.2B TOC/\text{CaCO}_3\text{ RELATIONSHIP AT WATCHET AND LYME REGIS}
Figure 3.3C CLAY/FeS/CaCO₃ RELATIONSHIPS AT WATCHET AND LYME REGIS.
Fig 3.3A VARIATION IN WHOLE ROCK COMPOSITION AT WATCHET

THICKNESS LOWER LIAS / Metres

ZONE
LIMESTONE +
LIGHT MARL 
DARK MARL 
LAMINATED SHALE
LAMINATED LIMESTONE 

% CaCO₃

% TOC_carb_free

% FeS₂_carb_free
Fig 3.4A DETAILED GEOCHEMICAL PROFILES THROUGH LANG'S BEDS 13-20, UPPER S. ANGULATA ZONE, SEVEN ROCK POINT, LYME REGIS

STRATIGRAPHIC

LOG

%CaCO₃ %δ¹⁸OORG %δ¹³CORG %%CLAY% %TOC %Fe₂⁺ %FeS₂

LIMESTONE LIGHT MARL DARK MARL LAMINATED SHALE

BULK SAMPLE GYRPHEA ISOPOE VALUE

RANGE OF VALUES IN GYRPHEA SPECIMEN BLG 33 (A-H)
Lang's beds 13-20, *angulata* zone, Seven Rock Point, Lyme Regis. Compare with Fig 3.4A and Appendix Section 2.1. A number of *Gryphaea* can be seen. The hammer is 39 cm long.
**Fig. 3.4C  INTERPRETATION OF S/DOP/Fe/TOC PLOTS**

<table>
<thead>
<tr>
<th>Results</th>
<th>Interpretation</th>
<th>Environment/Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>Pyrite forms only when organic matter present. Pyrite formation is iron-limited. DOP controlled by H$_2$S production (controlled by %organic matter).</td>
<td>Normally oxygenated bottom-water.</td>
</tr>
<tr>
<td>%S</td>
<td>%TOC</td>
<td></td>
</tr>
<tr>
<td>DOP</td>
<td>%TOC</td>
<td></td>
</tr>
<tr>
<td>%Fe</td>
<td>%TOC</td>
<td>Iron deposition may or may not be linked to organic matter deposition.</td>
</tr>
</tbody>
</table>

b) Pyrite formed diagenetically is organic-limited. Pyrite formed on seafloor is limited by the concentration of bottom-water H$_2$S (syngenetic). DOP controlled by H$_2$S production (controlled by %organic matter). Anoxic bottom water. eg. Black Sea sediment

| %S     | %TOC | | |
| DOP    | %TOC | | |
| %Fe    | %TOC | Iron and organic matter deposition linked. | |

c) Pyrite formed diagenetically and is iron-limited. DOP not controlled by supply of H$_2$S as readily converted iron used up. Poorly oxygenated, anoxic or fluctuating oxygenation of bottom-water. eg Black Ven Marls

| %S     | %TOC | | |
| DOP    | %TOC | | |
| %Fe    | %TOC | Iron deposition not linked to deposition of organic matter. | |

d) Pyrite formed diagenetically and is iron-limited. DOP not controlled by supply of H$_2$S as readily converted iron used up. Poorly oxygenated, anoxic or fluctuating oxygenation of bottom-water. eg Jet Rock

| %S     | %TOC | | |
| DOP    | %TOC | | |
| %Fe    | %TOC | Iron and organic matter deposition linked. | |

**Plot Use of plot for interpretation of pyrite formation.**

- **%S v %TOC**
  - Intercept=0 • Normal oxygenation. Int.=+ve • low oxygen levels or anoxia.
  - Slope dependent on: DOP v %TOC plot if organic-limited, %Fe v %TOC plot if iron-limited.

- **DOP v %TOC**
  - Slope=0 • Iron limited. Slope=+ve • Organic limited.
  - DOP=low • Normal oxygenation. DOP=high • low oxygen levels or anoxia.

- **%Fe v %TOC**
  - Slope=0 • Iron deposition independent of organic matter.
  - Slope=+ve • Deposition of organic matter and iron linked.

Based on Rainwell & Berner 1985.
Fig 3.4 D S/DOP/Fe\textsubscript{Fe} / TOC RELATIONSHIPS  
UPPER ANGULATA ZONE  
LYME REGIS

- %\text{S}_{\text{CARB. FREE}}
- %\text{DOP}_{\text{CARB. FREE}}
- %\text{Fe}_{\text{CARB. FREE}}

LIMESTONE  
LIGHT MARL  
DARK MARL  
DARK, LAMINATED SHALE
Trend represents slope for pure pyrite plus a constant amount of iron soluble in HCl.

Slope for pure pyrite

LIMESTONE + LIGHT MARL × LAMINATED ○ LIMESTONE
DARK MARL ◊ DARK, LAMINATED ◊ SHALE

S/TOC RELATIONSHIP AT WATCHET AND LYME REGIS
Fig 3.4: Stable isotopes of carbonate from the Angulata - Buckland zone time regions.
Fig 3:4G PREVIOUSLY PUBLISHED STABLE ISOTOPES OF CARBONATE FROM THE PRE-PLANORBIS BEDS - SEMICOSTATUM ZONE, LYME REGIS

LIMESTONE BED
LIMESTONE NODULE
LIGHT MARL
LAMINATED LIMESTONE
TREND FROM INSIDE TO OUTSIDE OF NODULE

DATA FROM:
CAMPOS + HALLAM 1979
AND
GLUYAS 1983
Fig. 3.4H

GRYPHAEA ARCUATA SPECIMEN BLG33 SAMPLE POINTS

%δ^18O_ppb

%δ^13C_ppb
Fig 3.41 STABLE ISOTOPES IN A LIMESTONE NODULE FROM LANG'S BED 37, BUCKLANDI ZONE, SEVEN ROCK POINT, LYME REGIS

SAMPLE POSITIONS

Positions of A15 and A16 projected to appear in the same plane as other samples.

‰° δ₄⁰PDB

‰° δ¹³C_PDB
WALSH POWER SPECTRAL ESTIMATION

TIME SERIES SINE WAVE TREATED AS THE SUM OF VARIOUS WALSH FUNCTIONS:

COMPONENT WALSH FUNCTIONS WITH RELATIVE AMPLITUDES, PHASE & WAVELENGTHS:

0.875 - --------------- λ = 8.0 cm SAL Function

-0.875 -

0.375 -

-0.375 -

0.375 -

-0.375 -

0.125 -

-0.125 -

(MODIFIED FROM KANASEWICH 1981 FIG 23.2)

eg. Normalized Power for
8cm Peak = 0.9711 = \( \frac{(0.875^2 \times 0.375^2) + (0.875^2 \times 0.125^2)}{(0.875^2 + 0.375^2 + 0.125^2)} \)
THE EFFECT OF HIATUSES UPON A PERFECTLY REGULAR TIME SERIES

**Fig 4.2B**

**Regular cycles only**

\[ N = 2048 \]
\[ \text{BW} = \text{H} \]

**TIME SERIES:**

\( 16 \text{cm} \) (REPEATED 128 TIMES)

**Regular cycles plus random gaps**

\[ N = 2048 \]
\[ \text{BW} = \text{H} \]

**TIME SERIES:**

\( 16 \text{cm} \) CYCLE 'PLUS 'RANDOM GAPS' (SEE FIG 4.2C)

**GAPS:**

- Random No. Columns 1 + 2 (Both 00-99)
- 1 = Separation of Gaps
- 2 = Thickness Loss at Each Gap

**BW** = Bandwidth = Frequency Resolution of Spectrum

**N** = No. of Sample Points Used to Generate Spectrum (= cm Here)
TIME SERIES 16cm CYCLE PLUS RANDOM GAPS

1 No of centimetres lost at gap
* Gap not apparent during transform

Top

Bottom

16cm
Fig 4.20

TIME SERIES GENERATED WITH RANDOM NUMBERS

On random number table column 1 = bed thickness = 0-9cm
column 2 = rock type codes = +1 if even number
       = -1 if odd number
Fig 4.2E

SPECTRUM OF RANDOM TIME SERIES

N = 2048
H Bw
UNSMOOTHED

N = 2048
H Bw
SMOOTHED

COMPARE FIG 4.3B (SAME SCALING)
TIME SERIES GENERATION

Figure 4.2F

TIME SERIES FOR PART OF PLIENSBACHIAN, M BRUGHETTO, N. ITALY

- SAMPLE POINT (SAMPLE INTERVAL = 1cm)

LIMESTONE

GREEN SHALE

TIME SERIES FOR PART OF HETTANGIAN, LAVERNOCK POINT, S. WALES

LIMESTONE

LIGHT MARL

DARK MARL

DARK, LAMINATED SHALE

LAMINATED LIMESTONE
CHOOSING SAMPLE INTERVALS:

SEQUENCE CONTAINS BEDS 1cm THICK

SAMPLE INTERVAL CHosen = 1.5cm

SAMPLeD SEQUENCE:

RECREATED TIME SERIES CONTAINS SPURIOUS LOW FREQUENCY COMPONENT:

SAMPLE INTERVAL = 1.0cm

SAMPLeD SEQUENCE:

RECREATED TIME SERIES = CORRECT REPRESENTATION OF SEQUENCE:
TESTING THE SIGNIFICANCE OF SPECTRAL PEAKS

A. Spectrum unsmoothed

N = 2048
BW H

16cm CYCLE +
RANDOM GAPS
(SEE FIG 4.2C).

B. Spectrum smoothed and tested against a white noise model

N = 2048
BW H

TIME SERIES AS A.

95% CONFIDENCE LEVEL

C. Subspectra

N = 1024
BW H

TIME SERIES AS A
BUT SPLIT INTO
'TOP' AND 'BOTTOM'.

CYCLES PER METRE
TIME SERIES IS REGULAR & ASYMMETRICAL (cf. LIMESTONE-SHALE SEQUENCES):

COMPONENT WALSH FUNCTIONS WITH RELATIVE AMPLITUDES, PHASE & WAVELENGTHS:

\[ \lambda = 40 \text{ cm} \]
\[ \lambda = 53 \text{ cm} \]
\[ \lambda = 160 \text{ cm} \]
\[ \lambda = 80 \text{ cm} \]
\[ \lambda = 160 \text{ cm} \]
\[ \lambda = 80 \text{ cm} \]
\[ \lambda = 53 \text{ cm} \]
\[ \lambda = 53 \text{ cm} \]
\[ \lambda = 40 \text{ cm} \]
Biostratigraphy from Cope et al. 1980
Fig 4.3B BASAL LIAS, LYME REGIS POWER SPECTRA

0.25
0.20
0.15
0.10
0.05
0.00

POWER

CYCLES PER METRE

0.6 0.8 1.0 1.5 2.0 2.5 3.0 3.5 4.0

85 cm (<93 kyr, >141 kyr) 41 kyr

51 cm (<56 kyr, >5 kyr) 21 kyr

<20 kyr

95% CL

N = 2048

H BW

0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00

POWER

CYCLES PER METRE

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0

N = 1024

H BW

0 - 10

2 4 6 8 10 12 14 16 18 20 22 24

<20 kyr

95% CI

5% CI

N = 2048

H BW
Fig 4.3C BASAL LIAS WATCHET TIME SERIES

Biostratigraphy from Palmer 1972 • Cope et al. 1980
Fig 4. 3D BASAL-LIAS WATCHET TIME SERIES

Aliisicus Zone

Sanquatoria Zone

NO EXPOSURE
Fig 4-3E BASAL LIAS WATCHET TIME SERIES

- S. anquilata Zone
  - A. bucklandi Zone

Depth markers:
- 60m
- 70m
- 80m
- 90m
- 90-77m

Temperature indicators:
- 20.4°C
Fig 4.3F BASAL LIAS WATCHET POWER SPECTRA

N = 2048

N = 4096

95% CL

<20 kyr

2.6 2.8 2.2 2.4 2.6 2.8 3.0
CYCLES PER METRE

POWER

0.02

0.04

0.06

0.08

0.10

0.12

0.14

0.16

0.18

0.20

0.22

0.24

0.26

0.28

0.30

N = 4096

N = 2048

95% CL

<20 kyr

95% CL

5%

Fig 4.35: Basal Liias Lavernock Point Time Series.
Fig 4.3H BASAL LISAS LAVERNOCK POINT POWER SPECTRA

- 341 cm (<430 kyr) ≈ 41 or 21 kyr
- 33 cm (<42 kyr) < 20 kyr

N = 1024
HBW

N = 512
HBW

N = 512
HBW

LOG_{10}(POWER)
Fig 4.31 BASAL Lias, NASH POINT TIME SERIES

Biostratigraphy from Trueman 1930
Fig 4-3J BASAL LIAS, NASH POINT POWER SPECTRA

N = 1024
H BW

<20kyr

21cm (<4kyr)

95% CL

Cycles per metre

N = 512
H BW

A

Cycles per metre

N = 512
H BW

B

Cycles per metre

<20kyr

95% CI

N = 1024
H BW

Log(Power)
Fig 4.3K BASAL LIAS, LONG ITCHINGTON TIME SERIES.

Biostratigraphy from Clements et al. 1975
Fig 4.3L BASAL LIAS, LONG ITCHINGTON POWER SPECTRA

N=1024
H=BW

N=512
H=BW

N=512
H=BW

N=1024
H=BW
Fig 5.1A RELATIONSHIP BETWEEN NUMBER OF CEMENTED HORIZONS + ZONE THICKNESS

Saltford Cutting, Avon
Keeling's Quarry, Avon
Watchet, Somerset
Lyme Regis, Dorset
Long Itchington, Warwick
Tolcis, Devon
Bannister, Nottingham

S, K, W, L, T, B

note: here 'Limestone' = Homogeneous + Laminated Limestone
Transgression

Onlap of the London Platform (Donovan et al. 1979).

