Read at the Annual Conference of the Ussher Society, January 1996

MICROFACIES ANALYSIS AND METRE-SCALE CYCLICITY IN THE GIVETIAN BACK-REEF SEDIMENTS OF SOUTH-EAST DEVON

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Garland, J., Tucker, M.E., and Scrutton, C.T. 1996. Microfacies analysis and metre-scale cyclicity in the Givetian back-reef sediments of south-east Devon. *Proceedings of the Ussher Society,* **9**, 031-036

The Givetian (Middle Devonian) of south-east Devon consists of reef and back-reef facies (Tor Bay Reef-Complex) developed on a shelf-edge rise. Three sections in the Newton Abbot area have recently been studied with emphasis on detailed logging, sampling and thin section analysis of the back-reef sediments. Eight microfacies have been identified ranging from shallow subtidal to exposed supratidal deposits, forming four groups.

1. Semi-restricted subtidal	- stromatoporoid floatstones, low-energy accumulations, least restricted facies
	- *Stachyodes* rudstones, high-energy back-reef talus
2. Restricted subtidal	- *Amphipora* floatstones, low-energy accumulations
	- gastropod packstones, back-reef sedimentation with temporary agitation
	- fossil-poor peloidal and fenestral wackestones, calm water deposition
3. Restricted intertidal	- peloidal grainstones with micritised grains, deposition in channels ripping up subtidal facies.
4. Restricted supratidal	- microbial laminites
	- immature palaeosols

A small-scale cyclicity can be identified by the arrangement of microfacies vertically. Typical cycles show a stromatoporoid-rich base, followed by an *Amphipora* floatstone, capped by a fenestral fossil-poor micrite. Locally emergence is indicated by juvenile soil development or laminite deposition. Cycles are on average 2 to 3 m thick. Fischer plots have been produced to show the pattern of cycle development through time, and comparisons between sections is attempted. The mechanism causing cyclicity is as yet still unclear, with an intricate balance between autocyclic and allocyclic factors being probable.

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INTRODUCTION

The Givetian reef and platform carbonates of south-east Devon have been described from a general palaeoenvironmental viewpoint (Scrutton 1977a, b; Selwood and Thomas, 1986; Selwood *et al.*, 1984), which has identified major facies variations and the broad palaeogeographical setting. The back-reef carbonates have not received detailed attention, although their setting within the general interior platform sequences has been described in a key section by Scrutton and Goodger (1987). This paper describes the microfacies present in the back-reef area and demonstrates their metre-scale cyclicity.

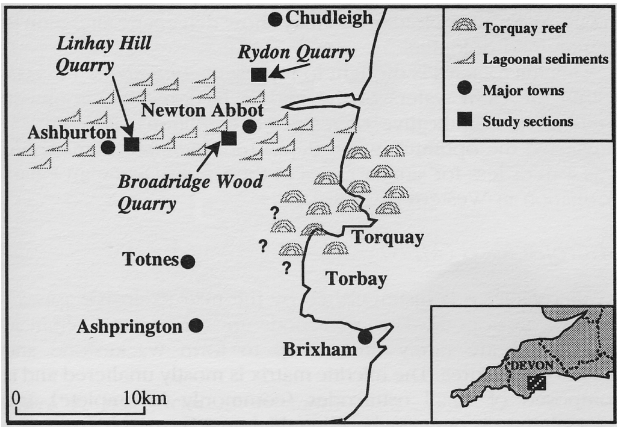


Figure 1. Location map showing non-palinspastic distribution of facies for Lower - Middle Givetian (redrawn from Scrutton, 1977b) and distribution of quarry sections.

Three sections of early-middle Givetian age back-reef carbonates have been studied (Figure 1), of which Broadridge Wood Quarry falls within the sequence documented by Scrutton and Goodger (1987). These sections are thought to have been located behind the reef-core facies developed at Torquay, although severe tectonic dislocation hampers palaeogeographical reconstruction. The carbonate platform is thought to have been developed on a topographic high along the shelf-edge margin, with an easterly extension of the South Devon Basin separating it to the north from near-shore clastics and continental facies on the Old Red Continental margin (Selwood and Thomas, 1986).

