Rugose coral biostromes in the late Viséan (Mississippian) of NW Ireland: Bioevents on an extensive carbonate platform

Markus Aretz [a,b,c,*], Hans-Georg Herbig [d], Ian D. Somerville [e], Pedro Cózar [f]

[a] Université de Toulouse, UPS (OMP), LMTG, 14 Avenue Edouard Belin, F-31400 Toulouse, France
[b] CNRS, LMTG, F-31400 Toulouse, France
[c] IRD, LMTG, F-31400 Toulouse, France
[d] Universität zu Köln, Institut für Geologie und Mineralogie, Zülpicher Str 49a, 50674 Köln, Germany
[e] School of Geological Sciences, University College Dublin, Belfield, Dublin 4, Ireland
[f] UEI y Departamento de Paleontología, Instituto de Geología Económica CSIC-UCM, Facultad de Ciencias Geológicas, José Antonio Novais 2, 28040 Madrid, Spain

ARTICLE INFO

ABSTRACT

The extensive upper Viséan (Asbian) platform carbonates in NW Ireland (Bricklieve Limestone Fm, Glencar Limestone Fm and Dartry Limestone Fm) contain distinctive rugose coral biostromes, which are dominated by different species of the genus *Siphonodendron*. These are in stratigraphic sequence: *pauciradiale* biostrome (oldest), *martini* biostrome and several *junceum* biostromes (youngest). They represent bioevents caused by special short-lasting ecological conditions and can be used as approximately synchronous horizons to correlate within the region.

The *pauciradiale* biostrome is the thickest, laterally most persistent and most variable in facies and biotic composition of all biostromes. It formed on a tectonically influenced platform with a landward–seaward zonation from northwest to southeast, mainly above storm wave-base and below fair-weather wave-base. The northwestern Streedagh facies is characterized by the presence of clusters of large sheet-like colonies of *S. pauciradiale*. The intermediate O'Donnell's Rock facies is unique for the predominance of the fasciculate genus *Solenodendron*. The southeastern Bricklieve facies represents the amalgamation of autochthonous and allochthonous coral debris and bioclastic debris with localized small patches of coral boundstone. Mass occurrences of fasciculate rugose corals re-appear in the *martini* biostrome. This biostrome developed in a shallower water setting, just above fair-weather wave-base on a levelled carbonate platform. The *junceum* biostromes are thinner, decimetre to some metres thick, and less persistent. They formed in deeper water mostly below storm wave-base, except for the composite 2nd *junceum* biostrome of the Bricklieve Mountains, which records a period of shallowing.

According to facies and coral morphologies, which were compared with modern scleractinian growth forms, sea-level variation exerted one of the strong controls on the rise and decline of the biostromes. The *pauciradiale* biostrome formed during an extended shallowing-upward cycle in a depth interval leading to the climax of *Siphonodendron pauciradiale*. The cycle ended with the development of the *martini* biostrome in shallow water. Its demise is probably caused by drowning during the late Asbian sea-level rise. During that time slice the *junceum* biostromes flourished in deeper water on the platform. Coral growth ceased almost completely after formation of the *junceum* biostromes during the falling sea level of the latest Asbian. Siliciclastic input and resulting turbidity, as well as turbulence formed a complex cascade of ecological constraints. In addition to the local tectonic influences, they combined to result in the "depth" factor which controlled the distribution of predominating coral populations and the succession of the different biostromes in the Asbian of NW Ireland.

1. Introduction

Beginning with the pioneer work of Vaughan (1905), corals within shallow-water carbonates have long been recognized as important for the stratigraphic division of the European Mississippian (e.g. Mitchell, 1989; Poty et al., 2006; Somerville, 2008). Coral accumulations, thickets and biostromes are common features in Mississippian shallow-water carbonate facies. Although in Britain and southern Belgium the usefulness of some of these beds as stratigraphic marker horizons has been demonstrated (e.g. George et al., 1976; Somerville, 1979; Aretz, 2002; Aretz and Nudds, 2005, 2007), only limited data are available on their faunal composition and variation, and depositional environments.

* Corresponding author. Université de Toulouse, UPS (OMP), LMTG, 14 Avenue Edouard Belin, F-31400 Toulouse, France.
E-mail address: markus.aretz@lmtg.obs-mip.fr (M. Aretz).

Northwestern Ireland contains an embayment of the vast Northwest-European late Tournaisian–Viséan carbonate platform. The proximity to the coastal zones of the Laurussian Continent to the north is one distinctive characteristic for this internal platform (George, 1958; Graham, 1996; Mitchell, 2004; Sevastopulo and Wyse Jackson, 2009). The deposition of fluvial and deltaic siliciclastic rocks is more common in this area than in most other parts of Western and Central Europe at that time. Upper Viséan rocks in northwestern Ireland are mainly limited to three NE–SW-trending structures; from north to the south these are, the Sligo, Ballymote, and Carrick synclines (George, 1958). The synclines are separated by the Ox Mountains Inlier and the Curlew Mountains Inlier, respectively (Fig. 1).

Upper Viséan carbonates from northwestern Ireland have been described in the important regional studies of Oswald (1955), George and Oswald (1957), Caldwell (1959) and Dixon (1972). Hubbard (1966, 1970) and Dixon (1970) have dealt with the splendid Viséan coral occurrences around the Donegal Bay area and Caldwell and Charlesworth (1962) described several horizons rich in *Siphonodendron*, which they termed 'coral-reefs', in the Asbian successions of the Bricklieve Mountains (southern Ballymote Syncline) (Figs. 1, 2). Dixon (1972) and Somerville et al. (2009) showed that at least some of these horizons could be traced throughout the Ballymote Syncline. Aretz (2002) addressed carbonate microfacies and distribution of corals in the *pauciradiale* biostrome of the Bricklieve Mountains and from Streedagh Point (Sligo Syncline) including some taxonomical descriptions. Aretz and Herbig (2003a) first commented on the palaeoecology and depositional setting of the *Siphonodendron* biostromes. The results of their short contribution and the succeeding studies of Cózar et al. (2005) and Somerville et al. (2009) formed the basis for this present paper. It attempts (i) to describe the different types of rugose coral biostromes and their lateral variations in northwestern Ireland within a stratigraphic framework; (ii) to interpret the environmental setting and factors controlling their rise and decline; and (iii) to use comparisons in morphology with analogous modern scleractinian corals to understand ecological constraints on growth style and water depth.

2. Depositional setting and stratigraphy

The spatial and temporal distribution of carbonate-dominated facies in the Mississippian succession of northwestern Ireland is mainly controlled by the advance and retreat of siliciclastic-dominated facies from the NNW (George, 1958; Graham, 1996). Particular advances took place during the Tournaisian, mid-Viséan, and latest Viséan–Namurian times and can be related to (1) the regional tectonic regime with a number of important displacement pulses during Mississippian time (see Mitchell, 2004), and (2) sea-level oscillations, especially during the late Viséan, triggered by the glaciation and deglaciation cycles in the southern hemisphere (e.g. Hance et al., 2001; Wright and Vanstone, 2001).

In a first generalized step, during the Viséan the Northwest Irish shelf is dominated by fluvial and deltaic depositions in the north and deposition of fully-marine mud-dominated and/or carbonate facies in southern areas. This pattern advocates for a generalized image of a southward-dipping shelf. However, this simple shelf geometry is much complicated by SW–NE or W–E-trending active fault systems (see Mitchell, 1992; Philcox et al., 1992; Somerville et al., 2009), which may have partly controlled the distribution of mudbanks and which acted during different times. During Arundian–Holkerian times, the Ox Mountains Inlier (OMI) was a major barrier for siliciclastic input from the NNW towards the SSE (Dixon, 1972; Graham, 1996). Therefore, the succession of the Sligo Syncline is much richer in siliciclastic rocks than the succession of the Ballymote Syncline.

