

Geometry and evolution of platform-margin bioclastic shoals, late Dinantian (Mississippian), Derbyshire, UK

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ABSTRACT

A belt of large-scale bioclastic sand shoals developed at the northern margin of the Derbyshire carbonate platform in northern England during the late Asbian–Brigantian (Dinantian). This belt was at least 2 km wide and extended at least 3 km parallel to the shelf margin. These sand shoals form a shoal complex at least 50 m in thickness composed mainly of bioclastic grainstone. The shoal complex has been divided into shoal sequences by boundaries which show toplap, downlap and onlap configurations. Some of these sequences contain clinoforms which are interpreted as large scale bedforms. Changes in internal geometry of these clinoforms indicate a passage from vertical accretion to basinward progradation during bedform development. These bedforms commonly overlie emergence surfaces and probably developed following a relative rise in sea-level of 20–25 m. Abandonment of these bedforms occurred as a result of subaerial exposure, high energy conditions causing erosional truncation, or the establishment of low energy conditions. Bedforms nucleated in a progressively basinward position throughout the deposition of the shoal complex resulting in basinward progradation of the complex as a whole.

INTRODUCTION

Carbonate sand shoals occur in a number of carbonate depositional systems such as ramps, rimmed shelves and epeiric platforms where they commonly form hydrocarbon reservoirs and host base metal deposits in association with shorelines and shelf breaks (e.g. Tucker, 1985). Carbonate sands have been extensively studied in modern environments where it has been shown that tidal regime and windward–leeward aspect of the shelf break exert a significant influence on the geometry and architecture of such sand bodies (e.g. Ball, 1967; Hine, 1977; Hine *et al.*, 1981). Other factors which are important in influencing the character of carbonate sand shoals include: antecedent topography, tectonic subsidence, eustasy and the type of carbonate sediment available. In the literature on both ancient and modern car-

bonate sands there is a bias towards those with a predominantly oolitic composition, whereas bioclastic sand bodies have received relatively little attention.

The objective of this paper is to describe a bioclastic–carbonate sand body complex of late Dinantian (Mississippian) age which formed in association with the northern margin of the Derbyshire carbonate platform in northern England. Particular attention will be paid to the internal geometry, facies variations and controls on the evolution of these carbonate sand bodies.

GEOLOGICAL SETTING

During late Dinantian times, northern England was situated immediately to the south of the palaeo-equator, and as a result, shallow siliciclastic-starved seas were dominated by carbonate deposition. The Derbyshire carbonate platform was one of several

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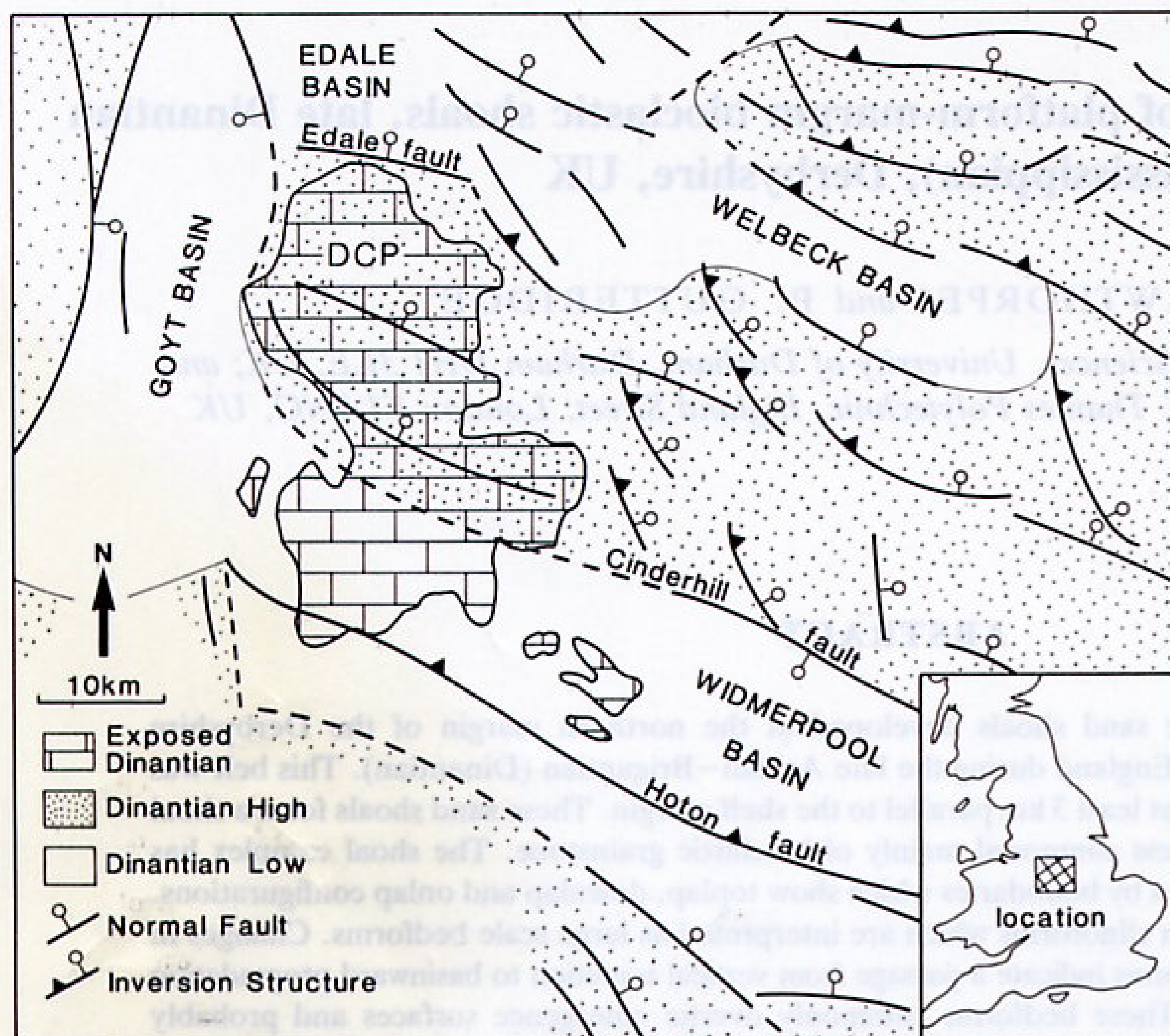


Fig. 1. Dinantian palaeogeography and structural setting of the Central Midlands showing the location of the exposed Derbyshire carbonate platform (DCP). The shelf-margin carbonate sand bodies discussed in this paper are located at the northern margin of the DCP, in the footwall to the Edale fault.

areas of shallow-water carbonate deposition which were located on a series of fault-controlled structural highs (Fig. 1). The Derbyshire carbonate platform formed in the footwall of the down-to-the-north Edale Fault which controlled the location and geometry of the Edale Basin in its hangingwall to the north. The southern platform margin is located on the hangingwall of the Hoton Fault which forms the major controlling fault of the Widmerpool Basin (Fraser *et al.*, 1990).

The bioclastic (mainly crinoidal) shoals described here formed during late Asbian to early Brigantian time along the northern margin of the Derbyshire carbonate platform, which is inferred to be a footwall carbonate margin (Lee, 1988; Gawthorpe *et al.*, 1989). These sand shoals are equivalent to the Monsal Dale and the lower part of the Eyam Limestones which were deposited in a variety of platform interior settings (Gutteridge, 1983, 1987, 1989). Scattered exposures of this bioclastic shoal complex occur between Castleton and Bradwell Dale (Fig. 2). Three large sections in Pin Dale, Hope Cement Works Quarry and Bradwell Dale provide excellent views of the internal geometry of this shoal complex.

These bioclastic shoals developed around the margin of the Derbyshire carbonate platform following a change in the nature of the platform margin

