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A Late Dinantian peloid cementstone–palaeoberesellid buildup from North Lancashire, England

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ABSTRACT

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Early lithified peloid cementstone–palaeoberesellid buildups of a previously undescribed type of Late Asbian (Late Dinantian) age occur near Carnforth in North Lancashire. One of these buildups formed a 1–2 m topographic feature and accreted a total thickness of 11 m before growth stopped. The buildup occurs near to a windward shelf margin which is grainstone shoal dominated.

The buildup and associated sediments comprise three main facies: (1) core facies of the palaeoberesellid *Kamaenella* and marine peloidal cements; (2) flanking crinoidal–bryozoan facies comprising grainstone, packstone and conglomeratic textures in which reworked core facies intraclasts are present; and (3) shoal–lagoonal facies typical of the shelf margin.

During the Asbian, *Kamaenella* was a successful coloniser of shallow, moderate- to low-energy, shelf environments subject to frequent and rapid sea-level changes, but it appears to have been only an opportunistic bioherm builder. The presence of rounded core-facies clasts in the flanking facies indicates that peloidal cementation lithified the buildup. These cements probably developed in response to microbial activity in low- to moderate-energy settings where framebuilder growth and sedimentation rates were low. Vertical growth of the buildup suggests that deposition kept pace with a rise in relative sea level.

Introduction

Styles of Carboniferous buildup development

Reef building communities underwent a crisis during the mid/late Devonian with the extinction of most coral species (Newell, 1972; Heckel, 1974; McGhee, 1989). In the Carboniferous, various types of buildup evolved in a sequence recognised by West (1988). He summarised that the following order mirrored the pre-Carboniferous evolution of buildups: (1) Mississippian (Dinantian/Namurian) mudmounds of microbial origin; (2) Westphalian A stromatolitic boundstones and associated algae; (3) Westphalian B/C/D chaetetid–*Komia*–foraminifera mounds; (4) Stephanian A/B red and green algal reef mounds; and (5) Stephanian C *Palaeoaplysina/Tubiphytes* mounds. Most of these buildups are "patch reefs" on shelves although the larger Early Dinantian Waulsortian type mudmounds usually occur on the toes of ramps (Lees, 1982; Lees and Miller, 1985; Lees et al., 1985; Wright and Faulkner 1990).

Other work (Wolfenden, 1958; Ota, 1968, 1977; Jackson, 1972; Bowman, 1979, 1985; Adams, 1984; Schenk and Hatt, 1984; Bancroft et al., 1986; Gibson, 1986; Jameson, 1987; Dix and James, 1987; Fang and Hou, 1987; Webb, 1987a, b; Edwards and Riding, 1989) indicates that Dinantian

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and Namurian buildup types demonstrate a great diversity and were not restricted to microbial mounds lacking an organic framework, as implied in the evolutionary sequence of West (1988). Bryozoans, skeletal and non-skeletal algae, corals, sponges and foraminifera all contributed at various times to organic framework reef mounds. Each example was usually restricted to the shelf interior of an individual platform at one time. Only rarely was a particular buildup type ubiquitous. British Dinantian ramp top/rimmed shelf carbonate margins are shoal dominated rather than mudmound or biogenic reef/buildup dominated (e.g. Burchette et al., 1990; Gawthorpe and Gutteridge, 1990); this absence of reef-built shelf margins is true of the Carboniferous as a whole (James, 1984).

Buildup colonisers were usually the same organisms that, for the vast majority of the time, were the ordinary shelf top biota. They appear to have operated as colonisers in an ad-hoc "have-a-go" fashion. Large frame builders (corals, chaetetid sponges and stromatolites) are usually present in Dinantian and Namurian shelf deposits, although even in these circumstances they are often absent from buildups on the same shelf. Colonisers usually initiated buildup development by taking advantage of local palaeogeographic settings that gave them a competitive advantage (Adams, 1984). As noted by Edwards and Riding (1989) most non-mudmound buildups comprise intertwined, scaffold-building "microframebuilders" which are associated with fenestral fabrics, microbial films and pore-filling marine cements. These fabrics were necessary for building a strong frame without larger elements.

Status of Kamaenella

The buildups described here represent the earliest known example of construction by the *Kamaenella / Donezella* group of organisms. Classification of these organisms is controversial. One group of workers considered them to be "microproblematica", possibly sponges, and use the names aoujgallids and moravamminids (Riding, 1977; Termier et al., 1977; Wray, 1977; Lees and Miller, 1985). The other group considered them to be beresellids and palaeoberesellids, of probable algal affinity (Elliott, 1970; Petryk and Mamet, 1972; Mamet, 1973; Mamet and Roux, 1974; Cuvashov and Riding, 1984). The names used in this paper are those of the latter group.

Objectives

The aim of this paper is to describe a *Kamaenella*-peloid cementstone buildup, propose a growth mechanism and then to examine its significance in relation to the depositional setting and other Carboniferous buildups. Finally, an attempt is made to examine why this buildup type and the others which developed in a similarly isolated style, did not succeed in dominating the Carboniferous shelf margins.

Geological setting

Occurrences of buildups

Exposures of buildups are restricted to the Urswick Limestone Formation in Dunald Mill Quarry, 3 km SE of Carnforth, North Lancashire, England (Fig. 1). Shelf to shelf margin limestones in this quarry are of late Asbian (Late Dinantian) age. The buildups occur in the most strongly cyclic upper part of the Urswick Limestone (Figs. 2, 3).

Other buildups were reported from this area by Hudson (1937) and Ramsbottom (1969). These are either poorly exposed or are now unidentifiable and were not studied.

Depositional setting

A cyclicity is seen in the Urswick Limestone. Where well developed, this comprises 10–20-m scale argillaceous packstone–wackestone-based, grainstone-topped units sometimes capped by thin peritidal micrites. These cycles are restricted to the southern part of the Lake District High, and were interpreted as shallowing cycles of local tectonic origin (Horbury, 1989), although climatic changes could vary water energy in a similarly cyclic fashion.

Cycles are usually punctuated towards their

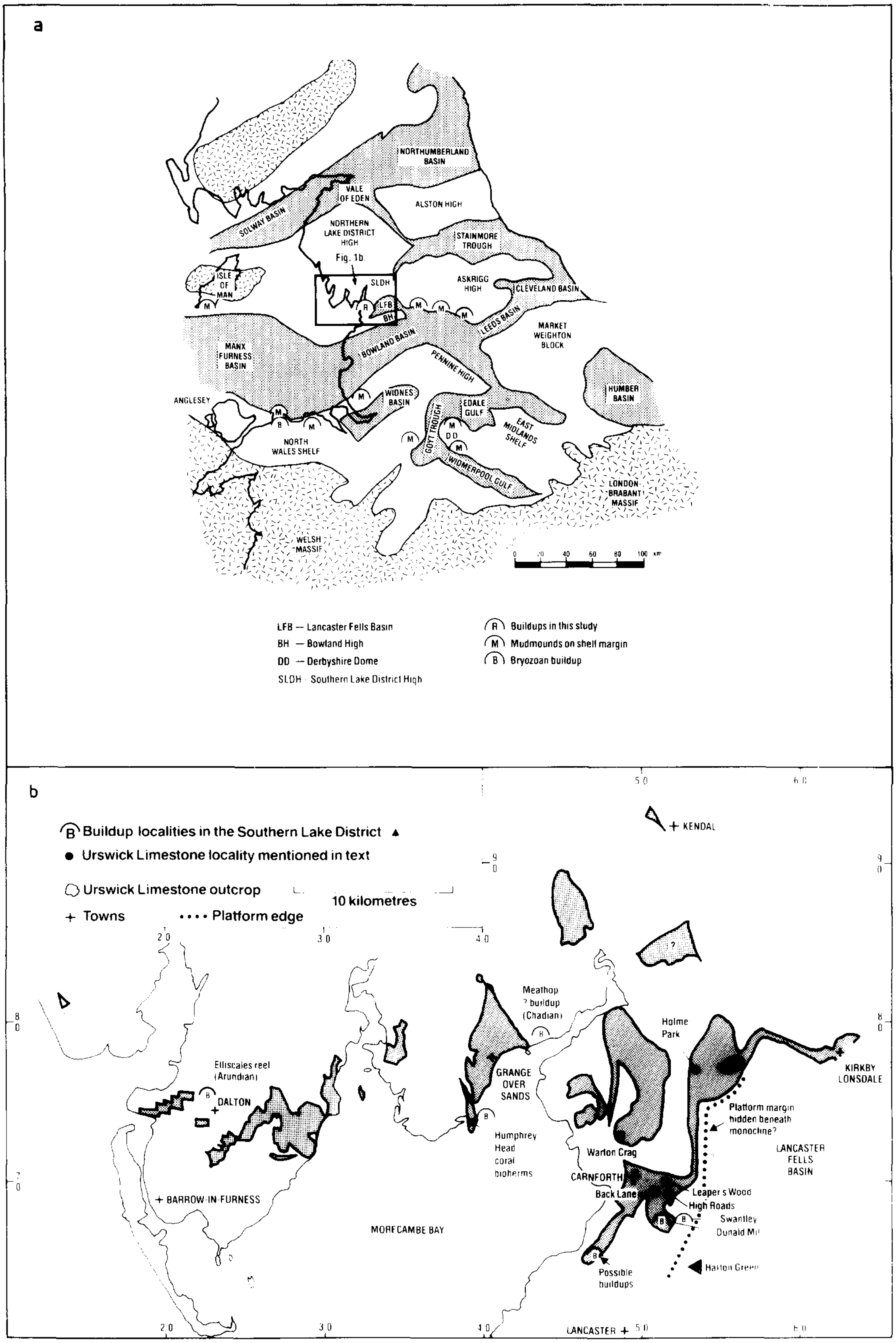

Fig. 1. (a) Regional Dinantian palaeogeography. (b) Location of the buildups in Dunald Mill Quarry and of other localities named in the text.