? Shallow water evidence in Dorset

Dorset Stratigraphy

Estimated relative water depth

Relative %dkm/ldsh

(Figs 28A + B)

Higher

BM

BVM

SWB

BLM

BM - Belemnite Marl
BVM - Black Ven Marls
SWB - Shales with beef
BLM - Blue Lias Member

HIATUS (Cope et al. 1980)
Abundant horsetail spores (Wall 1965)
Local hiatus (Hallam 1969) (coistone)
Insects near coast (Whalley 1985)
Bed 45 condensed (Hallam 1960a)
Many small gaps (Section 2-5)
Many small gaps (Section 2-5)

Pre-Planorbis

Planorbis

Liasicus

Angulata

Rucklandi

Semicostatum

 Obtusum

 Oxynotum

 Recifalatum

 Jamesoni

IBEX

Zone

Fig 5-3A SEA-LEVEL CHANGES IN THE EARLY JURASSIC IN BRITAIN
Surface productivity proportional to supply of nutrients

Nutrients supplied from runoff - size of arrows proportional to amount of nutrients

% Dinoflagellate \( \propto \) Productivity

% Coccolithophore \( \propto \) (High coccolith proportion \( \Rightarrow \) carbonate-rich sediment)

Fig 54A Productivity Model
Fig 5.48 Stratification Model (based on Hallam-Bradshaw 1979 and Barron et al. 1985).
Fig 5.5A GENERAL ENVIRONMENTAL MODEL FOR THE LATEST TRIASSIC AND EARLIEST JURASSIC IN SOUTH BRITAIN (cf Figs 5.4B and 5.5B)
Fig 5.5B

References used for Palaeogeography:

Hallam 1975                 Emergent areas.
Zeigler 1982                Islands and clastic influx.
Loughman 1982               N.W. Europe palaeogeography.
Bernoulli and Jenkyns 1974  S.European and N.African carbonate platforms.

Hay et al. 1982

Bloos 1982                  N.Atlantic rift evaporites and lakes in the N.America.
Troedsson 1951               German palaeogeography.
Batten et al. 1986           Scandinavian clastic influx.
Hallam 1975                  Clastics in East Scotland.
                          Clastics in West Scotland.
Fig. 5.5b Palaeogeography in the Hettangian and Early Sinemurian
Fig 6.2A

Field aspect of the Boom Clay Formation, Terhagen, near Antwerp.

Top: Vandenberghe's beds 14-32 (10.6m)
Bottom: Vandenberghe's beds 32-49 (7.7m)
Fig 6.2b BOOM CLAY FORMATION TIME SERIES

5 CODES
Calcereous clay silt

Clay Black clay
Bed Silt No. Brick Pit

2 CODES

Position of time series

Clay Silt

10 metres

0cm-
Fig 6.2C BOOM CLAY FORMATION POWER SPECTRA—Using S Rock Type Codes

N=4096
HBW

141cm (=139kyr) 136kyr
111cm (=109kyr) 109kyr
93cm (=92kyr) 95kyr
749cm (=48kyr) 41kyr

N=2048
HBW

N=2048
HBW

N=4096
1BW

Cycles per metre

Cycles per metre

Cycles per metre

LOG_{10} (Power)
Fig 6.2D BOOM CLAY FORMATION POWER SPECTRA Using 2 Rock Type Codes

- 205 cm (~202 kyr), 2
- 141 cm (~137 kyr), 136 kyr
- 111 cm (~109 kyr), 109 kyr
- 93 cm (~92 kyr), 95 kyr
- 749 cm (~48 kyr), 41 kyr
- 719 cm (~49 kyr), 21 kyr

Power

Cycles per metre

N=4096

N=2048

N=2048

N=4096
Fig 6.3A

Field aspect of the Kimmeridge Clay Formation, near Freshwater Steps, Kimmeridge, Dorset.

Top: The White Stone band near the top is a coccolith limestone. Underneath calcareous shale and oil shales are interbedded. The hammer is 39cm long.

Bottom: Close-up of the White Stone band coccolith limestone with an oil shale. Notice that both rock types are laminated. The oil shale appears to have suffered minor syn-compactional faulting. The lens cap is 5cm in diameter.
Fig 6.3B Upper KIMMERIDGE CLAY TIME SERIES
Fig. 6.3C Upper KIMMERIDGE CLAY TOP SECTION POWER SPECTRA

- 910 cm (≈392 kyr) 410 kyr
- 122 cm (≈53 kyr) 41 kyr

Cycles per metre

- N=8192
  - H BW

- N=6096
  - H BW
  - B
  - A

LOG₁₀ (Power)

Cycles per metre

- 15% CT
- 5% CT

- N=6096
  - H BW
Fig. 63D UKIMMERIDGE CLAY BOTTOM SECTION POWER SPECTRA

- 546 cm (≈116 kyr), 100 kyr
- 158 cm (≈34 kyr), 41 kyr
- <20 kyr

N=8192

Cycles per metre

- 2.0 2.4 2.8 3.2

- 2.0 2.4 2.8 3.2

N=6096

Cycles per metre

N=8192
**Alternations Section**

<table>
<thead>
<tr>
<th>Name</th>
<th>Bed Thickness</th>
<th>Alternations Section</th>
<th>Subzone</th>
<th>Zone</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>Slump</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>Grey limestone + grey or red purple shale</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>White Lst. + red/purple Sh.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mm-dm</td>
<td></td>
<td>Red limestone + red/purple shale</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>Red + white mottled marl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>as above marl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mm-dm</td>
<td></td>
<td>Yellow limestone + green marl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>Pink limestone + red marl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>White limestone + green marl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mm-dm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td></td>
<td>Slump</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>Grey limestone + grey or red purple shale</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>White Lst. + red/purple Sh.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>Red limestone + red/purple shale</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>Red + white mottled marl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>as above marl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>Yellow limestone + green marl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>Pink limestone + red marl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td>White limestone + green marl</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Zone**

- Lopatinum

**Stage**

- Aalenian
- Toarcian
- Pliensbachian

**Toarcian**

- H. falciferum
- D. levesquei
- G. thouarsense
- H. varibilis
- H. bifrons

**Pliensbachian**

- H. flexifera
- D. tenuicostatum
- P. spinatum
- P. papyrenum
- A. margaritatus
- A. gibbosus
- A. subnodosus
- A. stokesi
- P. doveyi

**Pliensbachian**

- H. flexifera
- D. tenuicostatum
- P. spinatum
- P. papyrenum
- A. margaritatus
- A. gibbosus
- A. subnodosus
- A. stokesi
- P. doveyi
Field aspect of the Toarician section (Ammontico Lombardo), Breggia Gorge.

Top: Bernoulli's beds 1-5.
Bottom: Part of Bernoulli's bed 1. The hammer is 39cm long.
Fig 6.6c. HREGJOIA GORGE TOARCIAN SECTION TIME SERIES

Bed Nos

Shale  Limestone

1906 cm
(Not including)
(slumps)

52C

52B

52A

2m

Pink Ist

White and pink lst

Pink lst

Red purple shale

Light grey limestone

Grey shale

Toarcian

Aalehian

Bed 5 (Slump)
Fig 64D BREGGIA GORGE TOARCIAN SECTION POWER SPECTRA

- 57 cm (<112 kyr), 100 kyr
- 18 cm (<35 kyr), \( f_{9.5} \) or \( f_{8.5} \) or 30 kyr
- 14 cm (<27 kyr), 21 kyr
- <20 kyr

N = 1024

implemented by:

- 57 cm (<112 kyr), 100 kyr
- 18 cm (<35 kyr), \( f_{9.5} \) or \( f_{8.5} \) or 30 kyr
- 14 cm (<27 kyr), 21 kyr
- <20 kyr

Cycles per metre

N = 512

CBW

N = 1024

CBW

LOG 10 (Power)
Fig 6.4E

Field aspect of the Upper Pliensbachian section (Upper Morbio Formation), Breggia Gorge.

Top: The section represents about 8m, younging to the left.

Bottom: The beds young to the right. The hammer is 39cm long.
Fig 64E BREGGIA GORGE Upper PLIENSBACKIAN SECTION TIME SERIES
Fig 6.4G BREGGIA GORGE U PLEISNOBACHIAN SECTION POWER SPECTRA

N=8192

N=6096

N=6096

N=8192
Fig 6.4H

Field aspect of the Middle Pliensbachian section (Lower Morbio Formation), Breggia Gorge.

Top: Wiedenmayer's beds 974-966. On the far side of the stream, top right, is the section illustrated in Fig 6.4E. The hammer is 39cm long.

Bottom: Wiedenmayer's bed 944. In the middle nodular terminations to a limestone bed probably indicate that the limestones are secondary. The lens cap is 5cm in diameter.
Fig 6.41 BREGGIA GORGE Middle PLIENSBACKIAN SECTION TIME SERIES

Shale Marl Limestone

1731cm -

Zone

2m

marguerites

greeol

0m
Fig 6.5A

Field aspect of the Belemnite Marls, Stonebarrow, Charmouth, Dorset.

Top: The whole of the Belemnite Marls is about 26m thick. The section clearly illustrates the characteristic interbedding. Beds Lang et al.'s beds 110a-118 used for the time series, occur in the middle and upper part where the measurements of bed thicknesses proved to be most reliable.

Bottom: Calcareous clay overlying argillaceous calcilutite with a burrow-mottled contact.
Fig. 6.5B BELEMNITE MARLS TIME SERIES

Bed No.s from Lang et al., 1928
Fig 6.5c BELFMNITE MARLS POWER SPECTRA

Cycles per metre

LOG$_{10}$(Power)

-1 to -10

N=1024
H BW

N=512
B/A

Cycles per metre

5% confidence

<20kyr

<39kyr, 21kyr

114cm (<83kyr, 47kyr)

<247kyr, <100kyr

49cm (<39kyr, 21kyr)
Fig 6.6A

Field aspect of the 'Siliceous Shales', Robin Hood's Bay.

Top: Sellwood's beds 3-7, alternating shale, shaley sandstone and sandstone.
Bottom: Large Storm scour, Sellwood's bed 3. The hammer is 39cm long.
Fig 6.6B 'SILICEOUS SHALES' TIME SERIES

Shale          Sandstone          Sellwood 1970a bed No Ammonite zone

1236 cm -

2m

Scours

Scours

Scours

Scours

Scours

Scours

1  2  3  4  5  6  7  8
Fig. 6C 'SILICEOUS SHALES POWER SPECTRA

N=1024
H-BW

<200kyr

55% CL

Cycles per metre

N=512
H-BW

B

A

Cycles per metre

LOG$_{10}$(Power)

N=1024
H-BW

95% CL

5% CL

Cycles per metre
Fig 6.7A

Field aspect of the Upper Birkhill Shales, Dob's Linn. Three relatively thick black mudstone beds can be seen interbedded with grey mudstone in the left of the photograph. The hammer is 39cm long.
Fig 6.7b  Upper Mirkhill Shales Time Series

Time series illustrated minus pyroclastic claystone beds.

Black Grey Graptolite mudstone mudstone zone

4.998 mm -
Fig. 6.7c. Upper Birkhill Shales Power Spectra

N = 4096

N = 2048

95% c.l.

5% c.l.
APPENDIX FOR CHAPTER 2

STRATIGRAPHIC LOGS FOR THE BASAL LIAS SECTIONS.
2.3 Stratigraphic log for the basal Lias at Lavernock Point.
2.4 Stratigraphic log for the basal Lias at Nash Point.
2.5 Stratigraphic log for the basal Lias at Long Itchington.
APPENDIX FOR CHAPTER 3

GEOCHEMICAL METHODOLOGY.
3.1 Bulk Sample Preparation.

All bulk samples were reduced to powder in the same way. 10-15 grams of rock were collected into polythene bags with a hammer and chisel from horizons 2cm thick at Lyme Regis and 3cm thick at Watchet. The specimens were crushed into pieces less than 3mm maximum length using a 6lb hammer and a metal plate. Marl and shale samples were ground for 10 minutes in a planetary ball-mill with agate pots (15g capacity). Limestone and laminated limestone samples were ground the same way, but for 15-20 minutes. Caking only occurred if the samples had not dried. The powders were stored in glass pots.

3.2 Gryphaea Specimen Preparation.

Specimen powders were only collected from left (lower) valves. Rock matrix was removed from the outer surface of the fossil using a dry tooth-brush and a steel pin. Powders were generated with a Burgess vibro-tool which has a vibrating tungsten carbide point. In most cases a point 1.5cm behind the umbo and along the median line was selected for drilling (position A on Fig 3.4H). In the case of specimens BLG12, 13, 17, 57 and 27 the umbos had been lost prior to or during collection so the normal position for drilling could not be used. Areas approximately 3 by 5mm on the outside of the shell were drilled, yielding 15-40mg of powder. The powder was stored in glass bottles.

Because Gryphaea grew its shell by adding successive growth layers to the inside of previous layers, the sampling mixed powder from several layers. Because of this and to allow Gryphaea specimens to be collected with the greatest possible stratigraphic resolution, no effort was made to select specimens of the same size/age.
3.3 Determination of %CaCO$_3$, %TOC and %FeS$_2$.

The Strohlein Coulomat 702 was used to determine total carbon or total sulphur in the rock powders. Unglazed porcellain 'boats' were pre-heated to 1000°C for 15-20 minutes and stored in a desiccator to remove organic matter and water.

To analyse for carbonate-carbon, 70mg of powder were weighed into each boat and heated at 450°C for 15 hours to remove organic matter from the sample without decomposing the carbonate. Analysis of each boat used the carbon setting on the Coulomat with the furnace at 1200°C. The carbonate was decomposed in a stream of pure oxygen yielding carbon dioxide and sulphur dioxide (from the pyrite) which was passed into a desiccating tube and then into a mixture containing urea designed to remove the sulphur dioxide. The carbon dioxide was dissolved by bubbling and stirring the gas into a solution with an accurately measured pH. Electrodes automatically passed an electric current through the solution to restore the pH value. The amount of electricity used was measured and provided the pH did not change too much the 'count number', reflecting the amount of electricity involved, was directly proportional to the amount of carbon dioxide dissolved. The pH was monitored and if it changed too rapidly then the stirrer was automatically turned off until the pH could be reset electrochemically. Once the rate of change of pH was below a certain limit, the count was stopped automatically and the next sample was inserted; the whole procedure took about 5 minutes. The count number was multiplied by 0.2 and divided by the weight in milligrams to yield the weight percent carbonate carbon. This was converted to the percent calcium carbonate assuming that virtually no dolomite was present (Sections 2.2, 2.3 and 2.6). The %TOC was determined exactly the same way but without the step to remove organic...
matter. The second value obtained equals carbonate carbon plus organic carbon so the %TOC was calculated by subtracting the two determinations.

