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Microfacies associations in Asbian carbonates: an example from the Urswick Limestone Formation of the southern Lake District, northern England

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Abstract: Semi-quantitative analysis of allochems from the Urswick Limestone Formation (Asbian) of the southern Lake District area of northern England has revealed a distinctive cyclicity of the microfacies. Cycle-top grainstone microfacies contain an algal flora comprising *Koninckopora*, *Anatolipora* and *Polymorphocodium*, with *Girvanella* filaments and *Ortonella* lumps. Other allochems include intraclasts, large peloids and thick-shelled bivalves and gastropods. The middles of cycles are mostly packstones and micro-grainstones and contain allochems dominated by small peloids and the algae *Kamaena*, *Kamaenella* and *Epistacheoides*, with the microproblematicum *Ungdarella* and relatively high abundances of micritic-walled foraminifera such as endothyrids. Cycle bases contain a diverse algal assemblage including *Coelosporella* and *Stacheoides*, with other allochems represented by trilobites, ostracodes, *Saccamminopsis*, foraminifera such as Archaediscidae, the base late Asbian guide *Howchinia*, the base early Asbian guides *Gigasbia gigas* and *Vissariotaxis*, bivalves, small gastropods, bryozoans, sponge spicules and bored grains. Other allochems are found throughout most cycles, decreasing only in the very shallowest (intertidal) facies, or have an irregular distribution, and include brachiopod debris, crinoid ossicles and coral fragments.

There are significant variations in allochem distribution according to palaeogeography. Close to the shelf margin there are higher abundances in the cycle top grainstones of the algae *Koninckopora* and *Anatolipora*, and also of the calcified filaments *Girvanella* and *Ortonella*, with thick-shelled gastropods, intraclasts and coarse peloids. At cycle bases, echinoderm arm plates and bryozoans are particularly abundant in packstone–wackestone textures. Platform interior facies are differentiated into a diverse open-marine type, with a high total abundance of bioclasts in the cycle base pack-wackestones including trilobites, *Coelosporella*, *Stacheoides*, *Kamaena* and bored grains, grainstones are dominated by small peloids, *Kamaenella* and *Ungdarella*), and a more restricted cycle type, in which total bioclast abundances are low.

Cyclicity on a 2–20 m scale in the late Dinantian (Asbian and Brigantian) carbonates of Europe and North America has been well documented from outcrop macrofacies studies (Somerville 1979*a*, *b*, *c*; Walkden 1987). This cyclicity has been interpreted as a product of fourth order glacio-eustacy (Walkden 1987; Horbury 1989). However, there is relatively little published work on the microfacies aspects of the cyclicity, although the theses of Gray (1981) on North Wales and Horbury (1987) on the southern Lake District cover this in some detail. White (1992) examined thin sections prepared by Horbury, and this thesis contains much information of palaeoecological and stratigraphic significance regarding the distribution of foraminiferal genera and species within the microfacies/macrofacies models developed initially by Horbury (1987, 1989). There is abundant palaeontological literature on microfossils (e.g. Petryk & Mamet 1972; Mamet & Roux 1974; Mamet *et al.* 1980; Skompski 1984, 1987), but this is mostly related to the problems of classification of the microproblematica which are abundant in the Late Dinantian (e.g. Riding 1977). Relatively little of this literature covers the micropalaeontological aspects of these carbonate systems in a thorough sedimentological sense.

The purpose of this paper is therefore to describe and interpret the palaeoenvironmental significance of the microfacies and allochems of Asbian cycle systems by reference to the macrofacies cyclicity.

Location

The Urswick Limestone Formation crops out along the southern margin of the Lake District

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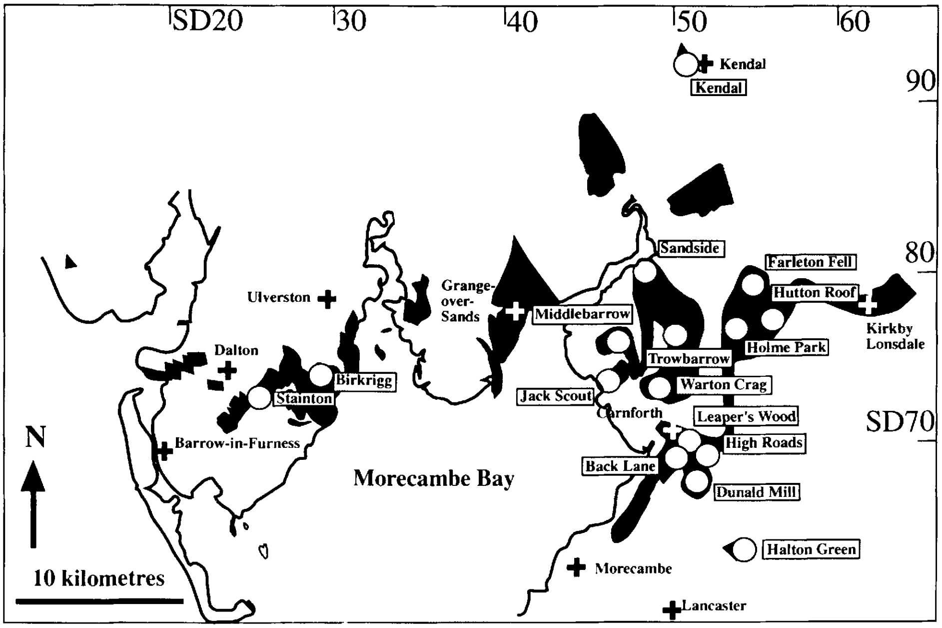


Fig. 1. Outcrop of Urswick Limestone Formation and sample localities.

of northern England (Fig. 1). It is up to 150 m thick and both the early and late Asbian are represented (Strank 1981; Horbury 1987). The rocks are strongly cyclic, with approximately 12–20 cycles developed, depending on the locality. The style of cycle development varies throughout the formation; at the base of both the early and late Asbian there are thin grainstone-dominated cycles separated by palaeokarsts and, in the late Asbian, by fenestral limestones. In the upper parts of the early and late Asbian, there are thicker cycles with packstone–wackestone bases and generally poorly developed grainstone cycle tops (Horbury 1989; Fig. 2). These stratigraphic variations are consistently developed throughout the 20 x 30 km study area, and may be comparable to cyclic carbonates described from the Sellafield area 50 km to the northeast (Barclay *et al.* 1994). In addition, some reference is made to the microfacies variations in contemporaneous outcrop material examined from the Oxwich Head Limestone on the Gower peninsula in South Wales by the second author. This paper is an extension to the work on *Kamaenella* presented in Adams *et al.* (1992), and also acts as a check on the broader significance of observations and conclusions derived from the Urswick Limestone study.