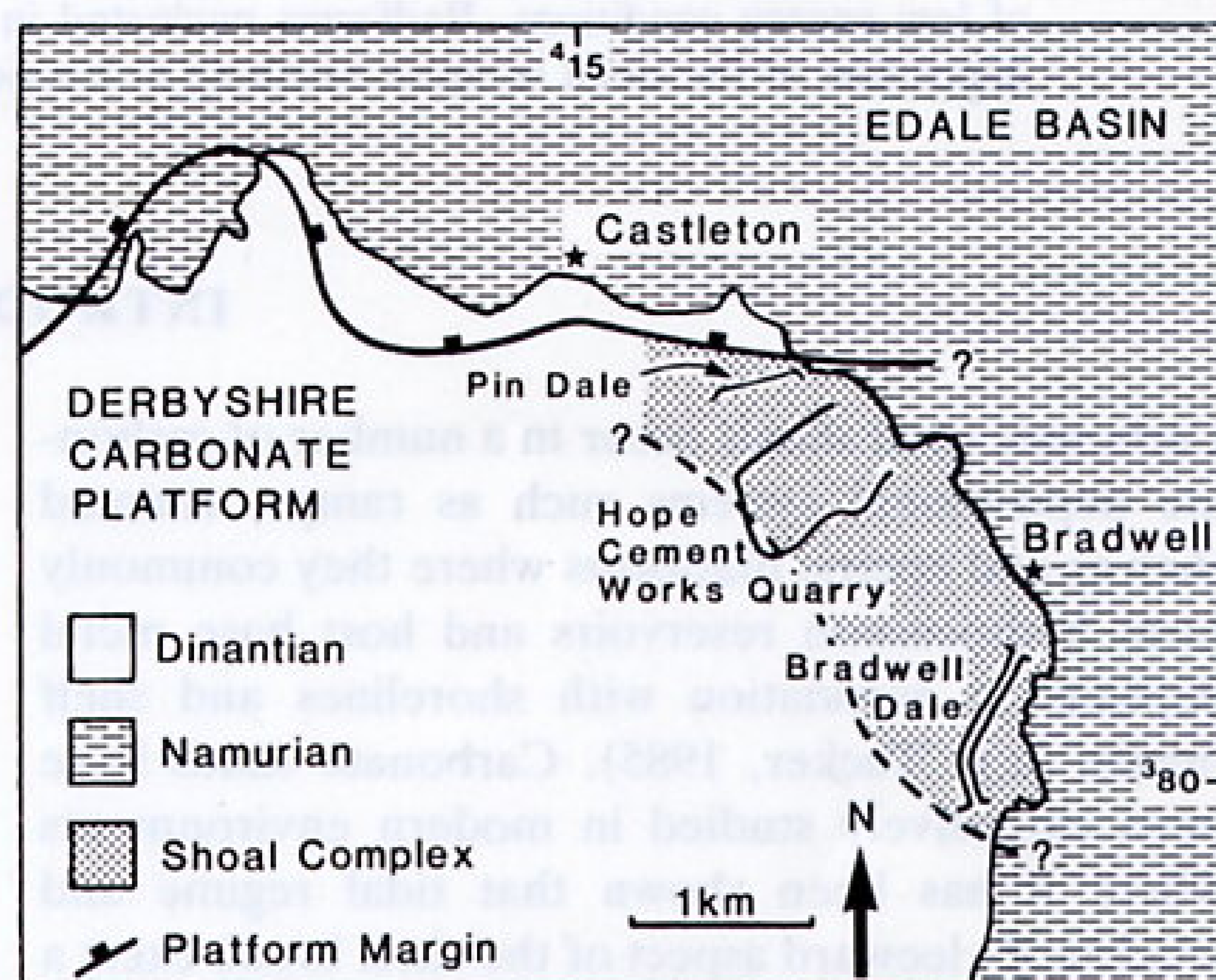


Fig. 2. Location map showing the main sections described in the text and the approximate limits of the shoal complex. Note that the eastward extent of the shoal complex and the platform margin are masked by the younger Namurian cover.

from a high to a low angle rimmed margin during the late Asbian (Broadhurst & Simpson, 1973). The change coincided with a phase of active extension which is recognized over much of northern England (Gawthorpe *et al.*, 1989). This extensional episode

caused reactivation of basement faults underlying the Derbyshire carbonate platform resulting in the initiation of an intrashelf basin (Gutteridge, 1987, 1989). Regional work on Dinantian basins in the subsurface and at outcrop shows that this late Asbian–early Brigantian episode of tectonism corresponds with the EC5 seismic sequence in the east Midlands (Fraser *et al.*, 1990).

The bioclastic shoal complexes have been referred to as ‘flat-reefs’ by previous workers (e.g. Shirley & Horsfield, 1940; Eden *et al.*, 1964; Stevenson & Gaunt, 1971). Such previous studies have concentrated on stratigraphical and palaeontological aspects of the bioclastic shoals whereas their sedimentology has not been discussed. The sequence boundaries identified in this study have been interpreted previously as major non-sequences and angular unconformities. The Asbian–Brigantian boundary has been correlated with one of the sequence boundaries described here from Pin Dale (e.g. Eden *et al.*, 1964; Stevenson & Gaunt, 1971). It follows from this study that many of these sequence boundaries have only local significance in terms of the evolution of the shoal complex and that the regional stratigraphical significance of the unconformities has probably been overstated.

INTERNAL GEOMETRY OF THE SHOAL COMPLEX

Application of a sequence stratigraphic approach in this study has enabled the recognition of a number of sequences within the shoal complex. The lateral and vertical relationships and the internal geometries of these sequences provide important information on the evolution of the shoal complex. Our approach is illustrated by Fig. 3.

The term *shoal complex* refers to the shelf margin bioclastic grainstone and associated facies as a whole. It is exposed for at least 3 km parallel to the shelf margin and forms a belt 1–2 m wide. The thickness of the complex is between 50 and 100 m. The shoal complex has been divided into a number of *shoal sequences* which are separated by *sequence boundaries* recognized by downlap, onlap, toplap and erosional truncation bedding configurations. The shoal sequences are several tens of metres thick and several hundred metres in lateral extent. Sub-sequences are recognized where there is evidence of a change of sedimentary style during deposition of a shoal sequence. This is usually seen as a change in clinoform geometry which implies a change in the style of accretion of the shoal sequence.

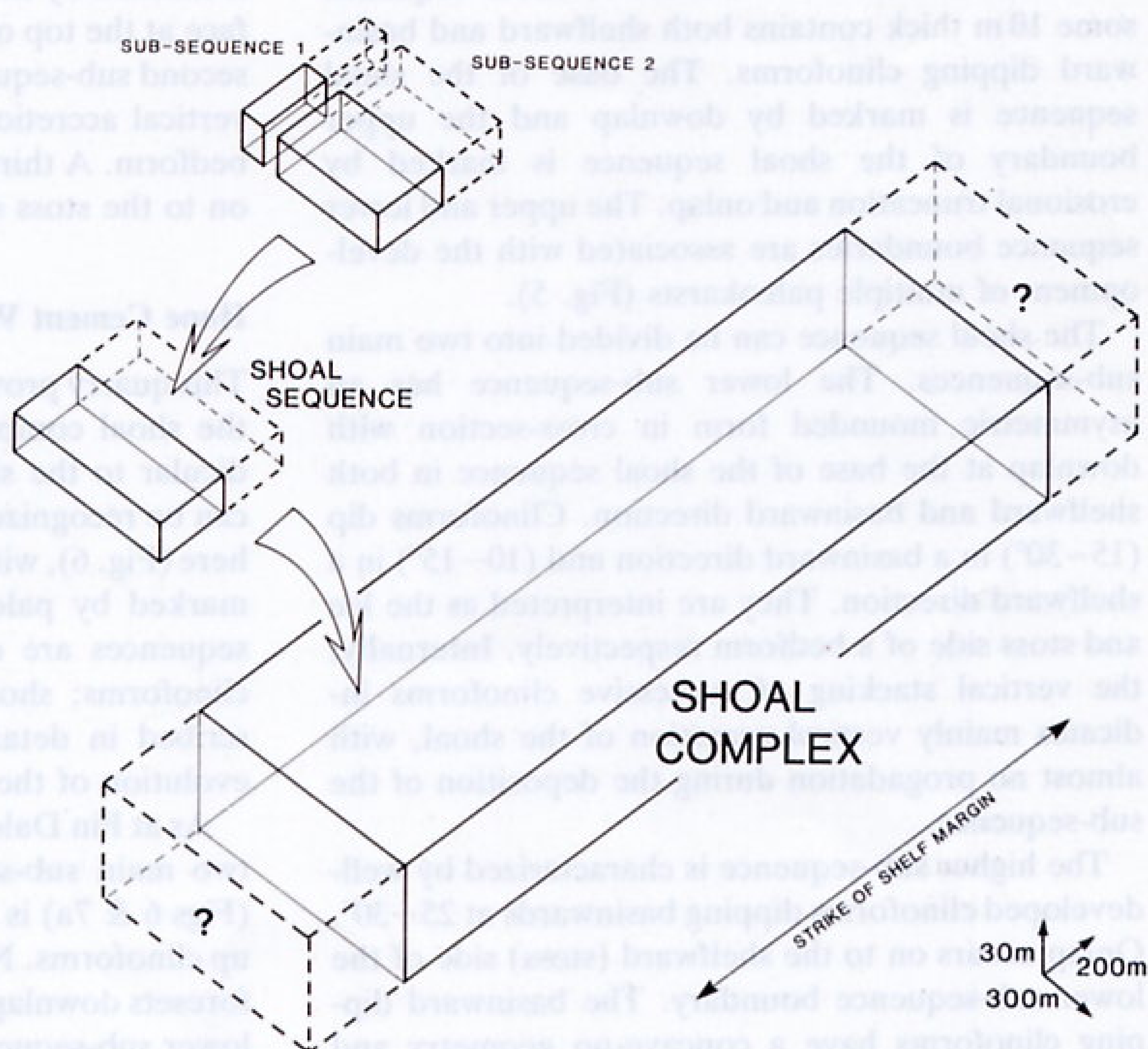


Fig. 3. Diagram illustrating the main elements of the shoal complex and their approximate dimensions. The principal building blocks of the shoal complex are shoal sequences which are bounded by unconformities, often paleokarst surfaces. Internally, shoal sequences can be subdivided into two main sub-sequences, often marked by a change in the clinoform geometry. Note that the dimensions of the shoal sequences and sub-sequences are relatively well constrained, whereas the dimensions of the shoal complex, particularly parallel to the shelf margin, are poorly constrained.

