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Late Dinantian (Brigantian) carbonate mud-mounds of the Derbyshire carbonate platform

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ABSTRACT

Carbonate mud-mounds developed during the late Dinantian (Brigantian) on the Derbyshire carbonate platform in the shelf interior, associated with the shelf margins, and on the shallow to middle part of an intraplatform ramp. Their growth was controlled by water depth and subsidence: carbonate mud-mounds which developed in areas of shallow water and low subsidence grew by lateral accretion, whereas those deposited in areas of deeper water and faster subsidence grew by vertical accretion. The carbonate mud in the mound cores consists of peloidal and homogeneous micrite with local neomorphism to microspar and pseudospar. The carbonate mud was produced on the mound core possibly as a result of microbially mediated precipitation. Stromatactoid cavities formed as a result of the modification of original cavities (probable shelter cavities) by internal erosion of the carbonate mud. The surface of these carbonate mud-mounds may have been bound by a microbial mat which supported steep depositional slopes. Immediately below the surface of the mound core the sediment was semi-consolidated and subjected to internal erosion. The degree of consolidation and lithification increased with increasing depth below the surface of the mound core.

INTRODUCTION

There are numerous examples of late Dinantian (Brigantian) carbonate mud-mounds which were established in shallow-water platform interior and margin settings on the Derbyshire carbonate platform. The aims of this paper are to describe the sedimentology, early diagenesis and biota of these late Dinantian carbonate mud-mounds and to discuss their implications for the origin of carbonate mud-mounds in general. Compared with the extensively studied Waulsortian carbonate mud mounds of the early Dinantian (e.g. Lees & Miller, 1985; Bridges *et al.*, this volume), the late Dinantian carbonate mud-mounds have been the subject of few sedimentological studies, and this paper enables comparisons to be made between the Waulsortian and late Dinantian carbonate mud-mounds.

Carbonate mud-mounds were present over much of the Derbyshire carbonate platform during the late Dinantian (Fig. 1). They occur at two stratigraphical levels within the Brigantian (Fig. 2): *group 1 mounds* are associated with the boundary between the Eyam Limestones and the underlying Monsal Dale Limestones; and *group 2 mounds* occur higher in the Eyam Limestones and were associated with bioclastic carbonate sand bodies deposited at the shallow part of an intraplatform ramp (Gutteridge & Currie, in press). Group 1 mounds were included in the Eyam Limestones Formation by Aitkenhead & Chisholm (1982), but Adams (1980) and Gutteridge (1991) showed that they are separated from the overlying Eyam Limestones by a stratigraphical break so they are now regarded as part of the Monsal Dale Limestones Formation.

FACIES TERMINOLOGY AND MOUNDING STYLE

Facies

These carbonate mud-mounds are made up of an association of three facies.

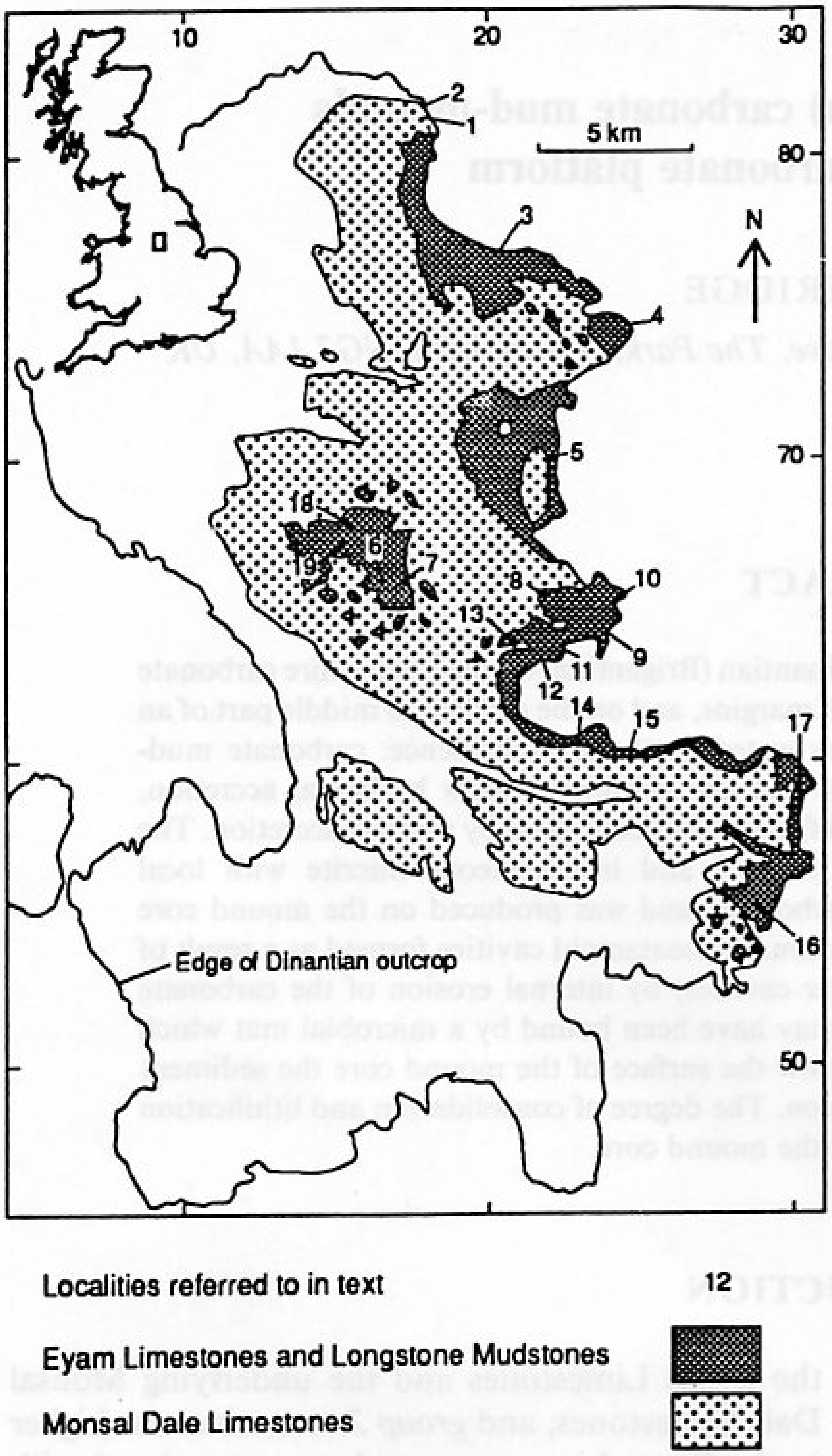

Fig. 1. Carbonate mud-mounds on the Derbyshire carbonate platform. Group 1 mounds: 1. Hope Cement Works Quarry (SK 159 820), 2. Jack Bank Quarry (SK 163 822), 3. Waterfall Farm (SK 195 769), 4. Calver Low (SK 237 746), 5. Quarry near Station Farm (SK 215 705), 6. Ricklow Dale (SK 165 662), 7. Lathkill Dale (SK 1685 6600), 8. Conksbury Bridge Borehole (SK 2142 6587), 9. Bowers Hall Borehole (SK 2325 6458), 10. Nutseats Quarry Borehole (SK 2369 6585), 11. Rheinstor Rock, Alport (SK 2185 6445), 12. Bradford Dale (SK 215 642) 13. Sidenooks Plantation (SK 1995 6415), 14. Grey Tor (SK 2347 6038), 15. Wynstor (SK 2405 6020), 16. National Stone Centre, Wirksworth (SK 2865 5515), 17. High Tor, Matlock Bath (SK 297 589). Group 2 mounds: 18. High Low Quarry (SK 153 684), 19. Upper Bricks Quarry (SK 149 678).

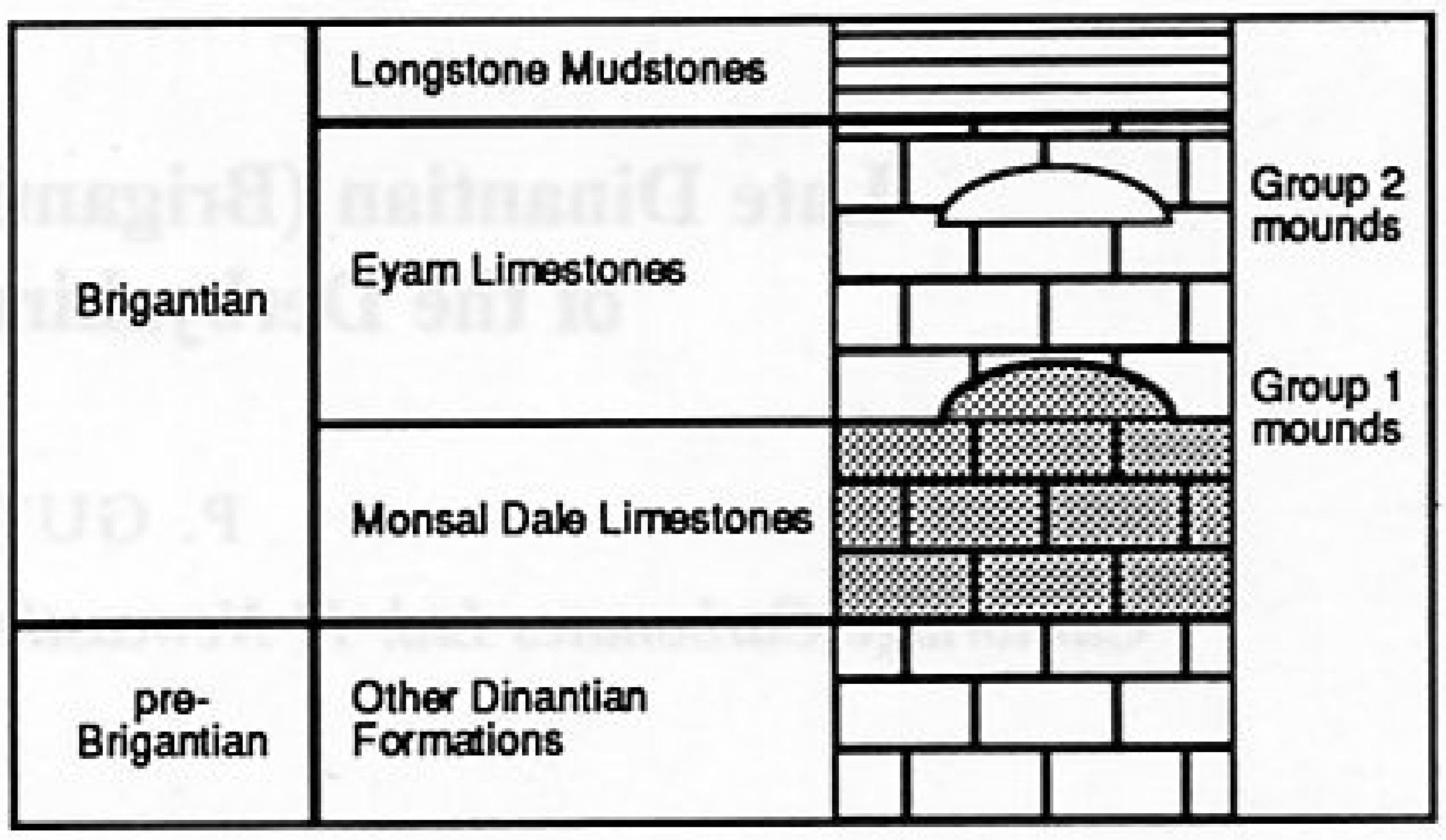

Fig. 2. Stratigraphy of the late Dinantian of the Derbyshire carbonate platform and the stratigraphical position of the carbonate mud-mounds. The boundary between the Monsal Dale and Eyam Limestones is taken from Gutteridge (1991).

The *mound-core facies* is a poorly-bedded wackestone/carbonate mudstone which occurs as lens-shaped bodies of unbedded, very pale grey or white limestone which formed mound-like accumulations on the Dinantian sea-floor. A *mound complex* refers to a carbonate mud-mound which contains several mound cores.

The *mound-flank facies* is laterally equivalent to the mound-core facies. It displays well-developed bedding which dips away from the mound core. The attitude of internal sediment within cavities shows that this dip was depositional in origin. The onlap of the mound-core and mound-flank facies by overlying sediments also demonstrates that the mound-core and mound-flank facies were areas of depositional relief.

The *intermound facies* was deposited in areas of no detectable depositional relief between the mound-core and mound-flank facies.