MICROFACIES

Eight microfacies have been identified within the back-reef succession and have been characterised using the scheme of Preat and Mamet (1989). Preat and Mamet (1989) studied Middle Devonian successions in Belgium and recognised thirteen major microfacies. Within this scheme microfacies 1, 2, 3, 7, and 11 are not recognised in the south-east Devon sections.

Microfacies 1 in the Belgian Ardennes is represented as argillaceous mudstones/wackestones with a diverse faunal assemblage of brachiopods, trilobites, crinoids, gastropods and bryozoans. The fauna is rarely disturbed and this microfacies records deposition in an open marine environment below normal wave base (Preat and Mamet, 1989). Microfacies 2 has a similar faunal assemblage to MF1, however evidence of cross-stratification, deposition of fauna in coquinas and the breakage of fauna suggests more wave activity. Microfacies 3 is suggested by Preat and Mamet (1989) to represent fore-reef deposits with a diverse faunal assemblage and moderate wave action. Microfacies 7 is also not present in the south-east Devon sections and is thought to depict oolitic sandbanks or dunes forming on the banks of the lagoon. Finally, microfacies 11 represents intraformational limestone pebble conglomerates and microbial mats deposited in the intertidal zone.

Those microfacies present in the south-east Devon sections can be assigned to four main depositional environments: semi-restricted subtidal, restricted subtidal, restricted intertidal and restricted supratidal (Figure 2).

Semi-restricted subtidal microfacies

Microfacies 4 (MF4)

The main components of microfacies 4 of Preat and Mamet (1989) are pyriform stromatoporoids that exhibit a floatstone texture. The stromatoporoids are on average 150 x 80 mm in size and are usually disturbed rather than in life position (see Plate 5 Scrutton, 1977a). Also associated with this microfacies are *Stachyodes* stromatoporoids, *Amphipora*, solitary corals (commonly showing encrustation by stromatoporoids), *Thamnopora*, gastropods, and *Stringocephalus* brachiopods. The matrix is a pink colour and thin-section analysis indicates the presence of dolomite rhombs which show a red iron rim. Angular microbial intraclasts, peloids and ostracodes are also widespread in the matrix. Bedding thickness ranges from 0.5 to 1.1 m, with an average of 0.9 m.