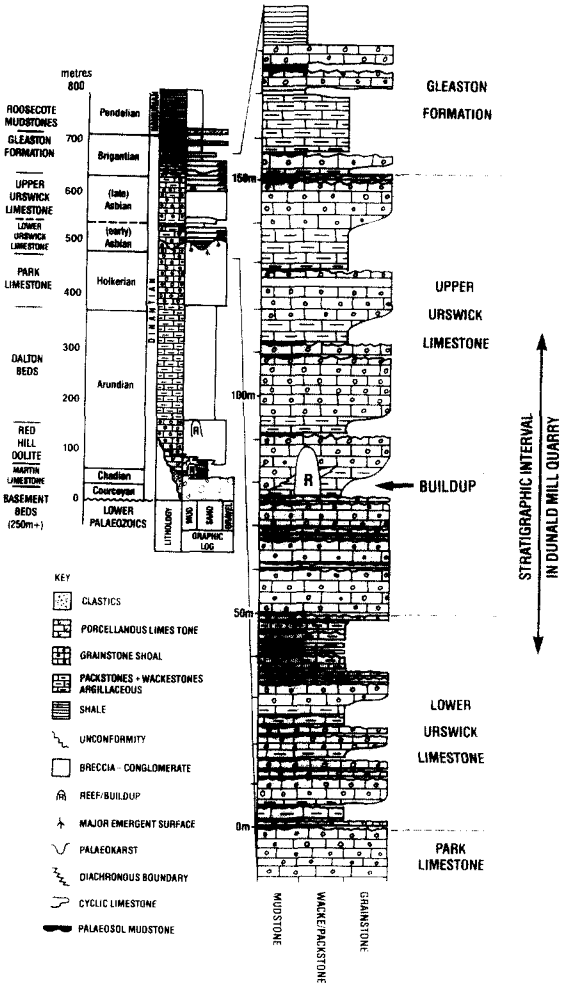

Fig. 2. Urswick Limestone stratigraphy in the Carnforth area and generalised Dinantian stratigraphy in the southern Lake District.

top by the appearance of one or more palaeokarstic surfaces. In the Dunald Mill area these show signs of deep (2–26m) erosion (Horbury, 1989). Similarly stacked palaeokarsts initially occur in the Asbian stage in Britain and appear in age-equivalent limestones in northern Europe, North America and the Soviet Union. These emergent events are interpreted as glacio-eustatic in origin, reflecting the initial expression of the Gondwanan ice caps (Horbury, 1989).

The shelf margin is situated to the S and E of Dunald Mill and was oriented SW to SSW, beyond which was the relatively enclosed Lancaster Fells Basin (Fig. 1). Towards the shelf margin, shoal facies dominate at the expense of lower-energy facies. The algae *Koninckopora*, *Anatoilpora*, *Girvanella* and *Ortonella*, intraclasts and thick-shelled turreted gastropods are all more abundant towards the margin than in either high- or low-energy shelf interior facies.

Slope breccias and turbidites are found at Halton Green, 4 km to the SE of Dunald Mill (Fig. 1). Clast analysis provides information about the unexposed shelf/slope break. This probably comprised a fenestrate bryozoan framestone/microsparite clast breccia cemented by early marine cements. Similar early marine cemented limestones are seen along the Asbian age shelf margin in North Derbyshire (Bingham and Walkden, 1990) and along the Craven margin in Yorkshire (pers. observ.).

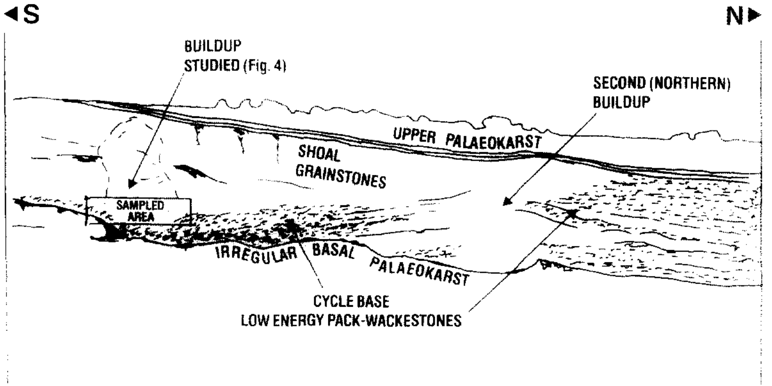

Fig. 3. Two buildups in the western face of Dunald Mill Quarry. The sampled buildup is on the left hand (southern) side of the face. A shoal accreted around and swamped the buildup studied and caps the second buildup. Line copy of photograph; textural contrast on print was always too subtle to reproduce well.

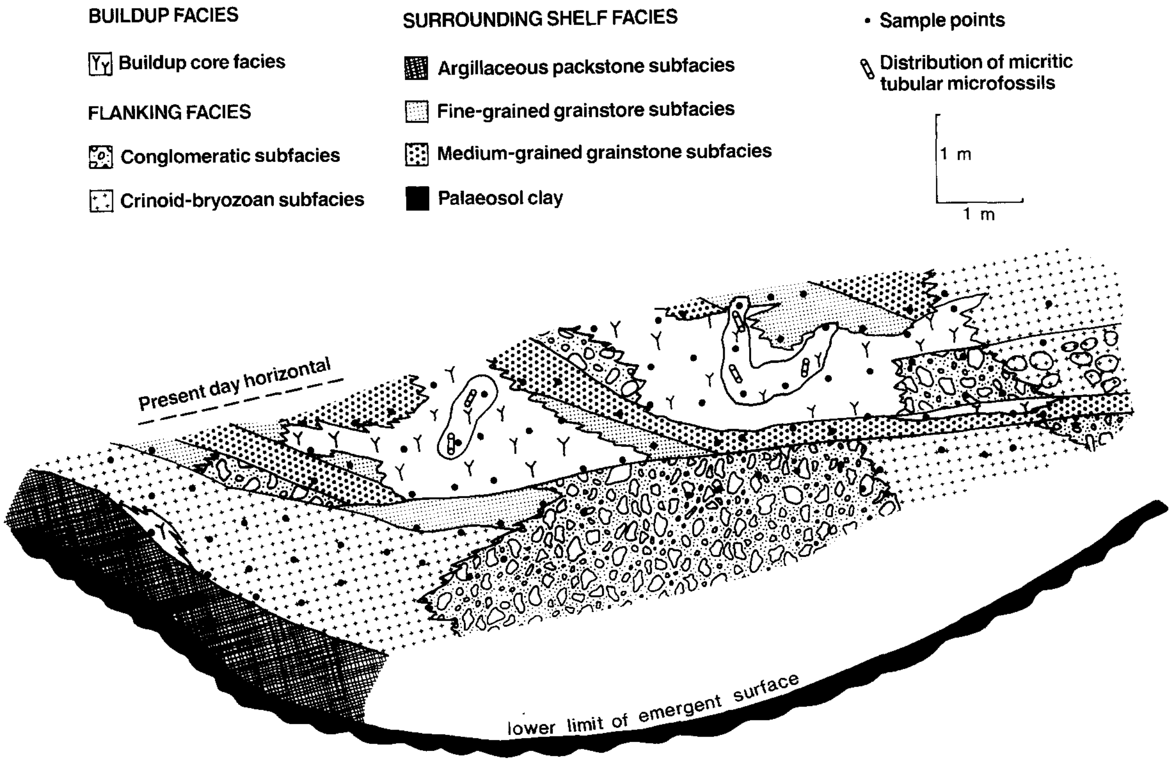

Fig. 4. Facies distribution within the sample grid, restored to depositional horizontal.

Techniques used

The base of one accessible buildup was sampled for a distance of 12 m and a height of 3 m using a 0.5 by 0.5 m grid interval (Fig. 4). Other buildups in the quarry and the upper part of the buildup sampled were inaccessible.

Each of the 108 samples taken was described when slabbed. Stained acetate peels were prepared for all samples using the technique outlined in Adams et al. (1984). In addition, 30 samples were made into polished thin sections for standard petrography.

Facies descriptions

Buildup core facies

This facies is typically a tan to pale brown *Kamaenella denbighi*-peloidal cementstone. Branching specimens can be seen petrographically (Figs. 5A, 5B). Many of the *Kamaenella* fragments are broken and lack micritisation.

The main framebuilding element is a pervasive peloid-spar cement which dominates this facies, locally occupying over 60% by volume (Figs. 5B, 5C). Peloids are well-sorted and range in size from 20 to 60 μm in diameter although sizes are usually 30 to 50 μm (Fig. 5C). Cements seeded on the peloids grade outwards in a drusy fashion with a steady increase in crystal sizes. Cements are inclusion-rich and demonstrate a range of fabrics including a dominant, indistinct, microsparry coarsening to pseudosparry calcite fabric similar to grumeuleuse texture (Fig. 5C) and later stubby laths to equant crystals of calcite which line cavities and coat grains (Fig. 5D). *Kamaenella* forms a significant but minor component of the rock, always under 20% by volume.

