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The initiation of Waulsortian buildups in Western Ireland

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ABSTRACT

The contact zone at the base of the Waulsortian (Upper Tournaisian) carbonate mud-bank complex in western Ireland has been investigated at four localities spaced over a distance of 120 km. At all localities, a transition facies up to 3 m thick, characterized by several types of grumous (clotted and/or peloidal) carbonate muds, immediately underlies the Waulsortian facies. These muds show a developmental sequence provisionally interpreted as a necessary precursor to the formation of Waulsortian polymuds. Such pre-bank precursors produced thin (a few decimetres) units of transition facies. The same mud types also persisted as an aureole around growing banks (mud-mounds). Migration of the aureole during bank progradation produced thicker units of transition facies. The distribution of skeletal grain types in the Waulsortian banks, the transition facies and the 'background' argillaceous bioclastic limestones show two trends: one regional and one local. The regional trend is expressed by progressive north–south attenuation and, in some cases (for example, plurilocular foraminifera), the disappearance of organism groups. It parallels changes in Waulsortian Phases (defined by skeletal grain-type assemblages) and is thought to indicate a southerly increase in water depth. The local trend, which occurs only in the two southern localities (deeper water), expresses differences between the skeletal grain content of the various lithofacies. These differences result partly from increased sensitivity to substrate texture by organism groups suffering southward attenuation (notably gastropods, hyalosteliid sponges, aoujgaliids, *Earlandia* and kirkbyacean ostracods) and partly from selective colonization, particularly of the transition facies, by tabulate corals and stick/ramose bryozoans. However, the developmental sequence of precursor carbonate muds is the same at all localities, indicating that the mud-making process (probably microbial) was independent of water depth.

Keywords Carbonate muds, Dinantian, Ireland, mud-mounds, palaeoecology, Waulsortian buildups.

INTRODUCTION

Waulsortian buildups formed by biogenic accretionary processes that produced submarine banks rich in lime mud, probably largely of microbial origin. They were the dominant carbonate mud-mound type in the early Carboniferous (Tournaisian). Although common in outer ramp settings, they formed over a considerable bathymetric range, extending from subphotic depths of 300 m or more to relatively shallow photic conditions in perhaps no more than a few tens of metres of water (Lees *et al.*, 1985; Lees & Miller, 1985, 1994, 1995, pp. 218–223; Lees, 1997, pp. 27–33).

The greatest known development of these buildups is in Ireland, where the banks aggregated to form a Complex up to about 1 km thick and originally extending over >30 000 km^2. The sharp lithological contrast between the Waulsortian facies and the 'normal' underlying limestones might be thought to indicate that a marked change in environmental conditions accompanied the onset of Waulsortian sedimentation. However, as the beds laterally equivalent to the banks are lithologically similar to those that underlie them, the initiation of the Waulsortian facies was obviously not related to any major, regional environmental change.

The basal contact of a bank is commonly very abrupt (Lees & Miller, 1995, p. 231, fig. 32). This appears to be at variance with reports of transitional zones up to several tens of metres thick underlying the Waulsortian facies in various parts of Ireland (e.g. Grennan, 1986; Strogen, 1988, p. 127). To clarify this seemingly anomalous situation and search for clues to the factors responsible for the initiation of the Waulsortian facies, a detailed petrographic study has been undertaken on this basal contact zone at four localities in western Ireland.

As the results of this study comprise two main blocks of data, the plan of presentation is adapted accordingly. After a section providing basic information on the localities studied and the methodology adopted, the first data block is introduced by a description of the limestone fabrics. Emphasis is given to the nature and distribution of the various carbonate muds encountered, particularly those that developed in the transition facies below the Waulsortian facies. The analysis and interpretation of these muddy fabrics that follows leads to the presentation of a model to account for their formation. The second data block, concerning the allochem grain-types (mainly bioclasts), is then introduced. Analysis and interpretation of their distributions leads to a model explaining regional and local variation patterns. Assessment of the relationships between the models concerning the muds and the organisms forms part of the conclusions.

STUDIED LOCALITIES AND THEIR SETTING

The localities studied (Fig. 1) lie along a line, about 120 km long, paralleling the sense of the major transgression that spread north and east across Ireland during the Tournaisian (Sevastopulo, 1979, p. 10; 1982, p. 66). The line extends northwards from the Shannon area, where aggregates of Waulsortian banks form a thick and laterally continuous Complex, to north County Galway, where the Complex has thinned and 'broken up' into groups of scattered banks. The

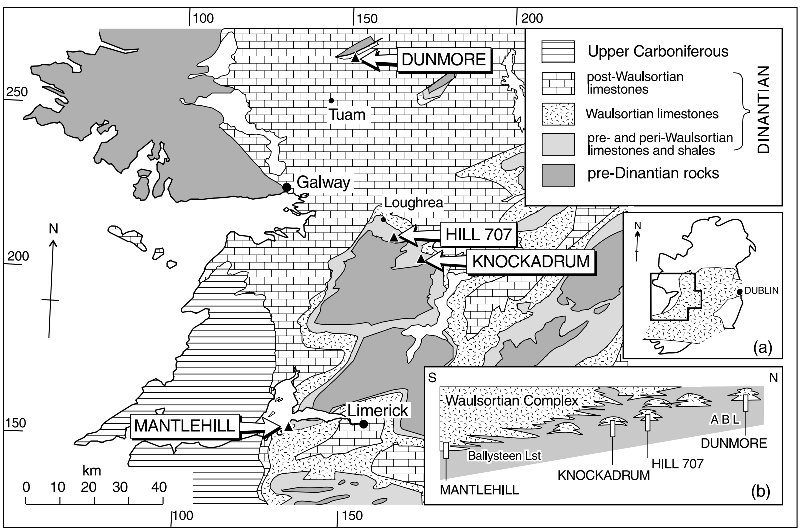

Fig. 1. The regional and stratigraphic context of the four studied localities. Faults omitted for clarity. Numbers shown in the margin refer to the Irish National Grid. The area shaded on the inset (a) shows the original extent of the Waulsortian Complex when fully developed in the late Tournaisian. Inset (b) is a highly schematic cross-section (with gross vertical exaggeration) indicating the broadly transgressive nature of the Waulsortian Complex and the tendency for isolated bank masses to occur under and on the original landward (here the northern) side of the continuous bank development. In inset (b), ABL = Argillaceous Bioclastic Limestone. In the text, the Ballysteen Limestone and the Argillaceous Bioclastic Limestone are grouped as the ABL facies.

localities, chosen for the quality of exposure of the basal zone, are as follows (Fig. 1):

1 Mantlehill: a natural exposure on the east bank of the Deel River where it joins the south side of the Shannon Estuary, about 300 m NW of Mantlehill House and 3 km NNW of Askeaton, Co. Limerick [Irish National Grid Reference (INGR) R 330534; Shephard-Thorn, 1963, p. 275].

2 Knockadrum: a disused quarry 14 km west of Portumna, Co. Galway (INGR M 710048; photograph in Lees & Miller, 1995, fig. 5B).

3 Hill 707: hill-top crags about 5 km SSE of Loughrea, Co. Galway (INGR M 640113). Details are given by Lees (1964, pp. 495–497), Miller (1986, pp. 313–319) and Lees & Miller (1995, fig. 5A). The section examined and sampled lies about 240 m NNW of the summit of the hill (at point C on fig. 10 of Lees, 1964).

4 Dunmore: the depth interval from 152 to 162 m in the drill-core from the vertical borehole MGR 82-35 drilled by Billiton Exploration Ireland about 3·5 km WNW of the village of Dunmore, Co. Galway (INGR M 476647). The core is now stored by the Geological Survey of Ireland.

Lithostratigraphy

The lithostratigraphy is broadly similar at all four localities: the Waulsortian buildups overlie a sequence of bedded, argillaceous limestones, the top 10 or more metres of which are cherty. Mantlehill, Knockadrum and Hill 707 lie in the 'Limerick Province' (Philcox, 1984), where these argillaceous limestones form the upper part of the Ballysteen Formation. Further to the north and east, closely similar rocks are known as the Argillaceous Bioclastic Limestone (ABL; see Fig. 1, inset b). To simplify the terminology and avoid problems of formal stratigraphic nomenclature, these beds will be considered here as the 'cherty ABL facies'.

The Mantlehill locality is situated in one of the thickest (about 1000 m) parts of the Waulsortian Complex. At the other localities, the Waulsortian succession is much thinner (up to several hundred metres) and is mainly formed of isolated banks or aggregates of banks, probably ranging individually from hundreds of metres to many kilometres across, enveloped by rocks of ABL facies. At each locality, a transitional facies can be recognized in the field between the cherty ABL and the Waulsortian facies. It is variously distinguished by bedding character, colour and texture of the limestone and by loss of chert. The thickness of the unit varies as follows: Mantlehill 1·9 m; Knockadrum 2·4 m; Hill 707 0·9 m; Dunmore 3·2 m.

It should be noted that the definition of transition facies is very specific (details follow) and should not be confused with other applications of the term 'transition' in the literature. For example, Strogen's (1988, p. 127) 'Transition Phase' is up to 30 m thick and comprises a range of lithologies: 'thinly bedded dark grey and more thickly bedded pale grey micrites, locally rich in chert, with sporadic development of small bank forms'. This is not the same as, although it may include, the transition facies in this study.

Biostratigraphy

On the available data, the selected localities show the same basal contact systematically offset in time – progressively younger from south to north. No biostratigraphic information is available from Mantlehill but, in the Pallaskenry borehole, about 8 km to the east, Somerville & Jones (1985, fig. 4) dated the base of the Waulsortian Complex as being low in the *Polygnathus mehli mehli* Subzone of the late Courceyan. At Dunmore, the northernmost locality, the Waulsortian facies started in the upper part of the *Scaliognathus anchoralis* Zone judging from the general map published by Andrew (1993, fig. 5.10b). This is compatible with data on the foraminifera, which, at Dunmore and Hill 707, indicate levels no higher than Cf3 (scale of Conil *et al.*, 1991). The age range represented thus probably extends through much of the *Scaliognathus anchoralis* Zone.

METHODOLOGY

Sampling

Closely spaced samples, contiguous where possible, were taken through the interval from the top of the cherty ABL to the basal part of the Waulsortian facies, and spot samples were taken above and below. At Dunmore, sampling was less dense and extended over a greater interval (about 5 m below to 2 m above the contact) because the development of the Waulsortian facies there appeared relatively progressive.

Petrography

A total of 162 thin-sections (mostly about 15 cm^2 rock area) was studied: 44, 35, 20 and 63 for Mantlehill, Knockadrum, Hill 707 and Dunmore respectively. Dolomitization and silicification were both noted as estimated percentages. However, after preliminary tests showed little to be gained by quantifying the various limestone fabric types, they were recorded on a presence/absence basis. Over 40 allochem grain-types, mainly skeletal debris, were recognized and ranked on a four-point scale. The ranking was based on visual estimates of volumetric (not numeric) importance of grain-types irrespective of the proportions of matrix or cement.

LIMESTONE FABRICS

Introduction

In general, the limestone fabrics are well preserved. At Mantlehill, neomorphism is more severe than elsewhere, so there is some loss of detail in the finer-grained fabrics, but this is not serious. Dolomitization and silicification both occur in parts of the sampled sequences. Dolomitization never obscures the primary fabrics, and only in a few samples is silicification extensive enough to interfere with determination of the allochems.

Most of the limestones fall in the wackestone–packstone range but, at Dunmore, the cherty ABL has much grainier intercalations than at other localities. In contrast, samples from Hill 707 are particularly fine-grained throughout. The only textural feature common to all sections is that the Waulsortian facies is dominantly wackestone, whereas the underlying facies are generally grainier, with wackestone only rarely recorded. However, this textural categorization is based on the general character of each thin-section and tends to disguise the fact that a variety of muddy fabrics occurs in the transitional facies underlying the banks. These muds are doubtless related to the micritic beds or pods (sometimes labelled as 'reefy', i.e. having some Waulsortian characters) reported by various authors from the beds below and from the lateral equivalents of Waulsortian buildups in Ireland (e.g. Philcox, 1984; Brown & Romer, 1986; Grennan, 1986; Strogen, 1988; Somerville *et al.*, 1992a).

The Waulsortian rocks themselves are known to be characterized by multicomponent muds (Lees, 1964) called *polymuds* by Lees & Miller (1985, 1995, pp. 209–210). These are highly structured deposits showing successive geopetal relationships in complex cavity systems. The bulk of these muds was deposited before remaining voids were filled with cements of cryptofibrous calcite (CFC) and/or blocky calcite, but it is not unusual to find mud generations deposited during the early stages of cement formation.

A possible link between the polymuds and the muddy fabrics of the transition facies is provided by the toe-bank facies (Whitbread, 1963). This is a particular type of muddy sediment that occurs at the toe of the inclined bank beds in the passage zone to their off-bank lateral equivalents. Described in detail by Miller (1986), the toe-bank lithology comprises poorly fossiliferous micritic lenses that become more frequent towards the bank and aggregate to form a pseudobreccia before passing laterally to the Waulsortian polymuds. The prime example described by Miller (1986) was situated on Hill 707, near Loughrea, at a point about 100 m from the section sampled in the present study.

Because of the wide variety of carbonate muds described by previous workers, special attention was given to the various mud types and their mutual relationships.

Mud types

Two main categories of carbonate muds occur: (1) grumous, i.e. more or less clotted or peloidal; and (2) non-grumous (Fig. 2). Both types exist in the Waulsortian polymuds. The term 'grumous' is used to emphasize the fact that the micritic clots (some of them peloids or containing peloids) in these fabrics never existed as free allochems. Admittedly, similar fabrics are commonly called 'peloidal', but that term is now applied to such a variety of features that it requires constant qualification if the meaning is to be clear. Moreover, it is also used for 'normal' limestones containing free peloids (for discussion, see Pickard, 1996, p. 68). As the latter also occur in some Waulsortian limestones, there is a need to make a clear distinction. The following varieties of carbonate mud have been recognized and logged.

Grumous

These fabrics, which range widely in character, are subdivided on their apparent density into three intergrading types.

Type 1. Pale, vaguely grumous and often in small (millimetric), poorly defined masses diffused between coarser grains (Fig. 2a).

Type 2. Slightly darker, and composed of denser, well-defined micritic micro-clots surrounded by microspar or coarser sparry calcite. This type often has a very open structure of loose floccules and occasional sparry fenestrae (Fig. 2b).

