

‘Pseudobreccias’ revealed as calcrete mottling and bioturbation in the Late Dinantian of the southern Lake District, UK

ANDREW D. HORBURY*† and HAIRUO QING‡

*Cambridge Carbonates Ltd., 74 Marsh Lane, Solihull, West Midlands B91 2PF, UK

†Department of Geology, Royal Holloway College, Egham, Surrey TW20 0EX, UK

‡Department of Geology, University of Regina, Regina, SK, Canada S4S 0A2

(E-mail: hairuo.qing@uregina.ca)

ABSTRACT

Two types of ‘pseudobreccia’, one with grey and the other with brown mottle fabrics, occur in shoaling-upward cycles of the Urswick Limestone Formation of Asbian (Late Dinantian, Carboniferous) age in the southern Lake District, UK. The grey mottle pseudobreccia occurs in cycle-base packstones and developed after backfilling and abandonment of *Thalassinoides* burrow systems. Burrow infills consist of a fine to coarse crystalline microspar that has dull brown to moderate orange colours under cathodoluminescence. Mottling formed when an early diagenetic ‘aerobic decay clock’ operating on buried organic material was stopped, and sediment entered the sulphate reduction zone. This probably occurred during progradation of grainstone shoal facies, after which there was initial exposure to meteoric water. Microspar calcites then formed rapidly as a result of aragonite stabilization. The precipitation of the main meteoric cements and aragonite bioclast dissolution post-date this stabilisation event. The brown mottle pseudobreccia fabrics are intimately associated with rhizocretions and calcrete, which developed beneath palaeokarstic surfaces capping cycle-top grainstones and post-date all depositional fabrics, although they may also follow primary depositional heterogeneities such as burrows. They consist of coarse, inclusion-rich, microspar calcites that are always very dull to non-luminescent under cathodoluminescence, sometimes with some thin bright zones. These are interpreted as capillary rise and pedogenic calcrete precipitates. The $\delta^{18}\text{O}$ values (-5‰ to -8‰ , PDB) and the $\delta^{13}\text{C}$ values ($+2\text{‰}$ to -3‰ , PDB) of the ‘pseudobreccias’ are lower than the estimated $\delta^{18}\text{O}$ values (-3‰ to -1‰ PDB) and $\delta^{13}\text{C}$ values of ($+2\text{‰}$ to $+4\text{‰}$ PDB) of normal marine calcite precipitated from Late Dinantian sea water, reflecting the influence of meteoric waters and the input of organic carbon.

Keywords Bioturbation, calcrete mottling, ‘Pseudobreccias’, southern Lake District, Urswick Limestone Formation.

INTRODUCTION

Previous work

The term ‘pseudobreccia’ has usually been used to summarize colour-differentiated, nodular, mottled, blotchy or spotted fabrics of uncertain origin in limestones and dolomites. Some of the most thoroughly and earliest documented pseudobreccias occur in the Late Dinantian (Mississippian)

of Britain. Dolomitized examples from the Asbian and Brigantian (D1 and D2) of South Wales were described by Dixon & Vaughan (1911). Garwood (1913) described pseudobreccias and similar ‘spotted beds’ and ‘stick beds’ from the D1 of north-west England. Bathurst (1959) concentrated on the petrography of pseudobreccias from North Wales and Yorkshire, whereas Somerville (1979a,b) noted relationships between ‘pseudobrecciation’, ‘rubbly beds’ and sedimentary

cyclicity in North Wales. It appears that pseudobreccia development is confined to the strongly cyclic stratigraphy that marks the onset of Gondwanan glacio-eustasy (Walkden, 1987). Underlying massive limestones, although of similar facies, are completely lacking in these textures (Horbury, 1987). The most thorough documentation of pseudobreccias, again from North Wales, was produced by Solomon (1989). More recently, Vanstone's (1996) regional study of Late Dinantian exposure surfaces documented that 'calcrete mottle horizons' are abundant in south Cumbria and north Lancashire in northern England but are relatively scarce on other platforms such as North Wales and Derbyshire. Vanstone (1996) also noted that 'calcrete mottles' have an 'inverse (distribution) relationship to that shown by rhizocretions'.

Many mechanisms have been postulated for the formation of pseudobreccias. Garwood (1913) thought that segregation of components during 'consolidation' of the sediment was responsible for breccia genesis and colour differentiation. Bathurst (1959) noted grain growth fabrics and suggested a neomorphic origin, whereas Somerville (1979a,b) recognized affinities with bioturbation. Solomon (1989) proposed that

pseudobreccias are early diagenetic mixing-zone cemented nodules, and Vanstone (1996) suggested (after Horbury, 1987) that the calcrete mottling was related to pedogenic and groundwater calcretes. All these papers contain elements of the interpretation presented here but, as will be shown by the conclusions drawn in this paper, the issue is more complex than summarized in any one of the above.

Terminology

Terminology is important; in this paper, 'mottle' refers to the fabric (spot and host carbonate matrix together) whereas 'spot' refers to the darker patches present within the mottle texture or 'matrix', the paler area.

Aims

This paper presents the results of an examination of an pseudobreccias in the Urswick Limestone Formation of Asbian (Late Dinantian) age from the counties of south Cumbria and north Lancashire in northern England (Fig. 1). This study forms part of a wider analysis of the sedimentology of the Urswick Limestone

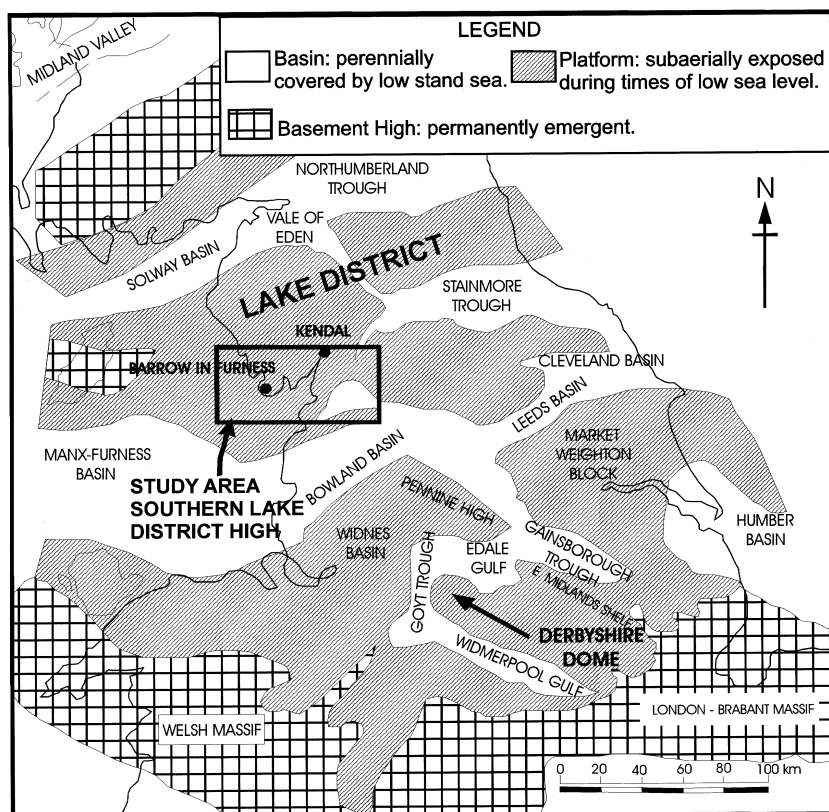


Fig. 1. Asbian palaeogeography for northern England with location of the study area around Morecambe Bay in the southern Lake District indicated by the boxed area (adapted from Horbury & Adams, 1989).

Formation (Horbury, 1987, 1989), which has involved a re-examination of Garwood's, (1913) work. The exceptional abundance, preservation and range of pseudobreccia textures encountered in the study area (particularly in smooth-weathered coastal exposures), merits detailed analysis. This has involved the application of modern analytical techniques (cathodoluminescence and stable isotopes) and new sequence stratigraphic, sedimentological and diagenetic concepts.

Methods

Microfabrics of the 'pseudobreccias', including microscopy of allochems and diagenetic features in spots as well as in the matrix, were studied under a normal petrographic microscope as well as by cathodoluminescence. Polished thin sections were examined using a Technosyn cathode luminescope model 8200, Mk II with operating conditions of 14–15 kV beam energy, 0.5 mA beam current and a vacuum of 50–60 mT. Black and white photographs were taken using Ilford XP-1 film with a standard exposure time of 2 min for cathodoluminescence (CL), whereas colour photographs were taken using 64ASA Kodachrome film. Burrow networks were digitized using a BBC microcomputer, and the resulting data were processed and displayed on a VAX computer.

GEOLOGICAL SETTING

The Urswick Limestone Formation is of Asbian (Late Dinantian) age (Fig. 2) and mostly crops out around the shores of Morecambe Bay (Fig. 1), either as low cliffs and rocky coastline or inland in quarries, crags and as limestone pavements. This variety of exposure types yields different information about the subtle colour and textural relationships found in pseudobreccias. The formation attains a maximum thickness of 150 m and may be divided into two parts, a lower (LUL) and an upper (UUL) division corresponding to the Early and Late Asbian respectively (Fig. 2).

The Urswick Limestone Formation is strongly cyclic throughout (Fig. 2). The basal parts of both the LUL and the UUL consist of shoaling-upward cycles 1–5 m thick of peloidal–bioclastic grainstones with occasional cycle caps of porcellanous mudstones containing fenestrae. These represent low rates of accommodation development (Horbury, 1989). In the upper parts of the LUL

and UUL, cycles are 10–20 m thick with bioclastic, often argillaceous wackestones and packstone bases that shoal upwards into peloidal–bioclastic grainstones (Fig. 2). These indicate high rates of accommodation development (Horbury, 1989).

Emergent surfaces punctuate all these cycle types, such that, throughout the LUL, they may be developed on any lithology, although in the UUL, the emergent surfaces are usually only developed on the shallower water grainstone and porcellanous mudstone facies. The emergent surfaces developed in response to rapid, >30 m falls in sea level exposing the sea bed (Horbury, 1989). Pedogenic fabrics developed on these emergent surfaces probably represent only a few tens of thousands of years of emergence (Vanstone, 1996).

FIELD DESCRIPTION OF THE MACRO FABRICS OF THE 'PSEUDOBRECCIAS'

The macrofabrics of the 'pseudobreccias', including the structure, texture, shape, abundance, spatial distribution and lateral correlation, were described based on field observations. Two basic types of pseudobreccia, those comprising grey (Fig. 3A) and brown (Fig. 3B) mottle fabrics, are distinguished in the field, although gradations between these do occur.

Grey mottle pseudobreccias

Grey mottle pseudobreccias only occur in cycle-base packstone–wackestones. They usually occur either as 'rubby beds' (Fig. 4A) consisting of grey nodules of limestone in an argillaceous matrix or as 'spotted beds' (Fig. 4B) consisting of grey spots up to 6 cm in diameter with sharp, well-defined margins in a lithified cream matrix. Individual spots are mostly homogeneous in colour (Fig. 4B), but some may have rims that are slightly darker than the centres. Dark spots frequently cross-cut paler spots (Fig. 4C), but there are no examples in which pale spots cut darker spots.

