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The environmental setting of Early Carboniferous mud-mounds

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ABSTRACT

With the demise of framework-producing reef communities during the Frasnian, the transgressing seas of the Early Carboniferous were characterized by non-framework buildups. This study examines the environmental setting of these buildups which were dominated by carbonate mud-mounds. Given the lack of consistency with which the terms 'Waulsortian', 'Waulsortian-like' and 'non-Waulsortian' have been applied in the past, it is argued that descriptors based on skeletal composition should be used to distinguish types of buildup.

From a literature survey of Early Carboniferous buildups which formed on the south and south-west margin of Laurussia, five types of buildup are proposed. These are:

1 fenestrate bryozoan-sponge spicule buildups;
2 crinoid-bryozoan buildups;
3 crinoid-brachiopod-fenestrate bryozoan buildups;
4 coralgal-*Aphralysia* and bryozoan-coralgal buildups;
5 trepostome-microthrombolite buildups.

This series of buildups reflects a general decrease in water depth. Types 1, 3 and 5 are essentially microbial carbonate mud-mounds; only type 4 shows evidence of framework textures.

Type 1 buildups formed during the Courceyan to mid-Chadian stages and are associated with deep-ramp, basinal and shelf-slope environments. Type 2 formed in turbid mid-ramp environments. Type 3 buildups developed in intrashelf basins during the Holkerian–Brigantian stages. Type 4 occurred in mid-shelf and shelf-margin settings during the late Chadian to Asbian. Type 5 formed in coastal marine locations during the Asbian and Brigantian. Overall it appears that buildups shifted to shelf-margin and intrashelf basins as these environments became established in the Asbian and Brigantian.

While there is evidence for an association between type 5 buildups and hydrocarbon seeps, the deep-water and marginal setting of type 1 and type 3 buildups is best explained by the nutrient supply from regional upwelling.

INTRODUCTION

Frame reefs, cluster reefs and microbial/biodetrital mud-mounds form a continuous spectrum of build-ups ranging from those with a clearly recognized skeletal frame to those with little evidence of an organic frame (Fig. 1) (Riding, 1990). The term 'mud-mound' is used here in the sense of a discrete buildup of carbonate with a significant proportion (over 30%) of carbonate mud or peloidal mud, but commonly containing a substantial content of non-muddy constituents, for example, bioclasts. There is an absence of any skeletal frame; however, some mud-mounds display a series of mud-supported cavity systems infilled by marine cements. Use of the term 'mud-mound' is intended here in a descriptive sense without direct implications for the genesis of the sediment or the structure. Early

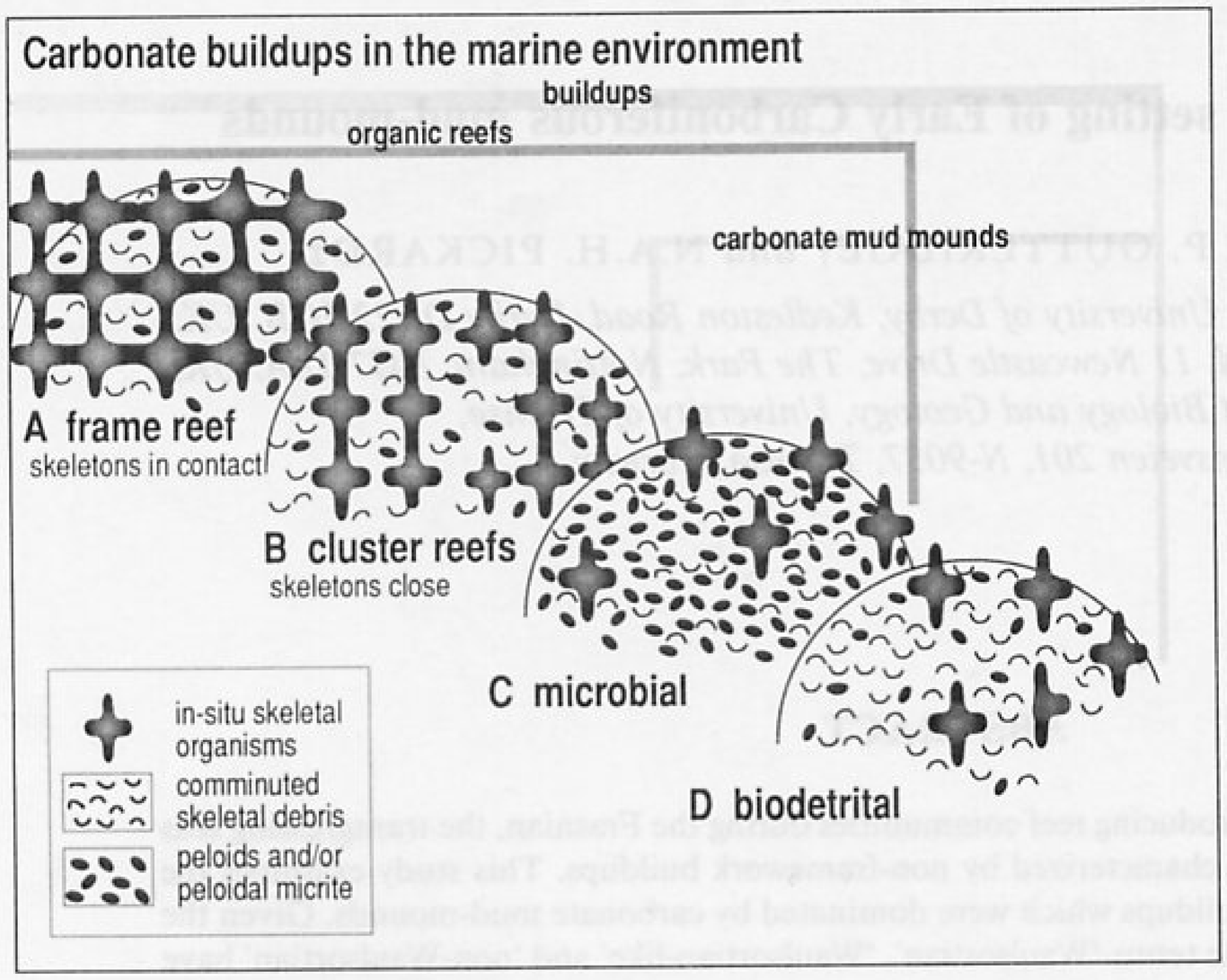

Fig. 1. The principal types of carbonate buildup in the marine environment. In category A there is a macroskeletal framework present. In category B the skeletal forms are locally juxtaposed but there is little framework development. Category C embraces microbial mud-mounds. Category D comprises buildups of biodetrital origin. Categories A and B follow Riding (1990).

Carboniferous buildups formed extensively on the southern and western margins of the contemporary continent Laurussia. Framework reefs are notably rare; the buildups are principally in the form of microbial/biodetrital mud-mounds, with one or two instances of probable cluster reefs (West, 1988). This paper considers the different types of Early Carboniferous buildups with particular emphasis on the mud-mounds, and attempts to account for some of the variations in composition and setting.

THE APPROACH

The paper will adopt the following approach. First we consider the Late Devonian extinction event and its effect on contemporary reefal communities. This has major significance for the buildups which formed in the Early Carboniferous. Then we consider the principal types of Early Carboniferous buildup and identify a series of different mound types based on skeletal composition and dominated by carbonate mud-mounds. Finally, we examine the environmental setting of these buildup types and assess the extent to which it is possible to explain their occurrence.

THE LATE DEVONIAN 'KELLWASSER' EVENTS

Copper (1988) argued that Phanerozoic reefal communities display a series of evolutionary successions, each related to an episode of extinction. In each succession, a pioneer phase of development led to a climax phase in which framework reefs became dominant. This in turn was followed by an extinction phase in which reef communities responsible for constructing frameworks were greatly depleted. Buggisch (1991), in his analysis of the Late Devonian extinction phase, highlighted three important points (Fig. 2).

First, the faunal record demonstrates that the reduction in shallow marine taxa took the form of a step-down extinction rather than a single event. The most important of these events took place in the *triangularis* and *gigas* conodont zones of the late Frasnian, known as the early and late Kellwasser events, respectively (Buggisch, 1991). Second, each 'Kellwasser' event was associated with rise in sea-level and relatively high global temperatures. Third, Buggisch noted that the extinction phases coincided with extensive deposition of organics (hence 'Kellwasser') and with positive $\delta^{13}C$ isotopes indicating anoxic bottom waters. Buggisch concluded that the warm surface waters would have generated a strat-

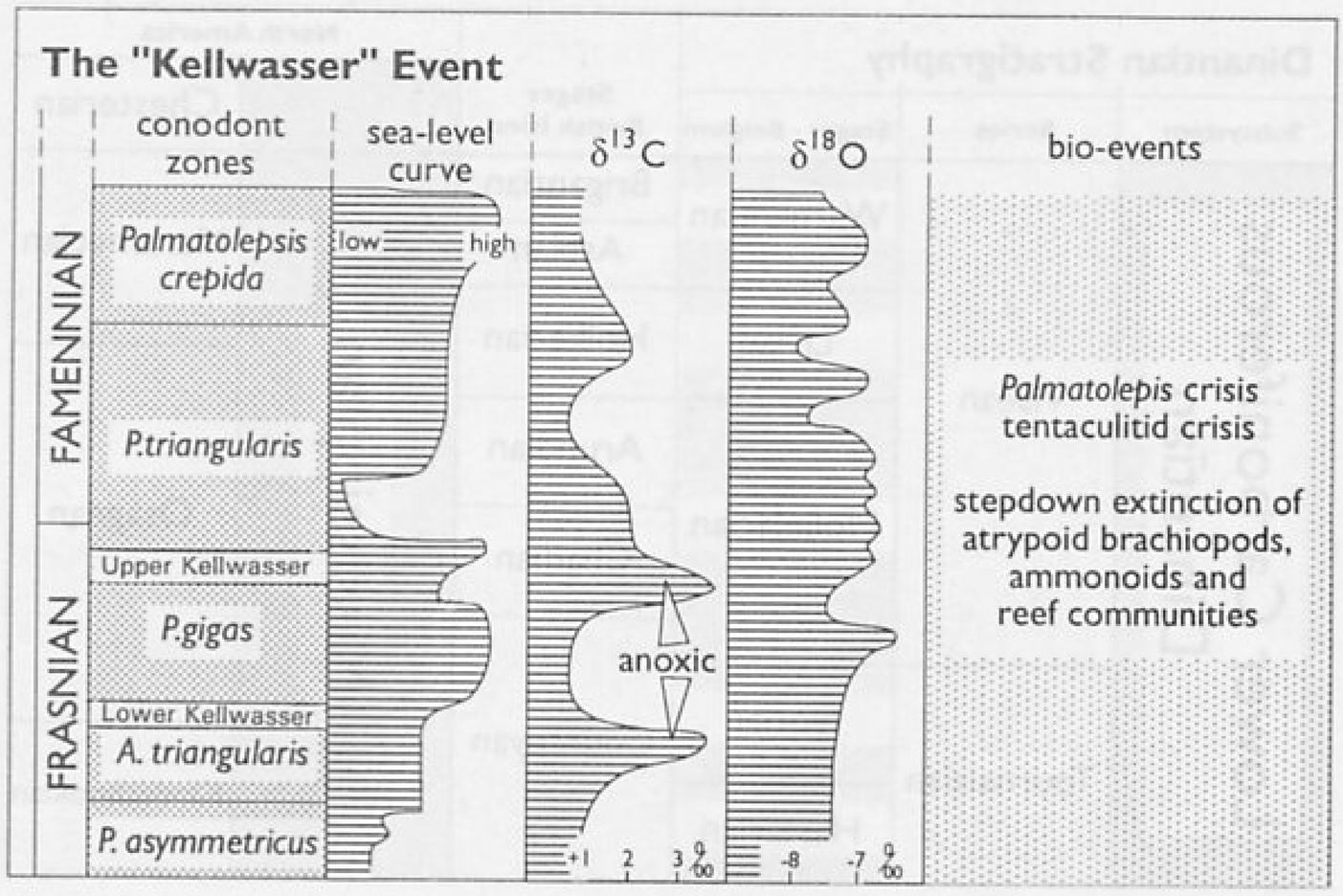

Fig. 2. Salient aspects of the Frasnian Kellwasser extinction events. Data drawn from Buggisch (1991).

ified ocean with the accumulation of anoxic, nutrient-rich waters at depth. As the climate cooled, denser surface waters caused oceanic overturn, bathing the contemporary reef systems with cold, oxygen-deficient, nutrient-rich waters.