Database

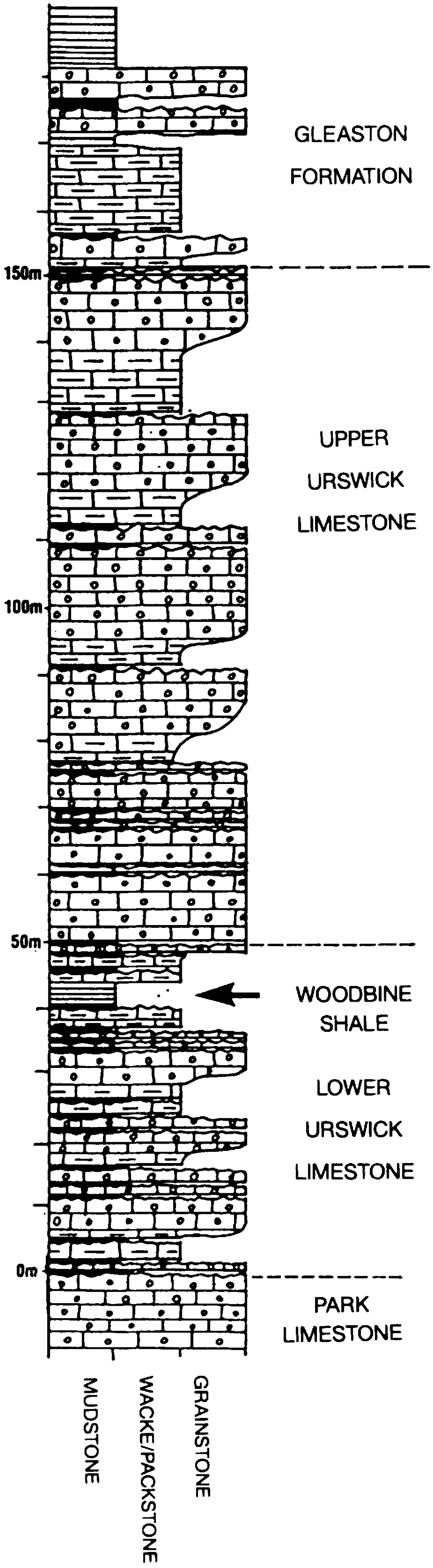
Some 3000 acetate peels and 700 thin sections formed the basis of this study. These were selected from 16 outcrop localities (Fig. 1), and are housed in the Geology Department at the Victoria University of Manchester.

Method of study

A simple cyclicity (Figs 2, 3) based on four macrofacies (argillaceous packstones–wackestones, grainstones, porcellanous micrites and terrestrial carbonates and clastics) has been defined in the field (Horbury 1989), although it was realized that these facies were often gradational and the actual patterns were more complex (Horbury 1987). Extensive petrography was therefore undertaken because it was found initially that precise field identification of these more subtle sub-macrofacies patterns was unreliable, due to differences in weathering characteristics of shoreline, hillside and quarry exposures, and because of the effects of thorough bioturbation by *Thalassinoides* and complex diagenesis.

Petrography reveals the presence of assemblages of allochems. Although some allochem assemblages contained allochems unique to that particular assemblage, most contained the same allochems, but in different proportions. Consequently, specific distinctive microfacies combining allochem assemblages and textural criteria were difficult to identify, since allochem compositions varied gradationally through the cycles. The problem is similar to that encountered with classification of the detailed variation in macrofacies. Position within a cycle and 'microfacies' could best be defined by sequential variations in allochem abundance and Dunham's classification. A sliding scale of 22 'microfacies' were identified, reflecting the gradational nature of allochem assemblages through an idealized cycle, with approximately one 'microfacies' per metre of an idealized cycle (Fig. 4).

An attempt at further understanding of allochem distribution resulted in the development of a semi-quantitative method of description. For each microfacies up to 20 thin sections (where available) were selected and the allochems classified on a semi-quantitative logarithmic scale as follows (Table 1). In each case, a magnification of ×30 resulting in a field of view of 2.5 mm was studied; thin sections containing large colonial bioclasts such as *Siphonodendron* or *Chaetetes*, for example, were not counted and were considered as part of the macrofacies study (Fig. 3). The average number of each allochem per field of view was assessed, and a value per microfacies of each allochem could then be calculated. Given the sequential microfacies succession within an idealized shallowing-up depositional cycle, trends of allochem abundance could then be plotted (Fig. 4). From this figure, the association of allochems with particular positions within depositional cycles can be easily demonstrated visually. This made interpretation of depositional environments simpler,



Key:

▦ GRAINSTONE SHOAL

▤ PACKSTONES + WACKESTONES ARGILLACEOUS

▤ SHALE

√ PALAEOKARST

▬ PALAEOSOL MUDSTONE

Fig. 2. Stratigraphic column of the Urswick Limestone Formation showing the cyclicity.

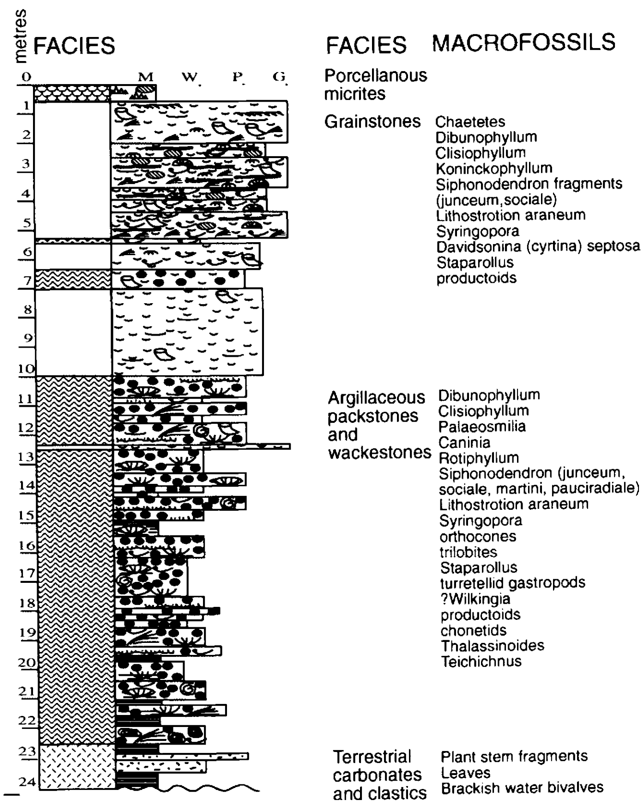


Fig. 3. Idealized Asbian cycle showing macrofacies.

and helped to constrain the depositional significance of some allochems which had not previously been studied in a palaeoenvironmental sense.

Point counting is unsatisfactory for description of carbonate microfacies, since important palaeoenvironmental criteria typically depend on the abundance of individuals, rather than being area-related. The semi-quantitative method of characterization allows consistent assessment of individual allochem abundances in each specimen that can be compared to texturally different specimens. It is also both faster and avoids problems of closure inherent in point-count data collection and interpretation.

Allochem distribution in an idealized cycle

Cycles in the Urswick Limestone Formation vary between 2 and 20 m in thickness (Horbury 1989). Allochem composition and trends in Dunham's classification of the 'idealized' Urswick Limestone cycle in Figs 3 and 4 typically show a shallowing-upwards succession. However, at the base of some cycles the macrofacies and microfacies may indicate an upwards-deepening trend, but these form only a minor part of the formation, are typically thin (<1 m) and are considered later in the paper.

Description

Cycle-base allochems. It is clear from Fig. 4 that some allochems are present only at the base of cycles in wackestone–packstone fabrics, for example, the algae *Coelosporella*, *Saccamminopsis*, *Stacheoides*, and other bioclasts such as trilobites, bryozoans and sponge spicules (Fig. 4, Figs 5a–c). Some small fragments of *Coelosporella* could be *Kulikia* (Mamet *et al.* 1980; Skompski 1986), although differentiation of these two when fragmented is difficult. Observations in