The Asbian carbonates studied herein are sandwiched in all synclines between siliciclastic-dominated deposits of Arundian to Asbian age (the traditional 'Calp') and Brigantian–Namurian deposits of the Leitrim Group ('Yoredale Series'). The existence of separate lithostratigraphic nomenclatures for each syncline reflects the lateral
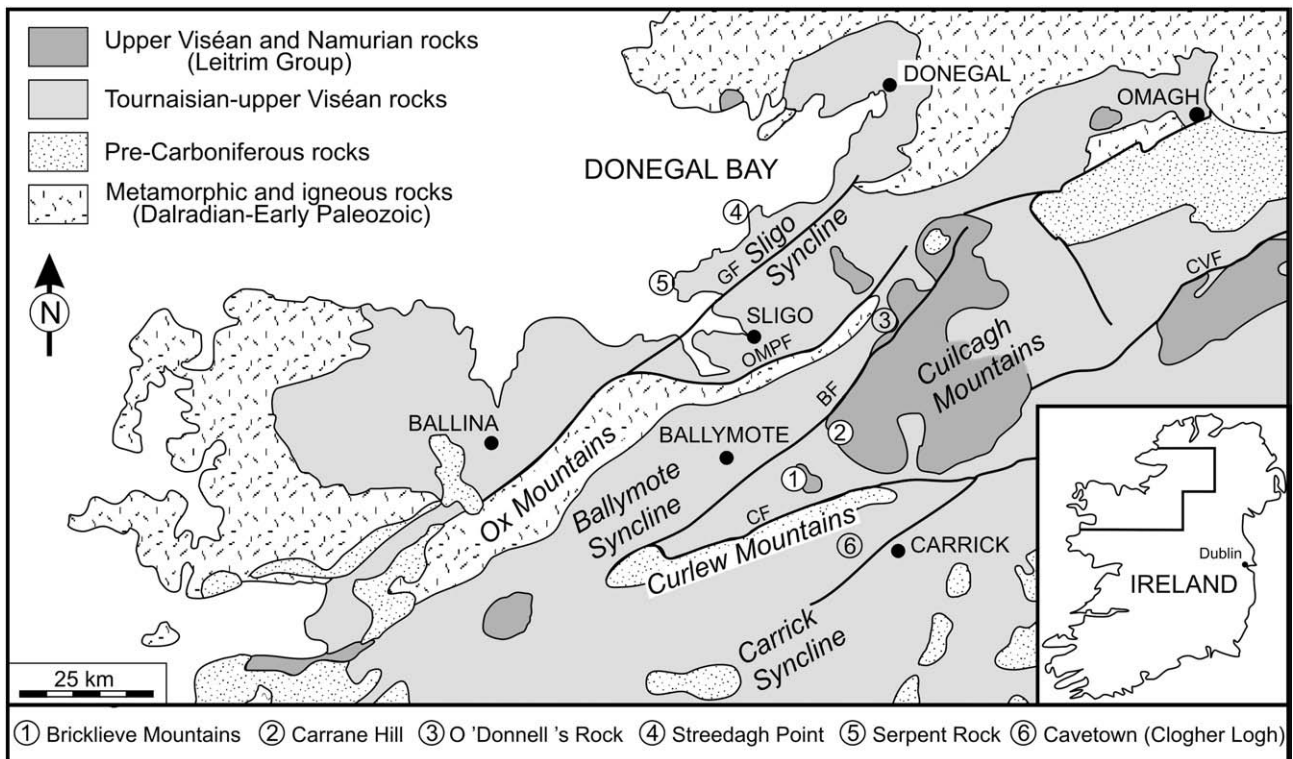
Fig. 1. Geology of northwest Ireland showing the main synclinal structures (modified from Dixon, 1972, fig. 1). BF = Belhavel Fault; CF = Curlew Fault; CVF = Clogher Valley Fault; GF = Grange Fault; OMPF = Ox Mountains - Pettigoe Fault. Localities: 1) Bricklieve Mountains, 2) Carrane Hill, 3) O'Donnell's Rock, 4) Streedagh Point, 5) Serpent Rock, 6) Cavetown.
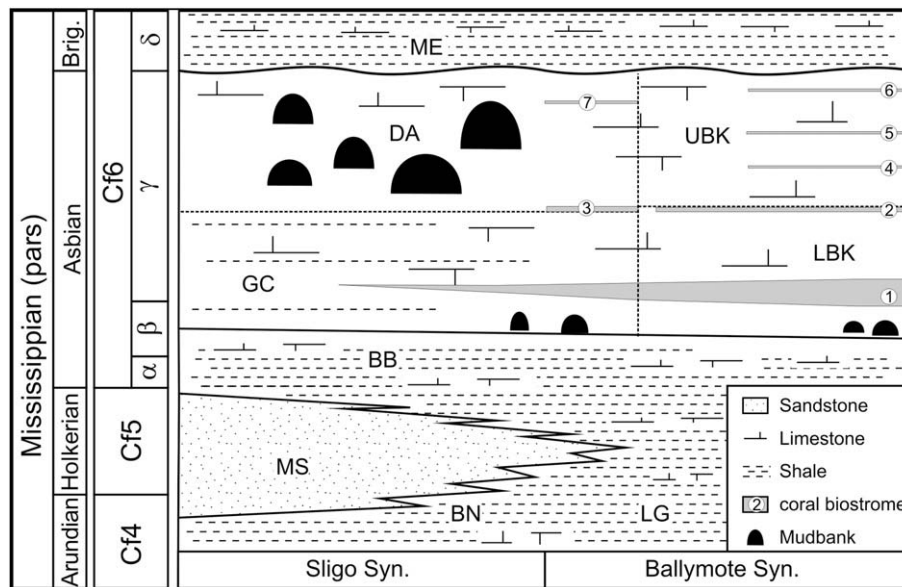
Fig. 2. Schematic overview on the lower and upper Viséan succession of the Sligo and Ballymote synclines. Lithostratigraphy is based on Oswald (1955), Dixon (1972), and Somerville et al. (2009). Biostratigraphy is based on Cózar et al. (2005) and MacDermot et al. (1996). Coral beds are indicated as grey boxes, mudbanks in black. (not to scale); BN: Bundoran Shale Formation; MS : Mullaghmore Sandstone Formation; BB: Benbulben Shale Formation; GC: Glencar Limestone Formation; DA: Dartry Limestone Formation; ME: Meenymore Formation (Leitrim Group); LG: Lisgorman Shale Formation; LBK: lower Bricklieve Limestone Formation; UBK: upper Bricklieve Limestone Formation. Brig. = Brigantian. Foraminiferal zones and subzones from Conil et al. (1991). 1. *pauciradiale* biostrome, 2. = *martini* biostrome in the central and southern Ballymote Syncline, 3. = *martini* biostrome in the O'Donnell's Rock area, 4–6. = *junceum* biostromes in the Bricklieve Mountains, 7. = *junceum* biostrome in the O'Donnell's Rock area.

facies variations. The Asbian succession of the Sligo Syncline is lithologically more variable than the coeval succession of the Ballymote Syncline further south due to longer lasting and more important siliciclastic (mud) input (Fig. 2). The stratigraphic interval of this study is represented in the Sligo Syncline by the Glencar Limestone Formation and the Dartry Limestone Formation, but in the Ballymote Syncline by a single unit, the Bricklieve Limestone Formation. Moreover, in the northern and northeastern part of this syncline (O'Donnell's Rock area and further NE; Fig. 1) Oswald (1955) also introduced the Glencar Limestone and Dartry Limestone formations, because of close lithological affinities with the Sligo Syncline succession.

The carbonate-dominated formations succeed the mud-dominated formations, which are the Benbulben Shale Formation in the North and Lisgorman Shale Formation in the South. In both synclines the Asbian carbonate succession is succeeded by the supratidal to subtidal siliciclastic-dominant strata of the Meenymore Formation (Leitrim Group; Fig. 2) (West et al., 1968), which is widespread above a palaeokarstic surface or erosional hiatus (Kelly, 1996; Legg et al., 1998; Somerville et al., 2009).

The lower siliciclastic units are of mostly Arundian and Holkerian age, but an early Asbian age has been proposed for the topmost beds of the Benbulben Shale Fm (see George et al., 1976; Kelly, 1996; Legg et al., 1998). Microfossils and corals clearly show that the Glencar Limestone, Dartry Limestone, and Bricklieve Limestone formations are all of Asbian age (Cf6β Subzone at the base and Cf6γ Subzone for most parts of the composite succession; Cózar et al., 2005, 2006). The first Brigantian (Cf6δ Subzone) fossils do not occur until sedimentation of the Leitrim Group began (see Cózar et al., 2006 for a more detailed review).

In this study, coral biostromes have been observed in Asbian rocks in various sections of the Ballymote and Sligo synclines in counties Sligo and Leitrim.

Colonial and solitary corals occur in low abundances in almost all Asbian facies in the studied area (see figs. 6 to 17 in Somerville et al., 2009). The proliferations of specific taxa resulted in the formation of biostromes, all dominated by the genus *Siphonodendron*. They are important marker beds in the succession and are named after Caldwell

and Charlesworth (1962) and Dixon (1972). Five main coral biostromes have been distinguished (numbered 1 to 7 in Fig. 2): *pauciradiale* biostrome (oldest), *martini* biostrome, 1st *junceum* biostrome, 2nd *junceum* biostrome, and 3rd *junceum* biostrome (youngest). They have been observed in 15 sections (Appendix A and Fig. 1).

The Cavetown section (Clogher Lough) on the northern limb of the Carrick Syncline (locality 6 in Fig. 1) is not described herein (for details see Cózar et al., 2005; Somerville et al., 2009), but references are made to it in the discussion.

3. The coral biostromes

3.1. Pauciradiale biostrome

The *pauciradiale* biostrome is the most widespread of all coral horizons and also the thickest in the studied area (Fig. 2). Three facies can be differentiated and are designated here (1) Bricklieve facies, (2) O'Donnell's Rock facies, and (3) Streedagh facies (Tables 1 and 2).

3.1.1. Bricklieve facies
The Bricklieve facies is found throughout the Ballymote Syncline with the exception of the northeast (O'Donnell's Rock area), and extends into the Carrick Syncline (Cavetown section). The following description, based on the results obtained around Kesh Corann, Bricklieve Mountains (Fig. 1), is representative for the entire facies belt.

The *pauciradiale* biostrome occurs in the lower part of the Bricklieve Limestone Fm and is about 50 m thick. The Kesh Corann Cavern section exposes at least 45 m of thickly-bedded limestone below the coral biostrome, and the contact with the Lisgorman Shale Fm is not exposed (Fig. 2). These limestones are mostly lime-mud dominated (mudstone to wackestone textures) and rich in pelmatozoan and bryozoan fragments, and locally sponge spicules. Silicification is widespread in the matrix of the limestones, chert nodules occur in several horizons (see fig. 14 in Somerville et al., 2009). The coral fauna is restricted to the scattered solitary rugosan *Siphonophyllia samsonensis* (Salée) (= *Si. benburbensis* auct., following the synonymy of Poty, 1981).

Table 1

Comparison of the three *Siphonodendron* coral biostromes in NW Ireland.

Biostrome	*Pauciradiale* biostrome	*Martini* biostrome	*Junceum* biostromes
Biostrome type	Parautobiostromes and clusters	Parabiostromes and autoparabiostromes	Monospecific to oligospecific autobiostromes
Thickness	8–50 m	5–10 m	0.15–7 m
Coral diversity	Low–high (4–13 species)	High (11 species)	Very low–moderate (1–7 species)
Dominant species	*S. pauciradiale* and/or *Solenodendron furcatum*	*S. martini, S. pauciradiale* or *S. sociale*	*S. junceum*
Other colonial species	*S. scaleberense, S. martini, S. sociale, Lithostrotion decipiens, L. vorticale, Solenodendron furcatum, Corwenia* sp.	*S. pauciradiale, S. scaleberense, S. sociale, S. irregulare, S. intermedium*	*S. pauciradiale, S. irregulare, S. sociale,* (all extremely rare)
Solitary species	*Siphonophyllia samsonensis, S. siblyi, Axophyllum pseudokirsopianum, Haplolasma* cf. *densum, Caninophyllum archiaci, Axophyllum* sp., *Dibunophyllum* sp.	*Siphonophyllia* cf. *siblyi, Palaeosmilia murchisoni, Haplolasma* cf. *densum, Caninophyllum archiaci, Clisiophyllum* sp.	*Siphonophyllia* sp., *Dibunophyllum* sp. *Pseudozaphrentoides, juddi, Caninophyllum archiaci, Clisiophyllum garwoodi* (all extremely rare)
Distinctive associated biota	Encrusting bryozoans, gigantoproductid brachiopods	Encrusting bryozoans, large crinoid stems, locally abundant foraminiferans, rare dasyclads	Red algae, green algae extremely rare, in situ gigantoproductid brachiopods (2nd *junceum* bed),
Proportion of in situ upright colonies	Low–high ([5–]10–50%)	Low (10–15%)	High (>50%)
Degree of Abrasion/fragmentation	Moderately low–very high	High	Low
Characteristic feature(s)	The thickest biostrome with pronounced lateral facies and thickness variation	Moderately thick, abundant fragmented and inverted colonies;	Thin biostromes consisting of several monospecific to oligospecific coral horizons
Depositional environment interpretation	Formation between storm wave-base and fair-weather wave-base	Formation above fair-weather wave-base	Formation mostly below storm wave-base but with occasional short-lived shallowing events

The *pauciradiale* biostrome in the Bricklieve facies is characterized by a mass occurrence of the nominal taxon *Siphonodendron pauciradiale* (McCoy). The volumetric dominance of *S. pauciradiale* is not surpassed throughout the succession by other coral species, although the fauna is relatively diverse (Table 2). *Si. samsonensis* is more common in the lower half of the biostrome than in its upper half, whereas at least in the Lough Labe section *S. martini* (Milne-Edwards and Haime) and *S. sociale* (Phillips) show increasing abundance near to the top of the section. Gigantoproductid brachiopods are associated in varying abundances (absent to common).