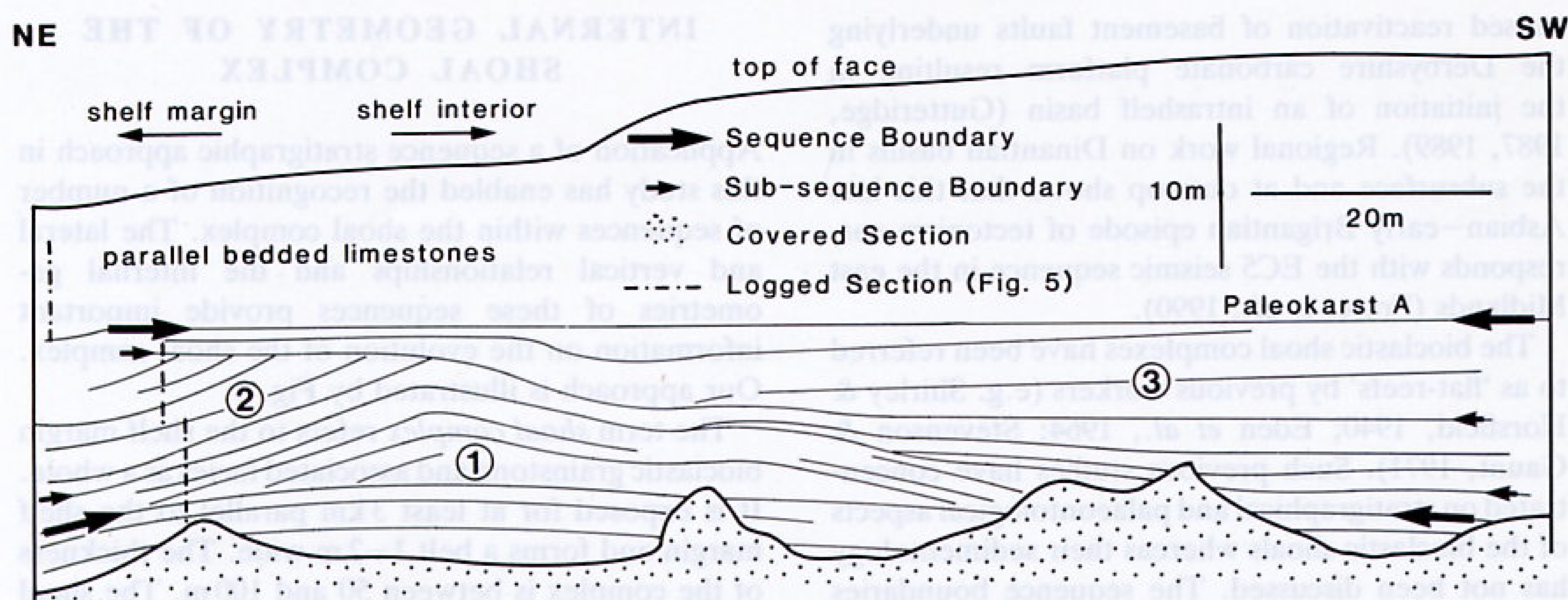


Fig. 4. Line drawing of part of the quarry at Pin Dale (SK159822) illustrating the main bedding plane configurations, sequence boundaries and sub-sequence boundaries. Note the mound-like form of sub-sequence 1 and downlap onto the lower sequence boundary. Sub-sequence 2 is characterized by well-developed clinofoms dipping towards the shelf margin and onlap onto the shelfward side of the lower strata. Sub-sequence 3 onlaps the stoss side of the bedform. The upper sequence boundary (paleokarst A) can be mapped into Hope Cement Works Quarry (see Fig. 6).

Pin Dale (Fig. 4)

Pin Dale is oriented approximately perpendicular to the shelf margin and shows the transition from the shelf break into the shelf-margin shoal complex over a lateral distance of ≈ 500 m. A shoal sequence some 10 m thick contains both shelfward and basinward dipping clinofoms. The base of the shoal sequence is marked by downlap and the upper boundary of the shoal sequence is marked by erosional truncation and onlap. The upper and lower sequence boundaries are associated with the development of multiple paleokarsts (Fig. 5).

The shoal sequence can be divided into two main sub-sequences. The lower sub-sequence has an asymmetric, mounded form in cross-section with downlap at the base of the shoal sequence in both shelfward and basinward direction. Clinofoms dip ($15\text{--}30^\circ$) in a basinward direction and ($10\text{--}15^\circ$) in a shelfward direction. They are interpreted as the lee and stoss side of a bedform respectively. Internally, the vertical stacking of successive clinofoms indicates mainly vertical accretion of the shoal, with almost no progradation during the deposition of the sub-sequence.

The higher sub-sequence is characterized by well-developed clinofoms dipping basinwards at $25\text{--}30^\circ$. Onlap occurs on to the shelfward (stoss) side of the lower sub-sequence boundary. The basinward dipping clinofoms have a concave-up geometry and

pass basinward into bottomsets which extend over the shelf margin, a distance of ≈ 100 m to the northeast from the bedform crest. No downlap is observed. The foresets attain at least 10 m in height; however, the exact geometry of the top of the foresets is masked by the development of a paleokarstic surface at the top of the shoal. The development of this second sub-sequence is interpreted as a change from vertical accretion to basinward progradation of the bedform. A third minor sub-sequence displays onlap on to the stoss side of the bedform.

Hope Cement Works Quarry (Fig. 6)

This quarry provides a section ≈ 100 m thick through the shoal complex and ≈ 600 m in length perpendicular to the shelf margin. Three shoal sequences can be recognized within the exposed shoal complex here (Fig. 6), with several of the sequence boundaries marked by paleokarstic surfaces. The three shoal sequences are characterized by basinward-dipping clinofoms; shoal sequence 2 (Fig. 6) will be described in detail as this most clearly displays the evolution of the sand bodies.

As at Pin Dale, the shoal sequence is divisible into two main sub-sequences. The lower sub-sequence (Figs 6 & 7a) is characterized by sigmoidal, convex-up clinofoms. No bottomsets are developed and the foresets downlap at a high angle (up to 30°) on to the lower sub-sequence boundary. The beds underlying

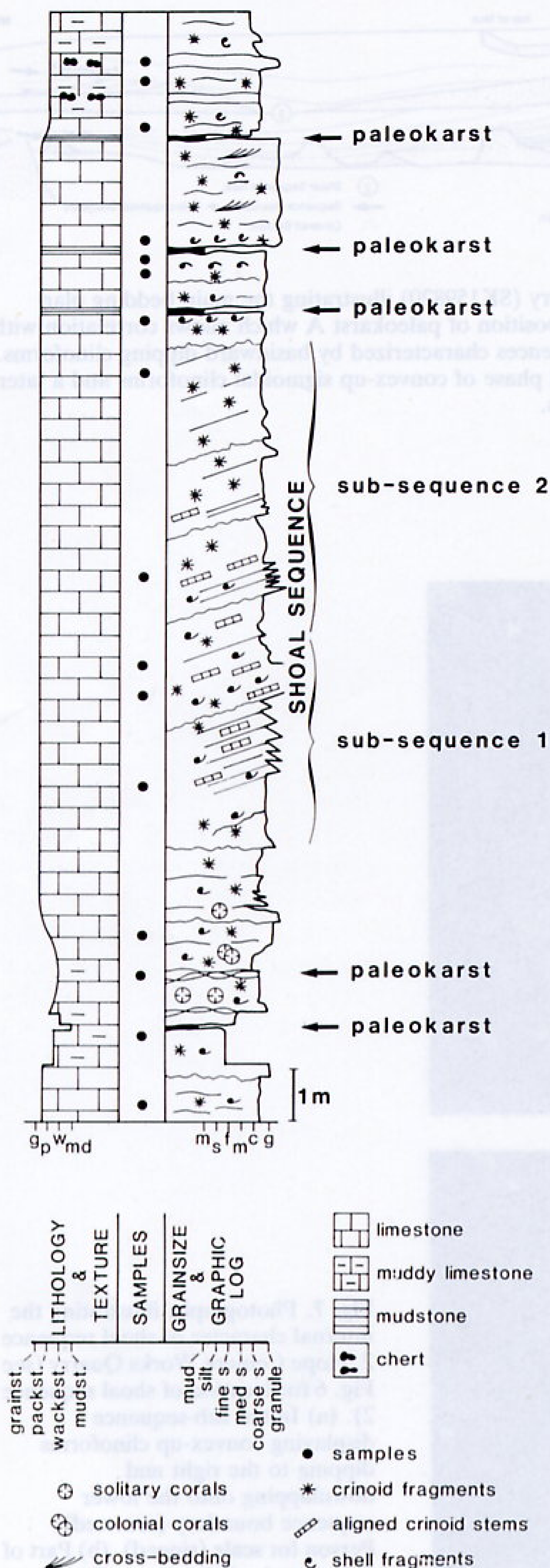


Fig. 5. Graphic log showing the sedimentological expression of the shoal sequence and sub-sequences in Pin Dale. For the location of the log see Fig. 4.

this sequence boundary contain rhizcretions and calcrete mottles indicating that the lower bounding surface was emergent prior to bedform development. The locus of the topset-foreset transition marked by successive clinofolds dips shelfward at $\approx 15^\circ$ indicating both accretion and basinward progradation during deposition of this sub-sequence.

Clinofolds within the higher sub-sequence have a concave-up geometry and bottomsets are well-developed (Figs 6 & 7b). Several truncation surfaces are present within this sub-sequence. Small-scale cross-stratification superimposed on the clinofolds is locally developed with palaeocurrents indicating basinward transport of sediment down the clinofolds.

Bradwell Dale (Fig. 8)

Bradwell Dale provides a section through part of the shoal complex oriented perpendicular to the shelf margin. One shoal sequence is exposed, containing basinward- and shelfward-dipping clinofolds which represent a section perpendicular to a former bedform crest. Two sub-sequences are recognized within this shoal sequence on the basis of clinofold geometry.

The lower sub-sequence represents the early stages of bedform growth and is a symmetrical upbuilding of thinly-bedded (0.05–0.1 m) crinoidal bioclastic grainstone-packstone. The clinofolds dip $12\text{--}14^\circ$ in a shelfward and basinward direction. The crest of the bedform trends $115\text{--}295^\circ$, which is sub-parallel to the shelf margin. Small-scale ripple cross-stratification is superimposed on these clinofolds indicating reworking of sediment by bimodal currents perpendicular to the bedform crest.

