

Wenlock cyclicity, palynology, and stratigraphy in the Buildwas, Coalbrookdale, and Much Wenlock Limestone formations, Shropshire, England

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ABSTRACT – *In the type area of the Wenlock Series in Shropshire, England, carbonate/mudstone cyclicity is recognizable at five different orders of magnitude. The first order cycle covers the Silurian, with a general decline in carbonate following the late Ordovician glaciation, a carbonate maximum represented by the Much Wenlock Limestone Formation, and decreasing carbonate in the late Silurian. The second order of cyclicity is represented by conspicuous carbonate intervals in the Buildwas and Much Wenlock Limestone formations. Minor increases in carbonate which represent third order cycles are noted at intervals within the Apedale and Farley members of the Coalbrookdale Formation. The second and some third order cycles are comparable in magnitude to Primo and Secundo episodes and events. The Farley Member of the Coalbrookdale Formation at Farley Dingle, contains 176 couplets in 20 m of nodular argillaceous limestone and calcareous mudstone. Variations of nodular limestone thicknesses in the couplets enable subdivision of the Farley Member into 16 fourth order cycles possibly related to orbital obliquity or precession cycles. Fifth order cycles within the Farley Member are considered to represent dilution cycles deposited over 1650 to 3300 years. The type Wenlock succession contains palynomorph assemblages of low geothermal alteration with diverse, well preserved acritarchs together with chitinozoans. A new acritarch species, *Tunisphaeridium farleyense* described herein forms up to 15% of the Farley Member's acritarch assemblage. Quantitatively the palynological assemblages reflect alternations in acritarch abundance for all orders of cyclicity; significant qualitative palynofloral changes are evident in the second and third orders of cyclicity.*

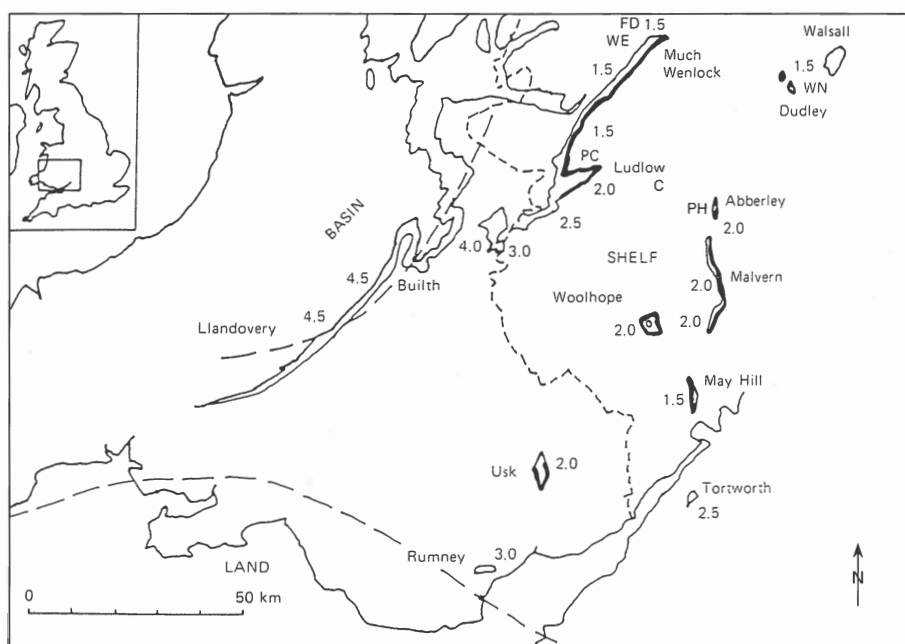
RIASSUNTO – [Ciclicità, palinologia e stratigrafia del Wenlock nelle formazioni di Buildwas, Coalbrookdale e del Calcare di Much Wenlock, Shropshire, England] – *Nell'area tipo della Serie del Wenlock (Shropshire), la ciclicità carbonati/argilliti è stata riconosciuta a cinque differenti ordini di grandezza. Il ciclo di primo ordine copre il Siluriano, con: a) un generale declino nei carbonati che segue la glaciazione del tardo Ordoviciano; b) un massimo dei carbonati rappresentato dalla Formazione del Calcare di Much Wenlock; c) un declino dei carbonati nel tardo Siluriano. Il secondo ordine di ciclicità è rappresentato da cospicue intercalazioni carbonatiche che si trovano nelle formazioni di Buildwas e del Calcare di Much Wenlock. In aggiunta, un minore aumento in carbonato, che rappresenta cicli di terzo ordine, è stato notato ad intervalli nei membri di Apedale e di Farley della Formazione Coalbrookdale. I cicli di secondo e alcuni cicli del terzo ordine sono comparabili in ampiezza agli episodi ed eventi Primo e Secundo. Il Membro di Farley della Formazione Coalbrookdale a Farley Dingle contiene in 20 metri 176 alternanze ritmiche calcari argillosi nodulari-argilliti calcaree. Variazioni nello spessore dei calcari nodulari nei ritmi permettono di suddividere il Membro di Farley in 16 cicli di quarto ordine forse correlati all'obliquità orbitale o ai cicli di precessione. Cicli di quinto ordine all'interno del Membro di Farley sono ipotizzati rappresentare cicli di diluizione depositi in 1650-3300 anni. La successione tipo del Wenlock contiene associazioni palinifere a bassa alterazione geotermale, con ben preservati e diversificati acritarchi insieme a chitinozoi. Una nuova specie di acritarchi *Tunisphaeridium farleyense*, descritta in questo lavoro, forma fino al 15% delle associazioni ad acritarchi del Membro di Farley. Quantitativamente, le associazioni palinologiche riflettono le fluttuazioni in abbondanza degli acritarchi, per tutti gli ordini di ciclicità, con significativi cambiamenti qualitativi delle palinoflore evidenti al secondo e terzo ordine di ciclicità.*

INTRODUCTION

Wenlock sediments occur over a wide shelf area of the southern Welsh Borderlands and English Midlands, including the Wenlock type sections and adjacent areas in Ape Dale and along Wenlock Edge (Text-fig. 1). Sedimentation was apparently continuous from the Llandovery/Wenlock boundary through to the highest Wenlock. The type Wenlock is divided into the Buildwas, Coalbrookdale, and Much Wenlock Limestone formations (Text-fig. 2).

The Wenlock sediments comprise silty mudrocks with subordinate argillaceous limestones. The calcareous mudstone horizons always contain less carbonate than the adjacent nodular limestones.