Hallock & Schlager (1986) have demonstrated the adverse affects of such waters on modern reefal systems. More recently, Cowen (1988) has postulated that zooxanthellate relationships, once disrupted by such events, take a considerable period of geological time to be fully re-established. Above all, one point from the stratigraphic record is clear: that after the late Frasnian, throughout the world, Devonian–Carboniferous buildup communities take the form of carbonate mud-mounds and rare cluster reefs (Buggisch, 1991). Fully formed major framework reefs did not occur again until the Permian.

TYPES OF EARLY CARBONIFEROUS BUILDUP

The use of the descriptor 'Waulsortian'

Some of the most impressive of Early Carboniferous buildups are those known as the *Waulsortian*, which have been described from Belgium (Lees *et al.*, 1985), Ireland (Lees, 1964) and the English Midlands (Bridges & Chapman, 1988) and elsewhere. The term 'Waulsortian' however, has not always been used consistently or with clarity (Lees 1988). Lees & Miller (this volume) have provided a full definition which indicates that: Waulsortian banks are buildups which display a series of generations of mud development (polymuds); they contain at least one of the four depth-related skeletal assemblages defined by Lees *et al.* (1985), and they are of Tournaisian or early Viséan age (Fig. 3). Thus, at the present time, Early Carboniferous buildups may either be classified as Waulsortian and provide evidence of one or more of the skeletal assemblages (A, B, C or D) or they do not meet the above criteria and may therefore, be classified as non-Waulsortian buildups. We believe that, in order to gain a deeper insight into the understanding of Early Carboniferous buildups, it is desirable to identify a number of compositional criteria which enable a series of buildup types to be distinguished. Waulsortian banks (*sensu* Lees & Miller, this volume) correspond to one or more of these buildup types but the application of the labels 'Waulsortian', 'Waulsortian-type' (King, 1986) and 'non-Waulsortian' is of limited value because they do not immediately convey a particular form, composition or genesis.

The identification of five buildup types

From our own research and literature survey of buildups which formed on the shelf margins of Laurussia during Early Carboniferous (Dinantian) times, we have identified five distinctive types of Dinantian buildup. These form a series that we

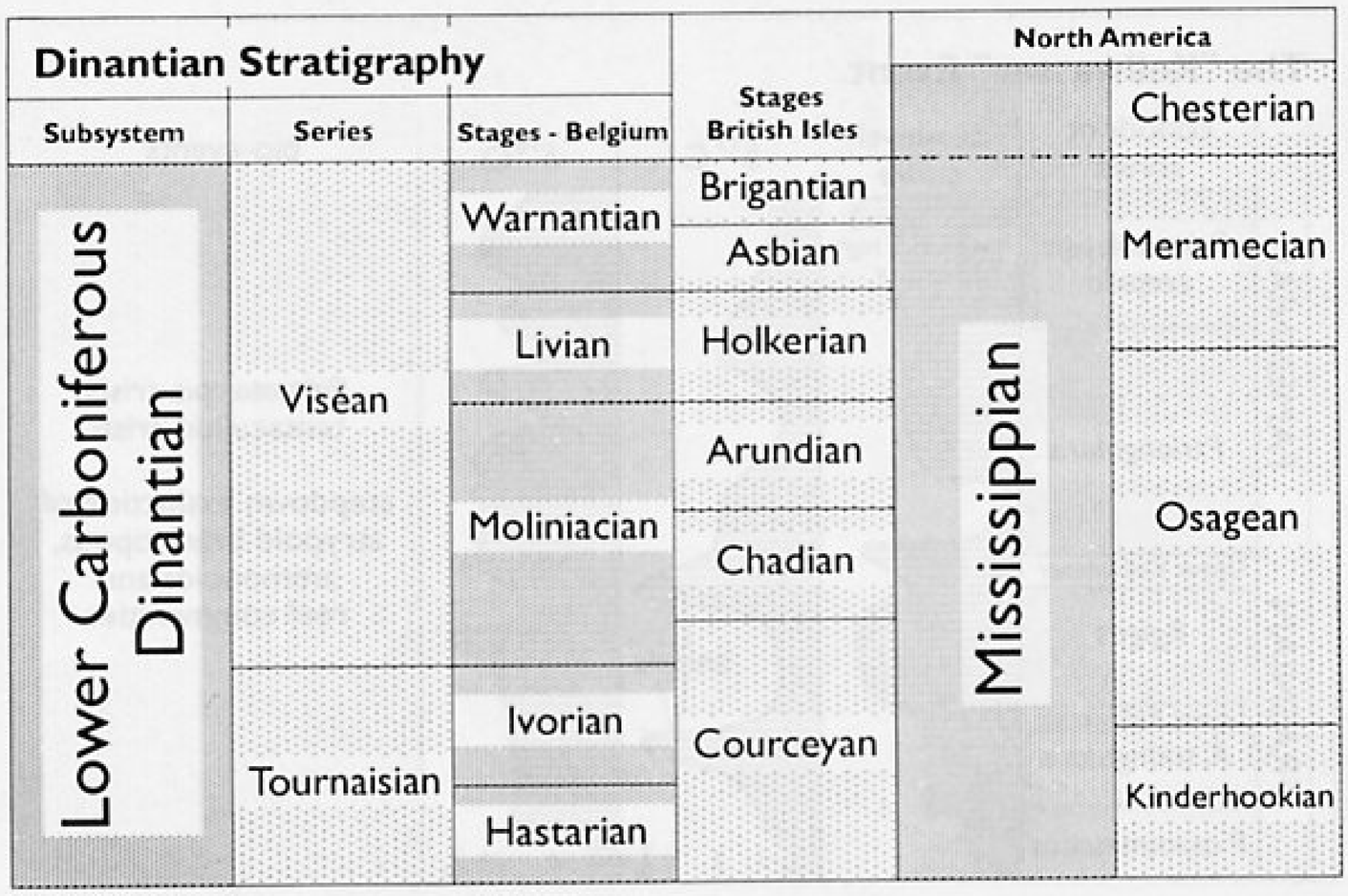

Fig. 3. Early Carboniferous stratigraphic stages in Belgium, the British Isles and North America. Data from George *et al.* (1976) and Paproth *et al.* (1983).

consider to reflect successively shallower marine conditions of formation (Fig. 4).

The buildup types recognized are, from deeper to shallower water:

1 Fenestrate bryozoan-sponge spicule buildups;
2 Crinoid-bryozoan buildups;
3 Crinoid-brachiopod-fenestrate bryozoan buildups;
4 Coralgal-*Aphralysia* and bryozoan-coralgal buildups; and
5 Trepostome-microthrombolite buildups.

Types 1, 3 and 5 are mainly in the form of mud-mounds, but many examples of buildup types 2 and 4 cannot be regarded as mud-mounds. In this paper we will consider them all because we believe that a contextual analysis will deepen our understanding of mud-mounds. The sections which follow describe examples representing each of the buildup types (Tables 1 and 2).

Type 1: fenestrate bryozoan-sponge spicule buildups

Buildups in this category are invariably carbonate mud-mounds. The mound core or bank facies is composed of fenestrate bryozoans, preserved as sheets or finely comminuted as hash, hyalosteliid spicules, and crinoid columnals embedded in a micrite matrix which often displays a clotted or peloidal texture (Table 1). These buildups may take the form of discrete mounds (e.g. Bridges & Chapman, 1988; Lees *et al.* 1985; Lees & Miller, 1985; Precht & Shepard, 1989) or as prograding tabular sheets (e.g. Lees, 1964). Type 1 buildups range up to 120 m in thickness and up to 4 km in extent. They provide evidence of steep contemporary slopes (up to 40°) and 80 m of topographic relief. Many Waulsortian banks (Phases A and B) are included within type 1.

The type 1 Dovedale mud-mound complex in the English Midlands has five associated facies: mound core, mound flank-fine, mound flank-coarse, intermound-fine, and intermound-coarse (Fig. 5). The bedded sediments of the mound flank-fine are charged with sponge spicules, whereas the sediments of the mound flank-coarse contain a high proportion of crinoidal debris, together with intraclasts of carbonate mud. The intermound-fine sediments are well-bedded, dark, bituminous carbonates with evidence of early compaction of crinoid columnals. Intermound-coarse sediments are much paler and contain a diverse skeletal assemblage of foraminifera, brachiopods, crinoids and calcified algae.

Type 2: crinoid-bryozoan buildups

Type 2 buildups are distinctly different from those of type 1 and are exemplified by the buildups described from the Fort Payne Formation of Kentucky, USA (Ausich & Meyer, 1990; Meyer *et al.*, this volume; Fig. 6). The principal differences are, first, that the buildups have a core which includes a substantial proportion of green shale; and second,

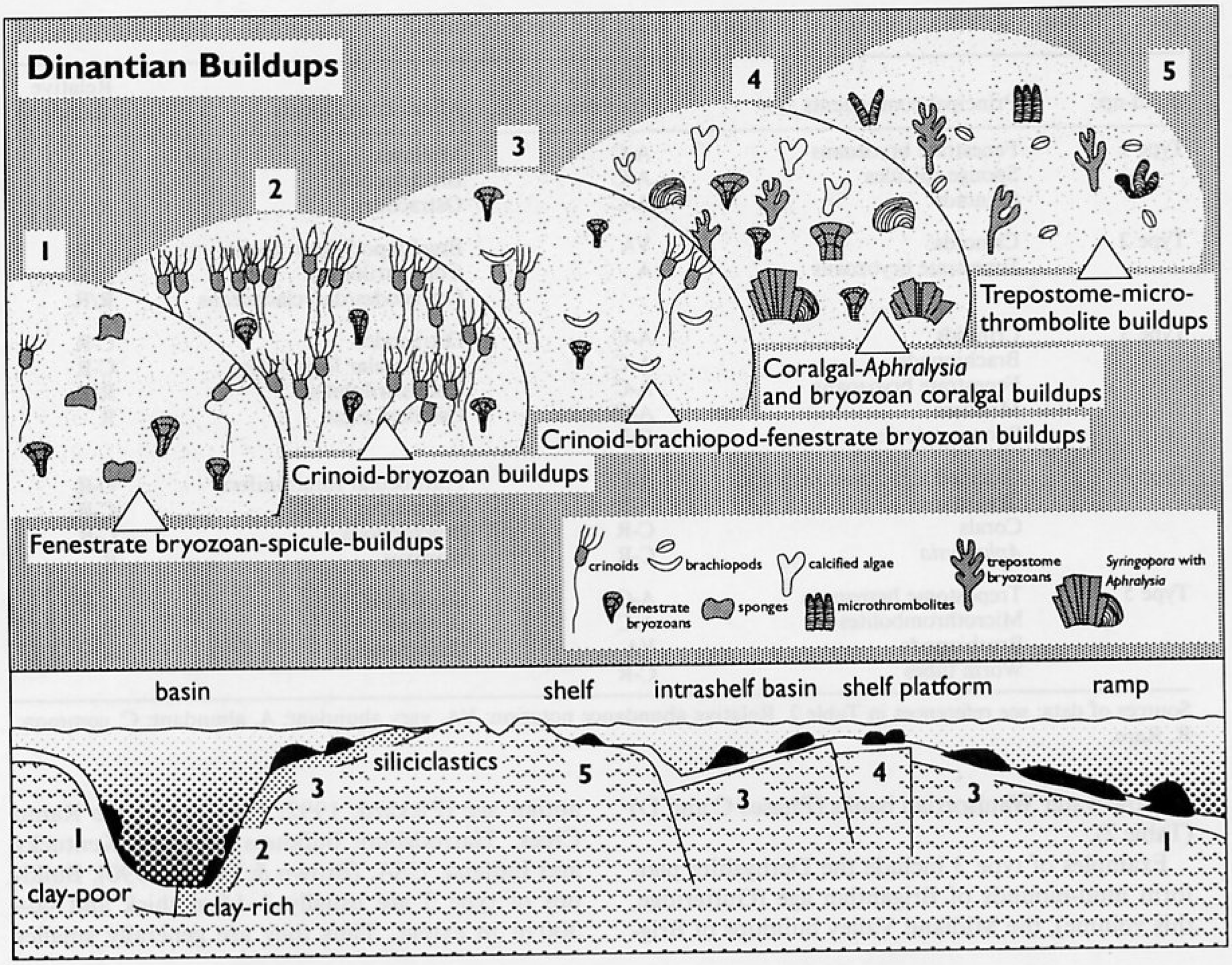

Fig. 4. The five types of Early Carboniferous buildup and their characteristic environmental settings. The buildup types are distinguished by the principal skeletal components.

that the skeletal contribution to the buildups, in the form of fenestrate bryozoans and well-preserved crinoids, normally exceeds 40% of the sediment. In some buildups the skeletal proportion exceeds 70%. The exceptional wealth of crinoids, both in terms of abundance and diversity, contrasts with type 1 buildups where crinoidal abundance is normally restricted to the flanks of the buildup.