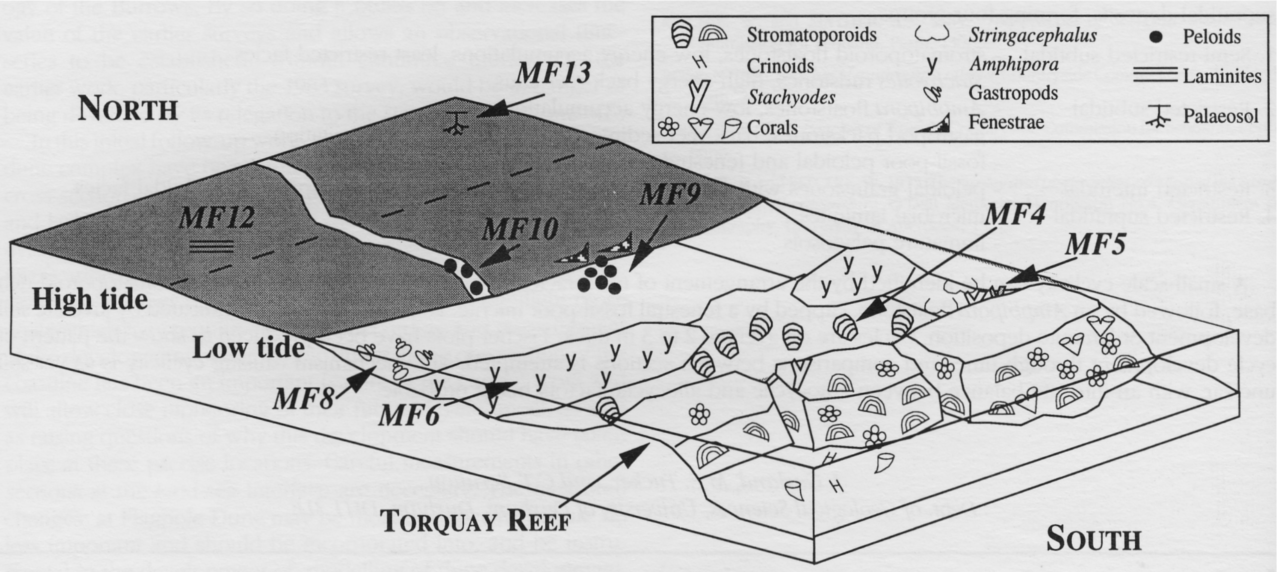


Figure 2. Palaeoenvironmental reconstruction for early - middle Givetian, showing distribution of microfacies.

Microfacies 4 is thought to have formed as sheet-like deposits in the low-energy shallow subtidal zone where occasional storm activity disturbed stromatoporoids. This microfacies is the least restricted microfacies seen in the back-reef sections of south-east Devon.

Microfacies 5 (MF5)

Stachyodes rudstones and grainstones are indicative of microfacies 5. *Stachyodes*, a stick-like stromatoporoid, is commonly broken up into 10 mm diameter grains. Debris of crinoids, solitary corals (commonly showing encrustation by stromatoporoids), thamnoporoids, *Actinostroma*, *Stringocephalus* (up to 60 mm in length) and *Amphipora* are also associated with this microfacies and are set in a sparitic matrix. A variety of different cements can be distinguished: syntaxial cements in optical continuity with crinoid grains, rare microstalactitic cements on the underside of *Stringocephalus*, isopachous cements surrounding grains and pore-filling baroque dolomite. Geopetal textures are also common. Locally the long axis of grains is aligned at an angle to the horizontal suggesting cross-stratification. Many beds show graded bedding, suggesting a waning-energy source.

This microfacies is thought to have been deposited as a high-energy accumulation probably as a back-reef talus.

Restricted subtidal microfacies

Microfacies 6 (MF6)

Microfacies 6 is characterised by the dendroid stromatoporoid *Amphipora*. These *Amphipora* branches are on average about 3mm in diameter and are up to 30 mm in length (Figure 3). In the field they display a spaghetti-like morphology and form a floatstone texture. Bedding is on average 0.5 m in thickness and *Amphipora* branches are commonly oriented parallel to bedding. Also associated with this microfacies are thamnoporoids and a variety of microfossils such as ostracodes, calcispheres, *Devonoscale* (Racki and Sobon-Podgórska, 1993) and microproblematica (commonly parathuramminids). The matrix is dominantly micritic in nature, locally peloidal, and may show diagenetic alteration to fine-grained dolomite.

This microfacies is thought to represent *Amphipora* 'thickets' within the calm waters of the middle back-reef environment. *Amphipora* is indicative of restricted conditions. Read (1973) suggested the optimum water depth for *Amphipora* limestones was 1 m or less for similar facies in the Upper Devonian Pillara Formation in Western Australia.

Microfacies 8 (MF8)

Microfacies 8 is distinguished by the near-exclusive appearance of gastropods. The gastropods are on average 12mm in length and are rarely broken up to form wackestone and packstone textures. The micritic matrix is mostly unaltered and is composed of small ostracodes (commonly incomplete) and calcispheres. At outcrop, bedding thickness is variable from <0.1 m to 0.7 m. The gastropods are generally concentrated at the base of the beds.

This facies is thought to be the result of storm action within the restricted lagoon.