The higher sub-sequence is marked by a change from vertical aggradation to lateral accretion of the bedform with the development of tabular to convex-up shelfward and basinward dipping clinofolds up to 0.5 m in thickness. Basinward dipping clinofolds dip at $20\text{--}22^\circ$ and contain superimposed tabular cross-stratification with cosets up to 0.2 m thick indicating basinward transport. Shelfward dipping clinofolds dip at $8\text{--}12^\circ$ and contain superimposed tabular cross-stratification with cosets up to 0.2 m thick indicating alternate shelfward and basinward transport.

Form of the shoal sequences

The term 'form' is used to describe the shape of the

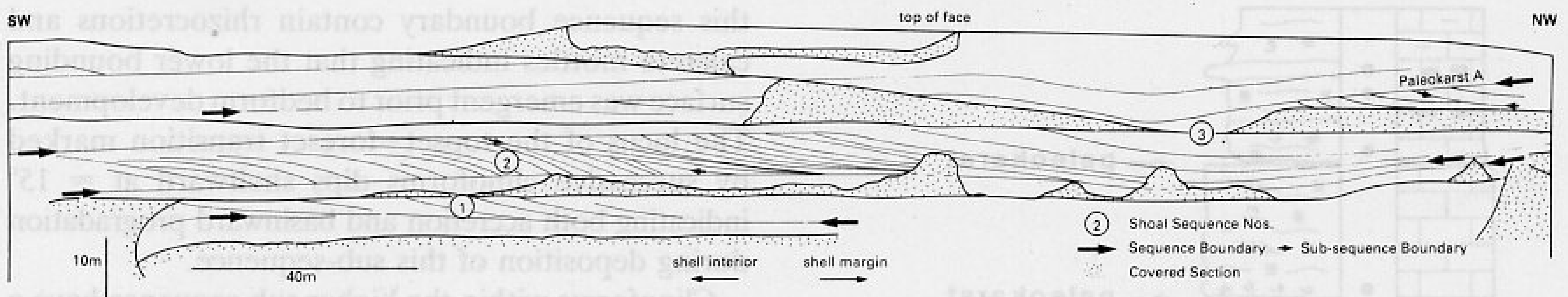


Fig. 6. Line drawing of the NW face of Hope Cement Works Quarry (SK159820) illustrating the main bedding plan configurations, sequence boundaries and sub-sequences. Note the position of paleokarst A which allows correlation with the Pin Dale section (Fig. 4). The section exposes three shoal sequences characterized by basinward dipping clinofoms. Note the two stage development of shoal sequence 2 with an initial phase of convex-up sigmoidal clinofoms and a later phase of oblique concave-up clinofoms with asymptotic bottomsets.

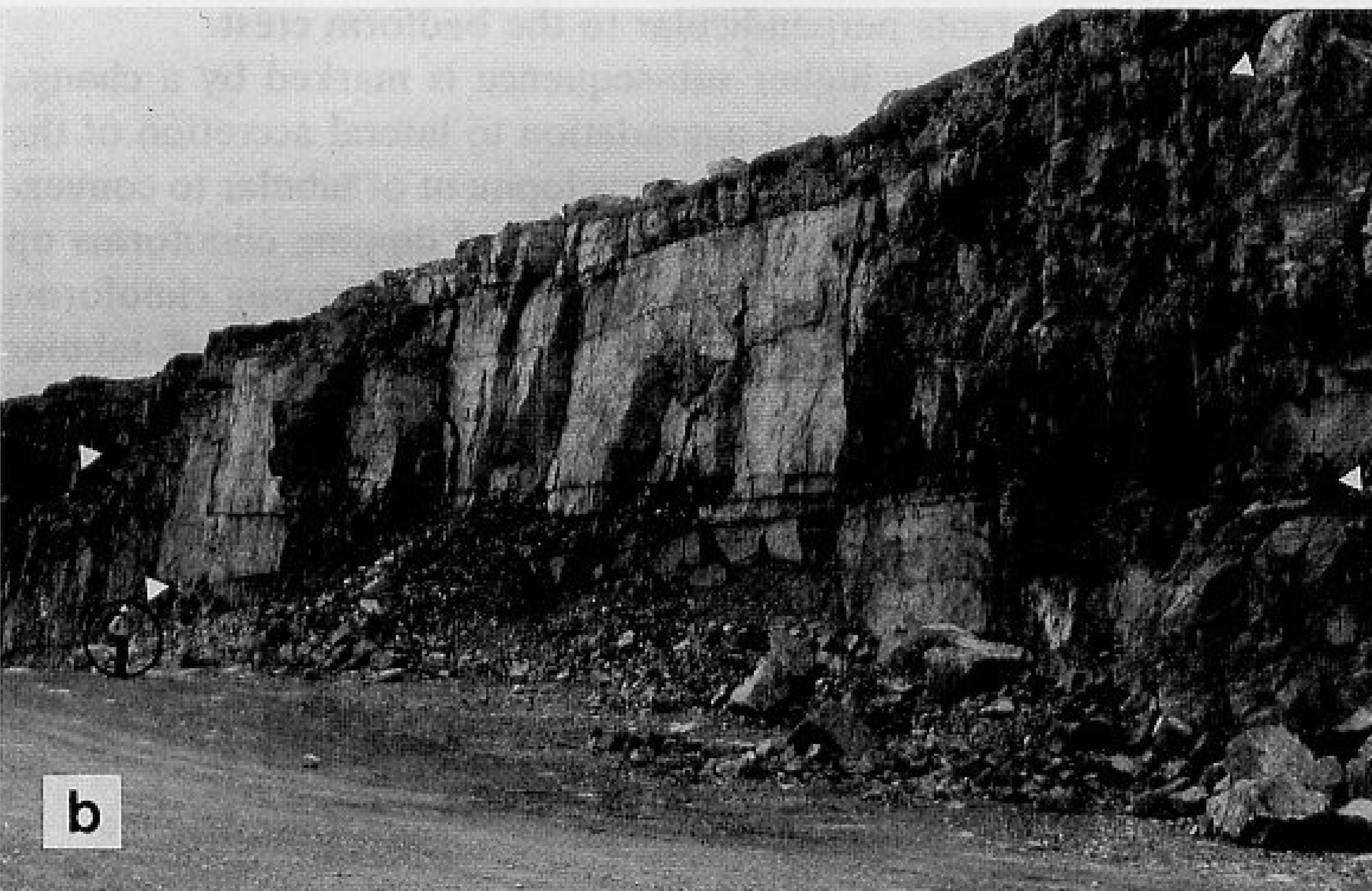


Fig. 7. Photographs illustrating the internal character of shoal sequence 2, Hope Cement Works Quarry (see Fig. 6 for location of shoal sequence 2). (a) Initial sub-sequence displaying convex-up clinofoms dipping to the right and downlapping onto the lower sequence boundary (arrowed). Person for scale (ringed). (b) Part of the second sub-sequence showing concave-up oblique clinofoms with well-developed bottomsets. Sequence boundaries arrowed, person (ringed) for scale.

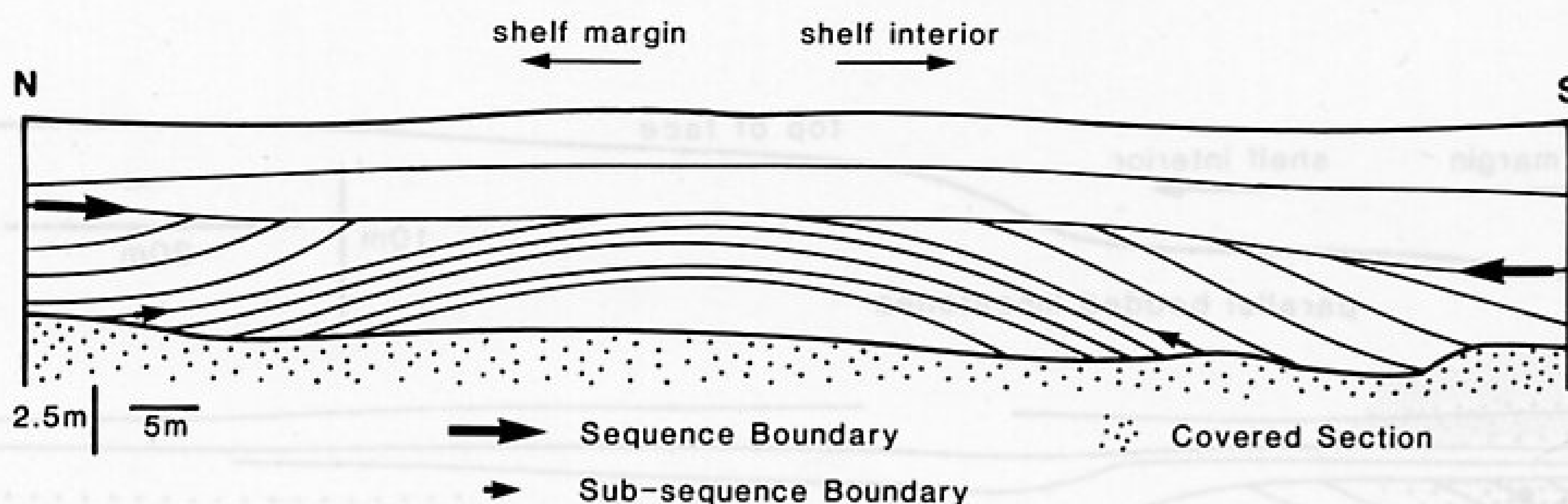


Fig. 8. Line drawing of the lower part of the quarry face at Bradwell Dale (SK173807), illustrating bedding plane configurations, sequence boundaries and sub-sequence boundaries. Note symmetrical upbuilding and mound-shaped form of lower sub-sequence and marked erosional truncation at the upper sequence boundary.

individual shoal sequences, the bedforms which produced them and the three-dimensional relationships between the shoal sequences which together constitute the architecture of the shoal complex. The main palaeokarstic surface developed at the top of the shoal sequence in Pin Dale and Hope Cement Works Quarry provides a means of correlation between the two exposures and allows constraints to be placed upon the three-dimensional form of the individual shoal sequences underlying this emergence surface. The absence of this shoal sequence in the southeastern face of Hope Cement Works Quarry places a minimum value for the along-strike dimension of the shoal sequence. These data, together with information from quarry faces, suggest that the shoal sequences have a sheet-like form ≈ 10 m thick, they are between 200 and 700 m wide measured perpendicular to the shelf margin and extend at least 300 m parallel to the shelf margin.