The determination of the amount of pyrite was carried out by measuring the amount of sulphur in the rocks. About 50mg of powder was used and a little powdered tin added to act as a flux. The Coulomat was put on the sulphur setting and the furnace heated to 1350°C. This time the sulphur dioxide produced was not removed from the gas and the pH of the solution was chosen such that the sulphur dioxide dissolved but the carbon dioxide did not. This procedure took around 10 minutes per sample. The conversion factor used with the count number was 0.01 and the %sulphur determined and converted into pyrite using the formula FeS$_2$. (This formula was confirmed using XRD in Section 2.3.) It is assumed that no elemental sulphur was present in these powders. The sulphur values obtained might reflect a proportion of gypsum (detected by XRD Section 2.3). However, as there is no evidence for hypersalinity in the normal marine environment of the basal Lias, any gypsum can be assumed to represent the surface weathering product of pyrite.

3.4 Determination of %Fe/R and DOP/R.

As discussed in Section 3.4.2a these parameters are defined as:

\[
\%\text{Fe}/R = \%\text{Fe/in pyrite} + \%\text{Fe/soluble in HCl}, \quad \text{DOP/R} = \%\text{Fe/pyrite} \times \%\text{Fe}/R.
\]

The sulphur measurement was used to calculate %Fe/pyrite. The hot HCl method of Berner (1970) extracts iron in the sediment that is able to react with hydrogen sulphide (Section 3.4.2a).

Approximately 100mg of sample powder was weighed into a conical flask and then 20ml of concentrated (11.5M) HCl added. The flask was placed on a pre-heated hot plate, brought up to boiling and allowed to
boil for 1 minute. The flask was removed and allowed to cool a little and the solution was gravity filtered into a volumetric flask (Whatman 42 filter paper, $\phi=2.7\mu m$). The flask was washed-out into the funnel using deionized water. Then the filter paper was washed several times. The volume of solution was made up using deionized water.

A Perkin-Elmer 306 acetylene-air atomic absorption spectro-photometer was used to determine the iron concentration of the solutions by comparison with standards. If the concentration of iron lay outside the linear part of the calibration curve the solutions were diluted accordingly. The weight of sample, the dilution factor, and the iron concentration measured were converted into values of $%\text{Fe/HCl}$.

To check that pyrite is not dissolved boiling concentrated HCl as assumed by Berner (1970), 97.1mg of powder from sample BL9 was mixed with 2.7mg of pure pyrite. The value of $\text{Fe/HCl}$ for this sample was previously measured as 0.67%. Thus allowing for the proportion of sample, 0.65%Fe would be measured for the mixture if no pyrite had dissolved. After repeating the procedure above, 0.74%Fe was measured so 0.09%Fe must have come from dissolution of the added pyrite. The amount of iron present in the added pyrite is 1.26mg (using atomic weights) so 7.1% of the iron in the added pyrite was dissolved. Therefore the measured values of $%\text{Fe/HCl}$ were overestimated by about 7%. However, as most iron in the value for $\text{Fe/R}$ comes from pyrite this error can be discounted. For instance sample BL328 has the greatest proportion of $\text{Fe/R}$ represented by $\text{Fe/HCl}$ of all the samples analysed. The values in this case were measured as: $\text{Fe/HCl}=0.14\%$, $\text{Fe/pyrite}=0.37\%$ and $\text{Fe/R}=0.51\%$. If $\text{Fe/HCl}$ was overestimated by 7%, the correct values should be: $\text{Fe/HCl}=0.13\%$ and $\text{Fe/R}=0.50\%$. So the overestimation of $\text{Fe/R}$ due to
the inaccuracies associated with the Fe/HCl measurement, is about 2\% (negligible compared to net experimental error).

3.5 Determination of $\delta^{18}O$ and $\delta^{13}C$.

Analyses were conducted at the BGS Gray's Inn Road Laboratory in London. Dark marl and laminated shale powders were placed in a stream of oxygen in a plasma furnace for 15 hours to remove organic matter. 25 specimen powders including all rock types were treated as though was present and substantial pyrite would cause $H_2S$ production during extraction. The extracted gases were passed over heated lead formate to remove $H_2S$ before any further purification took place. However, no reaction with the lead formate occurred so this part of the procedure was abandoned.

No subsequent preparations yielded $H_2S$ according to the mass spectra.

Extraction of $CO_2$ from the carbonate followed the procedure of McCrea (1950). Outgassed phosphoric acid was reacted for 15 hours with the sample after equilibration at 25.2°C in a water-bath. The liberated gas was passed through an acetone cold-trap (-90°C to remove water and phosphoric acid) into a liquid nitrogen cold-trap (-196°C). Keeping the nitrogen cold-trap filled, the gas collection vessel was evacuated to remove nitrogen gas, leaving the carbon dioxide frozen down in the trap. Analysis of the carbon dioxide was carried out with a Micromass three 903 mass spectrometer. Two or aliquots of the laboratory standard (MCS-8) were extracted and measured along with each sample series. The data were corrected for instrumental and isobaric effects using the methods of Craig (1957) and Deines (1970). The results were expressed in the del notation as permil deviation from the PDB standard:

$$\delta^{13}C = \left[ \frac{R_c \text{ sample}}{R_c} - 1 \right] \times 1000 \text{ permil, } \quad R_c = 13C/12C,$$
3.6 Reproducibility.

The determination of %C(in carbonate) and %C(total) -(used to determine %CaCO₃ and %TOC)-, and %S -(used to determine %FeS₂ and %Fe/pyrite)- involved repeated determinations for every sample. Values of %Fe/HCl (giving %Fe/R and DOP/R), δ¹⁸O, and δ¹³C were repeated for 10% of the samples analysed. For repeated samples the quoted and plotted values are averages. The pairs of results can only be used to assess the maximum 'error' in reproducibility likely for a particular type of determination. For instance, if the largest difference in values for all the pairs of sulphur determinations was 0.4% sulphur, then the maximum 'error' would be quoted here as ±0.2%. This method is crude but it gives some idea of the reproducibility involved.

Many geochemical parameters used here are calculated from a combination of others (eg DOP/R = Fe/py * Fe/R). The 'errors' for different types of determination have to be combined in these cases. The following general formulae have been used for this purpose:

Given three types of analytical determination: a, b and c, the maximum 'errors' associated are denoted: Ea, Eb & Ec.

If: \[ c = k \cdot a \] (k = constant), then \[ Ec = k \cdot Ea, \]
If: \[ c = a \pm b, \] then \[ Ec = \sqrt{(Ea)^2 + (Eb)^2} \]
If: \( c = a \), then

\[ Ec = \sqrt{(Ea - \text{Mean of } a)^2 + (Eb - \text{Mean of } b)^2} \]

On this basis the following values are meant to indicate the maximum errors associated with each type of analytical determination:

- CaCO\(_3\) \(-\) \(\pm 1.58\%\)
- Fe/Rcf\(-\) \(\pm 0.11\%\)
- TOCcf\(-\) \(\pm 0.25\%\)
- DOP/R\(-\) \(\pm 0.055\)
- FeS\(_2\)cf\(-\) \(\pm 0.23\%\)
- \(\delta^{18}O\)\(-\) \(\pm 0.14\) permil
- 'Clay'cf\(-\) \(\pm 1.7\%\)
- \(\delta^{13}C\)\(-\) \(\pm 0.05\) permil
APPENDIX FOR CHAPTER 4

COMPUTER PROGRAM FOR ILLUSTRATING TIME SERIES AND
GENERATING WALSH POWER SPECTRA.
4.1 Listing of Program WPSPEC.

```
WSPEC.FOR
PROGRAM TO ILLUSTRATE TIME SERIES AND/OR GENERATE WALSH POWER SPECTRA
WRITTEN IN FORTRAN TO RUN ON A 244VMX (VERSION 4.2) COMPUTER

WALSH POWER SPECTRA

TIME SERIES: THE TIME SERIES ARE OBTAINED BY DIGITISING MEASURED STRATIGRAPHIC
SECTIONS. FIRST A FILE CALLED "TSER.DAT" IS CREATED WITH FORMAT
(F5.0,1X,F6.2). THIS CONTAINS BED THICKNESS IN THE FIRST COLUMN
AND ROCK TYPE CODE (eg. LIMESTONE=1, SHALE=-1) IN THE SECOND.

RUNNING WPSPEC: ONCE WPSPEC.FOR IS STARTED THE DATA FROM TSER.DAT ARE READ INTO
THE ARRAY X. WPSPEC.FOR IS DIMENSIONED TO ACCEPT UP TO 2000 LINES
IN TSER.DAT AND UP TO 17000 DATA POINTS. FOR EXAMPLE IF TSER.DAT
HAD 2 LINES: ' 33. -1.0 ' AND ' 6. 1.0 ' THEN 39 POINTS
WOULD BE GENERATED. AFTER A VARIETY OF REMINDERS, THE NUMBER OF
POINTS, "N", IS PRINTED ON THE SCREEN. THE PROGRAM CAN BE LEFT AT
THIS POINT IF THE NUMBER OF POINTS IS WRONG AND THE DATA FILE
NEEDS EDITING.

THE PROGRAM CONTINUES WITH THE OPTION TO ILLUSTRATE THE DATA/TIME
SERIES (SEE "GENERATING HARD COPIES OF GRAPHS"). NEXT THERE IS AN
OPTION TO GENERATE POWER SPECTRA OR LEAVE THE PROGRAM. IF POWER
SPECTRA ARE TO BE GENERATED, THE TIME SERIES MUST HAVE THE NUMBER
OF POINTS (N) EQUAL TO AN INTEGER POWER OF 2 (i.e. 2,4,8,16,.....
...16384 - LIMITED BY THE DIMENSION STATEMENT).

ILLUSTRATING TIME SERIES:
THE PROGRAM GENERATES A GRAPHICAL OUTPUT FILE USING GHOST3C
LIBFILE SUBROUTINES. THE FILE IS CALLED "DEFAULT.GROD1" (SEE
BELOW FOR HARD COPIES OF GRAPHS).

GENERATING WALSH POWER SPECTRA:
FIRST THE NUMBER OF SAMPLES PER METRE IS REQUESTED ON THE
SCREEN. THE FORMAT IS F5.0, SO IF THE SAMPLE INTERVAL IS 1cm
FOR INSTANCE, THEN TYPE IN '100.'.

NEXT A SERIES OF OPTIONS ARE GIVEN. EACH OPTION ALLOWS THE
GENERATION OF A DIFFERENT OUTPUT FILE. THERE ARE 2 TYPES OF
FILE: A DATA FILE WITH A LIST OF "POWER" AND CORRESPONDING
"CYCLES PER METRE" VALUES (eg. "PSPEC.DAT"), OR 2 GRAPHICAL
OUTPUT FILES GENERATED USING GHOST30 LIBFILE SUBROUTINES
(eg. DEFAULT.GROD1)

CONTENTS
DATA FILE GRAPHICS FILE

UNSMOOTHED POWER PSPEC.DAT DEFAULT.GROD1
V. FREQ.
SMOOTHED POWER SPEC.DAT DEFAULT.GROD1
V. FREQ.
LOG10(SMOOTHED POWER) v. FREQ.

WHERE A SPECTRUM IS TO BE PLOTTED, THE AXES LIMITS ARE
REQUESTED ON THE SCREEN. THE PROGRAM SHOULDN'T FINISH WITH
"FORTRAN STOP" ON THE SCREEN.

STATISTICAL TESTS FOR POWER SPECTRA:
ALL THE POWER VALUES HAVE BEEN NORMALISED FOLLOWING
NOWOOD (1967, SEE REFERENCES AT END OF PROGRAM), THUS
FISHER'S TEST FOR WHITE NOISE IS EASILY APPLIED USING
NOWOOD'S TABLES (NO. MIS VALUE 'm' = THE NO. OF SPECTRAL
ESTIMATES WHICH = N/2 * 1). THE LOG10 POWER SPECTRA CAN BE USE
TO APPLY THE TEST FOR RED NOISE FOLLOWING SCHWARZACHER 1975
(pp210-212) AND DEGREES OF FREEDOM FOR SMOOTHED POWER SEE
BEACHAMP 1975 p100).

GENERATING HARD COPIES OF GRAPHS:
GRAPHICAL OUTPUT FILES OR "GRIDFILES" CAN BE DUMPED AS
HARDCOPIES USING A "CALCOMP 1012" GRAPHICS TERMINAL. FIRST
LOG-IN, MAKE SURE THE CALCOMP PLOTTING IS ON-LINE, TYPE
"CIUZ" AND THEN "DEFAULT.GROD1" AND THE SPECTRUM OR TIME
SERIES SHOULD BE PLOTTED. NOTE THAT PAPER COPIES CAN BE MOLD
BY DEFAULT.GROD1.

PROGRAM WPSPEC
DIMENSION X(200),0(17000),0(17000),0(17000),0(17000)
DIMENSION X(17000),0(17000),0(17000),0(17000)
DIMENSION X(17000),0(17000),0(17000),0(17000)

4.1 Listing of Program WPSPEC.