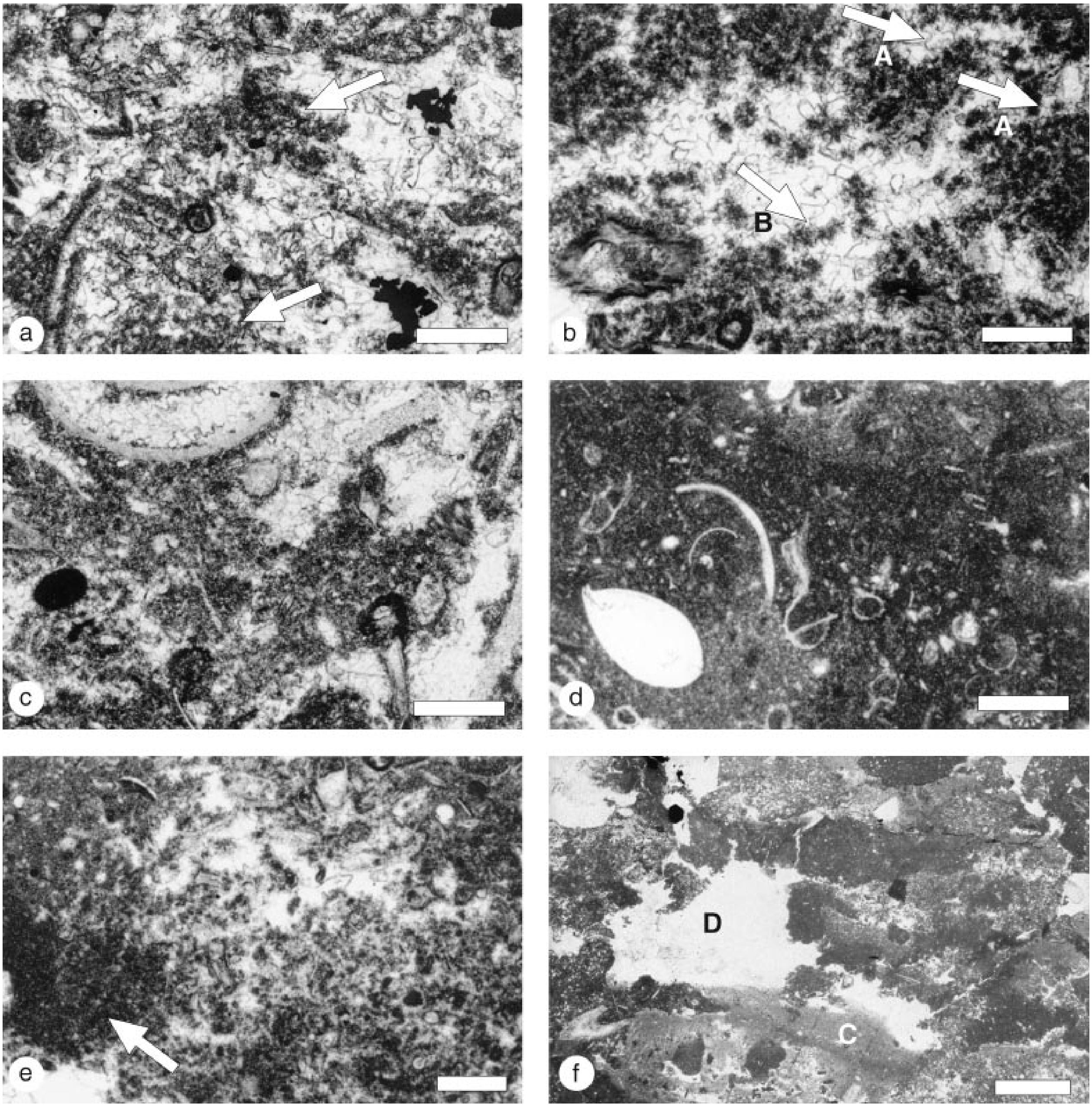

Fig. 2. Features of the precursor mud types and initial polymuds, shown in plain polarized light micrographs. Scale bar = 500 μm in (a)–(e) and 2 mm in (f). (a) Grumous Type 1 (arrows), Knockadrum. (b) Grumous Type 2, Knockadrum: note the sparry fenestrae and their flat floors (arrowed A) with no distinct geopetal sediment, and the rods of grumous fabric (arrowed B) suggesting calcification of microbial filaments (cf. Monty, 1995, fig. 19B). (c) Grumous Type 3, Knockadrum: the large bioclast at top left is a worm tube. (d) Non-grumous wackestone with ostracods and other skeletal debris, Dunmore. (e) Gradation from grumous Type 2 mud (occupying most of field of view) to grumous Type 3 and then to non-grumous mud on left (arrowed), Dunmore. (f) Very early development of polymud fabric at the base of the bank at Hill 707. Note that non-grumous muds are more important than grumous ones. Voluminous geopetal sediments (C) are capped by a final cavity fill of non-fibrous cement (D). The cracking of the non-grumous muds forming the roof of this cavity, together with the small mud clasts in the geopetal sediment below, demonstrate the coherent nature of the muds at an early stage (similar features from a comparable position were illustrated by Miller, 1986, fig. 4A). Such marked cracking may result from the absence of crypto-fibrous cement, characteristically the early cavity-filling fabric, which only appears about 40 cm higher in the bank.

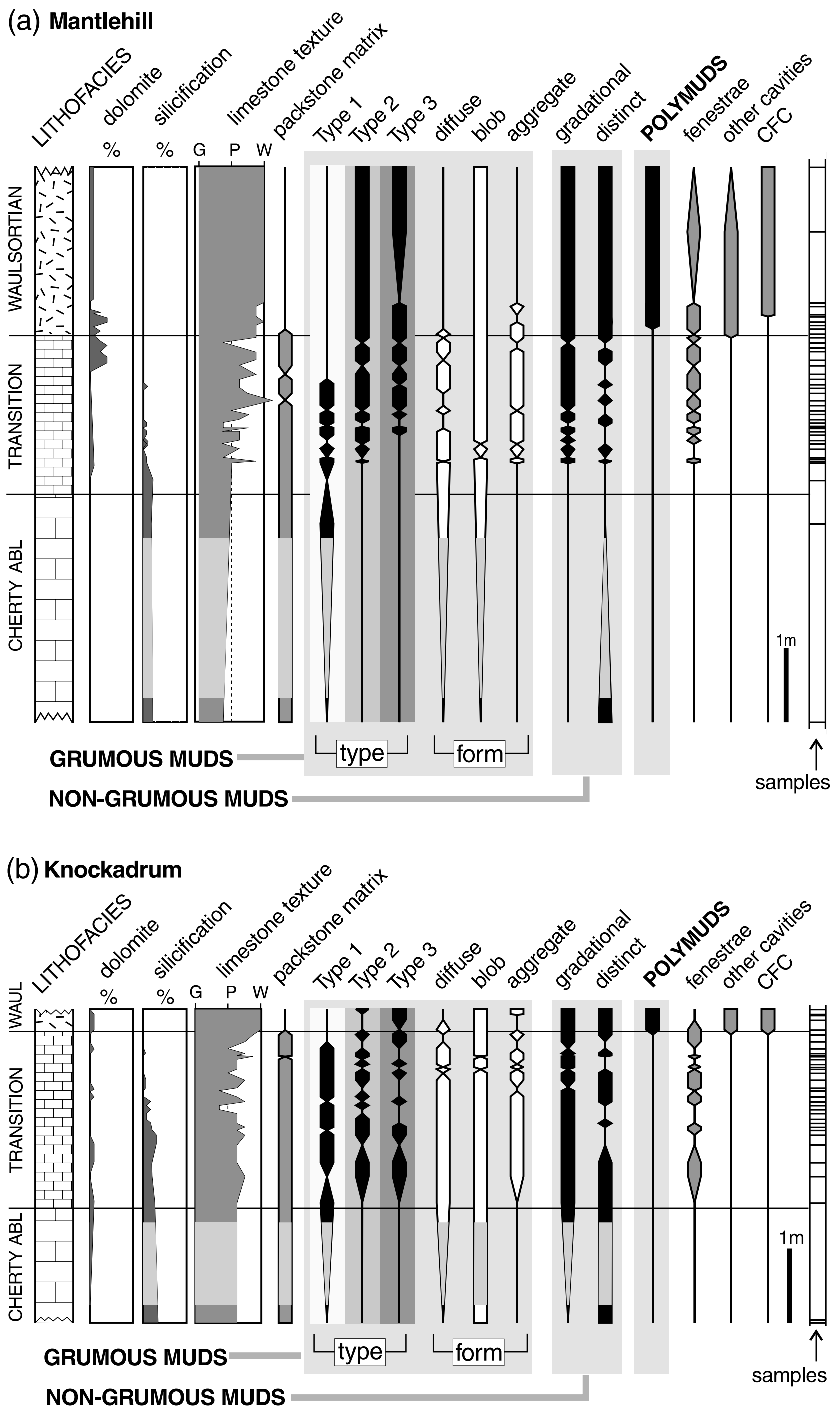

Fig. 3. Lithological and textural characters with particular emphasis on the carbonate muds and associated features. (a) Mantlehill ($n = 43$). (b) Knockadrum ($n = 35$). (c) Hill 707 ($n = 20$). (d) Dunmore ($n = 63$). As the general dip in the Dunmore section is low (5–10° measured in the ABL facies), no correction has been made for true thickness; the base of the Waulsortian bank in the drill-core lies at a depth of 155·2 m. Horizontal lines mark the boundaries between facies as determined in the field. The sampling column indicates the mid-point of each thin-section. Limestone texture is recorded on the Dunham scale (G, P and W = grainstone, packstone and wackestone). Textures intermediate between standard types indicate the presence of more than one category in the thin-section and their relative proportions. All mud characters and associated features (see text for descriptions) are recorded as presence/absence. CFC = crypto-fibrous calcite. 'Other cavities' includes shelter and stromatactoid cavities (spar-filled) generally much larger than the sparry fenestrae, which rarely exceed a few millimetres.

Type 3. Dark, optically dense and compact with closely packed, micritic micro-clots. An openwork structure with sparry patches is present in some instances (Fig. 2c).

Non-grumous

Bioclastic wackestones (and, more rarely, lime mudstones). There are two categories: those that are *distinct* (Fig. 2d) and those that will be called *gradational muds* because they grade imperceptibly into grumous muds (Fig. 2e).

Packstone matrix. Fine-grained sediment between the allochems.

Polymuds

These structured multi-generation muds showing successive geopetal relationships (Fig. 2f) contain

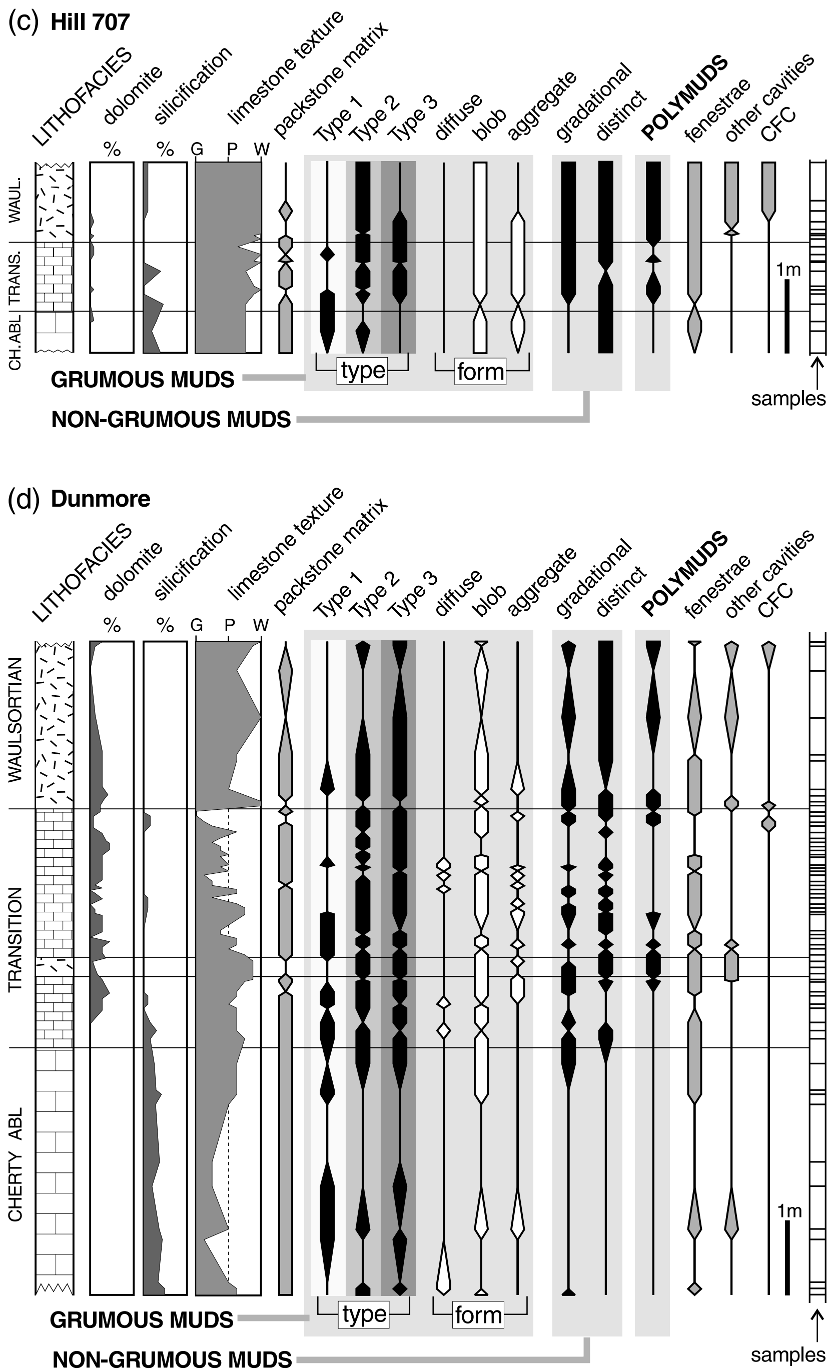

Fig. 3. Continued.

both grumous and non-grumous muds, the latter usually being dominant.

Occurrence of muds and associated features

The grumous muds occur in various forms, most commonly as blobs (a few millimetres to 1 or 2 cm across) ranging from lenticular (with long axes roughly parallel to bedding) to irregular. Even in the matrix of bioclastic packstones in the ABL, there are sometimes small inter-grain blebs of Type 1 mud. Blobs of all three types, but most commonly Types 2 and 3, may cluster in aggregates or, more rarely, extend into thin layers. Stylolites commonly delimit well-developed muddy blobs and disguise the original contact with the adjacent bioclastic sediment. However, when that contact is preserved, it is commonly abrupt. Compactional drape of skeletal debris over the blobs is common. In some instances, early, refittable and spar-filled cracks extend inwards from the margins.

Where fenestrae are present, they range from small, irregular sparry patches (up to a few millimetres across) to networks that are more extensive, although small-scale (Fig. 2). Many fenestrae show no shape differentiation between roof and floor, but some have a flat floor suggesting the presence of an internal sediment in a cavity. Commonly, however, the mud of the floor is grumous and indistinguishable from the remainder of the mass (Fig. 2b). In a few instances, a distinct geopetal internal sediment is present and consists of wackestone or lime mudstone. The grumous fabrics are normally poor in skeletal debris when compared with the wackestones, but the dark, compact variety quite often contains sponge spicules. Several of these grumous and non-grumous mud types may occur together. In the transition facies, any distinct patches of wackestone fabric present tend to show geopetal relationships with the grumous masses. This association exists occasionally in quite complex aggregates, but these can usually be readily distinguished from the more highly structured polymuds.