Other allochems are uncommon but include three types not found in other parts of the Urswick Limestone. *Kamaenella tenuis* (a larger species than *K. denbighi*) (Fig. 6A) occurs near the base of the buildup core and two types of micritic-walled tubular microfossils of uncertain affinity occur in the centre of the buildup core (Figs. 6B, 6C). All of these are present in their presumed life position. Groups of the alga *Ung-*

darella were also noted in life position (Fig. 6D) as well as an articulated smooth-shelled terebratulid brachiopod (*Dielasma*). Endothyrid and earlandid foraminifera are always well preserved and unmicritised (Figs. 5A, 6D, 7A). Thick-walled, articulated ?ostracods are also typical of the buildup core facies (Fig. 5A). All other bioclasts appear to have been transported in and include large disarticulated crinoid ossicles, brachiopod and bivalve fragments, thin-walled ostracod valves, calcispheres, turreted gastropods and the algae *Epistacheoides, Koninckopora* and *Kamaena*.

Irregularly shaped vuggy cavities up to 20 mm across are common (Figs. 5B, 5C, 5D, 6A, 6B, 6D, 7A). They closely resemble "spongiostromate" fabrics described from similarly peloidal buildups by Sun and Wright (1989). The larger cavities may represent shelter cavities initially formed by framebuilding elements, particularly *K. tenuis*. Later, these formed sites of micrite, peloid and early spar precipitation prior to infill by internal sediments (Fig. 7A). Some cavities demonstrate cross-cutting relationships with cements and bioclasts. Cavities are otherwise infilled with burial cements, fine-grained grainstones, brownish sparry calcite or pale brown crystal silts and other internal sediments (Fig. 7A).

Other occurrences of Kamaenella as a sediment stabiliser

In the Urswick Limestone platform interior small patches of *Kamaenella* bafflestone (packstone) to framestone (grainstone) occur (Figs. 7B, 7C). Well developed *Kamaenella*-peloid associations become increasingly common near to the shelf margin. Intraclasts of these lithologies have also been found throughout the shelf margin area and from debris flows in the Lancaster Fells (Horbury, 1987) and Bowland basins (pers. observ.).

Flanking facies

Flanking facies can be divided into two types: a crinoid–bryozoan dominated packstone to grainstone subfacies and a conglomeratic subfacies. The crinoid–bryozoan subfacies forms the matrix to the conglomeratic subfacies.

Crinoid–bryozoan subfacies

This is characterised by abundant stick bryozoan and crinoid fragments, notably crinoid arm plates (Fig. 7D). Textures are poorly sorted packstones (poorly washed biosparite, Fig. 8A) and grainstones (Fig. 7D). In hand specimen large crinoid ossicles are scattered in a mid to pale grey-brown fine-grained matrix.

Other allochems are varied but never abundant and include the algae *Ungdarella, Kamaenella, Stacheoides spissa, Epistacheoides, Polymorphocodium, Ortonella* fragments and fragments of bivalves, gastropods, *Chaetetes*, foraminifera, *Saccamminopsis*, calcispheres, hexacorals, *Lithostrotion*, brachiopods, echinoid spines and wackestone intraclasts.

Crinoid-only grainstones form a variant of this facies. Burrows filled with swirled textures of allochems and micritic, argillaceous sediment also occur.

A clotted micritic to peloidal cement is often present within 1 m of the core facies (Figs. 8B, 8C). Locally, isopachous prismatic cements occur (Fig. 8B). These are sometimes overlain by micrite sediment.

Conglomeratic subfacies

The conglomerates are clast- to matrix-supported and polymict. Clasts are usually rounded (Fig. 8D) and are typically between 5 and 10 mm in diameter but attain a maximum (known) diameter of 100 mm. They are subdivided into two types: (1) dominated by large clasts of core facies, and (2) dominated by smaller clasts of reworked crinoid–bryozoan subfacies and shelf packstones and wackestones (Fig. 8D). Other clasts include *Chaetetes*, large gastropods, brachiopods, bivalves, the alga *Ungdarella*, intraclasts of *Kamaenella*-micrite bafflestones, fine-grained grainstones of the shelf facies and medium-grained shelf-facies peloid–foraminifera grainstones. The colours of the clasts range from black to the pale grey of the reef core facies. The matrix sediment is similar to the crinoid–bryozoan subfacies.

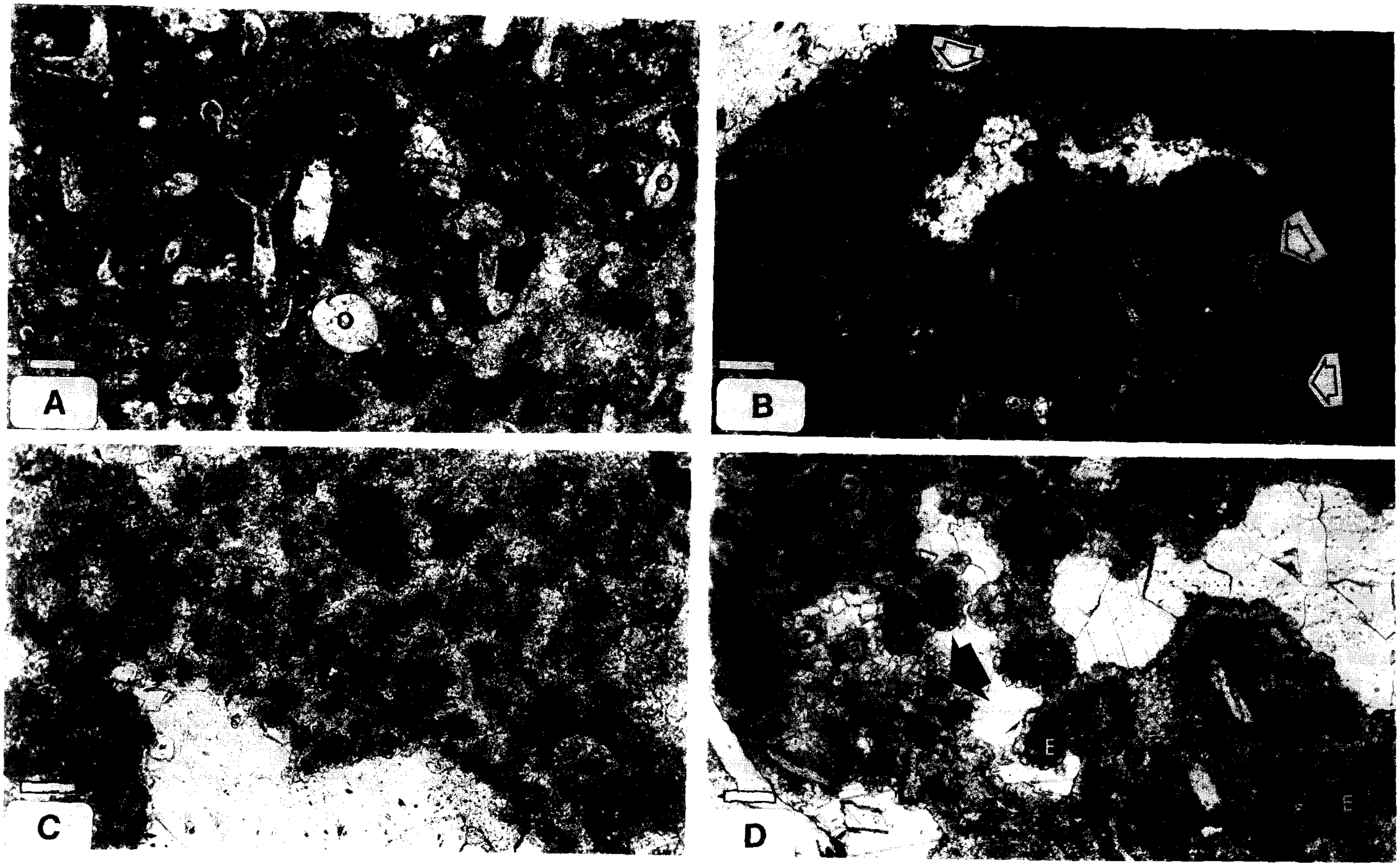

Fig. 5. (A) *Kamaenella* dominated buildup core facies, with erect, branching specimens (arrowed). Other organisms present are earlandid foraminifera (*E*) and thick walled ?ostracods (*O*). Scale bar 200 μm. (B) Buildup core facies with branching specimens of *Kamaenella* (arrowed), peloidal textures and spongiostromate textures (vugs). Note the absence of other organisms. Scale bar 500 μm. (C) Detail of peloidal cements. Peloid margins are fuzzy and indistinct, grading into inclusion-rich microsparry and pseudosparry calcite. The spongiostromate vug is filled with limpid calcite of burial origin. Scale bar 100 μm. (D) Well developed early inclusion-rich cements lining spongiostromate vugs; these developed after an initial micritic cement and minor peloidal fabrics (arrowed) of a probable microbial origin. Initial framework was provided by *Kamaenella*. Endothyrid foraminifera (*E*) are also present. Limpid burial cement fills vugs. Scale bar 500 μm.