Bedding occurs throughout the coral biostrome, often in beds 30–50 cm thick. Very typical is the heterogeneous composition of the entire coral horizon in respect to facies and fauna. Aretz (2002) differentiated three main lithofacies types (Fig. 3): coral boundstone with in situ colonies (I), coral debris limestones (II), and bioclastic grainstones (III). However in thin section, lime-mud is more common

in all three facies types than previously considered (Aretz, 2002), and therefore wackestone and packstone textures are dominant. Pelmatozoan and bryozoan fragments are the most common allochems. Foraminiferans, calcareous algae, brachiopods and sponge spicules occur, but are subordinate. Rapid horizontal and vertical changes between the three lithofacies types are characteristic, as observed in three parallel logged sections (A–C) in a four metre-wide interval in the lower part of the Carnaweeleen I section (Fig. 3). Only a few coral-dominated horizons persist horizontally for more than 10 m. In general, vertical changes seem to be more abrupt. Throughout the sections, no evidence for a cyclic nature or a succession of ecological stages (see Alberstadt et al., 1974; Copper, 1988) could be observed for these changes.

Estimation for all visited outcrops in the Bricklieve facies suggests a dominance of the coral facies (coral boundstones + coral debris limestone) in most sections, possibly in the order (2:1) compared to

Table 2

Comparison of the three types of *pauciradiale* coral biostromes in NW Ireland.

pauciradiale Biostrome	Bricklieve facies	O'Donnell's Rock facies	Streedagh facies
Growth form /average colony size	Superstratal/0.3 m high, 0.7 m diameter	Transported/0.1 m high, 0.15 diameter	Clusters/0.25 m high, 0.6–2 m diameter
Thickness	up to 50 m	16 m	6–20 m
Coral diversity	High (13 species)	Low (4 species)	Low–moderate (4–8 species)
Dominant species	*S. pauciradiale*	*S. pauciradiale* and/or *Solenodendron furcatum*	*S. pauciradiale*
Other colonial species	*S. scaleberense, S. martini, S. sociale, Lithostrotion decipiens, L. vorticale, Solenodendron furcatum* (very rare)	*S. martini*	*S. martini, S. sociale, Lithostrotion decipiens, L. vorticale, Corwenia* sp.
Solitary species	*Siphonophyllia samsonensis, S. siblyi, Axophyllum* sp., *A. pseudokirsopianum, Haplolasma* cf. *densum, Caninophyllum archiaci*	*Siphonophyllia samsonensis*	*Siphonophyllia samsonensis, Dibunophyllum* sp.
Associated biota	Sponges, bryozoans, foraminiferans, calcareous algae, brachiopods, echinoderms	Foraminiferans, calcareous algae, heterocorals, bryozoans, echinoderms	Foraminiferans, calcareous algae (very rare), heterocorals, bryozoans, trilobites, tabulate corals, brachiopods, echinoderms
Proportion of in situ upright colonies	Low (5–10%)	Very low (5%)	High (up to 50%)
Degree of abrasion/fragmentation	High	Very high	Moderately low
Lithofacies	Well-bedded, fine-grained wackestone/packstone (30–50 cm) — lenticular with thin shale seams	Well-bedded, fine-grained wackestone/packstone (30–60 cm) interbedded with shales and argillaceous limestones.	Alternating lenticular well-bedded, fine-grained wackestone/packstone (20–60 cm) interbedded with silty shales and argillaceous limestones.
Interpretation	Middle platform above the storm wave-base	Mud-rich, open marine moderately calm water middle to inner platform	Mud-rich, open marine moderately calm water middle to inner platform

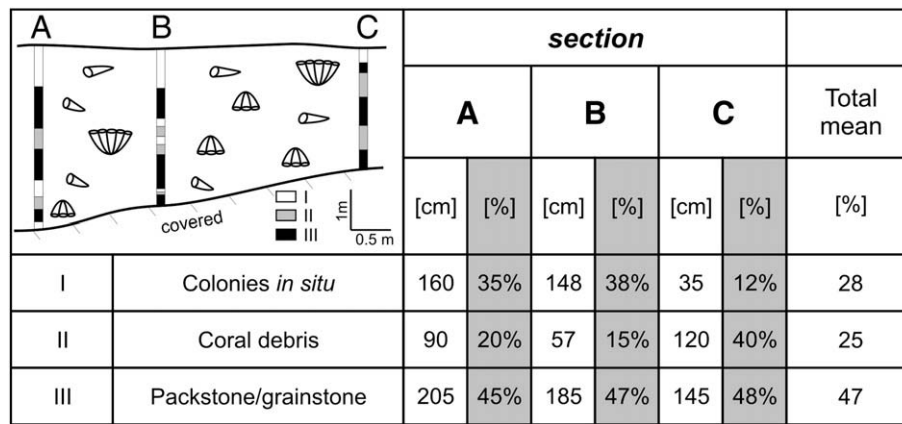|	section						
	A		**B**		**C**		Total mean
	[cm]	[%]	[cm]	[%]	[cm]	[%]	[%]
I	Colonies *in situ*	160	35%	148	38%	35	12%	28
II	Coral debris	90	20%	57	15%	120	40%	25
III	Packstone/grainstone	205	45%	185	47%	145	48%	47

Fig. 3. Overview on the distribution of main facies types in the three parallel logged sections (distance A–B: 1.5 m; B–C: 2.5 m) within the lower part of the *pauciradiale* biostrome in the Carnaweeleen section. Note the significant variations in the numbers for coral debris and corals in situ (modified from Aretz, 2002).

bioclastic packstone/grainstones. The coral facies is largely dominated by debris (>5:1). However, these ratios may vary substantially within single sections. The size of coral fragments is highly variable in the entire succession of the *pauciradiale* biostrome. Intact colonies of *Siphonodendron* are relatively rare (Figs. 3, 4A, B), although 9 of the 17 beds in the three parallel logs at Carnaweeleen I section contain colonies in life position (Fig. 4B). Some clusters of in situ colonies have been observed, forming localized coral frameworks, with maximum dimensions of 1.5 m height and 3 m width.

The coral debris is the result of in situ destruction of entire colonies into smaller fragments of various sizes (Fig. 4D). This process is best seen in the Lough Labe section, where various mostly intact colonies show partial destruction of their colony edges (Fig. 4C). Some colonies in the Lough Labe section show that bryozoans encrusted a wider surface area on the lowermost part of the colonies. This implies a superstratal growth of the colonies (see Insalaco, 1998), which contradicts the speculation of constratal growth by Warnke (1994). The succession on top of the *pauciradiale* biostrome is poorly exposed in the Bricklieve Mountains area, although in the Lough Labe section the overlying 5 m of strata are exposed at the top of the Hill 214 (Fig. 4A). There *S. martini* exceeds the dominance of *S. pauciradiale* and is accompanied by *Lithostrotion decipiens* (McCoy) and *L. vorticale* (Parkinson).

From scattered outcrops around Kesh Corann it is determined that the succession up-section consists of pale, thin- to thick-bedded, pelmatozoan and bryozoan-rich limestones. Fine-grained grain-supported limestones and foraminiferans become more abundant than in the lower intervals. Corals (*S. pauciradiale*, *S. martini*) occur scattered. However in the Carnaweeleen section and 1 km further SSE (see fig. 15 in Somerville et al., 2009), a marked abundance of *L. decipiens* is observed approximately 20–25 m above the top of the *pauciradiale* biostrome. These concentrations do form persistent horizons, but outcrop quality is too poor to demonstrate coral frameworks.

3.1.2. O'Donnell's Rock facies

This area adjacent to the Ox Mountains and NW of the Belhavel Fault coincides with the transitional zone, where the northern facies patterns of the Sligo Syncline interfingers with the southern facies patterns of the Ballymote Syncline (Figs. 1, 2).

The *pauciradiale* biostrome developed in the lower part of the Glencar Limestone Fm on top of medium- to thick-bedded limestones with intercalated shale beds (Fig. 2). Its base is a 0.2 m thick shaly limestone bed with an irregular base (c. 4 m above the base of the logged section, Fig. 5A). It consists mainly of coral debris. *Solenodendron furcatum* (Smith) (characterized by the presence of an aulos instead of a columella, compare Fig. 6A and E) is the dominant taxon in this debris (Fig. 5A, B), and *S. pauciradiale* occurs only rarely.

The overall thickness of the *pauciradiale* biostrome in the O'Donnell's Rock section is about 16 m (Fig. 5A). It is mainly composed of bedded limestone with shale intercalations. The two lithotypes combined form packages of 0.3–0.6 m, sometimes up to 1 m in thickness (Fig. 5C). The bases of the limestone beds are often irregular. The thickness of individual beds varies significantly throughout the succession, but do not follow a uniform trend. However, the packages become richer in carbonate content towards the top. The limestones comprise relatively impure wackestones and a few packstones (Fig. 6D–F), with pelmatozoans, bryozoans and sponge spicules as the dominat allochems. Aoujgaliids ('problematic red algae') occur occasionally (Fig. 6F; see also fig. 9 in Somerville et al., 2009). The carbonate content in the brownish shales varies, but seems to be relatively high. In the lower part of the *pauciradiale* biostrome, corals are more abundant in the shale units than in most limestone beds. This difference is levelled out up-section.