```

```
C SERIES OF NOTES LISTED ON SCREEN

WRITE(*,150)
5 FORMAT('')
WRITE(*,150)
WRITE(*,23)
WRITE(*,10)
10 FORMAT('')
WRITE(155)
15 FORMAT('')
WRITE(10)
20 FORMAT('')
WRITE(23)
23 FORMAT('')
WRITE(5)
WRITE(5)
WRITE(25)
25 FORMAT('')
WRITE(28)
29 FORMAT('')
WRITE(30)
30 FORMAT('')
WRITE(5)
C C RE4D IN TIME SERIES DATA FROM TSER.DAT AND STORE AS STRING OF VALUES IN ARRAY 'X' WITH 'N' POINTS
C
READ(1,65)(A(I),9(I),I=1,200)
65 FORMAT(5.0,1X,F0.2)
70 NROWS=1
J=0
DO 80 L=1,NROWS
DO 75 L=1,AC(I)
J=J+1
(75)AC(I)
75 CONTINUE
80 CONTINUE
N=J
WRITE(*,839)
85 FORMAT(IX,1XNUMBE OF POINTS ,15)
WRITE(*,5)
C C OPTION TO LEAVE PROGRAM GIVEN SO THAT TSER.DAT CAN BE EDITED
C TO CORRECT LENGTH IF NECESSARY.
C
WRITE(*,97)
90 FORMAT('')
95 FORMAT(II)
IFCLMN.EQ.DGO TO 1000
WRITE(*,5)
C C OPTION TO ILLUSTRATE TIME SERIES
C
WRITE(*,100)
100 FORMAT('')
READ(95)LOPT
WRITE(*,5)
IF(LOPT.EQ.13)GO TO 200
00 110 L=1,N
THICKCL=1
110 CONTINUE
C C PLOT TIME SERIES USING GHOSTED LIBFILE SUBROUTINES
C
AN=
CALL PAPER(1)
CALL PSPACECO.1067,0.9933,0.436,0.564)
CALL MAPS(0,0,AN,-2.0,2.03)
CALL PJOINTHICK(11,1,1)
CALL GEND
200 CONTINUE
C C OPTION TO GENERATE POWER SPECTRUM OR LEAVE PROGRAM
C
WRITE(*,72)
72 FORMAT('')
DO 300 J = 1, M, N
MN = (N/2) + 1
DO 375 I = 2, N, 2
PC(I) = X(I) - X(I-2)
375 CONTINUE
DO 450 K = 1, MN
TPSS = TPSS + PC(K) * PC(K)
450 CONTINUE

C CALL CYCLES PER METRE FOR POWER VALUES
YP(1) = 0.0
DO 500 J = 1, N, 2
Y(J) = Y(J-2) + Y(J-4)
500 CONTINUE

C WRITE VALUES TO OUT LINE "CYCLES...")
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
WRITE(6,5)
SCREEN REQUEST FOR AXES LIMITS

WRITE(*,575) F0RMAT(' TYPE IN AXES LIMITS REQUIRED: ') WRITE(*,580) F0RMAT(' ENTER MAX. FREQ. VALUE (FORMAT=F6.2): ') READ(*,585) APMAX WRITE(*,588) F0RMAT(' ENTER MAX. POWER VALUE (FORMAT=F5.3): ') READ(*,593) AMAX

PLOT SPECTRUM USING GHOSTD LIBFILE SUBROUTINES

CALL PAPER(1) CALL PSPACE(0.10,0.58,0.10,0.40) CALL MAP(0.0,AMAX,0.0,APMAX) CALL AXES CALL PTJOIN(0.1,NN,1) CALL SHOW

SMOOTH SPECTRUM USING A 3 POINT HAMMING WINDOW (SEACCH 1975)

MC = MM-1 CC1) = P1) CC2) = 0.5*P(2) + 0.5*P(3)
DO 700 J=3,MM CCJ) = (C.25*P(J-1)) + (0.50*P(J)) + (0.25*P(J+1)) CONTINUE

700 CONTINUE

NP = (CC1)*TPSS + (CC2)*TPSS + (CC3)*TPSS

710 CONTINUE

CC1) = C1) CC2) = 1.0 - 2.0,MM
FP(1) = (CC1) - 1) / TPSS

720 CONTINUE

WRITE(*,722) WRITE(*,722) WRITE(*,722)

722 FORMAT(' DO YOU WANT A SPEC.DAT FILE? YES=1, NO=0') READ(*,725) LMT WRITE(*,726) WRITE(*,726) WRITE(*,726)

WRITE VALUES TO DISK FILE SPEC.DAT

OPEN(UNIT=2,FILE='SPEC.DAT',FORM='FORMATTED',STATUS='NEW') WRITE(2,725) WRITE(2,725) WRITE(2,725)

725 FORMAT(14X,13SMOOTHED NP,14X,17T PSS,E10.4) WRITE(2,750)

750 FORMAT(14X,13POWER,11X,15CYCLES PER Mhz) WRITE(2,775) WRITE(2,775) WRITE(2,775)

775 FORMAT(14X,10.4,14X,6.4)

780 WRITE(2,800)

785 FORMAT(' PLOT SMOOTHED P vs. FREQ. YES=7, NO=0') READ(*,953) LMD IF(LMD.EQ.2.0)GO TO 780

SCREEN REQUEST FOR AXES LIMITS

WRITE(*,575) WRITE(*,575) WRITE(*,575)

WRITE(0,575) WRITE(0,575) WRITE(0,575)

CALL PAPER(1) CALL PSPACE(0.10,0.58,0.10,0.40) CALL MAP(0.0,AMAX,0.0,APMAX) CALL AXES CALL PTJOIN(0.1,NN,1) CALL SHOW

WRITE(*,722) WRITE(*,722) WRITE(*,722)
CALL PAPER(1)
CALL PSPACE(0.10,0.50,0.10,0.40)
CALL MAP(0.0,0.5,0.0,0.0,0.0)
CALL AXES
CALL PJUDINE(0.2,0.41)
CALL GRENO
900 CONTINUE
WRITE(*,910)
910 FORMAT(1X,'DO YOU WANT A LOGP.DAT FILE ? YES=1, NO=0')
READ(*,993)FP
WRITE(*,910)
WRITE(*,925)
925 FORMAT(1X,'PLOT LOG10(P) v. INDEX? YES=1, NO=0')
READ(*,993)FP
WRITE(*,965)FP
950 CONTINUE
990 WRITE(*,990)
STOP
END
APPENDIX FOR CHAPTER 5

PUBLICATIONS.
Fourier power spectra applied to Pleistocene records of climatic change have revealed cycles that match the duration of changes in Earth's orbital parameters (precession, obliquity and eccentricity). Thus Milankovitch's theory of climatic change was supported. Similarly, power spectra for geochemical data and bedding-plane spacing in Jurassic and Cretaceous pelagic rocks have been used to suggest orbitally-forced climatic changes.

Walsh power spectra have been applied, for the first time, to cyclic sedimentary rocks. The rocks studied (Blue Lias Formation) are believed to represent hemipelagic deposition on the early Jurassic continental shelf of S.W. Britain. Three sediment types reflect cycles in bottom-water anoxia combined with changes in the clay-to-carbonate mud ratio. The spectra reveal four cycles with estimated durations of the modern orbital-precession (19 and 23 kyr) and obliquity (11 and 43 kyr) changes. The cyclicity is, provisionally, related to orbitally-forced changes in the volume of runoff from adjacent landmasses. The durations allow estimation of mean sedimentation rate at different localities. Net sedimentation rate can be calculated assuming that one ammonite zone represents 1Myr. The ratio of these two figures suggests that 70% of the sediment that could have accumulated was actually eroded or was never deposited, leaving hiatuses within the series.

The data used are simply measurements of the thickness of beds of different sediment-types; therefore Walsh power spectra can be generated very easily. The effects of bioturbation, hiatuses and diagenesis are readily allowed for during generation and interpretation of the spectra. This application provides a quick and relatively simple method for the extraction of palaeoclimatological, stratigraphic and, perhaps, diagenetic information from ancient pelagic and hemipelagic rocks.
Hemipelagic shelf sedimentation and climatic cycles: the basal Jurassic (Blue Lias) of South Britain

G P Weedon

Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR (England)

Received May 23, 1985; revised version received August 22, 1985

The sedimentology, cyclicity and hiatuses of the Blue Lias Formation (basal Jurassic) were investigated at five localities in South Britain. Most carbonate mud, which is the dominant carbonate component, has been neomorphosed to microspar. However, carbonate mud was apparently supplied by coccoliths in zooplankton faecal pellets, suggesting hemipelagic sedimentation. Clay is assumed to have been supplied by rivers. The three sediment types involved reflect cyclic changes in bottom-water oxygenation levels combined with changes in the clay-to-carbonate mud ratio.

Walsh power spectra have been applied for the first time to measured sections in order to investigate the control of cyclicity. This application is analogous to palaeoclimatological studies of Pleistocene oxygen-isotope (ice-volume) records. The spectra show that 1 or 2 sedimentary cycles, of constant thickness, occur in four out of five sections, each of which represents several million years. The maximum possible duration of these cycles is too short for their generation by sea-level changes. Their regularity, stability and order of duration (tens of thousands of years) are consistent with the hypothesis of sedimentary cyclicity controlled by climatic change, itself forced by orbital changes in insolation (Milankovitch theory). The duration of both cycles recognised is less than 93,000 years (93 ka) and may record changes in orbital precession (21 ka) and obliquity (41 ka). Assuming that one ammonite zone represents 1 Ma, comparison of the longest-possible with the implied durations of the cycles, suggests that the sections are at best 20-40% complete. Loss of sediment may have occurred during winter storms or hurricanes. A model relating the sedimentary cycles to changes in the volume of runoff is proposed.

1. Introduction; orbital cycles and sedimentation

Since the classic paper by Hays et al. [1], Milankovitch theory has become a well established part of palaeoclimatological investigations (e.g. [2]). According to the theory changes in orbital parameters cause near-regular oscillations in the amount of radiation received at a given latitude and given time of year, and hence lead to climatic cycles ([3], and see Berger's paper in [4]). Cyclic variations in oxygen-isotope values and percentage carbonate within deep-sea cores have been ascribed to orbitally forced climatic changes as far back as the Miocene [5]. For times when no ice was present on the globe, for instance in the Triassic-Cretaceous, it has been speculated that certain cyclic marine and lacustrine rocks owe their cyclicity to a climatic control ([6,7], papers by de Boer, Olsen and Anderson in [4] and by Schwarzccher and Fischer in [8]). Barron et al. [9] showed, using a combination of geochemistry, sedimentology and General Circulation Model results, how cycles in the Greenhorn Formation of the North American Cretaceous probably recorded climatic cycles. An alternative approach towards demonstrating climatic control of sedimentation is the application of power spectral analysis [10]. Power spectra for Pleistocene data have been used to identify the role of orbital forcing because of its regularity and the characteristic duration of the orbital cycles [1]. The principal cycles involved are 100 ka (eccentricity), 41 ka (obliquity) and about 21 ka (precession) in duration [4].

In 1964 Schwarzacher [10] demonstrated regular cyclicity in limestone bed thickness for the Irish Carboniferous using power spectra. Carss and Neidell [11] suggested for Scottish cyclothems using a "marine" or "non-marine" classification that sedimentation was controlled glacio-eustatically or by local climatic cycles, in agreement with Schwarzacher's work.

The first application of power spectra to sedi-
ments formed on an ice-free globe was probably made by Dunn using geochemical data for the Kimmeridgian in South England [12]. This was continued for the Cretaceous in Italy (see de Boer in [4] and Schwarzacher and Fischer in [9]). All these studies indicated climatic control of cyclicity using Fourier power spectra. Walsh power spectra provide a fast method for the analysis of cyclic sections by using a coding system analogous to that of Carr and Neidell [11, fig. 4]. In this paper Walsh power spectra have been applied to Hettangian and Sinemurian rocks in South Britain (Fig. 1), using data measured along four coastal sections and within one active quarry. This application was made in order to investigate the possibility that their cyclicity was controlled climatically. The data used (which can be obtained from the author upon request) include a list of rock-type codes and thicknesses with the position of the spectral data (Fig. 1), bed numbers and ammonite zones. The zonal system used follows that of Dean et al. [13] and Cope et al. [14]. The zones and bed numbers were related to the measured data using [14] and the local stratigraphic descriptions [15-19].

Several rock types are interbedded on a centimetre-decimetre scale in tabular beds. They record cyclic changes in calcium carbonate, organic carbon contents and intensity of bioturbation. A long-standing controversy over the role of diagenesis complicates the picture of simple environmental changes as the sole cause of the cyclicity [20]. Diagenetic exaggeration of primary cyclicity is commonplace and does not prevent or invalidate spectral analysis [8,21]. However, a primary cyclicity must be demonstrated, otherwise application of power spectra for palaeoclimatic work is meaningless. For example, analysis of bedding-spacing would only reveal diagenetic processes if the bedding itself was solely diagenetic in origin. The recent work of House [7] uses a combination of logic and mathematical modelling. Unfortunately a subjective element enters this modelling and little effort was made to distinguish between di-

Fig. 1. Location of the sections measured and the time series obtained from them.
agenetic and primary cyclicity. In order to demonstrate the primary aspect of the cyclicity, the sedimentology and diagenesis is discussed here in some detail.

2. Description of rock types

In the field five rock types are recognised, viz. limestone, light- and dark-marl, laminated shale and laminated limestone, four of these are illustrated in Fig. 2. Light marls, dark marls and dark, laminated shales form beds from one to tens of centimetres thick which can be traced laterally for hundreds of metres and sometimes tens of kilometres [20]. The bed contacts are usually very sharp and planar. Limestone occurs as elliptical nodules enclosed by light marl or as beds with wavy or planar contacts. It is thought that the limestones formed during early diagenesis [20, 22, 23]. Specifically limestone formation is believed to have been by calcite cementation of the pore spaces of light marl (Fig 2). Laminated limestones are distinguished from limestones by internal lamination and a fetid odour. They are always enclosed by dark, laminated shales and usually have planar contacts; occasionally they occur in elliptical nodules with laminae passing inside. This rock type appears to represent dark, laminated shale cemented during diagenesis by analogy with the limestones. For a description of the fossils see [24–28]. A more detailed description of the different rock types given below, includes percentage calcium carbonate and organic carbon. Compositions were determined with a "Coulomat 702" for 15 g bulk samples from Lyme Regis and Watchet. 15 samples were analysed in duplicate for each

Fig. 2. Photograph of part of the angulata zone at Seven Rock Point, Lyme Regis. The hammer is 40 cm long.
rock type except the laminated limestone for which 6 samples were used.

Light marl. Forming light blue/grey friable beds this rock type is dominated by calcite microspar and disseminated clay. The homogeneity in the field and under thin-section probably indicates complete bioturbation. Macrofossils seem to be identical to those within the limestones except that benthos dominates due to the loss of ammonites during diagenesis (except for rare pyritized moulds). Scanning electron microscopy (SEM) of fractured surfaces reveals rare, isolated and poorly preserved coccoliths. Cathodoluminescence (CL) indicates that a large proportion of the carbonate is formed by ostracods. The ostracods are both united and disunited, form a wide range of sizes and are frequently self-supportive. Calcium carbonate: 35–57%, avg. 43%, organic carbon: 0.5–3.5%, avg. 1.3%.

Limestones. Limestones form homogeneous light blue/grey compact beds and nodules dominated by microspar with minor disseminated clay. Macrofossils are identical to those within the light marls excluding the ammonites which are a major component and are preserved as uncrushed calcite moulds [24]. SEM results are identical to those for light marls, confirming the work of Loughman [29]. CL indicates a very much lower proportion of ostracods relative to the light marls. However, within the limestones, the ostracods could only be detected by the presence of dull or non-luminescent internal matter, so in fact the proportion of ostracods present may well be higher than could be confidently inferred. Calcium carbonate: 64–89%, avg. 79%, organic carbon 0.3–1.1%, avg. 0.5%.

Dark marls. These form dark blue/grey friable beds which develop a crude fissility on weathering unlike the light marls. In thin-section most of the carbonate is present as elliptical microspar “blesbs” 80 by 250 μm in cross-section on average with their long-axes parallel to bedding. The blebs are discrete or concentrated to form laminae a few diametres thick. They do not contain any type of calcite bioclasts, palynomorphs or silt-grade quartz. They are surrounded by clay and amorphous organic matter forming discontinuous laminae. The clay and amorphous organic laminae, but more importantly the discrete nature of the blebs and associated laminae, indicate a lack of bioturbation. Macrofossils seem to be identical to those found within the light marls. The SEM reveals many dense aggregates of well-preserved coccoliths (Fig. 3) [28]. The aggregates’ size seems to be of the same order as that of the blebs. Occasionally individual coccolith rings can be seen to be partially engulfed by microspar crystals. CL reveals individual ostracods, not visible in transmitted light, which are embedded within organic matter and clay. Utilizing sections with burrow-fills of light marl within dark marl, the density of ostracods appears to be much lower in the dark marls. Calcium carbonate: 20–45%, avg. 33%, organic carbon: 1.0–6.5%, avg. 2.8%.

Dark, laminated shale. This rock-type is brown-black, well laminated and very fissile after weathering. Under thin-section the rock seems to be dominated by clay and organic laminae with rare microspar blebs. Macrofossils are dominated.