Throughout the Wenlock type area and Welsh Borderlands, these intervals with limestone horizons are commonly developed within the early Wenlock Buildwas Formation and correlative Woolhope Limestone and in the late Wenlock Much Wenlock Limestone Formation. The Farley Member, the upper part of the Coalbrookdale Formation, shows a general increase in carbonate prior to deposition of the Much Wenlock Limestone Formation. Cycles within the Wenlock are recognizable from both lithological and palynological variations. The definition of cyclicity used here is of oscillatory cycles between calcareous mudstone increasing in carbonate to argillaceous limestone with subsequent decrease to calcareous mudstone. The first order of cyclicity is the largest



Text-fig. 1 - Outcrop distribution of the Wenlock Series in South Wales and the Welsh Borderlands. Much Wenlock Limestone Formation outcrop in black. Numbers refer to thermal alteration index (TAI). Localities: C = Collington, FD = Farley Dingle, PH = Pennyhill, PC = Pitch Coppice, WE = Wenlock Edge, WN = Wren's Nest.

recognized, descending to the smallest, fifth order cycle. Variations in thickness of individual calcareous units follow the cyclic pattern and within this, the recognition of argillaceous limestone vs. calcareous mudstone is particularly important. With increased carbonate, nodular horizons often coalesce to form individual limestone horizons as in parts of the Farley Member of the Coalbrookdale Formation and Much Wenlock Limestone Formation.

WENLOCK STRATIGRAPHY

Thicknesses of Wenlock sediments along Wenlock Edge vary between *ca.* 265 m and 325 m (Bassett *et al.*, 1975). In some areas of the southeast Welsh Borderlands, Wenlock thickness increases to 290-430 m at Woolhope, Herefordshire, and to 270-390 m at May Hill, Gloucestershire (Bassett, 1974). Although these sediments mainly comprise monotonous calcareous silty mudstones and subordinate argillaceous limestones, an exception can be seen in the development of bioclastic limestones within the uppermost Much Wenlock Limestone Formation along the northern part of Wenlock Edge. Biostratigraphy of the Wenlock is based on graptolites (Bassett *et al.*, 1975), acritarchs (Dorning, 1981a; Dorning & Bell, 1987), and chitinozoans (Dorning, 1981b; Verniers *et al.*, 1997) (Text-fig. 2).

GEOCHRONOLOGY

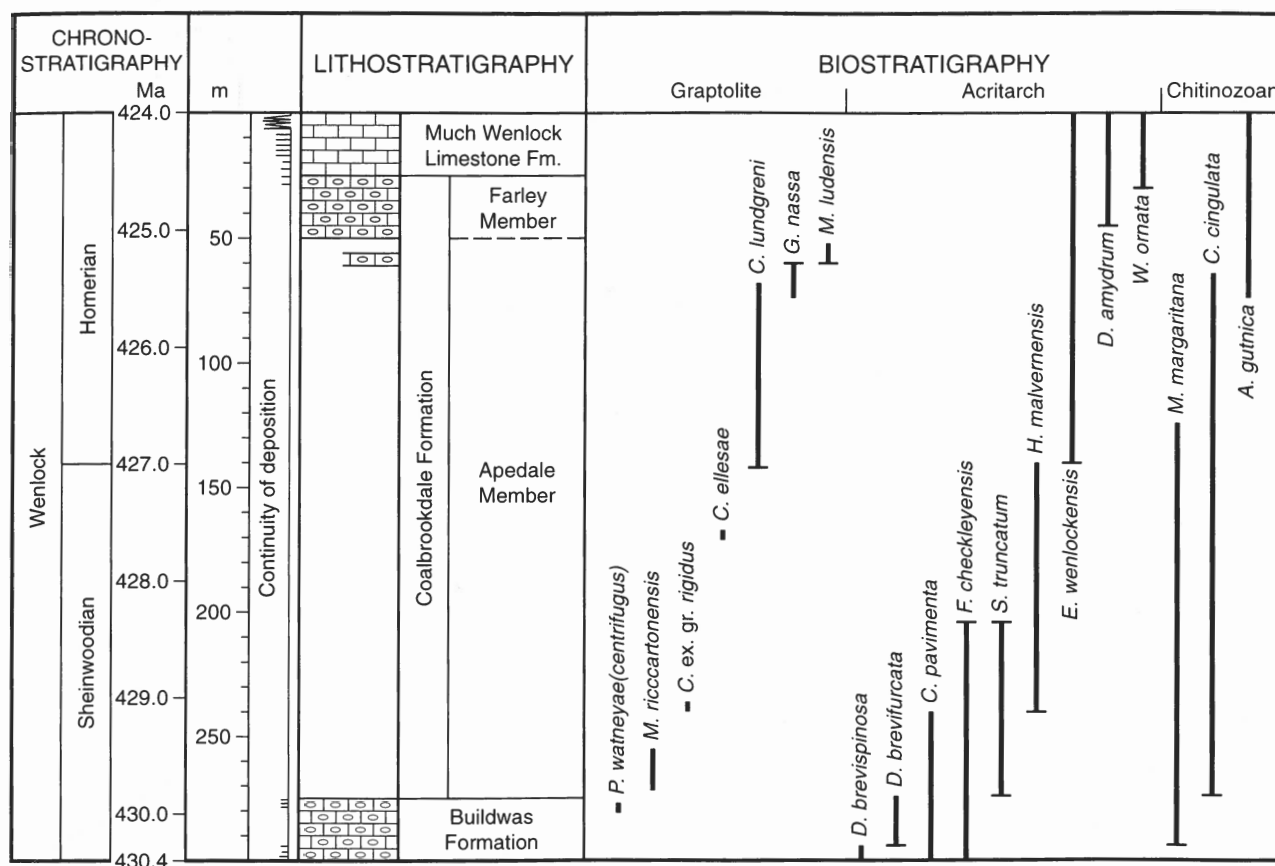
Harland *et al.* (1990) considered the duration of the Wenlock to be 6.4 Ma. Bassett (1989) and Tucker *et al.* (1990) suggested 5 Ma and 4 Ma respectively. In

assessing the duration of the Wenlock cycles, the geochronology of the Wenlock has been reviewed, and dates recalculated to a 2 sigma standard of error.

Harland *et al.* (1990) estimated the Wenlock/Ludlow boundary at 424 ± 8 Ma based on K-Ar in biotite of a sample from Millichope, Shropshire (Odin, Hurford *et al.*, 1986). The base of the Wenlock was estimated at 430.4 Ma (Harland *et al.*, 1990) from an equal-averaged duration of the graptolite biozones from the Ludlow/Wenlock boundary (424.0 Ma) to basal Llandovery (439.0 Ma). This projected age of 430.4 Ma for the Llandovery/Wenlock boundary is close to the estimated age of 430.5 ± 6 Ma based on a K-Ar biotite sample from Ireviken 3 in Gotland, Sweden. Assuming the nine graptolite biozones of the Wenlock are of equal duration, Harland *et al.* (1990) estimated the base of the Homerian to be 426.1 Ma, compatible with 425.8 ± 6 Ma for a K-Ar biotite sample from Horsne 3 in the mid Homerian Halla Beds of Gotland. The age of 427.4 ± 6 Ma for the K-Ar biotite from the Mulde Beds of Djupvik 1 on the west coast of Gotland appears to be a little older than expected (Odin, Hunziker *et al.*, 1986). Given a total Silurian duration of 30.5 Ma (Harland *et al.*, 1990) divided between the four series, the Wenlock is likely to extend over an interval totalling between 4 Ma and 8 Ma.