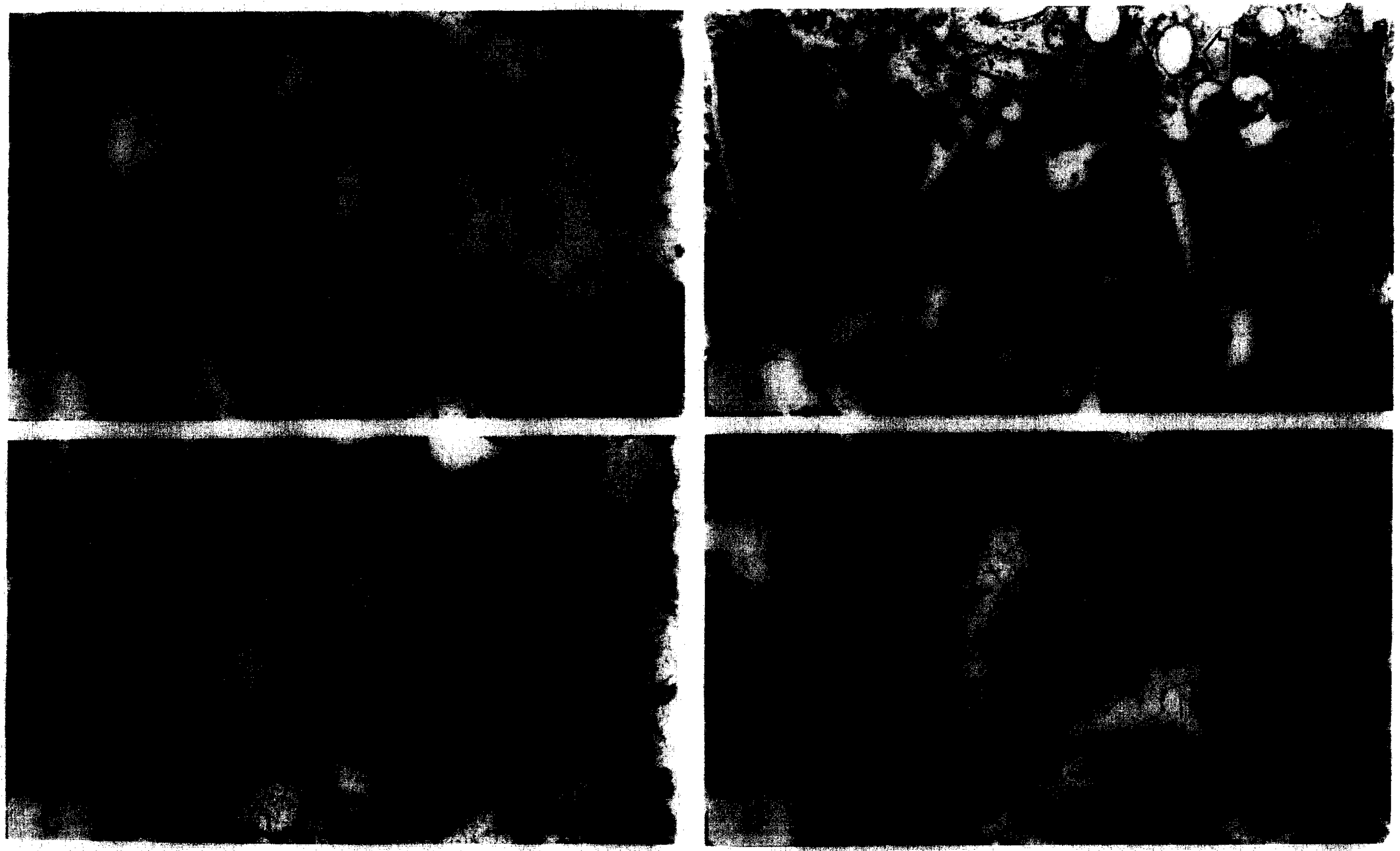

Fig. 6. (A) *Kamaenella tenuis* (big arrow) is a larger species than *K. denbighi* (small arrow). Cements are initially micritic, as films or peloids, and coarsen outwards into spongiostromate vug-lining inclusion rich microsparry calcite. Scale bar 500 μm. (B) Large micritic-walled tubular microfossil (arrowed) which forms a framework for the growth of peloidal cements. These may be either foraminifera or algae. Note the absence of other microfossils and the locally erect ?stems. Scale bar 500 μm. (C) Small micritic-walled tubular microfossil (arrowed). These appear fragmented and are possibly *Girvanella* or calcified cyanobacteria. Scale bar 500 μm. (D) *Ungdarella* (*U*) in growth position. Here the alga is associated with *Kamaenella* (arrowed) and endothyrid foraminifera (*E*). Early, sometimes peloidal, cements are well developed and several spongiostromate vugs are present. Scale bar 500 μm.

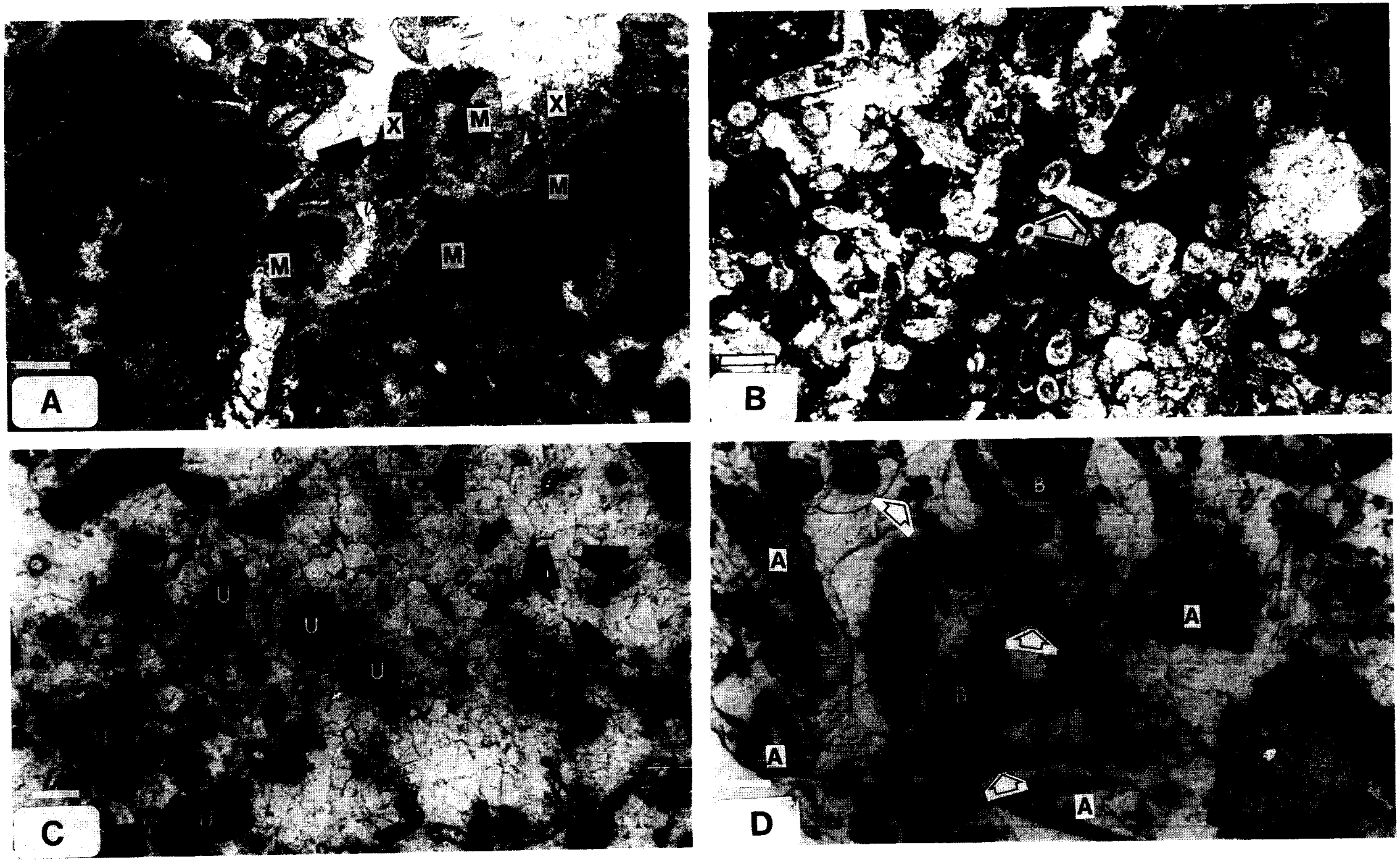

Fig. 7. (A) Cavity supported by micrite-encrusted *Kamaenella* (arrowed). Micrite cements (*M*) pass out into inclusion-rich spar cements followed by crystal silts (*X*). Scale bar 500 μm. (B) *Kamaenella* bafflestone from Back Lane Quarry. Bifurcating thalli (arrowed) and the micritic matrix are present. Scale bar 200 μm. (C) *Kamaenella* framestone, from Holme Park Quarry, a shelf interior locality. Delicate, bifurcating specimens (arrowed) are apparently suspended in this otherwise coarse-grained grainstone. This texture is interpreted as a plant in growth, or at least rolled, position. Specimens of micritised *Ungdarella* (*U*) grew with, or were trapped by, the *Kamaenella*. This type of microframebuilt texture was probably present on the buildup surface prior to peloidal cementation. Scale bar 400 μm. (D) Crinoidal grainstone from the flanking facies to the north of the buildup. Arm plates (*A*) are frequent; these are restricted to shelf margin crinoidal assemblages. Bryozoans (*B*) are usually associated with crinoids in these settings. Early diagenetic sediments were deposited over syntaxial overgrowths locally (arrowed). Scale bar 200 μm.