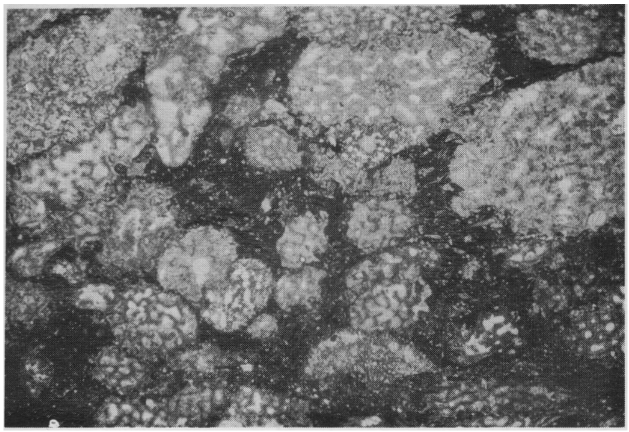


Figure 3. Microfacies 6. Amphipora floatstone. Amphipora with characteristic axial canal and 3mm in diameter. Matrix composed of fine grained dolomite rhombs. Sample number BW24, 17.1m from base of Broadridge Quarry section. Field of view 12mm x 7mm.

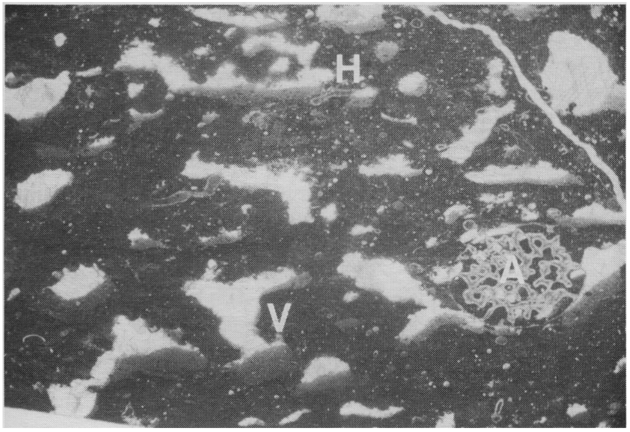


Figure 4. Microfacies 9. Peloidal and fenestral wackestone. Grains of dissolved Amphipora (A) and calcispheres. Facies extremely peloidal . Both vertical (V) and horizontal (H) fenestrae displayed, each with an internal sediment fill at base. Fenestrae 1-2mm wide. Sample number BW32, 29.8m from base of Broadridge Quarry section. Field of view 12mm x 7mm.

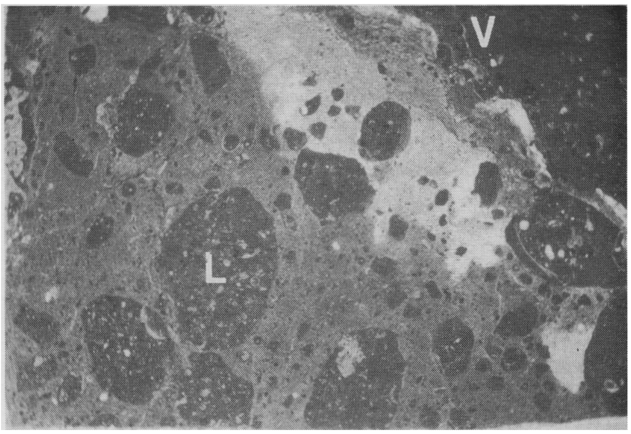


Figure 5. Microfacies 13. Immature palaeosol. 2-3mm diameter, subrounded lithoclasts (L) exhibiting floating texture. Wispy sediment-filled veins (V) representing drying and cracking of sediment due to prolonged exposure. Matrix extremely mottled. Sample number BW1, 0.5m from base of Broadridge Wood Quarry section. Field of view 12mm x 7mm.

Microfacies 9 (MF9)

The most common microfacies identified within the back-reef successions is microfacies 9. This microfacies is extremely well bedded, on average about 0.4 m thick beds, and is characteristically macrofossil-poor. The facies is extremely peloidal (peloids 0.1 to 0.2 mm diameter, spherical/oval shape) and exhibits wackestone, packstone and grainstone textures. Although macrofossils are rare, microfossils such as calcispheres, ostracodes (including millimetric *Leperditia*), parathuramminids, *Devonoscale* and other microproblematica are common. Bioturbation is prevalent. At certain horizons fenestral cavities are present (Figure 4). These can be categorised into two main groups:- vertical fenestrae and horizontal fenestrae. Vertical or tubular fenestrae are on average 0.5 to 1 mm in width and 3 mm in length, with an internal sediment fill. These cavities cross-cut stratification and may represent burrows. Horizontal fenestrae on the other hand are often oriented parallel to bedding and are 1 to 3 mm in width, having a flat base and digitated top. These form mainly by desiccation and shrinkage or by air and gas bubble formation (Shinn, 1968).