Colonial corals are invariably transported and fragmented. *So. furcatum* dominate in the more shaly limestone levels of the biostrome, whereas within the purer bioclastic limestone beds *S. pauciradiale* become more abundant. (see Fig. 5A between 4 and 12 m). *Si. samsonensis* occurs in many beds; rare specimens are only slightly eroded at the outer edge of the calyx and some are still in life position (S in Fig. 5D; see also Somerville et al., 2009, fig. 3C). The coral fauna is mostly restricted to the three taxa already mentioned, very rarely occurs *S. martini*.

Above the *pauciradiale* biostrome corals become rare, they are restricted to single occurrences of specimens or debris of *S. pauciradiale*, *S. scaleberense* (Somerville and Nudds), *Si. samsonensis*, and *Haplolasma* sp. Apart from the absence of corals, the sometimes impure limestones are comparable in texture and allochems to the older limestones. Much of the upper Glencar Limestone Fm is dolomitized, which partly prevents a detailed analysis. However, at the top of O'Donnell's Rock's scarp, a completely dolomitized 4 m-thick biostrome is identified with abundant *S. pauciradiale* and some *S. martini* with many inverted colonies. This was previously identified as the *S. martini* biostrome (Dixon, 1972; Cózar et al., 2005). However, a new quarry section 500 m SE of the scarp shows the contact of the top of the dolomitized Glencar Limestone Fm and the base of the lower Dartry Limestone Fm. The section contains a prominent 6 m-thick biostrome interval (see below), suggesting that the biostrome at the top of O'Donnell's Rock's scarp is a localized development of a younger *pauciradiale* biostrome within the Glencar Limestone Fm.

3.1.3. Streedagh facies

The Streedagh facies is the equivalent of the *pauciradiale* biostrome of the Ballymote Syncline in the Sligo Syncline. The description of the facies herein is based mainly on data collected by us from the well-known Streedagh Point section (Hubbard, 1966,
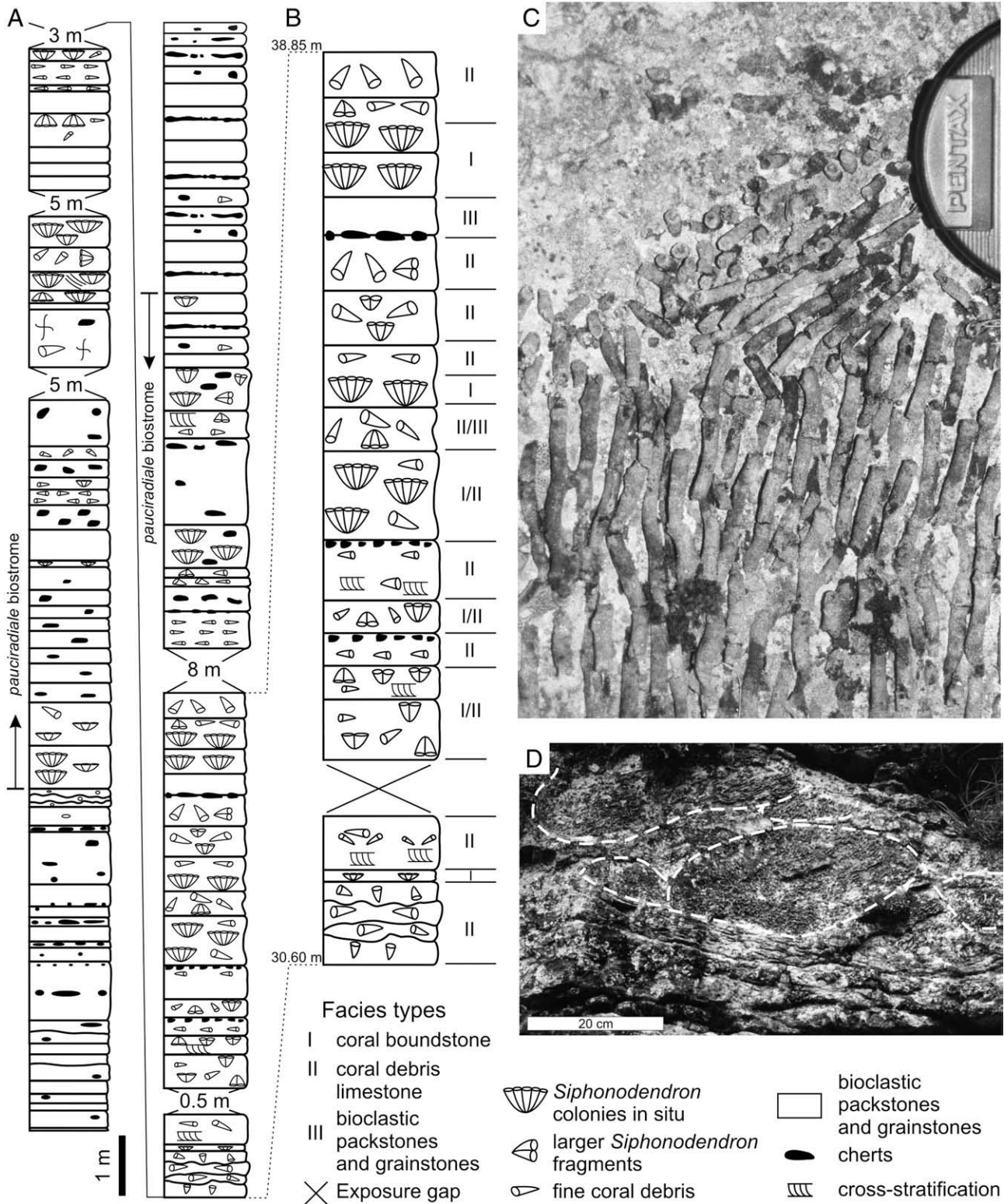
Fig. 4. Bricklieve facies. A. Stratigraphic log of the Lough Labe section on the western side of the lough, eastern side of Hill 214. B. Detail of a logged interval of coral dominance within the *pauciradiale* biostrome (between 30.60 and 38.85 m of the section in A). C. Autochthonous production of *Siphonodendron* debris through in situ fragmentation of an entire colony at Lough Labe. Note the different size of the coral debris starting from larger, semi-intact coral fragments at the base to single broken corallites above. Scale: lens cap is 5 cm. (from Aretz, 2002). D. *Siphonodendron* patch with some colonies growing upon each other in the *pauciradiale* biostrome at Carnaweeleen section. Note the rapid lateral facies change to coral debris facies.

1970; Dixon, 1970) with additional data from Serpent Rock (Hubbard, 1966)(Figs. 1, 2).

The horizons rich in *S. pauciradiale* are developed in the Glencar Limestone Fm, but their exact stratigraphic positions in relation to the top of the older Benbulben Shale Fm are not clear because no continuous exposure is known in this area. At Streedagh Point, c. 20 m of interbedded mudstone, shale, and fine-grained limestone are exposed in fault-bounded blocks. The basal unit of the succession at Streedagh Point (see
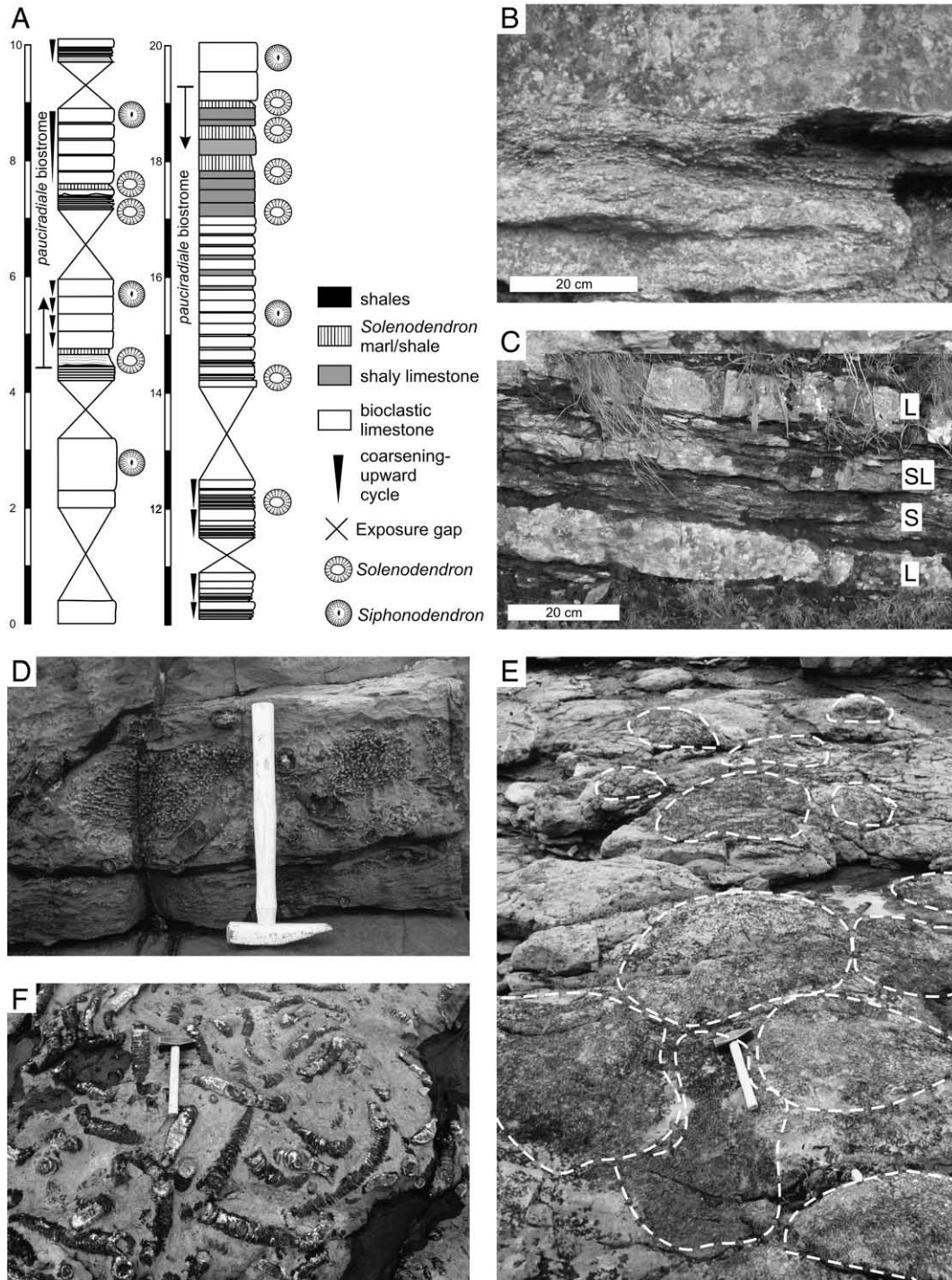
Fig. 5. O'Donnell's Rock facies (A–C) and Streedagh facies (D–F). A. Log of the *pauciradiale biostrome* at O'Donnell's Rock section. (Glencar Limestone Formation). B. Lithotype *Solenodendron* marl/shale and somewhat wavy bedding plane, O'Donnell's Rock. C. Cyclic sedimentation within the *pauciradiale biostrome* (about 12 m from the base). L. Fine-grained bioclastic limestone, S. Shale, SL. Shaly limestone, O'Donnell's Rock. D. In situ *Siphonophyllia samsonensis* enclosed by a *S. pauciradiale* colony, Serpent Rock. Scale: hammer handle is 25 cm. E. *Siphonodendron* patches in the upper part of the section, Streedagh Point. The colonies in the lower patch (foreground) are overturned. Scale: hammer handle is 25 cm. F. Bedding plane in the lower half of the section with a concentration of *Siphonophyllia samsonensis*, Streedagh Point. Scale: hammer handle is 25 cm.