Ausich & Meyer (1990) noted that some buildups comprise over 50% micrite and are therefore wackestone buildups or mud-mounds. Others have a matrix of skeletal sand with only 15% micrite content. These are crinoid packstone buildups. The latter include rugose corals, spiriferids and gastropods in the skeletal sand (Table 1). Type 2 buildups are moderate in size, ranging up to 5 m in thickness and 150 m in extent. Thus, they are generally smaller than the type 1 buildups.

Type 3: crinoid–brachiopod–fenestrate bryozoan buildups

Buildups of type 3 are invariably in the form of mud-mounds. In contrast to type 1, there is a wider range of skeletal debris, including numerous brachiopods, some foraminifera and rare calcified algae (Table 1). The matrix is composed of homogeneous and peloidal mud. Furthermore, crinoids and bryozoans, although very common, do not compare in abundance, diversity or quality of preservation with type 2. Buildups of type 3 include a number of

Table 1 Relative abundance of skeletal components in the five types of buildup

Build-up	Principal components	Relative abundance	Minor components	Relative abundance
Type 1	Fenestrate bryozoans	A-C	Molluscs	R
	Sponge spicules	A-C	Brachiopods	R
	Crinoids	A-C	Ostracodes	R
Type 2	Crinoids	VA	Brachiopods/gastropods	C-R
	Fenestrate bryozoans	A	Corals/trilobites	R/R
			Ostracodes/dasycladaceans	R/R
Type 3	Crinoids	A-C	Ostracodes	C-R
	Brachiopods	A-C	Plurilocular forminifera	C-R
	Fenestrate bryozoans	A-C	Corals/trilobites	R/R
	Molluscs	A-C	Calcified algae	R
	Sponge spicules	C-R		
Type 4	Calcified algae/cyanobacteria	A-C	Plurilocular foraminifera	C-R
	Bryozoans	A-R	Ostracodes	C-R
	Corals	C-R	Brachiopods	C-R
	Aphralysia	C-R	Bivalves	R
Type 5	Trepostome bryozoans	A-C	Spirorbids	C-R
	Microthrombolites	A-C	Bivalves	R
	Brachiopods	VA	Gastropods	R
	Worm tubes	C-R		

Sources of data: see references in Table 2. Relative abundance notation: VA, very abundant; A, abundant; C, common; R, Rare.

shallow-water Waulsortian banks (Phases C and D) (Table 2).

Examples of type 3 include the Derbyshire platform mud-mounds of Brigantian age (Gutteridge, this volume), the Midland Valley buildups of Brigantian age (Pickard, 1992; Fig. 7), and the Ramp Creek, Harrodsburg buildups of north Kentucky and Indiana, USA, (Brown & Dodd, 1990). Buildups of type 3 are usually 2–15 m thick and 40–300 m in extent. Thus they are generally smaller

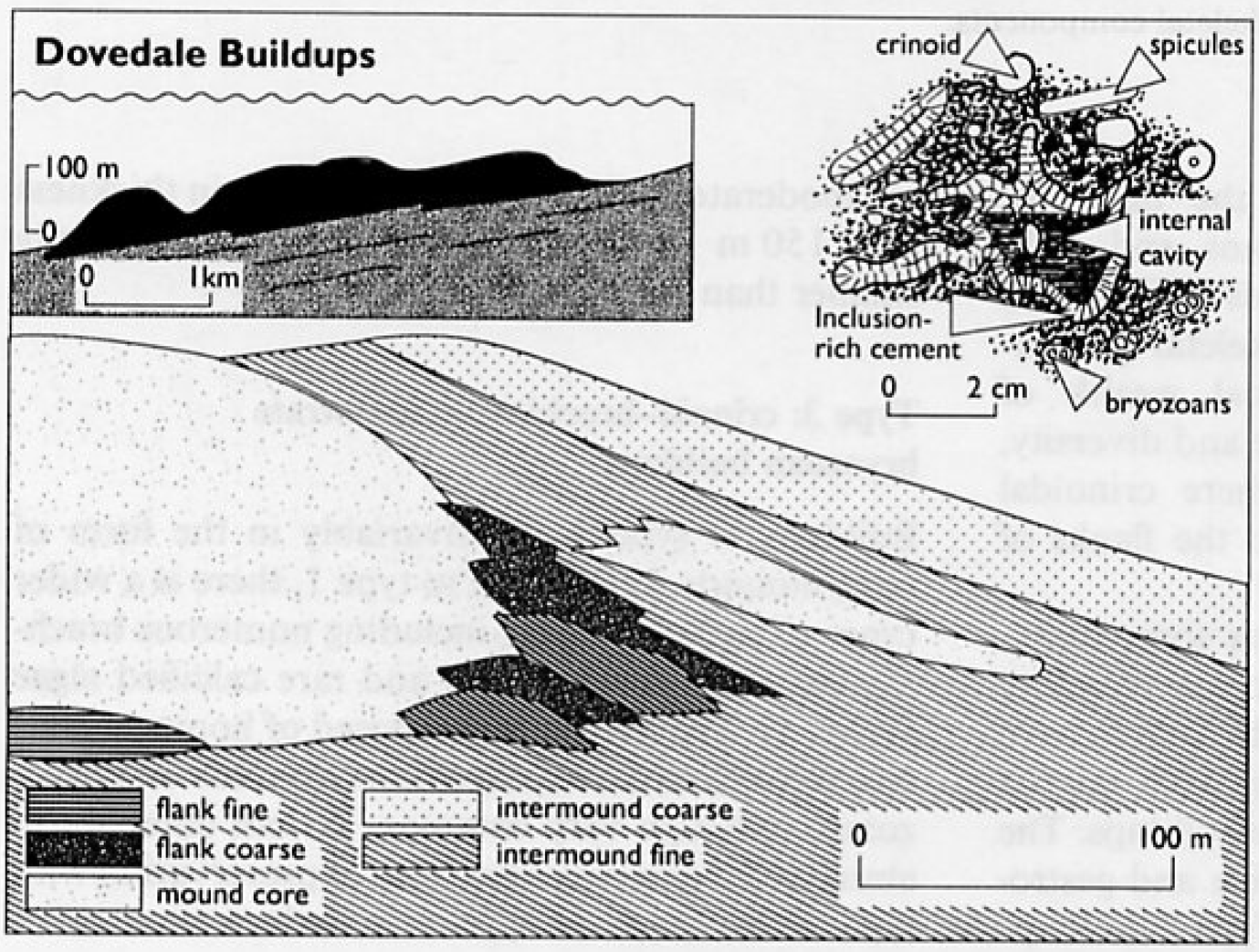

Fig. 5. The facies relationships recorded in the Dovedale mud-mound complex, as an example of type 1 buildups. Data from Bridges & Chapman (1988).

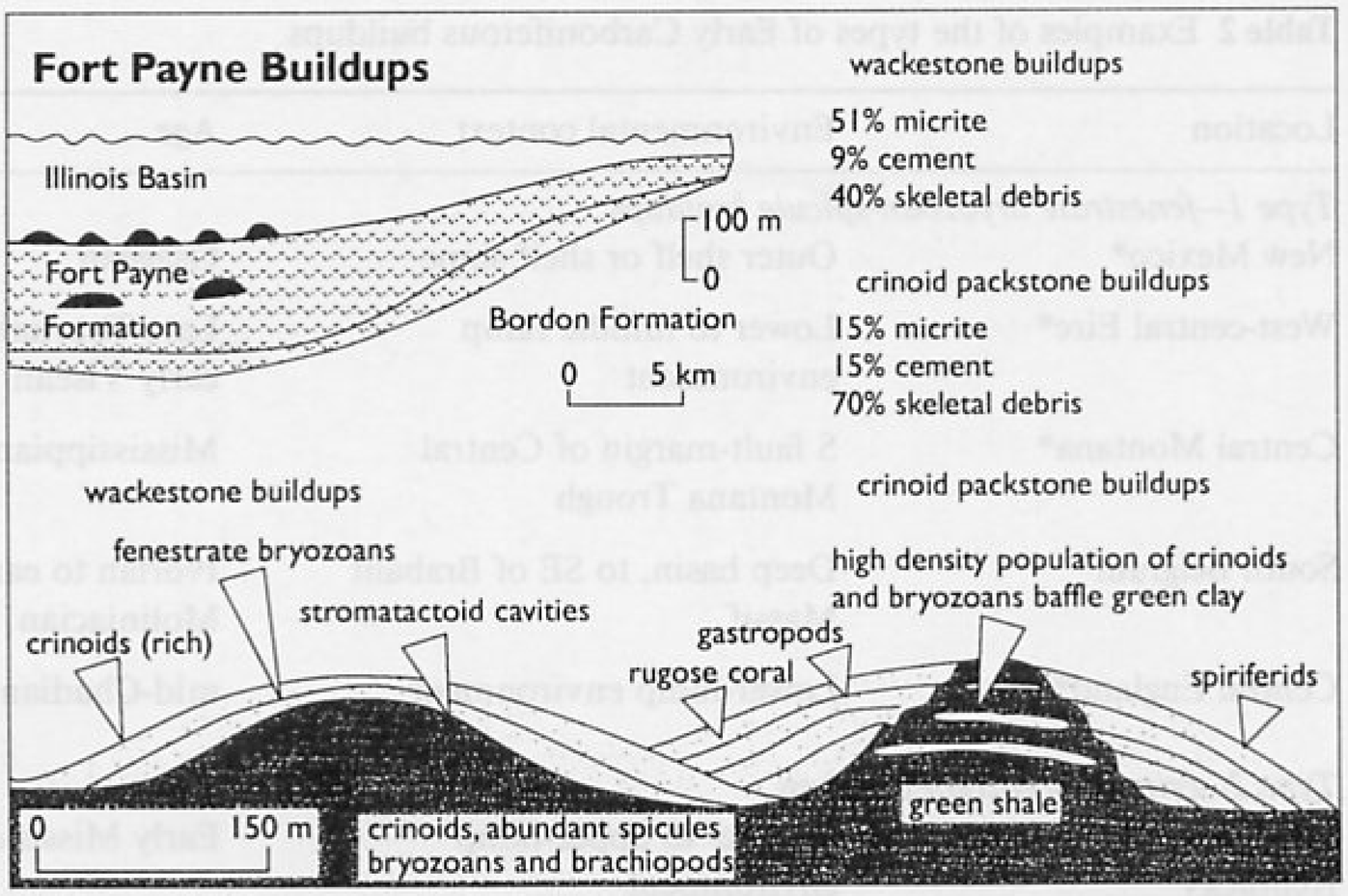

Fig. 6. The structure and composition of the wackestone and packstone buildups of the Fort Payne Formation, as an example of type 2 buildups. Data from Ausich & Meyer (1990).

than most examples of type 1, but they compare in size with type 2.