PALYNOLOGICAL TECHNIQUES

Standard palynological preparation techniques were used for the liberation and concentration of palynomorphs. The sediments were disintegrated and digested in hydrochloric acid, then a hydrofluoric and



Text-fig. 2 - Lithostratigraphy, biostratigraphy, and chronostratigraphy within the type area of the Wenlock Series. Standardized datum is taken at top of Much Wenlock Limestone Formation. Stratigraphy and graptolites after Bassett *et al.*, 1975.

hydrochloric acid mixture, followed by treatment with 35% nitric acid to remove pyrite. All samples were processed and mounted quantitatively on microslides to provide abundance values as numbers per gram. Over 140 stratigraphical samples were processed. Over 1000 specimens were counted per sample.

RESULTS

PALYNOLOGICAL ASSEMBLAGES

The Buildwas, Coalbrookdale, and Much Wenlock Limestone formations in the type area contain moderate numbers of well-preserved acritarchs and chitinozoans. Acanthomorph acritarchs are particularly common throughout and include *Diexallophasis* Loeblich, 1970, *Micrhystridium* Deflandre, 1937, and *Multiplicisphaeridium* Staplin, 1961. Chitinozoans are recorded from most samples, characteristically *Ancyrochitina* Eisenack, 1955, *Conochitina* Eisenack, 1931, and *Cingulochitina* Paris, 1981. The established acritarch biozonation (Dorning, 1981; Dorning & Bell, 1987) is based upon the

first appearance of distinctive acritarch species at specific horizons. From the base of the Wenlock these are the *Deunffia brevispinosa*, *Deunffia brevisfurcata*, *Cymatiosphaera pavimenta*, *Helosphaeridium malvernensis*, *Eisenackidium wenlockensis*, and *Dictyotidium amydrum* Biozones (Text-fig. 2). Swire (1993) referred to some of these as total-range biozones, though for stability in recognition with the potential for modification, definition based on the first appearance of a given species is considered preferable.

The base of the Wenlock can be recognized by the first appearance of *Deunffia brevispinosa* Downie, 1960, which is often accompanied by *D. ramusculosa* Downie, 1960. Within the Buildwas Formation there is the first appearance of *D. brevisfurcata* Hill, 1974 and *D. furcata* Downie, 1960 which are recorded throughout most of that formation. The *Cymatiosphaera pavimenta* Biozone (Dorning & Bell, 1987) is probably best identified by the first appearance of *Salopidium truncatum* Swire, 1993 because *C. pavimenta* (Deflandre) Deflandre, 1954 can be difficult to distinguish from other small species of the genus. This biozone is apparently equivalent in part

to the *riccartonensis* Graptolite Biozone. The introduction of *Helosphaeridium malvernensis* Dorning, 1981 can be used to recognize the higher part of the *C. pavimenta* Biozone. It is considered herein as a first appearance biozone, rather than the total range biozone (Swire, 1993). The lower part of this biozone often contains *Salopidium truncatum* and *Fracturicoronula checkleyensis* (Dorning) Swire, 1993. The higher part apparently includes the *ellesae* Graptolite Biozone.

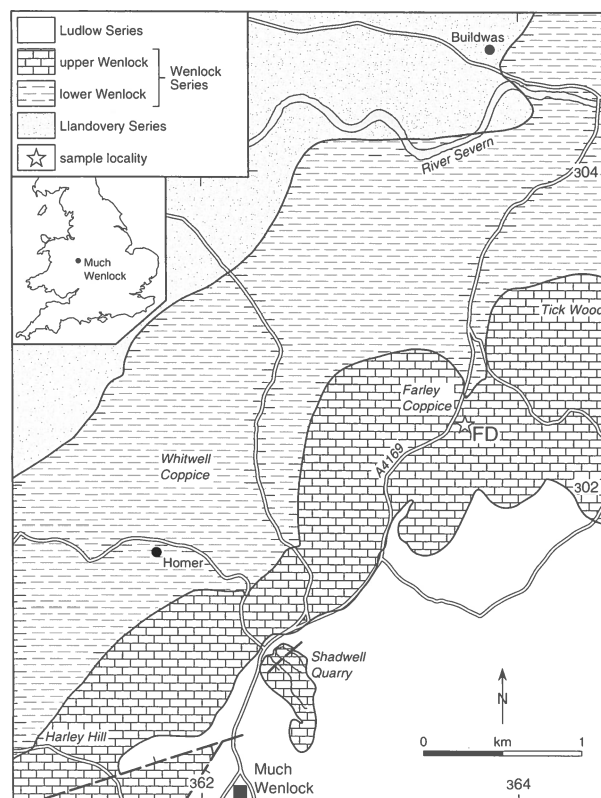
Eisenackidium wenlockensis Dorning, 1981 is introduced at the base of the Homerian, at the same horizon as the base of the *lundgreni* Graptolite Biozone. The first appearance of *Dictyotidium amydrum* (Tappan & Loeblich) Cramer & Diez, 1977 is followed by that of *Wrensnestia ornata* Dorning, 1981 later in the Homerian. One species of *Tunisphaeridium* Deunff & Evitt, 1968, encountered abundantly in the Farley Member, is newly described herein.

CYCLICITY

A broad first order cyclicity can be recognized through the entire Silurian of the Welsh Borderlands. The Silurian is part of a major sequence stratigraphic first order cycle of deposition which followed the late Ordovician glaciation in the mid Hirnantian and apparently continued into the Early Devonian. The late Wenlock represents the highest amount of carbonate compared to intervals of increased carbonate in the early Telychian *Pentamerus* Beds and late Gorstian Aymestry Limestone. Four different orders of magnitude of cyclicity occur within the Wenlock on the basis of relative carbonate content.

The second order cyclicity is noticeable as an increase in carbonate from the late Llandovery Purple Shales into the early Wenlock Buildwas Formation and correlative Woolhope Limestone (Text-fig. 7). The second major increase in carbonate deposition at the end of the Wenlock forms the Much Wenlock Limestone Formation, which is followed by the less calcareous early Ludlow Lower Elton Formation. Between the Buildwas and Much Wenlock Limestone formations, the generally less calcareous Apedale Member of the Coalbrookdale Formation lacks major limestone units. The Buildwas and Much Wenlock Limestone formations contain diverse acritarch assemblages with significant abundances of acanthomorph acritarchs typical of open marine shelf environments (Dorning, 1981c). Within the Apedale Member, however, some acritarch suites are of low diversity and are dominated by *Leiosphaeridia* Eisenack, 1958, suggesting deeper water conditions (Dorning, 1981c). This interval is characterized by increases in the chitinozoan *Cingulochitina cingulata* (Eisenack) Paris, 1981 which is believed to favour deeper water settings (Dorning, 1987).