Mounding Style

The mounding style of a carbonate mud-mound refers to the overall geometry and disposition of the facies described above (e.g. Lane & Ormiston 1982; MacQuown 1982). These carbonate mud-mounds show four mounding styles which are summarized in Fig. 3 as follows:

1 *Tabular mounds*. These are single mound cores which are 1–2 m in thickness and at least 25 m across (Fig. 4a, b). They have parallel tops and bases and pinch out laterally. Overlying beds commonly show onlap and compactional drape over the margins of these tabular mounds. Their depositional relief was probably only a few decimetres. There is no differentiation into mound-core and mound-flank facies at this stage of growth. Numerous

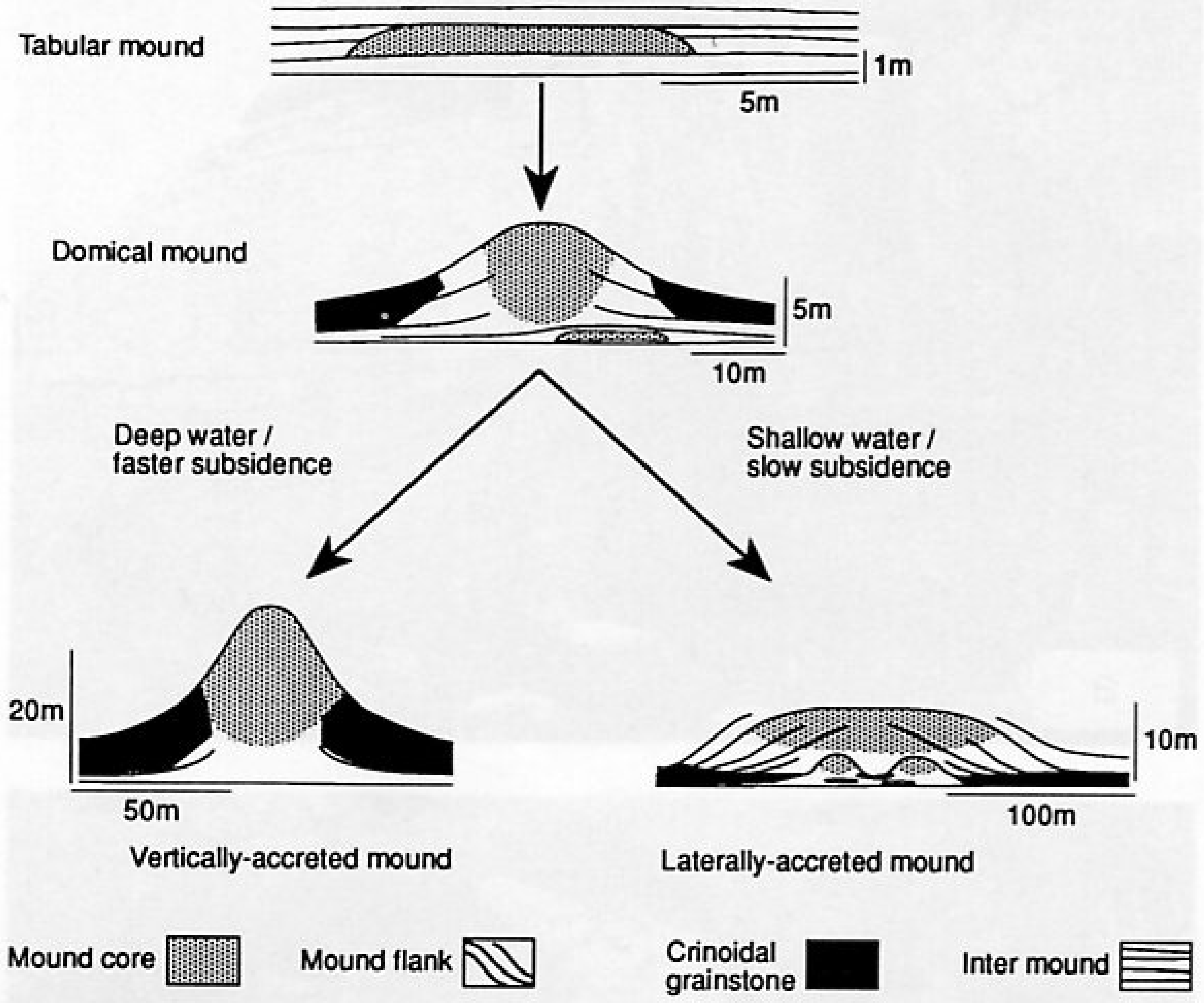

Fig. 3. Schematic representation of carbonate mud-mounds illustrating the subdivision into facies and mounding styles. All carbonate mud-mounds nucleate as tabular mounds and then develop into domical mounds. Subsequent growth is determined by water depth and subsidence rate: laterally accreted mounds grow in areas of shallow water and slow subsidence; vertically accreted mounds grow in areas of deeper water and faster subsidence.

tabular mounds are present at the base of many mound complexes. They are inferred to represent the earliest stage of mud-mound growth immediately following nucleation.

2 *Domical mounds.* These are symmetrical dome-shaped mounds which are up to 4 m in height and several tens of metres in diameter (Fig. 4c). Their depositional relief was probably of the order of a few metres. They are differentiated into mound-core and mound-flank facies. The internal structure of domical mounds shows that they developed by accretion about one or more tabular mounds. Domical mounds represent an intermediate stage of growth from which one of the following two mounding styles developed.

3 *Laterally accreted mounds.* These mud-mounds extend laterally for several hundreds of metres and are up to 20 m in thickness, of which the original depositional relief of the mound cores was 5–10 m (Fig. 5a, b). This mounding style develops by the lateral accretion and amalgamation of numerous domical mounds resulting in fewer but larger mound cores. Numerous mound cores are present in laterally accreted mound complexes.

4 *Vertically accreted mounds.* These mud-mounds extend laterally for several tens of metres and are up to 50 m in thickness of which the original depositional relief was 25–30 m (Fig. 5c, d). This mounding style develops by the vertical accretion of a small number of closely spaced domical mounds. Consequently only one or two mound cores are present in vertically accreted mound complexes.

PALAEOGEOGRAPHIC SETTING OF CARBONATE MUD-MOUNDS

The palaeogeography of the Derbyshire carbonate platform, together with the occurrence of the laterally and vertically accreted mounding styles of the carbonate mud-mounds, is shown by Fig. 6. Tabular and domical mounds are not shown because these are present in both laterally and vertically accreted mud-mound complexes and their occurrence show no relation to palaeogeography. During the Brigantian, the Derbyshire carbonate platform was differentiated into a variety of shelf, intraplatform ramp and intraplatform basin environments (Gutteridge 1983, 1987, 1989; Gutteridge & Currie, in press). Carbonate mud-mounds occur in shelf-interior settings, at the platform margins and on the shallow to middle part of the intraplatform ramp in the central part of the Derbyshire carbonate platform. They are absent in the intraplatform basin. The distribution of laterally and vertically accreted mounds shows a clear relationship with palaeogeographical setting.

Laterally accreted mounds are present in areas of

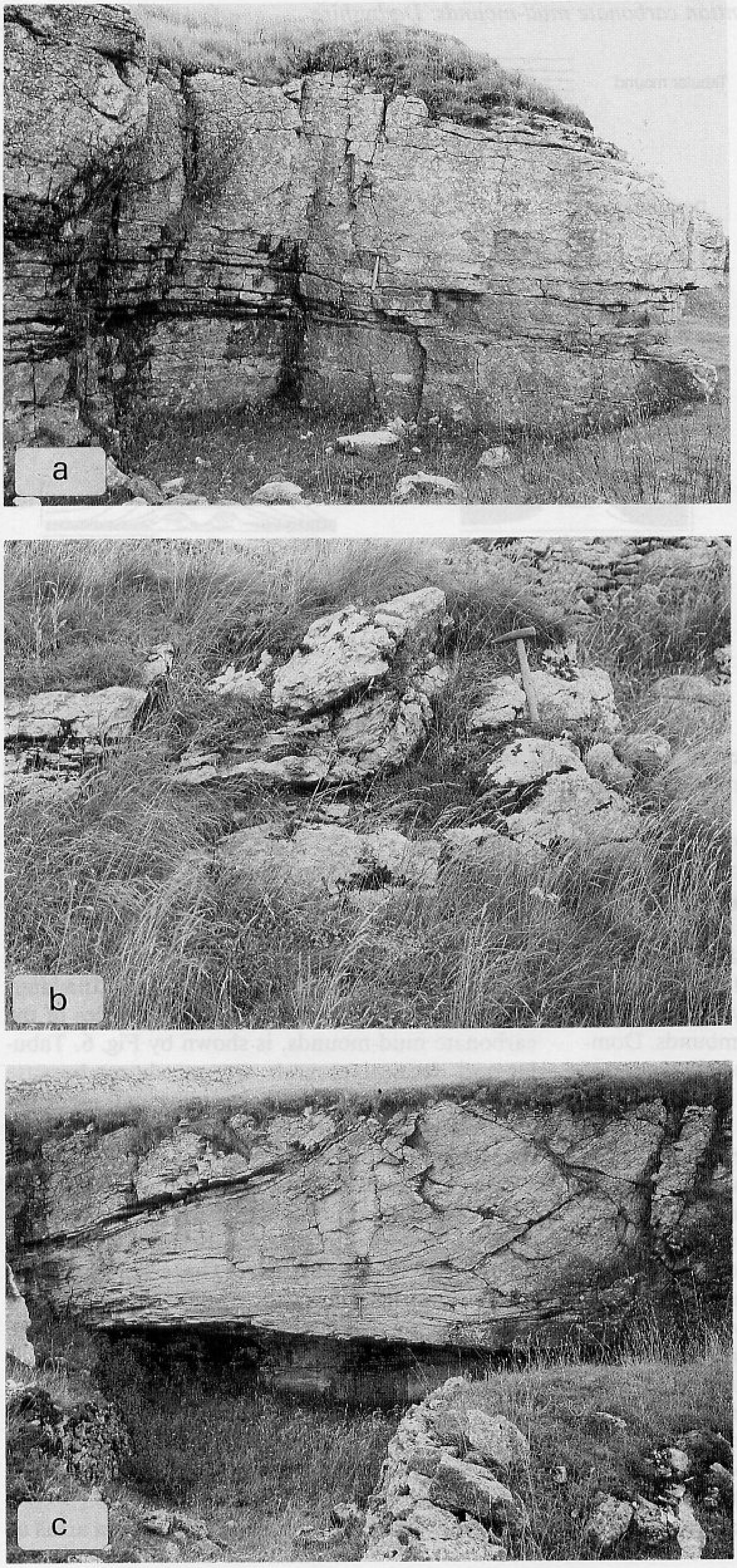

Fig. 4. (a) Tabular mound (group 2) associated with the bioclastic sand-body complex developed at the shallow part of the intra-platform carbonate ramp. The mound is approximately 1.5 m thick. The base of the hammer shaft is level with the base of the mound and the top of the quarry face corresponds to the top of the mound. Note the development of thin beds towards the top of the mound. These are strewn with disarticulated brachiopod valves and other reworked bioclasts. Locality 19 (Upper Bricks Quarry). (b) Lateral margin of a tabular mound present at the early stages of growth of the Lathkill/Ricklow Dale (group 1) mound complex. The shaft of the hammer rests on the mound and the steeply dipping beds in the left centre of the picture are a result of sedimentary and compactional drape over the margin of the mound. Hammer shaft is 0.35 m long. Locality 7 (Lathkill Dale). (c) Domical mound (group 2) associated with the bioclastic sand-body complex developed at the shallow part of the intraplatform carbonate ramp. Note the progressive steepening and the lateral spreading of the mound core during growth. Height of quarry face is approximately 2.5 m. Locality 18 (High Low Quarry).

shallow water in the shelf-interior and shallow-ramp settings. In contrast, vertically accreted mounds are present in deeper water in mid-ramp and platform margin settings. This distribution suggests that the mounding style was influenced by water depth and rate of subsidence. In areas of relatively shallow water and slow subsidence the vertical growth of the carbonate mud-mounds was