Type 4: coralgal-*Aphralysia* and bryozoan-coralgal buildups

Of all Early Carboniferous buildups, these come closest to being framework reefs and cannot be considered to be mud-mounds, although a mud matrix is present. These buildups are relatively small, 3–10 m thick and 5–50 m in extent. All buildups in type 4 have both tabulate corals and calcified algae present. In addition, some have *Aphralysia* encrusting *Syringopora* and thrombolites, as seen in the Furness buildups of Chadian–Arundian age, UK (Adams 1984; Fig. 8); others, such as the Llandudno buildups of Asbian age, have a range of encrusting, ramose and foliaceous bryozoans which dominate the structure (Bancroft *et al.* 1988; Fig. 9; see also Table 1). The Furness buildups have local frameworks and may be regarded as cluster reefs; but Bancroft *et al.* (1988) did not regard the bryozoan buildups as true framework reefs. Type 4 buildups are judged to have displayed very little topographic relief—less than 2 m (Adams 1984). Further examples of type 4 include the buildups of the Gays River formation in Nova Scotia (Boehner *et al.*, 1989a), and the palaeoberesellid (chlorophyte) buildups of north Lancashire, UK (Horbury, 1992). Type 4 buildups include some which closely resemble Phase D Waulsortian banks (Somerville *et al.* 1992).

Type 5: trepostome–microthrombolite buildups

The buildups of type 5 are exemplified by the mud-mounds in the Codroy Formation in western Newfoundland (Fig. 10). These buildups are characterized by the dominance of trepostome bryozoans and microthrombolites (Dix & James, 1987), and the notable absence of crinoids and corals (Table 1). The brachiopod *Beecheria* is prolific and Von Bitter *et al.* (1990) also described a number of mineralized tubes which they interpreted as faunal tubes possibly formed by worms in the vicinity of hydrothermal seeps. The sediment is strongly peloidal and includes cavities with geopetal fills. The buildups grew adjacent to laminated peloidal carbonates which formed in a palaeovalley eroded into Ordovician carbonates.

The Newfoundland buildups of type 5 are small (less than 10 m across), but other examples are up to 600 m across, for example, in the Windsor Group of Nova Scotia (Boehner, 1989; Boehner *et al.*, 1989b) and the Viséan of New Brunswick (McCutcheon, 1989).

Although individual carbonate buildups may be broadly categorized into one of the buildup types described above, some buildups changed markedly in composition and texture as they grew, for example the bryozoan-coralgal buildups of North Wales (Bancroft *et al.* 1988). It is therefore possible that, in the context of buildup types, some mud-mounds are composite. However, we have not as yet identified examples.

Table 2 Examples of the types of Early Carboniferous buildups

Location	Environmental context	Age	Authors
Type 1—fenestrate bryozoan-spicule buildups			
New Mexico*	Outer shelf or shelf slope	Osagean	Pray (1958)
West-central Eire*	Lower to middle ramp environment	Late Tournaisian to early Viséan	Lees (1964)
Central Montana*	S fault-margin of Central Montana Trough	Mississippian	Cotter (1965)
South Belgium*	Deep basin, to SE of Brabant Massif	Ivorian to early Moliniacian	Lees *et al.* (1985) King (1986)
Central England*	Lower-ramp environment	mid-Chadian	Bridges & Chapman (1988)
Type 2—crinoid-bryozoan buildups			
South-central Kentucky*	Middle- to upper-ramp environment	Early Mississippian	Ausich & Meyer (1990) Meyer *et al.* (this volume)
Type 3—crinoid–brachiopod–fenestrate bryozoan buildups			
Indiana/Kentucky*	Relatively shallow platform	Mid-Mississippian	Brown & Dodd (1990)
Dublin, Ireland*	Moderately shallow water in the Dublin Basin	Late Courceyan to early Chadian	Somerville *et al.* (1992)
North-west Ireland	Moderately shallow and shallow water basinal environments	Arundian	Kelly & Somerville (1992)
Midland Valley, Scotland	Local 'high' with moderately shallow water	Brigantian	Pickard (1992)
Derbyshire, UK	Shelf interior, platform margin and shallow to middle part of intraplatform ramp	Brigantian	Gutteridge (this volume)
Type 4—coralgal-Aphralysia/bryozoan coralgal buildups			
North-west England	Outer shelf in relatively shallow water	Chadian–Arundian	Adams (1984)
North Wales	Shelf margin in relatively shallow water	Asbian	Bancroft *et al.* (1988)
North County Dublin	Shallow water on the Milverton platform adjacent to the Dublin Basin	Late Chadian to Holkerian	Somerville *et al.* (1992)
Lancashire, UK	Buildup initiated on palaeokarst located to lee of shelf-margin shoal	Late Asbian	Horbury (1992)
Type 5—trepostome-microthrombolite buildups			
Western Newfoundland	Partially submerged cliffed palaeokarst with low temperature hydrothermal vents	Late Mississippian	Dix & James (1987)

* Considered to be Waulsortian by cited authors: see Fig. 3 for correlation of stages.

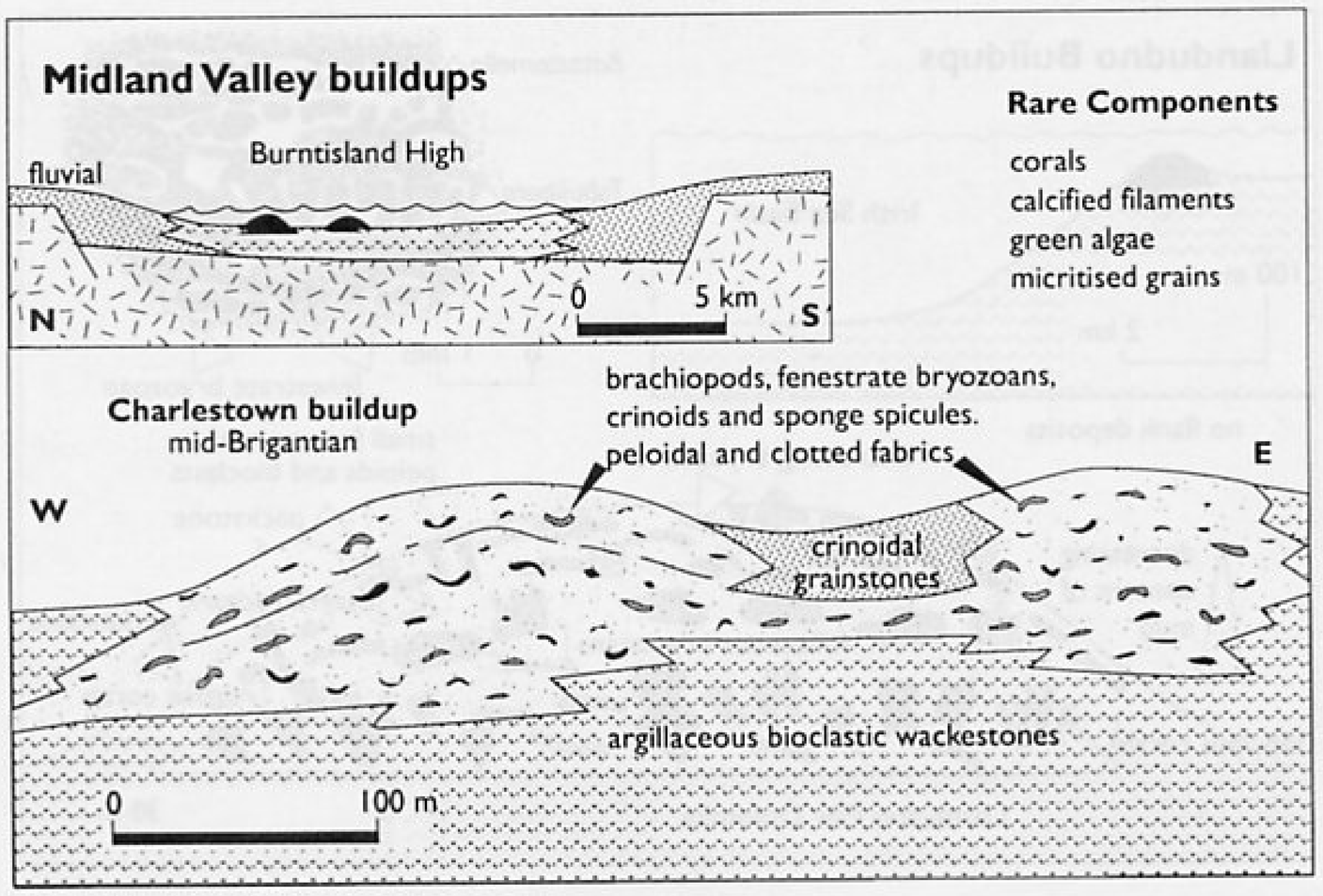

Fig. 7. The structure and composition of the Brigantian buildups of the Midland Valley, Scotland, as examples of type 3 buildups. Data from Pickard (1992).

THE DEPOSITIONAL SETTING OF EARLY CARBONIFEROUS BUILDUPS

S W Laurussia

In this section we trace the occurrence of the five buildup types in order to ascertain the depositional setting associated with each type. We will draw on examples documented from the southern and south-western margins of Laurussia.

In Early Carboniferous times southwest Laurussia was flooded by an extensive interior seaway (Fig. 11; Gutschick & Sandberg, 1983). In the east the Appalachian Highlands were bordered on the eastern side by a shallow sea, and on the west, by the Bordern delta which prograded into the Michigan/Illinois basins. Further west, the interior seaway featured a number of large islands and was bordered to the south by shelf-margin and slope environments which passed into the Marathon and Anadarko basins. To the west, the shelf was faulted to form the Central Montana Trough and the Peace River Embayment. This shelf was bordered by the Antler Trough which filled with siliciclastics derived from the Antler Highlands lying to the west.