The lack of macrofossils and the presence of fenestrae suggest that microfacies 9 was deposited in highly restricted settings in shallow subtidal to intertidal environments.

Restricted intertidal

Microfacies 10 (MF10)

Peloidal grainstones characterise microfacies 10. Peloids are on average 0.1 mm in diameter, internally structureless and very well sorted. Micritised grains are also common and probably represent original ostracode grains. Other constituents include ostracodes, lithoclasts, microproblematica (parathuramminids) and to a lesser extent *Amphipora*.

This microfacies represents deposition in intertidal channels, ripping up clasts of underlying MF9 facies (Preat and Mamet, 1989). This microfacies occurs at only one horizon in the Rydon Quarry section.

Restricted Supratidal

Microfacies 12 (MF12)

Laminite deposition is characteristic of microfacies 12. These are millimetric couplets of peloidal packstones and calcisphererich mudstones that are mostly unfossiliferous. A common feature is bed-parallel millimetric birdseye (irregular) fenestrae. Desiccation cracks are not present. This microfacies occurs in beds which vary in thickness from 0.27 to 0.9 m, and on the whole this microfacies is uncommon.

This microfacies is thought to be deposited in the restricted intertidal to supratidal zone possibly in supratidal ponds.

Microfacies 13 (MF13)

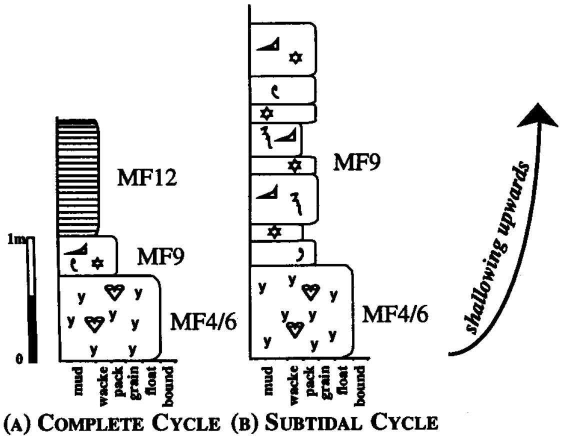
During periods of prolonged exposure within the supratidal environment juvenile soils (MF13) were able to develop. These are characterised in thin section by subangular to subrounded internally structureless lithoclasts ranging from <0.5 to 3 mm in diameter that form a floating texture in a mottled peloidal matrix (Figure 5). Wispy sediment-filled veins are also common and form due to drying and cracking of the sediment during exposure. Subtle alveolar structures were identified, mimicking rootlet tubules.

This microfacies was identified in only one horizon of the Broadridge Wood Quarry section and represents the most restricted facies.

CYCLICITY

Sequential analysis of the Givetian back-reef carbonates shows that the microfacies are arranged into a clear shallowing-upwards metre-scale cyclicity. Two types of cyclicity have been identified.

Complete cycles record sedimentation from the least restricted facies (MF4) to the most restricted facies (MF12-13) in one regressive phase (Figure 6). The base of the cycle displays a thick stromatoporoid-rich facies (MF4-6); this is followed by a fenestral fossil-poor wackestone/packstone facies (MF9) and is capped by supratidal laminite deposition. Bedding on the whole is planar in nature, with no erosive or karstic horizons. These cycles are on average 1.5 to 2 m thick and are relatively rare within the sections studied.



(A) COMPLETE CYCLE (B) SUBTIDAL CYCLE

Figure 6. Generalised logs showing (a) complete cycles and (b) more subtidal cycles.