Distribution of the muddy fabrics

A broad pattern is evident (Fig. 3). The fine-grained component of the cherty ABL facies generally occurs as packstone matrix, as small and sporadic developments of grumous fabrics (usually Type 1) and as occasional wackestone patches. The transition facies, initially defined on various macroscopic criteria, proves to have the same range of mud types and associated characters at all four localities. Grumous fabrics of various types and complexity dominate. Fully developed toe-bank features have only been noted at Hill 707 and Mantlehill. The grumous fabrics, which appear in the transition facies, also extend into the primary mud generation of the polymud system (the M1c of Lees & Miller, 1995, p. 209), where they commonly form rather larger, irregular masses (up to 1 or 2 cm across).

At Mantlehill, there appears to be a progressive increase in the complexity of the mud fabrics and associated structures upwards through the transition facies (Fig. 3a). This evolution is not obvious in the other three localities, so correspondence analysis (CA), which was shown by Hennebert & Lees (1991) to be a very effective ordination method with presence/absence data, was used in an attempt to find an underlying pattern. The analysis, using 13 parameters in presence/absence mode, showed a moderately developed ‘arch effect’ in the plane of axes 1 and 2 (Fig. 4a), indicating that the parameters lie on a compositional gradient. This proves to be a relay, within which the parameters have overlapping ranges. The position of each sample in the gradient can be expressed by a Relay Index (RI; technique of Hennebert & Lees, 1991, p. 630; see also Lees & Miller, 1995, fig. 22), which provides the horizontal scale for the relay (Fig. 4b). This index is here called the Mud-RI to distinguish it from the Bio-RI introduced later.

An association of packstone matrix muds and grumous Type 1 muds characterizes one end of the relay, whereas the polymuds, commonly with CFC cements, constitute the other. Between the two extremes, the development of grumous Types 2 and 3 is followed by that of gradational muds. An association of the various types of grumous and non-grumous muds then develops, and distinct non-grumous muds appear in geopetal relationships. This trend of increasing complexity culminates in the polymuds. As the muddy fabrics of the transition facies appear to herald the development of the Waulsortian polymuds, they can usefully be called *precursor muds*. Examples of their macroscopic features are shown in Fig. 5.

The succession of mud types and associated features represented in the relay is accompanied by a general increase in mud content (Figs 5 and 6). The succession is also essentially the same as that observed, in stratigraphic order, on the raw-data logs for Mantlehill (Fig. 3a). Logs on which the Mud-RI is plotted for each sample in stratigraphic order provide a useful method of representing the characters of the muddy fabrics through the sampled interval at each locality (technique of Hennebert & Lees, 1991, pp. 636–637). As Fig. 7 shows, these confirm the tripartite (facies) subdivision of the sequence and allow a closer definition of the limits of the transition facies than do the macroscopic criteria used initially. Henceforth, the transition facies will be redefined in terms of the presence of the precursor muds (grumous Types 2 and 3).

The precursors form a simple stratigraphic entity at Mantlehill and Hill 707, with Mud-RI trends that increase upwards in a zig-zag manner (the few low-RI ‘troughs’ are packstone layers). At Knockadrum, the precursor unit is also evident but, there, the RI trend *decreases* upwards after

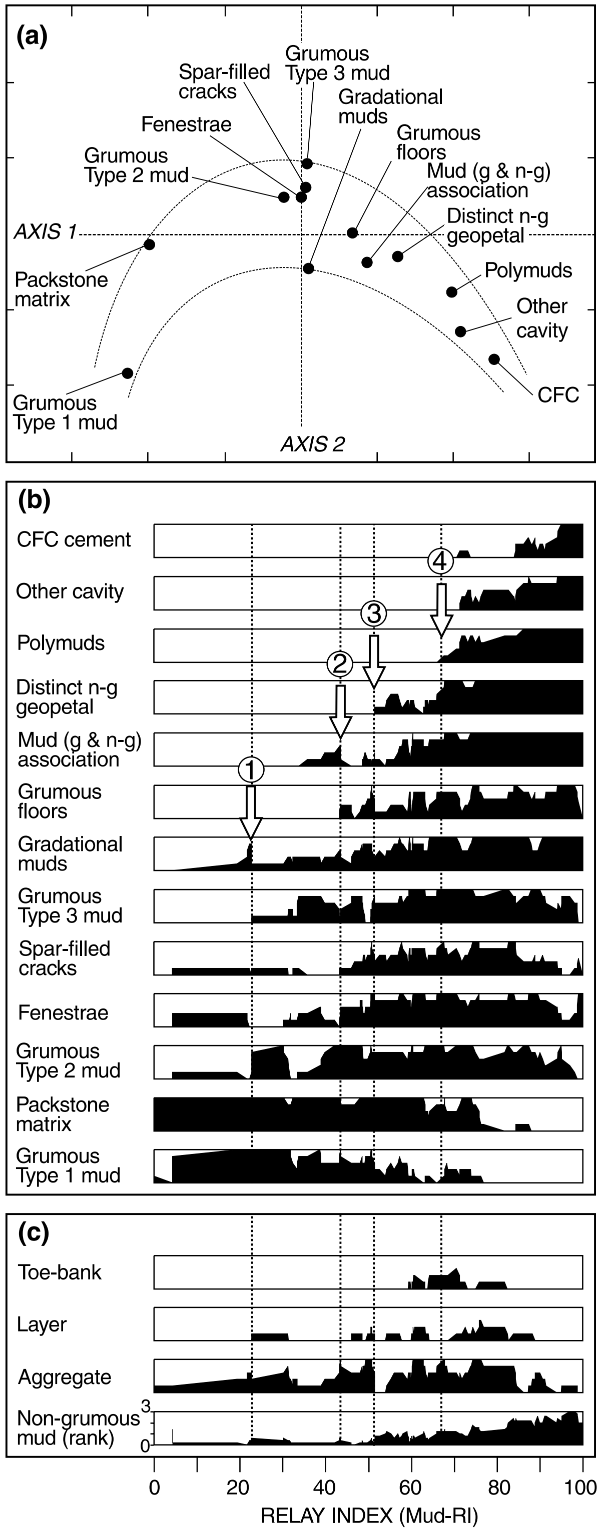

Fig. 4. Results of correspondence analysis (presence/absence mode) of mud types and associated fabrics. (a) Plot of the plane containing axes 1 and 2 showing the point cloud of the 13 parameters. Envelope curves outline the arch effect. Details of parameters are given in the text and Fig. 3. Conventions and abbreviations: 'grumous floors' are those of the fenestrae; 'g and n-g', grumous and non-grumous respectively; 'distinct n-g geopetal' refers to the presence of distinct wackestones showing geopetal relationships to grumous masses; 'other cavity' includes shelter and stromatactoid cavities (spar-filled) generally much larger than the sparry fenestrae, which rarely exceed a few millimetres. (b) Relay derived from the analysis. The relay index (labelled 'Mud-RI' to distinguish it from the Bio-RI introduced later) was obtained from the intercept of each sample on axis 1 (for details of technique, see Hennebert & Lees, 1991, p. 630; Lees & Miller, 1995, fig. 22). The presence/absence of each sample was then graphed, and the moving average of five samples was taken. Vertical scale = 0 (absence) to 1 (presence). The height of each curve thus provides an indication of frequency of presence. Note how the relay expresses the developmental sequence from the ABL (low Mud-RI) to the Waulsortian facies (high Mud-RI). Dashed vertical lines indicate stages in the sequence: (1) lower limit of transition facies; (2) initiation of grumous floors in fenestrae and increased frequency of cracking; (3) appearance of non-grumous geopetal muds; (4) start of polymud formation. (c) Distributions of four other characters not included in the analysis but plotted by using raw data and the RI of the samples derived from the relay. Vertical scale = 0 (absence) to 1 (presence) except where stated otherwise. 'Layer' and 'aggregate' = morphology of the mud masses; 'non-grumous mud (rank)' = relative importance measured on a scale of 0–3. Note: (i) the tendency for aggregation to increase erratically through the transition facies; (ii) the concentration of toe-bank near the point where polymud formation starts; and (iii) the increasing frequency and importance of non-grumous mud in the upper half of the relay.

an initial sharp increase. Dunmore displays much more irregularity, but there is obviously a thick unit rich in precursor muds.

ORIGIN AND DEVELOPMENT OF THE MUDS AND TRANSITION FACIES

Grumous and non-grumous muds

The grumous fabrics have the characters of deposits formed by microbial activity *in situ*. Similar fabrics were illustrated by Monty (1995, figs 5B and 8) and other workers studying mud-mounds (Monty *et al.*, 1995). The grumous muds would be categorized as automicrites by Reitner *et al.* (1995, p. 4 *et seq.*) and Neuweiler *et al.* (1999, pp. 840–842), who distinguished various fabric types and related them to formation via organic matrices (organomicrite). Some of these concerned 'organically filled confined spaces', including bacteria-rich sponges. Many of the

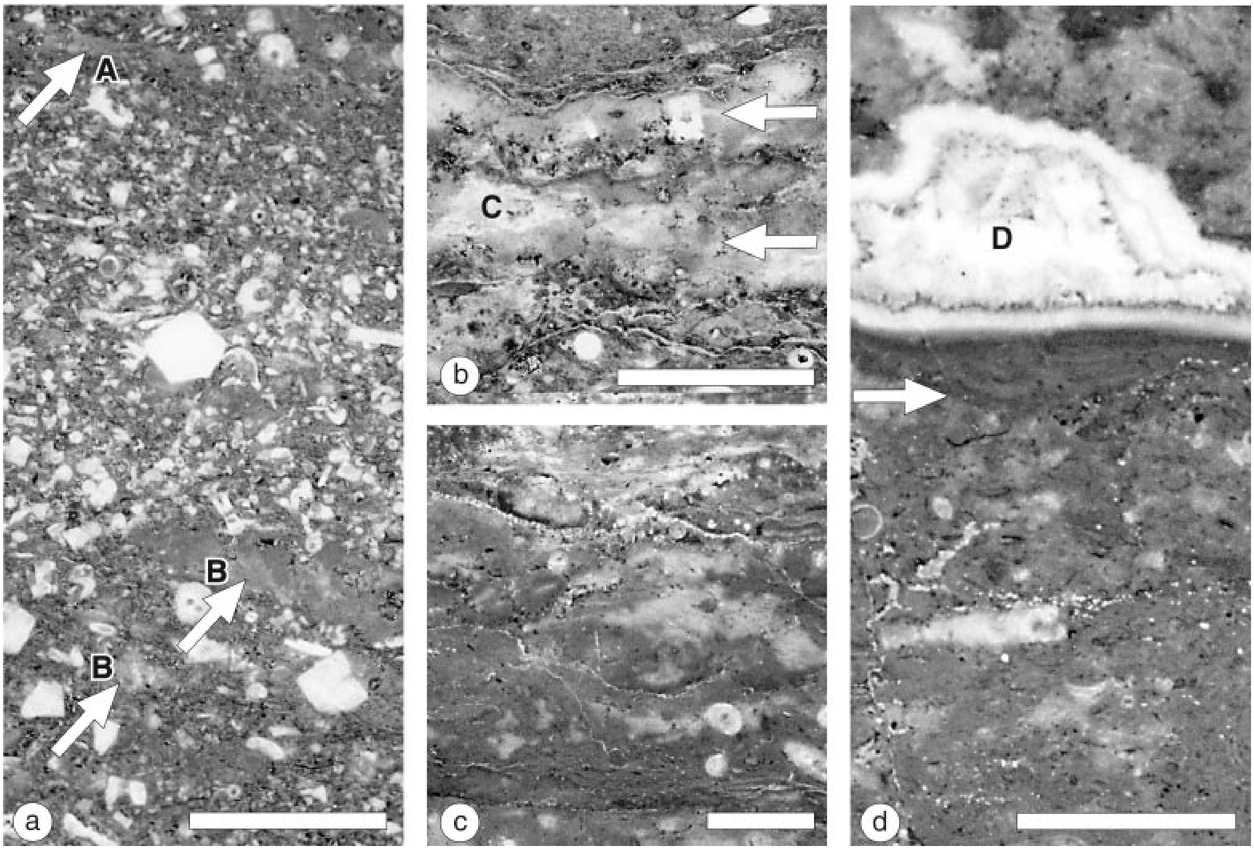

Fig. 5. Polished surfaces illustrating macroscopic features of precursor muds at various stages in the developmental sequence (indicated below by the Mud-RI for the corresponding thin-section). For details of the fabrics present at the various Mud-RI values, see Fig. 4. Note the general increase in muddiness from (a) to (d). Scale bar = 1 cm in all cases. (a) Thin, discontinuous layer (arrowed A) and a slightly disrupted mass of blobs and small aggregates (lower third of photograph; two examples arrowed B) of precursor muds lying in a crinoidal packstone–grainstone; 90 cm below the base of bank, Dunmore. Mud-RI = 60. (b) Two irregular layers of precursor muds (arrowed), locally bounded by stylolites, in a packstone–wackestone setting; Knockadrum. Mud-RI = 63. The pale blotches (e.g. at C), often pinkish in colour, are a common feature of these muds and can be seen, less well developed, in the other samples; their cause is unknown. (c) Bed formed from an aggregate of precursor mud blobs, mainly wackestone; 30 cm below the base of bank, Hill 707. Mud-RI = 80. (d) Basal contact (arrowed) of the bank at Knockadrum showing polymuds overlying a continuous mass of precursor muds (lower half of photograph). The precursor muds are mainly non-grumous. Textures are wackestone throughout. Mud-RI = 90–100. Note that the form of the large cavity (D) in the basal polymuds is unusual, as its walls were locally modified by dissolution before the introduction of the geopetal sediment and the cement fill (CFC followed by blocky calcite).

muddy masses in the transition and Waulsortian facies contain sponge spicules, so similar processes may have been involved there.

In contrast, many of the non-grumous lime mudstones and wackestones have geopetal relations with other muds and appear to have behaved as loose sediments, even if only for a short time. However, those non-grumous muds that have gradational contacts with, and appear to develop from, grumous ones may represent a change in the type of in-place microbial activity to one in which more homogeneous micrite was produced under conditions that allowed the incorporation of introduced skeletal debris.