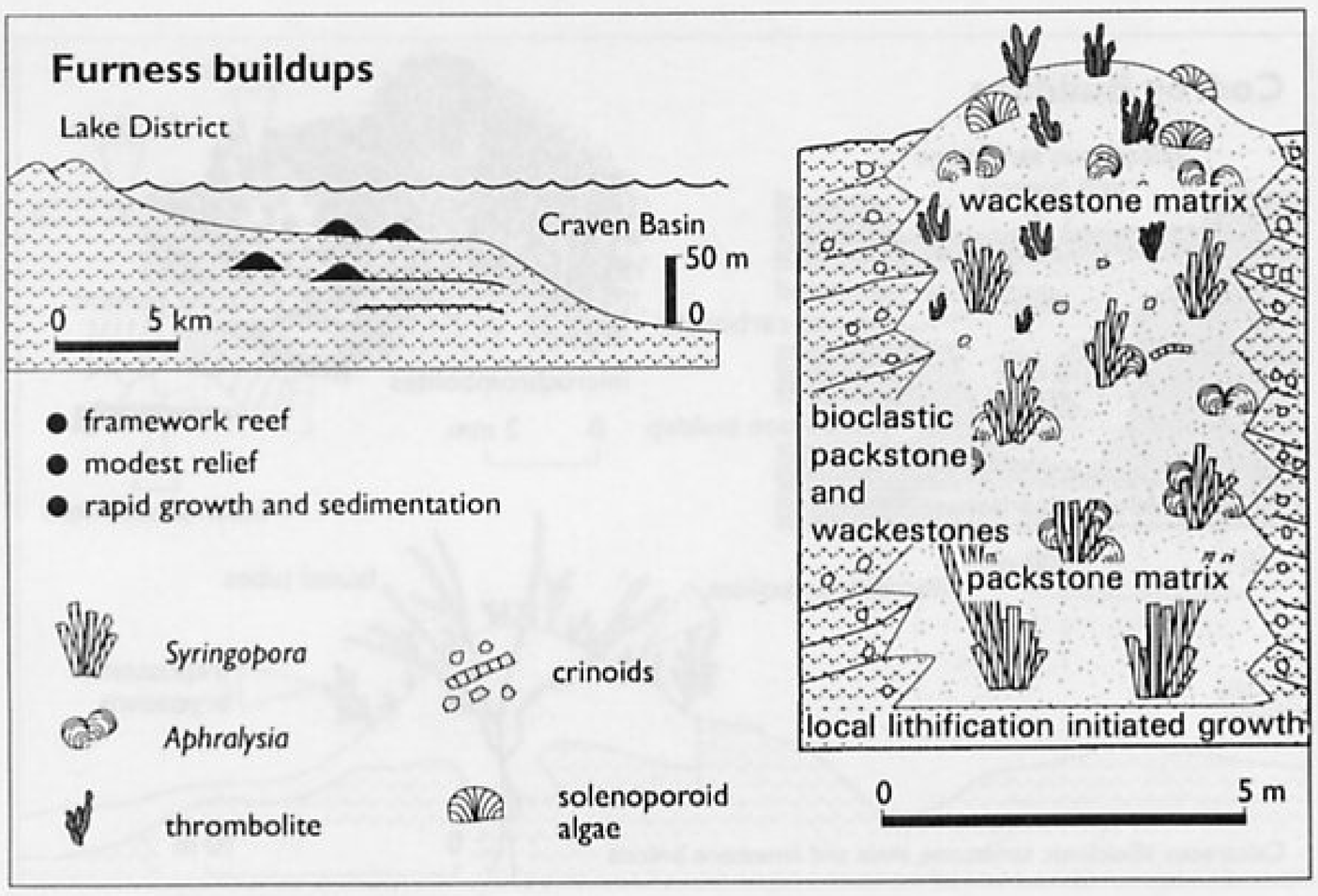

Fig. 8. The structure and composition of the Chadian–Arundian coralgal-*Aphralysia* cluster reefs of the Furness area, Lake District, UK, as examples of type 4 buildups. Data from Adams (1984).

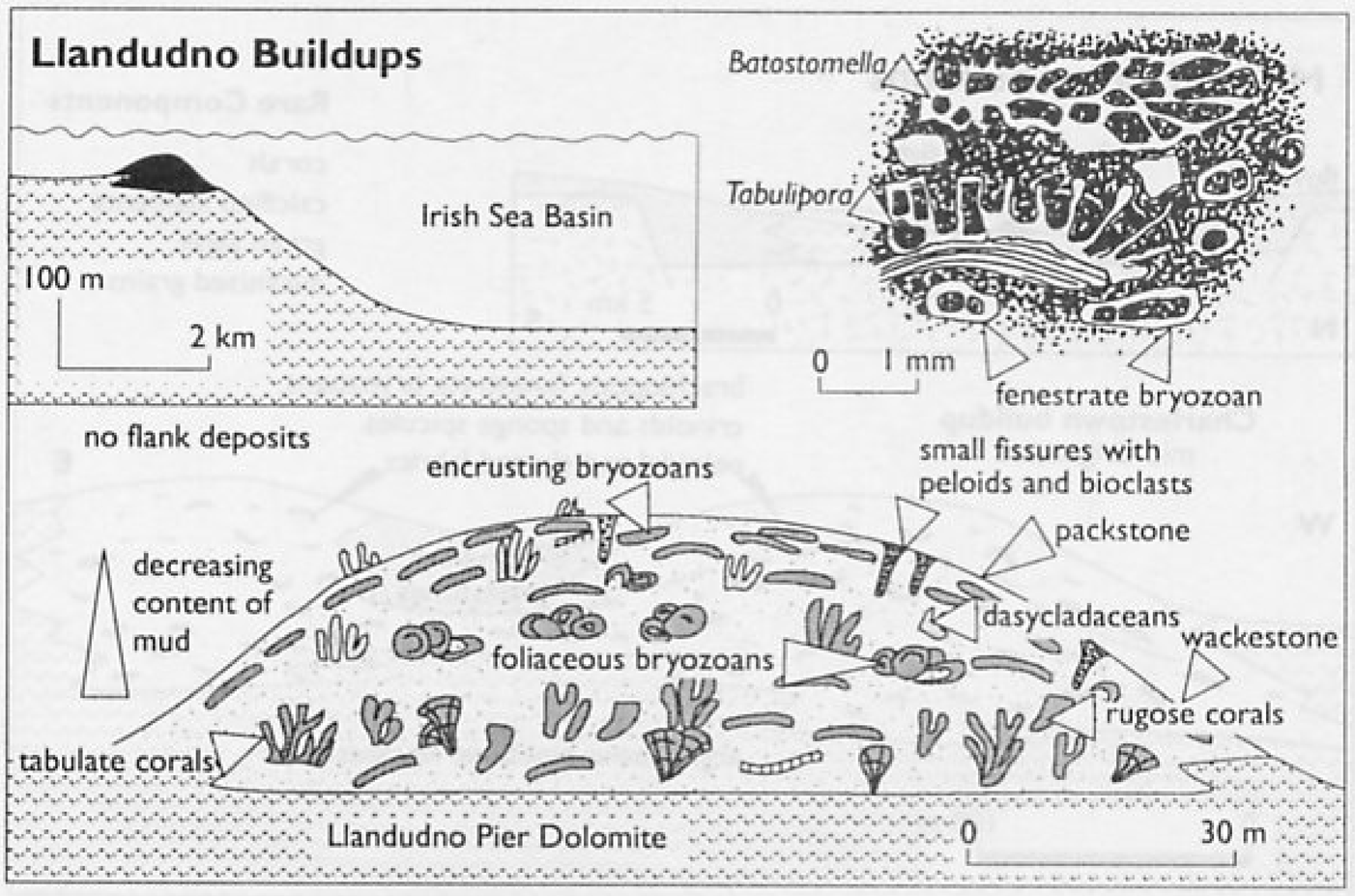

Fig. 9. The structure and composition of the Asbian bryozoan-coralgal cluster reefs of Llandudno and the North Wales Shelf, UK as further examples of type 4 buildups. Data from Bancroft *et al.* (1988).

Type 1 buildups formed in the Peace River Embayment, Alberta (Davies *et al.* 1989), and in the vicinity of the southern fault margin of the Central Montana Trough (Cotter, 1965; Precht & Shepard, 1989). Further south, type 1 buildups also occur close to the shelf margin of the Lake Valley/Chappel Shelves (Pray, 1958). Tracing the shelf margin to the north-east, carbonate buildups of type 1 also occur on the shelf slopes of the Burlington Shelf adjacent to the Illinois Basin. These buildups are surrounded by coarse crinoidal clastics which were emplaced by turbidity currents (King, 1986). However, on the eastern side of the Illinois Basin the buildups belong to type 2 (Fort Payne Ramp) and type 3 (Ramp Creek/Harrodsburg) close to the Bodern delta. The deep ramp buildups of type 2 have unusually high quantities of crinoidal and bryozoan remains, together with green clays (Ausich & Meyer, 1990). The Ramp Creek/Harrodsburg buildups (Brown & Dodd, 1990) display a more diverse skeletal assemblage than is seen in type 1 but lack the wealth of crinoidal/bryozoan debris seen in type 2 on the Fort Payne Ramp. The presence of clays in the type 2 buildups indicates that the sea was periodically turbid.

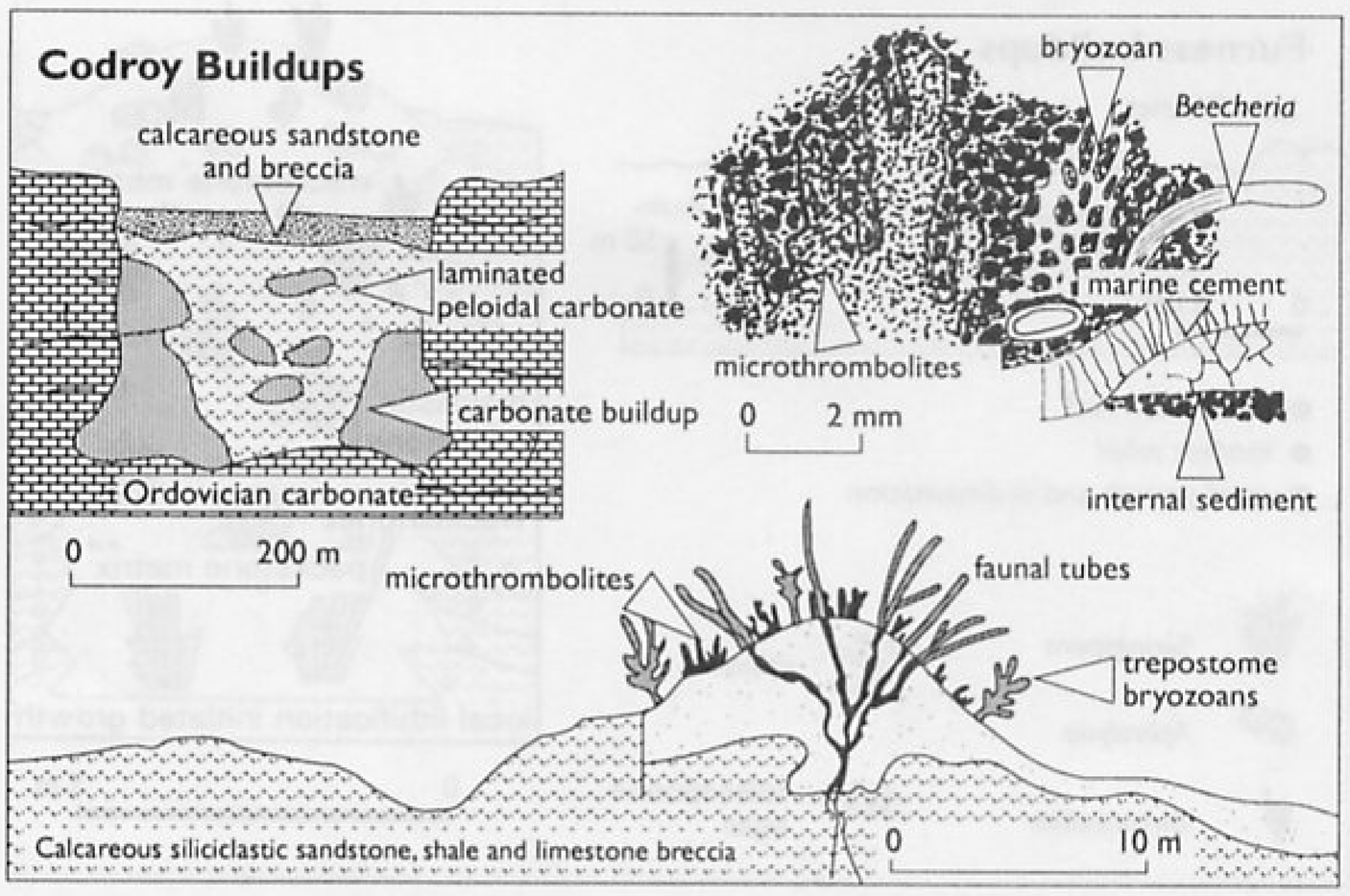

Fig. 10. The structure and composition of the Arundian–Holkerian trepostome–microthrombolite microbial mud-mounds of the Codroy Formation, western Newfoundland (Dix & James, 1987), as examples of type 5 buildups. Note the presence of mineralized tubes, interpreted as worm tubes associated with low-temperature hydrocarbon seep conditions (Von Bitter *et al.*, 1990).