A more typical cycle is dominated by subtidal facies (Figure 6). Once again regression is recorded by increasing restriction of the microfacies. Cycles have basal units showing a stromatoporoid-rich horizon (MF4-6). This is then followed by a thick macrofossil-poor peloidal wackestone horizon (MF9) which caps the cycle. Local fenestral horizons may indicate occasional emergence into the intertidal zone. These cycles are on average 2.5 m thick.

It is interesting to note that in all of the sections studied most of the carbonate deposition occurs within the regressive phase of the cycle. Transgressive-prone cycles are rare.

CYCLE STACKING PATTERNS

Cycles, whether they be complete or subtidal-dominated, are typically arranged into packages that show trends in thickness. This is clearly displayed at Linhay Hill Quarry (Figure 7a).

Fischer plots can be plotted to represent graphically cycle thickness variations through the succession (Figure 7b) (Sadler *et al.*, 1993). Cycle number is plotted against the cumulative departure from mean thickness, to objectively gain a visual impact of cycle thickness through time. Bundles of thinner than average cycles enter the plot with an overall negative slope, and thicker than average cycles have positive slopes. Cycles can be grouped into three packages. Initially, stacking patterns show an equal-thickness trend i.e. cycles are all the same thickness (cycles 1-9). This then develops into two packages which display thinning-upwards trends (cycles 10-13 and 14-18).

Using characteristic stacking patterns and/or marker bands an attempt can be made to correlate sections in south-east Devon (Figure 8). Marker bands such as stromatoporoid floatstones (thought to be sheeted deposits covering a wide area), laminites and soil horizons can be considered isochronous and may prove to be potential correlative horizons.

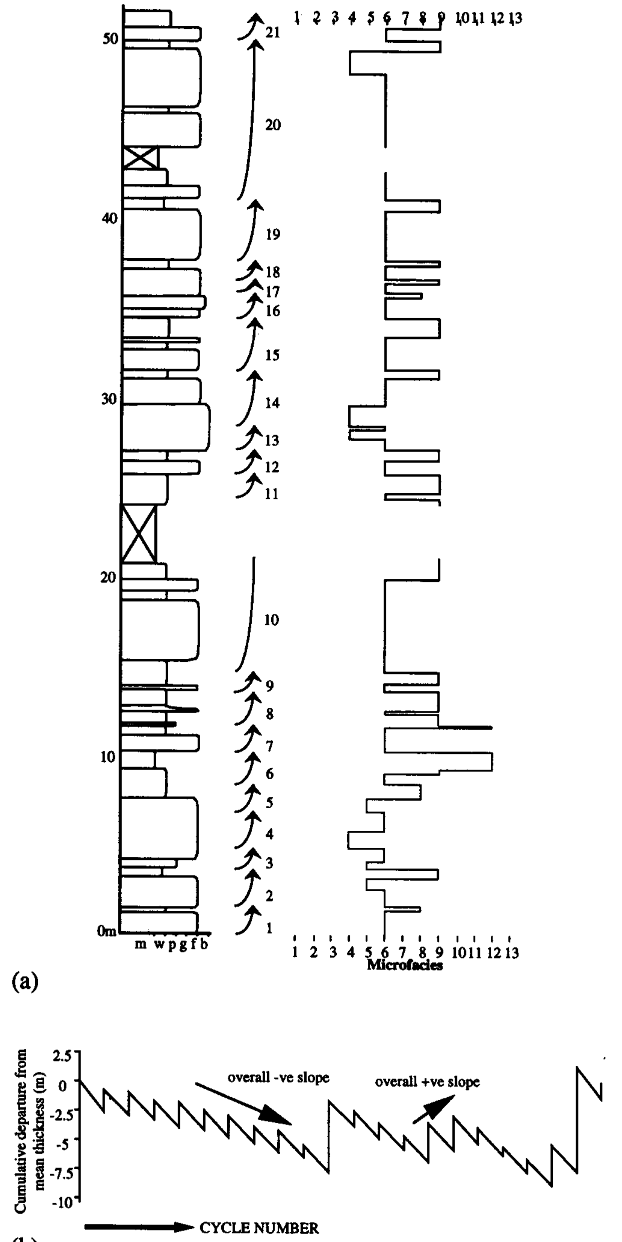


Figure 7a. Log for Linhay Hill Quarry near Ashburton. From left to right -texture (mud, wacke, pack, grain, float, boundstone), cycle number, microfacies. Figure 7b. Fischer plot for Linhay Hill Quarry displaying cycle stacking patterns.