Formation of the transition facies

At first sight, the position of the transition facies below the Waulsortian buildups suggests that precursor muds 'prepared the ground' in a way necessary for the establishment of the banks, by forming a patch on the sea floor before the bank started to grow. However, this takes no account of the possible effects of bank progradation. Nor does it explain the presence, in the transition facies, of the toe-bank lithology that developed in the lateral transition from bank to off-bank beds (Miller, 1986). This relationship suggests that the whole progression of precursor mud

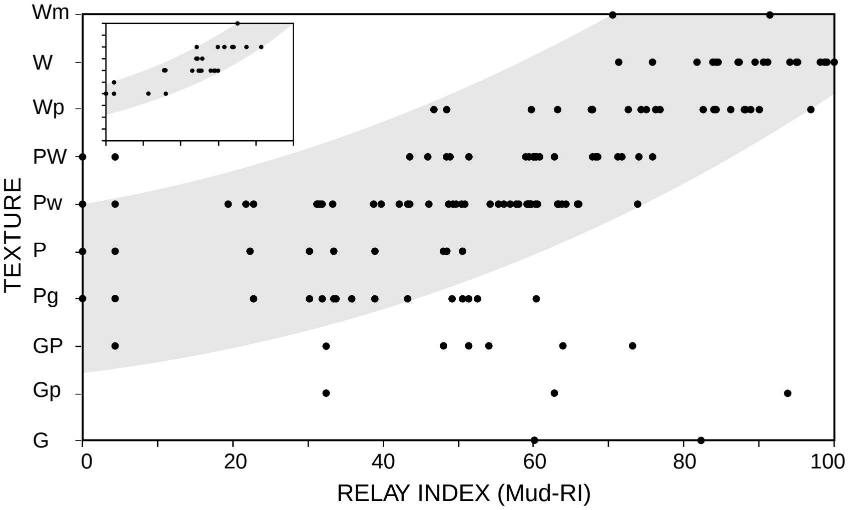

Fig. 6. Relay Index of mud characters (Mud-RI) plotted against limestone texture for all samples. 90% of them lie in the shaded area showing a broad trend of increasing muddiness with increasing RI, i.e. with increasing complexity of the precursor mud system culminating in the Waulsortian polymuds. This trend is also evident when samples of the transition facies are considered alone (see inset: Mantlehill). Samples outside the main trend, mainly from Dunmore, are grainy rocks in which the muddy masses are too small to influence the textural classification. G, P, W and M = grainstone, packstone, wackestone and mudstone. Intermediate texture codes indicate the presence of more than one category and their relative importance: for example, in Gp, the packstone component is subordinate to grainstone, whereas in GP, the proportions are equal.

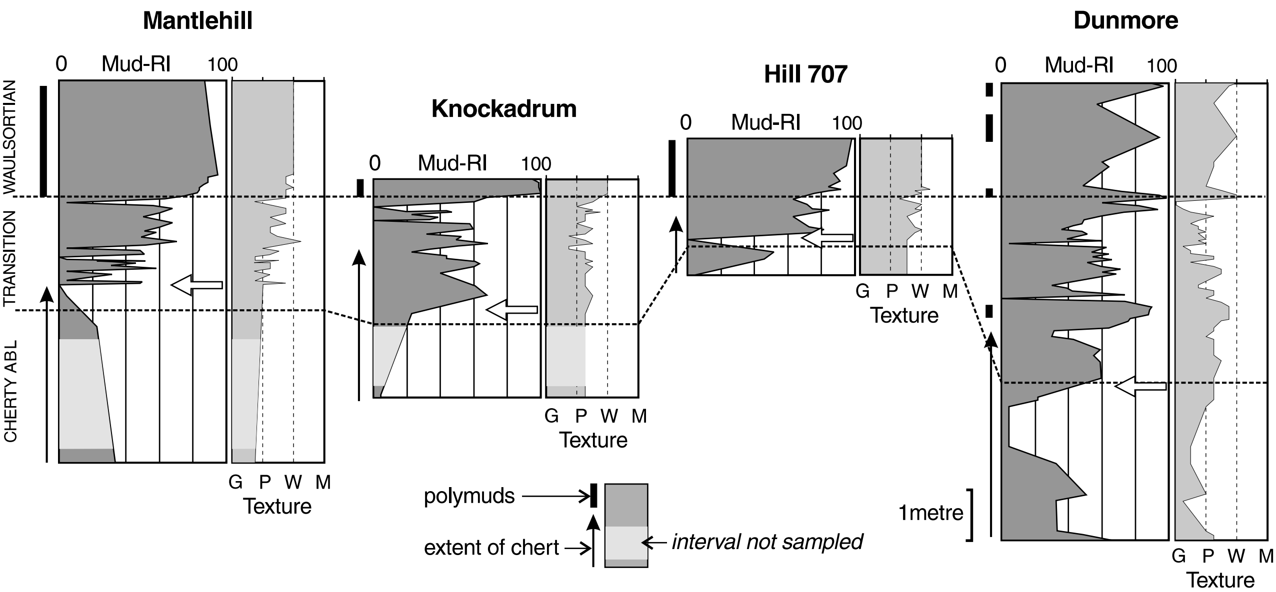

Fig. 7. Stratigraphic plots of the Relay Index of mud characters (Mud-RI) for each locality. Limestone texture and the stratigraphic extent of chert are shown for comparison. The correlation lines across the figure indicate the facies boundaries based on field evidence; the open arrows mark the base of the transition facies based on mud characters. G, P, W and M = grainstone, packstone, wackestone and mudstone. Note the zig-zag increase in Mud-RI through the transition facies at Mantlehill and Hill 707. At both localities, this is preceded by a drop in RI to near zero. Knockadrum shows quite a different pattern as there is no initial drop, and the trend up-section shows a *decrease* in average RI. The RI curve at Dunmore is much more irregular.

fabrics also formed in the lateral passage from bank to ABL facies, thus forming an aureole of sediment around the banks. In this scenario, the position of the transition facies underlying Waulsortian banks would be explained by bank progradation. As progradation is a common

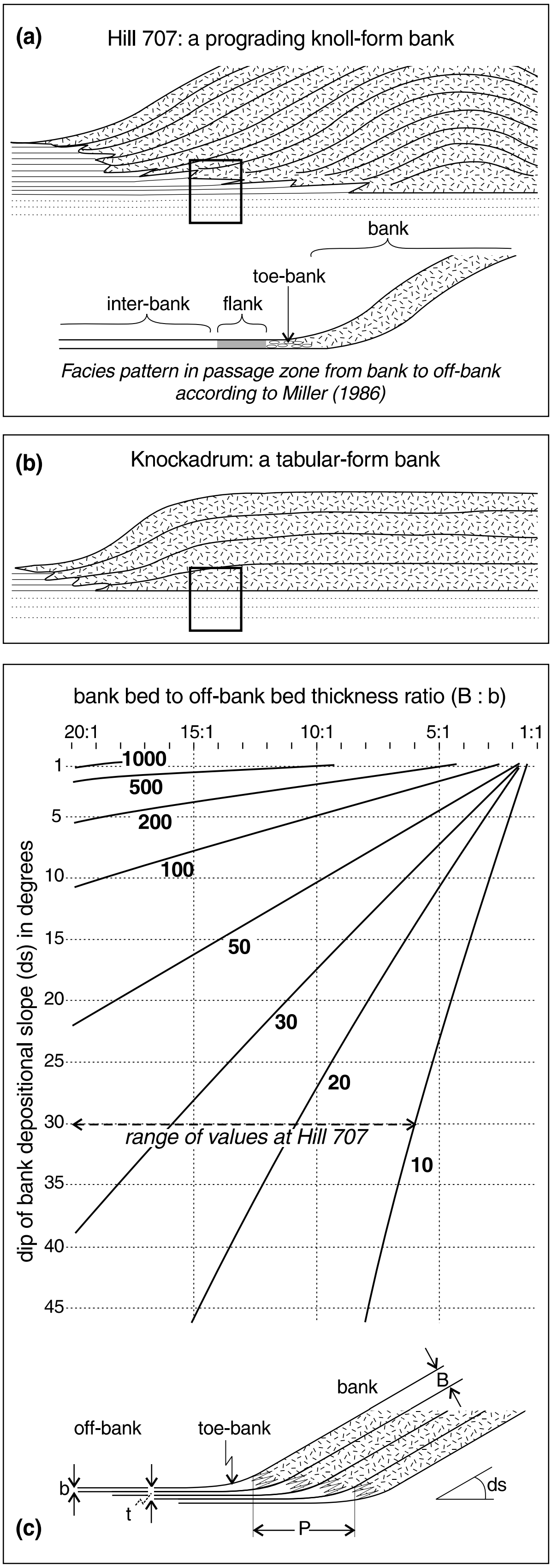

Fig. 8. (a) The upper diagram shows a schematic vertical cross-section through part of a prograding knoll-form bank as displayed at Hill 707. From the position of the studied section (rectangle), it is evident that the beds immediately underlying the bank are the off-bank lateral equivalents of a slightly earlier stage of bank growth. The lower diagram indicates the terminology used by Miller (1986) for the facies developed in the lateral passage from bank to off-bank (his 'inter-bank'). (b) Schematic vertical cross-section through part of a tabular-form bank such as that at Knockadrum. The beds immediately below the bank in the studied section (rectangle) are not the lateral equivalents of bank beds, and the transition facies cannot be explained by progradation. (c) The relationship between the thickness of transition facies beneath a Waulsortian bank and uniform bank progradation. The numbered curves indicate the progradation (P, in cm) required to develop laterally equivalent off-bank beds (t) 1 cm thick. For example, to produce a 1-m-thick transition facies with a sedimentation ratio of 15:1 and a bank slope of 35° requires about 25 m of progradation. The range of values for Hill 707 is indicated. As the transition facies represents a traverse from the edge of the aureole to the bank margin, the progradation distance equals the width of the aureole. Variables are the depositional slope (ds) of the prograding bank margin and the ratio of the thickness of laterally equivalent individual beds in the bank and off-bank (B:b). Note that combinations of very low depositional slopes and high bank/off-bank thickness ratios are not sustainable, as the depositional slope necessarily increases.

phenomenon in Ireland, it will be examined first.

Hill 707: formation by bank progradation

Hill 707 (Fig. 8a) was an appropriate place to test the progradation hypothesis as the studied section and the lateral passage described in detail by Miller (1986) are only about 100 m apart in the strongly prograding margin of a knoll-form bank (Lees, 1964, pp. 495–497). Miller (1986, p. 313) recorded that, at the point he examined, the lateral passage from the inclined bank beds to the thinly bedded, argillaceous inter-bank (= 'off-bank' here) facies occurs via toe-bank and a thinly bedded, crinoidal flank facies (Fig. 8a). The transition from bank to flank occurs within a distance of 1–3 m. This poses two problems:

1 How does this 'crinoidal flank facies' (wavy-bedded packstones and grainstones) fit into observations of the transition facies?

2 Can a thickness of nearly 1 m of transition facies at the sampling site be explained by progradation of a passage zone only 1–3 m wide?

As regards the crinoidal flank sediment, samples from Hill 707 are generally fine-grained and have neither grainstones nor fully developed packstones. Such grainy rocks may therefore be only locally developed and of small extent.

The problem of the thickness of the transition facies is much more serious. A narrow passage zone could have produced a thick transition facies if the margin of the actively growing bank was static. Such a situation did exist for a short time during growth of the bank on Hill 707 (Lees, 1964, fig. 10, point A), but this appears to have been exceptional: progradation was the dominant process. The amount of progradation required to produce a specified thickness of transition facies in a purely progradational system can be estimated from the depositional slope of the bank beds and the thickness ratio between bank beds and their off-bank lateral equivalents (Fig. 8c). Miller (1986) recorded a bank/off-bank thickness ratio of between 6:1 and 20:1 and depositional slopes of up to 40°. Lees' (1964, fig. 10) map shows that, in the zone between the two sampling sites, the bank slopes range between 20° and 35°, more commonly the latter. Assuming a value of 30°, the observed 90-cm-thick transition facies would require progradation of between about 9 m (at 6:1) and 34 m (at 20:1). The aureole would thus have been an order of magnitude wider than the 1–3 m mentioned by Miller (1986), and his crinoidal flank beds would have formed part of it. Unfortunately, the suggested relationships cannot be confirmed by direct observation because, at Miller's sampling site, exposures are restricted so that individual off-bank beds cannot be traced laterally for more than a metre or two. However, as progradation is dominant and lateral passages are observable, the existence of an aureole seems indisputable.

The Mud-RI log for this section (Fig. 7) shows a zig-zag, but progressive increase in values from the cherty ABL to the Waulsortian facies. This is consistent with the approach of a single bank, assuming that an increase in Mud-RI (i.e. an increase in complexity) corresponds to increasing proximity of the bank.

Knockadrum: formation without progradation

At Knockadrum, the bank is of tabular form (i.e. the basal bank beds are conformable with the underlying ones and are flat-lying), and the exposure shows a lateral passage to ABL facies. As there is very little marginal, and no observable basal progradation (Fig. 8b), it seems that the 2-m-thick transition facies observed in the sampled section cannot be explained by the process invoked at Hill 707. However, as has been shown elsewhere (Lees, 1994, pp. 42 and 45), it is practically impossible to predict with certainty the geometry and behaviour of a bank even 2 or 3 m behind the face of an exposure. Thus, the observable features of the Knockadrum exposure may not provide a sure basis for interpretation. Fortunately, the characters of the precursor muds themselves provide a clue. Examination of Fig. 7 reveals a zig-zag, but progressive upward *decline* in the Mud-RI through most of the transition facies, followed by a sharp increase near the base of the bank. The bulk of the transition facies thus appears to be unrelated to the bank above. It could represent the aureole of another (unexposed) bank nearby, perhaps with retrograde growth (Lees, 1994, p. 41) to explain the upward decline in RI values. However, the sharp increase in the Mud-RI curve within 20 cm of the base of the exposed bank is significant. Such a development immediately below a tabular-form bank, where no progradation is detectable, suggests that this is a real and perhaps necessary precursor to polymud and therefore Waulsortian bank formation.

Mantlehill and Dunmore: bank growth-form unknown

At Mantlehill, where the transition facies is 1·8 m thick, nothing is known of the growth geometry of the Waulsortian banks, and no lateral passage to off-bank facies can be observed. Shephard-Thorn (1963, p. 276) suspected that the base of the Waulsortian Complex in the area was diachronous, and one of the authors (A.L.) has observed lateral passage from inclined bank beds to off-bank limestones at the basal contact near Pallaskenry, about 7 km east of Mantlehill. The Mud-RI log (Fig. 7), although interrupted by several low Mud-RI troughs (in packstones), shows a progressive increase that would be consistent with the steady approach of a prograding bank. Interestingly, the toe-bank lithology is fully developed here, as it is at Hill 707. To explain the thickness of the transition facies, an aureole width of several tens of metres would be needed, assuming that the bank margin had a moderate depositional slope.

The drill-core at Dunmore provides no direct evidence for lateral relationships, but Philcox

(1984, p. 36) concluded, from the study of other boreholes nearby, that there is considerable variation in the stratigraphic level of the base of the Waulsortian buildups in this area. The Mud-RI log in most of the interval between the cherty ABL and the main Waulsortian buildup (Fig. 7) is irregular, so the lower part could readily be interpreted as resulting from the aureoles of one or more banks nearby. Indeed, at one level, there is a thin, weak and temporary development of polymuds. Significantly, this is preceded by a progressive development of the precursor mud sequence with four samples showing a systematic upward increase in RI values from about 60 to 88 (see Fig. 4 for mud characters corresponding to these values) resembling the situation immediately below the bank at Knockadrum. Similarly, the zig-zag increase in RI in the top 60 cm of the transition facies may well be related to initiation of the main overlying bank.

Summary and implications

Evidence from the four localities shows that bank progradation and associated migration of an aureole of precursor muds is a possible explanation for a thick development of transition facies showing progressive elaboration of precursor mud characters, including the toe-bank lithology. Thick developments lacking such progressive elaboration may be related to aureoles of other, nearby banks. Evidence from Knockadrum, and the polymud intercalation in the transition facies at Dunmore, indicates that a thin (<30 cm) unit of precursor muds could be a necessary preliminary to the establishment of a polymud system.