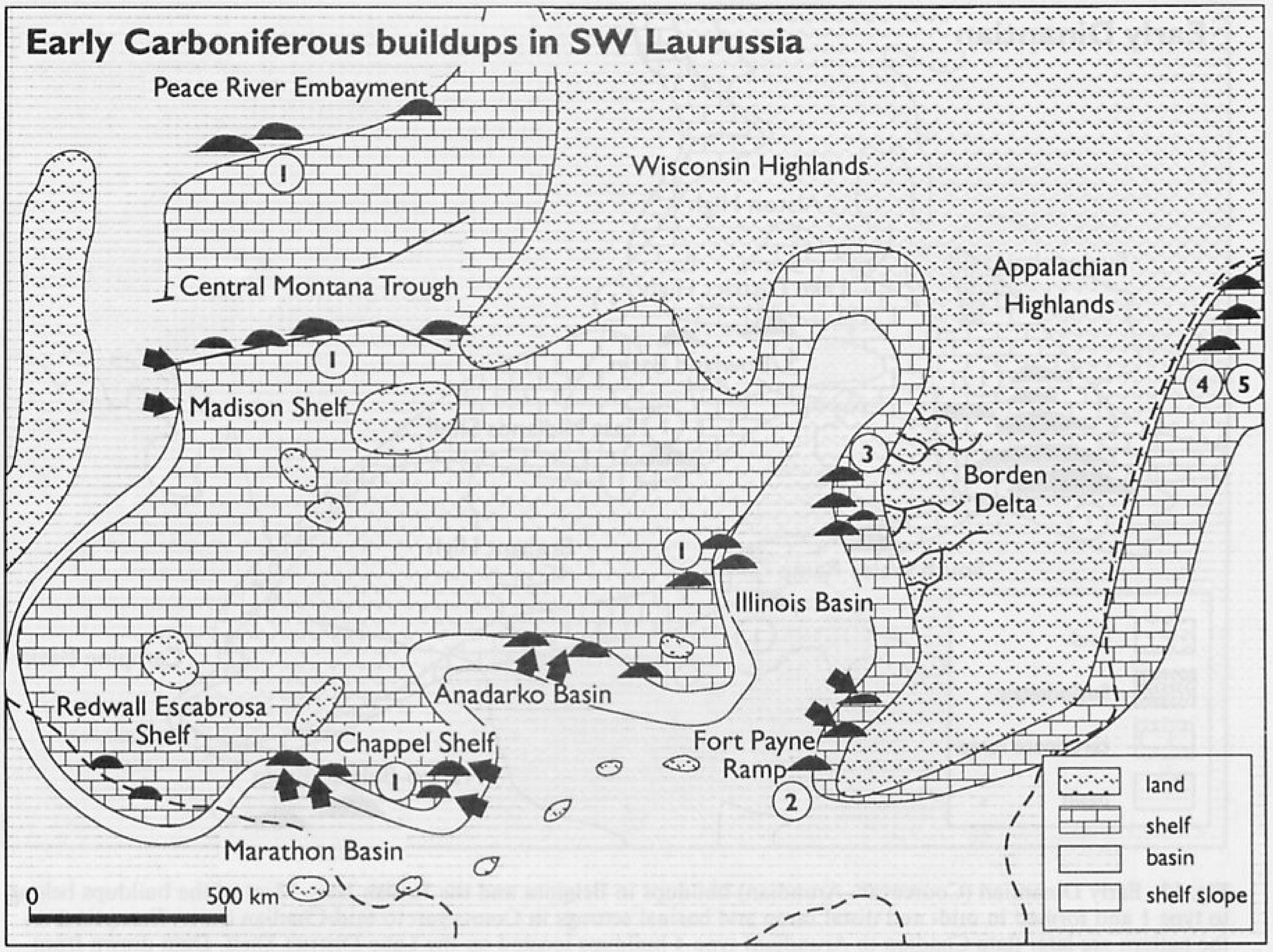

Fig. 11. Early Carboniferous buildups on the south-western margin of Laurussia. Palaeogeographic outline and inferred sites of upwelling from Gutschick & Sandberg (1983). Location of buildups from these authors and other authors cited in the text. Ringed numbers indicate the buildup type. Solid arrows indicate possible sites of upwelling. Dashed line indicates present-day coastline of the eastern and southern coast of USA.

The buildups which formed on the eastern side of the Appalachian Highlands in the areas which today make up the maritime provinces of Canada generally belong to types 4 and 5. The type 4 buildups of the Gays Rivers Formation display a local skeletal framework and have a diverse assemblage of tabulate corals, calcified algae, bivalves, gastropods and brachiopods (Boehner *et al.*, 1989a). The buildups of type 5 in the Windsor Groups are up to 80 m thick and 600 m wide. Bryozoans, algae, brachiopods and molluscs are all present, but corals are absent (Boehner, 1989; Boehner *et al.*, 1989b; McCutcheon, 1989).

Central Southern margin of Laurussia

As we approach the central southern margin of Laurussia, we trace the buildups which formed in north-western Europe—in southern Belgium, south-west England, South Wales, Ireland, the Pennine region and the Midland Valley of Scotland. In the early Dinantian (Courceyan–Chadian–Arundian) most of the buildups of this region belong to type 1 (Fig. 12). The classic buildups of Waulsort (type 1) in southern Belgium formed in the Franco-Belgian Basin. To the north-north-west, the buildups of Clitheroe (type 1) formed in the Bowland Basin (Miller & Grayson, 1982). Central and southern

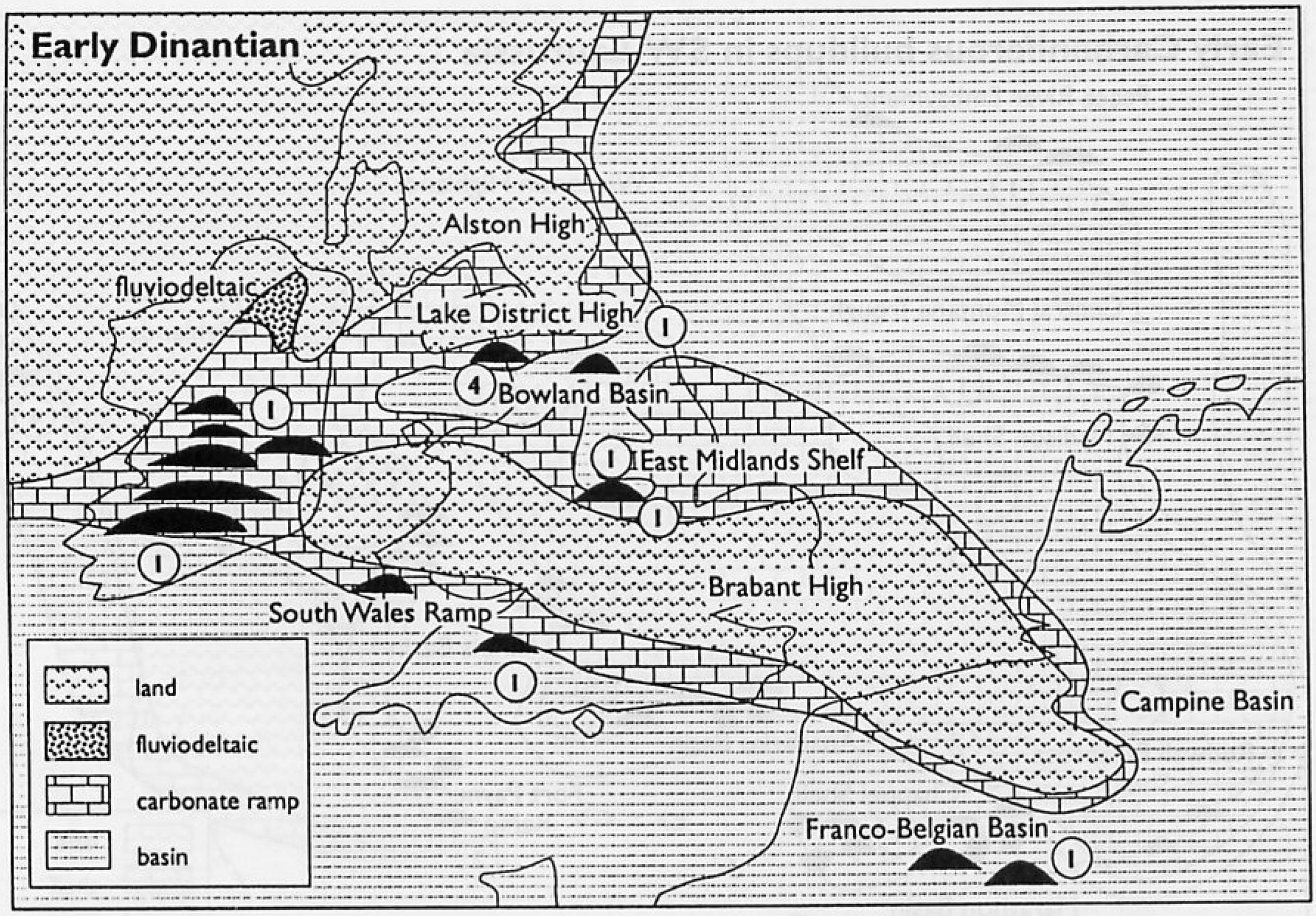

Fig. 12. Early Dinantian (Courceyan–Arundian) buildups in Belgium and the British Isles. Most of the buildups belong to type 1 and formed in mid- and distal ramp and basinal settings in Courceyan to mid-Chadian times. Exceptions to the pattern are later (late Chadian to Arundian) type 4 buildups located on the Lake District Shelf. Data drawn from authors cited in the text.

Ireland and South Wales were sites of contemporary ramps. Type 1 buildups are not common in South Wales; but they form extensive sheets of buildups in Ireland (Lees, 1964). The exception to the overwhelming dominance of type 1 is the occurrence of the type 4 coralgal-*Aphralysia* buildups of Furness (Adams, 1984) which grew in Chadian–Arundian times.

A survey of the buildups which formed in the region during late Dinantian times (Holkerian–Asbian–Brigantian) shows that type 3, representing a more diverse skeletal assemblage, takes over from type 1 and predominates. Buildups have been recorded in boreholes into the Viséan of the Campine Basin (Muchez *et al.*, 1987; Fig. 13) but there is insufficient evidence to indicate which type is represented. Further north, type 3 buildups formed on the Derbyshire Carbonate platform, and in the Midland Valley. Further examples have been described from the Isle of Man, Northern Ireland and central-south Ireland. In North Wales, type 4 build-ups dominated by bryozoans stand out as different from other contemporary buildups in the British Isles (Bancroft *et al.*, 1988).

The relationship between buildup types, structural setting and age

Type 1 buildups are associated with deep-water contexts (depth greater than 100 m), for example in the Peace River Embayment (Davies *et al.*, 1989), the Central Montana Trough (Precht & Shepard, 1989), the Burlington Shelf Slope (King, 1986), the distally steepened ramp in the Dublin Basin, Ireland (Nolan, 1989), the Bowland Basin, UK (Miller & Grayson, 1972; Gawthorpe 1986, 1987) and mid–deep-ramp settings in Staffordshire, UK (Bridges & Chapman, 1988), in south-west Wales