Many spots are elongate in one direction, a feature particularly evident on the rare bedding plane exposures of the 'rubby beds' developed in argillaceous limestone and shale (Fig. 4D). Along their length, swellings and possible bifurcation are sometimes observed. In order to understand these spots better, a block measuring 30 × 20 × 10 cm was slabbed and then progressively ground down to give ≈100 sections. The

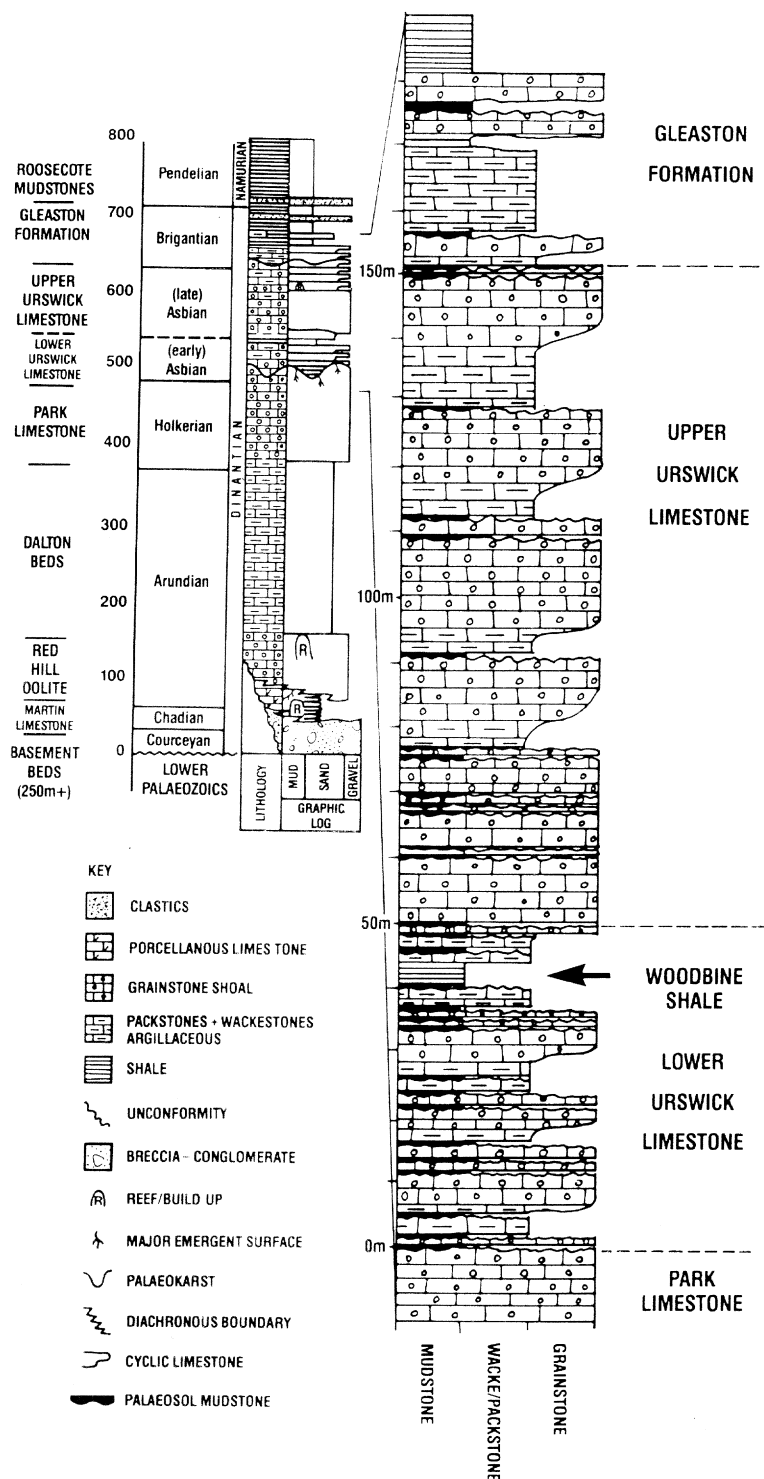


Fig. 2. Stratigraphic nomenclature and simplified lithologic columns in the study area (from Horbury & Adams, 1989).

outlines of the spots in each of these sections were digitized and ‘reassembled’ using a graphics program. The resulting image (Fig. 4E) shows tubular structures, Y-branching, swelling at nodal points and a boxwork pattern. The image shows one or two spots completely isolated within matrix; these were less than 3 cm along their

longest axis and had an irregular outline. Likewise, small 'wisps' and 'protrusions' of grey spots extended out from the main tubes. These types of finer mottle are locally well developed in the field (Fig. 4F).

Other fabrics include relatively large but paler grey spots of oval cross-section, which may

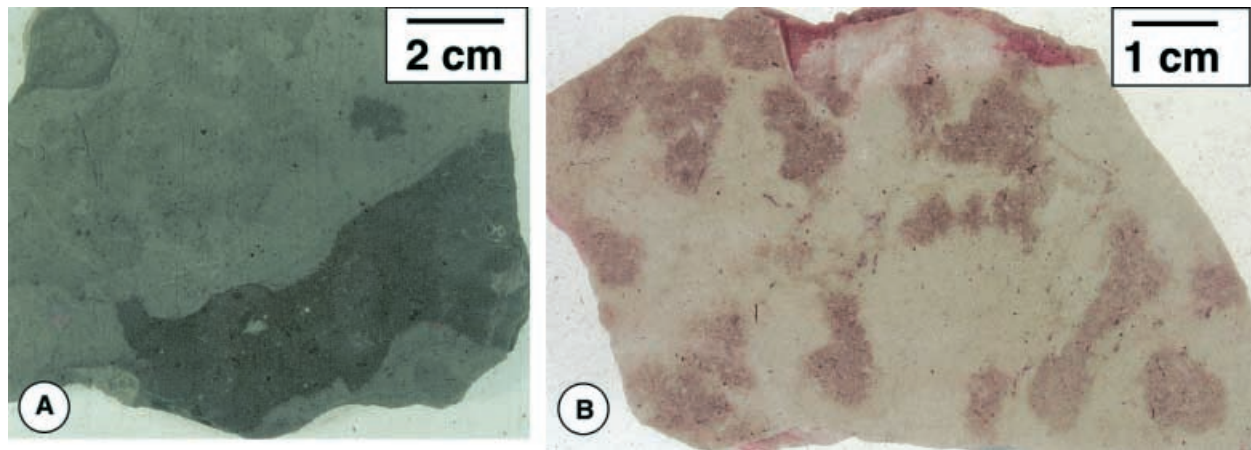


Fig. 3. (A) Grey mottles with darker rims than centres, slab from upper part of UUL, Bean Well Bank, 2 cm scale. (B) Small brown mottle texture, from the very top of the LUL at Trowbarrow Quarry, 1 cm scale.

measure >10 cm in diameter (Fig. 4G). These may be cut by 'tubes' 1–2 cm in diameter that have dark grey rims and geopetal floors, with a final fill of sparry calcite (Fig. 4G and H; cross- and longitudinal sections respectively). These are only developed locally and are also rarely found developed in sediment without the surrounding pale grey 'halo' (Fig. 4I).

It is notable that, in some cases, the sediment within the spots may be slightly coarser and more bioclastic, or finer than, that of the matrix. Spot infill sometimes contains 'swirled' textures of abraded allochems. This texture is often observed around the margins of, but never within, colonies of the corals *Siphonodendron* and *Syringopora* (Fig. 4D). Within cycles, the grey colouration fades upwards as packstones pass up into grainstones (Fig. 4J). Reworked fragments, often demonstrating the central cavity, are found in lag deposits (Fig. 4K) associated with the repeated emergence that affected the platform (Horbury, 1989).

Brown mottle pseudobreccias

The brown mottle pseudobreccia can be subdivided into forms with simple patterns, complex patterns and ring structures.

Simple patterns

Two general size/fabric types can be distinguished, the first being coarse, rounded spots up to 2 cm in diameter and elongate in one direction (Fig. 5A), also expressed as the 'stick beds' of Garwood (1913) (Fig. 5B and C). 'Sticks' may be filled with coarse sediment comprising concentrations of comminuted gastropods, thin-shelled

brachiopods and small *Syringopora* and *Siphonodendron* fragments, particularly *S. junceum*. Likewise, where damaged and abraded solitary rugose corals are present, the coarse spots often enclose them, and the spot sometimes mimics the outline of the coral as if concretionary (Fig. 5D).

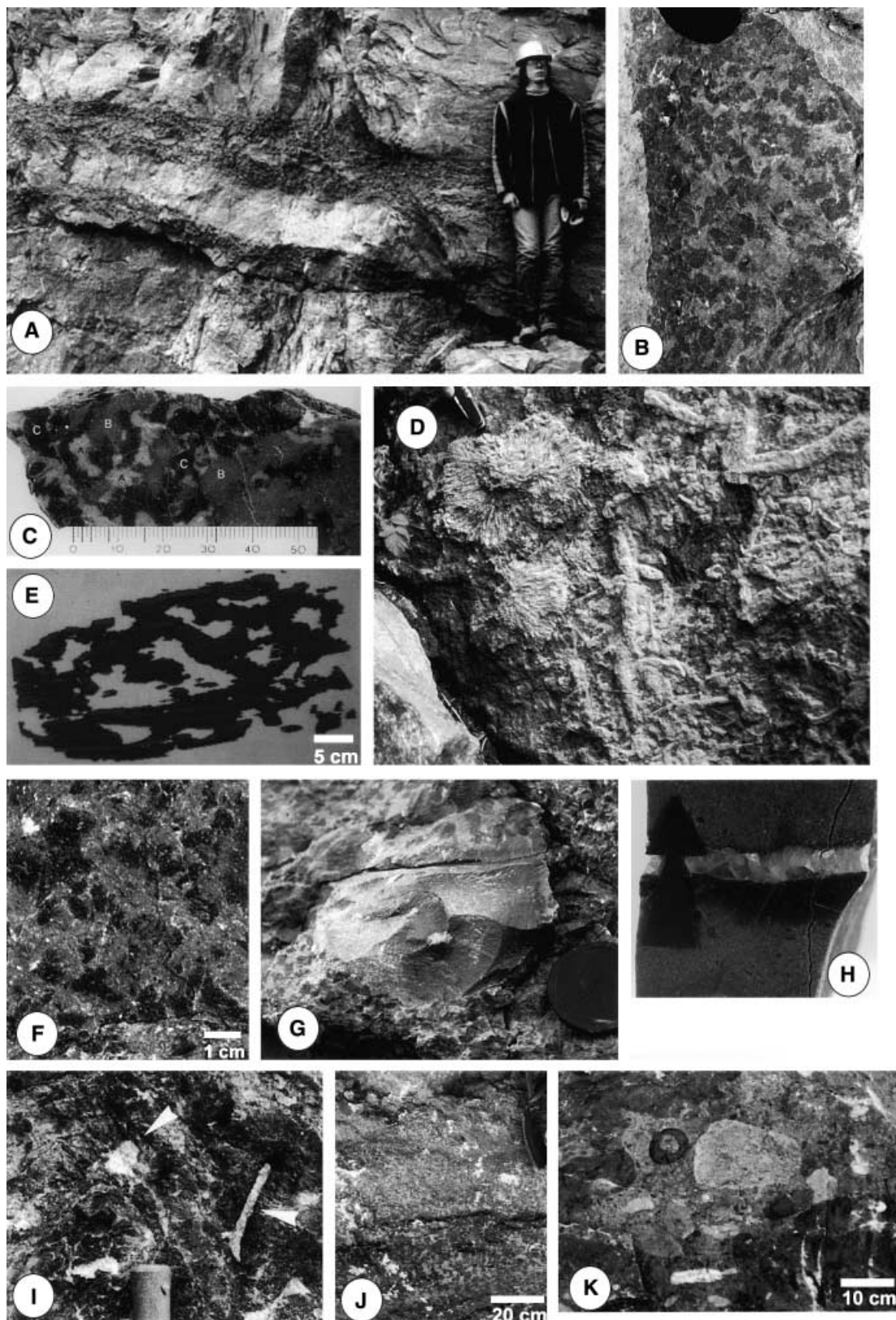
The second type comprises small spots up to 1 cm along their longest axis and with irregular outlines (Fig. 3B). Such fabrics are superimposed on colonies of *Syringopora* and *Siphonodendron* corals in growth position (Fig. 5E), and the brown colouration can be seen within both the corallite chambers and the matrix sediment as a cement (Fig. 5F).