![Fig. 3. Photomicrograph of a fractured surface of dark marl, basal bucklandi zone, Lyme Regis. A closely packed aggregate of coccoliths (centre) can be seen entirely surrounded by a clay- and organic-matter-rich matrix. Most aggregates observed are considerably larger, this picture may merely illustrate the tip of a normal sized aggregate (faecal pellet). The scale bar represents 10 μm.](image-url)
by crushed ammonite moulds and restricted benthos [24]. SEM reveals the same coccolith aggregates found in the dark marls which are, however, considerably rarer. CL shows that the carbonate is predominantly present as discrete ostracods embedded within the clay and organics. They occur in all orientations, as united and dis-united specimens, and in numbers approximately the dark marls. Calcium carbonate: 12-48%, avg. 14%, organic carbon: 2.3-10.8%, avg. 5.7%.

**Laminated limestones.** This rock type is the rarest; occurring mainly within the *planorbus* zone; however, at Watchet it can be found sporadically at least into the *bucklandi* zone. It forms very dark blue/grey compact beds and nodules with a fetid odour when broken. The rock is dominated by microspar and disseminated clay with lamination formed by light microspar with vague pelloids, pyrite and sand-silt grade bioclastic fragments. Few complete bioclasts have been observed except for benthonic foraminifera. No definite ostracods can be identified from initial CL work. Calcium carbonate: 69-88%, avg. 82%, organic carbon: 0.7-3.0%, avg. 1.4%.

**Burrow-mottling.** Mottling occurs between light and dark marls, and this is preserved where limestones have formed. However, bed contacts usually remain sharp so burrowing must have been restricted. Dark marl fills burrows inside light marl beds and vice versa (Fig. 2). Mottling is dominated by *Chondrites*, but it also includes *Rhizocorallium*, *Diplocraterion*, *Arenicolites* and *Thalassinoides*. The dominance of *Chondrites* may indicate very low oxygen levels within the sediment during the transition between light and dark marls: thus explaining the restricted burrowing [30]. Very rarely, burrow-fills of light or dark marls are found at the tops of dark, laminated shale beds. However, where dark, laminated shale overlies one of the other rock types, no mottling occurs at the contact.

**Hiatuses.** Hiatuses are not apparent from biostratigraphy. At each locality, all the ammonite zones identified are present without gaps (using the local biostratigraphic descriptions and following [13-19]). Certain field observations, however, may indicate ubiquitous minor disconformities. For instance, horizons of burrows with dark marl fills can be found entirely enclosed within light marl beds with no sign of the dark marl bed which supplied the fill-material. At Lyme Regis, loose blocks of limestone occasionally show limestone intraclasts. One polished and peeled block from Lang's bed 25 of the basal *conybeari* Subzone, reveals a multiply bored and encrusted dome-shaped surface (3 cm high by > 13 cm long) underlain by intraclasts [15]. The bored and encrusted surface lies within limestone (originally light marl) and grades laterally into normal bioclastic mudstone. It is overlain by bioclastic packstone grading up into carbonate mudstone. The surface probably indicates erosion and at least a temporarily exposed hard substrate. Other features perhaps indicating hiatuses include anomalously thin beds (1-3 cm). All the sediment types are represented in these beds. They are traceable for up to hundreds of metres with sharp, gently undulating upper contacts; occasionally they are cut out laterally for approximately 20 m. Thin horizons of concentrated bioclasts may indicate winnowing or some form of sediment injection. The lack of obvious biostratigraphic gaps and of irregular contacts makes recognition of hiatuses very difficult. The observations described above have been made frequently even at the most expanded section studied (Watchet). Hiatuses may represent a significant loss of deposited sediment, therefore, they must be considered during analysis of measured sections.

3. Sedimentology and diagenesis

The size and composition of the coccolith aggregates and their presence within laminated sediments is believed to indicate an origin as zooplankton faecal pellets [31,32]. The microspar "blebs" are thought to represent neomorphosed aggregates when their common size, shape and occurrence are considered. The description of the coccoliths can be found in [28]. Loughman's SEM work was restricted to the limestones, but the lack of undoubted coccolith rings led to the belief that most of the microspar originated from green algae [29]. It is proposed here that most of the carbonate mud of the light marls and limestones is in fact coccolith material now largely neomorphosed to microspar.

The cause of the neomorphism may have been
water-films absorbed onto clay minerals [33,34]. The ubiquitous clay may be expected to have caused neomorphism of all the coccoliths. However, individual organic membranes and organic pellicles around faecal pellets may have protected the individual rings and aggregates observed (Fig. 3) [32,35]. In this model the organic matter contents are suggested as the controlling factor, explaining why so few coccoliths are observed within the light marls and limestones.

To have dominated local carbonate mud production, benthonic green algae would have required very shallow water for their high productivity [36]. Yet there is a lack of shallow-water criteria until the laterally equivalent coastal Sutton Stone and Southerndown Beds are encountered in South Wales [24,29,37]. For instance there is no evidence for exposure, micritic envelopes to bioclasts, ooids or stromatolites. Conversely pelagic elements are both common and diverse. They include ammonites, belemnites, large nektan such as the Ichthyosaurs, as well as coccolithophores, acritarchs and dinoflagellates [27]. Further it is considered very unlikely by the author that water still enough for low bottom-water oxygenation and the preservation of laminae could have been very shallow. Carbonate mud arriving in suspension was clearly only a minor source because such a low proportion of the microspar is present as disseminated, isolated crystals within the dark, laminated shale and dark marls. A certain amount of mud may have been generated by the activities of infauna when present, but it is contended here that most carbonate mud was supplied as coccolith aggregates.

The criteria for a primary cyclicity, which involved light and dark marl and dark, laminated shale, are essentially those of Hallam [20]. The burrow-mottling between light and dark marl is believed to be diagnostic of their primary distinction, particularly since both light marl burrow-fills within dark marl and vice versa are observed (Fig. 2), (20), and Arthur et al. in [4]). Additionally dark marl preserves clay, organic and bleb-formed laminae and discrete blebs that would not have survived thorough bioturbation. Conversely the homogeneous light marls with intimately mixed clay and microspar probably do indicate ubiquitous burrowing. The rate Chondrites burrows penetrating the tops of dark, laminated shales also indicate a primary distinction of this sediment type from the others. Further, the lack of coccolith aggregates and blebs and the dominance of ostracod-rich carbonate, is thought here to represent a primary difference of this rock type and the dark marls. Nevertheless, it is possible that, quite apart from the limestone formation, there was some compositional exaggeration of these three rock types during diagenesis [20].

Early diagenesis led to carbonate cementation of pore spaces in the light marls and laminated shales thus producing limestones and laminated limestones and generating 5 rock types from 3 sediment types. The limestone nodules only formed within light marls (Fig. 2), and laminated limestone only within dark, laminated shales. This, and the way that the limestone beds are bedding parallel and only follow one stratigraphic horizon strongly suggests to the author that localization of cementation was controlled by primary compositions (cf. [21]).

Hallam showed that limestone bed thickness is constant, on average, regardless of the thickness of particular ammonite zones, i.e. it is independent of sedimentation rates. Additionally the number of limestones is reduced within thinner parts of a given zone [20]. These features do not have to be regarded as indicative of some rhythmic unmixing process independent of primary compositions. For instance, both observations can be explained if the main supply of carbonate for cementation was provided by dewatering fluids (cf. [29]). If the growth of a limestone was always terminated when porosity was reduced to a certain level, then higher sedimentation rates would have terminated growth earlier. But higher rates of compaction would have supplied carbonate from dewatering fluids faster, perhaps allowing faster cementation. If the two aspects of cementation, changing the time for growth and changing the rate of growth, cancelled each other then the average thickness of a limestone, once formed, would be constant and apparently independent of sedimentation rates. Additionally, the volume and average composition of the sediment supplying carbonate in dewatering fluids may have limited the number of limestones formed in a particular section. These ideas are merely intended to indicate that independent rhythmic unmixing need not apply. It is suggested here that cementation did occur during early di-
agenesis, but that it merely emphasised and was controlled by primary compositional variation.

Thus the three sediment types (pre-diagenetic) are considered to represent 3 distinct depositional environments. The deposition of light marl involved a rapid supply of carbonate mud, as zooplankton faecal pellets, relative to the supply of clay. Bottom waters were well oxygenated, which allowed thorough bioturbation. Dark marl deposition saw a reduction in the rate of supply of carbonate mud compared to clay, concurrently with the preservation of lamination and substantial organic matter. Clearly this records the development of anoxia within the sediment and perhaps a slight reduction in bottom-water oxygenation. During dark, laminated shale deposition a very low rate of supply of carbonate mud compared to clay, permitted ostracods to become the dominant carbonate component. Organic matter was preserved in large quantities with the lamination. The ostracods are associated with a dwarfed fauna, which indicates low bottom-water oxygenation. However, the numbers of ostracods suggest that the bottom water frequently contained at least low concentrations of oxygen, even if it was usually anoxic.

Environmentally the dark marls record intermediate conditions to the other two sediment types. “Hemipelagic shelf sedimentation” seems to be a reasonable classification for the rocks analysed considering the proportions of sediment composed of pelagic bioclasts and clay. Hiatus formation may have occurred during winter storms or hurricanes [29,38,39]. Since the cyclicity has been shown to be dominantly primary, the power spectra can be applied to test a hypothetical palaeoclimatic control.

4. Walsh power spectra: methodology

The details of the mathematics used can be found elsewhere [40,41]. Problems and procedure for the Fourier power spectral analysis of sedimentary rocks are discussed in [42]. A qualitative description of the generation of power spectra may help show that the method is straightforward and that geological application and interpretation is the most important aspect. There are four main steps in production of power spectra; generation of a time series (Fig. 4), the transform operation, power spectrum generation, and interpretation.

The generation of power spectra requires data sets called “time series” which look like wave-trains. They are obtained by sampling at a constant interval along the length of measured sections (Fig. 4). To generate a time series for the present application requires numerical codes to distinguish the different sediment types. The numerical codes are somewhat arbitrary, but it is believed from the sedimentology that the light marl represents an environment most different from the dark, laminated shale. The dark marl is considered intermediate in the environmental extremes represented. The limestones represent an environment identical, or almost so, to the light marls. But because of their early diagenetic cementation they have not undergone the same degree of compaction as the light marls. In order to allow for this diagenetic distortion of the original thickness relationships, the limestones have been given a similar but different code to the light marls. Analogous reasoning applies to the coding of the laminated limestones and dark, laminated shales. Thus the codes used at all the localities were: limestone = +1.5, light marl = +1.0, dark marl = 0.0 and dark, laminated shales = −1.0, laminated limestone = −1.5. Experimentation with spectra
for Long Itchington, using the alternative values of +1.0, +0.5, 0.0, -0.5, -1.0 and of +1.0, +1.0, 0.0, -1.0, -1.0 respectively, showed no significant difference to the results obtained with the original codes. For example, in Fig. 7 spectra for Long Itchington using codes +1.0, +1.0, 0.0, -1.0, -1.0 have been plotted next to spectra generated using the code values preferred for the rest of the analyses (Fig. 4). The code values serve to generate a step-like wave-train of sediment code vs. cumulative bed thickness (Fig. 4). The power spectra are used to analyse the time series for dominant sedimentary cycles of different thicknesses.

Section measuring requires a rounding-up unit that is used consistently. In this case all beds were measured to the nearest centimetre. The sampling must accurately record the thinnest bed measured (1 cm), so that spurious low-frequency cycles are not generated by "aliasing". Therefore, in this case the sampling interval was 1 cm. In the present application a time series can be constructed by recording sediment codes every 1 cm along the measured section.

The time series are step-like or discontinuous rather than made of smooth curves; thus they are best decomposed into component square waves. Walsh functions, rather than sine and cosine waves; hence the Walsh rather than Fourier transform was used for the analysis [40]. One advantage of the Walsh transform is that computation is faster because only addition and subtraction is required [41]. Additionally, as the data used are discontinuous, they can be generated very quickly from measured sections (Fig. 4). Fourier spectra are best applied to continuous data such as geochemical values which, of course, require much more work for generation.

During the transform operation, a time series is regarded as a complicated wave-train that can be generated by the summation of many regular waves of different frequencies. Power spectra are plots of squared amplitude values, from the transform, for each different frequency component. Greater "power" can be regarded as indicating a more important role for a particular frequency component if it is used to recreate the time series.

The transform algorithm is taken from Kanasewich [41]. The estimates were generated from the transform and smoothed using a 3-point Hamming window following Beauchamp [40]. Power values are normalized for an application of Fisher's test for white noise [43]. Power is plotted linearly against frequency which is expressed in "cycles per metre". This constitutes the first application of Walsh power spectra to sedimentary rocks known to the author. Examples of Walsh power spectra for geomagnetic reversals and oxygen-isotope records can be found in papers by Negi and Tiwari [44,45].

The position of the time series used is shown in Fig. 1. The peaks not passing the 95% confidence level for the high-resolution spectra (Figs. 5-7) are considered to be indistinguishable from white noise [43]. To test the stability of the remaining peaks the time series used for the high-resolution spectra were divided into two subsections and low-resolution spectra were generated [45]. Additional spectra have been generated where possible using time series of the same length as the subsections (Fig. 1). Thus for each locality a series of low-resolution spectra can, to a limited extent, be used to trace the development of peaks identified on the high-resolution spectra.

5. Walsh power spectra: results and interpretation