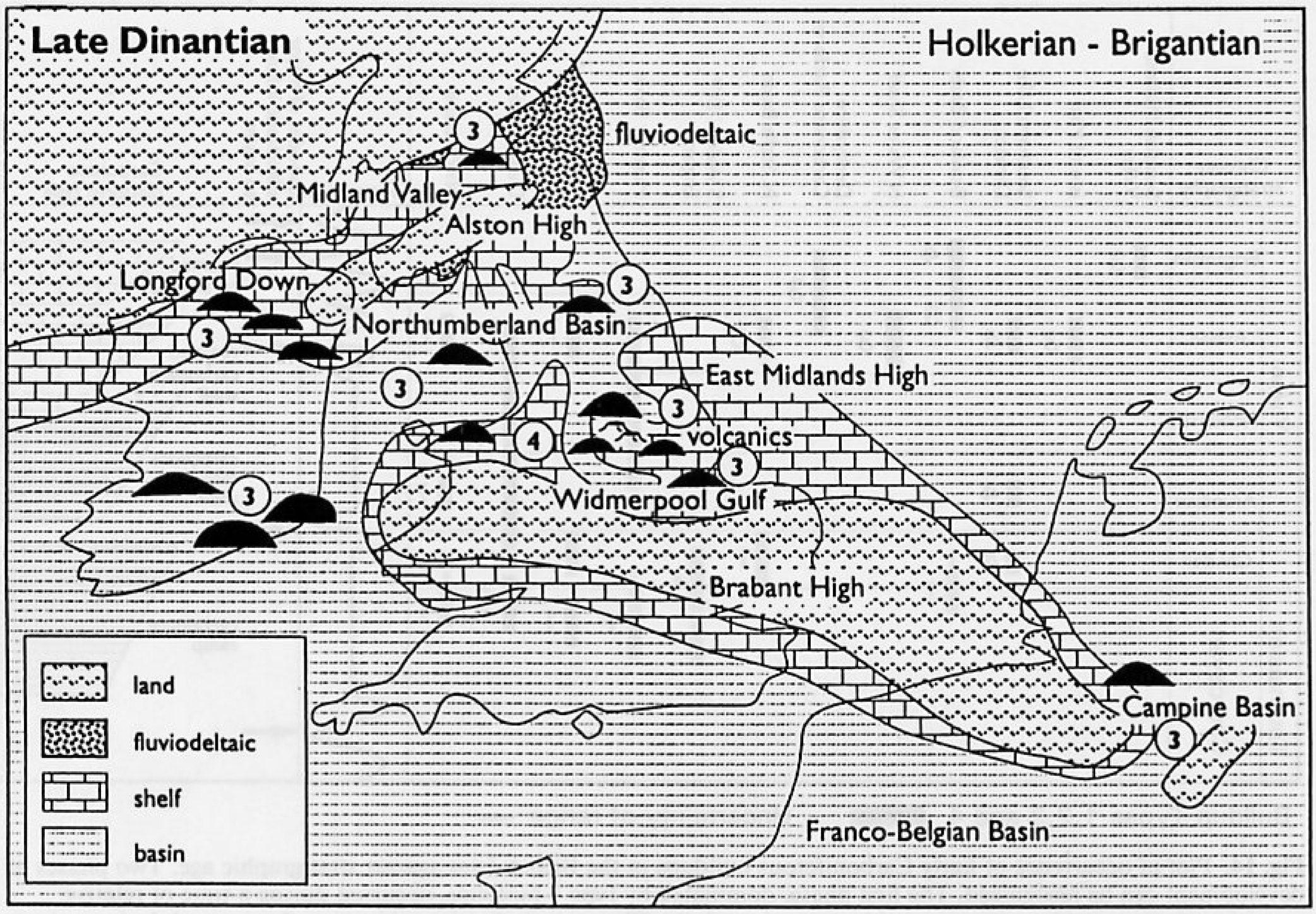

Fig. 13. Late Dinantian (Holkerian–Brigantian) buildups in Belgium and the British Isles. Most of the buildups belong to type 3 and formed on shelf margins and in intraplatform basin settings. Exceptions are the type 4 buildups which formed on the North Wales Shelf. Data drawn from authors cited in the text.

(Faulkner, 1989) and in Somerset, UK (Lees & Hennebert, 1982). These carbonate mud-mounds are, without exception, Courceyan to mid-Chadian (lower Mississippian) in age. The type 2 buildups of the Fort Payne Formation are interpreted as having formed in the deeper part of the photic zone, ~ 95 m (Ausich & Meyer, 1990), again in a ramp setting. There is little evidence for the contemporary development of other buildup types in shallow-ramp or shelf settings. However, type 4 cluster reefs formed on the Lake District Shelf during the late Chadian–Arundian (mid-Mississippian) times. As carbonate production continued, carbonate sequences built up to form shelves, margins and shelf slopes (Gawthorpe *et al.*, 1989). These provided new habitats for the faunal (and floral) communities which were responsible for buildup development. Buildup types 3, 4 and 5 formed in Holkerian, Asbian and Brigantian stages on the margins of the Askrigg High, UK (Arthurton *et al.*, 1988) and the Derbyshire platform, UK (Gawthorpe & Gutteridge, 1990). Type 3 also formed in shelf interior settings in north-central Ireland (Caldwell, 1959; Schwarzacher, 1961) and in intraplatform ramps within the Derbyshire platform (Gutteridge, this volume). These intrashelf buildups are of Brigantian age.

Analysis of the structural setting and age of the Early Carboniferous carbonate buildups in the British Isles (Fig. 14) suggests that there were two main phases of development. Phase 1 (Courceyan to late Chadian) witnessed the development of type 1 buildups on the mid to deep parts of carbonate ramps. During the Arundian and Holkerian the development of these buildups was reduced, but did not cease. Later, during the Asbian and Brigantian there was a renewed phase of development. Type 3 buildups formed in platform (or shelf) interior settings as a result of intrashelf ramp development reflecting extensional tectonism

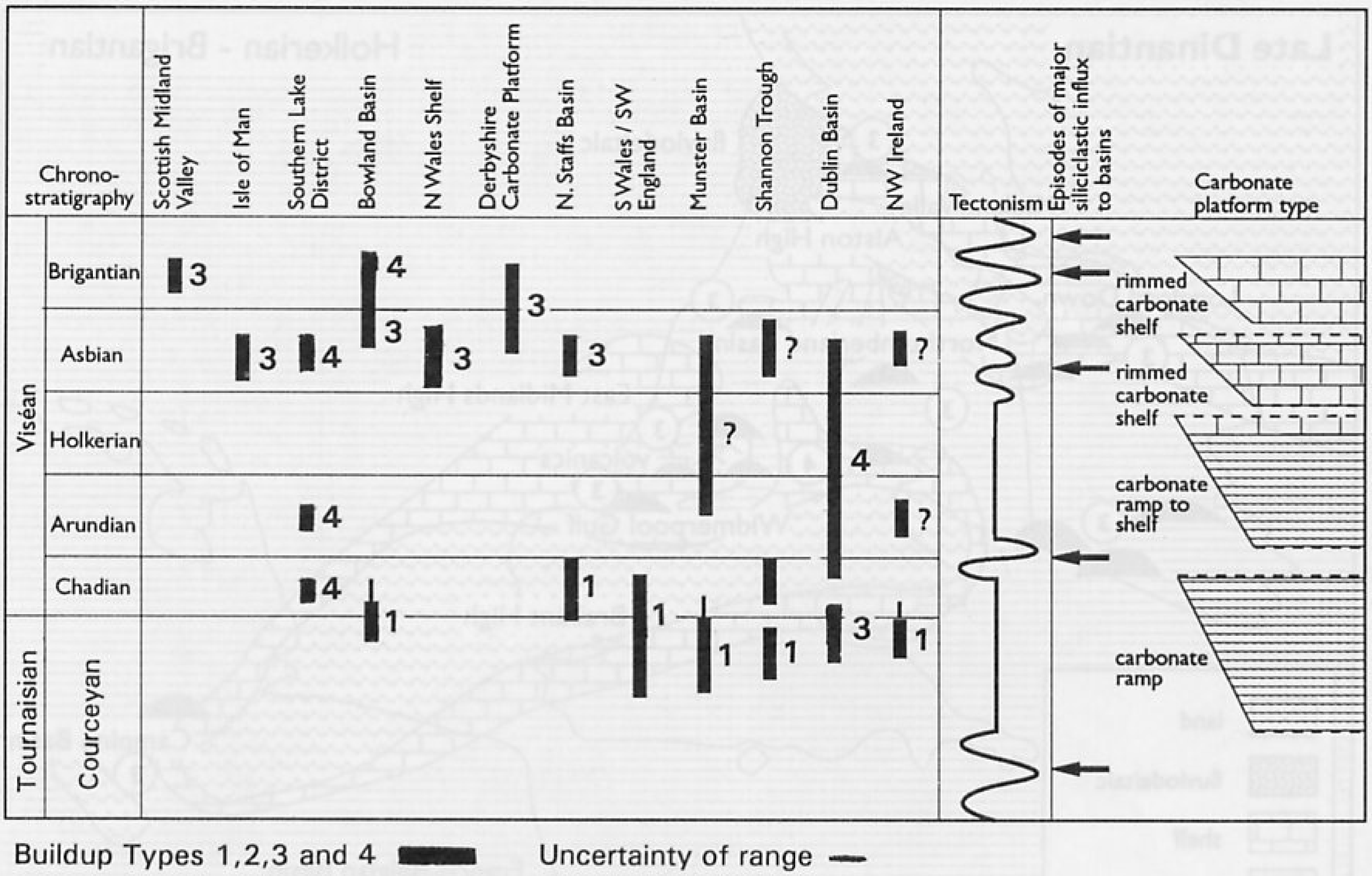

Fig. 14. Plot of occurrence of Early Carboniferous buildups in the British Isles against stratigraphic age. Two phases of development can be recognized. The first phase, dominated by type 1 buildups, occurred during a time of relative tectonic quiesence, and was terminated by tectonic activity. The second, dominated by type 3, occurred during a time of tectonic activity and terminated as siliciclastics, derived from the north, were delivered to the contemporary platforms.

(Fig. 15). Locally, in the Staffordshire Basin, UK, type 3 buildups of Asbian age nucleated on the crests of pre-existing Chadian mounds of type 1 (Aitkenhead *et al.*, 1985).

INFLUENCE OF TECTONISM ON NUCLEATION AND DEMISE OF MUD-MOUNDS

Recent studies have shown that Dinantian basins in northern England, North Wales and Ireland underwent alternating episodes of crustal extension and tectonic quiescence (Jones *et al.*, 1988; Gawthorpe *et al.*, 1989; Nolan, 1989; Ebdon *et al.*, 1990). During extensional episodes carbonate platforms were affected by localized footwall uplift resulting in subaerial exposure and temporary suppression of carbonate production by influxes of siliciclastic sediment. In basinal areas, extensional events often caused the reactivation of intrabasinal structures causing the development of submarine topography which are expressed as local facies changes. This submarine topography also formed the sites for growth of carbonate mud-mounds.

Figure 14 shows the relative timing of tectonic events and carbonate mud-mound development.

Nucleation of carbonate mud-mounds

Although the development of early Dinantian carbonate mud-mounds took place during a tectonically quiescent phase, syndepositional structures formed during basin initiation may have played an important role in providing sites for carbonate mud-mound nucleation in several basins. Carbonate mud-mounds in the Bowland Basin developed around fault-controlled intrabasinal highs (Gawthorpe 1986, 1987). In the Dublin Basin, carbonate mud-mounds developed in association with the