Complex mottle patterns

Small spots often grade into decimetric-sized 'rings' of coalesced coarser dark spots and then non-mottled paler sediment in the centre of the ring (Fig. 6A). Smaller 'rings' comprise a sharp, broken margin of semi-coalesced smaller spots with a diameter of 5 cm or more, containing the smaller mottle fabric within their centre (Fig. 6B). Also, mottle texture may grade into bands or circles/rings of non-mottled pale sediment (Fig. 6C). Domains of different mottle fabric may vary in dimension from 10 cm to several metres.

Brown rings

Brown ring structures are apparently only locally developed. They are found in the UUL around Grange-over Sands, particularly at Blawith Point, and are rarely seen in the uppermost LUL at Holme Park Quarry. Smaller structures are kidney like in form and comprise a well-defined dark brown micritic/microspar rim 4–5 cm in width encircling a paler central, 'medullary' area



(Fig. 6D). Larger structures are up to 2 m in diameter and sometimes have smaller structures developed on the outer margins ('s' in Fig. 6E).

Simple textured brown mottle fabric may be developed both within and outside these rings, although there is usually a band of unmottled

Fig. 4. Macrofabrics of grey 'pseudobreccias'. (A) Double 'rubbly bed', upper part of LUL, Stainton Quarry, geologist for scale. (B) Fine grey mottle texture, upper part of LUL, Middlebarrow Quarry, lens cap for scale. (C) Pale fine mottle texture (A) cut by later dark mottle texture (C), cm/mm scale. (D) Base of rubbly bed showing colonial corals surrounded by 'sticks' (*sensu* Garwood, 1913) of pseudobreccia, upper part of UUL, Trowbarrow Quarry, penknife for scale. (E) Computer image of digitized and stacked cuts (≈ 100 sections) through burrows in a slabbed block (cf. Fig. 3A) from Bean Well Bank showing Y-branching and nodes. (F) Fine grey mottle texture, upper part of LUL, Middlebarrow Quarry, 1 cm scale bar. (G) Grey tube within 'halo' of unmottled sediment, uppermost part of LUL, Middlebarrow Quarry, lens cap for scale. (H) Detail of (G) in longitudinal section (note that this is not a fracture) showing grey sediment geopetal at cavity base, uppermost part of LUL, Middlebarrow Quarry, arrow is 2 cm high. (I) Grey tubes in cross- and longitudinal section with white calcite infill (arrowed), uppermost part of LUL, Holme Park Quarry, hammer shaft top is 3 cm across. (J) Gradation in mottle colours in fallen block, paler at top, upper part of UUL, Sandside Quarry, height of field of view ≈ 1 m. (K) Conglomerate overlying sequence boundary with clasts including reworked tubular grey burrow (arrowed), very basal part of UUL, Dunald Mill Quarry, 10 cm scale bar.

sediment a few centimetres wide immediately outside the brown ring (arrowed in Fig. 6E). The three-dimensional shape of the rings is uncertain, but examples cut by joint planes suggest a crude, irregularly spherical shape.

Stratigraphic distribution

Brown mottle fabrics usually occur in the upper parts of the large-scale upward-shoaling cycles in the grainstone facies. In the middle parts of cycles, mottling is sometimes a greyish/brown colour and, in these instances, it is difficult to define pseudobreccia type (grey or brown) on field evidence alone.

As noted by Vanstone (1996) after Horbury (1987), two distinct types of 'calcrete mottle' (i.e. brown mottle) profile are distinguished, namely those detached from and those attached to the overlying exposure surface (Fig. 7). Detached horizons have brown mottle fabrics in distinct horizons (Fig. 7A), which may be traced for several hundred metres within and between localities. Such horizons are up to 4 m thick and often have sharp lower contacts (Figs 6F and 7A). The tops of these horizons are developed up to 3.5 m below palaeokarstic surfaces (Fig. 7A), although Vanstone (1996) noted that similar horizons in North Wales may be as shallow as

some 1.4 m below the palaeokarstic surface. Such profiles comprise the complex mottle patterns and are the site of brown ring structures. The attached brown mottle horizons show spot colour and definition gradually fading with depth from the exposure surface, becoming indistinguishable from matrix sediment at about 4 m depth (Fig. 7B). Vanstone (1996) noted slightly shallower depths of penetration of 1.6 m subsurface from Holm Park Quarry and up to 3 m in the Shap area. Brown mottle fabrics in these situations are locally developed over rhizocretions (Fig. 6G) and are associated with calcrete fabrics (Fig. 6H).

MICROFABRICS OF 'PSEUDOBRECCIAS'

Grey pseudobreccias

Grey mottle fabrics are developed in bioclastic wackestones and packstones and, to a limited extent, in some mudstones or very fine-grained peloidal grainstone fabrics. The diverse bioclast assemblage present in the spot and matrix sediment (Fig. 8A–C) comprises abundant benthic foraminifera, brachiopod, echinoderm, calcisphere, some algae (principally *Kamaenella*) and ostracods with lesser abundances of gastropods, bivalves, bryozoa, trilobites, corals, other algae (principally *Coelosporella*, *Kamaena* and *Stacheoides/Stacheia*) and sponge spicules. The bioclasts and muddy fabrics represent a normal marine, quiet water, inner platform environment within the photic zone, but probably below normal wave base in contrast to overlying cycle-top grainstones thought to represent above normal wave base environments.

Spots are characterized by the presence of many small (10–100 μm) crystals of non-ferroan calcite (Fig. 8A is a typical example). These crystals will be referred to henceforth as microspar calcite for descriptive purposes, without intending genetic implications. Some 70% or more of the inter- and intra-allochem area is occupied by microspar calcite, whereas the remaining 30% or less comprises later sparry calcite. In the most finely crystalline microspar calcite (Fig. 8B and C), there is only a marginal difference in crystal size between the spot (10–20 μm) and host matrix. Although non-carbonate micrite-grade fines are observed in thin section and acetate peel, true micrite (*sensu* Folk, 1965) is only present in the cycle-base facies in some foraminifera tests and algae. These are rarely subject to neomorphism, retaining their fine-grained textures to the

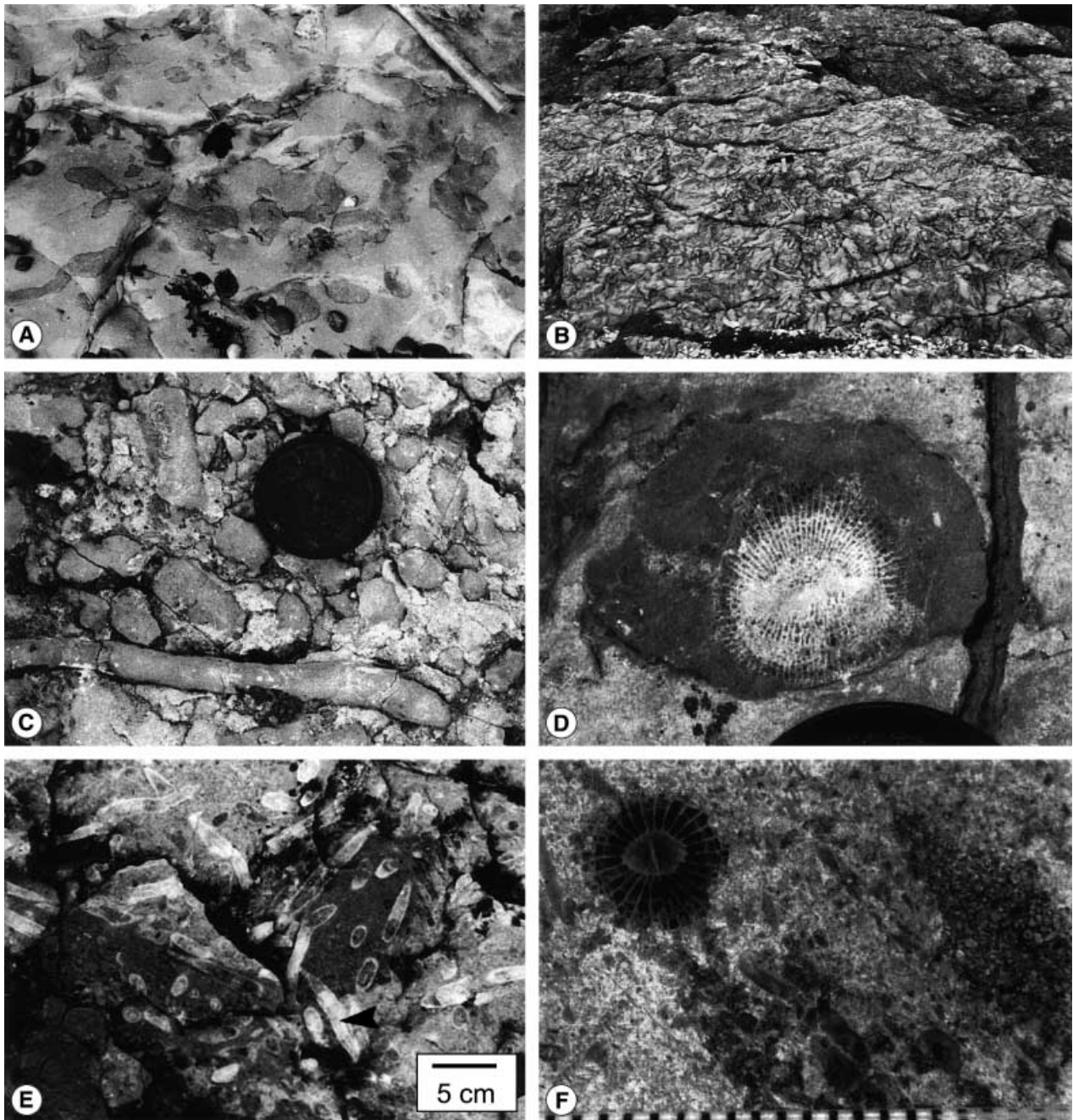


Fig. 5. Macrofabrics of the simple patterns of the brown 'pseudobreccias'. (A) Coarse brown mottle texture ('spotted texture') in shore outcrop, middle part of UUL, Humphrey Head, hammer shaft for scale. (B) Typical 'stick beds' of Garwood (1913), middle/top of UUL, Jack Scout, hammer for scale in very centre of field of view. (C) Detail of 'stick bed' showing lengths of burrows attributed to *Thalassinoides*, middle/top of UUL, Jack Scout, lens cap for scale. (D) Solitary rugose coral completely enclosed within a brown spot, middle/upper part of UUL, Jenny Brown's Point, lens cap for scale. (E) Small brown mottle texture cross-cutting an *in situ* colony of the coral *Siphonodendron*, middle part of UUL, Grange over Sands foreshore, 5 cm scale bar. (F) Small brown mottle texture in grainstone and as cements infilling *Siphonodendron* chambers, mm scale bar.

present. Microfabrics developed within the spots vary. In some examples, usually those in highly argillaceous matrix, calcite crystal size is quite coarse (50–100 μm ; pseudospar rather than

microspar) and inclusion rich (Fig. 8D). Some of the bioclasts, particularly bryozoa and algae such as *Stacheoides* and *Stacheia*, may be affected by neomorphism with loss of textural detail