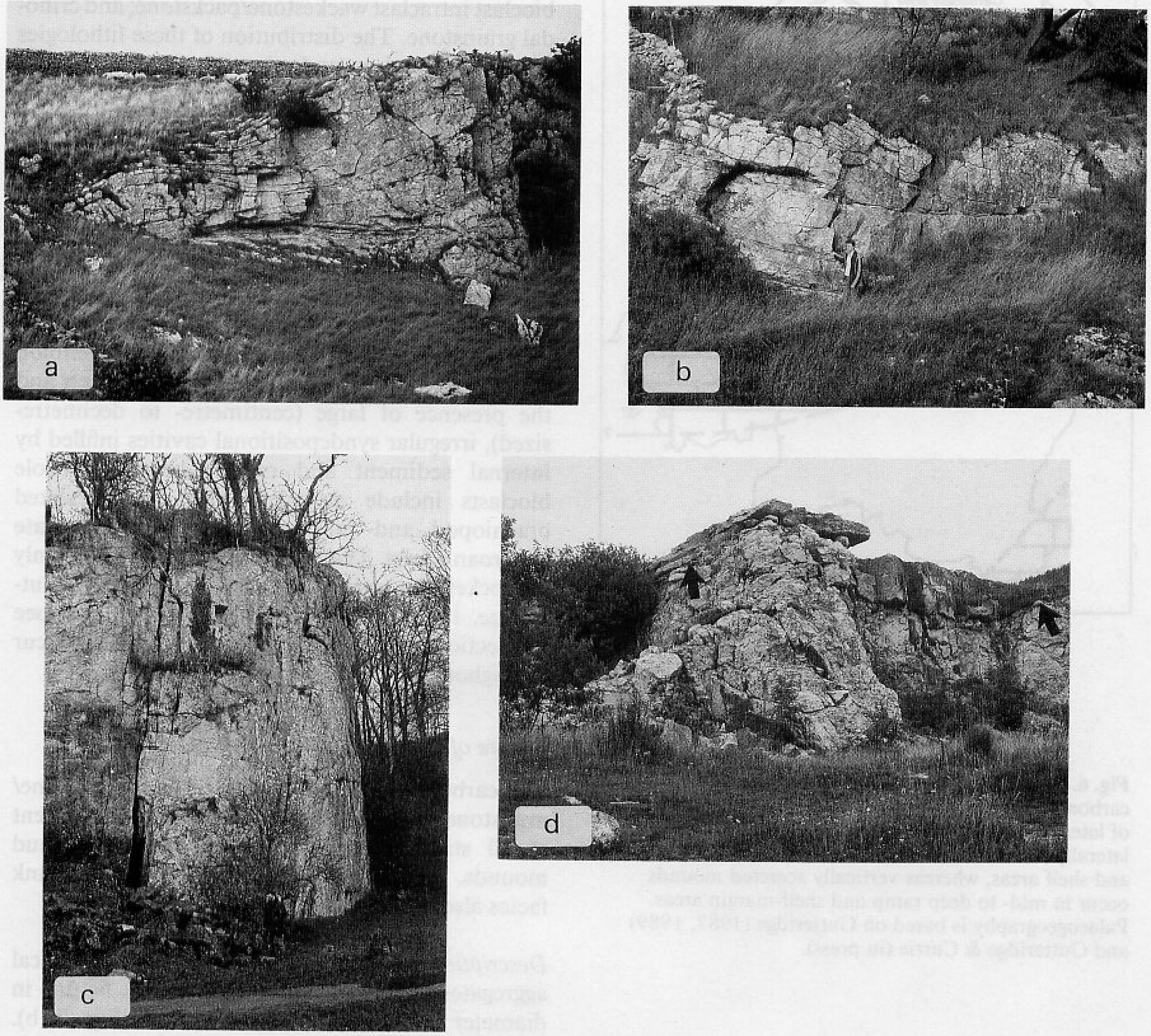

Fig. 5. (a) Laterally accreted mound (group 1) deposited in the shallow part of the intraplatform ramp. Mound-core facies, showing part of a laterally accreted carbonate mud-mound. The mainly unbedded mound core (right) passes left into the bedded mound-flank facies. Note the presence of a small tabular mound on the lower flank of the main mound core. Height of exposure is approximately 8 m. Locality 7 (Lathkill Dale). (b) Mound-flank facies of a group 1 mound. Bedding planes dipping to the right are mound-flank beds which dip away from a mound core to the left of the picture. Attitude of internal sediment within cavities shows that the dip is depositional in origin. The geometry of the mound flank shows that the mound was growing predominantly by lateral accretion with minimal vertical accretion. Height of the exposure is approximately 3 m. Locality 6 (Ricklow Dale). (c) Mound-core facies of a vertically accreted group 1 mound. Height of the exposure is approximately 15 m. The crest of the mound core is not exposed but it is at least 5 m higher than the top of the face, giving the mound a minimum relief of 20 m. Locality 11 (Rheinstor Rock, Alport). (d) Crest of the mound-core facies and overlying post-mound facies (contact arrowed) of a vertically accreted carbonate group 1 mound deposited at the southern margin of the Derbyshire carbonate platform. Height of the exposure is approximately 8 m. The total relief of the mound is approximately 30 m. Locality 16 (National Stone Centre, Wirksworth).

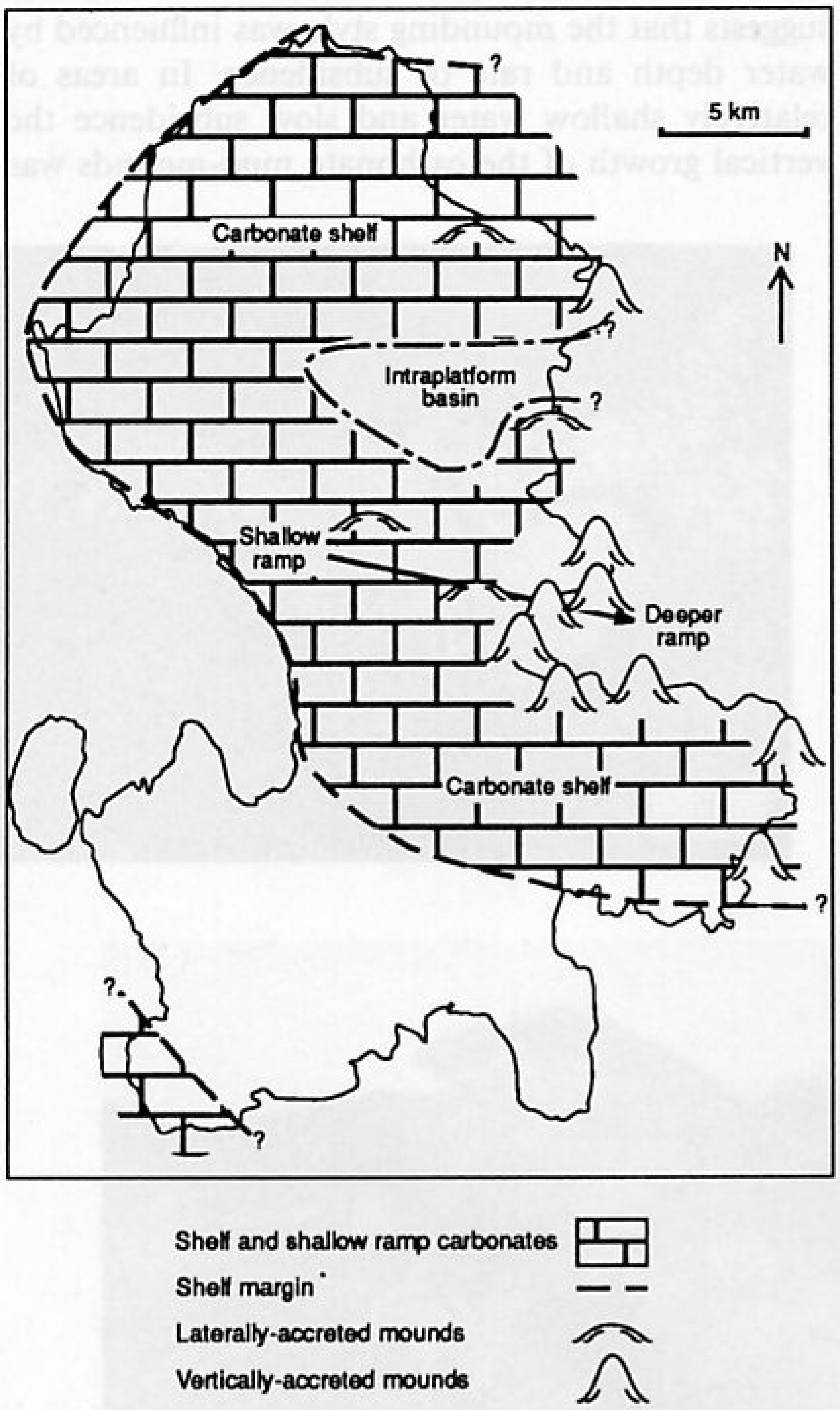

Fig. 6. Brigantian palaeogeography of the Derbyshire carbonate platform, showing the setting and distribution of laterally and vertically accreted mounds. Note that laterally accreted mounds in shelf occur in shallow-ramp and shelf areas, whereas vertically accreted mounds occur in mid- to deep ramp and shelf-margin areas. Palaeogeography is based on Gutteridge (1987, 1989) and Gutteridge & Currie (in press).

constrained by sea-level and they grew by lateral accretion; these mounds thus developed a low depositional relief of 10–15 m. In areas of higher subsidence near the shelf margins and in deeper water in the mid-ramp setting, vertical growth of the carbonate mud-mounds was less constrained, and they developed predominantly by vertical accretion; these carbonate mud-mounds were able to develop a much higher depositional relief of 20–30 m.

LITHOLOGY OF THE CARBONATE MUD-MOUNDS

Carbonate mud-mounds comprise the following three lithologies: bryozoan wackestone/mudstone; bioclast intraclast wackestone/packstone; and crinodal grainstone. The distribution of these lithologies within the mud-mounds depends on the stage of mud-mound growth and the mounding style.

Bryozoan wackestone/mudstone

This is an unbedded or poorly bedded wackestone grading to carbonate mudstone which forms the mound-core facies and the upper part of the mound-flank facies. It is distinguished from off-mound carbonate mud-rich lithologies by the distinctive texture of the carbonate mud, the common occurrence of intact fenestrate bryozoan sheets and the presence of large (centimetre- to decimetre-sized), irregular syndepositional cavities infilled by internal sediment and marine cement. Whole bioclasts include articulated and disarticulated brachiopod and mollusc valves and fenestrate bryozoan sheets. The 'shelly' bioclasts occur mainly in pocket-like concentrations (described by Gutteridge, 1990), outside of which they are rare (see the section on biota). Fenestrate bryozoans occur throughout the mound-core.

Nature of the carbonate mud

The carbonate mud of the bryozoan wackestone/mudstone displays three textures which are present at all stages of growth of the carbonate mud mounds. Intraclasts found in the mound-flank facies also contain these textures.

Description. Peloidal mud comprises spherical aggregates of micrite which are up to 50 µm in diameter set in a microspar matrix (Fig. 7a, b). Scanning electron microscopy (SEM) shows that these peloids have sharp edges and are surrounded by a matrix of microspar-sized calcite crystals. Under cathodoluminescence (CL) these peloids show a dull luminescence which contrasts with the brighter luminescence of the surrounding microspar.

Homogeneous micrite is a dense micrite with no internal structure discernible in peel or thin section. Under SEM it is a mosaic of equant micrite and microspar-sized calcite crystals. Under CL the