MICROFACIES

Shoal sequences at Pin Dale and Hope Cement Works Quarry (shoal sequence 3) were sampled for their microfacies. Four microfacies have been distinguished, their distribution is shown in Fig. 9.

Microfacies 1: Bioclast peloid intraclast grainstone (Fig. 10a)

Description

This microfacies is a grainstone with localized packstone texture. It contains a diverse allochem assemblage (Table 1) dominated by brachiopods, crinoids

and peloids. Minor constituents include bryozoans, foraminifera, algae and oncolites. The following three intraclast types are also present: type A: sorted bioclast peloid grainstone (Fig. 10b); type B: calcretized bioclast grainstone—packstone (Fig. 10c); type C: bioclast wackestone (Fig. 10d).

Allochems in microfacies 1 are poorly to very well-sorted, grain-size varies from fine-sand to granule size. All bioclasts are disarticulated and fragmented and are moderately- to well-rounded. Grain roundness increases with increasing degree of micritization. Peloids, formed by micritization of bioclasts, are abundant and range in size from medium sand to granule. Oncolites (Fig. 11a) have a bioclast or peloid nucleus around which there is a complete, concentrically laminated coating of uniform thickness. Some specimens are normally graded and have preferential sub-horizontal alignment of shell fragments. There is no evidence of bioturbation.

An isopachous radial-fibrous calcite cement (Fig. 11b) is locally present as the initial phase of cementation. This precedes aragonite dissolution and is followed by the precipitation of a ferroan pore-filling sparry cement. This radial-fibrous calcite cement is also found within type A intraclasts.

Interpretation

This microfacies contains a diverse open marine bioclast assemblage dominated by brachiopods, crinoids, bryozoans and foraminifera. All the bioclasts show a high degree of fragmentation and rounding which, together with the predominant grainstone texture, suggest a high energy environment and frequent reworking. However, sedimen-

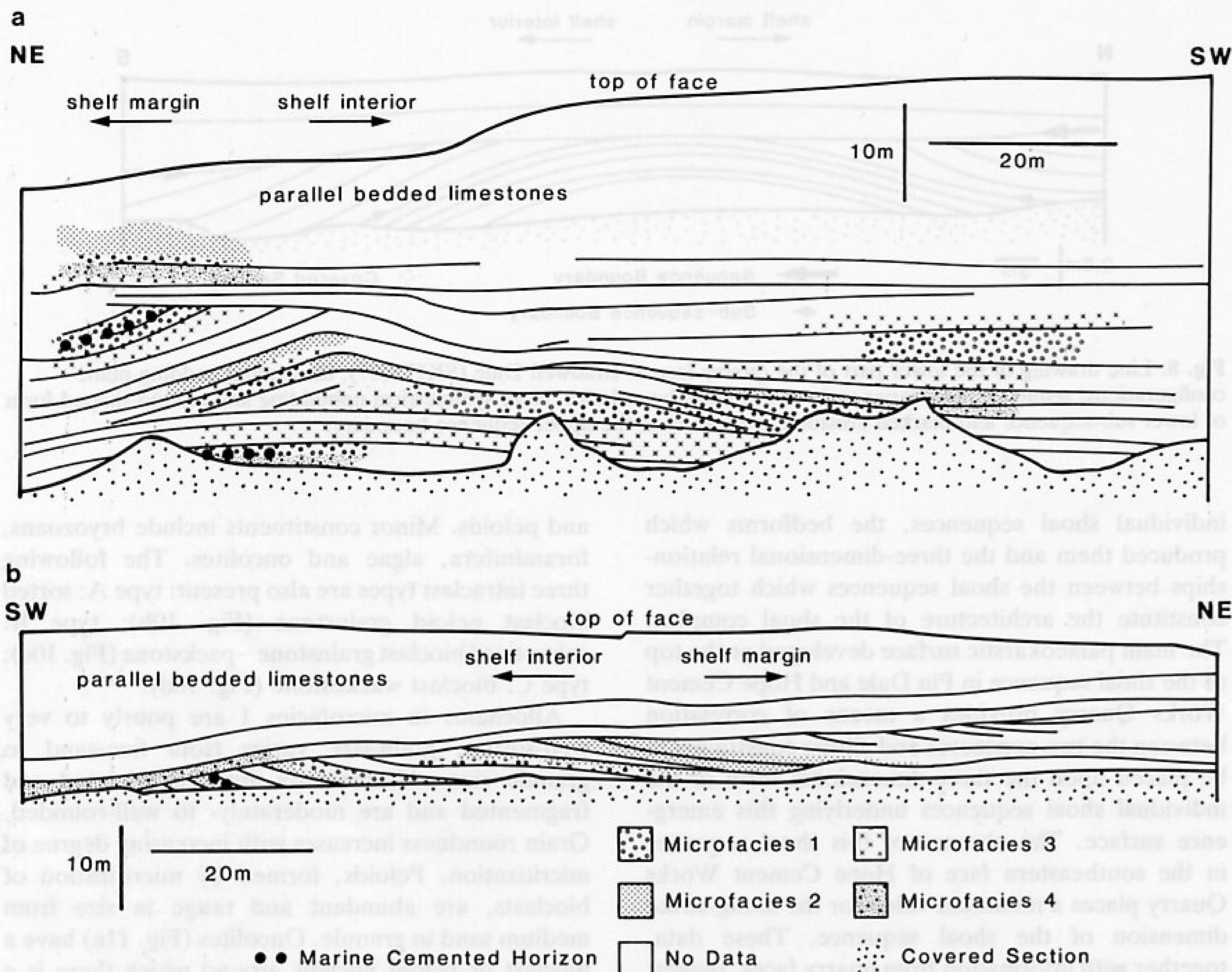


Fig. 9. Examples of microfacies distributions in shoal sequences. (a) Pin Dale (SK159822). (b) Sequence 3, Hope Cement Works Quarry (SK159820). Note the dominance of grainstones and packstones (microfacies 1 and 2) in the clinoforms and the occurrence of wackestones in parallel bedded carbonates above and below the shoal sequence boundaries and in onlapping sub-sequences (see Figs 4 and 6 for the location of sequence and sub-sequence boundaries).

tation rate was probably low as suggested by the high degree of micritization and abundance of peloids. Type A intraclasts were derived from a high energy, well-reworked fully marine environment. They were produced by erosion and reworking of cemented layers on the seafloor. Type B intraclasts are also interpreted as having been deposited originally in a high energy, fully marine environment. The micritic coating and pore bridging textures are interpreted as a pedogenic texture formed in a calcrete profile. This indicates that these intraclasts were reworked from parts of the shoal complex which were subaerially exposed or from shoal se-

quence boundaries. Type C intraclasts are similar to microfacies 4 which was deposited in sheltered areas within the shoal complex. The local preferential alignment of allochems is attributed to deposition by bedload processes or, in the case of layers of highly stacked shells, a high degree of winnowing. The radialfibrous cement is interpreted as a syndepositional marine phreatic cement because of its early diagenetic origin and its occurrence in the sorted grainstone intraclasts. The occurrence of cemented layers on the seafloor is attributed to periodic pauses in sedimentation.

Table 1. Qualitative analysis of the allochem assemblages, in the four main microfacies. The abbreviations for the intraclasts are; type A = sorted bioclast peloid grainstone, type B = calcitized bioclast grainstone – packstone, Type C = bioclast wackestone.