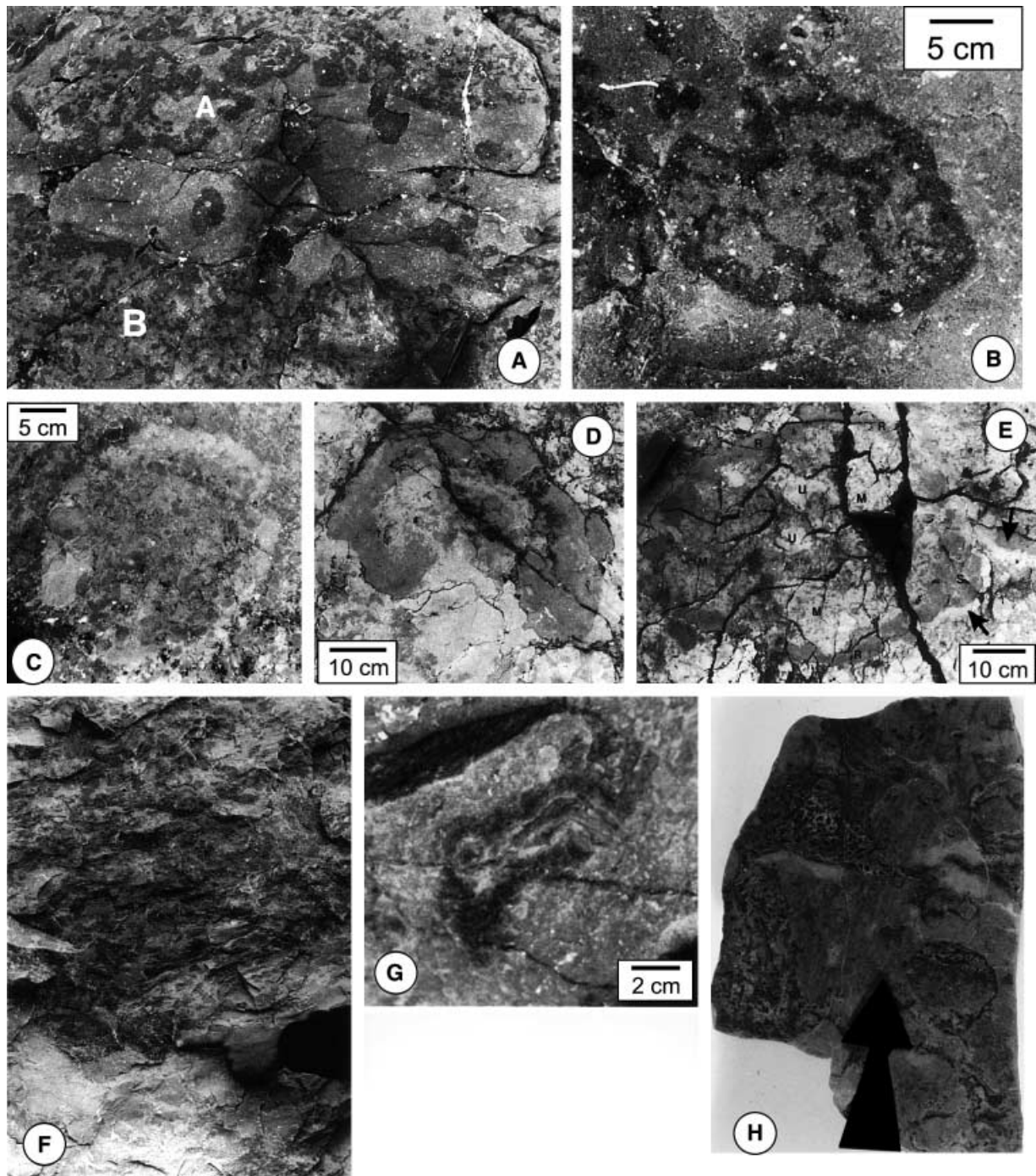


Fig. 6. Macrofabrics of the complex patterns and ring structure of the brown 'pseudobreccias'. (A) Fine (B) grading to coarser (A) brown mottle texture, surrounding areas of clearer sediment, middle part of UUL, Blawith Point, field of view ≈ 1 m. (B) Fine brown mottle texture inside small ring, surrounded by areas of clearer sediment, middle part of UUL, Blawith Point, 5 cm scale bar. (C) Pale ring structure within brown mottle fabric, middle part of UUL, Blawith Point, 5 cm scale bar. (D) 'Kidney'-type structure with thick walls and some fine mottling in medullary areas, middle part of UUL, Blawith Point, 10 cm scale bar. (E) Ring of dense brown mottle (R) surrounding fine brown mottle (M) and clear areas (U); there are also parasitic smaller dense brown spots (S), middle part of UUL, Blawith Point, hammer head for scale. (F) Distribution of brown pseudobreccias showing the base of a zone of intense development of coarse brown mottle above clear sediment, base of UUL, Stainton Quarry, hand for scale. (G) Elongate brown spot enclosing rhizocretion, base of UUL, Stainton Quarry, 2 cm scale bar. (H) Mixture of rhizocretions and brown mottle texture in calcrete horizon, top of LUL, Trowbarrow Quarry, arrow is 2 cm high.

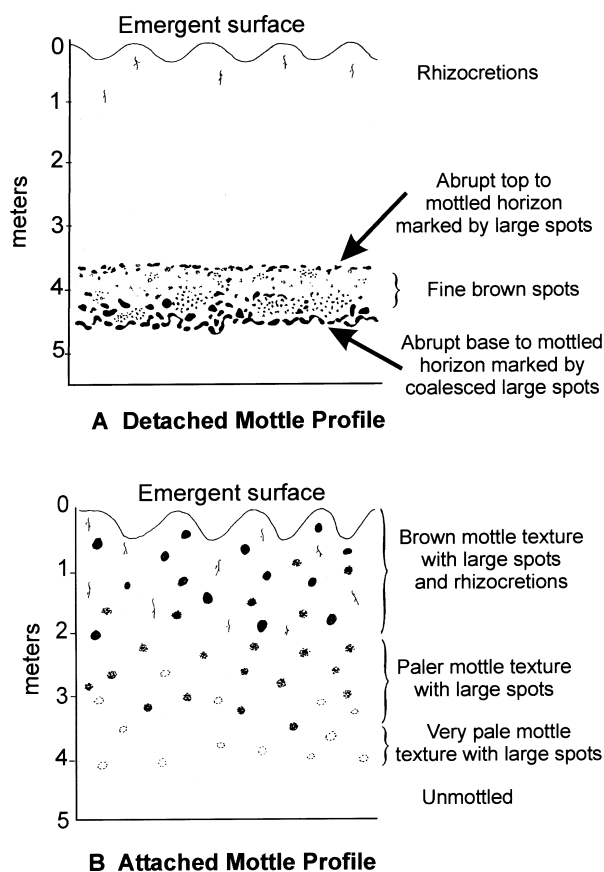


Fig. 7. Schematic diagrams showing the spatial distribution of brown pseudobreccias. (A) Brown pseudobreccia zone is detached from exposure surfaces along certain horizons. (B) Brown pseudobreccias developed immediately beneath palaeokarstic surfaces.

(Fig. 8E). These are similar to the fabrics described by Bathurst (1959), and the allochems are seen to 'float' within a microspar calcite matrix. In the UUL, there are locally clotted, pseudopeloidal 'grumuleuse' (cf. Cayeux, 1937) textures (Fig. 8F). Visible in spots, but not in the matrix, are moulds of fragments of molluscs, the alga *Coelosporrella* (Fig. 8B) and silicic sponge spicules (Fig. 8C). Abundances of former low- and high-Mg calcite allochems are similar in both spot and matrix.

Matrix sediment is usually either compacted, with microstylolites developed in a non-sutured seam pattern (*sensu* Wanless, 1979, 1982) if much clay is present or, if relatively clean, an anastomosing texture is developed and is cemented by crystals of a coarse, slightly ferroan calcite of burial origin. Small framboids of pyrite occur locally within spots; in such cases, the spot may show a coarsening of crystal size outwards, terminating in stellate prisms up to 1000 μm long and, locally, with cone-in-cone structures. These

textures are very similar in appearance to early diagenetic microspar fabrics in Pennsylvanian cyclic carbonates described by Wiggins (1986). Where the matrix is less argillaceous, crystal sizes in spots are usually smaller, in the order of 20–50 μm . In these instances, there is no neomorphism of bioclasts, although the microspar crystals may be inclusion rich.

Cathodoluminescence reveals a range of luminescence intensities, from dull to moderately or brightly luminescent (Fig. 9A and B). No completely non-luminescent calcites were observed as part of the spot fabric. Within any given thin section, the luminescence is usually constant in overall intensity (Fig. 9B), although speckled dull/bright fabrics are rarely developed (Fig. 9A) and, even more exceptionally, spired syntaxial overgrowths may be seen within the microspar calcite (Fig. 9C). Where present, stellate fringes are often brightly luminescent. Bioclast moulds are usually filled with calcite spar cements that are initially non-luminescent and then dull/moderate luminescent (Fig. 9B and D) but are never filled by the earlier microspar calcite. In the rare hollow tubular spots, there was growth into free space of sparite followed by internal sediment deposition; inclusion populations (Fig. 9E) and cathodoluminescence (Fig. 9F) may reveal euhedral triangular forms within such cements.

Brown pseudobreccias

The brown spots in thin section typically comprise allochems that are supported or float in a coarse, somewhat cloudy or brownish tinged matrix of anhedral calcite crystals up to 100 μm in diameter (Fig. 10A). Many of the crystals are syntaxial upon monocrystalline algae such as *Kamaenella* or *Kamaena*. Sometimes, these algae comprise the entire spot fill whereas the matrix may be much more micritic to peloidal–bioclastic (Fig. 10B). Spar in the spots sometimes occurs associated with or within laminar calcrete and alveolar textures (Fig. 10B). Originally micritic and micritized allochems within these spots do not usually exhibit any evidence of neomorphism.

For the most part, no growth fabrics are suggested by either crystal morphology or inclusions within crystals, although rarely there is an isopachous habit (Fig. 10A). Only in extreme cases where larger pores are developed are there fibrous brown cements with smooth crystal terminations; these show pendant morphologies on cavity roofs and meniscus morphologies on cavity bases. Under cathodoluminescence, brown spars are very