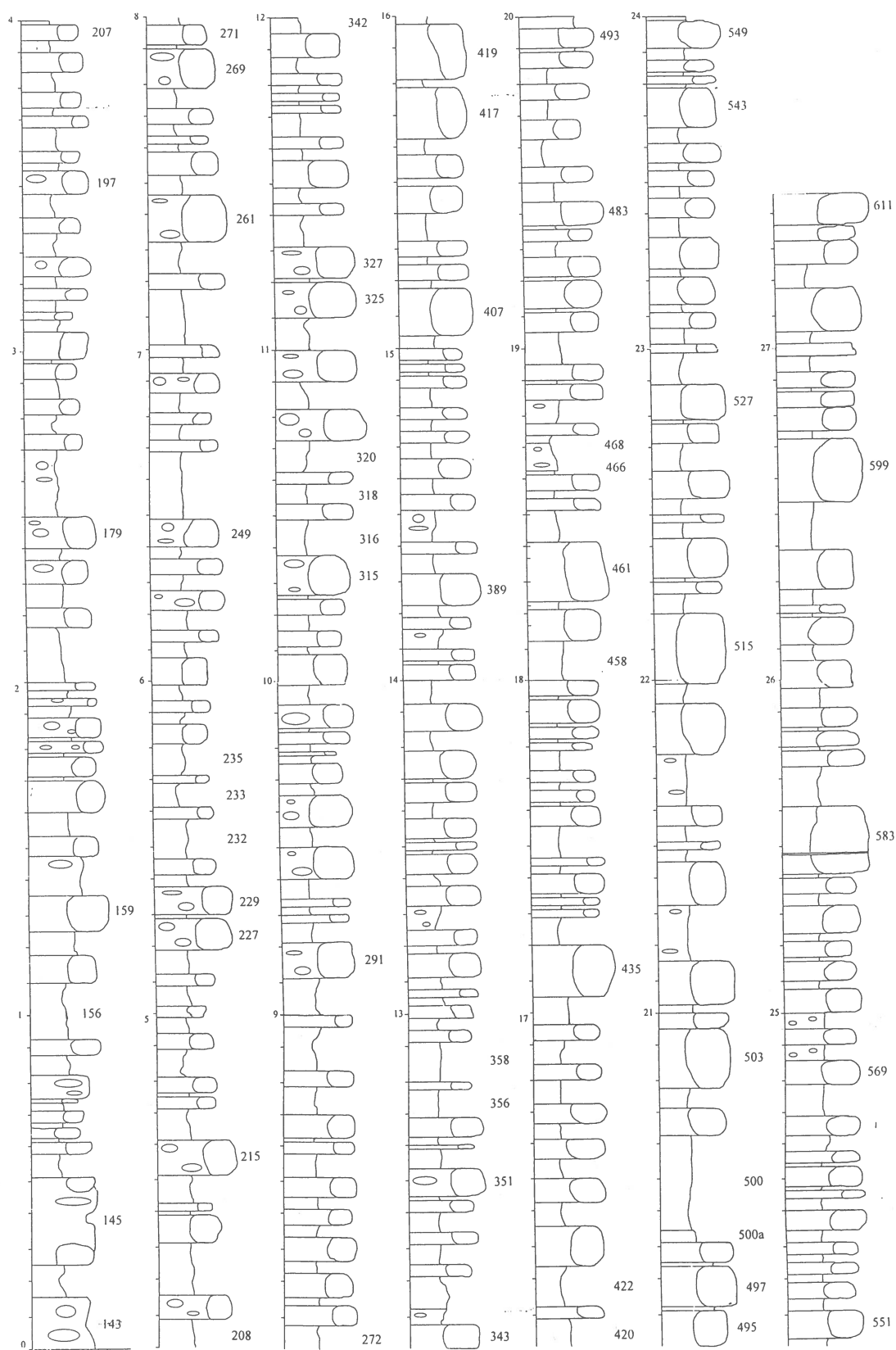
Third order cycles are represented by intervals



Text-fig. 3 - Locality map of type section of Farley Member of Coalbrookdale Formation at Harley Hill and Farley Dingle (FD), Shropshire.

with calcareous nodule horizons. These cycles include the Barr Limestone of the West Midlands, the nodular limestone developed within the Coalbrookdale Formation at Woolhope, and the two main limestones within the Much Wenlock Limestone Formation, as at Wren's Nest, Dudley, and Pennyhill Quarry in the Abberley Hills (Text-fig. 1). No specific palynological assemblage can be used to recognize the third order cycles, but there is an assemblage change from strata above and below. Dorning (1983) observed changes in acritarch assemblages from the topmost Coalbrookdale Formation into the Lower Quarried Limestone Member of the Much Wenlock Limestone Formation at Wren's Nest, Dudley. Here the *Salopidium granuliferum* assemblage is succeeded by the *Micrhystridium intonsurans* assemblage, which suggests that some palynofloral changes reflect the third order cyclicity.

Fourth order cycles are well-demonstrated in the Farley Member of the Coalbrookdale Formation (Text-fig. 3). The detailed analysis of the section at Farley Dingle, 3 km northwest of the type section at Harley Hill, near Much Wenlock, prompted the development of ideas regarding the relationships between bed thickness and cyclicity (Text-fig. 4). Sixteen cycles are recognizable in the 20 m section



Text-fig. 4 - Sedimentary log illustrating the Farley Member outcrop at Farley Dingle road cut, Shropshire. Bed numbers are shown for selected beds.

below the bentonite in the Farley Member (Text-fig. 4). The thicker argillaceous limestone beds are represented on Text-fig. 4 as bed numbers 159, 179, 197, 215, 227-229, 249, 261/269, 291, 315, 351, 389, 407, 417/419, 435, 461, and 497. The palynological composition is not markedly affected at this level of cyclicity. Typically, assemblages comprise over 99% acritarchs and prasinophytes with species of *Leiosphaeridia* (20-30%), *Micrhystridium* Deflandre, 1937 (10%+), *Veryhachium* Deunff, 1954 ex Downie, 1959 (10%+), *Salopidium* Dorning, 1981 (10%+), and *Diexallophasis* Loeblich, 1970 (10%+) usually the most abundant. Acritarch abundances in the Farley Member are between 500 and 2000 g⁻¹, compared with values for Palaeozoic open marine shelf seas of 100-10,000 g⁻¹ (Dorning & Bell, 1987). The assemblage typical of the Farley Member is comparable to the *Salopidium granuliferum* assemblage of Dorning & Bell (1987) from the Much Wenlock Limestone Formation (Text-fig. 5). However, species of *Ammonidium* Lister, 1970, *Salopidium*, and *Muraticavea* Wicander, 1974 occur in slightly lower percentages than reported from Wren's Nest. This may result from slightly different palaeoenvironmental conditions or perhaps the slightly older stratigraphic horizons of the Farley Member.