Hubbard, 1966 and Cózar et al., 2005) is mostly lime mudstones and shales, and contains only a sparse macrofauna. Higher up the section, the first brachiopods occur (see Somerville et al., 2009, fig. 4). Later, *Si. samsonensis* co-occurs with brachiopods. Extensive bedding planes in this interval contain abundant long, thick, geniculated cylindrical specimens of *Si. samsonensis* (Fig. 5F), which make the Streedagh Point section so famous (for details see Hubbard, 1966, 1970; Dixon, 1970).

The faunal diversity increases further and some *Dibunophyllum* sp. and the first colonies of *S. pauciradiale* occur. This assemblage is topped by *S. pauciradiale* clusters. At this level most beds consist of relatively pure limestones (see Cózar et al., 2005, fig. 3), which contain bryozoans, pelmatozoan ossicles, and a few calcareous algae and foraminiferans. About 5 m below the top of the section, *L. decipiens* occurs in a single horizon (Cózar et al., 2005, fig. 3).

In the Streedagh Point section, the *pauciradiale* biostrome is a ~3 m-thick interval rich in clusters of *Siphonodendron*, (Somerville et al., 2009, fig. 4), although the first horizons rich in *Siphonodendron* occur up to 3 m below. This 6 m-thick interval rich in *S. pauciradiale* is
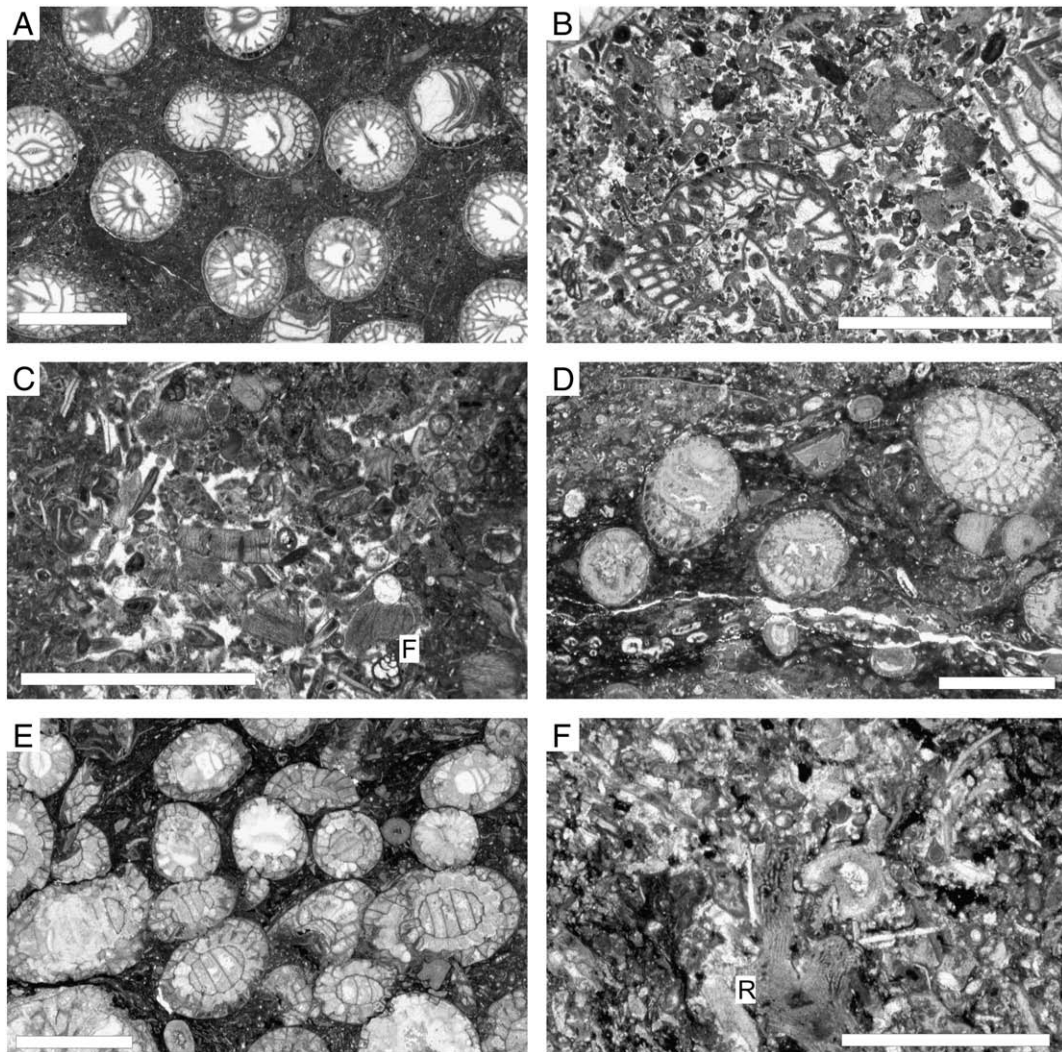
Fig. 6. Carbonate microfacies of the *pauciradiale biostrome*. A–C: Bricklieve facies. A. *Siphonodendron* boundstone. B. Small fragments of *Siphonodendron* in a pelmatozoan- dominated pack/grainstone. C. Pelmatozoan–bryozoan packstone. Note a foraminifer in the bottom right (F). D–F: O'Donnell's Rock facies. D. Highly silicified *Siphonodendron* debris and bryozoan fragments. E. *Solenodendron furcatum* from a shaly limestone with partially silicified corallites. F. Pelmatozoan-bryozoan packstone. Problematic aoujgaliid red algae (R) in the bottom centre. All scale bars = 5 mm.

relatively thin compared to the 20 m-thick interval in the Serpent Rock section. Thus the upper part of this biostrome is apparently absent at Streedagh Point.

A characteristic feature of the Streedagh facies is the scattered occurrence of *Siphonodendron* clusters consisting of 2–8 colonies (Aretz, 2002; Table 2). The distances between the clusters varies, but averages about 2–5 m. In the upper 3 m of the Streedagh section, the distances between the *Siphonodendron* colonies decreases considerably, and the succession develops a more pronounced biostromal character characterized by closely spaced colonies on extensive well-exposed bedding planes (Fig. 5E).

The relatively large colonies (up to 0.8 m in diameter) are often overturned (Fig. 5E), but only the colony margins are partly abraded. Total disintegration of an entire colony is not observed, thus resulting in relatively little *Siphonodendron* debris. The composition of the clusters is mostly monospecific. *S. martini* and *S. sociale* occur in very few clusters beside the always dominant *S. pauciradiale*. Sections perpendicular to the bedding show that *Siphonodendron* colonies are mainly concentrated in the upper half or at the top of limestone beds. The height of a single cluster does not exceed the height of the largest colony found in it. Colonies or single branches may penetrate laterally into adjacent colonies, but the direct superposition of two colonies has not been observed. The colonies are also mainly covered by shale

layers (few cm to 0.2 m thick) which constrained their vertical relief, thus causing undulating bases of superposed beds suggesting primary substrate relief. However, undulations have been levelled out by the top of the succeeding bed.

The surfaces on the bedding planes between the *Siphonodendron* clusters are either almost devoid of macrofossils (sometimes a few completely preserved crinoids), or contain small patches (up to 0.6 m in diameter) of fossil debris, which consists of fragments of tabulate corals (mainly *Syringopora* sp.), heterocorals, bryozoan and brachiopod fragments, and trilobites. The uppermost beds in the section contain thicker shales (ca. 0.5 m thick). The interbedded limestones contain mostly *S. pauciradiale* colonies, often overturned.

The section at Serpent Rock is >42 m thick with the *pauciradiale* biostrome 20 m thick. It contains an almost identical rugose coral assemblage to that at Streedagh Point. However, at Serpent Rock *Siphonodendron* colonies are recorded in many more beds, particularly in the upper 10 m of the biostrome, together with *Siphonophyllia,* often in intimate contact, and in some instances *Siphonophyllia* is clearly in growth position (Fig. 5D). *S. pauciradiale* and *S. sociale* are the dominant species in the biostrome with minor *S. martini* and *S. irregulare* (Phillips). There are also large clusters of *Siphonodendron* (measuring at least 2 m in diameter) similar to those at Streedagh Point. However, unlike Streedagh Point, there are several horizons of cerioid colonies (*L.*

decipiens and *L. vorticale*) mostly recorded in the lower part of the biostrome (Caroline Martin, personal communication).