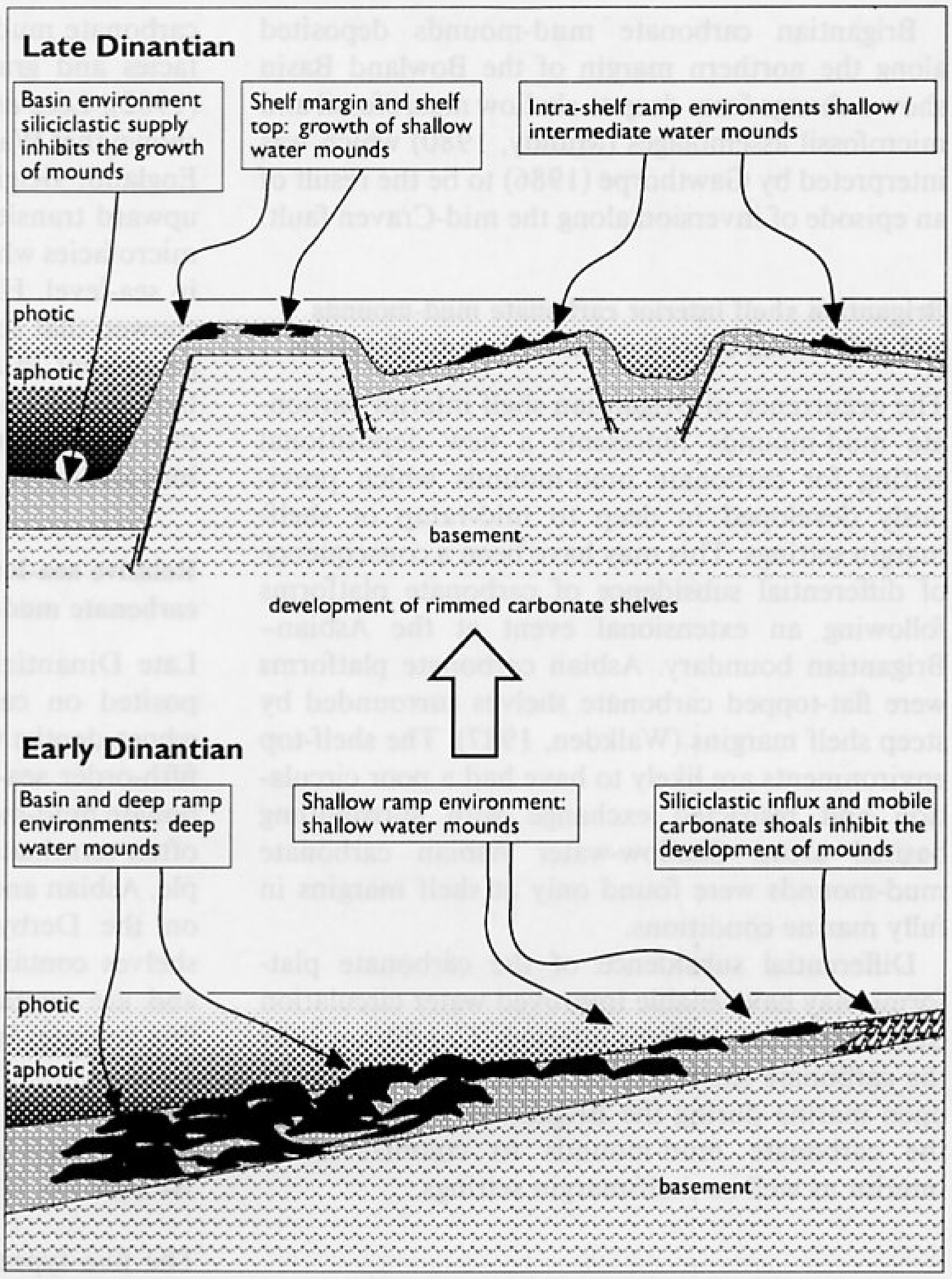

Fig. 15. Diagram illustrating how the development of shelf platforms and intrashelf ramp environments in the British Isles influenced the development of Early Carboniferous mud-mounds. The increasing supply of siliciclastics to basinal environments restricted buildup development to shelf margins and intrashelf ramps.

margins of fault blocks formed during an episode of late Tournaisian faulting (Jones *et al.*, 1988). Any links between nucleation of other Dinantian carbonate mud-mounds and synsedimentary tectonism is less clear, although inversion anticlines around the Derbyshire carbonate platform may have provided sites of shallow water on which Brigantian mud-mounds nucleated (Gutteridge, this volume).

Tectonics and the demise of early Dinantian carbonate mud-mounds

The demise of early Dinantian carbonate mud-mounds in many areas appears to coincide with an episode of crustal extension at the level of the late Chadian–Arundian boundary. This had several detrimental effects on carbonate sedimentation in general and the growth of carbonate mud-mounds in particular. The growth of intrabasinal features during the extensional event at the Chadian–Arundian boundary caused intrabasinal uplift which resulted in the demise and erosion of carbonate mud-mounds in the Dublin Basin and Navan areas (Nolan, 1989; Philcox, 1989). An increase of siliciclastic influx during the Chadian may have also caused the demise of early Dinantian carbonate mud-mounds in the Bowland Basin (Gawthorpe 1986, 1987). Carbonate mud-mounds in the Shannon Trough were terminated by an episode of volcanic activity which Strogen (1988) regarded as a local expression of the Chadian–Arundian extensional event.

Brigantian carbonate mud-mounds deposited along the northern margin of the Bowland Basin show a change from deep to shallow macrofossil and microfossil assemblages (Mundy, 1980) which was interpreted by Gawthorpe (1986) to be the result of an episode of inversion along the mid-Craven fault.

Brigantian shelf interior carbonate mud-mounds and differential subsidence of carbonate platforms

The occurrence of Brigantian shelf interior carbonate mud-mounds represents a new depositional setting for carbonate mud-mounds which previously developed in deep to mid-ramp or shelf-margin settings. This may have been a consequence of differential subsidence of carbonate platforms following an extensional event at the Asbian–Brigantian boundary. Asbian carbonate platforms were flat-topped carbonate shelves surrounded by steep shelf margins (Walkden, 1987). The shelf-top environments are likely to have had a poor circulation and restricted exchange with surrounding basinal areas. Shallow-water Asbian carbonate mud-mounds were found only at shelf margins in fully marine conditions.

Differential subsidence of the carbonate platforms may have enable improved water circulation over carbonate platform interiors. Conditions over the carbonate shelf may therefore have been more open marine during the Brigantian which allowed the carbonate mud-mounds to colonize shelf-interior as well as shelf-margin settings.

RELATIVE SEA-LEVEL VARIATIONS AND THE GROWTH OF CARBONATE MUD-MOUNDS

Conditions for carbonate production were most favourable during tectonically quiet periods when sedimentation was dominated by thermal subsidence and fourth- or fifth-order sea-level variations of glacio-eustatic origin (Horbury, 1989; Walkden, 1987). Carbonate platforms were established and expanded during tectonically quiescent periods, and the evolution of carbonate ramps into shelves took place during the Arundian to Asbian which was tectonically quiescent.

Microfacies and faunal assemblages

Sea-level variations are expressed in deep-water carbonate mud-mounds by changes in their microfacies and grain assemblages. Lees & Hennebert (1982), Lees *et al.* (1985) and Murphy (1988) have shown that Waulsortian mud-mounds in south-west England, Belgium and southern Ireland show an upward transition from deeper- to shallower-water microfacies which may reflect a late Tournaisian fall in sea-level. However, Bridges & Chapman (1988) showed that several depth-related microfacies may be present in a single carbonate mud-mound and that microfacies variations may be explained by downslope transport or growth of the mud-mound into shallower water rather than sea-level changes.

Relative sea-level variations and the demise of carbonate mud-mounds

Late Dinantian carbonate mud-mounds were deposited on carbonate shelves and shelf margins whose depths were within the range of fourth- and fifth-order sea-level variations. The growth of carbonate mud-mounds in carbonate shelf settings was often terminated by subaerial exposure, for example, Asbian and Brigantian carbonate mud-mounds on the Derbyshire and North Wales carbonate shelves contain calcrete features, vadose cements and are overlain by karstic surfaces (Gutteridge, this volume; Warren *et al.*, 1984).

BUILDUP COMMUNITIES: MAKING SENSE OF THE VARIATIONS

The five types of buildup have certain aspects in common. All five types are characterized by sessile suspension feeders. The deeper-water (type 1) mud-mounds have a benthic skeletal macrofauna dominated by fenestrate bryozoans and sponges. The type 2 buildups, with their cores of green clay, have a very high content of well-preserved crinoids. The association suggests that clay particles gave rise to relatively turbid conditions which were tolerated by a rich suspension-feeding fauna. The type 3 buildups are mud-mounds with a wider range of macroskeletal fauna, particularly fenestrate bryozoans, crinoids, brachiopods, bivalves and gastropods. Both the density and the diversity of the macroskeletal components are greater than in type 1, although the abundance and the quality of preservation of articulated remains do not compare with type 2.

The green shale (clay) cores to the type 2 buildups provide the clearest possible evidence for the

baffle mechanism operating and trapping clay particles (Ausich & Meyer, 1990). Meyer *et al.* (this volume) point out that there is no indication of erosion of the green shale prior to the deposition of the carbonates: the shale cores do not appear to be the product of differential erosion. Micrite forms an important element of the wackestone buildups but Ausich & Meyer (1990) and Meyer *et al.* (this volume) make no reference to peloids or a clotted texture. They interpret the carbonate mud as provided by non-preserved organisms dwelling on the buildup. There is no evidence for any microbial contribution comparable to that considered responsible for the peloidal/clotted micrites of the mud-mounds which make up buildup types 1, 3 and 5 (see discussion by Lees & Miller, this volume; Bridges & Chapman, 1988; Pickard, 1992 and Dix & James, 1987). Recognition of buildup types which have contrasting sources of carbonate raises the probability that it is simplistic to label buildups as microbial or non-microbial. Future research may usefully focus on the extent to which microbial processes contributed to the production of carbonate mud on different buildups.

The buildups of type 4 are notable for the density of coralgal-*Aphralysia* or coralgal-bryozoan remains and the local development of framework textures. In the absence of stromatoporoids, and large sheet-form tabulate corals, these local frameworks appear to represent colonization of the sea-floor by opportunistic organisms which were not mud producers.

Type 5 buildups are notable for the paucity of open marine organisms which are common on other types; for example, corals and crinoids are absent from the Codroy buildups (Dix & James, 1987). The mineralized faunal tubes described from these buildups (Von Bitter *et al.*, 1990), provide the strongest evidence for contemporary hydrothermal activity. Dix & James (1987) argued that microbial processes had a significant role in forming the peloidal muds and microthrombolites. Thus in Early Carboniferous buildups we see evidence for a microbial contribution to relatively deep (type 1), intermediate-depth (type 3) and shallow-water (type 5) mud-mounds.

EARLY CARBONIFEROUS BUILDUPS AND THE NUTRIENT SUPPLY

Modern reefal systems with well-developed skeletal frameworks flourish in warm oligotrophic conditions and are generally affected adversely by reduced water temperatures (below 10°C) and by changes to eutrophic conditions (Hallock & Schlager, 1986). These reefs are associated with shallow marine conditions which allow the penetration of light to zooxanthellate organisms. Recent studies have shown, however, that there are modern mound communities which flourish in deeper water. Boreen & James (1993) have reported bryozoan-sponge mounds forming at depths greater than 100 m off the shelf of south-eastern Australia. These mounds are forming in the vicinity of a zone of active upwelling and are showing growth rates of ~ 1.05 m kyr^{-1}. This supports to some extent the contention of Wright & Faulkner (1990) and Wright (1991) that regional upwelling may have been a significant source of nutrients which enabled the large deep-water microbial buildups (type 1) to grow. A second possible source of nutrients is that of cool-water hydrothermal seeps discharging hydrocarbons into the water column (Hovland & Thomsen 1989). While hydrothermal seeps have been postulated to explain type 5 buildups in Newfoundland, the observation that most type 1 buildups, dominated by microbial muds, formed in deep-ramp, mid-ramp and shelf-slope contexts is more commensurate with an oceanic supply of nutrients from passing upwelling currents. King's (1990, 1991) proposal that buildups formed in settings protected from tropical storms is not compelling because the structures themselves show much evidence for early lithification and resistance to adverse flow conditions (Bridges & Chapman, 1988). The predominant influence of the south-east trade winds (Gutschick & Sandberg, 1983) would have tended to induce offshore surface flows which in turn would have caused upwelling. We believe that this was probably a primary source of nutrients.

CONCLUSIONS

This study shows that Early Carboniferous mud-mounds are members of a spectrum of five types of buildup: fenestrate-bryozoan-sponge spicule buildups type 1; crinoid-bryozoan buildups (type 2); crinoid–brachiopod–fenestrate bryozoan buildups (type 3); coralgal-*Aphralysia* and bryozoan-coralgal buildups (type 4) and trepostome–microthrombolite buildups (type 5). Types 1, 3 and 5 are mud-mounds with evidence of microbial activity.

Types 1 and 2 formed in deep-water settings during the Courceyan to mid-Chadian; types 3, 4 and 5 formed in mid- to shallow-water shelf, shelf-margin and intrashelf basin settings during the Holkerian–Brigantian stages. Regional tectonism in the form of extensional events caused reactivation of intrabasinal structures resulting in submarine topography which formed nucleation sites for mud-mounds in basinal environments. Oceanic upwelling is considered a primary source of the nutrients which supported the microbial activity of the type 1 buildups. Future work needs to focus on the relative contribution of microbial and non-microbial muds in each buildup type.

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