Fifth order cyclicity is represented in the Farley Member by conspicuous couplets of argillaceous limestone nodules and calcareous silty mudstones; 176 couplets occur through 20 m of measured section. This constitutes 8.8 couplets/m and an average couplet thickness of 114 mm. Minimum and maximum thicknesses of mudstone and nodule horizons are 30-180 mm and 20-220 mm respectively. Several conspicuous, somewhat thicker mudstone beds that have a soapy texture are interpreted as including volcanic ash fall deposits or redeposited ash. The thickest mudstone (bed 500) is developed directly above the thickest ash fall bentonite (bed 500a) and a very thin bentonite is associated with bed 458. A series of distinctive mudstone units, including beds 156, 232-235, 316-320, 356-358, 420-422, 466-468, and 500, may also include redeposited ash fall. These beds occur at all levels and are signals additional to the fourth and fifth orders of cyclicity, as would be expected with sporadic pulses of volcanic ash deposition.

No fundamental difference in palynomorph composition is evident between adjacent nodular limestone and mudstone couplets, apart from three-dimensional preservation of palynomorphs within the nodules which is linked to their early diagenetic origin. Within the Farley Member, the third order cyclicity produces a set of conspicuous calcareous beds below bentonite 500a. This interval, from beds 495-499, which includes sample FD21b, has yielded a significantly different assemblage from the rest of the Farley Member. There is a shift from *Leiosphaeridia* to flange-bearing acritarchs which

Assemblage	<i>S. granuliferum</i>		<i>T. farleyense</i>
Locality	Wrens Nest	Farley Dingle	Farley Dingle
<i>Leiosphaeridia</i>	20 - 35%	6 - 30%	22%
<i>Veryhachium</i>	10 - 25%	13 - 28%	13%
<i>Micrhystridium intonsurons</i>	10 - 15%	7 - 25%	19%
<i>Diexallophasis</i>	6 - 16%	4 - 16%	3%
<i>S. granuliferum</i>	6 - 13%	2 - 10%	2%
<i>Ammonidium</i>	1 - 4%	0.1 - 2%	0.5%
<i>Muraticavea</i>	1 - 4%	0.1 - 0.5%	0%
<i>Cymatiosphaera</i> + <i>Dictyotidium</i>	0.5 - 1.5%	0.1 - 1.5%	10%
<i>Tunisphaeridium</i>	0.1 - 1%	0.1 - 1%	15%

Text-fig. 5 - Percentage distributions of main microphytoplankton species within the Farley Member, compared to the *Salopidium granuliferum* assemblage at Wren's Nest, West Midlands (Dorning & Bell, 1987).

form up to 25% of the assemblage, with *Tunisphaeridium farleyense* (15%) and species of *Cymatiosphaera*, *Duvernaysphaera* Staplin, 1961, *Dictyotidium* Eisenack, 1955, and *Quadraditum* Cramer, 1964 together accounting for another 10%. *Diexallophasis* and *Multiplicisphaeridium* Staplin, 1961 become much less abundant (each <5%).

Overall, the Farley Dingle section can be divided into two broad assemblages. The first represents that typical of the Farley Member, irrespective of couplet lithotype; the second is recorded from the limestone interval. The significant bentonite horizon (bed 500a) occurs at the base of the prominent mudstone and is one of two bentonites which are stratigraphical marker horizons.

The bentonite contains an assemblage of moderate diversity (28 species) and low abundance (53 g⁻¹); this is surprising, given that many Silurian bentonites from the Welsh Borderland lack palynomorphs. The microphytoplankton of the Farley bentonite is of the *Salopidium granuliferum* assemblage; *Leiosphaeridia* is predominant, followed closely by *Micrhystridium*, *Veryhachium*, *Multiplicisphaeridium*, and *Diexallophasis*. When compared to typical abundances, the assemblage represents a dilution factor to approximately 10%. This high abundance for a rapidly deposited bentonite suggests that during deposition there was at least some redistribution of the general acritarch assemblage from the sediment-water interface as well as gathering of the microplankton as the ash fall descended through the water column.

	Thickness (m)					
Estimated Duration (Ma)	297	4.0Ma	5.0Ma	6.0Ma	6.4Ma	8.0Ma
Estimated duration per metre	1.0	13,468	16,835	20,202	21,548	26,936
Much Wenlock Limestone Formation	25	336,700 (337,000)	421,625 (422,000)	505,050 (505,000)	538,700 (539,000)	673,400 (673,000)
Coalbrookdale Formation: Farley Member	26	350,168 (350,000)	437,710 (438,000)	525,252 (525,000)	560,248 (569,000)	700,336 (700,000)
Coalbrookdale Formation: Apedale Member	220	2,962,960 (2,963,000)	3,703,700 (3,704,000)	4,444,440 (4,444,000)	4,740,560 (4,471,000)	5,925,920 (5,926,000)
Buildwas Formation	26	350,168 (350,000)	437,710 (438,000)	525,252 (525,000)	560,248 (560,000)	700,336 (700,000)
2nd order: Much Wenlock Limestone Formation and Coalbrookdale Formation	271	3,649,828 (3,650,000)	4,563,035 (4,563,000)	5,454,540 (5,455,000)	5,839,508 (5,840,000)	7,299,656 (7,300,000)
2nd: order Apedale Member and Buildwas Formation	246	3,313,128 (3,313,000)	4,141,410 (4,141,000)	4,949,490 (4,949,000)	5,300,808 (5,301,000)	6,626,526 (6,626,000)
Average 2nd order	260	3,501,680 (3,502,000)	4,377,100 (4,377,000)	5,252,520 (5,253,000)	5,602,480 (5,602,000)	7,003,600 (7,004,000)
3rd order	20	269,360 (269,000)	336,700 (337,000)	404,040 (404,000)	430,960 (431,000)	538,720 (539,000)
3rd order with allowance for carbonate	18	242,424 (242,000)	303,030 (303,000)	363,636 (364,000)	387,864 (388,000)	484,848 (485,000)
4th order 20m, 15 cycles	1.33	17,912 (18,000)	22,390 (22,000)	26,680 (27,000)	28,730 (29,000)	35,824 (36,000)
4th order 20m, 16 cycles	1.25	16,835 (17,000)	21,043 (21,000)	25,252 (25,000)	26,935 (27,000)	33,670 (34,000)
5th order couplet average		1642 1650	2053 2050	2463 2500	2627 2600	3284 3300

Text-fig. 6 - Durations of second to fifth order cycles within the type Wenlock Series. Figures in brackets are rounded.