	Microfacies 1 Bioclast peloid intraclast gst.	Microfacies 2 Bioclast intraclast oncolite gst. – pkst.	Microfacies 3 Bioclast oncolite pkst. – wkst.	Microfacies 4 Bioclast wkst.
<i>Allochems in all samples</i>				
Abundant	Brachiopod shell and spine fragments Crinoid ossicles Echinoderm plates Peloids	Crinoid ossicles and stems Brachiopod shell and spine fragments	Brachiopod shell and spine fragments	Molluscs (bivalves and gastropods) Calcitized spicules
Uncommon	Bryozoans (stick type and fenestrate) Foraminifera (endothyrids and archaedisoids)	Bryozoans (stick type and fenestrate) Foraminifera (endothyrids and tetrataxids)	Bryozoans (stick type and fenestrate) Crinoid ossicles Echinoderm plates Foraminifera (tetrataxids)	Brachiopods Bryozoans (stick and fenestrate) Foraminifera (endothyrids)
<i>Allochems in some samples</i>				
Common	Foraminifera (tetrataxids, agglutinating types, earlandids) Algae (stachenids) Molluscs (bivalves and gastropods) Types A, B and C intraclasts	Algae (stachenids) Foraminifera (archaedisoids) Oncolite Type C intraclast	Mollusc shell fragments Algae (kamaenids and ungdarellids) Foraminifera (earlandids, endothyrids and agglutinating types)	Ostracods Foraminifera (archaedisoids) Algae (stacheoides)
Trace	Foraminifera (saccaminopsids) Oncolites Algae (kamaenids) Rugose and tabulate coral fragments Trilobite Calcitized monaxon spicules	Ostracod valves Algae (green, indet. and ungdarellid) Foraminifera (agglutinating types) Rugose coral Molluscs (bivalve and gastropod)	Algae (<i>Koninckopora</i> and stachendis) Foraminifera (saccaminopsids) Ostracods <i>Hexaphyllia</i> Peloids	Foraminifera (saccaminopsids) Green algae (indet.) Types A and C intraclasts

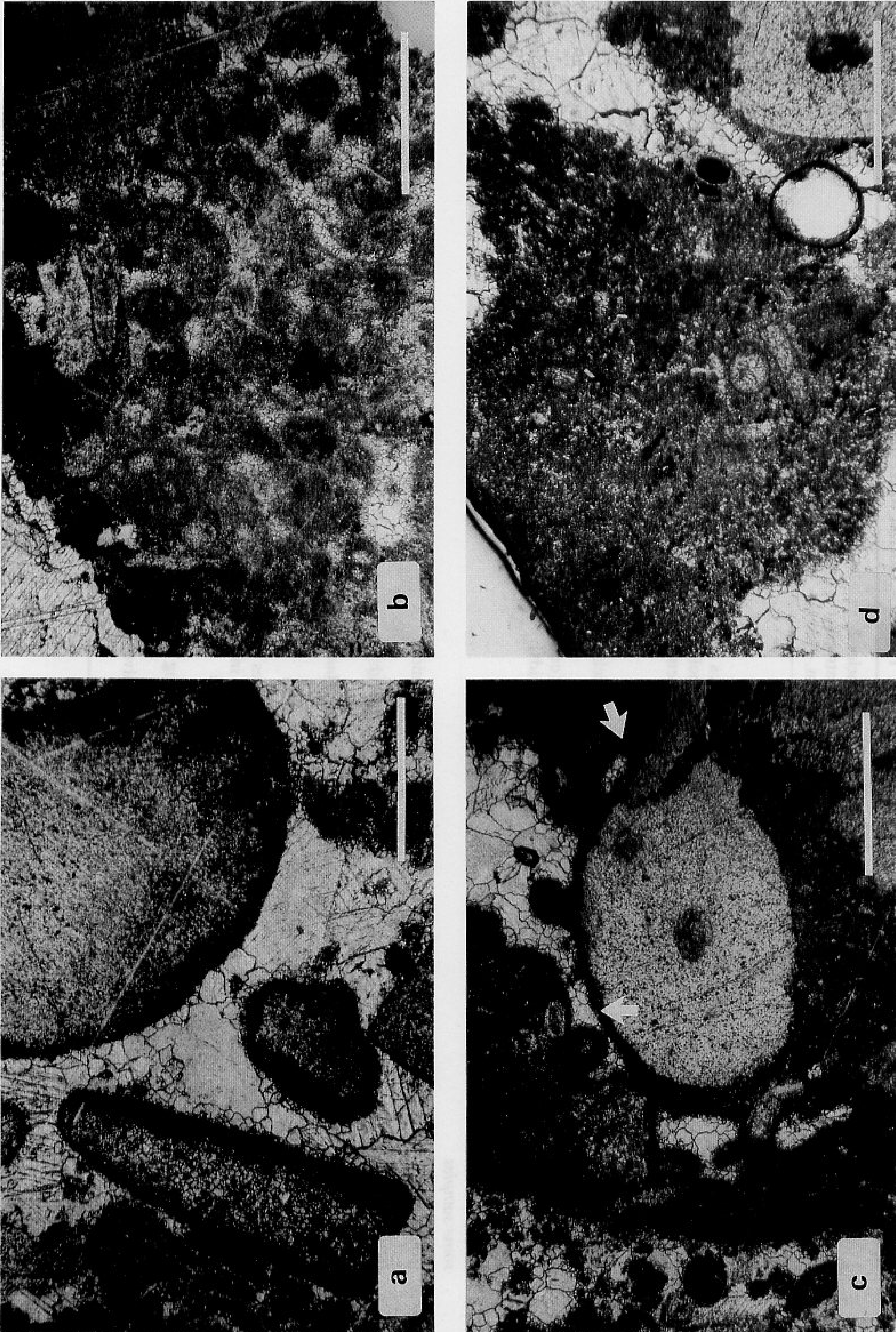


Fig. 10. Photomicrographs of microfacies 1 and intraclasts. (a) Bioclast peloid intraclast grainstone microfacies (microfacies 1). Note intensively micritized crinoid ossicles. Pin Dale, basinward dipping foresets sub-sequence 1. Photomicrograph of a peel. Scale bar = 250 μm . (b) Sorted bioclast grainstone intraclast. Pin Dale, basinward dipping foresets sub-sequence 1. Photomicrograph of a peel. Scale bar = 250 μm . (c) Calcretized bioclast packstone intraclast. Micrite lining intergranular porosity is arrowed. Pin Dale, basinward dipping foresets sub-sequence 1. Photomicrograph of a peel. Scale bar = 250 μm . (d) Bioclast wackestone intraclast. Pin Dale, basinward dipping foresets sub-sequence 1. Photomicrograph of a peel. Scale bar = 250 μm .

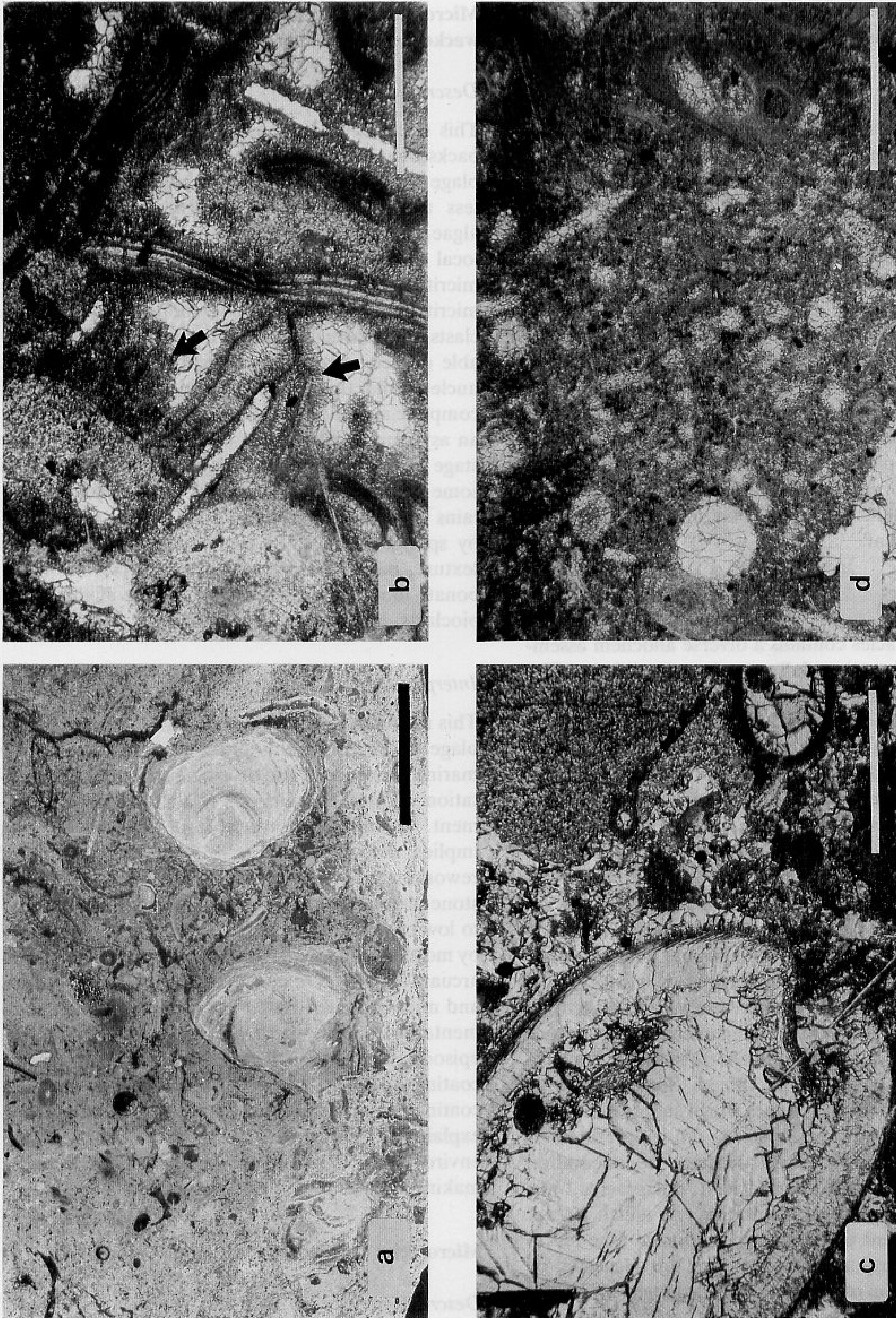


Fig. 11. Photomicrographs of microfacies 2, 3 and 4. (a) Bioclastic oncolite packstone – wackestone microfacies (microfacies 3). Oncolites show an initial complete concentric coating followed by an asymmetric coating. This implies an initial phase of continual agitation followed by a phase of decreasing agitation. Pin Dale immediately underlying lower shoal sequence boundary. Negative print of a peel. Scale bar = 1 cm. (b) Early marine isopachous radial fibrous cement (arrowed). From upper part of foreset in shoal sequence 3 at Hope Cement Works Quarry. Photomicrograph of a peel. Scale bar = 250 μm . (c) Bioclast intraclast oncolite grainstone – packstone microfacies (microfacies 2). From shoal sequence 3 at Hope Cement Works Quarry. Photomicrograph of a peel. Scale bar = 250 μm . (d) Bioclast wackestone microfacies (microfacies 4). Bed immediately overlying shoal sequence 3 at Hope Cement Works Quarry. Photomicrograph of a peel. Scale bar = 250 μm .