As can be seen from Figs. 5-7, there are peaks which pass the 95% confidence level on all the high-resolution spectra. Additionally the low-resolution spectra indicate reasonably stationary data. In each case one or two peaks pass the 95% confidence level and seem to be stable from the subsection spectra; although their power varies. Such peaks are interpreted as indicating a regular cyclicity in sedimentation and have been labelled with their respective cycle lengths in centimetres. They seem to be stable for between about 200 ka at Nash Point (most of a subzone), to about 4 Ma at Lyme Regis (4 zones). The regularity and stability of these cycles strongly suggests that sedimentation was controlled climatically [10]. A climatic explanation does not exclude the vertical change in power for particular cycles seen in Figs. 5-7, because Pleistocene sea-surface temperature data display similar changes for individual cycles [2]. However, before a climatic explanation can be accepted, some constraint on the duration of these regular sedimentary cycles is required.

The detection of stable peaks via the use of
subsections, indicates that sedimentation rates were near-constant at a given locality. If this were not the case, then a cycle of a particular length at the base of the section would have changed size so much by the top of the section that stable peaks would be absent. Perfectly constant sedimentation rates are not implied, however, because each peak on a spectrum is associated with a bandwidth implying a range of possible cycle lengths. Nevertheless, an estimation of sedimentation rates is a meaningful exercise.
Fig. 6. Walsh power spectra for Lyme Regis and Nash Point.
Fig. 7. Walsh power spectra for Lavernock Point and Long Itchington. The broken line spectra for Long Itchington were generated using codes: $+1, +1, 0, -1, -1$. All other spectra (continuous lines) were generated using the codes: $+1.5, +1, 0, -1, -1.5$. 
Fig. 1 shows that the relative, as well as the absolute, thickness of ammonite zones changes between localities, suggesting a variation in the proportion of sediment missing at hiatuses. For constant sedimentation rate the thickest ammonite zone must be the most complete and should provide its best estimate. Thus sedimentation rates have been calculated for each location using the thickest zone and the assumption that one zone represents about 1 Ma (74 zones in 69 Ma according to Harland et al. [46], cf. [7]). These rates have been used to estimate the duration of different regular cycles as indicated in parentheses in Figs. 5–7. The durations are maximum limits as even the thickest zone is likely to be incomplete.

The maximum duration of all the regular cycles is shown to be about 200 ka. For an ice-free globe the maximum rate of sea level change is about 1 cm/ka [6,47]. Therefore the largest range in sea level during one sedimentary cycle would be 1 m. It is therefore considered very unlikely here that sea level could have controlled the regular cyclicity although it may have affected sedimentation on a longer timescale [29,48,49]. It is proposed here that the regularity, persistence (millions of years), and order of duration (tens of thousands of years) of the cycles labelled in Figs. 5–7 can best be explained by climatic control of cyclicity. However, this cannot, as yet, be argued for Nash Point.

At Nash Point the cycle detected is given a maximum duration of 4 ka (Fig. 6). This section spans just one subzone of the three within the bucklandi zone. Being so short in duration, even if the sedimentation rate estimated is wrong by a factor of 2 or 3, it seems unlikely that the cycle detected represents one of the main orbital cycles. The low-resolution spectra show that this cycle is not stable for more than two thirds of the subzone. The Nash Point section is exceptional petrographically when compared to the other sections, but was included for completeness. There is an absence of dark, laminated shale and laminated limestone and abundant sand and silt grade bioclastic fragments and the estimated sedimentation rate is by far the largest calculated of all the localities studied. The exceptional sedimentology may reflect the proximity to the palaeo-shoreline [24,29,37]. The spectra for this section also indicate a substantial trend, or “zero” cycles per metre component, compared to the other locations. It remains possible that climate controlled sedimentation there, but the spectra may not demonstrate it because they represent too short a time span. Alternatively the trend may indicate a rapidly changing sedimentation rate or the local sedimentary processes may have masked the regular cycles.

The cycles identified at the other four locations do fit the climatic interpretation; the orbital components and durations may be identifiable. At Watchet and Lyme Regis 2 cycles have been detected (Figs. 5 and 6). The wavelength ratio of each pair of cycles is about 1.6, viz. 819 cm/512 cm and 85 cm/51 cm. This suggests that if climatically controlled, both pairs of cycles represent the same two orbital cycles. At Long Itchington (Fig. 7) as well as the main cycle of 205 cm, a cycle at 128 cm (indicated in parentheses) may also be present. This pair also have a wavelength ratio of 1.6. Unfortunately the cycle of 341 cm at Lavernock Point lies within the part of the spectrum with low wavelength resolution (Fig. 7). Thus it cannot be decided whether or not a cycle of (1.6 × 341) cm or of (341/1.6) cm is present. Nevertheless, it is postulated here that 2 cycles are involved at each locality and that the common wavelength ratio suggests that the same two orbital cycles were involved.

The most likely orbital cycles are 100 ka, 41 ka and 21 ka in duration following previous studies (see various authors in [4]). Yet cycles at 31 and 54 ka may be important components of Pleistocene data and other cycles are possible ([2,3] and Berger in [4]). The maximum duration for cycles at Lyme Regis is 93 ka. This suggests that the 41 and 21 (obliquity and precession) cycles are strongest candidates. The value of the common wavelength ratio suggests the same pair of the three main Pleistocene orbital cycles. Alternatively the 31 ka (obliquity) and 21 ka cycles would best explain the wavelength ratio. Of course the Jurassic obliquity and precession cycles may have had significantly different durations (but see [7]). The data used are considered here to be a “5-bit” representation of the variation of some climatic indicator, such as run-off. It is not certain that such a poor proxy-climatic record would correctly record wavelength ratios.

Therefore the best that can be inferred at present is: (a) two climatic cycles seem to have been involved; (b) their duration was probably less than
93 ka; (c) they probably represent one precession and one obliquity cycle; (d) they may have been 41 ka and 21 ka in duration. Notice that the sedimentation rates at Watchet exceeded those at Lyme Regis by between 4 and 10 times with no effect on the interpretation. Finally, if the cycle durations were 41 and 31 ka, then the maximum implied durations can be compared. This indicates that at best the sections are 20–40% complete for a one million year interval (see [7]), which appears to be realistic for shelf sedimentation. Such a large proportion of missing section is surprising considering the results of the spectral analysis. However, rather than being very closely spaced throughout the sections, the hiatuses may in fact be present in clusters or at isolated horizons. In such a circumstance the hiatuses would separate packets of complete section and this could account for both the large loss of section and the detection of regular cyclicity.

6. Summary and conclusions

The basal Jurassic sedimentary rocks studied in South Britain accumulated in a hemipelagic shelf regime, with a palaeolatitude of about 35°N [50]. Carbonate mud was mainly supplied by coccoliths contained in zooplankton faecal pellets. Clay is believed to have been supplied by rivers. Cycles in bottom-water oxygenation, which affected organic carbon contents and the amount of bioturbation, were associated with changes in the clay-to-carbonate mud ratio. Walsh power spectra suggest that these cycles were climatically controlled and provide a rapid method for the palaeoclimatic analysis of measured sections. Two orbital cycles are implied, probably related to precession and obliquity, of perhaps 21 and 41 ka (or perhaps 21 and 31 ka).

The mechanism that related climatic and sedimentary cycles is unclear at present. The model used by Rossignol-Strick et al. [51] to explain the formation of Pleistocene sapropels in the Mediterranean may, however, provide an appropriate analogue following Barron et al. [9]. As an extension to this model, Rossignol-Strick [52] suggested that orbital-obliquity cycles indirectly influenced sapropel formation via a mechanism that did not involve ice. Through this analogy, orbitally forced changes in precipitation are related to the sedimentary cyclicity. During low runoff, clay supply may have been so slow that coccolithophore-derived carbonate dominated the sediment. Normal oxygenation allowed bioturbation and led to low organic carbon contents in the sediment. During high runoff, clay supply along with ostracod productivity may have increased relative to the supply of coccolithic carbonate. The surface productivity of coccolith- and of non-coccolith-producing algae may have increased with additional nutrients from the runoff water which indirectly accounts for higher numbers of ostracods. Bottom-water anoxia may have been caused by higher productivity combined with additional terrigenous organic matter and perhaps by density stratification related to a low-salinity surface wedge. The anoxia led to the deposition of laminated and organic carbon-rich sediment. This presumes that greater clay supply exceeded an increased coccolith supply. Comparison of the longest-possible and implied durations for the regular cycles, suggests that the sections are 20–40% complete at best. Sediment was perhaps removed during winter storms or hurricanes, leaving hiatuses in the sections. It is concluded that climatic processes dominated sedimentation at certain localities in the basal Jurassic of southern Britain.

Acknowledgements

I am indebted to H.C. Jenkyns for abundant suggestions, including the faecal pellet hypothesis, and help throughout this project. M.H. Worthington and W. Schwarzacher are thanked for their help with the power spectra. Inspiration to apply Walsh rather than Fourier power spectra was derived from [44] and M.H. Worthington. Permission to enter the Rugby Portland Cement Co. Southam works (Long Itchington) was granted by G. Benham which is greatly appreciated. Thanks are also due to C.F. Elders in particular, as well as J.D. Woodhead, and P.C. Jackson for their criticism of the manuscript. I should also like to thank C. Johnson for geochemical help and S. Baker for his help with the CL. This work was carried out during tenure of a NERC research studentship at Oxford University.
References


17 W. Schwarzacher, An application of statistical time series analysis to a limestone-shale sequence, J. Geol. 72, 195-213, 1964.


19 R.G. Clements and members of the field studies in local geology class. The geology of Long Ickington Quarry (Rugby Portland Cement Co. Ltd., Southam Works), Pericival Guildhall, Rugby and Department of Geology, University of Leicester, 1975.


27 D. Wall, Microplankton, pollen and spores from the lower Jurassic in Britain, Micropaleontology 11, 131-190, 1965.


Comment and Reply on "Origin of minor limestone-shale cycles: Climatically Induced or diagenetic?"

COMMENTS

G. P. Weedon, Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, England

Hallam's (1986a) paper prompts the following remarks, which mostly concern the basal part of the Lias, especially in the Kimmeridge Clay and Kimmeridge Chalk.

1. It has already been shown that it is meaningless to apply power-spectral analysis to limestone-shale sequences based on diagenetic studies (Weedon, 1986). However, a wide variety of internal, external, and field evidence supports the view that some sequences are deposited on the seafloor of Britain in the earliest Jurassic (Hallam, 1964, 1986). Early diagenesis enhanced the primary cyclicity by cementation of the most CaCO₃-rich parts of the light marls and laminated shales, producing homogeneous and laminated limestones (Hallam, 1964). Burrow-mortled contacts between limestones and dark marls are present at every locality, where they are seen, so it is reasonable to assume that all limestones represent diagenetic exaggeration of carbonate-rich levels. More evidence for diagenetic exaggeration of primary variations includes the observation that, if enclosed entirely by limestone, limestone beds and nodules always occupy the same horizon (Weedon, 1986). Evidence against independent rhythmic sedimentation includes the correlation between percent CaCO₃ and percent TOC (carbonate-free) for the marls and shales (Le Roex, 1959).

2. The basal Lias limestones are argillaceous, which perhaps explains the poor preservation of coccoliths in this rock type (Weedon, 1986). Light marls with nodules always occupy the same horizon (Weedon, 1986). Evidence against independent rhythmic sedimentation includes the correlation between percent CaCO₃ and percent TOC (carbonate-free) for the marls and shales (Le Roex, 1959).

3. Hallam's (1986) statements concerning hiatuses are misleading. Evidence for many small gaps has been presented for many Lias sections, including those at Ave (e.g., Donovan and Kellaway, 1984; Kent, 1936; Weedon, 1986). Hallam's (1986a) Figure 2B could be interpreted as showing evidence for more hiatuses at the left-hand column. My earlier suggestion, that the large biostratigraphic gaps are absent when every ammonite zone is present, is probably erroneous, because the ammonite biostratigraphy was modified inside the region in question (D. T. Donovan, personal communication). Large gaps might yet be detected after further work on these rocks.

4. Hallam's (1986a) Figure 3, based on earlier work (Hallam, 1964), can be updated using recent literature, the simple linear relationship between number of limestones and thickness of zone is not supported. For example, at Wissett there are 12 limestone horizons (beds + nodules) in the P. planatus zone, which is 15.73 m thick, and the P. cancellatus subzone is 17.99 m thick and contains 14 limestone horizons (Palmer, 1972). The limestones at Wissett are identical to those described by Hallam (1964, 1986a).

5. I accept Hallam's (1964) view that the limestones are produced by diagenetic enhancement of primary cyclicity. Hallam's recent (1986a) presentation hinges on the nature of the limestones, which he correctly showed to be diagenetic. The fact that the average thickness of diagenetic limestones is less than the shale sequence remains consistent with our understanding of the formation of the limestones. The recent spectral analysis allowed for the influence of diagenesis, and it is reaffirmed that the primary cyclicity (laminated shale/burrowed marl) was produced by Milankovitch forcing (Weedon, 1986).

ACKNOWLEDGMENTS

I thank H. C. Jenkyns for critically reading this manuscript.
5.3 Continued.

REPLY

A. Hallam, Department of Geologi-cal Science, University of Birmingham, Birmingham B15 2TT, England

Although my article (Hallam, 1986a) dealt with more than the Blue Lias, designated a formation rather than a member by the Geological Society of London Stratigraphic Committee (Cope et al., 1980), in this discussion it is right to concentrate on this formation because the correct interpretation of its depositional and diagenetic history has an important bearing on that of many other limestone-shale sequences.

1. There is no doubt that burrow-marl limestone-marl contact and alternations of bioturbated and organic-laminated sediments are evidence of primary environmental differences, but these phenomena are by no means ubiquitous; many limestone-shale alternations reveal no difference, after allowing for compaction, other than CaCO₃ content.

2. The origin of the calcite microspar in the limestones is a problem, but it remains unaccepted that an origin from coccoliths, whose calcium might be expected to be comparatively resistant to dissolution. Are there are, no doubt, even thicker sequences elsewhere with more limestones.