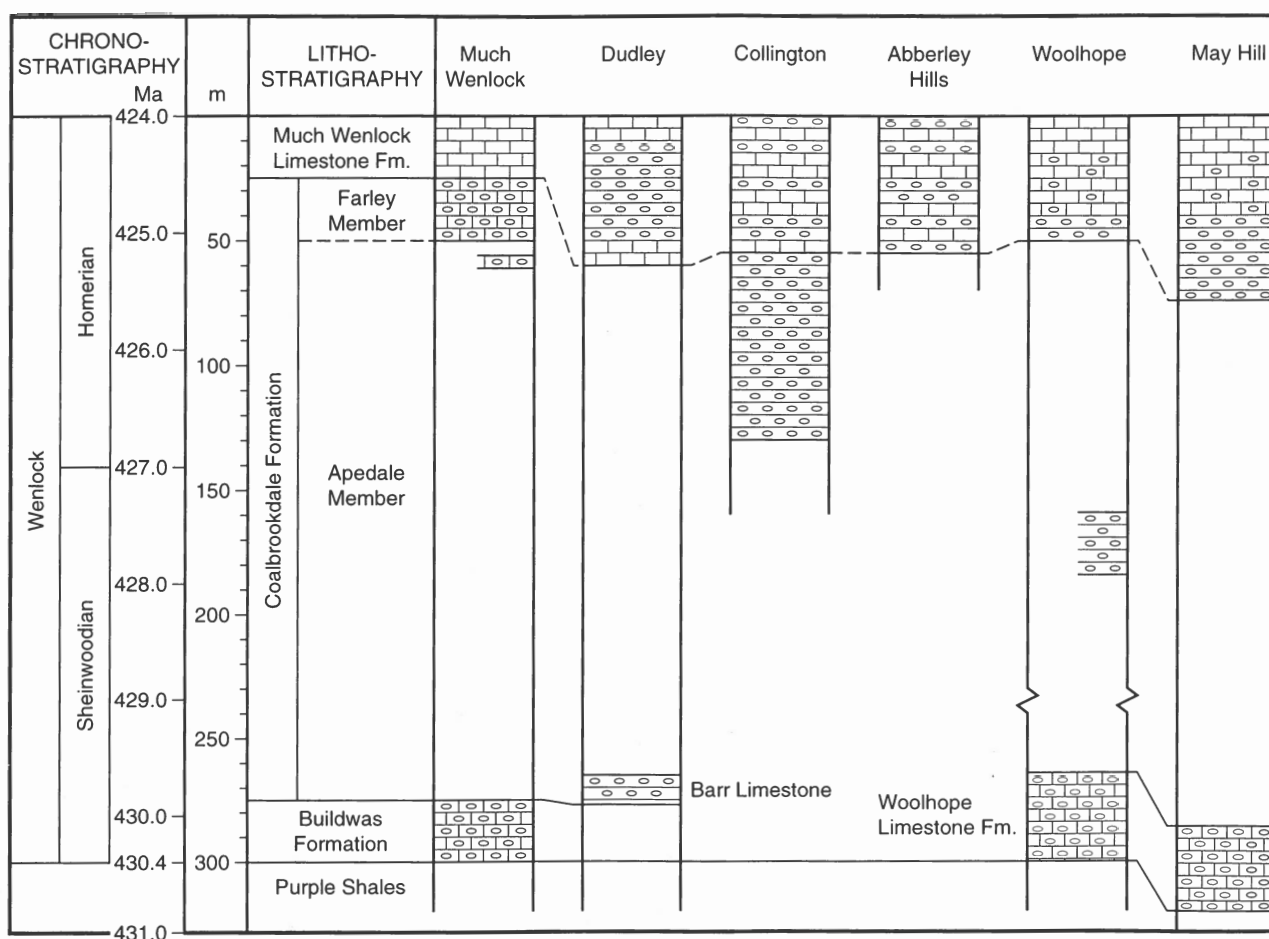
DISCUSSION

Most of the sediments in the Wenlock type area appear to have been deposited continuously for almost all of this time. Indeed, this was one of the reasons for selecting this area for the international reference sections (Bassett, 1989). In order to estimate the average duration of each order of cyclicity, one of the main criteria for recognition of cyclostratigraphy is evidence of depositional continuity at a relatively uniform rate (Gale, 1998). The Buildwas and Coalbrookdale formations were mostly deposited below wave base, and bioturbation at many horizons suggests oxygenated bottom conditions. Rare thin bioclastic limestones of the upper Farley Member imply slight shallowing just within storm wavebase. The Much Wenlock Limestone Formation includes limestones influenced by storm wavebase as well as sediments apparently deposited at or below wavebase. However, there is little evidence of even minor breaks in sedimentation other than those associated with pelmatozoan bioclastic limestones at the very top of the formation along the northern part of Wenlock Edge (Text-fig. 2). These suggest relatively

shallow marine conditions preceding slight deepening in the early Ludlow, which produced the calcareous silty mudstones of the Lower Elton Formation.

The estimated time-spans of the Wenlock cycles (Text-fig. 6) are based on total Wenlock time, as discussed previously herein, of 4 Ma (minimum duration), 5 Ma (Bassett *et al.*, 1989), 6 Ma, 6.4 Ma (Harland *et al.*, 1990), and 8 Ma (maximum).

Two calculations of second order cyclicity can be made by using either the Buildwas Formation and Apedale Member of the Coalbrookdale Formation as a cycle or the whole of the Coalbrookdale and Much Wenlock Limestone formations. The choice depends on whether the cycles are recognised as carbonate/mudstone or mudstone/carbonate (Text-fig. 2). Second order cycles record durations of between 3.3 Ma and 7.3 Ma, with an average between 3.5 Ma and 7.0 Ma. This order of magnitude is comparable to the Primo and Secundo episodes and events recognised by Jeppsson (1990) and described for the Llandovery and Wenlock by Aldridge *et al.* (1973) and Jeppsson *et al.* (1995). The major Primo and Secundo episodes are considered to be climatically driven and associated with changes in carbon dioxide flux. Intervals of



Text-fig. 7 - Stratigraphic correlation of the Wenlock Series in the Welsh Borderlands and Midlands. For localities see Text-fig.1.

increased carbonate and increased argillaceous material are referred to as Secundo and Primo episodes respectively. The early Wenlock Woolhope Limestone and Buildwas Formation are related to the Vattenfallet Secundo episode and the Much Wenlock Limestone Formation to the Hellvi and Klinte Secundo episodes.