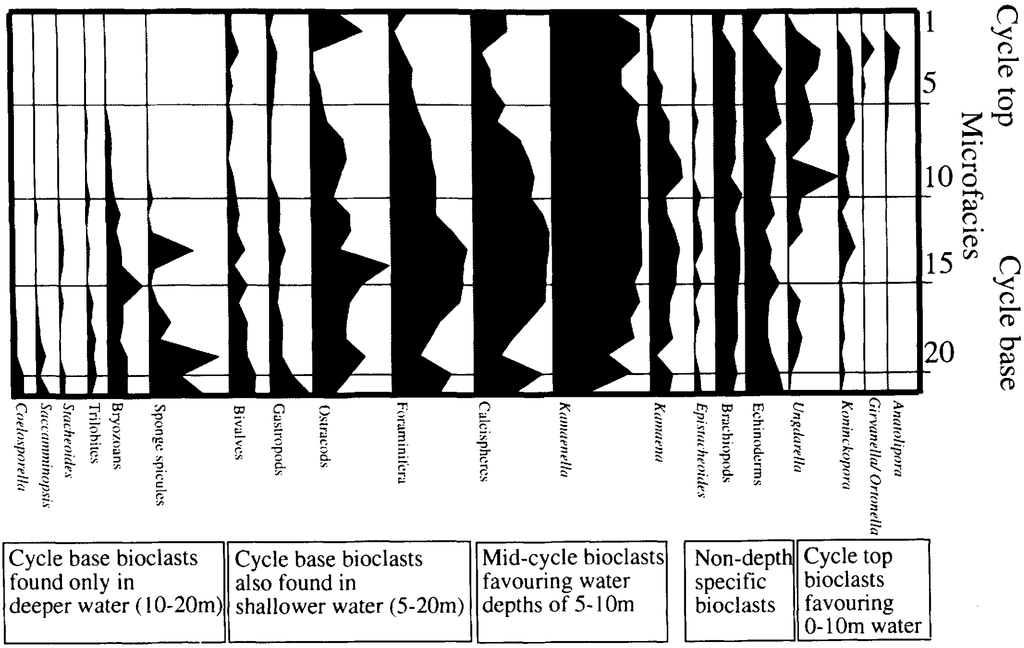


Fig. 4. Distribution of 'bioclasts' through an 'ideal' cycle.

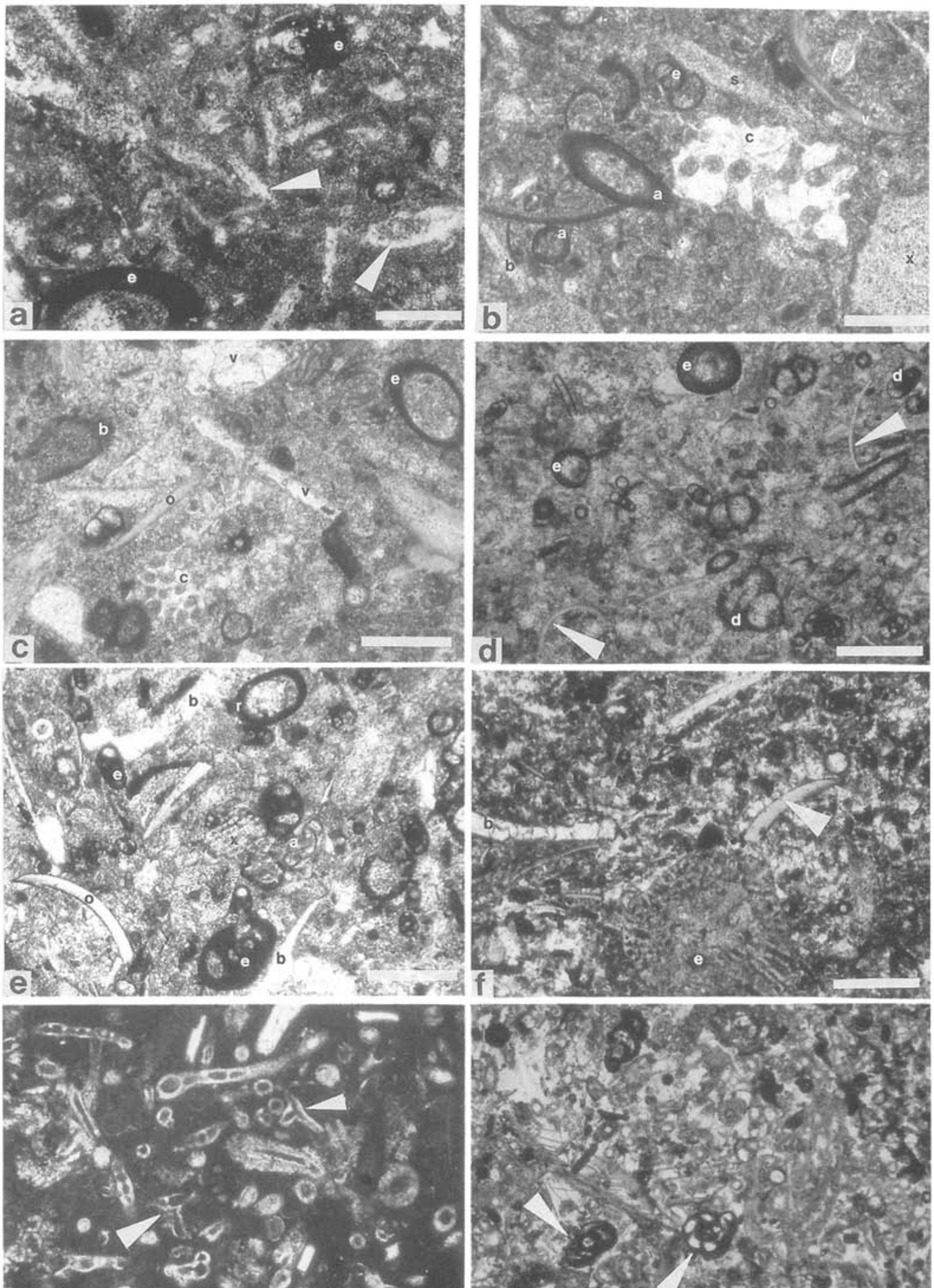
Mamet *et al.* (1980) suggested that *Kulikia* is part of a similar microfacies association, for example with *Earlandia*. Other bioclasts found in minor quantities at cycle bases include *Stacheoides* and oncoids with coats of *Girvanella*. In addition, foraminifera show a great generic diversity at the cycle base (White 1992), with Archaediscidae, the base late Asbian guide foraminifera *Howchinia*, the base early Asbian guide foraminifera *Gigasbia gigas* and *Vissariotaxis* (Horbury 1987), and the families Lasiodiscidae and Tetrataxidae (White 1992) being notably common. Some bioclasts, such as the alga *Coelosporella*, foraminifera (family Tetrataxidae) and *Saccamminopsis*, are particularly notable at the very base of cycles, whilst other bioclasts such as the foraminifera family Lasiodiscidae only appear above the cycle base (Horbury 1987; White 1992).

Table 1.

Allochems per field of view	Value
Over 10	10
5–9	6
3–4	3
1–2	2

Ostracodes, bivalves, small gastropods and bored grains are developed throughout the idealized cycle, but are dominant in cycle-base to cycle-middle packstone textures (Figs 5d, e). At the base of cycles, bivalves are generally thin-shelled and gastropods turreted. In the cycle base to cycle middle microfacies, a fine peloidal texture is locally preserved, such that cycle base microfacies are typically microsparry (Figs 5a–e) or micropeloidal (Fig. 5f) with much the same allochem abundances in both types of sediment.

Cycle-middle allochems. The middle of cycles mostly comprise clotted peloidal packstones and micro-grainstones and contain allochems dominated by small peloids, algae such as *Epistacheoides*, and the important palaeoberesellid algae *Kamaena* and *Kamaenella* with the microproblematicum *Ungdarella*. *Kamaenella* is particularly abundant in the middles of cycles, and may constitute up to 95% of all bioclasts present (Figs 5h, 6a). Adams *et al.* (1992) reported that at the locality of Ilston in the Gower area of South Wales, 67% of samples examined contain this bioclast as the most abundant, in 37% of the samples it comprised over half the bioclasts by volume, and in 12.8% of samples it comprised over 80% of the total bioclasts by volume. There are also relatively high abundances but often low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generic diversity of foraminifera families, which are typically not well developed in the cycle-base lithologies, such as Endothyridae (Horbury 1987), Ozawainellidae and Loeblichiidae with occasional Tournayellidae (White 1992).