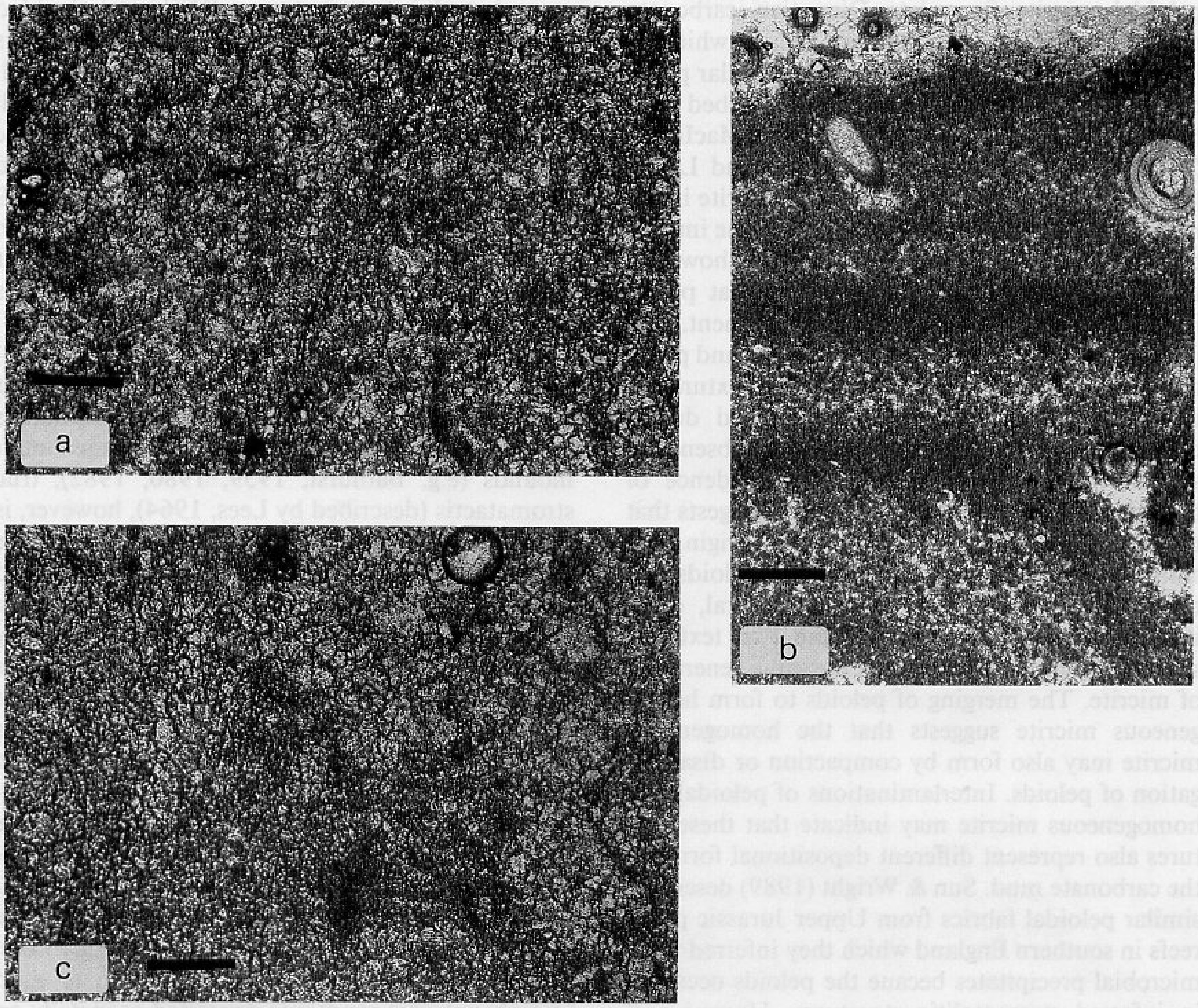

Fig. 7. Textures of the carbonate mud of the mound-core facies. Locality 6 (Ricklow Dale). (a) Peloidal micrite. Note the rounded aggregates of micrite set in a matrix of coarser calcite. Scale bar 50 μm. (b) Interbedded homogeneous and peloidal micrite. The packing density of the peloids increases towards the layers of homogeneous micrite and the peloids appear to merge. These layers are deformed around a compacted brachiopod. Scale bar 500 μm. (c) Transition between peloidal (right) and microspar (left) textures. Note that the peloids become progressively more dispersed within the microspar and irregular in shape. Peloids are much more irregularly shaped compared with those in (b). Scale bar 50 μm.

homogeneous micrite has a dull luminescence similar to that of the peloids in the peloidal micrite. Transitions from homogeneous to peloidal micrite show a progressive increase in packing density of peloids towards the homogeneous micrite. Peloids also tend to merge towards areas of homogeneous micrite. Homogeneous micrite is occasionally interlaminated with peloidal micrite in the matrix and as infills of intragranular porosity (Fig. 7b).

Microspar is texturally identical to the homogeneous micrite under SEM; the main difference is that it is composed of coarser microspar and pseudospar-sized calcite crystals (Fig. 7c). Under CL microspar shows an irregular mottled bright-dull luminescence. Boundaries between areas of peloidal and homogeneous micrite and microspar areas are transitional. In these transitional areas SEM shows that the larger microspar crystals cut across peloid margins.

Interpretation. The origin of the peloidal texture is problematical. Schwarzacher (1961) recorded peloidal micrite from late Dinantian carbonate mud-mounds from north-western Ireland which he interpreted as a depositional texture. Similar peloidal high-Mg calcite cement has been described from the internal cavities of recent reefs by MacIntyre (1977, 1985), Neumann *et al.* (1977) and Lighty (1985). The sheer volume of peloidal micrite in the matrix and the lack of any supporting frame implies that the peloids did not form as a cement; however, this does not rule out the possibility that peloid infills of intragranular pores may be cement. The presence of interlaminated homogeneous and peloidal micrite and the presence of these textures in intraclasts indicates that they originated during deposition or very early diagenesis. The absence of any burrowing macrofauna or any evidence of bioturbation in the mound-core facies suggests that these peloids are probably not of faecal origin. The similar luminescence properties of the peloids and the homogeneous micrite, and the lateral, often indistinct, transitions between the two textures, suggest that they may represent the same generation of micrite. The merging of peloids to form homogeneous micrite suggests that the homogeneous micrite may also form by compaction or disaggregation of peloids. Interlaminations of peloidal and homogeneous micrite may indicate that these textures also represent different depositional forms of the carbonate mud. Sun & Wright (1989) described similar peloidal fabrics from Upper Jurassic patch reefs in southern England which they inferred to be microbial precipitates becaue the peloids occurred in inferred stromatolitic structures. Unequivocal stromatolitic structures have not been found in the late Dinantian carbonate mud-mounds described here but it is possible that the peloids may have a similar microbially mediated origin. The microspar texture is interpreted as a later recrystallization of pre-existing micrite.

Syndepositional cavities

Marine cements. Some intraparticle pores and stromatactoid cavities (described below) are lined by an isopachous fringe of radiaxial fibrous calcite (RFC), as defined by Bathurst (1959) (Fig. 8a). This is interpreted as a marine cement because intraclasts of RFC are present in the mound-core and mound-flank facies; RFC is present within intraclasts; some of the cavities in which RFC occurs have been truncated by marine erosion (Gutteridge, 1990); RFC pre-dates vadose diagenesis of group 1 mounds and, in rare instances, RFC is interbedded with layers of peloidal carbonate mud. The RFC is interpreted as a direct marine precipitate (Kendall, 1985), rather than a recrystallized cement (Kendall & Tucker, 1973). The presence of microdolomite inclusions and increased levels of Mg compared with the surrounding carbonate mud (average 0.99 mol% $MgCO_3$ in the RFC; 0.52 mol% $MgCO_3$ in the carbonate mud matrix) and the lack of acicular aragonite relics seen in SEM suggests that this was originally a high-Mg calcite cement.

Stromatactoid cavities (Fig. 9). These are irregular anastomosing cavities which resemble stromatactis cavities described from other carbonate mud-mounds (e.g. Bathurst, 1959, 1980, 1982); true stromatactis (described by Lees, 1964), however, is absent. Sheet-spar described by Ross *et al.* (1975) is also absent. These stromatactoid cavities extend laterally for several centimetres and are up to 1 cm in height. The amount of syndepositional porosity (including that now infilled by cement) in these mound cores is much less (45%, measured by point counting) than in other carbonate mud-mounds (e.g. 60% recorded from Asbian mud-mounds in north-west Ireland by Schwarzacher, 1961, significantly less than many Waulsortian mounds). The distribution of these syndepositional cavities appears to be random, with no apparent preferential concentration along bedding planes seen in more complex Waulsortian mud-mounds (e.g. Lees, 1964). In the many cavities, a carbonate mud (mainly peloidal mud) was deposited geopetally on the relatively flat base of the cavity before the precipitation of RFC. This single generation of internal sediment was followed by a single layer of RFC. Multiple layers of interbedded RFC and internal sediment are rare in these mud-mounds, and the multiple generations of internal sediment ('polymud') are not developed (cf. Lees 1964; Lees & Miller 1985).

The ceiling of the cavities is complex, often showing a digitate morphology and often appearing to be either unsupported or partly supported by a bioclast such a fenestrate bryozoan sheet (Fig. 9a) or a brachiopod valve (Fig. 9b). In cases where a cavity is supported by a fenestrate bryozoan sheet, the micrite above the gaps between the zooecia often shows a scalloped appearance with semi-circular concave-upwards embayments up to 200 μm across (Fig. 8b). In other cavities micrite pillars 'connect' the zooecia to the cavity ceiling and the bryozoan

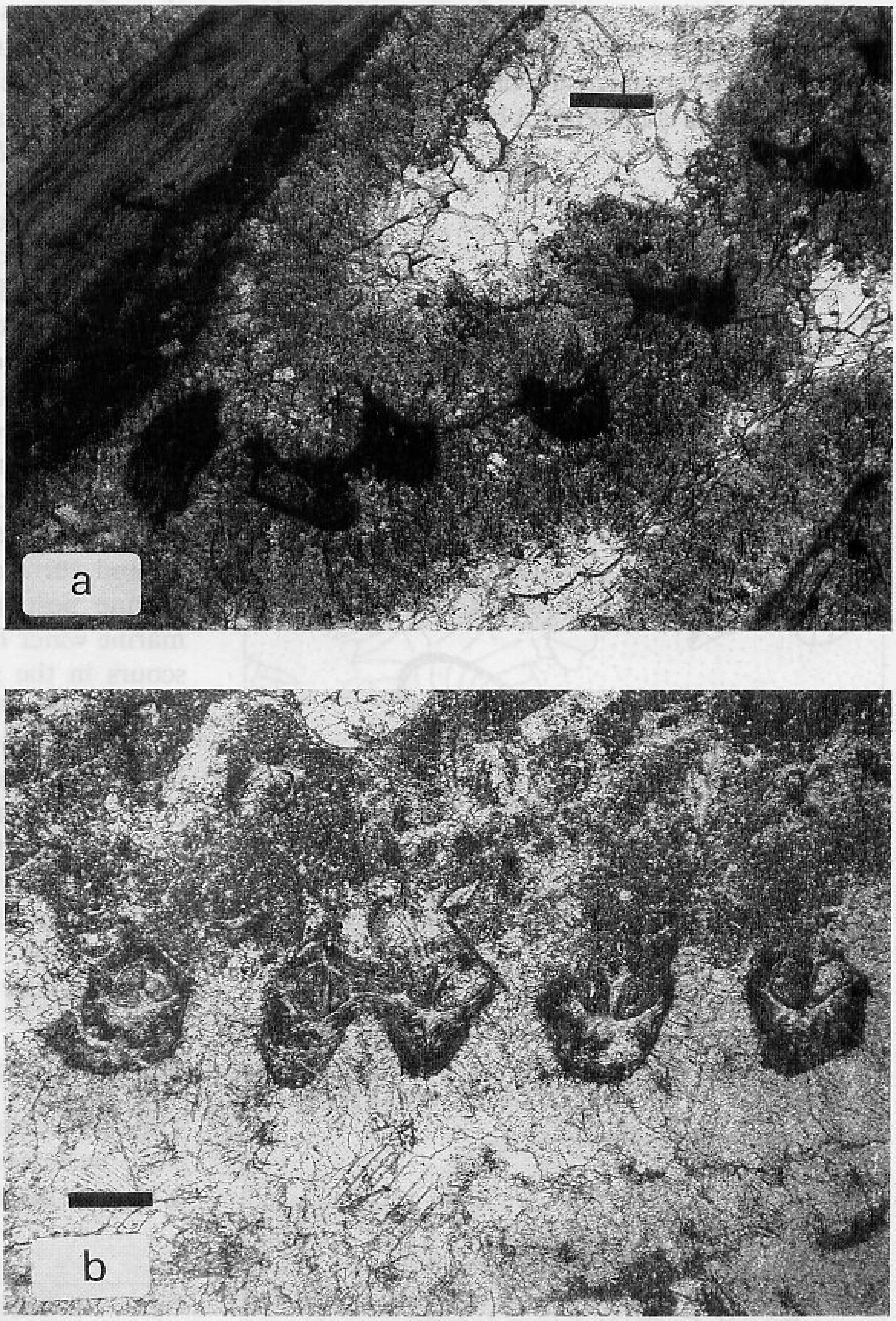

Fig. 8. Marine cement and syndepositional cavities in the mound-core facies. Locality 6 (Ricklow Dale). Scale bars 0.5 mm. (a) Isopachous fringe of RFC surrounding a fenestrate bryozoan sheet. (b) Partially supported cavity by fenestrate bryozoan sheet. Note that the roof appears to have collapsed through the gaps between the zooecia.

sheet is apparently suspended across the middle of a cavity with no connection either to the cavity ceiling or floor (Fig. 9a). In cases where the cavity ceiling is supported by a brachiopod valve, there is no scalloping of the micrite; however, the micrite has often been apparently removed around the margins of the valve forming downward-projecting micrite pendants (Fig. 9b).

These cavities are inferred to have developed in a dynamic system and their final form is produced by the competing processes of internal erosion or collapse of surrounding sediment, precipitation of marine cements on the cavity walls and the progressive lithification of the surrounding carbonate mud (cf. Wallace, 1987). The upward scalloping of the ceiling between bryozoan zooecia is interpreted as the result of the collapse or erosion of the unsupported micrite above the bryozoan sheet. If taken to completion, this process would produce the isolated pillars of micrite which connect the bryozoan sheet to the main body of micrite above, and eventually, with the complete removal of the micrite, the bryozoan sheet would be suspended across the middle of the cavity. Cavities 'sheltered' by brachiopod valves show no evidence of collapse or erosion and it is inferred that the valves protected the micrite from internal erosion or collapse. The origin of these cavities is not known but it is possible that shear fractures opened in the semi-lithified carbonate mud as a result of gravitational instability induced by the mound slope may have produced an early cavity system (e.g. Schwarzacher, 1961; Lees, 1964; Bridges & Chapman, 1988). It is also possible that they originated as shelter cavities which were supported by fenestrate bryozoan sheets and brachiopod valves and were modified by internal erosion and collapse. This may imply that the micrite may have been initially cohesive so that it could have been supported by a bryozoan sheet. The micrite may have subsequently lost this cohesion so that it could be eroded or collapse through the holes in the bryozoan sheet.