Storms strongly influenced the sedimentation. Many horizons in the section are rich in bioclastic debris, including fragmented corallites of colonies. Concentrations of giant *Siphonophyllia* occur often near the base of beds with usually sharp erosive base. The small compact *pauciradiale* colonies often show little abrasion, but invariably the colonies of the larger diameter corallites of *S. martini* and *S. sociale* are highly fragmented. The typically smaller-sized colonies of the latter two species have a more dendroid open-branching growth style.
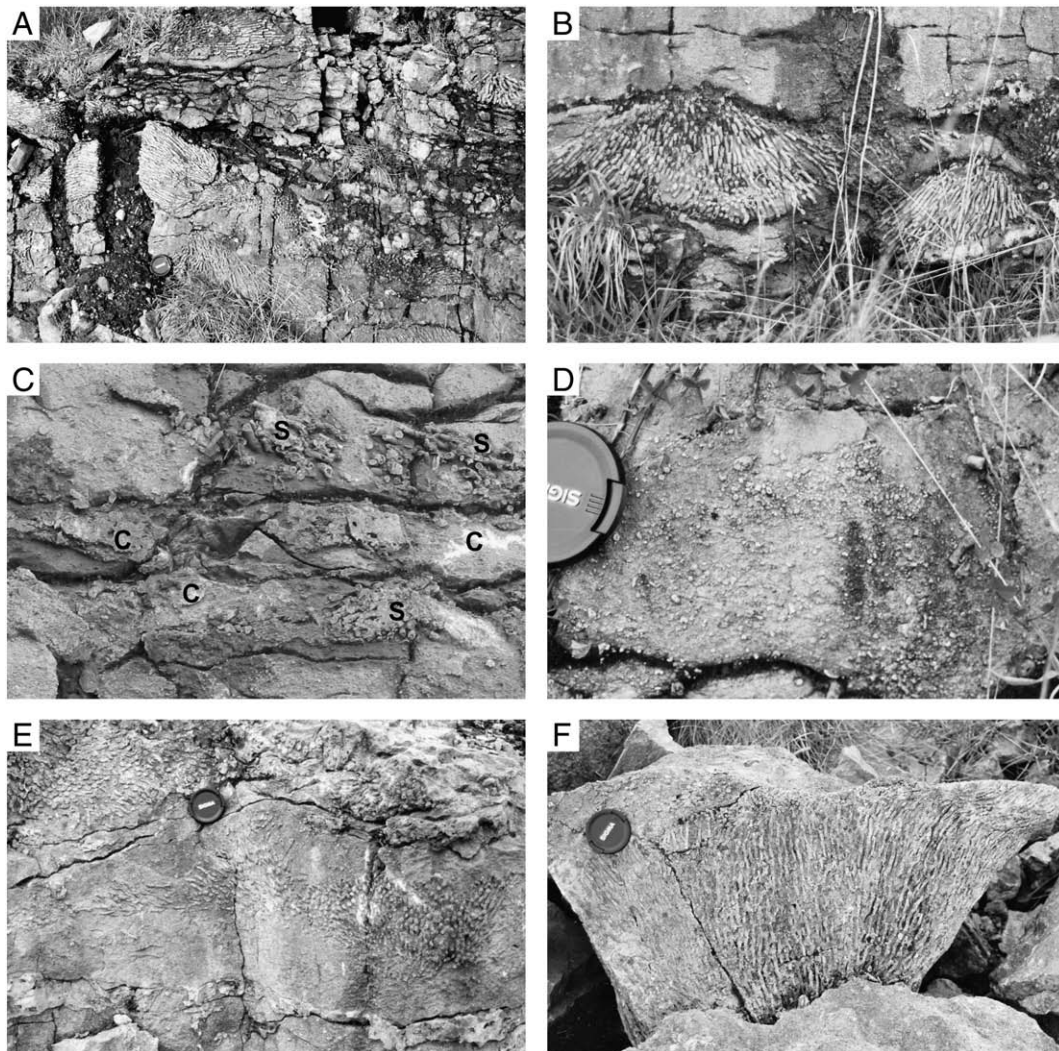
3.2. Martini biostrome

The top of the *martini* biostrome was considered as the boundary of the lower and upper Bricklieve Limestone Fm (sensu Caldwell and Charlesworth, 1962) and the boundary of the Glencar Limestone and Dartry Limestone formations in the O`Donnell´s Rock area (Dixon, 1972) (Fig. 2). The *martini* biostrome is located about 80 m above the top of the *pauciradiale* biostrome at the Kesh Corann Hill, Bricklieve

Mountains. According to Caldwell and Charlesworth (1962) the maximum thickness of the *martini* biostrome is c. 10 m.

One of the best exposures is a new road cut near Carrane Hill (Fig. 7A). There, the *martini* biostrome, c. 5 m thick, consists of normal-graded limestone beds, which locally form thicker units with a coarsening-upward trend. Shale intercalations occur. The thicknesses of individual units vary from a few centimetres (a single bed) up to some decimetres (a few beds). Units are often incomplete and the bases of most beds are erosive. The basal fine-grained limestones consist mainly of bryozoan and pelmatozoan fragments, but occasionally become rich in foraminiferans, ostracods, heterocorals and sponge spicules and rare dasyclad algae (Fig. 8C; see also fig. 11 in Somerville et al., 2009). A high variability between grain- and matrix-supported rocks is observed (cf. Fig. 8C and D), even in single beds. Towards the top of the units, the larger grain size is mainly due to rugose corals, and a few brachiopods, but the size of the pelmatozoan fragments may increase as well. The coral fragments are encrusted by bryozoans in various degrees. Micritised grains are observed throughout the biostrome (Fig. 8D).

The corals are generally broken, but some larger colonies may still be in place with erosional features around the colony edges (Fig. 7A). The degree of coral fragmentation varies widely, from very small

Fig. 7. Outcrop photos of the *martini biostrome*. A, B, D–F: lower Bricklieve Limestone Formation, Carrane Hill section. C: Glencar Limestone Formation, O'Donnell's Rock. A. middle part of the *martini biostrome*. Note the heterogeneous composition and rapid facies changes of the bed (width about 2 m). B. inverted colonies of *Siphonodendron martini* (on the left) and *Siphonodendron pauciradiale* (on the right). Reworking of the colonies took place in two separate phases (width about 0.5 m). C. Silicification in the O'Donnell's Rock section is seen in numerous silicified *Siphonodendron* debris (S) and chert nodules (C) (width about 0.20 m). D. Coarse pelmatozoan debris from the top of a graded tempestite bed. Scale: lens cap is 5 cm. E. peripheral growth pattern of a large *Siphonodendron martini* colony. Scale: lens cap is 5 cm. F. massive growth pattern in *Siphonodendron martini*. Scale: lens cap is 5 cm.
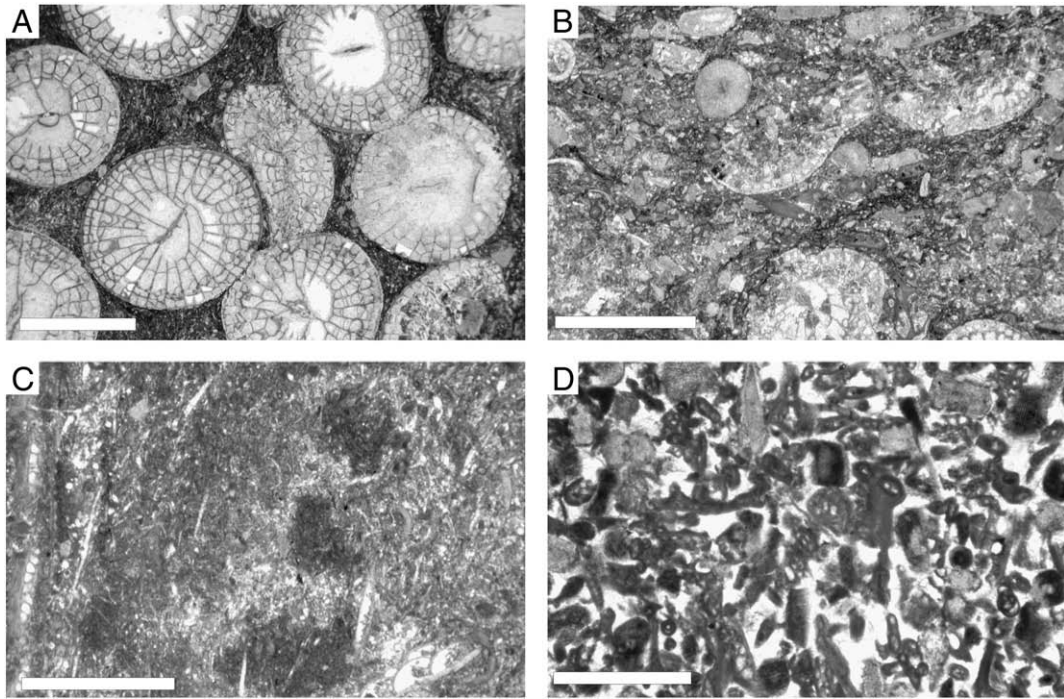
Fig. 8. Carbonate microfacies of the *martini biostrome* at Carrane Hill section. A. Large fragment of a *Siphonodendron martini* colony. Original configuration of the colony is almost preserved, but some corallites are broken or crushed (scale bar = 5 mm). B. *Siphonodendron* debris in pelmatozoan packstone (scale bar = 5 mm). C. Bioturbated bryozoan wacke/packstone with abundant elongated sponge spicules (scale bar = 2.5 mm), few meters below the *martini* biostrome. D. Bryozoan grainstone with a few foraminiferans, 5 m above the *martini biostrome*. (scale bar = 2.5 mm).

(fragments of a single corallite; Fig. 7A) to large (fragments 40 cm in diameter) in which the original configuration of the corallites is still preserved (Fig. 7B). Two main patterns of colonial growth are recognized: (1) colonies with axial growth resulting in a strong upward orientation with relatively constant colony diameter (Fig. 7F), and (2) colonies with peripheral growth which results in large, relatively flat, laterally elongate tabular colonies (Fig. 7E). The growth form influences the preservation of the colonies, because a somewhat higher fragility is observed in the peripheral growth pattern, and colonies with an inverted orientation (Fig. 7B) are predominately of the more 'massive' axial type.

The coral diversity is high. *Siphonodendron* species with large corallite diameters predominate. *S. martini* as the nominal species for the coral biostrome does not dominate every individual bed. In the Carrane Hill section the ratio of *martini* to *pauciradiale* is ~1:1. Furthermore, lithostrotionid corals include *S. intermedium* Poty, *S. sociale*, *S. scaleberense*, and questionable *S. irregulare*. Solitary corals (Table 1) occur scattered throughout the coral biostrome.

The contact of the *martini* biostrome and succeeding strata is not exposed in the Carrane Hill section. A fine-grained foraminiferal grainstone occurs about 5 m above the *martini* biostrome (Fig. 8D).

In the Bricklieve Mountains a poor exposure of the *martini* biostrome is known from the western side of Kesh Corann. Within a few metres of medium- to thick-bedded cherty limestone *S. martini* and *S. pauciradiale* colonies and debris become abundant. Single beds are dominated by the nominal species, others show a ratio of 1:1. Mud- and grain-supported textures occur, but their spatial relations could not be quantified. The top of the biostrome is not exposed.