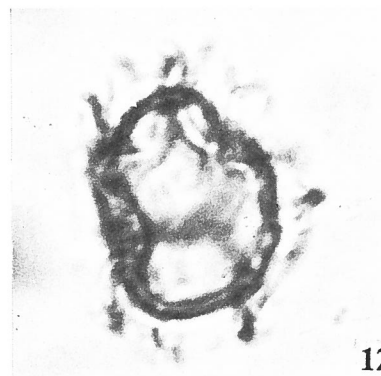
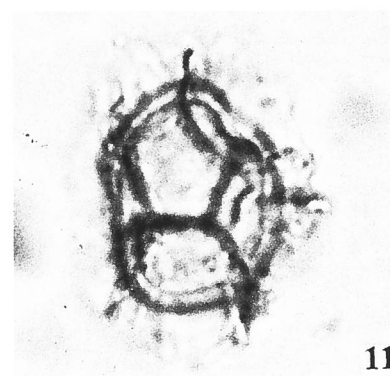
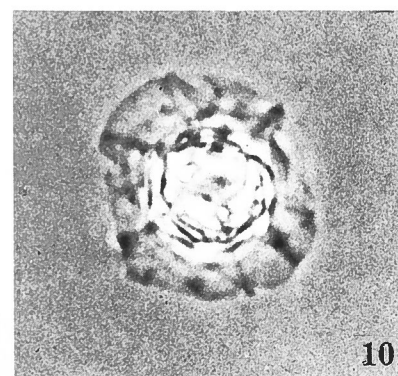
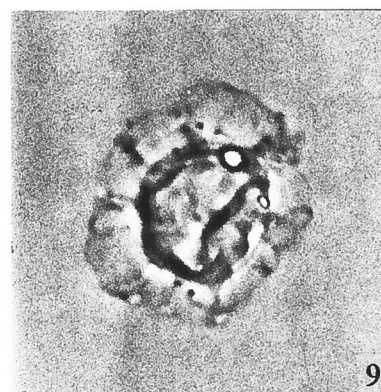
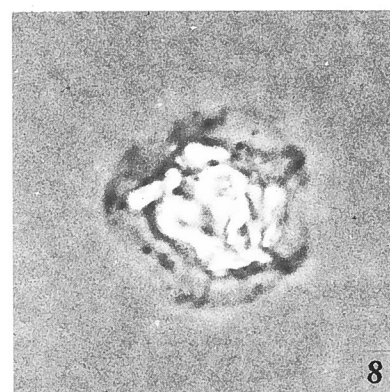
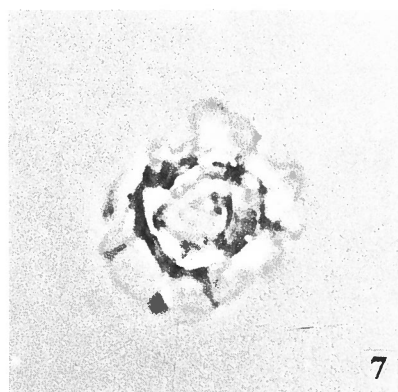
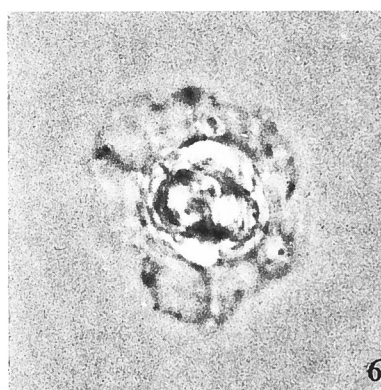
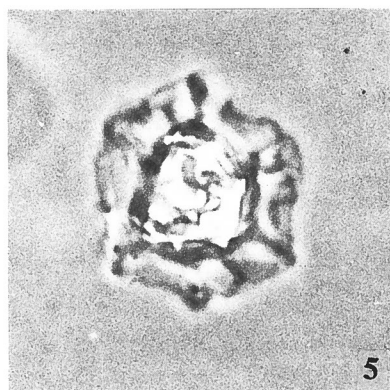
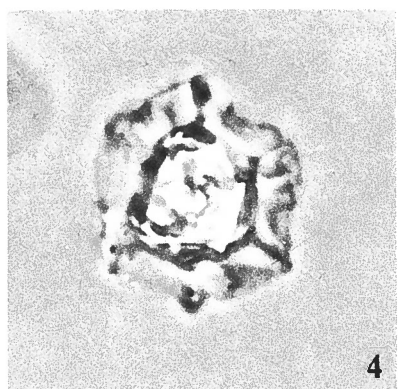
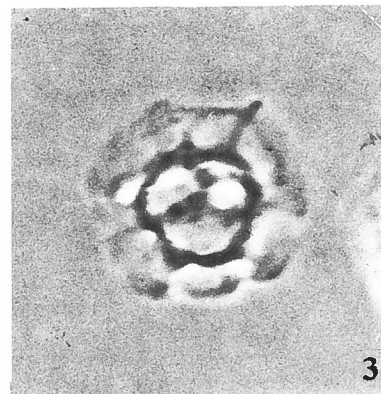
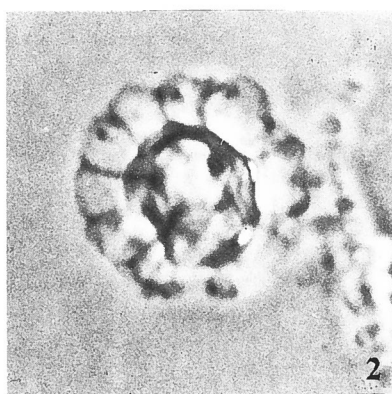
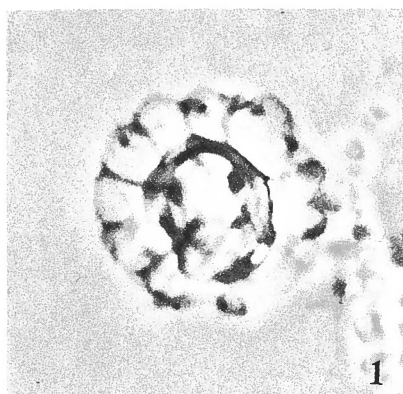
The third order cyclicity durations range between 270 Ka and 540 Ka. In the middle of the Much Wenlock Limestone Formation an increase in argillaceous material in the nodular beds occurs at Dudley, separating the Lower and Upper Quarried Limestone members (Text-fig. 7). This comprises the Mulde secundo event (Jeppsson *et al.*, 1995). The third order

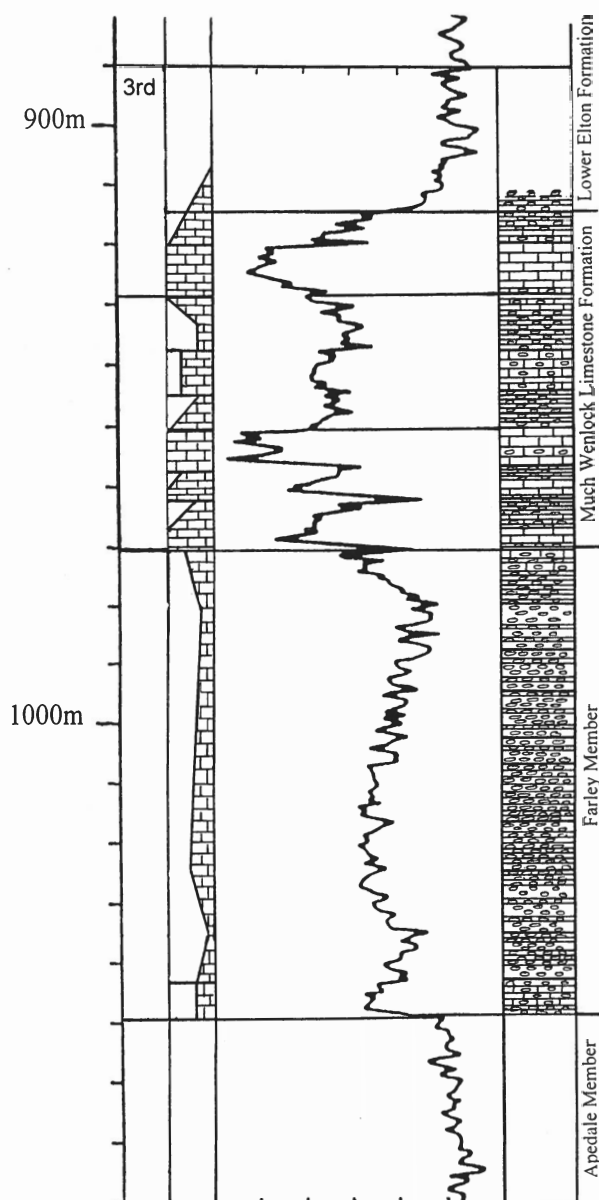
cyclicity is clearly recorded by the gamma ray log (Text-fig. 8) of the late Wenlock from the Collington borehole (Whittaker *et al.*, 1985, p. 21). Here, the reduced gamma ray values indicate prominent limestones between 970-950 m and 930-925 m. The prominent increase in carbonate at 1050 m may be equivalent to the nodular limestone ca. 25 m below the Farley Member along Wenlock Edge at Presthope (Greig *et al.*, 1968, p. 177). The order of magnitude of the third order cycles could possibly correspond to the 410 Ka orbital eccentricity cycle. No sedimentological or palynological record appears to correspond to the 106 Ka cycle.