3. There is no dispute that burrow-nestled limestone marl cooccur. In the Blue Lias, northern England and southern Wales across the North-West Lias boundary from more southerly to more northerly facies, a fact that I have interpreted as signifying a regional sea-deepening event (Hallam, 1960). The number of limestones per graptolite biozone must naturally vary considerably less in the Lias succession than in the North-West Lias. As for Weedoo's statement that "expanded parts of particular zones had more beds available for preservation," I fail to see how that term is used.

4. That minor hiatuses are present, within the scale of resolution of ammonite zones, is a fact I would not wish to deny, but it doesn't help Weedoo's argument if there is no independent physical evidence for such hiatuses. To make my point more clearly, let us consider an extreme case. I have interpreted as signifying a regional sea-deepening event. But the same problem arises with respect to the more fully studied southern facies sequence in Dorset, and it cannot be excluded even for Glamorgan, because there are no, or, even thicker sequences elsewhere with more limestones.

5. There is no dispute that burrow-marl limestone-marl contact and alternations of bioturbated and organic-laminated sediments are evidence of primary environmental differences, but these phenomena are by no means ubiquitous; many limestone-shale alternations reveal no difference, after allowing for compaction, other than CaCO₃ content. The origin of the calcite microspar in the limestones is a problem, but it remains unaccepted that an origin from coccoliths, whose calcium might be expected to be comparatively resistant to dissolution. Are there are, no doubt, even thicker sequences elsewhere with more limestones.

6. There is no dispute that burrow-nestled limestone marl cooccur. In the Blue Lias, northern England and southern Wales across the North-West Lias boundary from more southerly to more northerly facies, a fact that I have interpreted as signifying a regional sea-deepening event (Hallam, 1960). The number of limestones per graptolite biozone must naturally vary considerably less in the Lias succession than in the North-West Lias. As for Weedoo's statement that "expanded parts of particular zones had more beds available for preservation," I fail to see how that term is used.

7. In no sense do I wish to discourage quantitative research on stratal sequences that may reveal evidence of orbital cycles, but I think that alternations of bioturbated and laminated beds, signifying variations in degree of bottom-water oxygenation, are much more promising than limestone-shale alternations (Hallam, 1986b). The recognition that the number of ammonite zones in the north-western European Jurassic roughly corresponds to the number of million years assigned to the Jurassic (Hallam, 1986a) may help. The potential error is considerable, and the Blue Lias zone could signify a change from as little as 0.5 my to as much as 2 my. Therefore, estimates of duration will have a considerable bearing on which, if any, of the recognized orbital cycles are held responsible.

COMBINED REFERENCES CITED


APPENDIX FOR CHAPTER 6

TIME SERIES FOR VARIOUS FORMATIONS.
Time series for the Boom Clay Formation, around Antwerp:

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total Thickness</th>
<th>Clay</th>
<th>Silt + Clay</th>
<th>Sand</th>
<th>Clay + Silt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.0</td>
<td>5.0</td>
<td>5.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>20.0</td>
<td>5.0</td>
<td>15.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>30.0</td>
<td>5.0</td>
<td>25.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>40.0</td>
<td>5.0</td>
<td>35.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>50.0</td>
<td>5.0</td>
<td>45.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Code</th>
<th>Time Series</th>
<th>BCO</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>-1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>-1.0</td>
<td></td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>-1.0</td>
<td></td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-0.5</td>
<td></td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>-1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>-1.0</td>
<td></td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>145</td>
<td>-1.0</td>
<td></td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-0.5</td>
<td></td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>1.0</td>
<td>10/10 in Yarmouth, 1778.</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>-1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>1.0</td>
<td></td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>130</td>
<td>-1.0</td>
<td></td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>290</td>
<td>1.0</td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>-1.0</td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>284</td>
<td>1.0</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
6.2 Time series for the Kimmeridge Clay Formation, Kimmeridge.

<table>
<thead>
<tr>
<th>SAMPLE INTERVAL</th>
<th>MEASURED TOTAL THICKNESS = 1650 cm</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>THICKNESS</th>
<th>CODE</th>
<th>TIME SERIES</th>
<th>Zone</th>
<th>BED NAMES</th>
<th>THICKNESS</th>
<th>CODE</th>
<th>TIME SERIES</th>
<th>Zone</th>
<th>BED NAMES</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>62.</td>
<td>-1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44.</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td>105.</td>
<td>-1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28.</td>
<td>-1.65</td>
<td></td>
<td></td>
<td></td>
<td>64.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>703.</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td>19.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>27.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>554.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>34.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>467.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>451.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>16.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>101.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>101.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>75.</td>
<td>-1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>112.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>96.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>24.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42.</td>
<td>-1.5</td>
<td></td>
<td></td>
<td></td>
<td>7.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>10.</td>
<td>-1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>87.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>9.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>43.</td>
<td>-1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>105.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>5.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>111.</td>
<td>-1.</td>
<td></td>
<td></td>
<td></td>
<td>122.</td>
<td>-1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>132.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>190.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>52.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>46.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>9.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>77.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>43.</td>
<td>-1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40.</td>
<td>-1.5</td>
<td></td>
<td></td>
<td></td>
<td>5.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>10.</td>
<td>-1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>651.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>104.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>31.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>217.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>34.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>-1.</td>
<td></td>
<td></td>
<td></td>
<td>77.</td>
<td>-1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65.</td>
<td>-1.5</td>
<td></td>
<td></td>
<td></td>
<td>177.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>-1.</td>
<td></td>
<td></td>
<td></td>
<td>120.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34.</td>
<td>-1.5</td>
<td></td>
<td></td>
<td></td>
<td>161.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>5.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>-1.</td>
<td></td>
<td></td>
<td></td>
<td>7.</td>
<td>-1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>55.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>24.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>118.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>33.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>25.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>40.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>43.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>59.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>22.</td>
<td>-1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>490.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>67.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>12.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>17.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>17.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>43.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37.</td>
<td>-1.</td>
<td></td>
<td></td>
<td></td>
<td>43.</td>
<td>-1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.</td>
<td>-1.25</td>
<td></td>
<td></td>
<td></td>
<td>37.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>122.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>37.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23.</td>
<td>-1.</td>
<td></td>
<td></td>
<td></td>
<td>40.</td>
<td>-1.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td>51.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[Diagram of a chart showing time series and related data]
<table>
<thead>
<tr>
<th>Thickness</th>
<th>Code</th>
<th>Time Series</th>
<th>Zone</th>
<th>Bed Names</th>
<th>Thickness</th>
<th>Code</th>
<th>Time Series</th>
<th>Zone</th>
<th>Bed Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>62.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>204.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>210.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>62.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>74.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>52.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>110.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>167.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>312.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>107.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>58.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>119.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>56.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>61.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>-1.</td>
<td>1.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
- Yellow Ledge Stone Band (Laminated Ledge Stone)
- Grey Ledge Stone Band (Cementstone)
- Cattle Ledge Stone Band (Cementstone)
- Siltstone Zone
- Lower Section Alera
### Time series for the Toarcian section at Breggia Gorge

<table>
<thead>
<tr>
<th>Sample Interval</th>
<th>Thickness Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cm</td>
<td>190 cm</td>
</tr>
</tbody>
</table>

#### Bed Thickness and Code

<table>
<thead>
<tr>
<th>Sample</th>
<th>Code</th>
<th>Time Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed 1</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Bed 2</td>
<td>-1.00</td>
<td>-1.00</td>
</tr>
<tr>
<td>Bed 3</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Bed 4</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Bed 5</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Bed 6</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Bed 7</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Bed 8</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Bed 9</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Bed 10</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Bed 11</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

#### Bed Sequence

<table>
<thead>
<tr>
<th>Bed Number</th>
<th>Time Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed 12</td>
<td>1.00</td>
</tr>
<tr>
<td>Bed 13</td>
<td>1.00</td>
</tr>
<tr>
<td>Bed 14</td>
<td>1.00</td>
</tr>
<tr>
<td>Bed 15</td>
<td>1.00</td>
</tr>
<tr>
<td>Bed 16</td>
<td>1.00</td>
</tr>
</tbody>
</table>

#### Bed Interval

- **190 cm**
- **-1.00 cm**
- **1.00 cm**
- **-1.00 cm**
- **1.00 cm**
- **-1.00 cm**
- **1.00 cm**
- **-1.00 cm**
- **1.00 cm**
- **-1.00 cm**
- **1.00 cm**
- **-1.00 cm**
- **1.00 cm**
- **-1.00 cm**
- **1.00 cm**
- **-1.00 cm**
- **1.00 cm**
- **-1.00 cm**
- **1.00 cm**
- **-1.00 cm**
- **1.00 cm**
- **-1.00 cm**
- **1.00 cm**
- **-1.00 cm**
- **1.00 cm**
<table>
<thead>
<tr>
<th>Thickness</th>
<th>Core</th>
<th>Time Series</th>
<th>Grid</th>
<th>Thickness</th>
<th>Core</th>
<th>Time Series</th>
<th>Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>2.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>3.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>1.0</td>
<td></td>
<td></td>
<td>4.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>5.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>6.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>7.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>8.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>1.0</td>
<td></td>
<td></td>
<td>9.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>10.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>11.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>12.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>13.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>14.</td>
<td>-1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>1.0</td>
<td></td>
<td></td>
<td>15.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>16.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>1.0</td>
<td></td>
<td></td>
<td>17.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>18.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>19.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>1.0</td>
<td></td>
<td></td>
<td>20.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>1.0</td>
<td></td>
<td></td>
<td>21.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>22.</td>
<td>-1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>23.</td>
<td>-1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>24.</td>
<td>-1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>25.</td>
<td>-1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>26.</td>
<td>-1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>27.</td>
<td>-1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>28.</td>
<td>-1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>29.</td>
<td>-1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>-1.0</td>
<td></td>
<td></td>
<td>30.</td>
<td>-1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>Time</td>
<td>Relative Humidity</td>
<td>Thickness</td>
<td>Time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>------</td>
<td>-------------------</td>
<td>-----------</td>
<td>------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>0</td>
<td>90%</td>
<td>0.15</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>0</td>
<td>80%</td>
<td>0.10</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>0</td>
<td>70%</td>
<td>0.05</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>0</td>
<td>60%</td>
<td>0.00</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>5</td>
<td>90%</td>
<td>0.15</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>5</td>
<td>80%</td>
<td>0.10</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>5</td>
<td>70%</td>
<td>0.05</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>5</td>
<td>60%</td>
<td>0.00</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>10</td>
<td>90%</td>
<td>0.15</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>10</td>
<td>80%</td>
<td>0.10</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>10</td>
<td>70%</td>
<td>0.05</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>10</td>
<td>60%</td>
<td>0.00</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>15</td>
<td>90%</td>
<td>0.15</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>15</td>
<td>80%</td>
<td>0.10</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>15</td>