Allochems in cycle-top grainstones. Allochems found in grainstones at the top of cycles comprise *Anatolipora*, *Girvanella*, *Ortonella*, *Koninckopora* and *Polymorphocodium*, intraclasts, large peloids, ooids, thick-shelled bivalves and gastropods (Figs 6b–h, 7a). Commonly there are early marine isopachous cements (Figs 6g, h) and the coarse micritized grains often possess a matrix sediment of fine peloids which post-dates early marine cementation (Fig. 6g).

Allochems in cycle-top lime mudstones and wackestones. In the uppermost porcellanous mudstones and wackestones, abundances of calcispheres, ostracodes, thin-shelled bivalves and gastropods, intraclasts and oncoids increase (Figs 7b–d). Sediment fabric often appears to have been originally a compacted micropeloidal grainstone, and may also have abundant microbial-thrombolitic textures preserved where relatively uncompacted. At the top of cycles, pedogenic features such as alveolar textures, laminar calcrete and rhizocretions are also common (Fig. 7e).

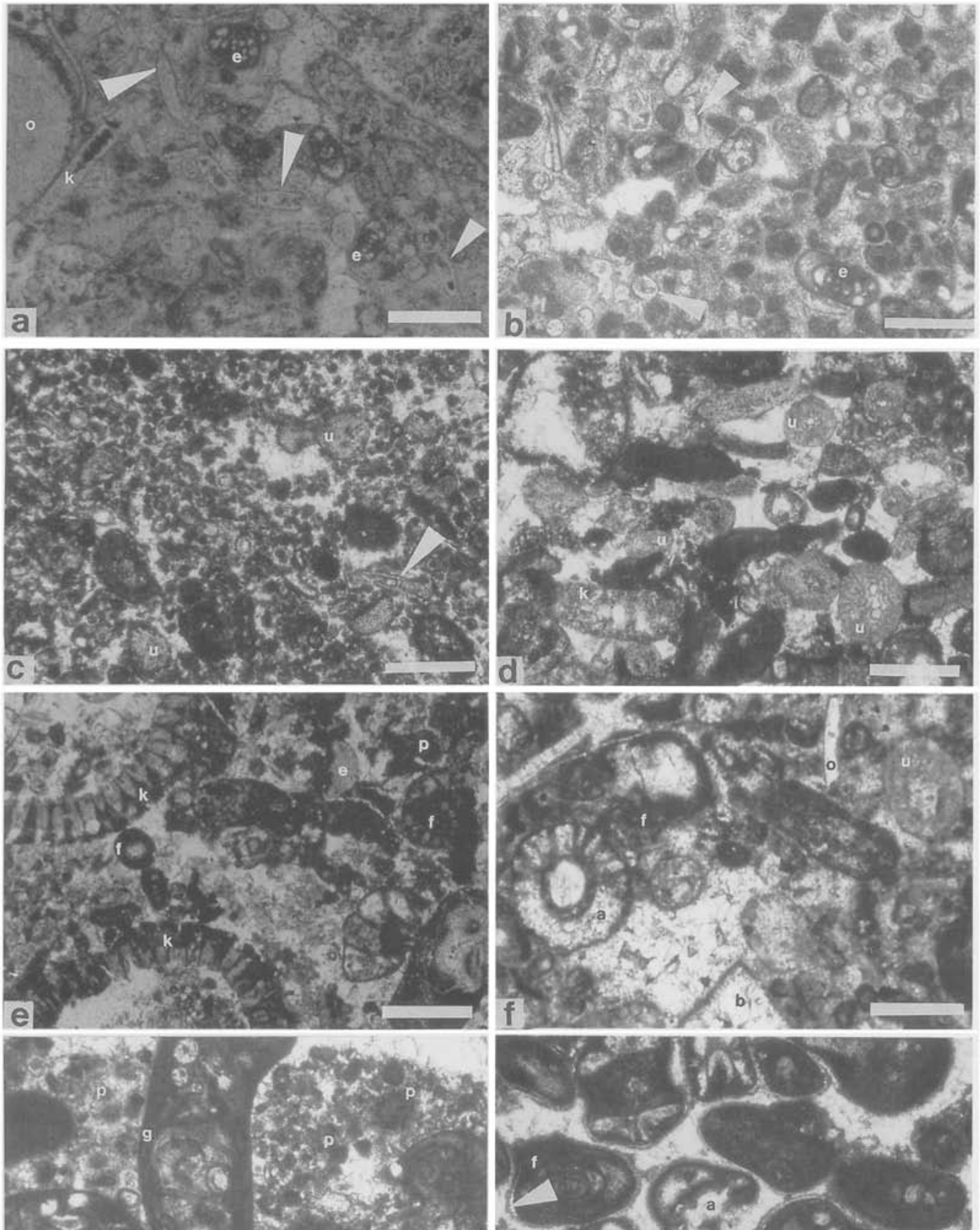
Allochems that show irregular or no regular trends through cycles. Some allochems as identified in thin section are found throughout most cycles, decreasing only at the very top or base of cycles, or have an irregular distribution. They are all macrofossil fragments and include brachiopods, crinoid ossicles and corals. The development of these macrofossils is often clearer from field logs, due to the difficulty of correctly identifying genera or species from fragments in thin sections; these relationships are discussed later.

Other trends and microfabrics. Echinoderms, ostracodes and foraminifera may locally be dominant in some samples, or absent from samples in which they are otherwise typical (Horbury 1987). At the base and middle of cycles, ostracodes are locally abundant, and often occur as nests or refuges within coral colonies such as *Siphonodendron* (Fig. 7f). Micritized omission surfaces are also commonly developed in the middle and particularly at the top of cycles (Fig. 7g).

Interpretation

Water depths. Most Asbian bioclasts do not have modern analogues; however, their water depth ranges can be determined approximately by restoration of typical cycle thicknesses, allowing for sediment compaction. The lower limit of significant micritization and peloid development is taken at 10 m water-depth, which is also the approximate depth of fair-weather wave-base and significant grainstone development. This also corresponds to the top of significant sponge spicule/bryozoan development and is the optimum depth of *Kamaenella* development. It is likely by extrapolation that the deepest water sediments were deposited at or about 15–20 m water-depth. The shallowest water sediments are relatively rare, and represent high-energy intertidal/shallow subtidal environments (ooid shoals) and intertidal-supratidal low-energy restricted sediments (porcellanous micrites).

Fig. 5. Photomicrographs of important litho- and biofacies. Scale bar 200 μm in all cases. (**a**) Cycle-base bioclastic wackestone, dominated by sponge spicules (now calcite casts, arrowed), and earlandiid foraminifera (e). Early Asbian, Farleton Fell. (**b**) Cycle-base bioclastic packstone. Diverse biota with fragment of *Coelosporella* (c), also earlandiid (a) and endothyrid (e) foraminifera, ostracode valve (o), bivalve (b), sponge spicule (s) and echinoderm ossicle (x). Early Asbian, Stainton Quarry. (**c**) Cycle-base bioclastic packstone with diverse biota including well-preserved *Coelosporella* thallus (c), earlandiid foraminifera (e), bryozoan (b), ostracode (o) and bivalve (v) fragments. Early Asbian, Stainton Quarry. (**d**) Cycle-base bioclastic packstone dominated by benthic foraminifera, mainly earlandiids (e) and endothyrids (d), also ostracod valves (arrowed) and *Kamaenella* in a microsparry matrix. Late Asbian, Sandside Quarry. (**e**) Cycle-base bioclastic packstone with a diverse biota including archaediscid (a) and endothyrid (e) foraminifera as well as earlandiids (r), ostracode valves (o), bivalve fragments (b) and echinoderm plates (x). Early Asbian, Farleton Fell. (**f**) Cycle-base bioclastic peloidal packstone–grainstone with small peloids in a sparite cement. Bioclasts include bivalves (b), ostracode valves (arrowed) and *Epistacheoides* (e). Early Asbian, Warton Crag. (**g**) Probable cycle-base bioclastic packstone, dominated by well-preserved *Kamaenella* showing branching (arrowed), from an intraclast in a cycle-top grainstone unit. Late Asbian, Stainton Quarry. (**h**) Cycle-middle grainstone dominated by comminuted *Kamaenella* (pale grey tubes and circular sections), with endothyrid foraminifera (arrowed); a generally low-diversity biota. Early Asbian, Warton Crag.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General depositional setting. The bioclast assemblages indicate a typically open marine environment, with evidence of slight restriction and faunal impoverishment, mainly where the sediment was deposited in very shallow water environments. Additionally, totals of bioclast values for each microfacies show that the most diverse assemblages of bioclasts occurred close to the base of cycles (Fig. 8), suggesting that this was a highly productive depositional setting. The slight decrease in abundance of bioclasts at the cycle base (about 22 m beneath the idealized cycle top) reflects an increase in the proportion of lime mud and the development of more wackestone facies; work by Davies (1984) on slightly thicker Brigantian cycles in North Wales suggested that the lithofacies at 20 m or more beneath cycle tops comprises mostly mudstones and wackestones. This was probably the depth at which lowered pO_2 and light penetration may have become critical factors in carbonate sediment production on these shelves. However, at the base of cycles the presence of bored grains, and the encrusting of grains by bryozoans and *Girvanella*, all indicate the presence of depositional hiatuses, probably during the lag time between rise in relative sea-level and the beginning of significant carbonate production (cf. Schlager 1981).