Microfacies 2: Bioclast intraclast oncolite grainstone—packstone (Fig. 11c)

Description

This microfacies is a grainstone with development of local packstone texture. The allochem assemblage (Table 1) is dominated by brachiopods and crinoids. Minor constituents include bryozoans, foraminifera and algae. Peloids and micritized allochems are absent. Allochems are poorly to well-sorted. Bioclasts are disarticulated and fragmented although some whole brachiopod valves are present. Bioclasts show some evidence of sponge borings. Oncolites and bioclast wackestone intraclasts are also present. Oncolites have a bioclast nucleus with a complete coating which shows asymmetric thickening. There is local preferential alignment of shells and crinoid stems sub-parallel to bedding and normal size grading is present. An isopachous radial-fibrous calcite cement similar to that in microfacies 1 is locally present.

Interpretation

This microfacies contains a diverse allochem assemblage representing fully marine conditions. The grain-supporting texture, high degree of disarticulation, fragmentation and rounding of the allochems, together with the presence of oncolites indicate generally high energy conditions. The complete coating of the oncolite nuclei suggests a high frequency of rolling. However, the asymmetric thickening of the coating indicates alternating low energy conditions when the oncolites were stationary. The occurrence of packstone is attributed to infiltration carbonate mud through the sediment following a change to lower energy conditions. The bioclastic wackestone intraclasts indicates reworking of low energy sediment from sheltered areas adjacent to the sand body complex. A significant contrast with microfacies 1 is that the allochems within this microfacies have not been micritized. Some, however, have been bored by sponges which suggests a significant pause in sedimentation. This difference is interpreted in terms of differing sedimentation rates. In contrast to microfacies 1, microfacies 2 was subject to a higher sedimentation rate which did not allow sufficient time for micritization to take place. Bedload transport and winnowing are suggested by the orientation of bioclasts and stacking of shells. As in microfacies 1 the radial-fibrous calcite cement is interpreted as a marine phreatic cement.

Microfacies 3: Bioclast oncolite packstone—wackestone (Fig. 11a)

Description

This microfacies is transitional in texture between packstone and wackestone. The allochem assemblage (Table 1) is dominated by brachiopods with less abundant crinoids, bryozoans, foraminifera, algae, bioclast wackestone intraclasts, oncolites and local peloids. Allochems have generally not been micritized, although some have been partially micritized and some display sponge borings. Bioclasts are disarticulated and fragmented with a variable degree of rounding. Oncolites have a bioclast nucleus and the coatings show an early stage of complete accretion of uniform thickness followed by an asymmetric thickening of the coating. A further stage of incomplete partial accretion is shown in some oncolites. The coating of some oncolites contains several horizons which have been penetrated by sponge borings. In some specimens a mottled texture, picked out by a patchy distribution of carbonate mud and a preferential arcuate alignment of bioclasts, is present.

Interpretation

This microfacies contains a similar allochem assemblage to microfacies 1 and 2 and represents fully marine conditions. The disarticulation and fragmentation of bioclasts suggests a high-energy environment. However, the variable degree of rounding implies that allochems with differing histories of reworking are present and the packstone—wackestone texture suggests final deposition in a moderate-to low-energy environment. Bioturbation is indicated by mottling of the sediment and the occurrence of an arcuate alignment of bioclasts. The paucity of peloids and micritized and bored grains indicates that sedimentation rates were generally high, although episodic, as indicated by bored layers within oncolitic coatings. The change in the nature of the oncolitic coatings from symmetrical to asymmetrical can be explained either as a decrease in the energy of the environment, or to increasing size of the oncolite making it more difficult to be moved.

Microfacies 4: Bioclast wackestone (Fig. 11d)

Description

This wackestone has an allochem assemblage (Table

1) which differs from that of other microfacies in that it is dominated by molluscs and calcified spicules with brachiopods and crinoids as relatively minor components. Sorted bioclast peloid grainstone and bioclast wackestone intraclasts are also present. Bioclasts show a range of preservation states; the majority are disarticulated and fragmented with a high degree of rounding. However, whole unabraded bioclasts and fragmentary bioclasts with angular fracture surfaces are also present. This microfacies commonly displays a mottled texture which is picked out by a patchy distribution of carbonate mud and the development of an arcuate preferential alignment of bioclasts.

Interpretation

The dominance of molluscs and calcitized spicules suggest unusual salinity or a low oxygen content of the environment. The wackestone texture and the occurrence of whole bioclasts with minimal abrasion suggest deposition in a generally low energy environment. However, the presence of highly disarticulated, fragmented and rounded bioclasts suggests that these may have been reworked elsewhere and transported into the lower energy environment. The occurrence of intraclasts also indicates input of reworked sediment from surrounding areas. The common occurrence of sediment mottling and the arcuate preferential alignment of bioclasts is attributed to bioturbation.

EVOLUTION OF THE SHOAL COMPLEX

Bedform dynamics

Figure 9 shows that the clinofolds within shoal sequence 3 at Hope Cement Works Quarry and Pin Dale comprise alternations of microfacies 1 and 2 with the local occurrence of microfacies 3 in the Pin Dale bedform. This alternation is interpreted in terms of episodic bedform migration. During pauses in bedform migration, rates of sediment burial were low allowing micritization of grains and cementation of the bedform surface to occur. During bedform migration, rates of sediment burial were much higher and micritization was retarded allowing the deposition of 'fresh' bioclastic sediment. The occurrence of microfacies 3, particularly in bottomset beds, is interpreted as the establishment of low energy conditions allowing deposition and infiltration of micrite into the sediment of the bedform. Microfacies 4 is

generally restricted to areas adjacent to the main shoal sand bodies, and to the sequences overlying the shoal complex.

At all localities there is evidence of a two-stage development of the bedforms. This is shown schematically in Fig. 12, which is based on shoal sequence 2 in Hope Cement Works Quarry. This two-stage development is inferred to represent the initial upbuilding of the bedform during a phase when sedimentation rate was 'catching-up' with relative sea-level rise. The onset of basinward progradation reflects a limitation of vertical growth, possibly by sea-level stillstand, or that sedimentation had caught up with relative sea-level rise. Following this the bedform prograded basinwards with minimal vertical accretion. At the Hope Cement Works Quarry the bedform represented by shoal-sequence 2 prograded by 500–700 m basinwards. At Pin Dale progradation resulted in spill over the shelf break, and supply of sediment to the basinal area to the north.

Within the clinofolds, low angle erosion surfaces which truncate underlying clinofolds are interpreted as reactivation surfaces formed by high energy events during which the topography of the bedform was partly eroded. Re-establishment of the bedform after the development of these truncation surfaces is either by the conformable deposition of clinofolds, or downlap of clinofolds onto the reactivation surface (e.g. shoal sequence 3 at Hope Cement Works Quarry, Fig. 9b).

At Bradwell Dale, shelfward and basinward dipping clinofolds and bimodal smaller-scale cross-stratification indicates both shelfward and basinward sediment transport. This, together with the large scale of the bedform may suggest a tidal influence on the deposition of the shoal complex. However, the marked asymmetry of the shoal complex suggests a dominant ebb tidal current. The predominant basinward transport of sediment across the shelf margin along strike to the west suggests that prevailing offshore wind or storm driven currents may also have been important along the shelf margin. Thus the shoal complex probably developed under a mixed storm–tide influence.

The extent of progradation may have been limited by sediment production or by extrinsic factors such as emergence or flooding due to relative sea-level change. The mechanism of nucleation, development and abandonment of these bedforms, as illustrated by the shoal sequences, has important consequences for the development and architecture of the shoal complex as a whole which is discussed in the next section.