EXPLANATION OF PLATE 1

- Figs. 1-10 - *Tunisphaeridium farleyense* sp. nov. 1) FD21b (1), D45, holotype, upper surface. 2) FD21b (1), D45, holotype, lower surface. 3) FD21b (1), L38. 4) FD21b (1), H41/1, upper surface. 5) FD21b (1), H41/1, lower surface. 6) FD21b (1), E44/1. 7) FD21b (1), H40/4. 8) FD21b (1), M39. 9) FD21b (1), K39/1. 10) FD21b (1), N44.
Figs. 11, 12 - *Cymatiosphaera pavimenta* (Deflandre) Deflandre, 1954. Mik (p) 13001, W3, single mount. 11) upper surface. 12) lower surface.

All figures x2000; sample/slide code is followed by England Finder reference.





Text-fig. 8 - Gamma ray log signature and cycles for the Farley Member and Much Wenlock Limestone Formation in the Collington borehole. Maximum gamma ray values represent argillaceous horizons and lower values increasing carbonate content.

Sixteen cycles at a fourth order magnitude occur within the 20 m of Farley Member below the bentonite at the base of bed 500. Estimated average durations are between 17 Ka and 34 Ka. This order of magnitude falls into the range of precession and obliquity proposed for the Silurian with precession between 16.5 Ka and 19.3 Ka and obliquity between 31 Ka and 37.5 Ka (Berger *et al.*, 1989). Accordingly, it is difficult to suggest which mechanism is responsible for the cyclicity, though possibly both were involved. In the Ludlow area, the lower part of the

Much Wenlock Limestone Formation shows conspicuous 1-2 m alternations of increased and decreased carbonate content. In the Collington borehole (Text-fig. 8) the minor changes in gamma ray values within the 1050-900 m interval are considered to signify variations in carbonate content that may also be fourth order cycles.

The smallest scale, fifth order cycles have durations ranging between 1650 and 3330 years. This appears to be considerably shorter than any known Milankovitch cycle related to either precession or obliquity. Variations in total solar energy production may explain such cycles. The estimated duration of the Farley Member based on sediment thickness may be inaccurate, but if the fifth order cyclicity was related to precession at 16.5 Ka then 20 m of Farley Member would be 2.5-5 Ma in duration (five to ten times that estimated on sediment thickness). This seems most unlikely, given the lithological uniformity and apparent lack of hiatuses in the 250 m of Buildwas and Coalbrookdale formations.

The fifth order cycles may be dilution cycles that relate to carbonate production with silt and clay dilution. Because the palynological assemblages do not change significantly within fifth order couplets, major changes in productivity are unlikely to account for the lithological changes forming the couplets. It seems that there was a continuous background of carbonate deposition with repetitive influxes of argillaceous material from areas on the shelf. Some evidence to support this is observed above the main bentonite horizon, which is followed by one of the thickest mudstone units, suggesting that volcanic ash inhibited nodule formation for some time after this event.

CONCLUSIONS

Within the type area of the Wenlock in the Welsh Borderlands, five orders of cyclicity are recognized: a first order for the whole Silurian, second and third order related to Primo and Secundo episodes and events, fourth order possibly related to Milankovitch cycles, and fifth order of dilution cycles. The palynological assemblages of the Coalbrookdale and Much Wenlock Limestone formations show considerable variety within the second and third orders, relating to climate change. Little variation is recorded at the fourth and fifth orders, suggesting that these do not reflect significant alterations in oceanic palaeoenvironment.

SYSTEMATIC PALAEOLOGY

Incertae Sedis "group" ACRITARCHA Evitt, 1963

Genus TUNISPHAERIDIUM Deunff & Evitt, 1968

Type species - *Tunisphaeridium tentaculiferum* (Martin, 1967) Cramer, 1970 = *T. concentricum* Deunff & Evitt, 1968.

TUNISPHAERIDIUM FARLEYENSE sp. nov.

Pl. 1, figs. 1-10

Diagnosis – Small spherical vesicle. Many simple, solid, wire-like processes. Processes shorter than vesicle and interconnected by a thin membrane.

Holotype – Pl. 1, figs. 1, 2, slide FD21b (1) (10–64 µm), England Finder reference D45; housed in the Centre for Palynology, University of Sheffield, England. Dimensions: vesicle diameter 12 µm; 11 processes, 6 µm long.

Description – Vesicle laevigate, spherical to sub-spherical, thin-walled (1 µm). Vesicle diameter 10–15 µm (20 specimens). Processes 8–12 in number, regularly distributed on vesicle, homomorphic, solid, wire-like; length variable (5–7 µm; 20 specimens). Thin diaphanous membrane up to 7 µm high connecting adjacent processes. Flange often crimped at junction with process terminations. No excystment structure observed.

Type locality and stratum – Farley Dingle, Shropshire, Farley Member of the Coalbrookdale Formation, Limestone horizon 499, directly below bentonite horizon bed 500a.

Etymology – From Farley Dingle.

Comparison – *Tunisphaeridium farleyense* sp. nov. differs from *T. parvum* Deunff & Evitt, 1968 in its smaller overall diameter and lesser number of processes which often attain 50–60% of the vesicle diameter in length. Furthermore, no delicate filaments are developed within the membrane as in *T. parvum*. Other species of *Tunisphaeridium* differ from *T. farleyense* in possessing processes that are almost equal in length to the vesicle diameter. Superficially, *T. farleyense* resembles *Cymatiosphaera pavimenta*. Adopting the diagnosis of Deflandre (1945), Downie (1959, pl. 1, figs. 11–12) illustrated forms he referred to as *C. pavimenta*. However, the latter differs from *T. farleyense* in possessing polygonal lacunae. In the topotype material, the vesicle of *T. farleyense* is often deformed by pyrite. However, the membrane is typically well-preserved and not damaged or missing, as is often characteristic of larger species of *Tunisphaeridium* including *T. parvum* and *T. tentaculiferum*.

Stratigraphic distribution in the type locality – Middle Farley Member, Coalbrookdale Formation, mid Homerian, late Wenlock.

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