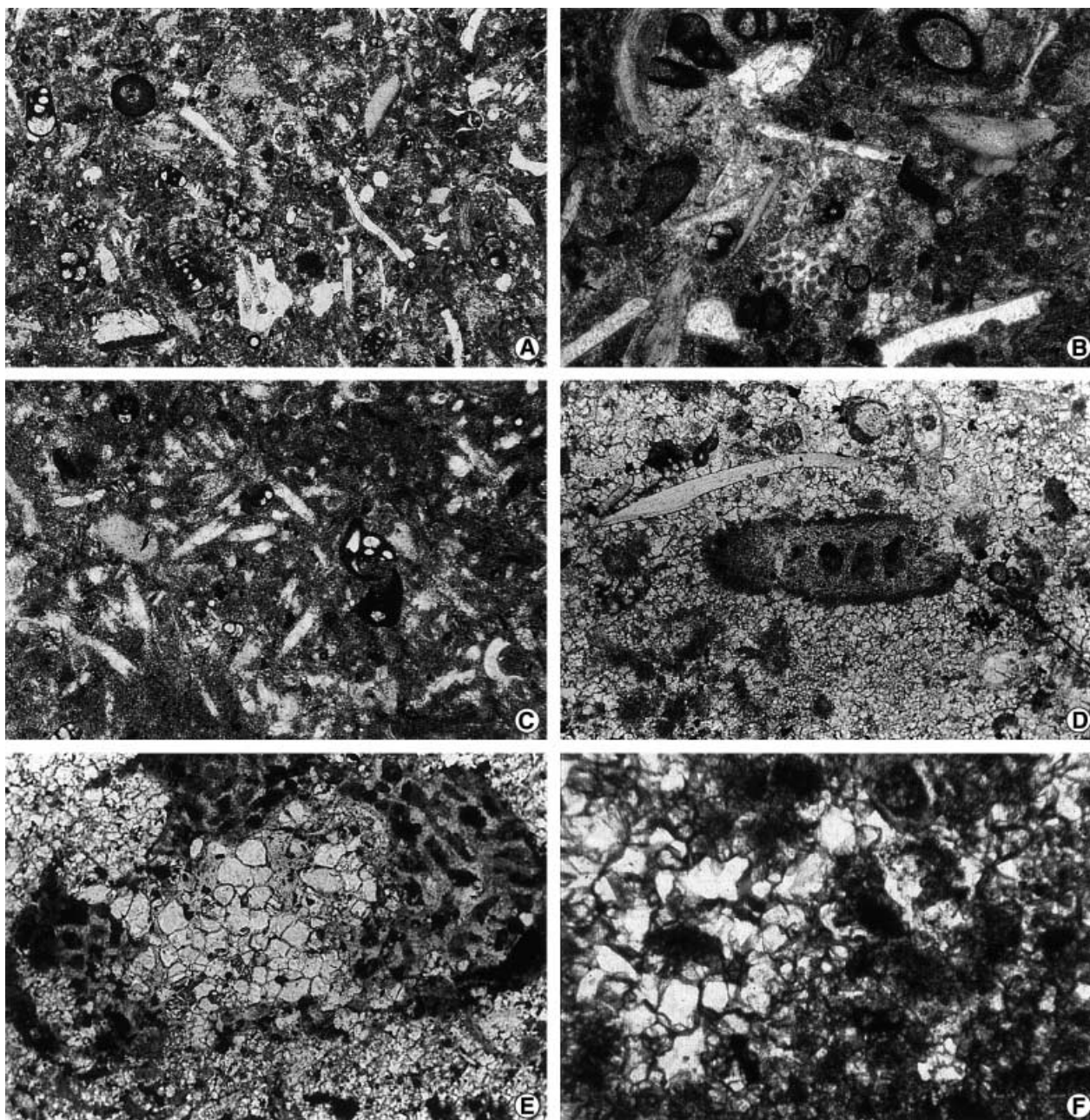


Fig. 8. Microfabrics and CL images of grey pseudobreccias. (A) Typical view of grey mottle in thin section, upper LUL, Stainton Quarry, field of view 2 mm. (B) Fine crystalline microspar surrounding a typically diverse allochem assemblage including the alga *Coelosporrella* in the centre of the field of view. From within the grey mottle texture, upper LUL, Stainton Quarry, field of view 2 mm. (C) Sponge spicule moulds infilled with sparry calcite, upper LUL, Farleton Fell, field of view 2 mm. (D) Very coarse pseudospar showing some evidence of neomorphism of allochems, upper UUL, Sandside Quarry, field of view 1 mm. (E) Very coarse pseudospar showing some evidence of neomorphism of allochems, upper UUL, Sandside Quarry, field of view 1 mm. (F) Coarse micropseudospar showing a slightly clotted peloidal texture, upper UUL, Trowbarrow Quarry, field of view 0.75 mm.

distinctive and exhibit complex growth patterns not revealed by ordinary light microscopy (Fig. 10C and D). Brown spars are typically very uniform, very dull to non-luminescent with approximately one-third of all examples studied

being zoned with moderate or brightly luminescent subzones (Fig. 10D). Crystal morphologies as revealed under CL are euhedral prisms (Fig. 10C) rather than an anhedral mosaic as suggested by crystal boundaries in plane polarized light. Large

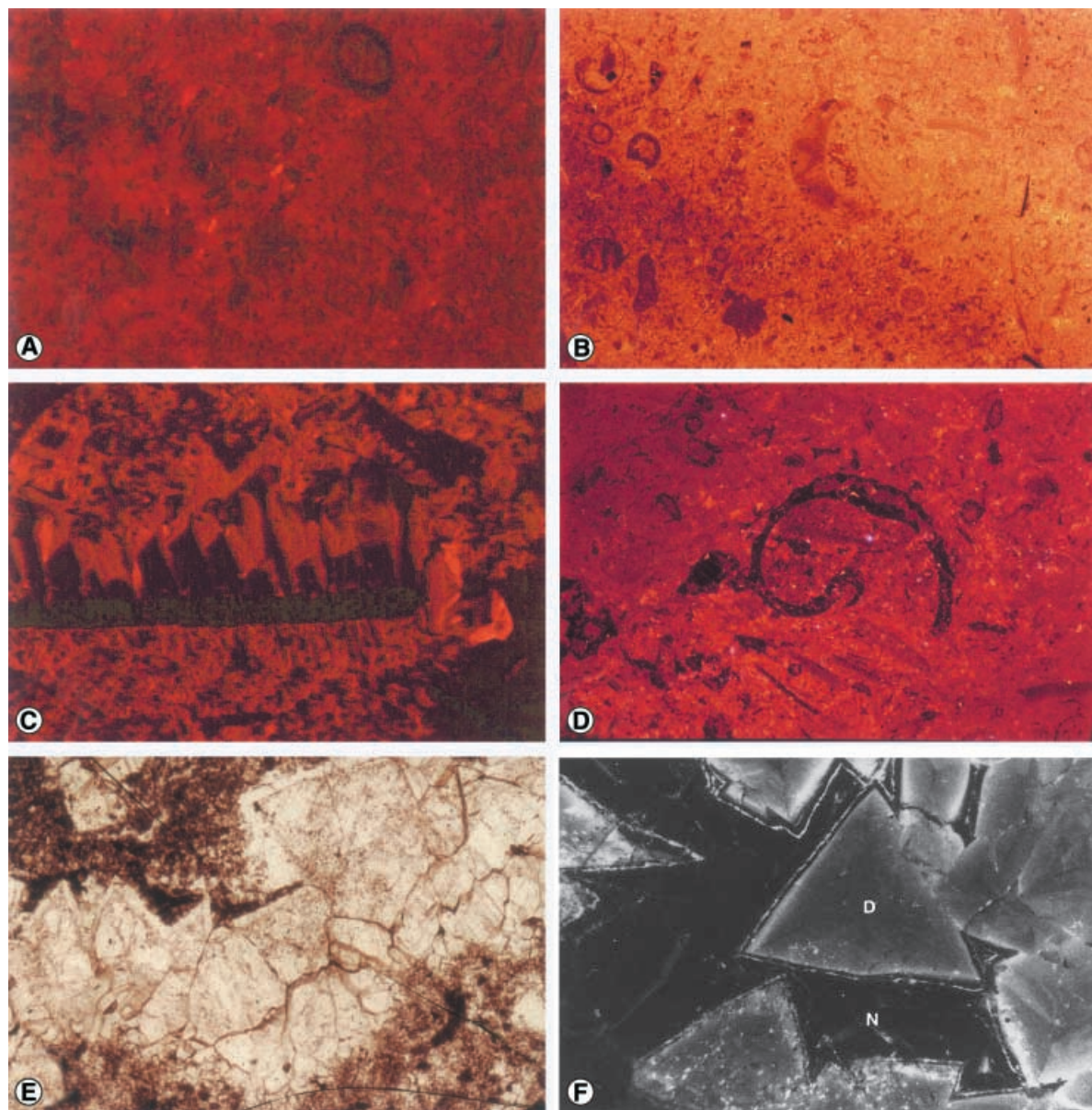


Fig. 9. (A) CL image of Fig. 8F, showing speckly moderate luminescence of cements in grey spot, upper UUL, Trowbarrow Quarry, field of view 1 mm. (B) CL of moderately bright luminescent grey mottle microspar surrounding aragonite moulds infilled with non-luminescent meteoric spar then dull burial spar, upper LUL, Middlebarrow Quarry, field of view 2 mm. (C) Spired overgrowth in grey burrow infill sparite, upper UUL, Trowbarrow Quarry, field of view 1 mm. (D) CL of gastropod mould in microspar. Mould has an infill of non-luminescent meteoric spar then dull luminescent burial spar, upper UUL, Sandside Quarry, field of view 2 mm. (E) Plane polarized light of early inclusion-rich spar cements within hollow tube, followed by limpid spar and then sediment geopetal, upper UUL, Trowbarrow Quarry, field of view 2 mm. (F) Euhedral terminations of early burrow/tube fill cements [moderate luminescence (D)] passing into later non-luminescent meteoric cements [black with an initial bright subzone (N)]; note that this is one of the few examples in which 'brown' cements can be seen to post-date 'grey' cements, upper UUL, Trowbarrow Quarry, field of view 1 mm.

monocrystalline substrates such as echinoderms and algae and earlier (usually dull luminescent) cement phases often develop syntaxial overgrowths, which comprise the same zone sequence as the brown spars (Fig. 10D). The zone sequences often cannot be traced for more than a few milli-

metres before a different sequence occludes porosity. Non-zoned brown spars may therefore alternate with zoned brown spars within one thin section, although usually the zoned brown spars are observed to thin with amalgamation of zoned towards non-zonal areas, with the intermediate

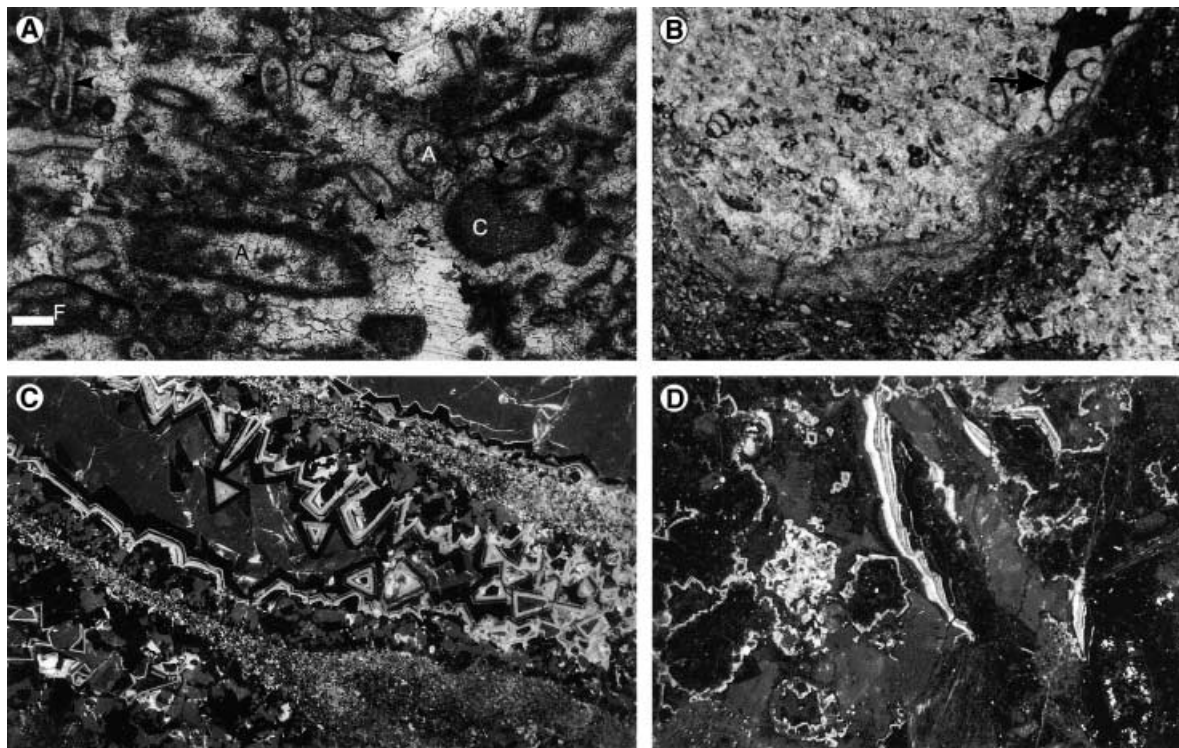


Fig. 10. Microfabrics and CL images of brown pseudobreccias. (A) Allochems (A, *Anatolipora*; F, benthic foraminifera; E, echinoderm debris; arrow, *Kamaenalla*) with coarse brown spar cement in typical brown mottle texture, lower UUL, Dunald Mill Quarry, field of view 2 mm. (B) Brown spar cemented spot, surrounded by laminar calcrete with some alveolar texture (arrowed) and then compacted matrix, lower UUL, Holme Park Quarry, field of view 2 mm. (C) Typical development of later complex-zoned brown sparite in coral chambers, LUL, Trowbarrow Quarry, field of view 2 mm. (D) Development of non-luminescent/zoned cements showing thick late brighter zones, LUL, Middlebarrow Quarry, field of view 2 mm.

area typically exhibiting non-zoned, non-luminescent brown spar terminated by a final brightly luminescent zone followed by a non-luminescent rim (Fig. 10D). Coral chambers are often filled with sequences of zoned cements that cannot be traced between chambers, although several chambers some distance apart may be filled with the same cement sequence (Fig. 10C). These spars also occur within unfilled tubes post-dating the grey mottle calcite microspar (Fig. 9F), central canals of rhizcretions, alveolar textures and moulds after aragonitic bioclasts (Fig. 9D). In other examples, aragonitic bioclast moulds are filled with post-brown spar cements although the intermould porosity was filled with these brown spars.