The bioclasts that show little or no dependence on position within the cycle, as observed in thin section, are typically large robust organisms which were probably readily transported and did not break-up easily in the higher energy shallow-water environments. Most brachiopod, coral and echinoderm genera probably lived in the sub-fairweather wave-base environments as indicated by macrofacies, but would have been transported into shallower water during storms. The presence of foraminifera as abraded fragments, in packstone intraclasts or, with micritic chamber fills, in grainstones, indicates that there was much reworking of material into shallow water (White 1992).

Palaeoenvironmental indicators. Algal genera have proved to be the most useful markers, since different algae tend to occur throughout each cycle, and enable a zonation to be built up. Algal families, (e.g. Dasycladaceae) are, however, environmentally wide-ranging (for example, containing *Coelosporella*, *Kamaena*, *Kamaenella*, *Anatolipora* and ?*Koninckopora*). Foraminifera are useful environment guide-fossils for the basal and middle part of cycles, but are not particularly abundant in the upper parts of cycles (White 1992). However, they are environmentally diagnostic at a family as well as genus level.

Significance of Kamaenella. Distribution of bioclasts through the depositional environments represented by the microfacies succession may have been controlled by the presence of abundant *Kamaenella*. For example, the distribution of foraminifera genera and palaeoberesellids is typically mutually exclusive through cycles in the Urswick Limestone Formation (White 1992). The *Kamaenella*-dominated middle part of the cycle separates the basal cycle allochem assemblages from the cycle-top allochem assemblages. White (1992) argued that "...the environments which allowed the palaeoberesellids to become established or resulted from their successful colonisation may have been restricted in some way which was

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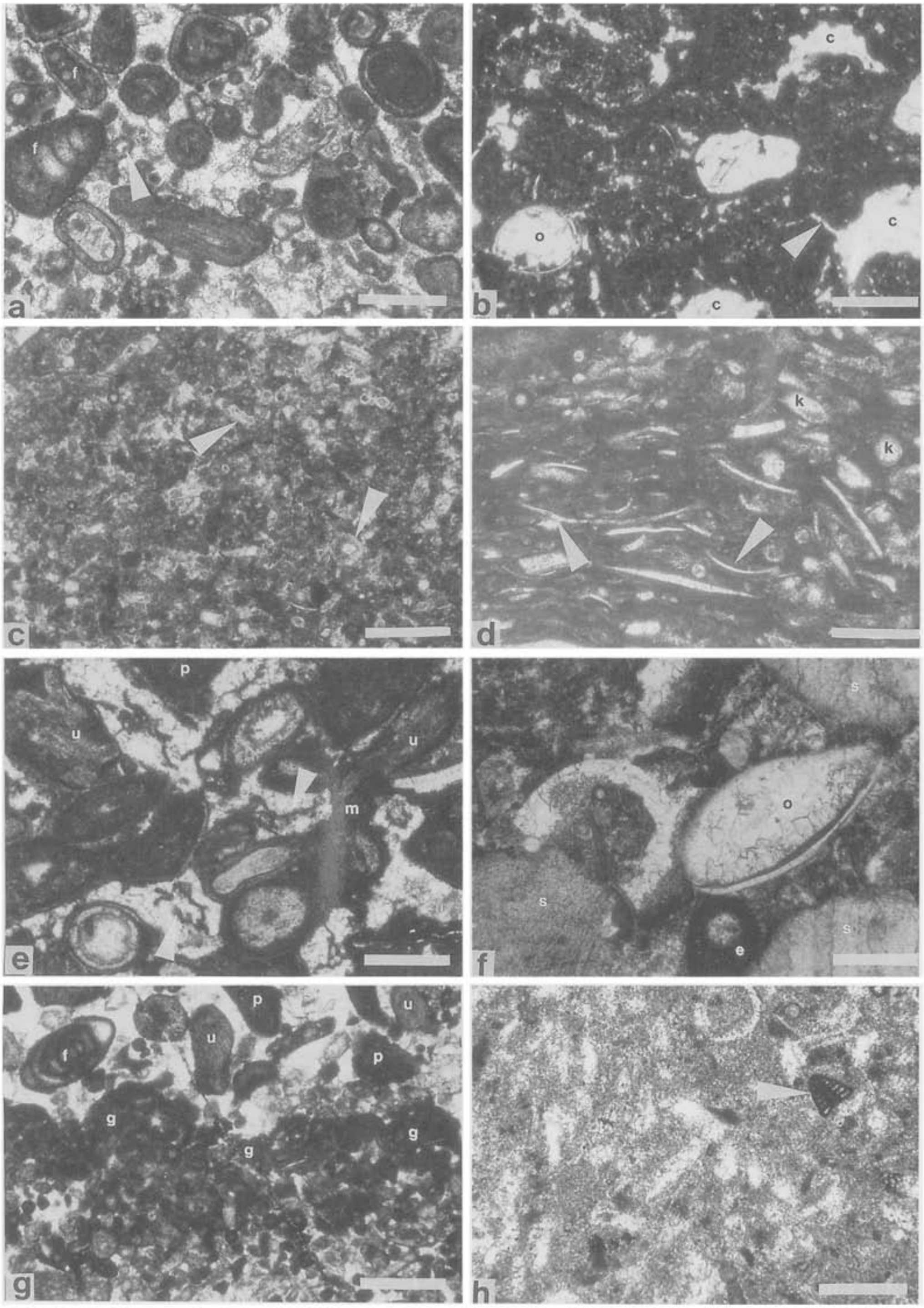
Fig. 6. Photomicrographs of important litho- and biofacies. Scale-bar 200 μm in all cases. (**a**) Cycle-middle bioclastic grainstone with a biota dominated by *Kamaenella* (arrowed) and occasional *Kamaena* (k), endothyrid foraminifera (e) and echinoderm plate (o), with well-developed inclusion-rich marine cements between bioclasts. Late Asbian, Sandside Quarry. (**b**) Cycle-middle bioclastic peloidal grainstone dominated by micritized unidentifiable debris and recognizable endothyrid foraminifera (e) and *Kamaenella* (arrowed) with traces of isopachous cement. Late Asbian, Back Lane Quarry. (**c**) Cycle-middle bioclastic peloidal grainstone, dominated by fine (?faecal) pellets, together with *Ungdarella* (u) and *Kamaenella* (arrowed). Late Asbian, Stainton Quarry. (**d**) Cycle-top bioclastic peloidal grainstone dominated by *Ungdarella* (u) and peloids formed from heavily micritized bioclasts (dark areas), also *Kamaena* (k). Late Asbian, Stainton Quarry. (**e**) Cycle-top bioclastic peloidal grainstone with large *Koninckopora* (k) in a matrix of comminuted Kamaenella (grey, inclusion-rich areas), foraminifera (f), echinoderm plates (e) and peloids (p). Early Asbian, Middlebarrow Quarry. (**f**) Cycle-top bioclastic peloidal grainstone with a diverse biota including *Anatolipora* (a), *Ungdarella* (u), bivalve (b) and ostracode (o) fragments, micritized foraminifera (f) and peloids formed from heavily micritized bioclasts (dark). Late Asbian, Back Lane Quarry. (**g**) Cycle-top intraclastic peloidal grainstone; some intraclasts are grapestones with superficial ooid coatings (g), with infiltrated fine peloidal sediment (p) and local isopachous cement. Late Asbian, Dunald Mill Quarry. (**h**) Cycle-top bioclastic peloidal grainstone with most peloids probably being heavily micritized *Anatolipora* and foraminifera (f). Isopachous cements have locally spalled off grains (arrowed) before precipitation of pore-filling cement. Late Asbian, Warton Crag.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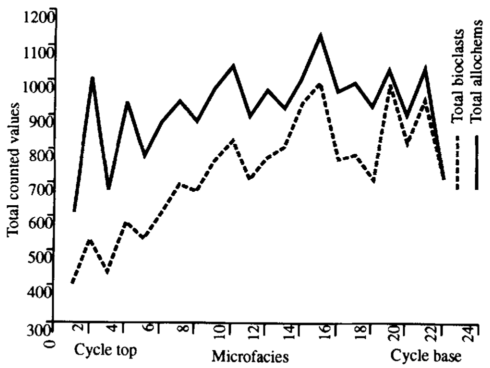