However, it is clear looking at the Fischer plots for the sections that correlation does not seem possible. This may be due to a number of reasons. As a result of poor stratigraphic control, poor exposure and post-sedimentary tectonism in the study area it is difficult to establish if the three sections were deposited at the same time. It is known that they are all Givetian in age, but since the Givetian is 7.1Ma in duration (House, 1995b) it may be that the sections are not synchronous. Another reason may be that there was an autocyclic mechanism controlling cyclicity; this is an aspect that needs to be addressed.

MECHANISMS OF CYCLE DEVELOPMENT

The cause of repeated metre-scale shallowing-upwards cycles has been much debated in the last three decades (i.e. Hardie, 1986; Tucker and Wright, 1990). The mechanisms causing this cyclicity can be divided into three broad categories:

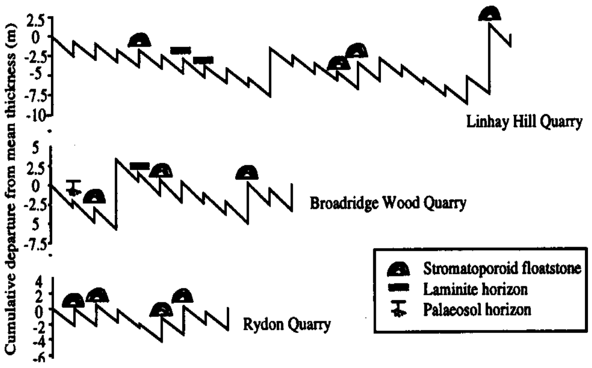


Figure 8. Fischerplots for Linhay Hill Quarry, Broadridge Wood Quarry and Rydon Quarry. Potential correlative horizons are shown (stromatoporoid floatstones, laminite horizons, palaeosol horizons). Note that there appears to be little correlation between sections on the bases of cycle thickness pattern or location of distinctive beds.

Sedimentary Control (Tidal Flat Progradation)

Shallowing-upwards profiles can be developed by a purely autocyclic mechanism, where continual regional subsidence or conversely sea-level rise occurs. This mechanism relies on the theory that most carbonate generation (carbonate factory) is in the subtidal zone, and it is only in storm events and wave or tidal reworking that deposition occurs in tidal flat environments. Therefore, as sediments build up vertically and tidal flats prograde, the area of carbonate production decreases and hence deposition slows and eventually ceases. Because the platform is continually subsiding a transgression will inevitably occur and the whole process will be re-established.

There is also the tidal island mechanism of Pratt and James (1986). This scenario suggests that the platform is never completely exposed or submerged, but is dotted with tidal flat islands which accrete and migrate laterally with time at variable rates, but keeping pace with rising sea-level through eustasy or subsidence.

Tectonic Mechanism

There are two tectonic mechanisms for small-scale relative sea-level fluctuations: events such as faulting, volcanic outpourings and local basin filling will cause variations in the in-plane stress of a continent, and ultimately uplift of the basin margin (Cloetingh *et al*, 1985). Jerky subsidence and periodic movement on faults (stick-slip) will cause small-scale variations in subsidence (Cisne, 1986).

Eustatic control

Metre-scale repetition of facies requires frequent and relatively low amplitudes of relative sea-level fluctuation. A popular explanation for this would be that of glacio-eustasy. This mechanism results from periodic variations in the complex interactions between the Earth-Moon-Sun orbital patterns (House, 1995a). Perturbations of the Earth's orbit cause variations in solar insolation which in turn can initiate or deplete the extent of ice-sheet and mountain-ice development. This is intrinsically linked to small-scale sea-level fluctuations.