Brown spars are often developed on fragments of bivalves and gastropods in which neomorphism was incomplete and later dissolution had occurred. Although not easily demonstrated, approximately half the non-luminescent, very dull or zoned spars are developed in samples that were not brown mottled in hand specimen. For some reason, these cements did not develop the brown colouration, although they are genetic-

ally similar to the true brown spars. The closest correlation between cement character and brown spar is between the very dull, inclusion-rich spars, and the lowest correlation is with the most strongly zoned spars. The general succession of cement is from very dull luminescent and inclusion rich to non-luminescent to non-luminescent with bright subzones. Therefore, the brown spars are characteristically formed early within this sequence, similar to the observation of Solomon (1989). The whole sequence of cementation is never observed in a single thin section.

OXYGEN AND CARBON ISOTOPES

Six samples were selected to cover the full range of pseudobreccia and related rock type colour and texture, consisting of grey burrow pseudobreccia, brown mottle pseudobreccia, laminated calcrete, a reworked spot in a conglomerate, grey diffuse burrow pseudobreccia and brown diffuse mottle pseudobreccia (Fig. 11). These were sampled for a total of 35 analyses of oxygen and carbon isotopes

(Fig. 11). The precision of carbon and oxygen isotope values from replicate analysis of standards (NBS 19 and internal standards) is within 0.1‰ for carbon isotopes and 0.2‰ for oxygen isotope analyses. In all these samples, the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of both spots and their host carbonate matrix were analysed and compared (Fig. 11).

The $\delta^{18}\text{O}$ values of the pseudobreccias range from -5‰ to -8‰ (PDB) (Fig. 11), which are much lower than the estimated $\delta^{18}\text{O}$ values (-3‰ to -1‰ PDB) of normal marine calcite precipitated from Late Dinantian sea water based on the analyses of pristine brachiopod shells and marine calcite cements (Popp *et al.*, 1986; Veizer *et al.*, 1997). The $\delta^{13}\text{C}$ values of the 'pseudobreccias' vary from +2‰ to -3‰ (PDB) (Fig. 11). Most values are distinctly lower than the estimated $\delta^{13}\text{C}$ values of (+2‰ to +4‰ PDB) for Late Dinantian normal marine calcites (Popp *et al.*, 1986; Veizer *et al.*, 1997), although some of the $\delta^{13}\text{C}$ values, e.g. in diffused brown mottle pseudobreccia (Fig. 11D), are close to the estimated $\delta^{13}\text{C}$ values of Late Dinantian marine calcites. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in this study also overlap with values from other platforms, e.g. as reported by Hollis & Walkden (1996).

Two general patterns can be identified from the results of the oxygen and carbon isotopic analyses. The first pattern is that the $\delta^{13}\text{C}$ values of spots are related to their intensity of colouration. The $\delta^{13}\text{C}$ values of darker coloured spots are much lower, around -3‰ PDB for grey and 0–2‰ PDB for brown (Fig. 11A and B), compared with the $\delta^{13}\text{C}$ values of diffuse spots, which have $\delta^{13}\text{C}$ values of 0.3–1‰ PDB for grey (Fig. 11C) and 1–2‰ PDB for brown (Fig. 11D). The second feature is related to the $\delta^{13}\text{C}$ values of spots vs. the $\delta^{13}\text{C}$ values of their host carbonate matrix. The $\delta^{13}\text{C}$ values of both grey spots (Fig. 11A) and brown spots (Fig. 11B) are lower than the $\delta^{13}\text{C}$ values of their host matrix, whereas the $\delta^{13}\text{C}$ values of diffuse spots (Fig. 11C and D) are much closer to those of their host matrix.

DISCUSSION AND INTERPRETATION

Grey pseudobreccias

Origin as burrows

The lengths of pseudobreccia seen on bedding planes (Fig. 4D) and the reconstructed image (Fig. 4E) closely resemble back-filled networks of *Thalassinoides*. Supporting evidence for this consists of the avoidance of large bioclasts and

Fig. 11. Cross-plots of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of all pseudobreccias and their matrix. The estimated $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of normal marine calcite precipitated from Late Dinantian sea water based on the analyses of brachiopod shells and marine calcite cements are shown in a grey box (Popp *et al.*, 1986; Veizer *et al.*, 1997).

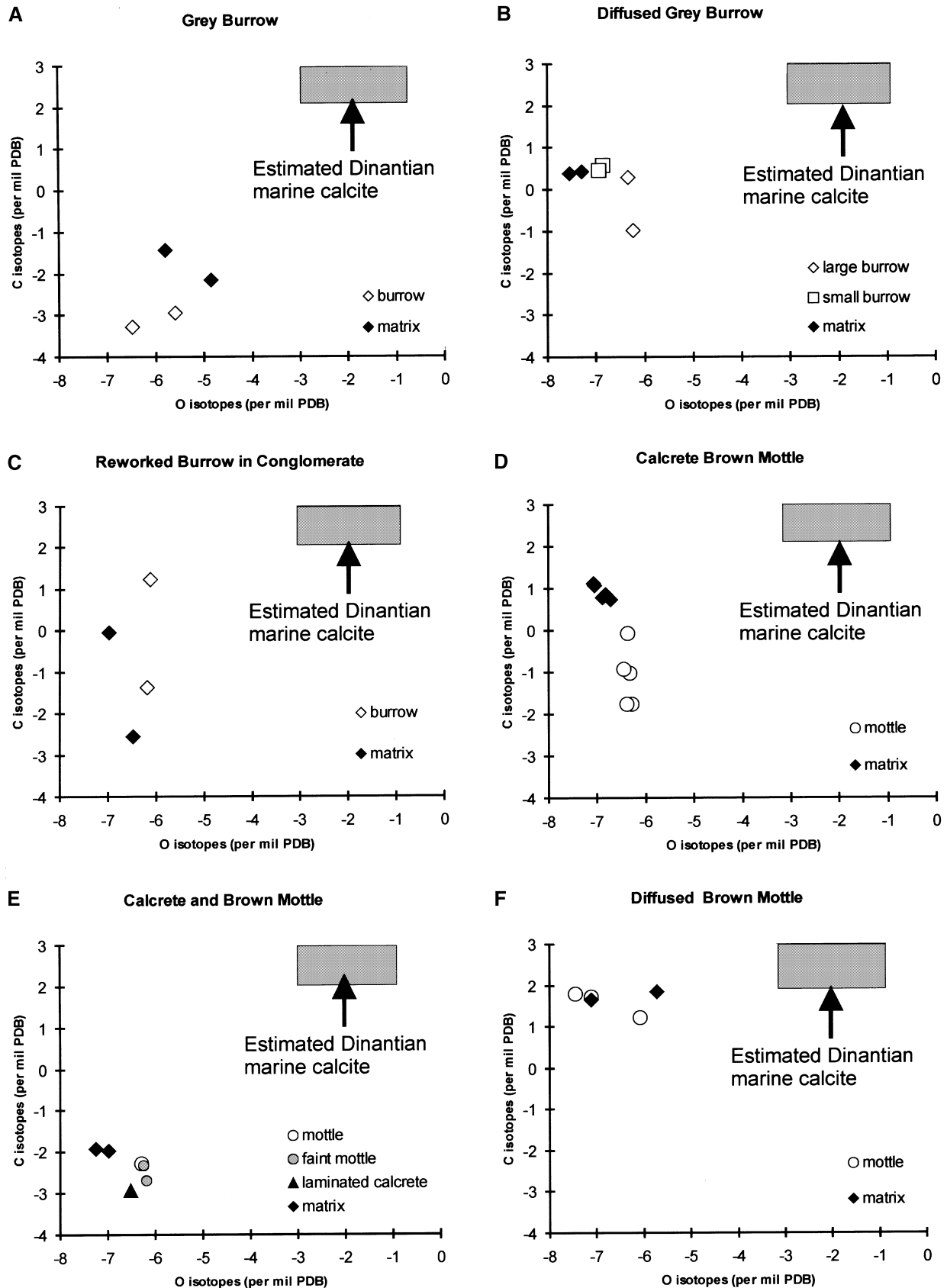
interpretation of swirled textures as spreite. Finally, the rare development of abandoned open tubes (Fig. 4G–I) as well as collapsed dwelling burrows is comparable with bioturbation-related fabrics reported by Kissling (1999) from the Ordovician of the Williston Basin.

The possible role of organics

On open-marine, shallow-water shelves, aerobic decay processes result in complete decomposition of reactive organic material beneath the sediment–water interface (Curtis & Coleman, 1986; Curtis *et al.*, 1986), e.g. in the upper 2 cm of modern sediments in Florida (Furukawa *et al.*, 1997). In this study, where open burrow tubes are preserved, a 5 cm diameter 'halo' of pale sediment is often present around the tube (Fig. 4G). This may imply that open burrows were normally a source of oxygen that, in turn, caused aerobic decay of organic material in the adjacent matrix. This has also been demonstrated for modern crustacean burrow systems (Frey & Howard, 1975; Morrow, 1978).

However, microspar calcite within spots has a distinctly lower $\delta^{13}\text{C}$ value than estimates of Dinantian normal marine calcites (Fig. 11), which suggests a contribution of carbon from decomposition of organic matter (Allan & Matthews, 1982). The most intense grey colouration of the spots is associated with the lowest $\delta^{13}\text{C}$ values (implying high original organic carbon contents) compared with the co-existing host 'matrix' (Fig. 11), whereas paler spots have higher $\delta^{13}\text{C}$ values (implying lower original organic carbon content) and less contrast with the matrix $\delta^{13}\text{C}$ values (Fig. 11C and D).

Deep burrows may therefore be important sites of organic concentration below the zone of surface oxidization. This is partly because complex 'dwelling' burrow systems are lined with secreted mucus membranes to keep the walls from collapsing (Fursich, 1973; Meadows, 1986). Walls may also be supported by physical packing of excreta (Kissling, 1999), and burrows are often sites of storage of faecal pellets and fungal growth (Frey & Howard, 1975). Organic material is thought to be important in the early diagenesis



of the burrow by altering the kinetics of carbonate reactions; in particular, early dolomitization of burrows is a common feature (Kendall, 1977; Mason, 1980; Kissling, 1999; Qing *et al.*, 2001; Pu & Qing, 2003) in addition to pyrite precipitation (Thomsen & Vorren, 1984).

Timing of lithification

The lithification of the grey burrow pseudobreccias and the host carbonate matrix is interpreted as occurring early, at least before early subaerial exposure based on the following observations:

1. Occurrence of lithified burrows in deposits reworked into basal lag conglomerates deposited above subaerial exposure surfaces (Fig. 4K).
2. Local preservation of open burrows in these carbonate rocks (Fig. 4G–I), although the small ‘wisps’ of pseudobreccia indicate the collapse of incompletely back-filled burrow systems.
3. Lower $\delta^{18}\text{O}$ values with respect to estimated values of normal marine calcite precipitated from Late Dinantian sea water (Fig. 11), suggesting the influence of groundwaters and the beginning of lithification during subaerial exposure at cycle tops.
4. Microspar precipitation predating dissolution of aragonitic bioclasts and subsequent infill of mouldic porosity by non-luminescent meteoric cement interpreted as meteoric in origin (Horbury & Adams, 1989).