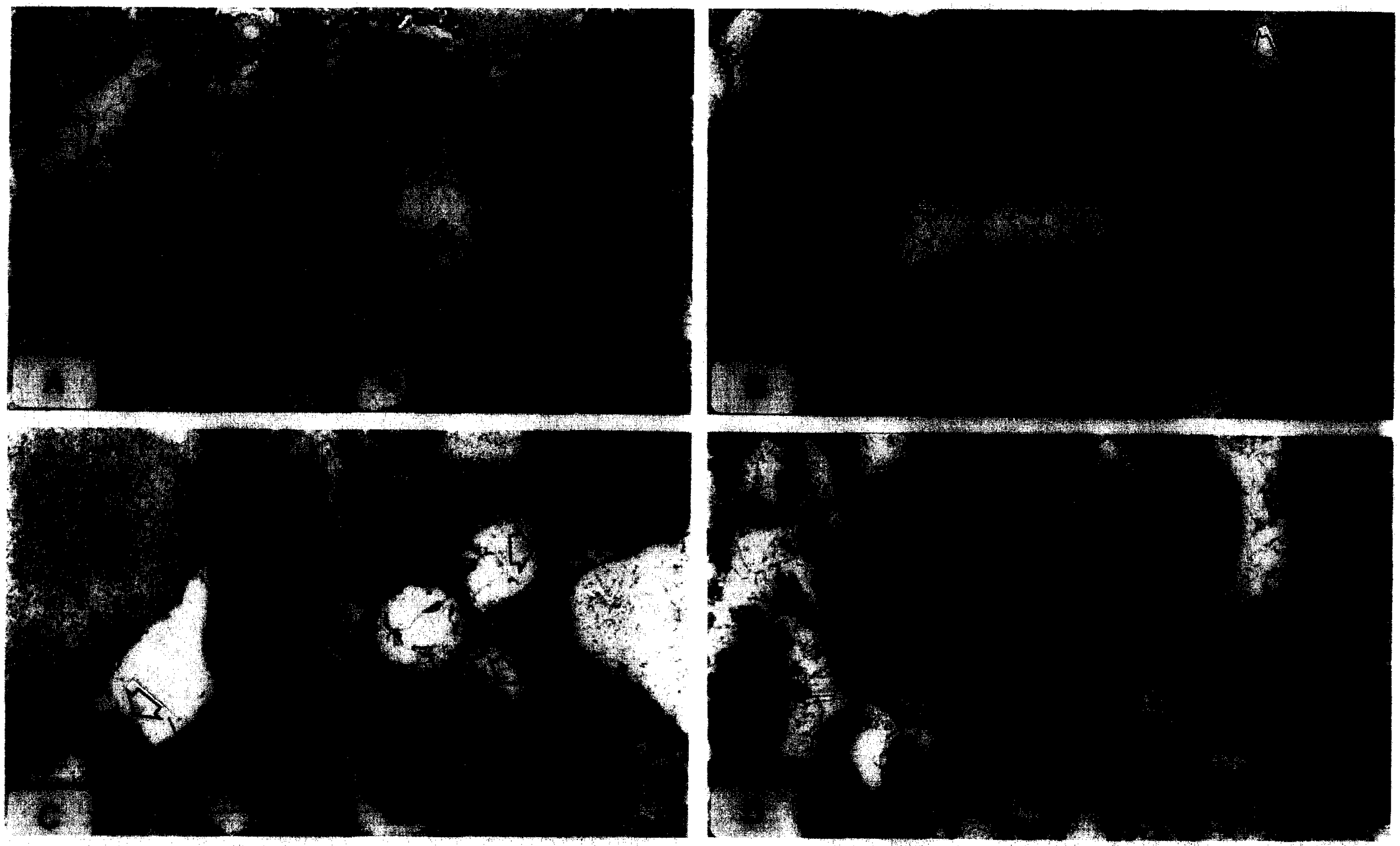

Fig. 8. (A) Crinoidal–bryozoan packstone (poorly washed biosparite texture). This includes an intraclast (*I*) and many arm plates. Scale bar 500 μm. (B) Crinoidal–bryozoan grainstone with an early diagenetic, inclusion-rich, isopachous cement (arrowed) post-dating peloidal cements (*P*). These fabrics are only found in flanking facies within 1 m of the buildup core facies. Scale bar 500 μm. (C) Crinoidal–bryozoan grainstone with early peloidal cements and inclusion-rich sparite (arrowed) similar to textures associated with the buildup core facies. Scale bar 200 μm. (D) Rounded clast of crinoid–bryozoan grainstone in the conglomeratic subfacies. This was lithified by early ?marine cements and a later generation of micrite sediment, possibly introduced during reworking. Other clasts, crinoid ossicles and bryozoans occupy the rest of the field of view. Scale bar 500 μm.

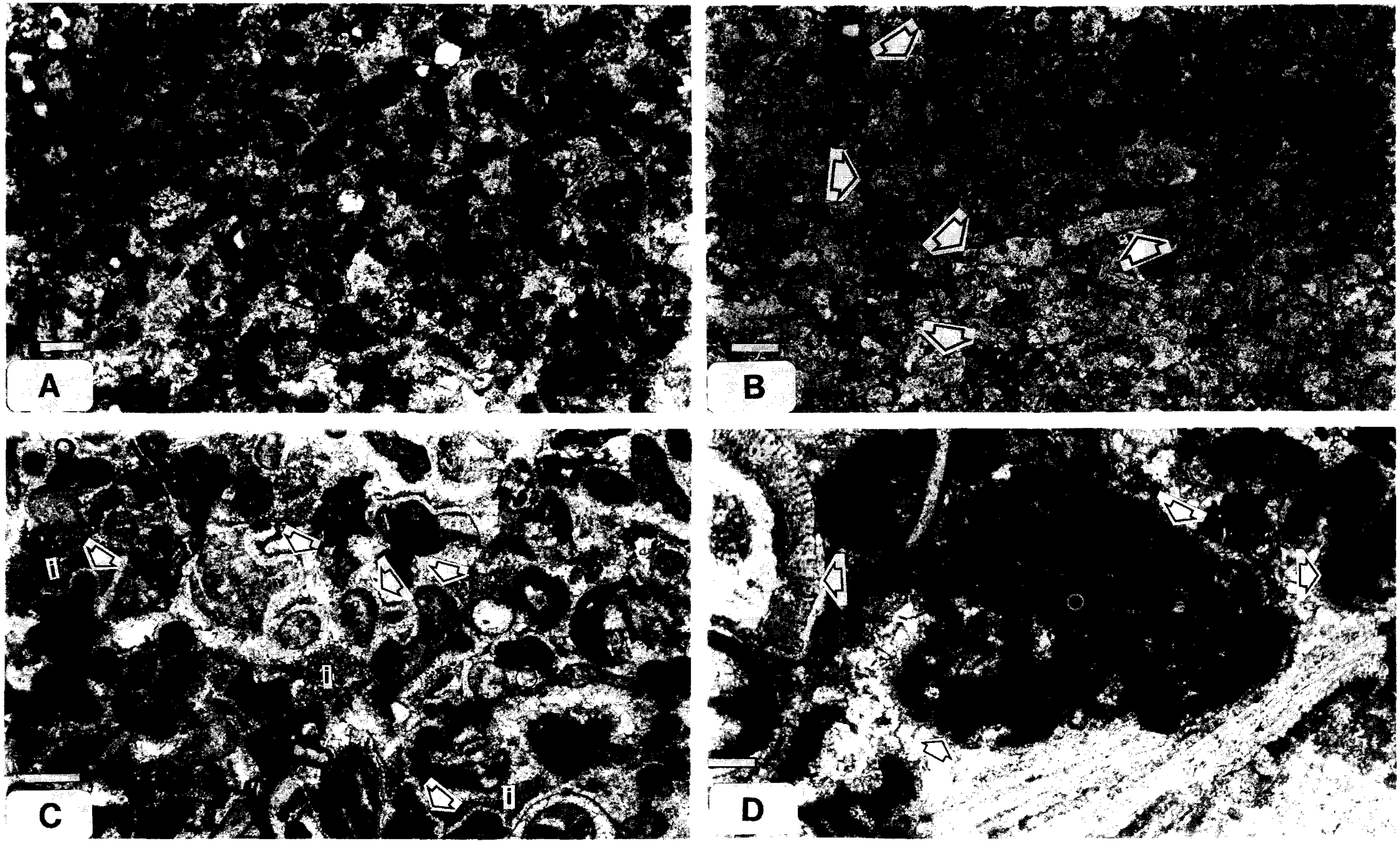

Fig. 9. (A) Fine-grained peloidal grainstone. Note the good sorting and numerous micritised fragments, probably of *Kamaenella*. This fabric is supported by granular brown cements of probable meteoric origin. Scale bar 200 μm. (B) Fine-grained *Kamaenella* grainstone. Some specimens are arrowed. The absence of cementation in this part of the thin section resulted in compaction. Same thin section as (A). Scale bar 200 μm. (C) Medium-grained peloidal–bioclastic grainstone. Isopachous marine cements (arrowed) are covered by micritic to silty internal sediments (*i*). Scale bar 500 μm. (D) Coarse-grained peloidal–bioclastic grainstone from the top of the sampled area of buildup. A lump of *Ortonella* (*O*) and marine cements (arrowed) are present. Scale bar 200 μm.

Shelf facies

The shelf facies are divided into three types, all of which occur elsewhere on the platform (see Horbury, 1987, 1989). These are: (1) fine-grained grainstone subfacies, (2) medium-grained grainstone subfacies, and (3) argillaceous packstone subfacies.