Fig. 8. Variation in total values of bioclasts and allochems in an 'ideal' cycle.

unfavourable to many foraminifera with the exception of Endothyridae and Archaediscidae". Similar exclusion of bioclasts by beresellid algae has been suggested for *Donezella* in buildups in the Namurian of Spain (Bowman 1979). The development of abundant *Kamaenella* thickets at or about fair-weather wave-base is typical of Asbian platform facies (Adams *et al.* 1992). *Kamaenella* may thus have served to prevent, by baffling or scarcity of growth sites, the colonization of habitats by other larger calcareous organisms. The high rates of production of *Kamaenella* sediment may also have swamped production of other bioclasts and allochems in this zone.

It was noted during study of the *Kamaenella* cementstone reef at Dunald Mill Quarry (Horbury 1992) that the reef core facies contained few bioclasts other than the foraminifera family *Endothyridae* and the genus *Earlandia*, thick-walled ostracodes and the microproblematicum *Ungdarella*. The few other bioclasts in the core facies were transported in, despite being present in abundance in flanking facies (e.g. echinoderms and bryozoans). Horbury (1992) concluded that the observed density of preserved *Kamaenella* in the reef core would probably not have been sufficient to have prevented other organisms from colonization of this substrate. However, the actual live reef may have been a site of denser *Kamaenella* encrustation. Adams *et al.* (1992) demonstrated that the *Kamaenella* grainstones were mostly reworked during storms, such that the *Kamaenella* thalli growing on the reef were periodically broken off, and were only rarely cemented into the reef framework.

The exclusion of foraminifera from *Kamaenella*-dominated sediment has been attributed by White (1992) as being a function of substrate or local microenvironment control determined by algal colonization, with the few genera of foraminifera able to survive being present in high abundances (e.g. Endothyracea and Ozawainellidae and large Archaediscidae). These robust foraminifera also tend to be spherical to subspherical or spindle-shaped, and may have been adapted to cope with the higher-energy upper part of cycles, or were more resistant to abrasion (White 1992). Foraminifera from the Lasiodiscidae family and fragile members of Endothyraceae and Ozawainellidae are completely absent from higher parts of the idealized cycle, indicating the difficulty in distinguishing substrate versus preservation control on foraminiferal abundance in the geological record (White 1992). However, the notable changes in allochem composition at about the level of the fair-weather wave-base indicates that there was a significant environmental break at this level which was exploited and partly controlled by the abundant development of *Kamaenella*.

Fig. 7. Photomicrographs of important litho- and biofacies. Scale bar 200 μm in all cases. (**a**) Cycle-top bioclastic oolitic grainstone. Larger bioclasts (foraminifera, f) and large peloids have two or three superficial coatings, in a matrix of finer peloids and *Kamaenalla* (arrowed). Late Asbian, Stainton Quarry. (**b**) Cycle-top mudstone showing fenestral cavities (c), desiccation cracks (arrowed) and articulated ostracodes (o). Biota are of very low diversity and abundance. Late Asbian, Stainton Quarry. (**c**) Cycle-top microdetrital grainstone dominated by finely-comminuted *Kamaenella* (arrowed) and small peloids; this is probably a depositional grainstone that was later compacted. Late Asbian, Warton Crag. (**d**) Cycle-top bioclastic wackestone dominated by ostracode valves (arrowed) and with a few *Kamaenalla* fragments (k). Late Asbian, Farleton Fell. (**e**) Cycle-top palaeosol, showing alveolar textures lining/filling intergranular cavities (arrowed) and micritic bridges between grains (m). Grains visible include *Ungdarella* (u) and peloids (p). Late Asbian, Warton Crag. (**f**) Intra-*Siphonodendron* biota, typified by articulated ostracodes (o) and earlandiids (e) preserved between the corallites of *S. junceum* (s). Early Asbian, Warton Crag. (**g**) Micritized surface at cycle top. Micritization is of a fine earlandiid *Kamaenella* peloidal grainstone (g), and overlying sediment is a coarse grainstone with *Ungdarella*, foraminifera (f) and peloids (p). Late Asbian, Stainton Quarry. (**h**) Cycle-base biota, typified by *Vissariotaxis* (arrowed) in sponge spicule-dominated wackestone–packstone. Early Asbian, Stainton Quarry.

Allochem variation through the Urswick Limestone Formation

Similar broad microfacies are developed throughout the formation. However, some allochems are stratigraphically controlled, in that they are not always present in otherwise similar microfacies throughout the formation. In the early Asbian there is an abundance of *Coelosporella* in cycle-base packestones and wackestones which is not mirrored in the late Asbian. Microfossils present in the late Asbian but absent in the early Asbian include *Saccamminopsis* in cycle-base packstones and wackestones; in grainstones of the cycle middle and top *Ungdarella* appears, and in cycle-top grainstones there are *Anatolipora* and *Polymorphocodium*. Microfossils commonly developed in the late Asbian but poorly developed in the early Asbian include *Girvanella* and *Ortonella* in cycle-top grainstones. These differences mirror established macrofossil variation in the local stratigraphy, for example, the presence of *Davidsonina* (*Cyrtina*) *septosa* in cycle-top grainstones in the late Asbian but not in the early Asbian (Rose & Dunham 1977; Horbury 1987), and the presence of *Lithostrotion araneum* in the cycle-base wacke-packstones of the late Asbian but not the early Asbian. Because these differences are typically of abundance rather than absolute presence or absence, caution must be applied in the use of these microfossils for precise stratigraphic subdivision, besides the obvious problems with the strong facies control on many of these microfossils. For example, *Ungdarella* in South Wales is only well developed in the latest Late Asbian where it appears to replace *Kamaenella* in abundance (Adams *et al.* 1992), whereas it is developed in the earliest late Asbian in the Urswick Limestone Formation.