Origins of microspar

The closest analogue for early diagenetic microspar precipitation is the stabilization of metastable mud beneath tidal flat hammocks on Andros Island (Steinen, 1978, 1979, 1982). Metastable aragonite and high-Mg calcite muds are exposed to fresh/brackish waters during tidal flat progradation, at which time the metastable components are subject to dissolution; pore waters become oversaturated with respect to low-Mg calcite and concomitantly precipitate microspar. Lime mud stabilization does not affect micritic low-Mg calcitic and coarser crystalline aragonitic allochems (Steinen, 1978, 1979, 1982). Low-Mg micritic allochems are not dissolved because they are stable in porewaters already saturated with respect to low-Mg calcite. Lack of dissolution of coarse crystalline aragonite is possibly a result of reaction kinetics in which small crystals with high surface area/volume ratios are more easily dissolved than large crystals (Bathurst, 1975, p. 254). The importance of cyclicity and evidence of subaerial exposure in the Urswick Limestone

Formation becomes apparent as a control on the development of the grey mottle pseudobreccias, in that, for the first time in the Dinantian, there was repeated subaerial exposure and potential for meteoric stabilization of organic-rich subtidal sediments. Similar facies in underlying units lack grey mottle pseudobreccias because there was no repeated subaerial exposure. A freshwater influence on burrow diagenesis has also been described from cyclic Pennsylvanian carbonates by Wiggins (1986), who also invoked a meteoric control on microspar development in burrows and shelter porosity. However, Wiggins (1986) also noted that microspars are probably universal to any diagenetic environment in which metastable carbonate dissolution yields solutions oversaturated with respect to calcite.

Mechanism

It is suggested that, if the burrow system was rapidly covered by sediment, for example by a storm deposit or by progradation of cycle-top grainstones, active burrowing stopped. As a consequence, the normal geochemical recycling and decay process resulting in early oxidation of reactive organic material (cf. Furukawa *et al.*, 1997) also stopped. At this point, the whole burrow system was isolated from the surface, and the decay ‘clock’ for organic matter within the burrow was slowed considerably. Subsequent subaerial exposure then ‘fixed’ the colouration of the burrows by microspar formation, dependent on the amount of organic material remaining. The CL colour of the microspar indicates that this water was slightly reducing to reducing and was certainly not oxygenated. Non-ferroan calcite with minor pyrite, as seen locally, indicates precipitation in a sulphate-reducing zone (Raiswell, 1987, 1988). The data presented here imply that a high proportion of remnant organic material must have catalysed or aided the transformation of metastable lime mud into microspar. Shallower parts were likely to be more oxygenated than deeper parts of the meteoric lens and may have reinitiated a second phase of aerobic decay of organic material, possibly explaining the generally paler colours of lithified burrows higher in the cycle (Fig. 4J). Matrix sediment was affected differently because it is probable that only metastable aragonitic shell material and lime mud, but no organic material, were present; this could have been a source of some of the carbonate precipitated in the burrow system, by a process of ‘diagenetic unmixing’ (Ricken, 1986). Similar sequestering of carbonate from shales to form

nodules both within the shales and in sandstones adjacent to argillaceous successions is well known (e.g. Gluyas, 1984). Carbonate examples are less commonly described, but biostromes in the Cretaceous of Italy show a large-volume dissolution of radiolitic rudist shell material, which was produced, among other mechanisms, by 'chemical gradients' close to crustacean burrows (Sanders, 2001).

Brown pseudobreccias

Brown mottle pseudobreccias are interpreted as pedogenic fabrics on the basis of their association with palaeokarsts, their infilling and growth over rhizcretions and alveolar textures as outlined earlier and as also proposed by Solomon & Walkden (1985) and Solomon (1989).

Climate control and detailed timing

Short-lived (tens of thousands of years) Late Dinantian subaerial emergent events record a semi-arid climate with rhizcretion development, followed by a more tropical phase typified by karstification as suggested by Vanstone (1996). Brown mottle development appears to be characteristic of the middle of the phase of emergence. Short-lived subaerial emergence is also supported by the observation that the main aragonite bioclast dissolution event post-dates the initial brown calcite precipitation. In the Urswick Limestone Formation, the general absence of well-developed laminar calcretes and the relative scarcity of rhizcretions (Vanstone, 1996) indicate that the climate was slightly wetter compared with other platforms, which can also in turn be correlated with preferential development of the brown mottle fabrics on this platform.

Genesis of brown mottle pseudobreccias

Rhizcretions are confined to the near-surface 1–2 m of sediment (Horbury, 1987); the water table is therefore placed between 0.5 and 2 m below the palaeokarst top (Vanstone, 1996). In a semi-arid climate, wet season precipitation would liberate carbonate for precipitation (Hird & Tucker, 1988), yet the arid season would cause fluctuations in the water table by evaporation in the capillary rise zone and affect porewater Eh, pH and saturation with respect to calcite. Therefore, if the permanent water table was low, a temporary zone of meteoric phreatic water may be expected above it during the wet season (cf. Semeniuk & Searle, 1985). As this dried out during the dry season and the water table fell, cements that precipitated

would normally be of meteoric phreatic origin, as observed by the euhedral crystal habit of the brown cements in the Urswick Limestone Formation. Rare pendant and meniscus fibrous brown cements are interpreted as representing precipitation in the overlying meteoric vadose zone (cf. Longman, 1980) where degassing of CO₂ is rapid (Hanor, 1978). Brown spots have similar negative $\delta^{18}\text{O}$ and negative $\delta^{13}\text{C}$ values to the laminar calcrete micrite (Fig. 11E), also suggesting the presence of shallow meteoric groundwaters during precipitation of calcite and a significant influence of organic carbon in the diagenetic system. The environment of precipitation of brown mottle textures is therefore interpreted as being very shallow meteoric phreatic (0.5–15 m deep) and affected by local variations in groundwater flow and evaporation.

Brown colouration probably relates to contamination by organic inclusions derived from the overlying soils, as noted for example in North Wales by Solomon & Walkden (1985). Speleothems within karstified Brigantian mudmounds in Derbyshire show similar brown colouration (Gutteridge, 1983). The supply of calcite was probably from stabilization/dissolution of metastable allochems in overlying sediment and large-scale solution on the palaeokarstic surfaces. Observed small-scale diagenetic heterogeneities (e.g. changes in cement zonation from pore to pore) arise from:

- (i) the semi-arid seasonal climate (Gray, 1981; Wright, 1984; Horbury, 1987) affecting the position of the water table;
- (ii) precipitation within the lenticular upper phreatic zone in which diagenesis is usually complex (Longman, 1980; Esteban & Klappa, 1983); and
- (iii) local porosity and permeability variations controlled by sediment heterogeneity, overprinted by early diagenetic heterogeneities.

Factors related to simple mottle patterns

Two factors are considered important in understanding the origin of brown mottle patterns: (i) permeability pathways during early diagenesis; and (ii) the presence of nuclei. The 'stick beds' of Garwood (1913) are clearly parts of *Thalassinoides* burrow systems. Burrows may represent permeability pathways; for example, burrows in the Permian Grayburg Formation of Texas have porosities of 10–32% and permeabilities of 2–400 mD, whereas matrix sediment had values of 2–9% and 0.002–2.0 mD (Caldwell

et al., 1996). Carnian siliciclastic deposits of North Carolina provide another analogue, in that pedogenic micrite occurs as a cement in burrows as well as in rhizoliths and nodules (Driese & Mora, 2001).

Nuclei types are locally important, as shown by preferential development of brown cement around solitary rugose coral fragments. In addition, brown cements are well developed where burrows show high concentrations of burrow-sorted monocrystalline algal fragments (*Kamaenella*, *Kamaena*) (a feature similar to the 'tubular tempestites' described from the Recent sediments by Wanless *et al.*, 1988). Rhizocretions are also associated with spot formation, but this could imply either a function of permeability related to root penetration or because pedogenic micrite in rootlets formed an ideal nucleation substrate for later pedogenic cements, or both of these.

Reasons for spots overprinting intact *Siphonodendron* colonies and, to some extent, gastropod and productoid brachiopod shells remain unclear. However, these cannot be examples of control by bioturbation or rootlets.

Origin of the attached and detached brown mottle profiles

Detached mottle profiles comprising complex mottle patterns closely resemble the groundwater (capillary rise zone) precipitates of Semeniuk & Searle (1985), where cements precipitate in a zone of evaporation overlying a relatively deep water table. This suggests a relatively arid climate. The attached mottle profile probably represents a pedogenic precipitate and/or CO₂ degassing in the vadose zone, by analogy with the calcrete fabrics of Semeniuk & Searle (1985). In this case, the water table may have been shallow such that the soils were poorly drained (e.g. Mount & Cohen, 1984). This suggests a wet climate in which precipitation was related to localized evaporation during arid seasons.

Their intimate relationship with mottle fabrics suggests that the brown and pale ring structures are genetically inter-related. However, these are more difficult to explain, as they lack modern or ancient analogues. Regularity of patterning changes dictates that there must be some decimetric-scale factor unrelated to local (centimetric-scale) variations such as that noted above for simple mottle fabrics. At present, it is only possible to suggest that 'domains' of mottle fabric are a product of local circulation and precipitation cells within the capillary rise zone.

CONCLUSIONS

Two types of pseudobreccia mottle fabric are identified in the Late Dinantian Urswick Limestone Formation of the southern Lake District, UK. The grey mottle pseudobreccia is formed by early preservation of organic material in abandoned cycle-base *Thalassinoides* burrow systems that was rapidly placed within the sulphate reduction zone due to high depositional rates. This was then 'fixed' as microspar calcite by early meteoric diagenesis. Spot shape and colour relate to the degree of backfill and the period of aerobic oxidation of the sediment before initial burial. The presence of both lime mud and organic material in the burrows represent the ingredients of this diagenetic process.

Brown mottle pseudobreccias formed by precipitation of cycle-top calcretes during subaerial exposure. Two textures of brown mottle pseudobreccia fabric are recognized. One is detached by up to 5 m from the emergent surface to which it is related, and this is interpreted as a capillary rise calcrete, typical of a semi-arid environment. The second type is directly attached to the emergent surface and is a product of pedogenic precipitation and/or CO₂ degassing in a more humid climate. Simple mottle fabrics can be related to the presence of burrows and rootlets, but other textures in which spots overprint bioclasts are not fully understood. Complex geometries of calcrete mottle fabric may relate to circulation cells within the capillary rise zone. Therefore, the location of different brown mottle fabrics with respect to overlying emergent surfaces probably reflects palaeoaridity and the positions of palaeowater tables.

ACKNOWLEDGEMENTS

Andrew Horbury would like to thank Tony Adams at Manchester University for his guidance and discussion during the course of this work, and for his initiative and support in suggesting this particular project at a critical stage in A.D.H.'s geological career. A.D.H. would also like to thank Robin Nicholson of Manchester University for discussion on suitable terminology for these textures, and William Sowerbutts of Manchester University for his assistance in the computer reconstruction of burrow networks. Hairuo Qing thanks Royal Holloway College, University of London, for use of the isotopic laboratory for analyses, and NSERC

(Discovery Grant 155012) for the partial funding of this project.