Fine-grained grainstone subfacies

This is a well sorted pale greyish brown grainstone dominated by small (< 200 μm) peloids and fragments of sparry calcite probably generated by the alga *Kamaenella* (Figs. 9A, 9B). Other bioclasts are rare but include the algae *Ungdarella, Koninckopora, Kamaenella tenuis, Kamaena* and *Epistacheoides*. Small articulated brachiopods, calcispheres, intraclasts and fragments of gastropods and crinoid ossicles also occur.

Medium-grained grainstone subfacies

These are mid to pale grey-brown, poorly sorted grainstones dominated by peloids of variable size and shape (Fig. 9C). Bioclasts are occasionally present and include crinoid ossicles, ostracod valves, foraminifera (often micritised), echinoid spines, brachiopod, bivalve and gastropod fragments, the algae *Kamaenella, Ungdarella, Koninckopora, Anatoilpora* and fragments of *Ortonella* (Fig. 9D). Intraclasts of buildup core facies occur in some samples. Early cementation, particularly of the finer-grained variants, is often isopachous with later internal sediment fills to cavities (Fig. 9C).

Argillaceous packstone subfacies

These are strongly bioturbated packstones and wackestones containing abundant, diverse open marine biota. Siliciclastic fines are concentrated in microstylolites, resulting in a rubbly appearance. Compared to elsewhere in the Urswick Limestone (e.g. Horbury, 1989) the proportion of oncoids, crinoids and *Lithostrotion* fragments are at their highest in this facies close to the buildup.

Facies geometry

Relationship with surrounding sediments

The buildup occurs in the west wall of the new quarry at Dunald Mill, within the lowest large-scale (12 m thick) cycle of the Upper Urswick Limestone (Figs. 2, 3). The limestones to the north of the buildup are dark grey and poorly bedded and represent low-energy deposition (Horbury, 1989). They grade upwards and towards the south into massive, pale brown, well jointed limestone. This represents a shelfwards prograding shoal which initially flanked the southern side of the buildup and finally smothered it.

At the top and the base of the cycle are palaeokarstic surfaces. Within the cycle, one and possibly two other palaeokarsts are developed: these mark falls in relative sea-level that punctuated and temporarily halted cycle development. The buildup is not cut by these palaeokarsts, which only appear to the north of the buildup. A 1–2 m deep depression is present on the cycle base palaeokarst immediately beneath the buildup. Below this surface to the south there is evidence of water table cave formation (e.g. Wright, 1982) and extensive pedogenic and meteoric diagenetic alteration (Horbury, 1987).

Buildup geometry

The buildup core and associated sediments appear massive, pale grey and domed in cross-section. These facies accreted 11 m vertically and are 9 m wide (Fig. 3). Dipping flanking beds are absent, although another buildup to the north does exhibit slopes (Fig. 3).

The 1–2 m deep depression on the cycle base palaeokarst is draped by a bed of argillaceous packstone subfacies (Fig. 4). Overlying this is a bed of conglomerate and crinoid–bryozoan subfacies. A small patch of buildup core facies occurs on the base of this bed on the southern side of the sampled area (Fig. 4).

Massive limestones are developed above the crinoid–bryozoan subfacies. These comprise a rather complex facies mosaic including two areas of buildup core, of approximately similar size. Both areas of core facies accreted upwards and in a southerly direction, interbedding with the fine- and medium-grained shelf grainstone subfacies in units 0.5 to 1 m thick and, locally, with some conglomerates (Fig. 4). Sample correlation suggests that these layers dip 25–30° to the north. To the north of the core facies there are conglomeratic, passing into bedded crinoidal–bryozoan subfacies (Fig. 4). Relationships above the sampled section are poorly constrained.

Interpretation

Pre-buildup sediments

Argillaceous packstone subfacies were initially deposited over a palaeosol, which in turn caps the undulose basal palaeokarst. This indicates development of a low-energy shelf with a diverse open marine biota (Horbury, 1987, 1989).

The succeeding crinoidal–bryozoan subfacies also represents low-energy, open marine inner shelf deposition and indicates sediment supply from a nearby crinoid thicket, perhaps flanking a buildup.

Clasts of buildup core and argillaceous packstones and wackestones within the conglomerate and crinoidal–bryozoan subfacies indicate the breakup of a buildup out of the plane of the quarry section. This suggests that buildups may have nucleated directly on the palaeosol, although the point of nucleation for the buildup studied is not exposed.

Buildup core

The two cores accreted vertically and laterally to the south, apparently up the flanks of the grainstone shoal. Growth of the southern core was followed by a period of inundation by shoal grainstones, after which the northern core developed.

Role of organisms. The dominance of peloidal cement in comparison with microframebuilders suggests that the buildup core was only initially supported or secured by framebuilders and soon after became a site of early marine peloidal cement precipitation. Cementation quickly encased fragments of bioclasts as indicated by their lack of micritisation. Storm damage and bioerosion probably accounts for the many broken, angular fragments of *Kamaenella* and *Ungdarella* in the core facies.

K. tenuis appears to have been an initial coloniser since it occurs mainly at the base of the buildup core facies. The unidentified tubular organisms contributed to the framework in the centre of the buildup core reflecting a simple ecological zonation.

The presence of the brachiopod *Dielasma* contrasts with its absence from the typical shelf facies of the Urswick Limestone (Horbury, 1987). *Dielasma* inhabited hard substrates to which it could attach its pedicle by byssus threads (e.g. Gutteridge, 1990). Other fauna such as the thick-shelled ostracods and endothyrid/earlandid foraminifera probably also inhabited similarly specialised niches which were absent on the soft and muddy shelf floor.

The scarcity of organisms other than *Kamaenella* in the buildup core suggests that some form of baffling or exclusion was operating. Allochems abundant in flanking beds, such as crinoids and bryozoans, are particularly notable by their absence. The likely densities of *Kamaenella* in this buildup would probably have been inadequate to act as baffles. Reasons for the exclusion of crinoids and bryozoans are very speculative; their absence was possibly due to growth in a position leeward of the buildup and/or to topographic relief on the buildup. Other organisms may have found a lithified substrate unsuitable for colonisation.

Peloidal cements. Peloidal cements are the dominant fabric in the buildup core and for this reason their origin is addressed. Similar cements are often associated with reefs and bioherms in varying degrees throughout geological history. There is little consensus to peloidal cement origin; either they develop in response to bacterial activity (e.g. Chafetz, 1986) or by inorganic precipitation (e.g. Macintyre, 1985; Aissaoui, 1988). Conventional inorganic precipitation as a porefill seems unlikely in this example considering the large volumes involved and high proportion of cement to framebuilders. Peloidal cements are also atypical of the smooth-rimmed isopachous, inorganic marine cements that are found in Urswick Limestone shelf grainstones (Horbury, 1987, 1989).

A close analogue for these peloidal cements are the microbial peloids, spongiostromate fabrics and pseudo-thrombolitic fabrics described by Sun