On the SE side of Kesh Corann at Murhy, the complete *martini* biostrome is well exposed, in a 10 m thick scarp section. Many colonies of *S. martini*, *S. sociale* and *S. pauciradiale* are overturned. Moreover, there are thin intervals (20–30 cm thick) where there is a marked alternation of domal *S. pauciradiale* and *S. martini* colonies which are not laterally persistent.

In the O'Donnell's Rock II section Somerville et al. (2009) described the *martini* biostrome in the basal part of the Dartry Limestone Fm. A new quarry section 250 m NE of the radio transmitter at O'Donnell's Rock exhibits a fine-grained, pale grey cherty limestone facies typical of the Darty Limestone Fm, and contains a biostrome 6 m thick, about 5 m above the base of the formation (see fig. 10 in Somerville et al., 2009). It has a very similar fauna to the *martini* biostrome in the Carrane Hill and Kesh Corann (Murhy) sections. The coral abundance is lower, and the colony sizes are somewhat smaller, but the coral diversity remains relatively stable. An almost 1:1 ratio for *S. martini* to *S. pauciradiale* could be observed. In general, decreased coral abundance results in a wider spacing of the coral horizons and a higher amount of pelmatozoan–bryozoan packstones with little or no coral debris. The general amount of fine debris seems to be higher than at Carrane Hill. Some coarsening-upward units are exhibited. Numerous chert nodules of very different shapes and sizes, almost entirely silicified limestone horizons, and silicified skeletal organisms occur in this section (Fig. 7C), features which have to a lesser extent also been observed in most other sections.

In the Carrick Syncline (Clogher Lough section, Cavetown; locality 6 in Fig. 1) the *martini* biostrome is not recorded (Caldwell and Charlesworth, 1962). However, the presence of a 5 m-thick biostrome rich in the large corallite diameter *S. sociale* lying above the *pauciradiale* biostrome and below the single exposed *junceum* biostrome may be considered as the lateral equivalent of this horizon in the Bricklieve Mountains (Cózar et al., 2005; Somerville et al., 2009, fig. 18).

3.3. Junceum biostromes

The *junceum* biostromes are the youngest coral biostromes of the studied area. Three *junceum* biostromes have been observed in the upper Bricklieve Limestone Fm in the Bricklieve Mountains, one in the Dartry Limestone Fm in the O'Donnell's Rock area (Fig. 9A, B), and one in the Clogher Lough section in the Carrick Syncline (Cózar et al., 2005; Somerville et al., 2009).

At O'Donnell's Rock the *junceum* biostrome occurs some tens of metres above the *martini* biostrome. The section (Fig. 9B) starts with a
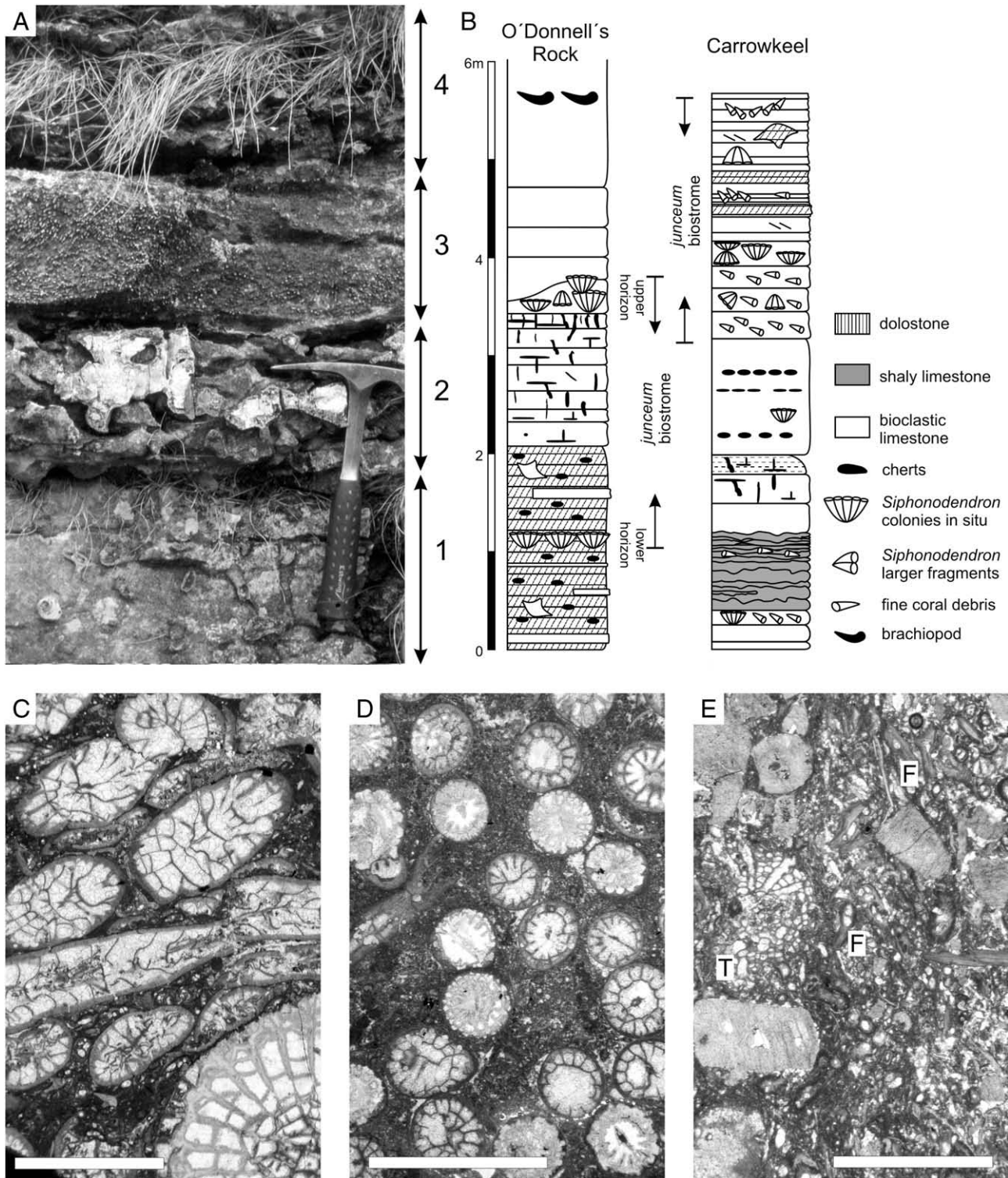
Fig. 9. A. Upper horizon of the *junceum* biostrome (Dartry Limestone Formation) at O´Donnell´s Rock section. 1 — bioclastic limestone with some round to elongated chert nodules, 2 — bed of high chert concentration 3 — autobiostrome of *Siphonodendron junceum* (see Fig. 9B c. 2.5 m in log), 4 — fine-grained bioclastic limestone above the biostrome. Scale: hammer is 25 cm. B. Logs of the *junceum* biostrome at O'Donnell's Rock and the 1st *junceum* biostrome at Carrowkeel section, Bricklieve Mountains. Note the very different thicknesses of the beds. (Scale in metres). C. *Siphonodendron junceum* and *Dibunophyllum* sp. from the *junceum biostrome* at O'Donnell's Rock (scale bar = 5 mm). D. *Siphonodendron junceum* in fine-grained bioclastic matrix (mainly bryozoan fragments) in the Carrowkeel section (scale bar = 5 mm). E. Bryozoan-pelmatozoan packstone in the *junceum* biostrome at Carrowkeel section showing fenestellid (F) and trepostome (T) bryozoans (scale bar = 2.5 mm).

dolomite-rich unit (>2 m thick), which contains abundant chert nodules. Some pelmatozoans debris is still recognizable in relict burrowed bioclastic wackestone and packstone. A 10 cm thick horizon of *S. junceum* within this unit is the lower horizon of the *junceum* biostrome in this section. This unit is topped by a 1.4 m-thick pale

limestone, which consists of alternations of pelmatozoan–bryozoan wackestones and packstones with few foraminiferans, and ungdarellid calcareous red algae (see fig. 10 in Somerville et al., 2009). Chert nodules are abundant in this unit. Their outer shape is variable, often irregular to ovoid, but some are elongated and branching (Fig. 9A). The overlying

bed (Unit 2 in Fig. 9A) is 14–17 cm thick, and consists of more than 70% chert nodules. This cherty unit is topped by the 15–35 cm thick upper horizon of the *junceum* biostrome (c. 2.5 m in log in Fig. 9B; unit 3 in Fig. 9A). With the exception of single *S. pauciradiale* and *S. martini* colonies and one specimen each of *Dibunophyllum* sp. and *Siphonophyllia* sp., the biostrome is virtually monospecific (Fig. 9C). The bed consists of colonies, which are mostly in situ, some being overturned, coral fragments of variable sizes, and some pelmatozoan debris. The composition of the bed varies irregularly, laterally and vertically. Packstone and wackestone textures are observed between colonies and corallites. The bioclast spectrum comprises pelmatozoans, bryozoans, a few foraminiferans, and sponge spicules. The upper limit of the coral bed is undulose. The succeeding bioclastic limestones (more than 3 m thick) are mostly fine-grained bioclastic packstone. Several thin, more coarse-grained horizons are intercalated, bearing brachiopods, small solitary corals, and crinoids.

The three *junceum* biostromes of the Bricklieve Mountains are horizons up to several metres in thickness. A persistent composition throughout the interval is rare. Some laterally distinctive intervals with a high abundance of the nominal species *S. junceum* can be identified. The 1st *junceum* biostrome is developed c. 20–25 m above the *martini* biostrome in the Bricklieve Mountains (Caldwell and Charlesworth, 1962; Dixon, 1972).

In the Carrowkeel area the composition of the 1st *junceum* biostrome (c. 2.5 m thick; Fig. 9B) is highly variable. Horizons of *S. junceum* colonies, coral debris, dolomitic limestone, and bioclastic limestone alternate. Chert nodules of variable forms occur throughout, sometimes being elongated and branching. The bioclastic limestone is often a fine-grained, bioturbated packstone, sometimes poorly washed, which is rich in bryozoans and pelmatozoans, and contains problematic red algae (*Ungdarella* sp.) and foraminiferans (Fig. 9D, E). In situ *S. junceum* colonies are rare except in the middle part of the biostrome, where a more or less laterally persistent horizon is developed.