It remains to consider (1) the origin of the aureole; and (2) the cause of the increasing complexity that characterizes both thin transition units below banks where progradation cannot explain their presence (i.e. 'real' precursors) and thicker ones that formed in the aureole of a prograding bank.

The origin of the aureole: transported or *in situ*?

As the grumous mud types occur in both the precursors and the Waulsortian polymuds, derivation from material wafted off the banks must be considered. However, as Miller (1986) argued, the (grumous) mud lenses of the toe-bank formed more or less in place. The following arguments tend to support this and extend it to the precursor muds as a whole.

1 Although bank derivation is consistent with the observed increase in mud content with increasing proximity to the bank, such a process does not account for the progressive increase in complexity of mud types and their associated textural and structural features.

2 Except at Dunmore, where there are relatively frequent signs of breakage and reworking (Fig. 5a), evidence of fracture of the muddy blobs consistent with breakage off a larger mass is slight. The marginal cracking occurred *in situ*. It was regarded by Miller (1986, p. 317) as having 'formed by pre-compactional dewatering in a firm gel-like substrate'.

3 When floors are present in the fenestrae of grumous mud blobs, they match the present polarity and are not disturbed, as would be expected if the blobs had been transported.

4 Wackestone, which dominates in the Waulsortian facies, is absent from or only a minor component of the transition facies.

5 Derivation of the precursor muds from a bank nearby would not account for the presence of the precursor sequence before the initiation of a bank on a new site (e.g. in the uppermost 20 cm below the bank at Knockadrum).

Formation of precursor muds: a model

The *in situ* formation of both the aureole and a pre-bank precursor mud carpet can be assimilated into a single model (Fig. 9). As the aureole would have to be laterally graded in character to account for the observed progression in mud characters, a similar feature can be envisaged in a pre-bank carpet. The initial stage would be the formation on the sea floor of a patch of simple precursor muds. Enlargement of the patch, and the resulting differences in age and maturity between the centre and spreading margins, could account for the centripetal increase in complexity of the mud characters. As the Waulsortian polymuds appear to be the natural culmination of this developmental process, they would be expected to form somewhere in the central part of the patch. Even at this early stage, therefore, the first Waulsortian bank bed would have a laterally graded aureole around it. If the aureole was persistent, bank progradation and the resulting migration of the aureole would construct transition facies units of the type and dimensions observed. At present, there is no observational evidence to confirm this – detailed study of a tabular-form bank and its lateral equivalent is required.

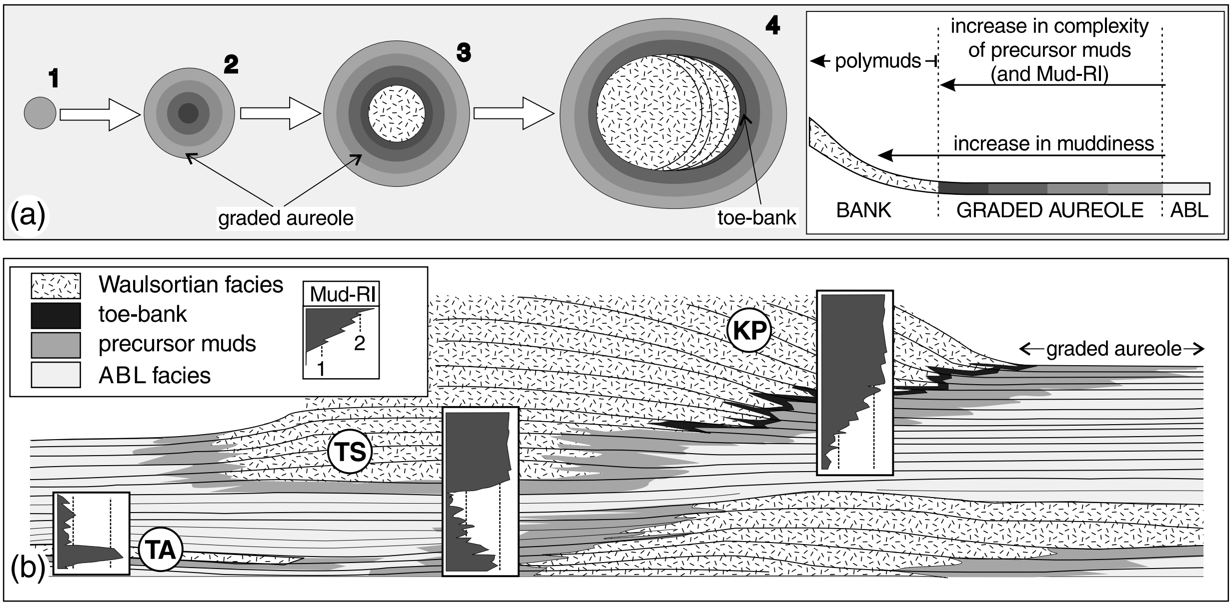

Fig. 9. Model showing the envisaged relationships of precursor muds to Waulsortian banks. (a) Schematic plan view of the postulated developmental sequence starting from (1) an initial patch of simple precursor muds. (2) As the patch spread, the muds gradually increased in complexity centripetally. (3) The Waulsortian polymuds then began to form in the centre. (4) The precursor muds persisted as a graded aureole around the bank, which is shown prograding. (b) Vertical section showing the relationships between the precursor muds and various bank growth-forms. The degree of development of the precursor mud sequence is indicated by the Mud-RI curves, where (1) marks the value at which precursor muds start and (2) the beginning of polymud formation. TA = an aborted tabular-form bank (such as that below the main Waulsortian bank at Dunmore): the Mud-RI shows a rapid increase through a thin transition facies because it is a true precursor and there is no progradation. TS = a tabular-form bank with static margin (e.g. Knockadrum): the Mud-RI in the thin transition facies unit immediately below the bank shows a rapid increase for the same reason as TA; the thicker unit of transition facies in the lower part of the log with Mud-RI *decreasing* upwards is related to another bank that is migrating away from the site. KP = a prograding knoll-form bank (e.g. Hill 707 and, probably, Mantlehill): because of bank progradation, the Mud-RI increases gradually through a thick transition facies (including a toe-bank facies).

Initiation of the Waulsortian facies: the final step to polymuds

As has been reported previously (Lees & Miller, 1995, fig. 32), the onset of polymud formation can be abrupt. For example, at Knockadrum, where, according to the model studied here, the whole precursor sequence related to the initiation of the bank is about 20 cm thick, the final step to polymuds with well-developed geopetal muds and CFC cements occurs over a few millimetres (Fig. 5d). Such a rapid development seems characteristic of a situation in which there was no progradation. The onset of polymuds is similarly abrupt at Dunmore. In contrast, at Hill 707, a strongly prograding knoll-form bank, there is a tentative development of weak polymuds (no CFC) within the transition facies (Fig. 3c), presumably resulting from pulsating development of the approaching bank margin. The definitive move to polymuds finally occurs through a thickness of about 10 cm, within which there is considerable cracking of both grumous and non-grumous muds (Fig. 2f). The first CFC cements occur about 40 cm higher. Similarly, at Mantlehill, the progression from sediment comprising a jumble of grumous blobs to a polymud with a well-developed cavity system extends over a thickness of 22 cm. Again, the appearance of CFC cements is delayed (a further 5 cm).

Thus, situations in which progradation is known or suspected appear to produce basal Waulsortian contacts in which polymud development occurs through some 10–20 cm, whereas where progradation is absent, polymud initiation is more abrupt. The relay showing increasing elaboration of grumous muds and associated fabrics culminating in polymuds suggests that this is a developmental process. Certainly, by the time the polymuds started to form, some of their basic mud types (e.g. grumous Types 2 and 3) had already appeared, and some of the others can be explained by *in situ* microbial activity below the bank surface (Lees & Miller, 1995, p. 257).

Such a sequence of predominantly grumous precursor fabrics might be expected to lead to buildups of the type seen, for example, in the Viséan of eastern Ireland (Somerville *et al.*, 1992b) and Scotland (Pickard, 1992), where 'peloidal' fabrics are very important. However, this does not happen here. Although the grumous muds persist into the Waulsortian banks as part of the primary mud generation, the polymuds cannot be explained simply as 'more of the same'. The appearance of distinct geopetal sediments late in the precursor mud succession heralds the development of various non-grumous muds, some of them in the primary generation of the polymuds and others as geopetal internal sediments in the cavities. These are volumetrically more important than the grumous fabrics. Admixture with surficial bioclastic material is common in these muds, so redistribution must have been extensive.

Some additional process therefore seems to have occurred to trigger polymud development and cause the notable increase in sedimentation rate that led eventually to bank building. The nature of this trigger remains elusive. It is unlikely that oceanographic processes were responsible because, if this model is correct, polymud formation only occurred within the precursor mud patches. As the Waulsortian Complex spread across Ireland this must have occurred many thousands of times and over a wide range of water depth and hydrodynamic energy. Moreover, there is evidence that new banks could initiate while others were dying only a few tens of metres away (Lees, 1994). All this, together with the sequential relationship between precursor muds and polymuds, suggests that the trigger arose naturally through organic and related biochemical processes within the confines of the precursor mud patch. The nature and scale of the changes introduced by the trigger imply the intervention of a new parameter that stimulated microbial activity to produce micrite at a markedly greater rate and in a much more complex structure riddled with cavities. Such increased organomicrite production may have been related to new sources of decaying organic matter. Reitner & Neuweiler (1995, p. 62) cited sponges as being effective in this respect, and Neuweiler *et al.* (1999, p. 854) suggested that the 'increasing complexity of fabrics involved infers that polymud fabrics might be indicative of a major contribution to reefal accretion by metazoans, such as sponges'. As sponges existed in both the ABL and the Waulsortian facies, their arrival, as a group, cannot be invoked to provide the trigger. However, Lees (1964, pp. 518–523) argued that some of the depositional fabrics in Waulsortian banks could be explained by internal rearrangement as a result of collapse following the decay of voluminous soft-bodied organisms (which may also have contributed to micrite production). Perhaps, therefore, the mature precursor mud patches provided ideal conditions for colonization by a particular group of sponges or other soft-bodied metazoans whose metabolism and decay set in train the microbial processes leading to the formation of polymuds.

Warnke & Meischner (1995, p. 42) reported a similar, sponge-related problem from the Upper Viséan mud-mounds of north-west Ireland. They too favoured microbial degradation of the soft tissue of siliceous sponges as the mechanism for micrite production, but observed that such sponges were common both on and off the mud-mounds. They therefore suggested that the mounds resulted from local concentrations of sponges associated with carbonate production triggered by warm water seeps related to nearby faults. Such a mechanism is difficult to envisage in the Waulsortian Complex because of its enormous lateral extent and lack of such intimate relationships with faults. Furthermore, the introduction of warm waters might have been expected to affect the indigenous biota, but no such feature is known.

The evidence from the precursor mud sequence suggests that reinforcement of carbonate precipitation mechanisms resulting from positive feedback processes involving organisms is more likely than an external trigger. Whatever it was that stimulated polymud formation, the increase in sedimentation rate alone might well have had a 'knock-on' effect by changing the pattern of early diagenetic degradation of buried organic materials and favouring different microbially mediated processes. These, in turn, may have stimulated the formation of early micritic cements, stabilizing the muds and allowing the formation of large cavity systems in which crypto-fibrous cements subsequently grew.

Wider implications

Although it seems that no precursor mud sequences have been reported from positions immediately underlying carbonate mud-mounds at other stratigraphic levels, this does not mean that they do not exist. Waulsortian buildups have been studied for many decades in various parts of the world, but precursors have not been detected previously. Their recognition in Ireland may have been helped by the rapid spread (about 200 km in the timespan of the *Polygnathus mehli mehli* condont Subzone) and wide extent of the Waulsortian Complex there. The rapid spread entailed frequent bank nucleation, often followed by extensive progradation, both conditions likely to make the transition facies with its precursor muds relatively obvious. The wide extent provided more opportunities for the exposure of study sites. In other situations, where buildups were more isolated and progradation less common, precursors may be present but in a much more discreet form. They would then only be detected if the few centimetres below the basal contact of a buildup were subject to specific sampling and petrographic scrutiny.

Recognition of precursor sequences, however small, is important for the elucidation of mechanisms involved in mud-mound formation. Hypotheses advanced to account for the sudden appearance of a major mud-mound lithofacies, complete with complex primary and early diagenetic fabrics, may well be significantly different from those required to explain growth starting from a few isolated blobs of microbially mediated grumous mud within normal sediments.

NATURE AND DISTRIBUTION OF ALLOCHEM GRAIN-TYPES

Observations

The distributions of 25 of the grain-types logged are shown on Fig. 10. They will be described and analysed using the following terms:

Dominance: volumetric importance relative to other grain-types in a sample. 'Dominant' and 'subdominant' correspond to ranks 1 and 2 on the measuring scale used.

Range: the distribution of a grain-type relative to the three lithofacies in any one locality.

Persistence: percentage of the samples from a given locality in which a grain-type is present.

Diversity: expressed as a Diversity Index, which records, as a percentage, the number of grain-types present in a sample out of those shown in Fig. 10.

Dominance. All the limestones belong to one major family insofar as fenestrate bryozoans and pelmatozoans are volumetrically the most important grain-types (often overwhelmingly so) in most samples. Indeed, at Dunmore, these organisms share the dominance virtually throughout. Only a few other organisms, mainly brachiopods and sponge spicules, ever attain such importance (Fig. 10).

Persistence and range. A few grain-types are ubiquitous, or nearly so, at all localities. They include the dominant or subdominant grain-types, fenestrate bryozoan and pelmatozoan, but also others, such as ostracod, which have very high persistence but are generally minor volumetrically. Sponge spicules and stick bryozoans both have persistence values in the range 66–100%. However, the values for many other grain-types vary markedly from place to place, some systematically, some erratically.

Those grain-types that vary systematically show a common tendency for increasing persistence from Mantlehill northwards to Dunmore. This trend is so strong that grain-types that are highly persistent (>85%) and range through all three lithofacies increase in number northwards from 7 at Mantlehill to 14 at Dunmore. Two of the 14 (plurilocular foraminifera and moravamminids) are absent from Mantlehill and Knockadrum and make their appearance sporadically at Hill 707 (Fig. 11a). Eight relatively minor grain-types present in every locality but showing this regional change in persistence are plotted in Fig. 11b. Most of these are rare (perhaps only one or two grains per thin-section) at localities where persistence is low and are more numerous in samples from localities where persistence is high. At localities where a particular grain-type is of low persistence, it may show some restriction of range, being unrecorded from one or more lithofacies. There are several examples of this at Mantlehill (hyalosteliid sponge spicules, *Earlandia*, gastropods and aoujgaliids), but there are fewer and fewer further north as persistence increases. The significance of these restricted distributions will be discussed later.