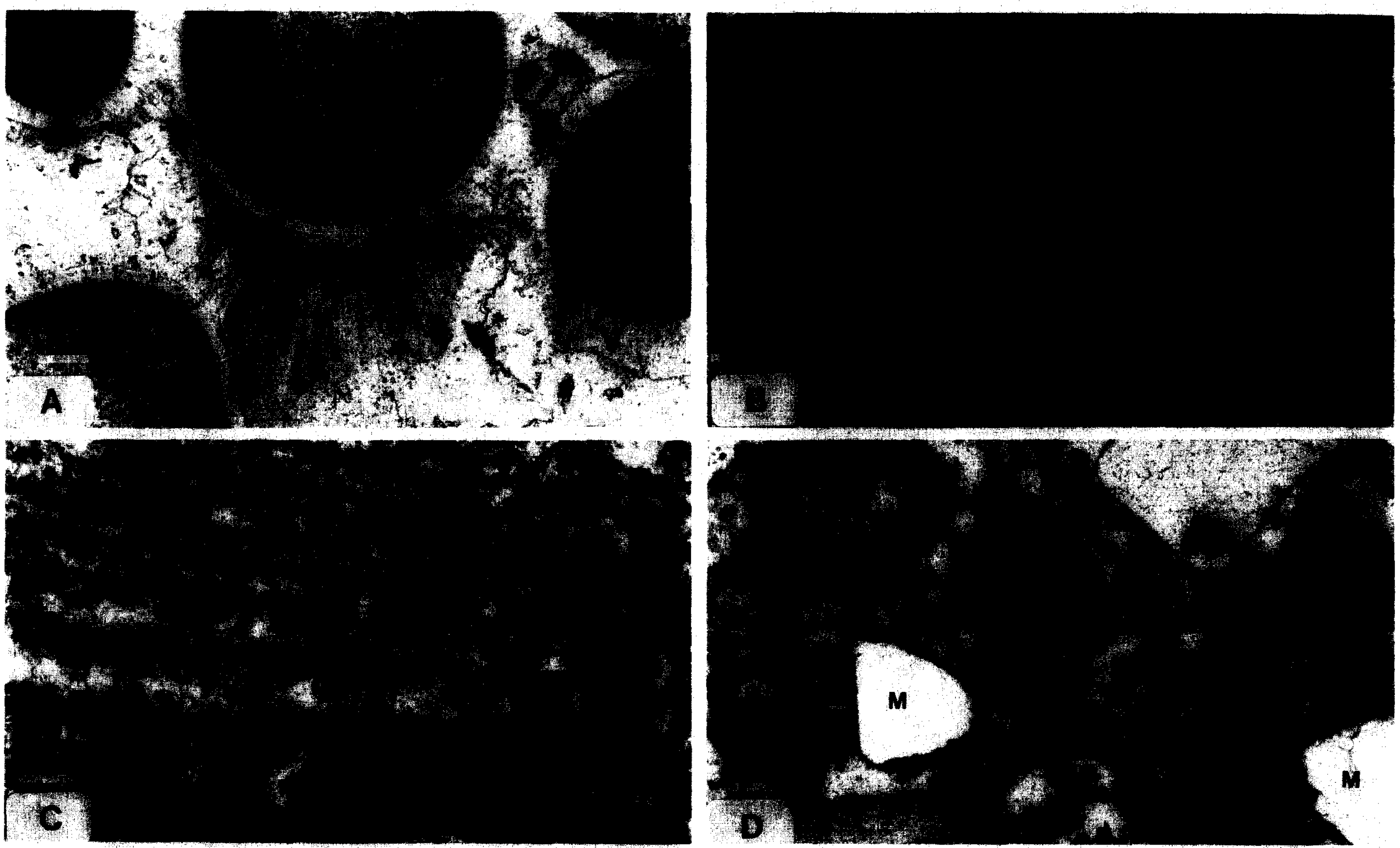

Fig. 10. (A) Typical inorganically precipitated isopachous marine cement (arrowed) from a cycle top in Leaper's Wood Quarry near Carnforth. The cement forms a smooth rim around the grains and possesses a relict fibrous–prismatic structure. Later cements are vadose meteoric dripstones (*V*) and burial cements. Scale bar 100 μm. (B) Thrombolite from the earliest late Asbian in Dunald Mill Quarry. Successive domed structures are developed within an otherwise high-energy sedimentary unit. Scale bar 2000 μm. (C) Detail from (A) showing the exclusively fine peloidal internal structure. Laminae are formed by compaction or concentration of peloids in alternate layers. Scale bar 500 μm. (D) Peloidal and micritic–microsparry cements (arrowed) infilling intergranular and intragranular, but not mouldic (*M*) porosity in a bioclastic–peloidal oolite from Leaper's Wood Quarry. Note how many of the peloids appear to "float" within porosity and the bimodal particle size (peloids vs. ooids). These relationships suggest a cement origin for the peloids. Scale bar 200 μm.

and Wright (1989) from the Corallian (Jurassic) of southern England. These were interpreted to indicate growth in areas of low sedimentation rates and low to moderate turbulence. Supporting evidence for a microbial origin of the buildup core textures comes from the presence of pseudo-stromatolitic/thrombolitic structures lower in the quarry (Figs. 10B, 10C). These comprise laminae composed exclusively of fine-grained peloidal fabrics, even in relatively high-energy dominated, coarse-grained intraclastic–peloidal grainstone units. They are also interpreted as microbial by analogy with Kennard and James (1986). Other Urswick Limestone shelf margin settings in the Carnforth area were sites of peloidal cement precipitation, e.g. in oolite shoals (Fig. 10D) (Horbury, 1987). Therefore, elsewhere on the shelf, particularly towards the margin, these types of fabrics could form, although only when associated with framebuilders did they aid in construction of buildups. These types of peloidal cements are interpreted by analogy as a microbially mediated precipitate.

Flanking sediments

The peloidal–bioclastic grainstones that eventually enveloped the buildup were probably transported from the south as indicated by field relationships (Fig. 3). The presence of a well developed talus fan on the northern (lee) side of the buildup is indicated by gradation from clast to matrix-supported conglomerates away from the buildup. On the south flank of the buildup occurs a thin conglomerate with clasts of core facies. The presence of buildup core material in these conglomerates indicates that the buildup stood proud of the sea floor, with a suggested relief in the order of 1–2 m.

Discussion

Mechanisms of buildup initiation, growth and termination

The buildup developed initially on an undulose sea floor, where a depression on the underlying palaeokarst coincided with the leeward margin of a grainstone shoal (Fig. 11). A Recent analogy is Rodriguez Bank, a mudmound offshore of eastern Florida, which is developed over a palaeovalley (Turmel and Swanson, 1976). They suggested that the valley topography acts as a trap for fine sediment which was then colonised by an algal flora different to that on the surrounding drowned karst. These factors, a low-energy environment created by a local topography, may favour buildup initiation in instances where the framework builders were small and delicate.

After initiation, growth of the buildup was maintained by microbial peloid–spar cementation of the interstices between the baffling algae. The style of accretion of the core facies up the leeward slope of the shoal (Fig. 4) suggests an intimate relationship with the shoal. Sun and Wright (1989) concluded that microbial–peloid cements were confined to situations in which sedimentation rates were slow. They also noted that peloidal cements were best developed in areas of low to

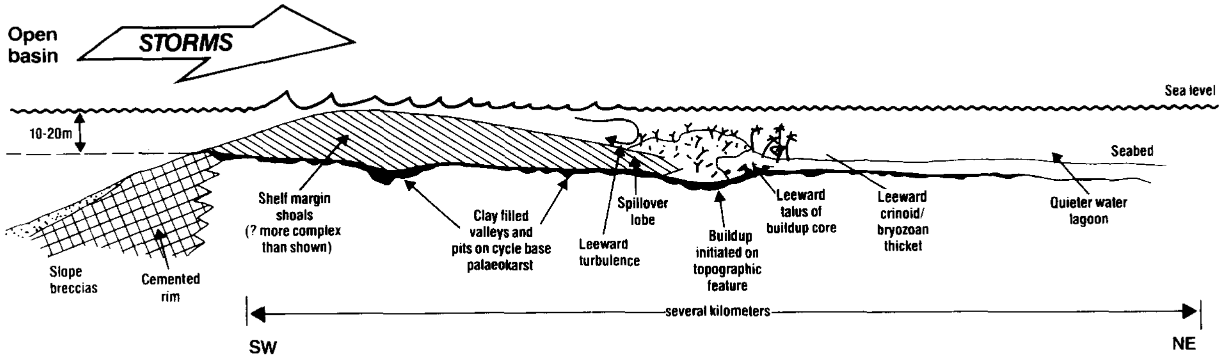

Fig. 11. Suggested reconstruction of the late Asbian shelf margin in the Carnforth area.

moderate turbulence. By this analogy, the leeward toe of shoal setting would have favoured cementation since slight turbulence and eddies could have maintained relatively low sedimentation rates, winnow fines, introduce nutrients and pump water through porespaces.

Sufficient relief initially existed over the buildup to prevent swamping by shoal material transported in from the south. Later, the buildup accreted into higher-energy environments which would likely have proved too severe for continued growth of *Kamaenella*. In the absence of a dominant framebuilder, microbial precipitation probably did not continue on a large scale, although small low-relief stromatolitic/thrombolitic structures may have persisted. Progradation of the peloidal–bioclastic shoal complex would then have terminated buildup accretion.

Buildup zonation

Unfortunately the limited vertical accessibility did not allow a full study of ecological zonation and evolution. The sampled area represents only the initial pioneer and colonisation stages of Wilson (1975) and James (1978) in which a few, usually branching, species are present in relatively low-energy environments. James (1983) noted that only the large, platform margin framework reefs usually pass this stage, so it seems likely that the buildup was *Kamaenella*-dominated throughout. The presence of *K. tenuis* at the base of the buildup core facies and the tubular organisms in the centre indicate a simple zonation.

Relationship of the buildup to palaeowind directions

The peloid–bioclastic shoal to the south of the buildup probably developed as part of a windward margin complex (Fig. 11). Grain size distributions, the progradation direction of the shoal as seen from field relationships (Fig. 3) and the facies asymmetry of the buildup and surrounding sediments, indicate that the prevailing currents were from the south. This agrees broadly with inferred storm directions from the Early Dinantian of South Wales (Burchette, 1987) and the Late Dinantian of northern Derbyshire (Gawthorpe and Gutteridge, 1990). Holocene shelf margin shoals showing dominantly unidirectional sediment transport directions are typical of marine sand belts moved by storms and ocean currents rather than tidal bar belts (Ball, 1967). In windward settings, the Holocene examples show that transport is mostly bankwards, but with minor offshelf movement (Ball, 1967). In this position buildups would have received nutrients upwelling along the basin margin.

Comparison with other Carboniferous buildups

(Palaeo)beresellid buildups

To date, no other examples of *Kamaenella* or other palaeoberesellid buildups have been recorded according to West's (1988) or my literature survey. The closest analogue is the beresellid *Donezella*, which has been recorded from shelf centre Namurian bafflestone mounds in Spain which measure 6–10 m high by up to 30 m wide (Bowman, 1979, 1985). These are lower and broader than the *Kamaenella* buildups. *Donezella* forms 10–25% of the whole rock and is associated with occasional encrusting foraminifera, the red alga *Ungdarella*, thrombolites and other bioclast fragments, notably *Komia* (Racz, 1964; Bowman, 1979, 1985), a generally similar association to that in the *Kamaenella* buildup described here. Similarly, only a primitive zonation of colonisers is developed in each example. However, Bowman (1979) attributed the low numbers of non-beresellids to baffling of coarse sediment by *Donezella*, a process which seems unlikely on the cement-dominated *Kamaenella* buildup.