The presence of marine cement within these cavities implies that they were connected to the mound surface and had an active circulation of marine pore-water through them. The input of marine water may have been through the erosional scours in the surface of the mound described by Gutteridge (1990). It is also possible that circulating water may have contributed to the collapse and internal erosion of the carbonate mud. The precipitation of marine cement within the cavities and the lithification of the surrounding carbonate mud would have eventually stabilized the cavities. The relationship between the development of the cavities and the nature of the mound substrate is discussed later in this paper.

Bioclast intraclast wackestone/packstone

This is a bioclast wackestone with minor packstone with well-developed bedding between 0.2 and 0.75 m in thickness. Bioclasts present include bryo-

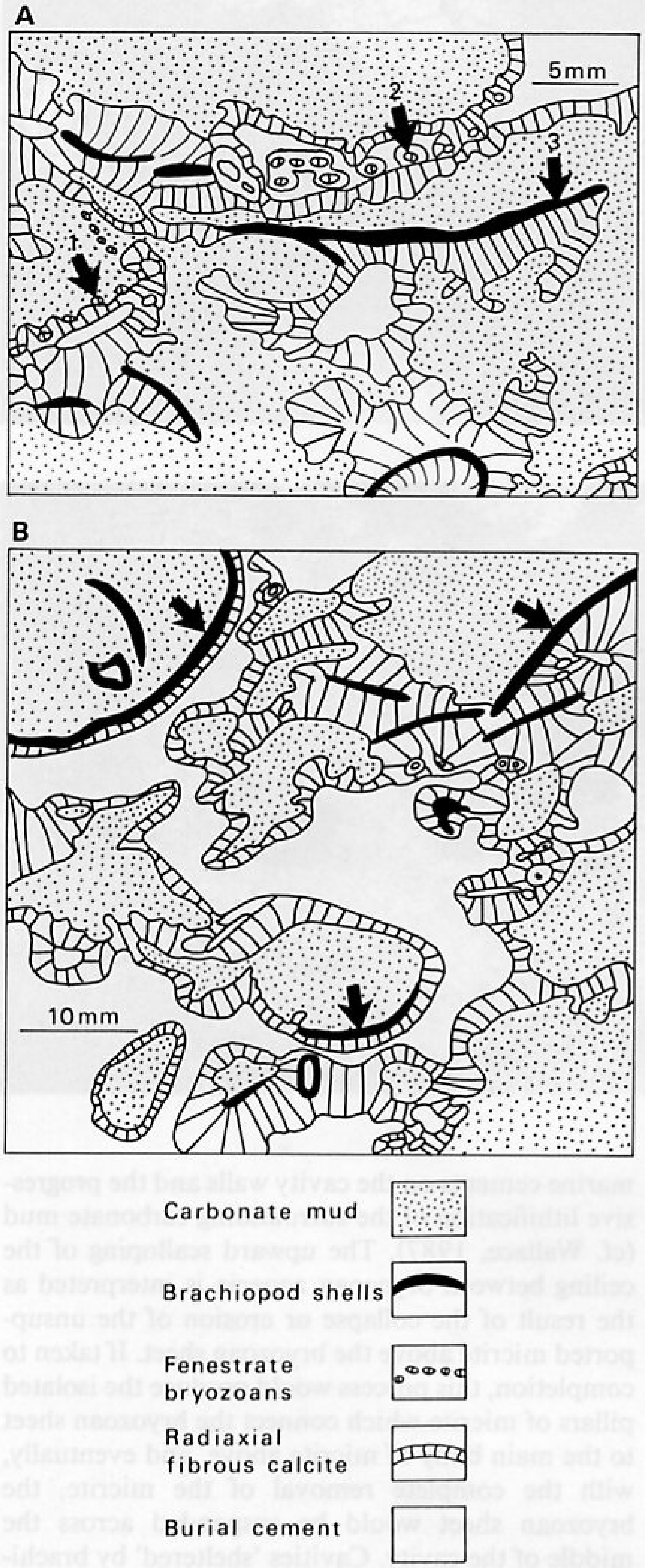

Fig. 9. (*Left*) Syndepositional cavities in the mound-core facies. Note that no syndepositional internal sediment is present. Both figures are drawn from acetate peels. Locality 6 (Ricklow Dale). (A) Cavity in mound core. Cavities associated with fenetrate bryozoan sheets. Note that the ceiling of the cavity shows a variety of complex digitate forms. These range from the ceiling apparently supported by the bryozoan sheet (1) to a bryozoan sheet apparently suspended across the centre of a cavity (2). Compare the shapes of these cavities with cavities supported by brachiopod valves (below). (B) Cavity in mound core. Cavities associated with brachiopod valves (arrowed). Note that the ceiling of parts of these cavity are 'supported' by brachiopod valves. Complex scalloping of the cavity ceiling is absent (cf. Fig. 8b) and the micrite appears to have been removed from around the margins of the valve forming convex-downward projections in the cavity roof.

zoans, brachiopods, crinoid ossicles and plates. These are mainly whole and disarticulated, but there is no evidence of reworking as there is little abrasion and fragmentation; there thus appears to have been minimal transportation. Locally derived intraclasts composed of peloidal wackestone identical to that of the mound-core facies are also present; these are often rounded and show signs of disaggregation, indicating that they were partly consolidated at the time of sedimentation.

This lithology is present in the mound-flank facies of laterally accreted mounds (Fig. 5b). The attitude of partial geopetal infills of internal cavities of crinoid stems and articulated brachiopods shows that the dip away from the associated mound core is depositional in origin (Fig. 10a). The transition from the mound flank to the mound-core facies is marked by a loss of distinct bedding planes towards the mound core (Fig. 5a). The transition from the mound-flank to the intermound facies is marked by a progressive change to a thinly bedded bioclast intraclast crinoidal packstone towards the inter-

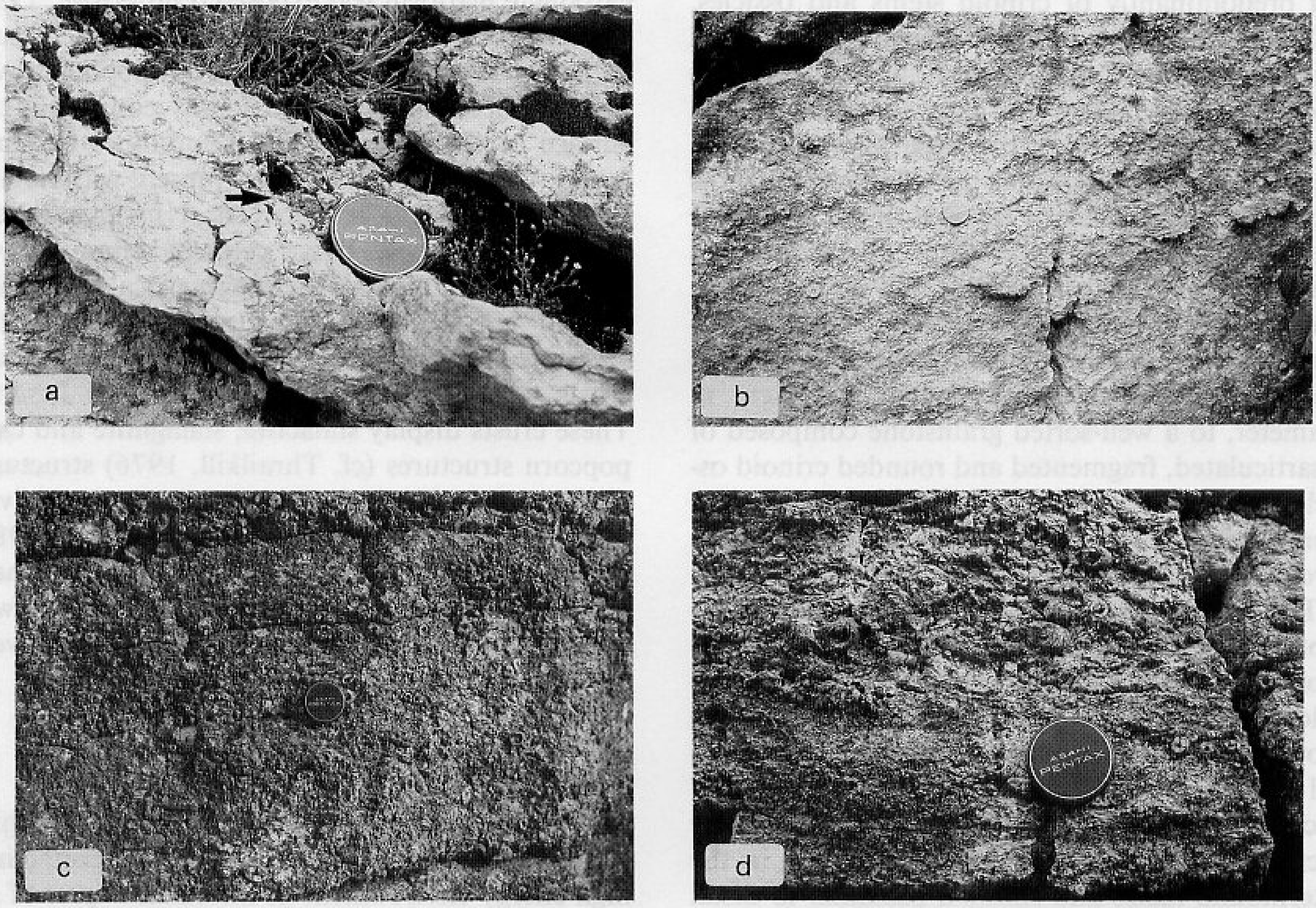

Fig. 10. (a) Mound-flank facies of a laterally accreted group 1 mound. This shows the upper part of the mound-flank facies in a laterally accreted mound. This is a thickly bedded bioclast wackestone. The attitude of a geopetal infill of the visceral cavity of a brachiopod (arrowed) shows that the dip (approximately 20° to the right) is depositional in origin. Locality 7 (Lathkill Dale). (b) Mound-flank facies of a vertically accreted mound (group 1). This is a poorly-sorted crinoid grainstone which dips some 25° to the left. Geopetal infills show that this dip is depositional in origin. Locality 16 (National Stone Centre, Wirksworth). Lens cap is 5 cm in diameter. (c) Intermound facies of a laterally accreted mound (group 1). This is a flat-bedded crinoidal grainstone similar to that of the mound-flank facies shown in (b). The majority of the crinoid stems are articulated in lengths of up to 30 cm. Flat-bedded crinoid grainstone with abundant large articulated crinoid stems. Locality 7 (Lathkill Dale). Lens cap is 5 cm in diameter. (d) Intermound facies of a laterally accreted mound (group 1), same carbonate mud-mound as (c) but in a more distal position with respect to the mound-core facies. The intermound facies consists of beds comprising well-sorted crinoid grainstone, which occasionally show cross-bedding (lower part of photograph), interbedded with poorly sorted crinoid grainstone as in (c), (upper part of photograph). These indicate a progressively higher-energy environment away from the mound-core facies. Locality 6 (Ricklow Dale). Lens cap is 5 cm in diameter.

mound facies. The amount of depositional dip decreases towards the intermound facies (Fig. 5b).

This lithology also occurs in the intermound facies of tabular and domical mounds. In this case it is medium-bedded and there is no evidence of any depositional dip. The bioclasts show more evidence of disarticulation and abrasion, indicating deposition in a low- to moderate-energy environment, probably close to normal wave base.

Crinoidal grainstone

This is a bioclast grainstone which shows bedding between 0.1 m and 0.3 m in thickness and consisting predominantly of crinoid stems and ossicles. Other bioclasts are rare and include brachiopod (mainly productid) valves and spines, fenestrate and ramose bryozoans and occasional rugose and parasitic tabulate corals; the latter encrust crinoid stems. Rounded wackestone intraclasts which show none of the characteristic textures of the carbonate mud found in the mound cores may have been derived from the surrounding off-mound areas. This lithology varies from a poorly sorted grainstone which contains abundant articulated crinoid stems up to 0.2–0.25 m in length and 3 cm in diameter, to a well-sorted grainstone composed of disarticulated, fragmented and rounded crinoid ossicles. The preservation of large articulated crinoid stems implies a generally low-energy (possibly sheltered) environment with little reworking.