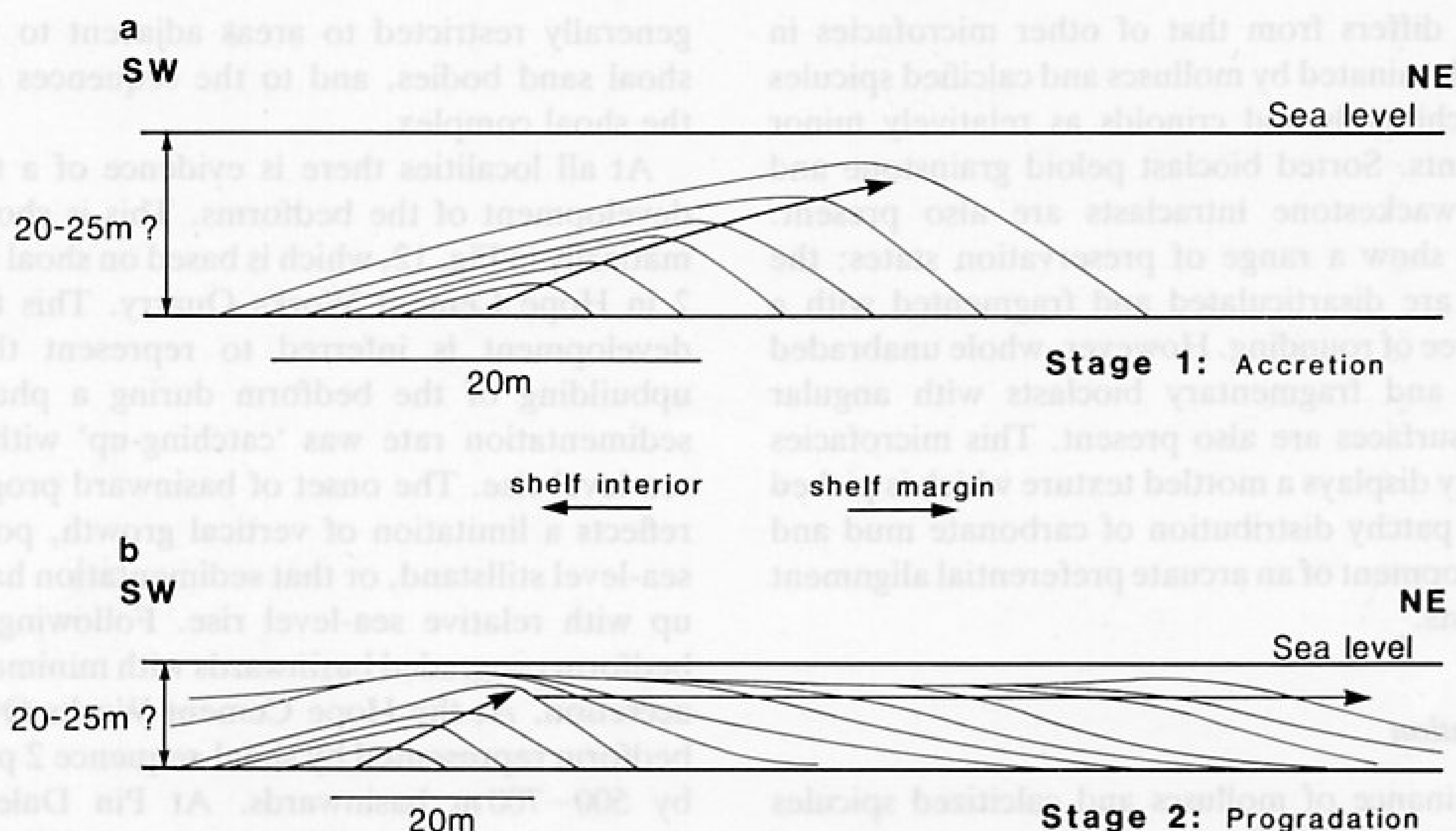


Fig. 12. Shoal sequence evolution based on examples from Pin Dale, Hope Cement Works Quarry and Bradwell Dale. (a) Stage 1 predominantly vertical accretion of bedform associated with relative rise of sea-level. Clinofolds are sigmoidal and convex-up, with downlap onto lower sequence boundary which is often a paleokarst. (b) Stage 2 stillstand of sea-level limits vertical accretion of the bedform with the result that it progrades basinward, under the influence of storm and tidal currents. Clinofolds have an oblique, concave-up geometry with asymptotic bottomsets.

Controls on shoal complex evolution

Where the lower sequence boundary of the shoal sequences is exposed, it is marked by evidence of emergence such as a paleokarst or calcrete. This implies that the bedforms developed during a relative sea-level rise which flooded an emergent platform. The bedform dynamics discussed above suggest an initially rapid relative transgression followed by stillstand. The dimensions of the bedforms suggest that episodic relative sea-level rises of at least 20–25 m took place during deposition of the shoal complex.

Features associated with the upper bounding surfaces of the shoal sequences suggest that abandonment of these bedforms occurred as a result of three processes: (1) erosional truncation, where the topography of the bedform was planed-off by a high energy (storm?) event; (2) development of low energy conditions over the bedform followed by onlap and burial of the bedform. This is seen at Pin Dale (Figs 4 & 9a) where the main bedform is onlapped by microfacies 4 which was deposited in a low energy, (deeper water?) setting; and (3) emergence, due to shoal up-building or relative fall in sea-level.

Hope Cement Works Quarry provides evidence

of the architecture of the shoal complex. The three shoal sequences (Fig. 6) form a total thickness of ≈ 50 m. Younger shoal sequences are progressively offset in a basinward direction relative to the immediately underlying sequence. The younger shoal sequences nucleate close to the crest of the bedform in the underlying sequence. The architecture of the shoal complex is thus one of progressive basinward-stacking of shoal sequences. The facies relationships parallel to depositional strike are unclear owing to poor exposure. These shoal sequences coalesce to produce a shoal complex which is wedge shaped, thinning away from the shelf margin towards the shelf interior. They form a belt varying from several hundred metres to several kilometres in width and several kilometres in length along depositional strike.

The predominant basinward sediment transport and bedform progradation is seen in modern carbonate platform margins of the windward-protected and leeward types (Hine *et al.*, 1981). There is no evidence of a persistent barrier parallel to the shelf margin in the form of a 'reef' or emergent area which could have afforded protection of the shelf margin. A leeward setting of the northern margin of the Derbyshire carbonate platform would be in

agreement with the E–W or SE–NW prevailing Dinantian storm tracks deduced by Schofield (1982).

CONCLUSIONS

A complex of bioclastic–carbonate sand shoals some 2 km wide and extending for several kilometres along strike developed at the northern margin of the Derbyshire carbonate platform during the late Asbian and early Brigantian. This complex is divided into several shoal sequences separated by sequence boundaries recognized by toplap, onlap and downlap bedding configurations. These shoal sequences contain clinofolds which represent large-scale bedforms. The internal geometry of these shoal sequences indicates an initial stage of development dominated by vertical accretion which is followed by a phase of basinward progradation. The bedforms prograde by a maximum of 500–700 m and are seen to spill over the shelf margin. These bedforms developed on emergent surfaces, probably in response to a relative rise in sea-level of 20–25 m. Tidal currents and storm activity were both important in controlling the internal geometry of the shoals. The bedforms are made up mainly of bioclast grainstone with local packstone and wackestone, the latter reflecting lower energy conditions. The grainstone is a mixture of unmicritized ‘fresh’ sediment deposited during episodes of bedform migration and highly micritized peloidal sediment reflecting pauses in bedform migration.

Abandonment of the bedforms took place by high energy events planing-off the bedform topography, establishment of low energy conditions, or subaerial exposure. Early cementation of the bedforms occurred during pauses in migration and during meteoric diagenesis associated with subaerial exposure. The bedforms nucleated in a progressively basinward position throughout the deposition of the shoal complex, resulting in basinward progradation of the facies complex as a whole.

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REFERENCES

- BALL, M.M. (1967) Carbonate sand bodies of Florida and the Bahamas. *J. Sed. Petrol.* **37**, 556–591.
- BROADHURST, F.M. & SIMPSON, I.M. (1973) Bathymetry on a Carboniferous reef. *Lethaia* **6**, 367–381.
- EDEN, R.A., ORME, G.R., MITCHELL, M. & SHIRLEY, J. (1964) A study of part of the margin of the Carboniferous Limestone ‘Massif’ in the Pin Dale area of Derbyshire. *Bull. Geol. Surv. G.B.* **21**, 73–118.
- FRASER, A.J., NASH, D.F., STEELE, R.P. & EBDON, C.C. (1990) A regional assessment of the Intra-Carboniferous play of northern England. In: *Classic Petroleum Provinces* (Ed. Brooks, J.) Spec. Publ. Geol. Soc. Lond. (in press).
- GAWTHORPE, R.L., GUTTERIDGE, P. & LEEDER, M.R. (1989) Late Devonian and Dinantian basin evolution in northern England and North Wales. In: *The Role of Tectonics in Devonian and Carboniferous Sedimentation in the British Isles* (Eds Arthurton, R.S., Gutteridge, P. & Nolan, S.C.) Occ. Publ. Yorks. Geol. Soc. **6**, pp. 1–23.
- GUTTERIDGE, P. (1983) *Sedimentological study of the Eyam Limestone Formation in the east central part of the Derbyshire Dome*. Unpublished 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 within 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.) Occ. Publ. Yorks. Geol. Soc. **6**, pp. 171–187.
- HINE, A.C. (1977) Lily Bank, Bahamas; history of an active oolite sand shoal. *J. Sed. Petrol.* **47**, 1554–1582.
- HINE, A.C., WILBER, R.J. & NEUMANN, A.C. (1981) Carbonate sand bodies along contrasting shallow bank margins facing open seaways in Northern Bahamas. *Bull. Am. Assoc. Petrol. Geol.* **65**, 261–290.
- LEE, A.G. (1988) Carboniferous basin configuration of central and northern England modelled using gravity data. In: *Sedimentation in a Synorogenic Basin Complex: The Upper Carboniferous of Northwest Europe* (Eds Besly, B.M. & Kelling, G.) pp. 69–84. Blackie, Glasgow.
- SCHOFIELD, K. (1982) *Sedimentology of the Woo Dale Limestone Formation, Derbyshire*. Unpublished PhD thesis, University of Manchester.
- SHIRLEY, J. & HORSFIELD, E.L. (1940) The Carboniferous Limestone of the Castleton – Bradwell area, North Derbyshire. *Q. J. Geol. Soc. Lond.* **96**, 271–299.
- STEVENSON, I.P. & GAUNT, G.D. (1971) The Geology of the Country around Chapel en le Frith. *Mem. Geol. Surv. G. B.*, Sheet 99, p. 444.
- TUCKER, M.E. (1985) Shallow marine carbonate facies and facies models. In: *Sedimentology: Recent Developments and Applied Aspects* (Eds Brenchley P.J. & Williams, B.J.P.) Spec. Publ. Geol. Soc. Lond. **18**, pp. 147–169.