DISCUSSION

Due to the inadequate exposure, poor stratigraphical constraints and post-sedimentary tectonism, pinpointing a mechanism responsible for this cyclicity proves very difficult.

The lack of correlation between sections may support the sedimentary mechanism. An important aspect of this is that at any one time along the platform margin different areas can be in different stages of sedimentation and subsidence. Therefore correlation is unlikely.

The tectonic mechanism is problematic. During the Middle Devonian syn-sedimentary tectonism is not obvious. The majority of extensional tectonics occurred pre-Middle Devonian, and thrust tectonics occurred in post-Namurian times (Selwood and Thomas, 1986). Substantial volcanics (Kingsteignton Volcanics Group, Foxley Tuffs) were extruded in the study area, but it seems unlikely that this mechanism is periodic enough to produce the cyclicity seen in the sediments.

A eustatic control would be an acceptable explanation for the cyclicity, but is very difficult to prove. Fischer plots (Figure 8) do reveal a grouping of cycles into bundles of 4 to 9 units. However, this is not the characteristic `pentacycle' arrangement which may indicate the operation of composite eustasy. Because the sections are not well dated and are relatively short it is impossible to calculate the duration of cycles and to ascertain which orbital perturbation is occurring (i.e. precession, obliquity, eccentricity). An important aspect of the model is also that the solar insolation variations, and hence the small-scale sea-level fluctuations, would be global. Therefore correlation between sections should be possible. Although no correlation can be made between the south-east Devon sections, this mechanism should not be dismissed as the sections are not known to be the same age.

It is interesting to note that Middle Devonian back-reef carbonates occur world-wide and exhibit a similar cyclic nature. Many sections have been studied and all three mechanisms have been suggested as causing the cyclicity (Aachen area of Germany, Kasig, 1980; eastern Great Basin USA, Elrick, 1995; Moroccan Meseta, Cattaneo *et al*., 1993; Belgian Ardennes, Preat and Mamet, 1989; Poland, Preat and Racki, 1993; Western Australia, Read, 1973).

A different approach was used by House (1995b) to determine the importance of glacio-eustasy in the Givetian. Analysis of a pelagic cyclicity which has no apparent tectonic or autocyclic overprint indicates a strong precessional orbital cyclicity. Therefore, it is clear that orbital forcing had a strong influence on sedimentation in the Givetian, but in shallower lagoonal sediments it is unclear whether this mechanism was the major factor actually controlling the cyclicity.

Interestingly, greenhouse climatic conditions typified the Middle Devonian times. Globally warm temperatures, high mean ocean temperatures and sluggish ocean circulation did not facilitate the establishment of polar ice caps. Therefore it appears that fluctuations in the extent of mountain ice rather polar ice participated in producing the Middle Devonian cyclicity seen in south-east Devon.

CONCLUSIONS

1. Eight microfacies have been identified ranging from shallow subtidal to supratidal deposits
2. Two types of cyclicity have been identified:
   (i) shallowing-upwards complete cycles
   (ii) dominantly subtidal cycles with intertidal fenestral caps
3. Cycles typically arrange themselves into packages that show trends in thicknesses
4. Correlation between the sections in south-east Devon is not possible. This may be due to the sections being of different ages or the sections resulting from different controls on cyclicity
5. As a result of the poor stratigraphical data, inadequate exposure and post-depositional tectonism it is very difficult to pinpoint the mechanism causing cyclicity, but it is most likely to be an intricate balance between autocyclic and allocyclic processes.

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ACKNOWLEDGEMENTS

JG would like to acknowledge NERC for financial assistance. Thanks must also go to E. and J. W. Glendenning Limited, Mr. Westaway and colleagues for permitting JG to work at Linhay Hill Quarry. The manuscript has been improved by two anonymous reviewers, whose comments were gratefully received. Finally thanks must go to Dougal Jerram for his exhilarating assistance and discussion in the field.