The crinoid grainstone is not associated with tabular mound cores but only appears in the intermound area when domical mound cores have developed (Fig. 3). In vertically accreted mounds the mound-flank facies consists of poorly sorted crinoidal grainstone and not the bioclast wackestone/packstone described above (Fig. 10b). In laterally accreted mounds, this lithology is present in the intermound facies and shows a proximal to distal variation with respect to the mound core: closest to the mound core, the intermound facies consists of poorly sorted crinoid grainstone with abundant large articulated crinoid stems (Fig. 10c); in a more distal setting, away from the mound core, the crinoidal grainstone becomes better sorted and small-scale cross-stratification appears (Fig. 10d). This suggests that the carbonate mud-mounds grew in a generally high-energy environment, probably above normal wave base. The apparently low-energy conditions in which the poorly sorted crinoid grainstone was deposited may be a result of the sheltering effect of a crinoidal 'thicket' which surrounded these carbonate mud-mounds.

The distribution of the crinoidal grainstone suggests that the mound-core facies of laterally and vertically accreted mounds were surrounded by a crinoidal 'thicket'.

Lithologies overlying the carbonate mud-mounds

Group 1 mounds

Group 1 mounds are separated from the overlying Eyam Limestones by an emergence surface which represents a period when much of the Derbyshire carbonate platform was exposed (Gutteridge, 1991; Gutteridge & Currie, in press). Evidence of subaerial exposure includes calcrete development over their surface and over the laterally equivalent top surface of the Monsal Dale Limestones (Adams, 1980). Vadose cements are also present within relict marine pores and in subvertical fissures in the mound-core facies. These cements often show a pendant morphology or an asymmetrical thickening around pores which indicates formation in the vadose zone. They also occur as thick speleothem crusts which line the base and sides of fissures. These crusts display stalactite, stalagmite and cave popcorn structures (cf. Thrailkill, 1976) structures and contain reworked calcrete intraclasts derived from the overlying calcrete profile (Adams, 1980; Gutteridge, 1983). The speleothems within these fissures are overlain by marine sediment which was deposited when the carbonate mud-mounds were reflooded.

Group 2 Mounds

These carbonate mud-mounds occur within a bioclastic sand-body complex which was deposited in a high-energy environment at the shallow part of an intraplatform ramp (Gutteridge & Currie, in press). They contain no evidence of subaerial exposure. The upper surfaces of these carbonate mud-mounds are marked by broken and reworked bioclasts, together with brachiopod spines which presumably have been exhumed by erosion (Fig. 4a). These features suggest that the demise of carbonate mud-mounds in this setting may have been caused by a series of high-energy erosive events which caused severe scouring of the mound surface.

FRACTURING IN THE MOUND CORE

The mound core is cut by fractures which show evidence of formation at varying stages of lithification of the carbonate mud. Three types of fractures have been recognized.

Type 1 fractures. These are up to 2 mm in width, have no preferential alignment and are often branched or anastomosing. The fracture walls are highly irregular and opposing walls show a very poor geometric fit. Bioclasts occasionally protrude into the fracture and in some cases the fracture appears to have formed around a bioclast. Internal sediment is often present as a geopetal infill. Type 1 fractures are sometimes preferentially developed in layers of peloidal micrite. Their ragged edges and partial infill by internal sediment suggest that the walls were subject to erosion and prone to collapse. These fractures formed in soft, semi-cohesive sediments.

Type 2 fractures. These are up to 1 mm in width are subvertical in attitude. They are occasionally branched, forming a locally developed 'exploded jigsaw' texture. The edges of fractures are rounded but show a moderate to good geometric fit of opposing walls. Fracturing occurs preferentially around bioclasts, although some fractures cut bioclasts. Internal sediment is rare and consists of intraclasts derived by roof collapse. Type 2 fractures both cross-cut and pass into type 1 fractures. The preferential parting of the carbonate mud around bioclasts seen in type 1 and 2 fractures suggests that the carbonate mud was able to tear around bioclasts implying that these fractures formed in a semi-lithified but cohesive mud. The better geometric fit of walls of type 2 fractures and the scarcity of internal sediment suggests that type 2 fractures formed in more cohesive (but not fully lithified) sediment. This may indicate formation either at a deeper level in the sediment or during a later stage of diagenesis than type 1 fractures.

Type 3 fractures. These fractures range in width from 3 mm to hairline (detectable under CL by their infill of brightly luminescent calcite). They have a subvertical attitude. The edges of the fractures are angular and show a very good geometric fit with opposing walls. Type 3 fractures cut across carbonate mud, bioclasts, both early and late cements and type 1 and 2 fractures. These fractures contain brightly luminescent cement which formed during burial, and are also found in other facies of the Monsal Dale and Eyam Limestone Formations (Gutteridge, 1983). They formed at a late stage of diagenesis in fully lithified sediment and are interpreted as tectonic fractures.

Shinn *et al.* (1983) described *in situ* brecciation, similar to type 2 fractures, from a Permian phylloid algal mound. They suggested that this brecciation orginated by differential compaction of the partly cemented carbonate mud matrix which contains shelter cavities formed around phylloid algae. This process may be relevant to explaining some of the fractures in carbonate mud-mounds as shelter cavities may have formed around fenestrate bryozoans and brachiopod valves in a similar way to the phylloid algae. Miller (1986) and Bridges & Chapman (1988) recorded fracture systems similar to the type 1 and 2 fractures described here from carbonate mud-mounds in Ireland and northern England, respectively. Miller (1986) and Bridges & Chapman (1988) both inferred a semi-consolidated gel-like consistency of the carbonate mud during deposition, together with a progressive downward increase in the degree of lithification.

BIOTA

Detailed faunal lists from these carbonate mud-mounds can be found in Biggins (1969), Stevenson & Gaunt (1971), Timms (1978), Gutteridge (1983, 1990), Aitkenhead *et al.* (1985), Tilsley (1988) and Brunton & Tisley (1991). Figure 11 shows the relative abundance of the main taxonomic groups and their distribution through the facies of these carbonate mud-mounds. There is no evidence of any depth-related faunal zonation similar to that found by Mundy (1980) in carbonate mud-mounds of the same age associated with the southern margin of the Askrigg Block in North Yorkshire. This may be because the carbonate mud mounds described here were comparatively low-relief structures deposited in relatively shallow-water platform-top settings.

Brachiopods and molluscs

The occurrence and palaeoecology of brachiopods and molluscs has been discussed by Gutteridge (1990). In mound cores within laterally and vertically accreted mound complexes the brachiopod and mollusc fauna occurs in isolated pockets sur-

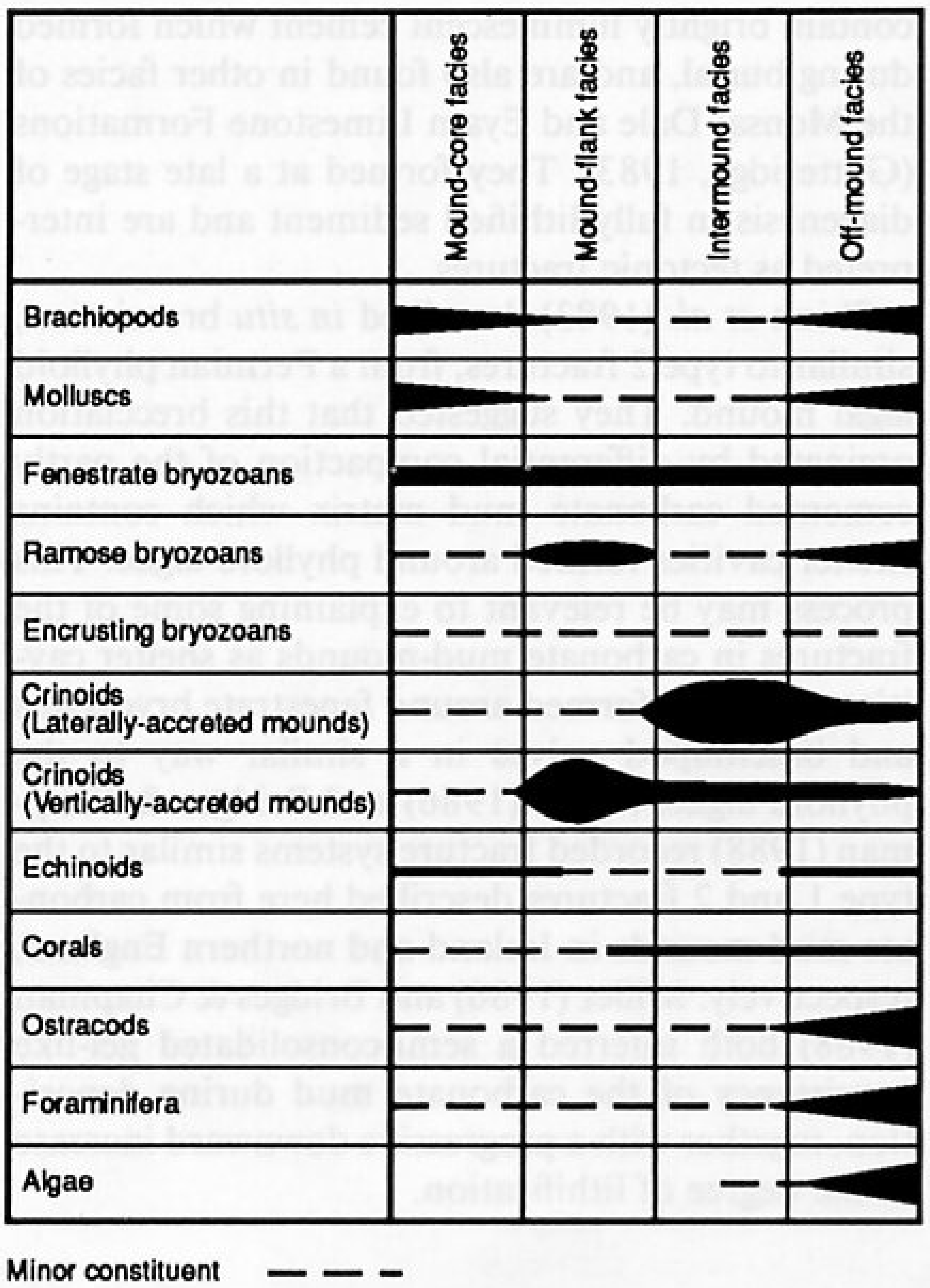

Fig. 11. Relative abundance and distribution of the major taxonomic groups within carbonate mud mounds.

rounded by mound-core facies virtually barren of macrofauna (Fig. 12). These pockets are interpreted as erosional hollows in the depositional surface of the mound core which were colonized in preference to surrounding areas. The substrate relationships of the shelly fauna show that it comprises mainly forms adapted to live on a soft, semi-consolidated substrate (Gutteridge 1990, Fig. 6).

Bryozoans

Fenestrate bryozoans are found throughout the carbonate mud-mounds. Within the mound-core facies they are preserved mainly as intact fans and sheets with minor breakage and abrasion, whereas they occur as reworked fragments in other facies. Ramose bryozoans are most abundant in the mound-flank facies and are mainly fragmented. Encrusting bryozoans have been found in all facies, but are rare; where they are preserved in life position they invariably encrust bioclasts such as brachiopod valves. The scarcity of encrusting bryozoans may reflect the lack of hard substrates.