Among the grain-types with erratic persistence are the following (persistence percentage given in the order of localities from south to north): rugose corals (12, 34, 0, 27), tabulate corals (88, 77, 0, 51), encrusting bryozoans (79, 86, 35, 94), worm tubes (77, 54, 40, 91) and indeterminate molluscs (33, 29, 65, 43). Some of these have a restricted range in some of the sections, the most striking being the tabulate corals in the transition facies and basal Waulsortian at Mantlehill. Within that interval, they are present in all samples and, in

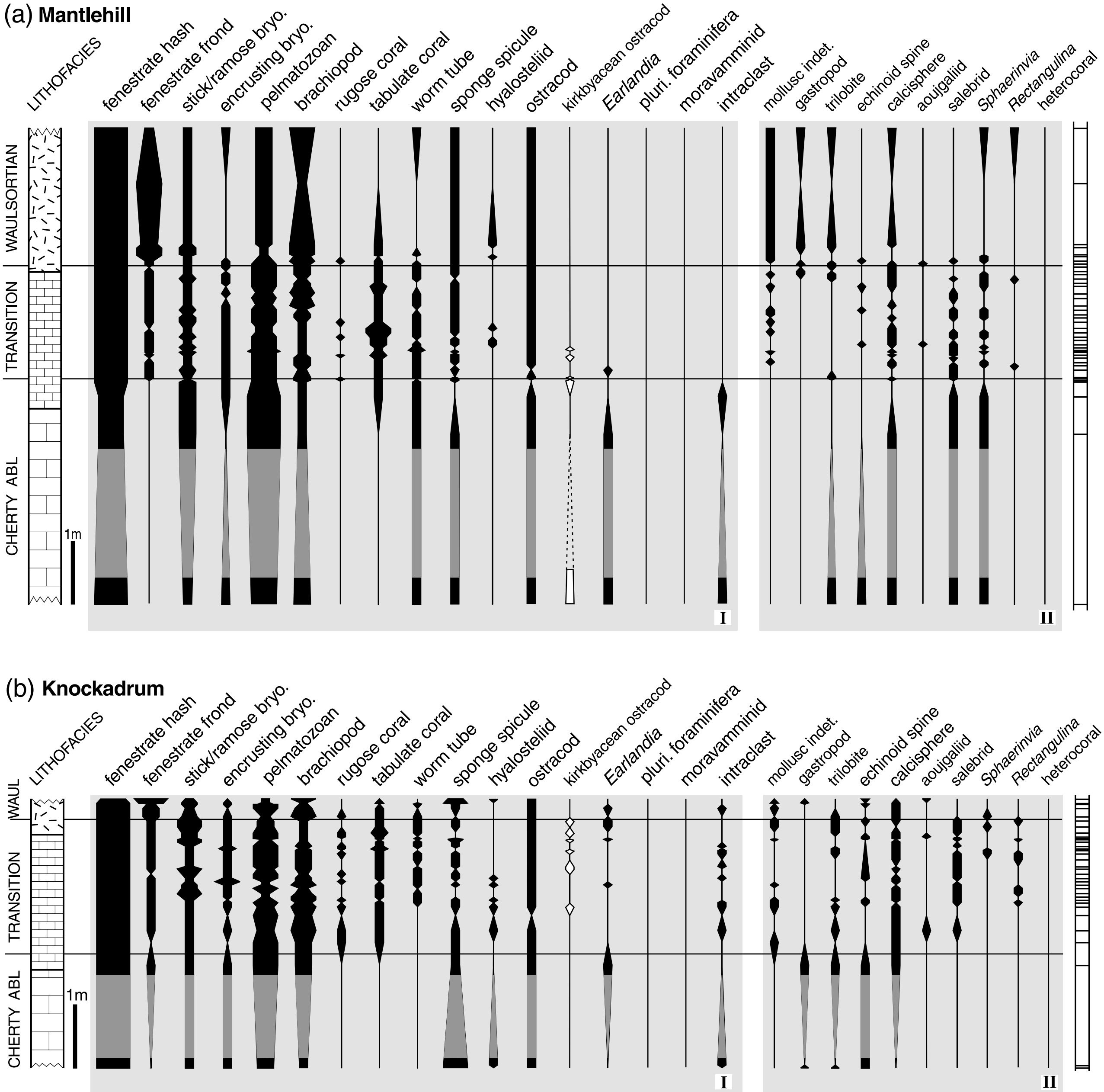

Fig. 10. Distribution of grain-types: (a) Mantlehill ($n = 43$); (b) Knockadrum ($n = 35$); (c) Hill 707 ($n = 20$); (d) Dunmore ($n = 63$). Each grain-type was recorded on a four-point ranking scale based on visual estimates of the volumetric importance of grains independent of the proportions of matrix or cement. Pale ornament in the logs of the Cherty ABL at Mantlehill and Knockadrum indicates an interval not sampled. The sampling column indicates the mid-point of each thin-section. The grain-types plotted in box I are those that exceed the lowest rank in at least one locality. The kirkbyacean ostracods are an exception, but they are placed here for comparison with the main ostracod trend. The width of the bar corresponds to the ranking – the wider the bar, the higher the rank; a thin vertical line indicates absence. In box II, the grain-types are always minor, never exceeding the lowest rank at any locality. The lithofacies indicated by ornaments in the left-hand column are those determined in the field, whereas the horizontal lines across the figure show the limits of the transition and Waulsortian facies based on the arrival of precursor muds and polymuds. Conventions: 'fenestrate bryozoan', small hash is logged separately from larger fragments of frond (five zooecia or more); 'pelmatozoan', mainly crinoid; 'sponge spicule', this column excludes the large 'hyalosteliid' spicules, which are logged separately; 'moravamminid', groups all the tubular microfossils, septate or not, of the order Moravamminida (Termier *et al.*, 1975, 1977) and includes some, such as the palaeoberesellids, which have been regarded as dasycladacean algae (Skompski, 1987); 'pluri-foraminifera', plurilocular foraminifera of all types; 'mollusc indet.', includes all mollusc fragments not identifiable as gastropods, which are logged separately.

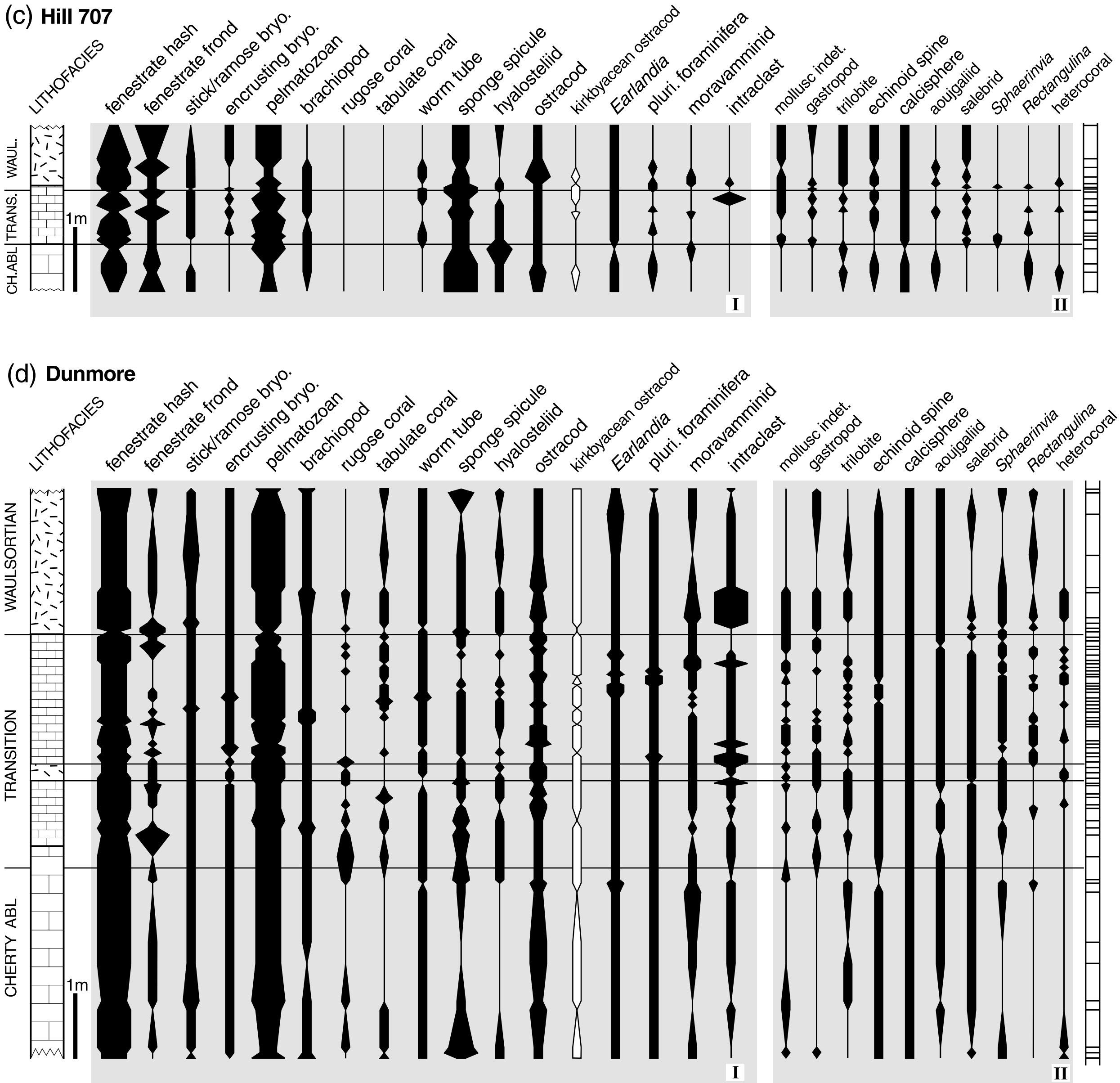

Fig. 10. Continued.

the middle of the transition, attain subdominant rank. A similar, but less marked distribution occurs at Knockadrum. However, the two northern localities are quite different: tabulates are absent from Hill 707 and occur sporadically throughout at Dunmore. Such a concentration of tabulates just below the base of the Waulsortian facies as that at Mantlehill have never been encountered elsewhere by the authors and no record of similar occurrences in the literature is known.

Grain types quantified by number. If it were possible to attain greater taxonomic refinement, more differences between and within the sampled sequences would probably emerge. For most organism groups, such refinement is impossible in thin-section, but it was attempted for stick bryozoans and plurilocular foraminifera whose numbers were also recorded.

Four stick bryozoan taxa were recognized: *Rhombopora*, *Pseudonematopora*, *Hexites* and *Sulcoretopora*. Of these, only *Sulcoretopora* shows a patterned distribution. Absent from Mantlehill and Knockadrum, it is moderately persistent in low numbers at Hill 707 and becomes the most persistent and abundant taxon at Dunmore (Fig. 11a). The total numbers of stick bryozoan individuals per sample (standardized to an area of 10 cm^2) also reveal differences between

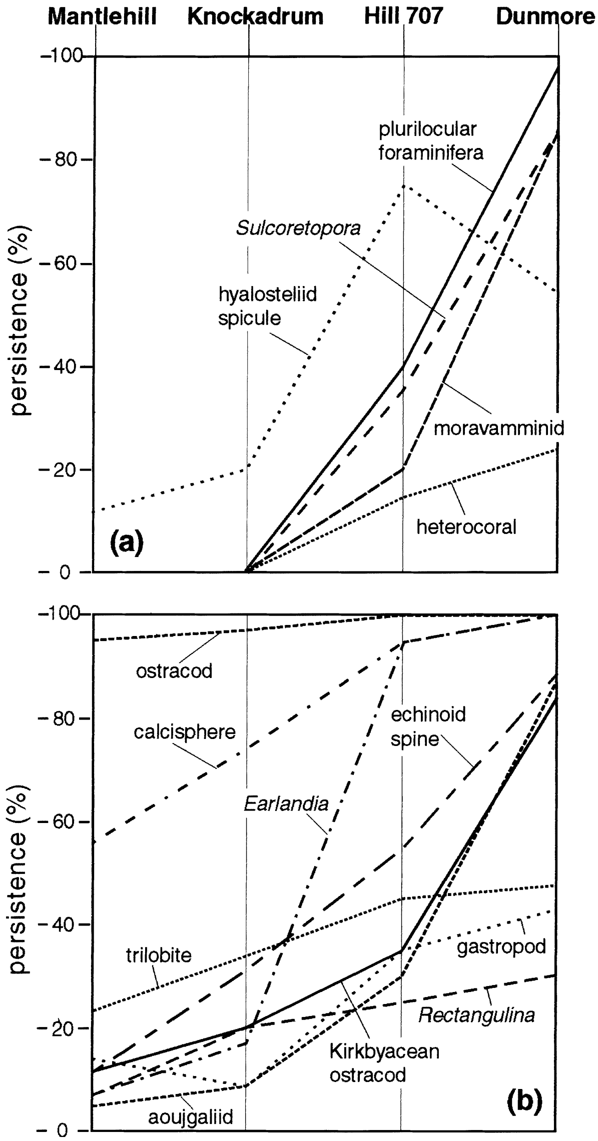

Fig. 11. Skeletal grain-types showing the regional trend of increasing persistence towards the north. (a) Four grain-types occurring only in the two northern sections; the hyalosteliid spicules are added to show their behaviour relative to the foraminifera and moravamminids (all three being key grain-types in Waulsortian Phases B and C). (b) Grain-types present in all localities but displaying increasing persistence northwards.

the southern and northern localities. At Mantlehill and Knockadrum the numbers are high (maxima 40 and 51 respectively) and are concentrated in or near the transition facies (Fig. 12). In contrast, at Hill 707 and Dunmore the variation is irregular through all facies, and the numbers are never very high (maximum about 7 per sample at Hill 707; 20 at Dunmore). Concentrations of stick bryozoans similar to those at Mantlehill and Knockadrum have been reported from the beds below Waulsortian buildups in Belgium (Lees *et al.*, 1985; p. 142).

Plurilocular foraminifera are present only at Hill 707, where numbers are low (0–3 per standardized sample), and Dunmore, where numbers vary dramatically from zero in a few samples to more than 70. The higher numbers (>10) occur in the grainier rocks. Of the types recorded (tetrataxids, *Eotextularia diversa*, endothyrids), *E. diversa* is the only one with a restricted distribution. At Hill 707, it only occurs in the Waulsortian facies, where it is present in three of the eight samples. At Dunmore, the taxon is absent from the lowest eight ABL samples in the present study (including one with nearly 30 foraminifera), even though it exists sporadically lower in the succession (A. Lees, unpublished data). However, it appears just before the main arrival of the precursor muds in a sample with low numbers, of which it forms over 70%, and then persists in most samples up into the Waulsortian facies. Here, then, is another example of increasing persistence and greater lithofacies tolerance from south to north.

Analysis of grain-type distribution

As previous experience has shown the value of correspondence analysis (CA) in detecting environmental gradients from grain-type distributions (Hennebert & Lees, 1991), this technique was used here. The resemblance between the presence/absence distribution patterns of organisms in the Waulsortian facies and those of coeval, proximal off-bank lateral equivalents has already been noted in various parts of the world (e.g. Lees *et al.*, 1985; Lees & Miller, 1995, pp. 221–222; Jeffery & Stanton, 1996). As the similarity is also evident in the present study, CA was applied to the whole data set. Pelmatozoans and fenestrate bryozoans were excluded because they are ubiquitous.