REFERENCES

- Allan, J.R. and Matthews, R.K. (1982) Isotope signatures associated with early meteoric diagenesis. *Sedimentology*, **29**, 797–817.
- Bathurst, R.G.C. (1959) Diagenesis in Mississippian calcilutites and pseudobreccias. *J. Sed. Petrol.*, **29**, 365–376.
- Bathurst, R.G.C. (1975) *Carbonate Sediments and Their Diagenesis*. Elsevier, Amsterdam, 658 pp.
- Caldwell, C.D., Harpole, K.J. and Gerard, M.G. (1996) Reservoir characterisation of the Upper Permian Grayburg Formation in preparation for a horizontal-well CO₂ flood, South Cowden Unit, West Texas. In: *Platform Carbonates in the Southern Midcontinent, 1996 Symposium* (Ed. K.S. Johnson), *Oklahoma Geol. Soc.*, **101**, 339–353.
- Cayeux, L. (1937) Les anomalies de structure et de composition de phosphates albiens du bassin de Paris et les enseignements qui en découlent. *CR Hebdomadaires Seances Acad. Sci.*, **205**, 1022–1023.
- Curtis, C.D. and Coleman, M.L. (1986) Controls on the precipitation of early diagenetic calcite, dolomite and siderite concretions in complex depositional sequences. In: *Roles of Organic Matter in Sediment Diagenesis* (Ed. D.L. Gautier), *SEPM Spec. Publ.*, **38**, 23–33.
- Curtis, C.D., Coleman, M.L. and Love, L.G. (1986) Pore water evolution during sediment burial from isotopic and mineral chemistry of calcite, dolomite and siderite concretions. *Geochim. Cosmochim. Acta*, **50**, 2321–2334.
- Dixon, E.E.L. and Vaughan, A. (1911) The Carboniferous succession in Gower (Glamorganshire), with notes on its fauna and conditions of deposition. *Q. J. Geol. Soc. London*, **67**, 477–567.
- Driese, S.G. and Mora, C.I. (2001) Paleopedology and stable isotope geochemistry of Late Triassic (Carnian) Paleosols, Durham sub-basin, North Carolina; implications for paleoclimate and paleoatmospheric pCO₂. *Geol. Soc. Am., Abstracts with Prog.*, **33**, 27–28.
- Esteban, C.M. and Klappa, C.F. (1983) Subaerial exposure environment. In: *Carbonate Depositional Environments* (Eds P.A. Scholle, D.G. Bebout and C.H. Moore), *AAPG Mem.*, **33**, 1–54.
- Folk, R.L. (1965) Some aspects of recrystallisation in ancient limestones. In: *Dolomitisation and Limestone Diagenesis* (Eds L.C. Pray and R.C. Murray), *SEPM Spec. Publ.*, **13**, 14–48.
- Frey, R.W. and Howard, J.D. (1975) Endobenthic adaptations of juvenile thalassinidean shrimp. *Bull. Geol. Soc. Denmark*, **24**, 283–297.
- Fursich, F.T. (1973) Thalassinoides and the origin of nodular limestone in the Corallian Beds (Upper Jurassic) of southern England. *Neues Jb. Geol. Paläontol. Monat.*, **3**, 136–156.
- Furukawa, Y., Lavoie, D. and Stephens, K. (1997) Early diagenesis of biologically reworked carbonate sediments near the Dry Tortugas, Florida. *Geol. Soc. Am., Abstracts with Prog.*, **29**, 153.
- Garwood, E.J. (1913) The Lower Carboniferous succession in the northwest of England. *Q. J. Geol. Soc. London*, **68**, 449–586.
- Gluyas, J.G. (1984) Early carbonate diagenesis within Phanerozoic shales and sandstones of the NW European Shelf. *Clay Minerals*, **19**, 309–321.
- Gray, D.I. (1981) *Lower Carboniferous shelf palaeogeographies in North Wales*. Unpubl. PhD Thesis, University of Newcastle-upon-Tyne.
- Gutteridge, P. (1983) *Sedimentological study of the Eyam Limestone Formation in the east-central part of the Derbyshire Dome*. Unpubl. PhD Thesis, University of Manchester.
- Hanor, J.S. (1978) Precipitation of beachrock cements: mixing of marine and meteoric waters vs. CO₂ degassing. *J. Sed. Petrol.*, **48**, 489–501.
- Hird, K. and Tucker, M.E. (1988) Contrasting diagenesis of two Carboniferous oolites from South Wales; a tale of climatic influence. *Sedimentology*, **35**, 587–602.
- Hollis, C. and Walkden, G. (1996) The use of burial diagenetic calcite cements to determine the controls upon hydrocarbon emplacement and mineralisation on a carbonate platform, Derbyshire, England. In: *Recent Advances in Lower Carboniferous Geology* (Eds P. Strogon, I.D. Somerville and G.L. Jones), *Geol. Soc. London Spec. Publ.*, **107**, 35–50.
- Horbury, A.D. (1987) *Sedimentology of the Urswick Limestone in South Cumbria and North Lancashire*. Unpubl. PhD Thesis, University of Manchester.
- Horbury, A.D. (1989) The relative roles of tectonism and eustasy in the deposition of the Urswick Limestone in South Cumbria and North Lancashire. In: *The Role of Tectonics in Devonian and Carboniferous Sedimentation in the British Isles* (Eds R.S. Arthurton, P. Gutteridge and S.C. Nolan), *Yorks. Geol. Soc. Occ. Publ.*, **6**, 153–169.
- Horbury, A.D. and Adams, A.E. (1989) Meteoric phreatic diagenesis in cyclic late Dinantian Carbonates, northwestern England. *Sed. Geol.*, **65**, 319–344.
- Kendall, A.C. (1977) Origin of dolomite mottling in Ordovician limestones from Saskatchewan and Manitoba. *Bull. Can. Petrol. Geol.*, **25**, 480–504.
- Kissling, D.L. (1999) Life and death roles of Red River Thalassinoides. *AAPG Bull.*, **83**, 1184–1185.
- Longman, M.W. (1980) Carbonate diagenetic textures from near-surface diagenetic environments. *AAPG Bull.*, **64**, 461–487.
- Mason, T.R. (1980) Formation and diagenesis of Visean trace fossils from Ireland. *Lethaia*, **13**, 229–237.
- Meadows, P.S. (1986) Marine biology; Biological activity and seabed sediment structure. *Nature*, **323**, 207.
- Morrow, D.W. (1978) Dolomitisation of Lower Palaeozoic burrow-fillings. *J. Sed. Petrol.*, **48**, 295–306.
- Mount, J.F. and Cohen, A.S. (1984) Petrology and geochemistry of rhizoliths from Plio-Pleistocene fluvial and marginal lacustrine deposits, east Lake Turkana, Kenya. *J. Sed. Petrol.*, **54**, 263–275.
- Popp, N.B., Anderson, T.F. and Sandberg, P.A. (1986) Brachiopods as indicators of original isotopic compositions in some Paleozoic limestones. *Geol. Soc. Am. Bull.*, **97**, 1262–1269.
- Pu, R. and Qing, H. (2003) Pool characterization of Ordovician Midale Field: implication for Red River play in northern Williston Basin, southeastern Saskatchewan, Canada. *AAPG Bull.*, **87**, 1–17.
- Qing, H., Kent, D.M. and Bend, S. (2001) Preliminary results of isotopic geochemistry of Ordovician Red River carbonates, subsurface of southeastern Saskatchewan: Implication for process of dolomitization and diagenetic modification of dolomites. In: *Summary of Investigations 2001*, Vol. 1. Saskatchewan Geological Survey, Saskatchewan Energy Mines, Miscellaneous Report 2001-4, **1**, 3–9.
- Raiswell, R. (1987) Non-steady state microbiological diagenesis and the origin of concretions and nodular limestones. In: *Diagenesis of Sedimentary Sequences* (Ed. J.D. Marshall), *Geol. Soc. London Spec. Publ.*, **36**, 41–54.

- Raiswell, R.** (1988) Evidence for surface reaction-controlled growth of carbonate concretions in shales. *Sedimentology*, **35**, 571–575.
- Ricken, W.** (1986) *Diagenetic Bedding: a Model for Marl–Limestone Alternations*. Lecture Notes in Earth Sciences 6. Springer-Verlag, Berlin, 210 pp.
- Sanders, D.** (2001) Burrow-mediated carbonate dissolution in rudist biostromes (Aurisina, Italy); implications for taphonomy in tropical, shallow subtidal carbonate environments. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **168**, 39–74.
- Semeniuk, V. and Searle, D.I.** (1985) Distribution of calcrete in Holocene coastal sands in relationship to climate, south-western Australia. *J. Sed. Petrol.*, **55**, 86–95.
- Solomon, S.T.** (1989) The early diagenetic origin of lower Carboniferous mottled limestones (pseudobreccias). *Sedimentology*, **36**, 399–418.
- Solomon, S.T. and Walkden, G.M.** (1985) The application of cathodoluminescence to the diagenesis of an ancient calcrete profile. *Sedimentology*, **32**, 877–896.
- Somerville, I.D.** (1979a) A sedimentary cyclicity in late Asbian (Upper D1) limestones in the Llangollen district of North Wales. *Proc. Yorks. Geol. Soc.*, **42**, 317–341.
- Somerville, I.D.** (1979b) A sedimentary cyclicity in early Asbian (Lower D1) limestones in the Llangollen district of North Wales. *Proc. Yorks. Geol. Soc.*, **42**, 397–404.
- Steinen, R.P.** (1978) On the diagenesis of lime mud: scanning electron microscope observations of subsurface material from Barbados, W.I. *J. Sed. Petrol.*, **48**, 1139–1148.
- Steinen, R.P.** (1979) On the diagenesis of lime mud: scanning electron microscope observations of subsurface material from Barbados, W.I., a reply. *J. Sed. Petrol.*, **49**, 1355–1361.
- Steinen, R.P.** (1982) SEM observations on the replacement of Bahaman aragonitic mud by calcite. *Geology*, **10**, 471–475.
- Thomsen, E. and Vorren, T.O.** (1984) Pyritisation of tubes and burrows from late Pleistocene continental shelf sediments off North Norway. *Sedimentology*, **31**, 481–492.
- Vanstone, S.** (1996) The influence of climatic change on exposure surface development: a case study from the Late Dinantian of England and Wales. In: *Recent Advances in Lower Carboniferous Geology* (Ed. P. Strogon, L.O. Somerville and G.L. Jones), *Geol. Soc. London Spec. Publ.*, **107**, 281–301.
- Veizer, J., Bruckschen, P., Pawellek, F., Diener, A., Podlaha, O.G., Carden, A.F.G., Jasper, T., Korte, C., Strauss, H., Azmy, K. and Ala, D.** (1997) Oxygen isotope evolution of Phanerozoic seawater. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **132**, 159–172.
- Walkden, G.M.** (1987) Sedimentary and diagenetic styles in late Dinantian carbonates of Britain. In: *European Dinantian Environments* (Eds A.E. Adams and V.P. Wright), pp. 131–155. John Wiley, Chichester.
- Wanless, H.R.** (1979) Limestone response to stress: pressure solution and dolomitisation. *J. Sed. Petrol.*, **49**, 437–462.
- Wanless, H.R.** (1982) Limestone response to stress: pressure solution and dolomitisation. Reply. *J. Sed. Petrol.*, **52**, 328–332.
- Wanless, H.R., Tedesco, L.P. and Tyrrel, K.M.** (1988) Production of subtidal tubular and surficial tempestites by Hurricane Kate, Caicos Platform, British West Indies. *J. Sed. Petrol.*, **58**, 739–750.
- Wiggins, W.D.** (1986) Geochemical signatures in carbonate matrix and their relation to deposition and diagenesis, Pennsylvanian Marble Falls Limestone, central Texas. *J. Sed. Petrol.*, **56**, 771–783.
- Wright, V.P.** (1984) The ecology of Early Carboniferous Palaeosols. In: *First Meeting on European Dinantian Environments* (Eds A.E. Adams, T.P. Burchette, J. Miller, R.D. Vaughn and V.P. Wright), pp. 92–95. Department of Earth Science, Open University, UK.

*Manuscript received 11 August 2003;
revision accepted 21 September 2003.*