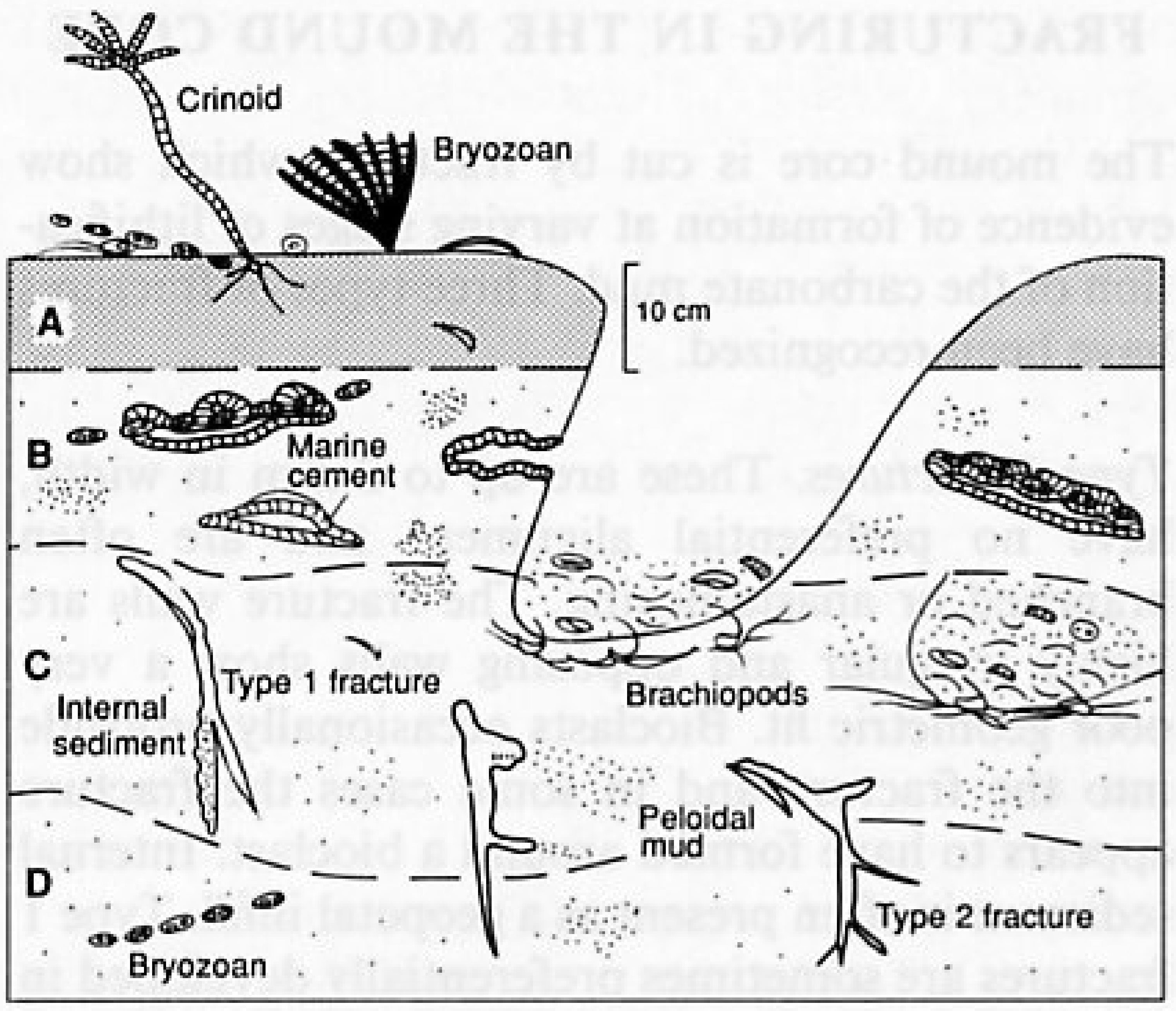

Fig. 12. Interpretation of the carbonate mud-mound substrate. (A) Surficial binding, probably a microbial mat which binds the top few centimetres. The lower surface of the mat represents the depth at which it dies as a result of burial. Carbonate mud may be produced within this microbial mat. (B) Semi-consolidated carbonate mud immediately below the microbial mat. The majority of internal erosion and marine cementation takes place in this zone. (C) Consolidated but unlithified carbonate mud. This forms a soft substrate where it is exposed at the base of erosional hollows. There is a limited amount of internal erosion and marine cementation. Type 1 fractures form in this zone. (D) Downward increase in the degree of consolidation and lithification in the mud-mound. There is no internal erosion or marine cementation. Type 2 fractures form in this zone.

Echinoderms

Crinoids are found in all facies. Rare articulated stems and calices have been found in the mound core. The occurrence of crinoids in the mound-flank and intermound facies varies according to mounding style and has been described above. It appears that both laterally and vertically accreted mounds were surrounded by a dense crinoidal 'thicket'. Echinoid spines and plates are occasionally found within the mound core.

Corals

In common with other Dinantian carbonate mud-mounds the coral fauna is very sparse compared with off-mound facies. *Lithostrotion* and *Siphonodendron* are present in the mound cores. *Hexaphyllia, Dibunophyllum, Lithostrotion, Siphonodendron, Diphyphyllum* and *Orionasteria* have been found in the mound-flank and intermound facies, and the tabulate coral *Emmonsia* occurs in the intermound facies where it encrusts crinoid stems and brachiopod spines.

Other groups

Ostracodes are rare in all mound facies. They have been found in group 1 mounds where they are preserved in fissures which formed during subaerial exposure of the carbonate mud-mounds (see above). The ostracodes colonized these fissures when the carbonate mud-mounds were reflooded after the period of emergence.

Foraminifera are rare in comparison with off-mound facies. Those present include archaediscids, endothyrids and occasional tetrataxids.

Other very rare members of the biota include trilobites, sponge spicules, *Chaetetes* and ?*Aphralysia*. These have not been preserved *in situ*.

Skeletal algae and micritized grains have not been found in these carbonate mud mounds. This is in marked contrast to the off-mound facies of the Eyam and Monsal Dale Limestones which contain green, ?dasycladacean, red algae and calcispheres as well as abundant micritized grains.

DISCUSSION

Controls on mud-mound growth

The palaeogeographical setting and associated sediments indicate that these carbonate mud-mounds grew in a shallow subtidal setting probably above normal wave base in the majority of cases. The mechanism and controls on nucleation are not known. Tabular mound cores developed by accretion and amalgamation into large but fewer domical mounds. The subsequent growth of the mounds was controlled by the depositional setting (see Figs 3 & 6).

The trapping of detrital carbonate mud as a mechanism of mound growth is not sustained by these carbonate mud-mounds. The texturally distinctive carbonate mud is restricted to the mound cores and the upper parts of the mound-flank facies and is not present in the off-mound facies. There is also no recognizable detrital sediment of external origin in the mound-core facies. The symmetrical morphology of mound cores and distribution of associated facies also argue against trapping of detrital carbonate mud supplied by an external current. Since crinoids did not colonize the intermound and mound-flank areas until the mound cores developed significant relief, crinoids appear to have played no role in the nucleation of these mud-mounds (cf. Wilson, 1975, Fig. V-15). Fenestrate bryozoans have also been cited as contributing to baffling carbonate mud and supporting the steep depositional slopes (e.g. Pray, 1958). The occurrence of fenestrate bryozoans in the Brigantian carbonate mud-mounds described here supports the conclusions of Schwarzacher (1961), Troell (1962), Cotter (1965) and Miller & Grayson (1972) who also suggested that it is unlikely that fenestrate bryozoans played any role in trapping carbonate mud or stabilization of depositional slopes. Evidence from these Brigantian carbonate mud-mounds supports the presence of an *in situ* producer of carbonate mud on the mound cores.

Origin of the carbonate mud and nature of the substrate

The following lines of evidence suggest that there was some form of binding of the surface of the mound core: mound cores often have steep depositional slopes; the carbonate mud could support steep-sided erosional scours in the surface of the mound cores (Gutteridge, 1990); the carbonate mud of the mound core was deposited in a predominantly high-energy environment which implies some degree of protection from erosion; and there is no evidence of bioturbation in the mound core. A wide range of possible candidates have been suggested to fulfil the role of sediment binder. A seagrass-like plant which presumably occupied a similar niche to *Thalassia* in recent carbonate environments has been suggested by Lees (1964) and Gutteridge (1983). It now seems unlikely as the carbonate mud-banks stabilized by *Thalassia* are almost entirely detrital accumulations of carbonate mud with none of the complex internal cavities, cements and sediment types present in these types of carbonate mud-mounds (Turmel & Swanson, 1976; Bosence *et al.*, 1985; Tedesco & Wanless, this volume). It is, however, possible that certain types of carbonate mud-mound formed in this way (e.g. Petta & Gehard, 1977; Brown & Dodd, 1990;

Tedesco & Wanless, this volume). Bourque & Gignac (1983) suggested that sponges were responsible for the binding and stabilization of carbonate mud-mounds with the peloidal carbonate mud texture inferred to be a diagenetic alteration of the sponges (cf. Pratt, 1986; Bourque & Gignac, 1986). Sponge spicules, however, are an insignificant component of the mound cores described here, and no *in situ* sponges have been found. It is unlikely that sponges were abundant enough to constitute a framework. A stromatolitic framework formed by an algal-bacterial community was suggested by Pratt (1982) to have stabilized the surface of carbonate mud mounds. In this model, detrital carbonate mud was trapped by the stromatolitic mat. The trapping of detrital sediment has been ruled out of the carbonate mud mounds described here. Miller & Grayson (1972), Lees & Miller (1985), Miller (1986), Bridges & Chapman (1988), Kelly & Somerville (1992), Pickard *et al.* (1992) and Somerville *et al.* (1992) have also suggested some form of microbial sediment binder.

A feature of these carbonate mud-mounds is the absence of skeletal algae and micritization of grains and substrates. This is suprising in view of the common occurrence of skeletal algae and micritized grains in the off-mound facies and the occurrence of these features and allochems in the shallowest depth phase (Phase D) of the Waulsortian (Lees *et al.*, 1985; Lees & Miller, 1985). Algae may have been present either as non-calcified forms or not preserved—e.g. *Penicillus* disaggregates completely to produce aragonite mud (Stockman *et al.*, 1967). In the latter case, such an alga would have contributed to carbonate mud production.

Figure 12 shows a schematic cross-section through the uppermost metre or so of a mound core showing the inferred nature of the substrate and state of lithification of carbonate mud. It is envisaged that the surface of the mound core was bound by some type of mat-like community (possibly of microbial origin). This mat grew at the surface and died when it was buried to a shallow depth of the order of several centimetres. The carbonate mud may have originated as a microbially mediated precipitate formed within the surficial binding. The distribution of mud production over the surface of the mound core may have been similar to the many point sources scattered over the mound surface envisaged by Jackson & DeKeyser (1984a,b) and Bridges & Chapman (1988). In the topmost few centimetres the sediment is bound by the surficial binding and can support the steep slopes, erosional scours and shelter cavities.

As sediment is buried through the dying front of the surficial binding it becomes semi-consolidated, and internal erosion and collapse of sediment around shelter cavities commence. Gutteridge (1990) showed that the substrate relationships of the brachiopod and bivalve fauna in the mound-core facies indicated a soft substrate within the erosional scours. These erosional hollows are inferred to have breached the surficial binding to expose the underlying semi-consolidated sediment which was a suitable substrate for the shelly macrofauna (see Fig. 12). The presence of the macrofauna would also armour the sediment within these hollows. The erosional hollows are gradually infilled by the deposition of bioclastic sediment and the encroachment of carbonate mud production from surrounding areas. Some syndepositional cavities were also breached by the erosional hollows which allows input of marine pore-water and circulation within the immediate subsurface resulting in internal erosion and the precipitation of marine cement. These cavity systems were gradually stabilized by the precipitation of marine cements on the cavity walls and the progressive lithification of the surrounding carbonate mud.

As the sediment undergoes further burial, it becomes progressively consolidated by compaction and lithified by precipitation of cement (e.g. Cowan 1982). Fracturing, possibly induced by slope instability takes place at this stage with the morphology of these fractures reflecting the state of lithification of the carbonate mud. These fractures are not connected to the surface, do not have any active pore-fluid circulation and, in consequence, contain no marine cement. Miller (1986) and Bridges & Chapman (1988) envisaged a similar progressive downward consolidation of carbonate mud.

Comparisons with Waulsortian carbonate mud-mounds

There are important differences in the depositional setting and internal complexity between the Brigantian carbonate mud-mounds described here and Waulsortian carbonate mud-mounds as defined by Lees (1988). The system of syndepositional cavities in Waulsortian mud-mounds appears to be much more extensive and their sequence of infill by internal sediments and marine cements is much more complex than in these Brigantian carbonate mud-mounds. In addition, Lees *et al.* (1985) and Lees & Miller (1985) recognized a depth-related microfacies zonation of Waulsortian carbonate mud-mounds from which they were able to estimate their depth of deposition. A detailed study of the microfacies of the late Dinantian carbonate mud-mounds using the methodology of Hennebert & Lees (1985) and Lees *et al.* (1985) has not been done, but a similar range of microfacies does not appear to be present in these Brigantian carbonate mud-mounds, which may reflect the narrow range of their depth of deposition in platform-top settings.

From descriptions of carbonate mud-mounds of various ages by Kelly (1989), Bridges *et al.* (this volume), Kelly & Somerville (1992), Pickard *et al.* (1992) and Somerville *et al.* (1992), it is apparent that a continuous spectrum of carbonate mud-mound types ranging from strictly Waulsortian to types resembling the Brigantian mud-mounds described in this paper are present. There appears to be no strict stratigraphical limit on the different mound types, e.g. Kelly (1989) described Asbian mounds from north-west Ireland which resemble Waulsortian carbonate mud-mounds. The Brigantian carbonate mud-mounds described here resemble Viséan buildups from north Co. Dublin described by Somerville *et al.* (1992). Five major buildup types have been recognized in the Lower Carboniferous by Bridges *et al.* (this volume). The mud-mounds described here are crinoid–brachiopod–fenestrate bryozoan buildups (type 3 buildups) which form part of a continuous spectrum ranging from mud-mounds (including the Waulsortian) to buildups having a poorly developed skeletal framework (Bridges *et al.*, this volume, Fig. 4).