An analysis using 16 grain-types (all of them skeletal) produced a good arch effect in the plane of axes 1 and 2, indicating the presence of a relay (Fig. 13; the Relay Index for this is called the Bio-RI to distinguish it from the Mud-RI discussed earlier). The basic pattern is one in which three grain-types, stick bryozoa, brachiopod and ostracod, are present throughout. Below them in the relay are encrusting bryozoa, which are usually sporadic, but are rare at high Bio-RI values, and the two coral groups, both of which show the same tendency to a greater degree. In contrast, all the other grain-types appear as successive addi-

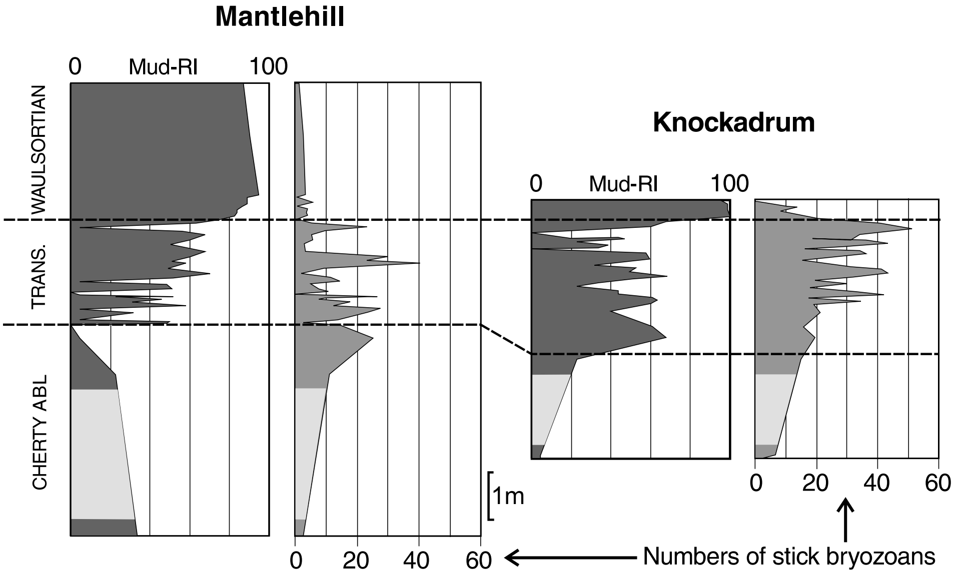

Fig. 12. Numbers of stick bryozoans at Mantlehill and Knockadrum and their relation to the characters of precursor muds (as represented by the Mud-RI). Note the broadly inverse relationship between the Mud-RI and bryozoan numbers in the transition facies. The term 'bryozoan numbers' expresses the number of individuals counted per thin-section standardized to an area of 10 cm^2.

tions whose distributions are increasingly restricted to high Bio-RI values. Stratigraphic plots of the Bio-RI for each locality reveal significant differences between the localities (Fig. 14). They also show marked lowering of the RI in the transition facies at Mantlehill and Knockadrum, but not elsewhere.

Interpretation of the basic pattern

The order of the organisms in this relay resembles that for the Waulsortian facies alone, described by Lees & Miller (1995, fig. 26, pp. 219–223). It also has significant features in common with the grain-type relay found in the limestones of the Upper Tournaisian ramp of south-west England (Hennebert & Lees, 1991) and with distribution patterns found in rocks of similar age in New Mexico (Jeffery & Stanton, 1996). All were interpreted in terms of a bathymetric gradient. Comparison with the present results is most easily made by reference to the Waulsortian Phases (A–D), which are essentially consecutive parts of the Waulsortian grain-type relay. The main components of the Phases are as follows (Lees *et al.*, 1985; Lees & Miller, 1985, 1994, p. 27, 1995, p. 218; Lees, 1997, pp. 31–33):

(A) fenestrate bryozoans, crinoids and ostracods, with or without brachiopods, molluscs, other bryozoans and sponge spicules (except hyalosteliids);

(B) as (A) but with the addition of hyalosteliid sponge spicules;

(C) as (B) plus plurilocular foraminifera and, commonly, moravamminids;

(D) as (C) plus calcareous chlorophyte algae.

These assemblages were interpreted in terms of water depths ranging from subphotic, perhaps 300 m or deeper (A), to relatively shallow photic (D), probably extending into a few tens of metres.

Examination of the relay (Fig. 13b) shows that the relative positions of the key grain-types (hyalosteliids, plurilocular foraminifera, moravamminids) correspond to those of the Waulsortian Phases. Thus, following the bathymetric interpretation, this means that a low Bio-RI indicates deeper water conditions than a high one. As in the Waulsortian relay, the distribution of intraclasts and grainstone fabrics (Fig. 13c) suggests increasing mechanical energy with increasing Bio-RI, i.e. towards the 'shallower' end of the relay.

Interesting additions to known distribution patterns are the heterocorals and the bryozoan *Sulcoretopora*, both of which appear to be restricted to the 'shallower' end of the relay. However, this may be spurious. Heterocorals of the type observed here only appear late in the Tournaisian (Cossey, 1997, p. 1032), so their presence in the 'shallower' northern localities, which are supposedly a little younger than Mantlehill and Knockadrum, may be a function

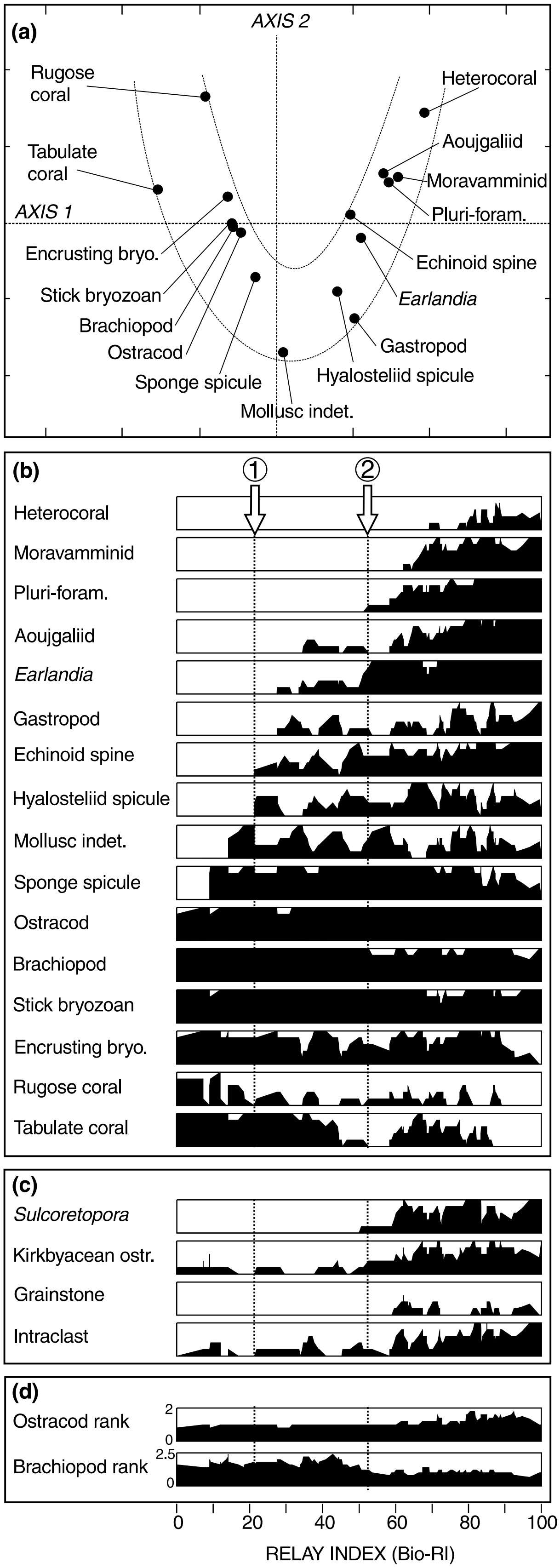

Fig. 13. Results of correspondence analysis (presence/absence mode) of skeletal grain-types. (a) Plot of the plane containing axes 1 and 2 showing the point cloud of the 16 grain-types. Envelope curves outline the arch effect. (b) Relay derived from the analysis. The Relay Index (labelled 'Bio-RI' to distinguish it from the Mud-RI used earlier) was obtained from the intercept of each sample on axis 1 (for details of the technique, see Hennebert & Lees, 1991, p. 630; Lees & Miller, 1995, fig. 22). The presence/absence of each sample was then graphed, and the moving average of five samples was taken. Vertical scale = 0 (absence) to 1 (presence). The height of each curve thus provides an indication of the frequency of presence. (c) Other parameters not included in the analysis but plotted for comparison. Vertical scale = 0 (absence) to 1 (presence). (d) Two of the grain-types included in the analysis but plotted here in terms of rank. Compare with presence/absence plots in (b). Although both organisms are virtually ubiquitous, and rank was not taken into account in the analysis, the brachiopods are shown to rank more highly at the 'deeper' (low Bio-RI) end of the relay, whereas ostracods tend to be more important at the 'shallow' (high Bio-RI) end. The vertical lines arrowed (1) and (2) indicate the levels in the relay at which the hyalosteliid spicules and plurilocular foraminifera appear, key grain-types for Waulsortian Phases B and C respectively.

of stratigraphic level. The same may apply to *Sulcoretopora* because, although the genus exists earlier, it seems to be unknown in Ireland before the late Tournaisian.

The Waulsortian rocks at the four localities under study can readily be allocated to specific Phases: Mantlehill and Knockadrum have samples of Phases A and B, Hill 707 has B and C, whereas Dunmore is C throughout.

Application to regional and local variation patterns

Regional variation

Much evidence indicates systematic regional variation along the line represented by the studied localities. It includes the presence/absence of particular grain-types, their persistence, abundance, diversity, Relay Index and restriction of range in the three lithofacies. In the upper part of the ABL and the transition facies there is an overall tendency for the Diversity Index to increase northwards (44·2% at Mantlehill, 46·4% at Knockadrum, 56·2% at Hill 707, 75·0% at Dunmore; Fig. 14). The average Bio-RI shows a similar trend (Mantlehill 14·6, Knockadrum 19·5, Hill 707 62·6, Dunmore 81·6).

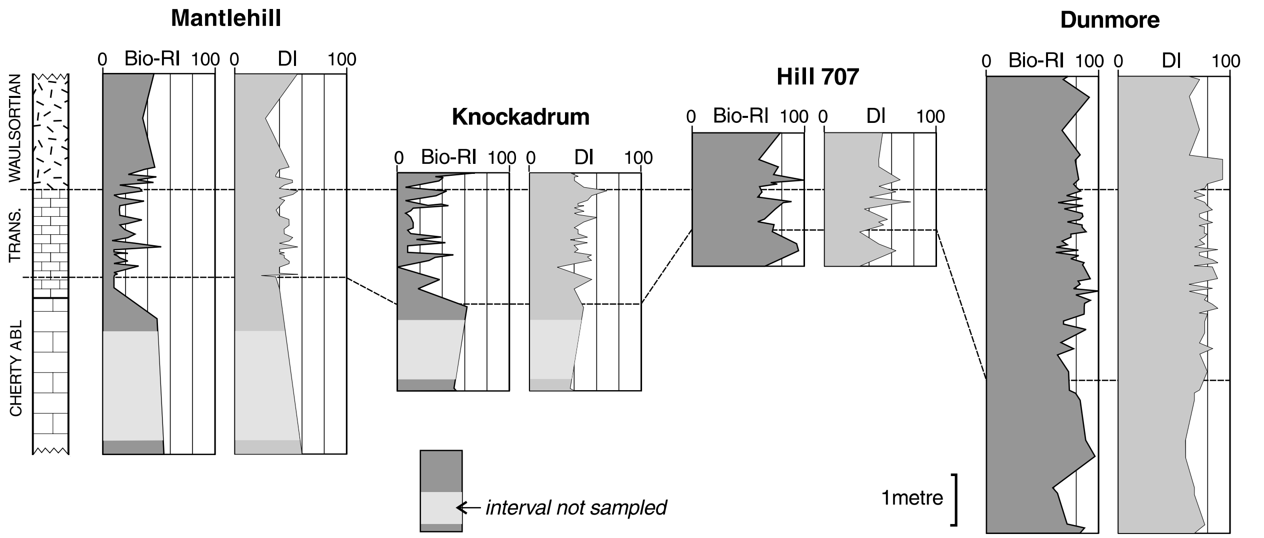

Fig. 14. Stratigraphic plots of Relay Index (Bio-RI) from correspondence analysis of skeletal grain-types (see Fig. 13) together with logs of the Diversity Index (DI). The latter records, as a percentage, the number of grain-types present in a given sample out of those shown in Fig. 10. The lithofacies indicated by ornaments in the left-hand column are those determined in the field, whereas the correlation lines across the figure show the limits determined by the arrival of precursor muds and polymuds. Note: (1) the increase in average values of both RI and DI from Mantlehill to Dunmore; (2) how the RI curves (but not the DI) distinguish the transition facies at Mantlehill and Knockadrum, but not at the other localities.

The same pattern occurs in the Phases of the overlying banks, thus confirming the trend detected by the pilot study of Irish Waulsortian buildups by Lees & Miller (1985, pp. 168–170), who noted that 'those (buildups) possessing the lower Phases (A and B) occur in a belt from Co. Limerick to Co. Galway and the Irish Midlands, while those with higher Phases (C and D) occur further east and north'. There also, diversity increased in parallel with the Phase changes from A to D (Lees & Miller, 1985, fig. 6). Although this trend is accompanied by a northward younging of the base of the Waulsortian facies, it cannot be explained by such stratigraphic differences, because, with the possible exception of the heterocorals, all the relevant organisms existed elsewhere in Europe during that time interval. This includes the zonal guide foraminifera *Tetrataxis* and *Eotextularia diversa* (e.g. Conil *et al.*, 1991, fig. 4), whose disappearance towards the south is related to the fact that there are no plurilocular foraminifera in the localities south of Hill 707.

Ecological control appears to have been dominant throughout the sequence because the grain-type assemblages of the upper part of the ABL and the transition facies resemble those of the overlying Waulsortian banks whose sediments accumulated essentially in place (Lees & Miller, 1995, pp. 223–227). The only realistic alternative to be considered is grain transport, for which there is no convincing evidence. At Dunmore, the presence of grainstone layers, disruption of precursor muds (Fig. 5a) and relatively common intraclasts suggests that these intervals represent deposition in relatively high mechanical energy, probably during storms. However, at the other localities, no depositional structures suggesting mass transport or any other long-distance displacement have been observed. Small grains can be transported in suspension for long distances, but the persistence trends do not appear to correspond to transportability. Local transport from any nearby Waulsortian banks could perhaps account for some features in the transition facies but cannot be extended to the ABL. The observed south–north increase in persistence of many organism groups (Fig. 11) and the appearance of plurilocular foraminifera and moravamminids are therefore related to environmental conditions, which, for them, improved progressively towards the north. Much of the observed variation in grain-type distribution is thus related to a regional pattern of northward shallowing.