Bowman (1979) noted that *Donezella* only initiated mounds in "very calm, clear, shallow conditions of normal salinity" during maximum transgression, a similar habitat to *Kamaenella* buildups. Sometimes these buildups were initiated on low-relief mudmounds which had, in turn, formed because of localised deposition due to hydrodynamic features such as interfering currents (Bowman, 1985), a similar setting noted for initiation of *Kamaenella* buildup here. Both organisms are interpreted to have been unable to continue bioherm growth in moderate to high-energy environments. A slightly higher turbulence associated with the *Kamaenella* buildup may account for the absence of micritic bafflestone textures as developed in *Donezella* mounds (Bowman 1979, 1985). Although the role of cementation is not stressed, photomicrographs show textures similar to the peloidal/micrite/fine sparite cements described in this paper and large vuggy cavities are also present (Bowman, 1979, 1985).

Other examples of *Donezella* as a buildup coloniser are the Westphalian B of Nevada (Rich, 1969) and Texas (Lambert and Stanton, 1986). Lambert (1986) suggested that *Donezella* is palaeoecologically analogous to *Halimeda*.

Small mudmounds

Small, early lithified, low-relief mudmounds with peloidal and micritic lump textures sometimes served as the nuclei for *Donezella* bafflestones (Bowman, 1985) but British Late Dinantian mudmounds do not demonstrate an association with *Kamaenella*. Mudmounds are notably absent from the Dinantian of the Lake District, whilst they are well developed on age-equivalent shelf tops and margins in Derbyshire (Gutteridge, 1983, 1990), North Wales and Ireland (Lees and Miller, 1985). Crinoidal–bryozoan thickets are typical flanking facies to both *Kamaenella* buildups and mudmounds and by analogy, *Donezella* mounds are intimately related to low-relief mudmounds (Bowman, 1985). These similarities suggest that differences between mudmound and (palaeo)beresellid depositional settings were probably slight.

Reasons for the mutual exclusivity of mudmounds versus *Kamaenella* buildups may have been in terms of subtle differences in energy dependence. Sun and Wright (1989) noted that similarly (peloidal) cemented Jurassic buildups in Southern England may have a genetic link to mudmounds in that both are probably microbially precipitated, with mudmound textures representing lower turbulence/energy environments. *Kamaenella* buildups in North Lancashire were protected from strong currents in the lee of the windward margin shoal belt. They may represent a type of buildup which could develop in slightly higher-energy settings than those in which mudmounds thrived.

Other buildups

The *Kamaenella*-peloid cementstone buildups demonstrate few features in common with other Carboniferous buildup types. Most other buildups also developed at or within 5 km of a shelf margin/ramp top and were usually initiated at or during maximum transgression. They are mostly small, within an order-of-magnitude of size of each other and it was not until the Westphalian C (Desmoinesian) that shelf top buildups (phylloid algal mounds) grew large enough to become economic oil reservoirs (West, 1988). Algal stromatolite/*Girvanella* buildups described by Wolfenden (1958) occupy a very similar palaeogeographic setting. These developed as banks parallel to the shelf margin and are up to 30 m high by 10 m wide and some 400 m long. They comprise "clotted limestones" and fibrous calcite crystals in association with a microcrystalline matrix and a low skeletal component. These may represent an intermediate ?thrombolitic stage between mudmounds and *Kamaenella* buildups. More complex buildups, for example the foraminifera/algal/coral type described by Adams (1984) were similarly lithified and could reasonably be called "reefs".

Significance in terms of Carboniferous buildup types

Relationship of this study to West's (1988) hierarchy.

In the Carboniferous, the large framebuilders present failed to build extensive platform margin reefs. Possible reasons are reviewed in West (1988) who suggests that the Frasnian extinction event may have effectively "reset the clock" with the result that buildup organisation in the Dinantian was at a similar level of organisation to the Cambrian. To illustrate this he notes that the Dinantian and Namurian buildups "tend to have no definite organic framework". However, many Dinantian and Namurian bioherms, of which the *Kamaenella*-peloid cementstone buildups described here form an example, demonstrate that organisms could develop true lithified organic frameworks and that "evolution" mimicking the pre-Carboniferous buildups is either a coincidence or an artefact of bias in the database on

Carboniferous buildups. The unusual point about framework buildup types is not that they were absent or even atypical of the Dinantian and Namurian; the main problem is understanding why they could never establish themselves as widespread patch reefs or even shelf margin reefs in a geographic or temporal sense.

Suggestions for the limited development of microframebuilt reefs

One reason why microframebuilders like *Kamaenella* failed as buildup constructors was because delicate, branching metazoans need a barrier in order to protect them from destruction (James, 1983). This essentially precludes building reefs in high-energy shelf break habitats. Secondly, their lack of adaptation or evolutionary progression in terms of buildup development and complexity is suggested by comparing *Donezella* to *Kamaenella* buildups, both of which were simple and principally monogeneric in organisation. This indicates that they were unlikely candidates to evolve into the multi-organism structures which James (1978) suggests are necessary to form large shelf margin type buildups. In addition, these organisms only formed buildups with the aid of microbial lithification, suggesting a critical balance was necessary between the presence of palaeogeographic settings suitable for (palaeo) beresellids to flourish and suitable sites or conditions for microbial colonisation. Unless these factors changed, there was little likelihood of (palaeo)beresellid buildups being other than short-lived and localised to shelf tops.

Suggestions for the limited development of large frame built reefs

Reasons for the failure of large framebuilders to dominate the Dinantian/Namurian shelf margins are speculative. The buildups of this type described by Wolfenden (1958), Ota (1968, 1977), Adams (1984), Jameson (1987), Fang and Hou (1987) and Webb (1987b) were often locally successful and represent the closest that buildups came to, but never quite made, dominance of the shelf margin. During the Early Dinantian the dominant carbonate systems were ramps (Ahr, 1989) which Wright and Faulkner (1990) attribute to a deeper water shift in dominant carbonate productivity when compared to rimmed shelves. In ramp settings, carbonate buildups are typically relatively isolated and rarely form linear buildups, suggesting that the absence of Early Dinantian linear reefs or buildups may have been due to the predominance of ramp systems. This logic can, of course, be applied in reverse, in that ramps were well developed partly because large framebuilders were relatively inactive.

In the later Dinantian and Namurian unusual organisms, typically small calcareous algae like *Kamaenella*, came to dominate the shelf interior facies such that a macrofauna is present only as a small proportion of the total sediment. The algae may have been partially responsible for a shift in carbonate production back into shallower water, encouraging the development of rimmed shelves (Adams et al., 1992). Platform margins were grainstone dominated and again a framebuilding macrofauna is present but only poorly developed. This suggests that the macrofauna found difficulty in becoming established, possibly due to a substrate control such as spat nucleation sites. *Chaetetes* is a good example of a known Late Carboniferous buildup constructor (West, 1988). In the Urswick Limestone, *Chaetetes* inhabited the higher-energy environments dominated by loose, probably continually shifting, fine sand grade or finer microfossil grainstones dominated by calcareous algae (Horbury, 1989). In these, suitable marine cemented horizons or large bioclasts are rare, perhaps explaining why *Chaetetes* rarely developed over 10 cm in diameter.

Argillaceous input could have added to the stress on large filter feeding framebuilders whilst it may not have affected smaller organisms, typically algae, as strongly. Large quantities of siliciclastics were often input onto shelves and into basins from Caledonian and early Hercynian terrains resulting in cyclic, mixed clastic/carbonate environments (e.g. Bowman, 1985). Carbonate shelves worldwide were often argillaceous, if not dominated by siliciclastic mud, e.g. in southern Turkey (Janvier et al., 1984) and along the Tethyan Himalayas (Gansser, 1964), in addition to the previously cited references. These factors would contrast most Carboniferous shelves with

Late Tertiary carbonate environments, usually relatively isolated from siliciclastic input, where framebuilder growth was and is healthy.

Conclusions

The opportunistic palaeoberesellid *Kamaenella* was capable of initiating and developing small, lithified, shelf marginal buildups in shallow, normal-salinity water, provided that microbial precipitation of cement occurred at the same time. The peculiar situation in which this took place in North Lancashire was above a low-relief palaeokarst feature in the lee of a windward margin shoal complex subject to periodic storm activity. Due to moderate turbulence, sedimentation rates were slow such that framebuilder growth and cementation could be maintained and kept pace with sedimentation. A low-diversity biota inhabited the buildup core, reflecting specialist adaptation to a hard substrate. Only a simple ecological zonation of the buildup developed. Biota of the flanking facies are typical of Carboniferous buildups and were not included within the core facies due to relief on the buildup (1–2 m) and their dominantly leewards habitat. Buildup development was terminated by growth into a high-energy environment. Dominance of *Kamaenella* probably reflects its opportunism in a strongly cyclic sedimentary sequence.

Later Carboniferous *Donezella* bafflestones and associated organisms were similar, in terms of size, type, diversity and structural role. These seem to be the closest analogue to the *Kamaenella* buildups, but comparison of their organisation suggests that as buildup constructing organisms the (palaeo)beresellids did not evolve significantly. On any given shelf, *Kamaenella*–peloid cementstone buildups are mutually exclusive of mudmounds, although the two types of buildup occur in similar settings.

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Note added in proof

Immediately prior to publication, the examination of three cored 100 m boreholes to the W and SW of the buildup revealed additional small occurrences of core facies in the upper part of the Urswick Limestone. In addition, the most distant borehole penetrated a core facies-dominated interval interbedded with shoal grainstones throughout the upper part of the Urswick Limestone. This is thought to represent the shelf break of late Asbian age in this area.