<td>70%</td>
<td>0.05</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>15</td>
<td>60%</td>
<td>0.00</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>20</td>
<td>90%</td>
<td>0.15</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>20</td>
<td>80%</td>
<td>0.10</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>20</td>
<td>70%</td>
<td>0.05</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>20</td>
<td>60%</td>
<td>0.00</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 6.4 Time series for the Upper Pliensbachian section at Breggia Gorge

**Sample Interval:** 1 mm  
**Time Series:** 14.5 mm  
**Total Thickness:** 145 mm

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>115</td>
<td>1.00</td>
<td>1113</td>
<td>50.0</td>
<td>1.00</td>
<td>1097</td>
</tr>
<tr>
<td>38</td>
<td>-1.00</td>
<td>1114</td>
<td>15.0</td>
<td>-1.00</td>
<td>1076</td>
</tr>
<tr>
<td>60</td>
<td>1.00</td>
<td>1119</td>
<td>185.0</td>
<td>1.00</td>
<td>119</td>
</tr>
<tr>
<td>2</td>
<td>-1.00</td>
<td>1122</td>
<td>10.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>1.00</td>
<td>1111</td>
<td>114.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>-1.00</td>
<td>1110</td>
<td>11.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td></td>
<td>59.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>-1.00</td>
<td>1109</td>
<td>2.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>1.00</td>
<td></td>
<td>30.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>-1.00</td>
<td></td>
<td>1.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>119</td>
<td>1.00</td>
<td>1108</td>
<td>59.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>-1.00</td>
<td>1107</td>
<td>1.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>219</td>
<td>1.00</td>
<td>1106</td>
<td>111.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>-1.00</td>
<td></td>
<td>10.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>113</td>
<td>1.00</td>
<td></td>
<td>180.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-1.00</td>
<td>1105</td>
<td>3.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>165</td>
<td>1.00</td>
<td></td>
<td>75.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-1.00</td>
<td></td>
<td>1.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>193</td>
<td>1.00</td>
<td>1104</td>
<td>257.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-1.00</td>
<td>1103</td>
<td>25.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>1.00</td>
<td></td>
<td>47.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>-1.00</td>
<td></td>
<td>15.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>117</td>
<td>1.00</td>
<td></td>
<td>251.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-1.00</td>
<td></td>
<td>15.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>119</td>
<td>1.00</td>
<td>1101</td>
<td>72.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>-1.00</td>
<td>1100</td>
<td>14.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>1.00</td>
<td></td>
<td>64.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-1.00</td>
<td></td>
<td>22.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>185</td>
<td>1.00</td>
<td></td>
<td>56.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>-1.00</td>
<td></td>
<td>10.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>1.00</td>
<td></td>
<td>224.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>-1.00</td>
<td></td>
<td>22.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>1.00</td>
<td></td>
<td>105.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-1.00</td>
<td></td>
<td>28.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>224</td>
<td>1.00</td>
<td></td>
<td>77.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-1.00</td>
<td></td>
<td>27.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>1.00</td>
<td></td>
<td>41.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-1.00</td>
<td></td>
<td>1.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>229</td>
<td>1.00</td>
<td></td>
<td>41.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>-1.00</td>
<td></td>
<td>10.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>138</td>
<td>1.00</td>
<td></td>
<td>45.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>-1.00</td>
<td></td>
<td>10.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>1.00</td>
<td></td>
<td>12.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>-1.00</td>
<td></td>
<td>78.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1.00</td>
<td></td>
<td>18.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-1.00</td>
<td></td>
<td>57.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>165</td>
<td>1.00</td>
<td></td>
<td>10.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>-1.00</td>
<td></td>
<td>35.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>116</td>
<td>1.00</td>
<td></td>
<td>13.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>226</td>
<td>-1.00</td>
<td></td>
<td>31.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>1.00</td>
<td></td>
<td>35.0</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-1.00</td>
<td></td>
<td>10.0</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>-------</td>
<td>-----------------</td>
<td>----------</td>
<td>-------</td>
<td>-----------------</td>
</tr>
<tr>
<td>50</td>
<td>+1.00</td>
<td>1029</td>
<td>1030</td>
<td>-1.00</td>
<td>1031</td>
</tr>
<tr>
<td>13</td>
<td>+1.00</td>
<td>1071</td>
<td>1072</td>
<td>-1.00</td>
<td>1073</td>
</tr>
<tr>
<td>13</td>
<td>+1.00</td>
<td>1075</td>
<td>1076</td>
<td>-1.00</td>
<td>1077</td>
</tr>
<tr>
<td>25</td>
<td>+1.00</td>
<td>1079</td>
<td>1080</td>
<td>-1.00</td>
<td>1081</td>
</tr>
<tr>
<td>5</td>
<td>+1.00</td>
<td>1083</td>
<td>1084</td>
<td>-1.00</td>
<td>1085</td>
</tr>
<tr>
<td>45</td>
<td>+1.00</td>
<td>1087</td>
<td>1088</td>
<td>-1.00</td>
<td>1089</td>
</tr>
<tr>
<td>15</td>
<td>+1.00</td>
<td>1091</td>
<td>1092</td>
<td>-1.00</td>
<td>1093</td>
</tr>
<tr>
<td>35</td>
<td>+1.00</td>
<td>1095</td>
<td>1096</td>
<td>-1.00</td>
<td>1097</td>
</tr>
<tr>
<td>12</td>
<td>+1.00</td>
<td>1099</td>
<td>1100</td>
<td>-1.00</td>
<td>1101</td>
</tr>
<tr>
<td>20</td>
<td>+1.00</td>
<td>1103</td>
<td>1104</td>
<td>-1.00</td>
<td>1105</td>
</tr>
<tr>
<td>35</td>
<td>+1.00</td>
<td>1107</td>
<td>1108</td>
<td>-1.00</td>
<td>1109</td>
</tr>
<tr>
<td>11</td>
<td>+1.00</td>
<td>1111</td>
<td>1112</td>
<td>-1.00</td>
<td>1113</td>
</tr>
<tr>
<td>305</td>
<td>+1.00</td>
<td>1115</td>
<td>1116</td>
<td>-1.00</td>
<td>1117</td>
</tr>
<tr>
<td>35</td>
<td>+1.00</td>
<td>1119</td>
<td>1120</td>
<td>-1.00</td>
<td>1121</td>
</tr>
<tr>
<td>285</td>
<td>+1.00</td>
<td>1123</td>
<td>1124</td>
<td>-1.00</td>
<td>1125</td>
</tr>
<tr>
<td>18</td>
<td>+1.00</td>
<td>1127</td>
<td>1128</td>
<td>-1.00</td>
<td>1129</td>
</tr>
<tr>
<td>40</td>
<td>+1.00</td>
<td>1131</td>
<td>1132</td>
<td>-1.00</td>
<td>1133</td>
</tr>
<tr>
<td>35</td>
<td>+1.00</td>
<td>1135</td>
<td>1136</td>
<td>-1.00</td>
<td>1137</td>
</tr>
<tr>
<td>50</td>
<td>+1.00</td>
<td>1139</td>
<td>1140</td>
<td>-1.00</td>
<td>1141</td>
</tr>
<tr>
<td>20</td>
<td>+1.00</td>
<td>1143</td>
<td>1144</td>
<td>-1.00</td>
<td>1145</td>
</tr>
<tr>
<td>35</td>
<td>+1.00</td>
<td>1147</td>
<td>1148</td>
<td>-1.00</td>
<td>1149</td>
</tr>
<tr>
<td>11</td>
<td>+1.00</td>
<td>1151</td>
<td>1152</td>
<td>-1.00</td>
<td>1153</td>
</tr>
<tr>
<td>304</td>
<td>+1.00</td>
<td>1155</td>
<td>1156</td>
<td>-1.00</td>
<td>1157</td>
</tr>
<tr>
<td>160</td>
<td>+1.00</td>
<td>1159</td>
<td>1160</td>
<td>-1.00</td>
<td>1161</td>
</tr>
<tr>
<td>27</td>
<td>+1.00</td>
<td>1163</td>
<td>1164</td>
<td>-1.00</td>
<td>1165</td>
</tr>
<tr>
<td>59</td>
<td>+1.00</td>
<td>1167</td>
<td>1168</td>
<td>-1.00</td>
<td>1169</td>
</tr>
<tr>
<td>18</td>
<td>+1.00</td>
<td>1171</td>
<td>1172</td>
<td>-1.00</td>
<td>1173</td>
</tr>
<tr>
<td>73</td>
<td>+1.00</td>
<td>1175</td>
<td>1176</td>
<td>-1.00</td>
<td>1177</td>
</tr>
<tr>
<td>60</td>
<td>-1.00</td>
<td>1179</td>
<td>1180</td>
<td>-1.00</td>
<td>1181</td>
</tr>
<tr>
<td>58</td>
<td>-1.00</td>
<td>1183</td>
<td>1184</td>
<td>-1.00</td>
<td>1185</td>
</tr>
<tr>
<td>45</td>
<td>-1.00</td>
<td>1187</td>
<td>1188</td>
<td>-1.00</td>
<td>1189</td>
</tr>
<tr>
<td>315</td>
<td>-1.00</td>
<td>1191</td>
<td>1192</td>
<td>-1.00</td>
<td>1193</td>
</tr>
<tr>
<td>36</td>
<td>-1.00</td>
<td>1195</td>
<td>1196</td>
<td>-1.00</td>
<td>1197</td>
</tr>
<tr>
<td>175</td>
<td>+1.00</td>
<td>1199</td>
<td>1200</td>
<td>-1.00</td>
<td>1201</td>
</tr>
<tr>
<td>74</td>
<td>-1.00</td>
<td>1203</td>
<td>1204</td>
<td>-1.00</td>
<td>1205</td>
</tr>
<tr>
<td>70</td>
<td>-1.00</td>
<td>1207</td>
<td>1208</td>
<td>-1.00</td>
<td>1209</td>
</tr>
<tr>
<td>28</td>
<td>-1.00</td>
<td>1211</td>
<td>1212</td>
<td>-1.00</td>
<td>1213</td>
</tr>
<tr>
<td>105</td>
<td>+1.00</td>
<td>1215</td>
<td>1216</td>
<td>-1.00</td>
<td>1217</td>
</tr>
<tr>
<td>34</td>
<td>-1.00</td>
<td>1219</td>
<td>1220</td>
<td>-1.00</td>
<td>1221</td>
</tr>
<tr>
<td>225</td>
<td>-1.00</td>
<td>1223</td>
<td>1224</td>
<td>-1.00</td>
<td>1225</td>
</tr>
<tr>
<td>17</td>
<td>-1.00</td>
<td>1227</td>
<td>1228</td>
<td>-1.00</td>
<td>1229</td>
</tr>
<tr>
<td>51</td>
<td>+1.00</td>
<td>1231</td>
<td>1232</td>
<td>-1.00</td>
<td>1233</td>
</tr>
<tr>
<td>93</td>
<td>-1.00</td>
<td>1235</td>
<td>1236</td>
<td>-1.00</td>
<td>1237</td>
</tr>
<tr>
<td>71</td>
<td>+1.00</td>
<td>1239</td>
<td>1240</td>
<td>-1.00</td>
<td>1241</td>
</tr>
<tr>
<td>39</td>
<td>-1.00</td>
<td>1243</td>
<td>1244</td>
<td>-1.00</td>
<td>1245</td>
</tr>
<tr>
<td>88</td>
<td>-1.00</td>
<td>1247</td>
<td>1248</td>
<td>-1.00</td>
<td>1249</td>
</tr>
<tr>
<td>45</td>
<td>-1.00</td>
<td>1251</td>
<td>1252</td>
<td>-1.00</td>
<td>1253</td>
</tr>
<tr>
<td>7</td>
<td>-1.00</td>
<td>1255</td>
<td>1256</td>
<td>-1.00</td>
<td>1257</td>
</tr>
<tr>
<td>32</td>
<td>-1.00</td>
<td>1259</td>
<td>1260</td>
<td>-1.00</td>
<td>1261</td>
</tr>
<tr>
<td>19</td>
<td>-1.00</td>
<td>1263</td>
<td>1264</td>
<td>-1.00</td>
<td>1265</td>
</tr>
<tr>
<td>34</td>
<td>-1.00</td>
<td>1267</td>
<td>1268</td>
<td>-1.00</td>
<td>1269</td>
</tr>
</tbody>
</table>
### 6.5 Time series for the Middle Pliensbachian section at Breggia Gorge

<table>
<thead>
<tr>
<th>Thichness</th>
<th>Code</th>
<th>Thickness</th>
<th>RCP</th>
<th>Zone</th>
<th>Thichness</th>
<th>Code</th>
<th>Thickness</th>
<th>RCP</th>
<th>Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>94</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>148</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>131</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Sample interval:** 1 cm

**Total thickness:** 1731 cm

**Limestone:** 100%

**Marl:** 0%

**Scale:** 1 cm
Time series for the Belemnite Marl, Charmouth.
6.7 Time series for the 'Siliceous Shales', Robin Hood's Bay.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Code</th>
<th>Time Series</th>
<th>Bed No.</th>
<th>Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.</td>
<td>-1.00</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>85.</td>
<td>-1.00</td>
<td>32</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>16.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32.</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23.</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.</td>
<td>-1.00</td>
<td>58</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>1.00</td>
<td>34</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>-1.00</td>
<td>10.</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>102.</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>58.</td>
<td>0.00</td>
<td>18.</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>34.</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44.</td>
<td>-1.00</td>
<td>40</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>76.</td>
<td>0.00</td>
<td>19</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>19.</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40.</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>0.00</td>
<td>131</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>-1.00</td>
<td>91</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>56.</td>
<td>1.00</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30.</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>72.</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>-1.00</td>
<td>19</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>19.</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100.</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>-1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- From HALLAM, 1970
6.8 Time series for the Upper Birkhill Shales, Dob's Linn.

**THICKNESS** = 7.29 m

**Petrographic Claystone** = 69.3 %

<table>
<thead>
<tr>
<th>Thickness (cm)</th>
<th>Code</th>
<th>Time Series</th>
<th>Petrographic Claystone</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0</td>
<td>-1.00</td>
<td>6.8 Time series</td>
<td>7.68 m</td>
</tr>
<tr>
<td>4.6</td>
<td>1.00</td>
<td>BEAK</td>
<td>9.0</td>
</tr>
<tr>
<td>5.2</td>
<td>-1.00</td>
<td>GAIA</td>
<td>3.0</td>
</tr>
<tr>
<td>5.1</td>
<td>1.00</td>
<td>CLAYMARLE</td>
<td>1.0</td>
</tr>
<tr>
<td>3.0</td>
<td>-1.00</td>
<td>17.</td>
<td>-1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>-1.00</td>
<td>14.</td>
<td>-1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>12.</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>-1.00</td>
<td>4.</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>2.</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>-1.00</td>
<td>139.</td>
<td>1.00</td>
</tr>
<tr>
<td>135.</td>
<td>1.00</td>
<td>6.</td>
<td>-1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>-1.00</td>
<td>2.</td>
<td>1.00</td>
</tr>
<tr>
<td>4.0</td>
<td>-1.00</td>
<td>11.</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>1.</td>
<td>-1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>3.</td>
<td>1.00</td>
</tr>
<tr>
<td>4.3</td>
<td>-1.00</td>
<td>174.</td>
<td>1.00</td>
</tr>
<tr>
<td>9.0</td>
<td>1.00</td>
<td>1.</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>-1.00</td>
<td>26.</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>2.</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>-1.00</td>
<td>17.</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>1.</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>-1.00</td>
<td>86.</td>
<td>1.00</td>
</tr>
<tr>
<td>17.0</td>
<td>1.00</td>
<td>128.</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>-1.00</td>
<td>57.</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>9.</td>
<td>1.00</td>
</tr>
<tr>
<td>26.0</td>
<td>1.00</td>
<td>26.</td>
<td>1.00</td>
</tr>
<tr>
<td>4.0</td>
<td>-1.00</td>
<td>3.</td>
<td>1.00</td>
</tr>
<tr>
<td>3.0</td>
<td>1.00</td>
<td>68.</td>
<td>1.00</td>
</tr>
<tr>
<td>4.4</td>
<td>-1.00</td>
<td>2.</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>30.</td>
<td>-1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>-1.00</td>
<td>39.</td>
<td>-1.00</td>
</tr>
<tr>
<td>10.0</td>
<td>1.00</td>
<td>6.</td>
<td>-1.00</td>
</tr>
<tr>
<td>9.0</td>
<td>1.00</td>
<td>2.</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>-1.00</td>
<td>41.</td>
<td>-1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>12.</td>
<td>1.00</td>
</tr>
<tr>
<td>9.0</td>
<td>1.00</td>
<td>14.</td>
<td>-1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>3.</td>
<td>1.00</td>
</tr>
<tr>
<td>5.0</td>
<td>-1.00</td>
<td>12.</td>
<td>-1.00</td>
</tr>
<tr>
<td>131.</td>
<td>1.00</td>
<td>289.</td>
<td>1.00</td>
</tr>
<tr>
<td>7.0</td>
<td>-1.00</td>
<td>6.</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>4.</td>
<td>1.00</td>
</tr>
<tr>
<td>3.0</td>
<td>1.00</td>
<td>1.</td>
<td>-1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>66.</td>
<td>1.00</td>
</tr>
<tr>
<td>9.0</td>
<td>1.00</td>
<td>5.</td>
<td>-1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>55.</td>
<td>1.00</td>
</tr>
<tr>
<td>154.</td>
<td>1.00</td>
<td>2.</td>
<td>1.00</td>
</tr>
<tr>
<td>TIME Zone</td>
<td>TIME SMALL</td>
<td>TIME LARGE</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>------------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>-1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32.</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>-1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>-1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>-1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>41.</td>
<td>-1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>-1.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>