Local variation between lithofacies

At Mantlehill and Knockadrum, some grain-types are restricted in their occurrence to part of the sampled sequence and tend to coincide broadly with the lithofacies. For example, at Mantlehill (Fig. 10a), *Earlandia* is restricted to the ABL, indeterminate molluscs to the transition and Waulsortian facies, and gastropods to the Waulsortian. This restriction is reflected in the Bio-RI curves (Fig. 14), which show striking differences between the lithofacies at those two localities. At Mantlehill, a sharp drop just below the base of the transition facies is followed by zig-zag recovery to ABL values near the base of the Waulsortian facies. In contrast, at Knockadrum there is a zig-zag *decline* before higher values again become the norm in the Waulsortian facies.

Such changes invite comparison with texture and the onset of the precursor muds at the two localities, where similar broad trends are evident (cf. Figs 7 and 14). At Mantlehill, most of the peaks in Mud-RI and Bio-RI coincide with an increase in the muddiness of the sample. After the initial Bio-RI drop, the grainier rocks have a low Bio-RI association (including encrusting and stick bryozoans, brachiopods, ostracods and sponge spicules), whereas the muddier ones have, in addition, one or more of the grain types entering higher in the relay. This is obviously not caused by depth oscillation. The organisms responsible for the change are all organisms that systematically increase in persistence from south to north (Fig. 11). For many of them, the southward attenuation occurs by a restriction of the textural range with which they are associated (Fig. 15). Thus, the general tendency for an increase in the Bio-RI through the transition facies towards the base of the Waulsortian facies at Mantlehill is related to increasing muddiness. Moreover, those organisms that appear in the transition facies and persist into the Waulsortian facies at Mantlehill (gastropods, indeterminate molluscs and hyalosteliids) are all associated with the muddier sediments. The same arguments apply to the transition facies at Knockadrum, but to a slightly lesser degree, because the textural 'tolerances' of some of the organisms are greater than those at Mantlehill (Fig. 15).

All these changes appear to be essentially ecological because selective transport from nearby banks or elsewhere cannot account for the features observed. This is also true of the tabulate corals and stick bryozoans, both of which are particularly well developed in and adjacent to the transition facies at Mantlehill and Knockadrum. North of Knockadrum, the differentiation between lithofacies diminishes and apparently disappears so that, at Dunmore, the lithofacies are indistinguishable on their grain-type content at the degree of taxonomic refinement usually attained in thin-section (Fig. 10d). Differences do exist there, but they are cryptic, relying on better taxonomic differentiation for their discovery, as exemplified by the behaviour of *Eotextularia diversa* (see above).

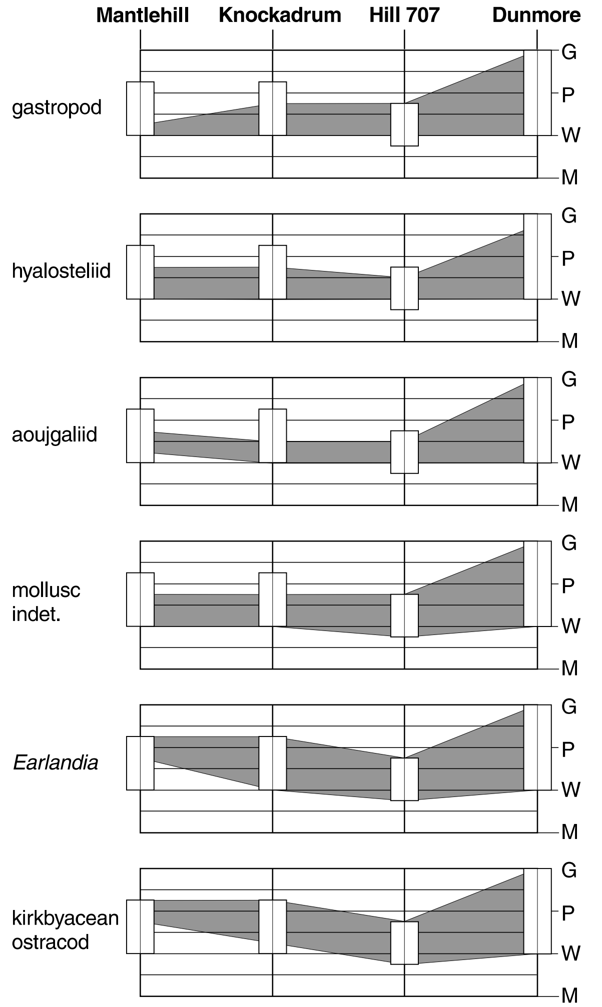

Fig. 15. Textural range occupied by some organisms showing increased textural restriction from north (Dunmore) to south (Mantlehill). The broad white bars at each locality indicate the total textural range present there. G, P, W and M = grainstone, packstone, wackestone and mudstone. For details of organisms, see description in Fig. 10.

Considered as a whole, the onset of the Waulsortian facies is thus marked by few biotic changes. In view of its relatively distinctive macrofauna, this may be surprising. The low degree of taxonomic detail obtainable in petrographic studies is doubtless responsible for some of the poor discrimination. However, it is significant that, in both southern and northern localities, a few organism groups appear or develop in the transition facies and 'anticipate' the arrival of the Waulsortian facies. The development of the precursor muds may well have provided substrates, and perhaps nutrients, akin to those of the Waulsortian facies, thus reducing the changes attendant on the formation of the banks.

A general model

The main elements of the variation shown by the organisms are given in Fig. 16, in which the strongest trend is related to water depth. Differences in biota between lithofacies follow this regional pattern inasmuch as they only occurred in areas interpreted as having relatively deep water. The relationship between Bio-RI and water depth cannot be regarded as linear, but it is reasonable to suppose that the similarities between the Bio-RI and DI of Mantlehill and Knockadrum indicate only slight environmental differences between these areas. In contrast, a relatively sharp change occurs between Knockadrum and Hill 707. This was unexpected, as the localities are only 10 km apart. Assuming no change in relative sea level during any time interval that might exist between the establishment of the Waulsortian banks at these two sites, the sea-floor gradient between them was probably relatively steep.

Rough estimates of the range of water depth at the various localities can be based on the tolerance limits of plurilocular foraminifera (250 m) and hyalosteliid sponges (280 m) deduced by Lees *et al.* (1985) for Waulsortian and peri-Waulsortian rocks in Belgium. The limit for the foraminiferan *Tetrataxis* has recently been more reliably established at about 200 m (Lees, 1997, pp. 28–29). Knockadrum and Mantlehill lay in water deeper than that required by foraminifera. The sporadic presence of hyalosteliid sponges suggests a depth of the order of 280 m. A similar value may be indicated by the rare aoujgaliids at Mantlehill as they all resemble *Mametella*, a taxon that Brenckle (1977, p. 250) suspected of being a rhodophyte alga. The deepest recorded modern calcareous rhodophytes occur at about 270 m (Littler *et al.*, 1985).

At Hill 707, only a few plurilocular foraminifera are present (including *Tetrataxis*), so the depth there may have been of the order of 200 m. Dunmore, with its richer and more abundant foraminiferal faunas, was significantly shallower, perhaps less than 150 m, and probably lay within storm wave-base. A more precise depth estimate for Dunmore is not attempted because of uncertainty regarding the validity of moravamminids as bathymetric criteria. These organisms, which generally accompany the foraminifera (Fig. 13b), have been regarded as dasycladacean green algae (Skompski, 1987), but there are problems with this interpretation (see Lees & Miller, 1995, p. 222). No other, undoubted green algae were recorded.

The bathymetric profile of Fig. 16 shows a palaeoslope inclined to the south, consistent with the generally accepted northward regional transgression. However, that profile is not an instant 'snap-shot' because it expresses the situation envisaged for each locality at the time when the Waulsortian facies was established there. Therefore, the profile would only approximate to the real situation under conditions of constant sea level and a sedimentation rate equal to subsidence. Neither of these conditions can be assumed. In particular, the northward spread of the Waulsortian banks could have been accompanied by progressive lowering of sea level if the major regression recorded in Belgium through the *Scaliognathus anchoralis* Zone (Lees, 1997) extended to western Ireland.

CONCLUSIONS

A transition facies, with distinctive macroscopic and petrographic features, has been identified immediately below the Waulsortian facies at each of the four study localities. The characteristic components are small, discrete masses or aggregates of 'precursor' muds consisting of various grumous fabrics and relatively minor wackestones. The grumous muds have the characters of microbial deposits. The precursor muds form a series of increasing textural and structural complexity including the toe-bank facies and culminating in the Waulsortian polymuds. All are thought to have formed largely *in situ*.

The model proposed to account for the observed variations in the disposition of the precursor muds envisages their development in two consecutive stages. The first of these, which preceded and was probably an essential preliminary to the establishment of a Waulsortian bank in a new area, was the formation of a patch of simple precursor muds on the sea floor. A centripetal increase in the complexity of mud types and fabrics, resulting from spreading of the patch, would account for the progressive upward

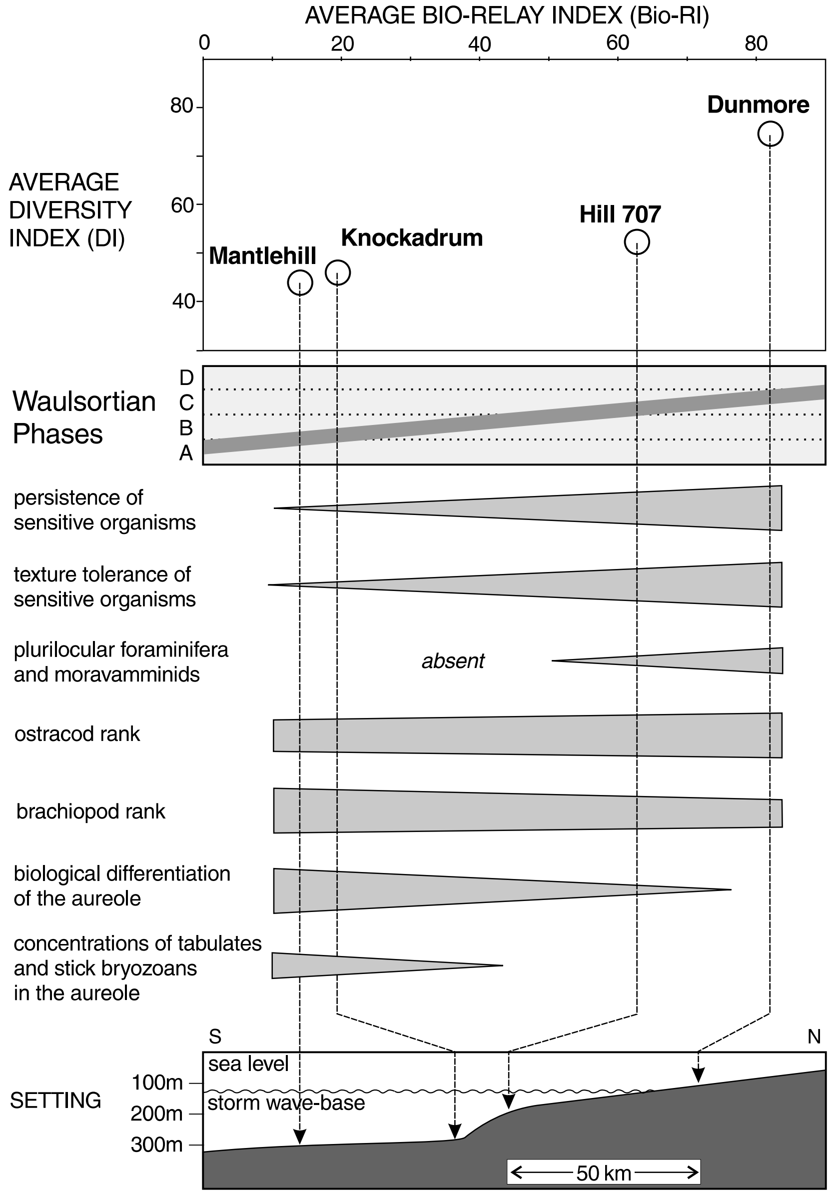

Fig. 16. Summary and interpretation of main regional trends shown by the distributions of the organisms recorded during petrographic analysis. 'Sensitive organisms' are those that vary in abundance systematically along the bathymetric gradient (for persistence, see Fig. 11; for texture tolerance, see Fig. 15). 'Rank' refers to the systematic change in relative importance of the organisms concerned. The 'aureole' is the area around growing banks that was characterized by the presence of 'precursor' muds. The bathymetric model presents the postulated situation for each locality at the time when the Waulsortian facies was initiated there. However, the stratigraphic differences between localities mean that this model cannot be regarded as static. At least some of the northward shallowing expressed here may have been the result of falling sea level if the late Tournaisian regression recorded elsewhere in Europe also affected western Ireland.

development observed in the thin units (a few decimetres) of transition facies produced by this process. The increase in complexity appears to have led naturally to the formation of the Waulsortian polymuds in the most mature (central) part of the patch. Some additional trigger seems to have been required to initiate polymud formation. Its nature remains obscure, but organic processes linked to the sequential development of the precursors appear more likely than changes in oceanographic parameters or the intervention of other, external, environmental modifiers. The second developmental stage of the model requires the persistence of 'precursor' mud formation in the form of an aureole around the newly established bank. The observed thicker sequences of transition facies (up to a metre or more) can be explained by the migration of such an aureole around a prograding bank. The thickness of the deposit would be a function of the width of the aureole, the bank/off-bank sedimentation ratio and the depositional slope of the bank margin. As in the first stage, the vertical succession through the transition facies formed by a migrating aureole would show progressive upward increase in the complexity of mud characters. Transition facies units showing irregular rather than progressive development of the precursor mud sequence are probably related to aureoles around other banks nearby.

The distributions of skeletal grain-types show two trends: one regional and the other local. The regional trend, common to all three lithofacies, is expressed by a progressive north–south attenuation of some organism groups and the disappearance of others. It corresponds to a systematic change in Waulsortian Phases from C in the north to A and B in the south. This pattern is thought to result from a north–south increase in water depth. Differences in stratigraphic level may influence this interpretation if the late Tournaisian regression known elsewhere in Europe extended to this part of Ireland. Variation in grain-type content *between* lithofacies is evident only at the two 'deeper' localities (Mantlehill and Knockadrum). There, it is related to the development of the precursor muds, which was accompanied by the loss of certain organism groups present in the Argillaceous Bioclastic Limestone facies and by the appearance of others that persist into the Waulsortian facies. Much of this differentiation concerns organism groups showing north–south attenuation, with the decline in persistence being accompanied by increased sensitivity to sediment (substrate) texture. Variation between lithofacies does exist in the northern sections, but it is more subtle and can only be detected in those organisms in which refined taxonomic identification is possible. Viewed as a whole, therefore, the regional bathymetric gradient had a much more obvious effect on the biota than the local change in lithofacies. The absence of any striking and systematic biotic change (of organisms identifiable in thin section) coincident with development of the Waulsortian facies appears to be related to the presence of the precursor muds, which provided substrates and nutrients anticipating those of the Waulsortian banks.

As the precursor muds and their developmental sequence are the same in all four localities, their formation and the initiation of the accompanying Waulsortian banks were independent of the regional bathymetric gradient and the associated environmental changes (light, hydraulic energy) that so strongly influenced the biota.

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