Walkden (1982) suggested a high energy depositional setting for *Koninckopora*, as in this study, whilst Schofield (1982, p. 33), working on the Holkerian of Derbyshire, noted the reverse, in that *Koninckopora* was indicative of low energy environments and the red alga *Stacheia* was indicative of high energy deposition. Reasons for this apparent change in habitat between the Holkerian and Asbian are unclear.

Microfacies variation across the platform

There are significant variations in allochem distribution according to palaeogeography, which deviate from the 'idealized cycle' concept. The late Asbian shelf margin near Lancaster contains higher than average abundances of the algae *Koninkcopora* and *Anatolipora* in cycle-top grainstones, and also of the calcified filaments *Girvanella* and *Ortonella*, with thick-shelled gastropods, intraclasts and coarse peloids. In cycle-base packstones and wackestones, which are generally thin in this setting (Horbury 1989; White 1992), echinoderm arm plates and bryozoans are commoner, particularly in the lee of *Kamaenella*-dominated reefal facies (Horbury 1992). White (1992) noted that the greatest diversity of foraminiferal families, typically Endothyridae and Archaediscidae, occurred within the medium-grained grainstones rather than in the crinoidal–bryozoan flanking facies to the *Kamaenella*-cementstone reef. Also, the foraminifera of the family Lasiodiscidae are restricted to shelf margin localities (White 1992).

Platform interior facies are typically diverse open marine types, with a high total abundance of bioclasts in the cycle-base packstones and wackestones including notable trilobites, *Coelosporella*, *Stacheoides*, *Kamaena* and bored grains; cycle-top grainstones are dominated by small peloids, *Kamaenella* and *Ungdarella*. Storm-influenced platform interior microfacies mainly occur in the early Asbian in the Warton Crag area, and are typically defined by the presence of mid-cycle microfacies dominated by *Kamaenella* occurring in the basal part of cycles, indicating a localized lowering of wave-base. In South Wales, *Kamaenella* is similarly abundant in the 'lagoonal' facies as developed in the northern exposures of the Gower outcrop (Adams *et al.* 1992).

There are notable variations to the typical platform allochem assemblages and microfacies in the Farleton Fell/Holme Park Quarry/Hutton Roof area when compared with the platform interior to the east. Sponge spicules are common in the cycle-base wackestones and packstones of the early Asbian, but are rarely found in the early Asbian elsewhere. In the late Asbian, total bioclast abundances in cycle-base wackestones and packstones are low, and cycle-base wackestones are relatively porcellanous. The microproblematicum *Ungdarella* is found throughout the early Asbian, whilst elsewhere it is only found in the uppermost 20 m (Horbury 1987).

In the five depositional cycles comprising the early Asbian in the study area (Horbury 1989), the percentage of coarse peloidal grainstones present in the cycle-top grainstones decreases upwards through the formation as follows: from 40%–28%–28%–1%–3% (Horbury 1987). This reflects the coastal onlapping and development of the nearshore sediment variant of the idealized cycle in the basal three cycles in the study area (Horbury 1989). In the condensed platform-interior grainstone section of late Asbian age in Stainton Quarry, there is a high abundance of ooids, intraclasts, thick-shelled gastropods and *Koninckopora.* This assemblage is similar to the platform margin microfacies assemblage, but also contains evidence of coastal onlap associated facies (see later section on sequence stratigraphy). Similar thin, condensed oolitic–intraclast dominated platform interior-facies, with only scarce *Kamaenella*, occur in the northern outcrop of the Asbian succession in South Wales (Adams *et al.* 1992), and may also indicate the presence of an onlap margin.

Sequence stratigraphic controls on microfacies development

Most of the marine sediment in the Asbian platform stratigraphy was deposited during sea-level highstands, at eustatic maxima (Horbury 1989). The idealized microfacies 'cycle' reflects, therefore, highstand deposition, characterized by a bioclastic–peloidal composition. This is similar to the specialized shelf margin sediment composition of the late Asbian and early Brigantian of northern Derbyshire noted by Gawthorpe & Gutteridge (1990).

In any cyclic stratigraphy, there must be a record of the lowstand and transgressive systems tract (Vail *et al.* 1977). In the case of the Asbian of the study area, at Leaper's Wood Quarry there is a 26 m deep palaeovalley fill, recording karstification, lowstand and transgressive systems tract deposition which is significantly different to the typical platform-interior highstand facies. There are also lower relief features at other localities that have similar lowstand/transgressive systems tract facies, allowing a more detailed picture to be built up for facies/microfacies changes through a complete cycle (Fig. 9). Lowstand deposits are reflected by a variety of palaeokarst and local palaeosol features, followed by fluvial–estuarine–fan delta clastic carbonates. These have a scarce but completely different biota in growth position compared with the biota of the highstand carbonates, with a dominance of pectinid and other bivalves (Horbury 1987). All other bioclasts present show evidence of significant abrasion and transport, and were probably derived from karstification of highstand carbonate. Transgressive systems tract sediments are typified by an abundance of oolitic–peloidal–microbioclastic grainstones, which are locally associated with plant debris, stromatolites, peritidal micrites and oncolitic limestones where the preserved transgressive systems tract is a thin unit (for example, at Trowbarrow Quarry where an oolite/stromatolite unit marks the initial flooding of a late Asbian palaeokarst). These sediments are faunally impoverished, with only occasional *Chaetetes* macrofauna observed in growth position and no significant *in situ* microbioclastic components.

The differences in macrofacies/microfacies of the lowstand, transgressive systems tract and highstand sediments is indicative of a freshwater/brackish lowstand system, very shallow marine transgressive systems tract sediments and the fully open marine highstand system. During the lowest sea levels, the connection of the lowstand rift basin seas with open oceanic circulation was probably very poor, and fresh water may have significantly affected at least the surface waters of these basins. For this reason, brackish faunas are developed close to the basin margin. During transgression, the thick units of oolite developed at Leaper's Wood Quarry in the palaeovalley fill reflect deposition in a coastal onlap setting, with aggradation of high-energy shallow-water environments which later spilled out onto the karstified platform top. Only following the maximum flood event did the platform carbonates begin to accumulate, following a hiatus at which time grains and intraclasts were bored, and transgressive systems tract allochems were bioturbated into the overlying units. Highstand deposition commenced with water depths of up to 20 m and fully open marine conditions.

Relationship of microfacies to macrofacies

The microfacies broadly correspond to the macrofacies of Horbury (1989) as noted in Fig. 4. Macrofossil elements show a similar style of variation in abundance through the idealized cycle as do the microfauna and flora (Fig. 3). Combination of both macro- and micro-facies/faunal/floral data have helped to constrain four marine-environment groups (Horbury 1987). These were used to interpret the anatomy of the platform interior environments, and comprise: (a) sub-fairweather wave-base mudstones to packstones; (b) storm-influenced sub-fairweather wave-base packstones and grainstones; (c) above fair-weather wave-base shoal grainstones; and (d) intertidal–supratidal flat low-energy mudstones and wackestones.