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REFERENCES

Adams, A.E. (1980) Calcrete profiles in the Eyam Limestones (Carboniferous) of Derbyshire: Petrology and regional significance, *Sedimentology*, **27**, 651–660.

Aitkenhead, N. & Chisholm, J.I. (1982) A standard nomenclature for the Dinantian formations of the Peak District of Derbyshire and Staffordshire. *Inst. Geol. Sci. Rep.*, **82/8**.

Aitkenhead, N., Chisholm, J.I. & Stevenson I.P. (1985) Geology of the country around Buxton, Leek and Bakewell. *Mem. Brit. Geol. Surv.*, Sheet 111.

Bathurst, R.G.C. (1959) The cavernous structure of Mississippian *Stromatactis* reefs in Lancashire. *J. Geol.*, **67**, 506–521.

Bathurst, R.G.C. (1980) Stromatactis—origin related to submarine-cemented crusts in Palaeozoic mud mounds. *Geol.*, **8**, 131–134.

Bathurst, R.G.C. (1982) Genesis of stromatactis cavities between submarine cemented crusts in Palaeozoic carbonate mud buildups. *J. Geol. Soc. Lond.*, **139**, 165–181.

Biggins, D. (1969) *The structure, sedimentology and palaeoecology of a Carboniferous reef knoll at High Tor, Derbyshire.* PhD thesis, University of London.

Bosence, D.W.J., Rowlands, R.J. & Quine, M.L. (1985) Sedimentology and budget of a Recent carbonate mound, Florida Keys. *Sedimentology*, **32**, 317–343.

Bourque, P.A. & Gignac, H. (1983) Sponge-constructed stromatactis mud mounds, Silurian of Gaspé, Québec. *J. sedim. Petrol.*, **53**, 521–532.

Bourque, P.A. & Gignac, H. (1986) Sponge-constructed stromatactis mud mounds, Silurian of Gaspé, Québec—Reply. *J. sedim. Petrol.*, **56**, 461–463.

Bridges, P.H. & Chapman, A.J. (1988) The anatomy of a deep water mud mound complex to the southwest of Dinantian platform in Derbyshire. *Sedimentology*, **35**, 139–162.

Brown, M.A. & Dodd, J.R. (1990) Carbonate mud bodies in middle Mississippian strata of southern Indiana and northern Kentucky: end members of a middle Mississippian mud mound spectrum? *Palaois*, **5**, 236–243.

Brunton, C.H.C. & Tilsley, J.W. (1991). A check list of brachiopods from Treak Cliff, Derbyshire, with reference to other Dinantian (Lower Carboniferous) localities. *Proc. Yorks. Geol. Soc.*, **48**, 287–295.

Cotter, E. (1965) Waulsortian type carbonate banks in the Mississippian Lodgepole Formation of central Montana. *J. Geol.*, **73**, 881–888.

Cowan, P. (1982) Diagenesis of lime mud, Mississippian age bioherms, Sacramento Mountains, New Mexico. In: *Symposium on the Palaeoenvironmental Setting and Distribution of the Waulsortian Facies* (Eds Bolton, K., Lane, H.R. & LeMone, D.V.). El Paso geol. Soc. and University of Texas at El Paso.

Gutteridge, P. (1983) *Sedimentological study of the Eyam Limestone Formation in the east central part of* *the Derbyshire Dome.* PhD thesis, University of Manchester.

Gutteridge, P. (1987). Dinantian sedimentation and the basement structure of the Derbyshire Dome. *Geol. J.*, **22**, 25–41.

Gutteridge, P. (1989) Controls on carbonate sedimentation in a Brigantian intrashelf basin (Derbyshire). In: *The Role of Tectonics in Devonian and Carboniferous Sedimentation in the British Isles* (Eds Arthurton, R.S., Gutteridge, P. & Nolan, S.C.). Occasional Publication of the Yorkshire Geological Society, **6**, 181–187.

Gutteridge, P. (1990). The origin and significance of the distribution of shelly macrofauna in late Dinantian carbonate mud mounds of Derbyshire. *Proc. Yorks. Geol. Soc.*, **48**, 23–32.

Gutteridge, P. (1991). Revision of the Monsal Dale/Eyam Limestones boundary (Dinantian) in Derbyshire. *Mercian Geol.*, **12**, 71–78.

Gutteridge, P. & Currie, S. (in press) Carbonate sedimentation on a Brigantian intraplatform ramp, Derbyshire, U.K. *Sedim. Geol.*

Hennebert, M. & Lees, A. (1985) Optimised similarity matrices applied to the study of carbonate rocks. *Geol. J.*, **20**, 123–131.

Jackson, W.D. & DeKeyser, T. (1984a). Microfacies analysis of Muleshoe Mound (early Mississippian), Sacramento Mountains, New Mexico: a point source model part I. *West Texas Geol. Soc.*, **23**(5), 6–10.

Jackson, W.D. & DeKeyser, T. (1984b). Microfacies analysis of Muleshoe Mound (Early Mississippian), Sacramento Mountains, New Mexico: a point source model part II. *West Texas Geol. Soc.*, **23**(6), 6–10.

Kendall, A.C. (1985) Radiaxial fibrous calcite: a reappraisal. In: *Carbonate Cements* (Eds Schneidermann, N. & Harris, P.M.). Spec. Publ. Soc. econ. Paleont. and Miner, Tulsa, **36**, 59–77.

Kendall, A.C. & Tucker, M.E. (1973) Radiaxial fibrous calcite: a replacement after acicular carbonate. *Sedimentology*, **20**, 365–389.

Kelly, J.G. (1989) *The late Chadian–Brigantian geology of the Carrick-on-Shannon and Lough Allen Synclines, north west Ireland.* PhD. thesis, University College, Dublin.

Kelly, J.G. & Somerville, I.D. (1992) Arundian (Dinantian) carbonate mudbanks in north west Ireland. *Geol. J.*, **27**, 221–241.

Lane, N.G. & Ormiston, A.R. (1982) Waulsortian facies, Sacramento Mountains, New Mexico: Guide for an international field seminar. March 2–6 1982. In: *Symposium on the Palaeoenvironmental Setting and Distribution of the Waulsortian Facies.* (Eds Bolton, K., Lane, H.R. & LeMone, D.V.), pp. 115–182. El Paso Geol. Society and University of Texas at El Paso.

Lees, A. (1964) The structure and origin of the Waulsortian (Lower Carboniferous) 'reefs' of west-central Eire. *Phil. Trans. R. Soc. Lond.*, ser. B, **247**, 483–531.

Lees, A. (1988). Waulsortian 'reefs': the history of a concept. *Mém. Inst. Géol. Univ. Louvain*, **34**, 43–55.

Lees, A. & Miller J. (1985) Facies variation in Waulsortian buildups. Part 2. Mid-Dinantian buildups from Europe and North America. *Geol. J.*, **20**, 159–180.

Lees, A., Hallet, V. & Hibo, D. (1985) Facies variation in Waulsortian buildups. Part 1. A model from Belgium. *Geol. J.*, **20**, 133–158.

Lighty, R.G. (1985) Preservation of internal reef porosity and diagenetic sealing of submerged early Holocene barrier reef, southeast Florida. In: *Carbonate Cements* (Eds Schneidermann, N. & Harris, P.M.). Spec. Publ. Econ. Paleont. and Miner., Tulsa, **36**, 123–151.

MacIntyre, I.G. (1977) The distribution of submarine cements in a modern Carribean fringing reef, Galeta Point, Panama. *J. sedim. Petrol.*, **47**, 503–516.

MacIntyre, I.G. (1985) Submarine cements — the peloidal question. In: *Carbonate Cements* (Eds Schneidermann, N. & Harris, P.M.). Spec. Publ. Soc. econ. Paleont. Miner., Tulsa, **36**, 109–116.

MacQuown, W.C. (1982) The Lower Mississippian Waulsortian facies of Tennessee and Kentucky. In: *Symposium on the Palaeoenvironmental Setting and Distribution of the Waulsortian Facies.* (Eds Bolton, K., Lane, H.R. & LeMone, D.V.) pp. 34–42. El Paso geol. Soc. and University of Texas at El Paso.

Miller, J. (1986) Facies relationships and diagenesis in Waulsortian mud mounds from the Lower Carboniferous of Ireland and N. England. In: *Reef Diagenesis.* (Eds Schroeder, J.H. & Purser, B.H.), pp. 311–335. Springer-Verlag, Berlin.

Miller, J. & Grayson, R.F. (1972) Origin and structure of the Lower Viséan "reef" limestones near Clitheroe, Lancashire. *Proc. Yorks. Geol. Soc.*, **38**, 607–638.

Mundy, D.J.C. (1980) *Aspects of the palaeoecology of the Craven Reef Belt (Dinantian) of North Yorkshire.* PhD thesis, University of Manchester.

Neumann, A.C., Kofoed, J.W. & Keller, G.H. 1977. Lithoherms in the Straits of Florida. *Geology*, **5**, 4–10.

Petta, T.J. & Gehard, L.C. (1977) Marine grass banks—a possible explanation for carbonate lenses, Teepee Zone, Pierre Shale (Cretaceous), Colorado. *J. Sedim. Petrol.*, **47**, 1018–1026.

Pickard, N.A.H., Jones, G. Ll., Rees, J.G., Somerville, I.D. & Strogen, P. (1992) The Lower Carboniferous (Dinantian) stratigraphy and structure of the Walterstown–Kentstown area, Co. Meath, Ireland. *Geol. J.*, **27**, 35–38.

Pratt, B.R. (1982) Stromatolitic framework of carbonate mud mounds. *J. sedim. Petrol.*, **52**, 1203–1227.

Pratt, B.R. (1986) Sponge-constructed stromatactis mud mounds, Silurian of Gaspé, Québec — discussion. *J. sedim. Petrol.*, **56**, 459–460.

Pray, L.C. (1958). Fenestrate bryozoan core facies, Mississippian bioherms, southwestern United States. *J. sedim. Petrol.*, **28**, 261–273.

Ross, R.J., Jaanusson, V. & Friedman, I. (1975) Lithology and origin of middle Ordovician calcareous mud mound at Meiklejohn Peak, southern Nevada. *Prof. Pap. US Geol. Surv.*, **871**, 48 pp.

Schwarzacher, W. (1961) Petrology and structure of some Lower Carboniferous reefs in northwestern Ireland. *Bull. Am. Ass. Petrol. Geol.*, **45**, 1481–1503.

Shinn, E.A., Robbin, D.M., Lidz, B.H. & Hudson, J.H. (1983) Influence of deposition and early diagenesis on porosity and chemical compaction in two Palaeozoic buildups: Mississippian and Permian age rocks in the Sacramento Mountains, New Mexico. In: *Carbonate Buildups—a Core Workshop.* (Ed. Harris, P.M.) Soc. econ. Miner. Paleont. Core Workshop 4, 182–222.

SOMERVILLE, I.D., PICKARD, N.A.H., STROGEN, P. & JONES, G.LI. (1992) Early to mid-Viséan buildups in north Co. Dublin, Ireland. *Geol. J.*, **27**, 151–172.

STEVENSON, I.P. & GAUNT, G.D. (1971) Geology of the country around Chapel en le Frith. *Mem. Brit. Geol. Surv.*, Sheet 99.

STOCKMAN, K.W., GINSBURG, R.N. & SHINN, E.A. (1967) The production of lime mud by algae in south Florida. *J. sedim. Petrol.*, **37**, 633–648.

SUN, S.Q. & WRIGHT, V.P. (1989). Peloidal fabrics in Upper Jurassic reefal limestones, Weald Basin, southern England. *Sedim. Geol.*, **65**, 165–181.

THRAILKILL, J. (1976) Speleothems. In: *Stromatolites* (Ed. Walter, M.R.). Developments in Sedimentology, **20**, 73–88. Elsevier, Amsterdam.

TILSLEY, J.W. (1988) New data on Carboniferous trilobites from the Peak District, Derbyshire, England. *Proc. Yorks. Geol. Soc.*, **47**, 163–176.

TIMMS, A.E. (1978) *Aspects of the palaeoecology of productoid and associated brachiopods in the Middle to Upper Viséan 'reef' limestones of Derbyshire.* PhD thesis, University of Manchester.

TROELL, A.R. (1962). Lower Mississippian bioherms of southwestern Missouri and northwestern Arkansas. *J. sedim. Petrol.*, **32**, 629–664.

TURMEL, R.J. & SWANSON, R.G. (1976) The development of Rodriguez bank, a Holocene mudbank in the Florida Reef tract. *J. sedim. Petrol.*, **46**, 497–518.

WALLACE, M.W. (1987) The role of internal erosion and sedimentation in the formation of stromatactis mudstones and associated lithologies. *J. sedim. Petrol.*, **57**, 695–700.

WILSON, J.L. (1975) *Carbonate Facies in Geologic History.* Springer-Verlag, Berlin, 471 pp.