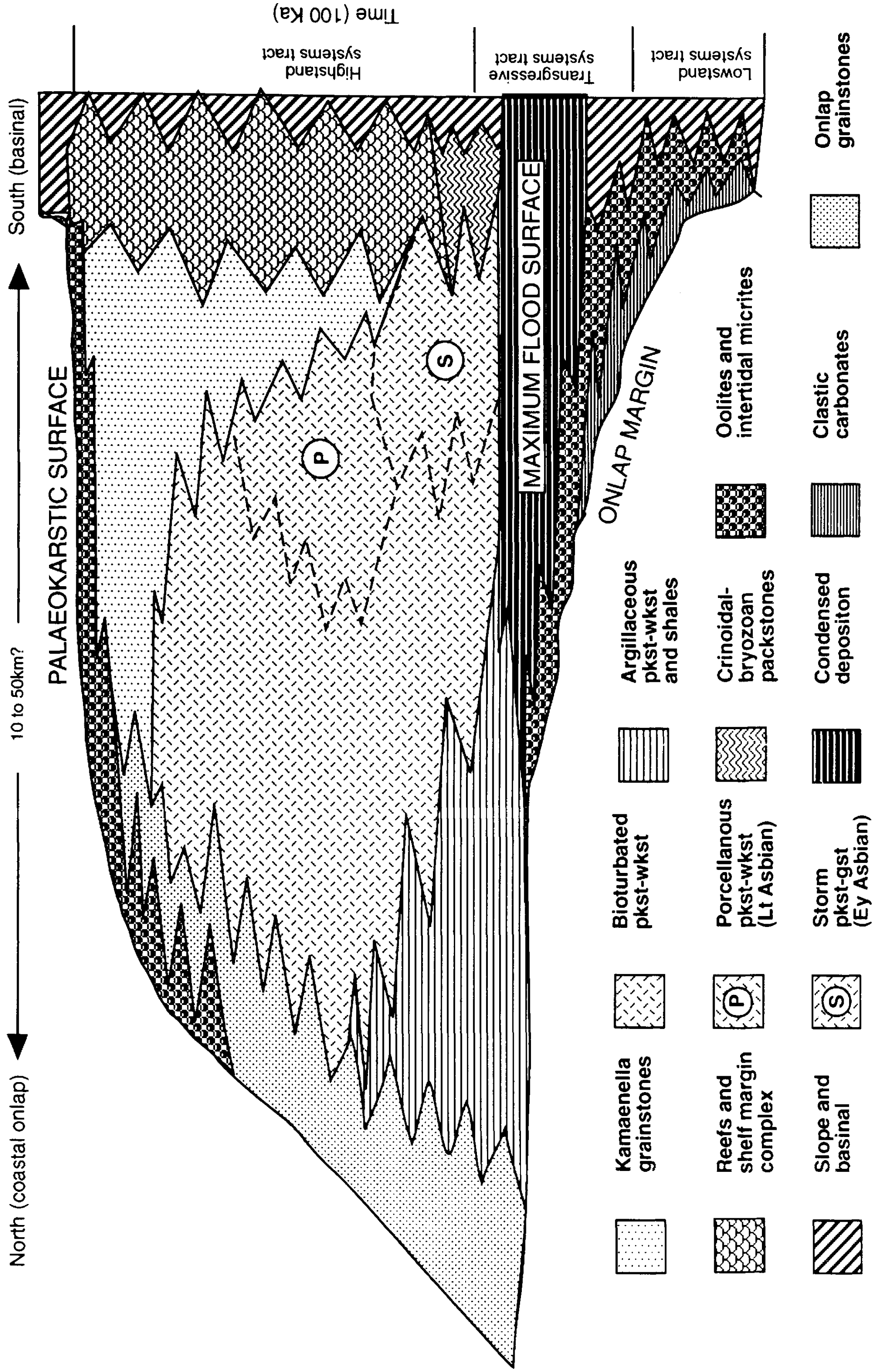

Fig. 9. Schematic chronostratigraphy of an Urswick Limestone cycle.

From these environment groups, deviation of cycles from the 'idealized cycle' are better accounted for. Horbury (1987) defined a total of seven sedimentary systems derived from an understanding of these local microfacies distributions. There are three variants in the early Asbian (nearshore cycle, storm cycle and normal shelf cycle types) and four in the late Asbian (normal-marine and restricted-marine cycle bases, normal shoaling and platform-edge shoaling cycle tops). Platform margin facies of early Asbian age were not encountered in the study. From these geographical variations in microfacies and macrofacies data, a schematic chronostratigraphy of a shelf cycle can be constructed (Fig. 9). This must be used in conjunction with the 'idealized' cycle in order to interpret fully the depositional environments across the study area.

Discussion

The basal parts of the cycles contain many bioclasts which have been used to define formation and stratigraphic tops, e.g. *Saccamminopsis*, *Girvanella*, *Howchinia* and *Vissariotaxis* (Fig. 7h). These 'diagnostic' bioclasts are only present where the style of cyclicity is such that the basal facies of cycles are developed. Since development of cycle-base facies was typically a function of local subsidence style (Horbury 1989), the stratigraphic precision of these bioclasts may be called into question. The main formation/chronostratigraphic boundaries in the southern Lake District all coincide with major sequence-stratigraphic boundaries and changes in style of stacking of sedimentary cycles.

Where major lithology changes occur, the 'facies boundaries' typically reflect missing gradational section, and changes in relative sea-level may possibly be inferred to control such surfaces, both at the top and base of cycles and within cycles. The generally flat-bedded character of the Urswick Limestone in outcrop, together with the general scarcity of progradational features, suggests that the platform top mostly comprised very low angle ramps and banks over which gradual environmental variation took place. Rapid lateral microfacies changes on the platform top are generally scarce, with evidence of extensive coastal onlap and storm activity controlling variations in the earliest Asbian. During the late Asbian, coastal onlap was important only in the west at Stainton Quarry. Vertical variations from cycle to cycle reflect the longevity of the coastal onlap influence, and also reflect variations in cycle stacking patterns and possibly the development of the platform margin.

Compositions of highstand, lowstand and transgressive systems tract sediments are important in understanding the effects of eustacy on the half-graben basin system. It is obvious from this study that the main production of sediment as loose grains was during the highstand, whilst the subtidal deposition during the lowstand was too brackish and during the transgressive systems tract was too restricted to produce a significant amount of loose sediment. The only sediment shed at this time was probably meteorically stabilized fragments of karstified limestone (Horbury & Gawthorpe 1993). This has implications for the timing of platform progradation and the relationship of turbidite type to sequence stratigraphy in half-graben basins. Palaeogeographies should illustrate these three extremely different types of depositional setting by more than one map reconstruction.

Conclusions

Microfacies indicate strong differences between highstand, transgressive and lowstand systems tract deposition. The highstand systems tract sediments typically comprise open marine platform-top carbonates deposited in water depths of 0–20 m. Lowstand systems tracts were brackish and coastal (where they are preserved), whilst the transgressive systems tracts were dominated by high-energy shallow subtidal–intertidal settings typical of coastal onlap margins.

The most sensitive environmental indicators through an 'ideal' cycle are calcareous algae, both in terms of water depth indication and position on the platform. Calcareous algae also form the major bioclast component in most of the platform sediment. Foraminiferal genera and families are also indicative of depositional environments, but only in the middle and base of cycles. Other types of bioclasts and allochems are generally restricted to the top or base of cycles (e.g. ooids and bryozoans), or are developed throughout cycles and have little diagnostic use as microfacies or environmental markers (e.g. brachiopods and echinoderm debris).

The development of abundant *Kamaenella*, which grew in thickets at or about wave-base, probably controlled the division of cycles into three broad biological zones.

Many allochems used for stratigraphic purposes in the Late Dinantian are only found in cycle-base lithologies. Their presence or absence is mostly dependant on cycle stacking patterns and was ultimately controlled by local tectonics rather than by biological evolution. Cycle bases were the most productive environments in terms of diversity.

Microfacies can be correlated with, and help constrain, interpretation of field macrofacies. Both macro- and microfacies are intergradational, with no 'sharp' compositional boundaries due to bioturbational mixing of sediment and habitat overlap. Where major lithology changes occur, 'facies boundaries' typically reflect missing gradational section, and changes in relative sea-level may possibly be inferred to control such surfaces.

Sediment accreted vertically as a system of very low angle ramps and banks within each cycle. There is little or no evidence of significant progradational infill of the platform-top accommodation space. Lateral variations in microfacies were probably due to coastal onlap and storm activity; vertical variations from cycle to cycle mainly reflect the longevity of coastal onlap systems, and cycle stacking patterns.

Important microfacies variations from the ideal platform interior cycle comprise shelf margin, storm-dominated, restricted platform-interior and nearshore coastal onlap cycle variants.

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