In the nearby Maelahoo section Cózar et al. (2005) recorded from the 1st *junceum* biostrome in addition to the predominating *S. junceum,* only 1–2 specimens of further colonial and solitary corals (Table 1). The 2nd *junceum* biostrome in this section, up to 7.0 m thick and c. 20 m above the 1st *junceum* biostrome, is the thickest of the three *junceum* biostromes. It consists of three individual *junceum* horizons; the highest horizon is associated with bands of in situ concave-up concentrations of gigantoproductid brachiopod shells (Somerville et al., 2009, fig. 16), but there is no direct relationship between the corals and brachiopods, e.g. no firmground or obvious signs of attachment. The lithological variability of the entire biostrome is comparable to the 1st *junceum* biostrome, but the abundance of gigantoproductid horizons is a major difference compared to the other *junceum* biostromes (Cózar et al., 2005).

The coral fauna recovered from the 2nd *junceum* biostrome comprises *S. junceum* and extremely sparse (1–2 specimens) *S. pauciradiale*, *S. irregulare*?, *L. decipiens*, *L. maccoyanum* (Milne-Edwards and Haime), *Clisiophyllum* sp., and *Caninophyllum archiaci* (Lewis). However, in the nearby Doonaveeragh section, only *S. junceum* was observed (Cózar et al. 2005).

The 3rd *junceum* biostrome (15 m above the 2nd *junceum* biostrome), consists of a thin monospecific horizon of *S. junceum* (2 m thick), which is embedded in bioclastic wackestones rich in bryozoans and pelmatozoans. Chert nodules in various sizes and forms are common to this interval. The colonies are partly in situ, but coral debris is also common.

4. Discussion

4.1. Development of the rugose coral biostromes in time and space based on comparison with modern scleractinians

The delineated biostromes are characterized by different thicknesses, lateral facies differentiations, internal construction modes and the predominance of different species of the lithostrotionid coral *Siphonodendron*. *S. pauciradiale* and *S. martini* stratigraphically co-occur throughout the Asbian. They are joined by *S. junceum* in the late Asbian (Aretz and Nudds, 2005; Rodríguez and Somerville, 2007). Therefore, their mass occurrences within the biostromes, each an approximately synchronous accumulation, are a sensitive response to punctuated ecological conditions affecting the large carbonate platform. They can be understood as 'bioevents', which are defined as beds or intervals of strata that are characterized by either unusual ('exotic') events or acmes of common faunal elements. Bioevents are responses to rapid environmental changes, creating short-lasting, special ecological conditions on the local, regional or global scale. The bioevent concept, developed and most successfully applied in Cretaceous strata (Ernst et al., 1983; Kauffman and Hart, 1995 among many others) is a correlative tool successfully applied throughout the Phanerozoic (e.g. Walliser, 1986, 1995; Brett and Baird, 1997a), but to our knowledge is less commonly used in Carboniferous rocks. An interesting example is given by West et al. (1997) for Pennsylvanian chaetetid, coral and bivalve bioevents ('epiboles', Brett and Baird, 1997b).

Northwestern Ireland was situated just to the south of the late Mississippian palaeoequator (Scotese, 2002) in the tropical realm. Thus, changing sea-surface temperatures can be neglected and the most important variables appear to be changing water depth, as well as fluctuations in sedimentary input, turbidity and nutrients deriving from terrestrial runoff from the Laurussian Continent in the north and northwest. In fact, an impoverished microbiota (calcareous foraminiferans and only sporadically occurring calcareous algae and a general absence of dasycladaceans, Cózar et al., 2005, 2006) has been related to turbid platform environments (Somerville et al., 2009). This might give the false impression of exaggerated water depths, especially since suspension feeders (crinoids and bryozoans), which also might indicate elevated nutrient input, are the most common organisms throughout the studied area.

Aretz and Herbig (2003a) initially proposed a ramp model based on the geometry of the biostromes and water depth. In this model the wedge-shaped *pauciradiale* biostrome (Fig. 2) would have formed on a southward-dipping ramp around storm wave-base. The *martini* biostrome grew after filling of that ramp wedge and formation of an extended platform in shallower water above fair-weather wave-base and the *junceum* biostromes after drowning of the platform in deeper water during the high sea levels of the late Asbian. However, more detailed investigations have now established that sedimentation occurred primarily on an extensive carbonate platform with intraplatform basins and intervening highs (see Somerville et al., 2009). Thus, the structural configuration of the basin might be responsible at least in part for the different facies of the *pauciradiale* biostrome, as well as the different numbers and compositions of the *junceum* biostromes (Figs. 2, 10).

In addition, morphological differences between the predominating coral taxa have to be taken into account. Surprisingly little is known about the autecology of Carboniferous rugose corals, but comparison with modern scleractinian habitats gives valuable insights into controlling factors like light, turbulence, turbidity, nutrients, sedimentation rates and the resulting, complex factor of "water depth".

In modern environments scleractinian corals with branched delicate growth forms predominate in less turbulent conditions, e.g. mostly deeper water. This is due to minimal breakage of the corallites (Chappell, 1980). From the Red Sea, Fricke and Schuhmacher (1983) showed that in phaceloid forms, the coralla become more isolated, at times dwarfed and low growing with depth, e.g. with fading light. For zooxanthellate species, a depth threshold exists. In the twilight zone, platy and crustose growing species take over, which offer a greater colonial surface for photosymbionts (Chappell, 1980; Fricke and Schuhmacher, 1983). Deeper water colonial azooxanthellate species are preferably delicate branching forms (e.g. Bernecker and Weidlich,
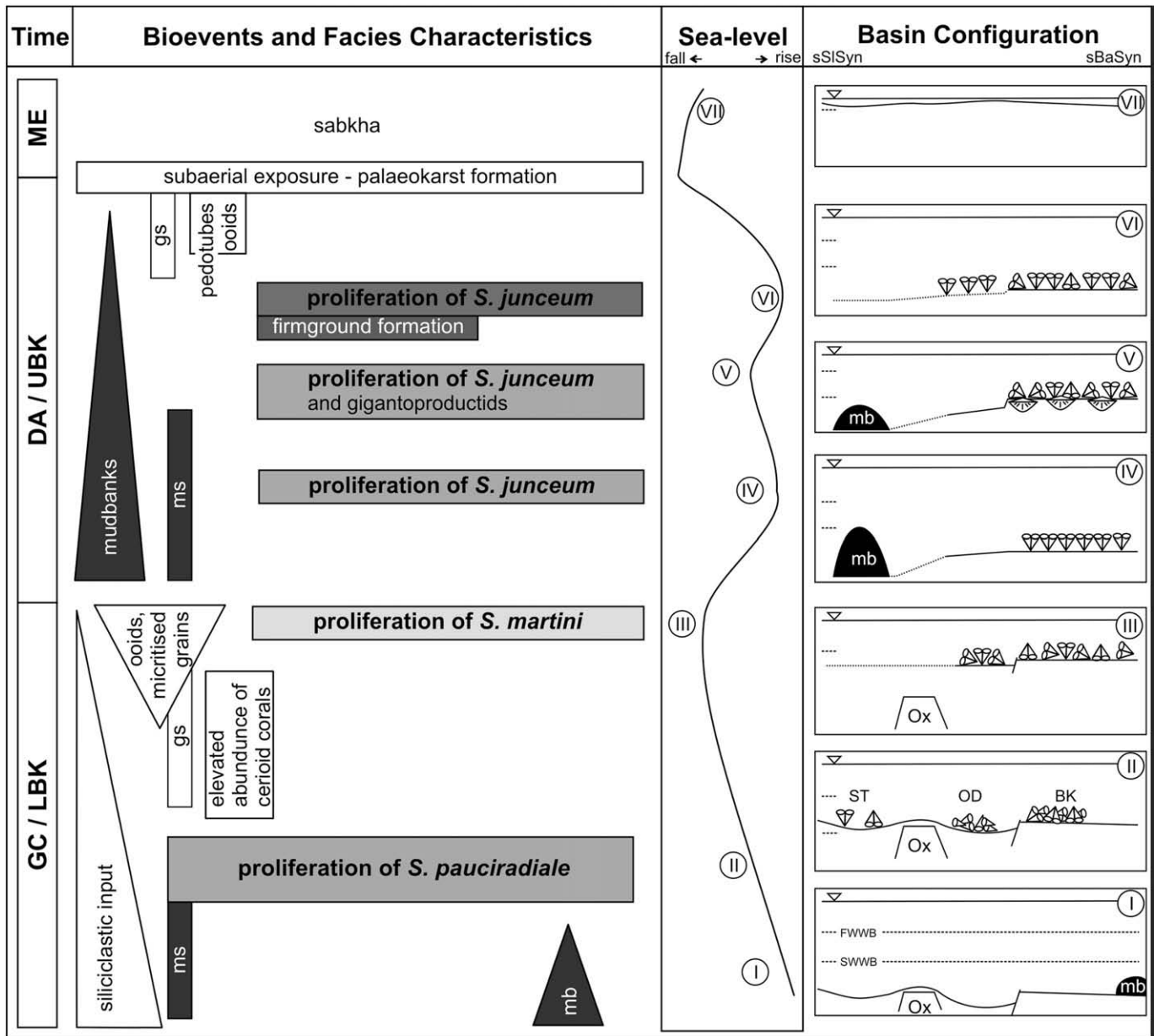
Fig. 10. Overview on important key factors and events in relation to sea-level and basin configuration. Factors hinting for deeper water are shaded; factors for shallow water are in white. The Roman numerals (I, II etc.) next to the sea-level curve indicate the approximate position of the sketches for the stages of basin configuration at the time of biostrome formation. In the *pauciradiale* biostrome (stage II), ST: Streedagh facies, OD: O'Donnell's Rock facies, BK: Bricklieve facies. The figure is not to scale. ms: dominance of mud-supported textures, gs: dominance of grain-supported textures, mb: mudbank, sSlSyn: southern Sligo Syncline, sBaSyn: southern Ballymote Syncline, Ox: basement of the Ox Mountains Inlier (See Fig. 3 for abbreviations of Formations).

2008) or have only a limited number of large polyps. Both morphologies increase tissue surface and thus improve the uptake of particulate and dissolved nutrients from the water (Fricke and Schuhmacher, 1983). Decreasing availability of nutrients with depth would also explain the morphological gradient in phaceloid corals described by Fricke and Schuhmacher (1983), which strongly resembles the gradient between *Siphonodendron* ssp. and *S. junceum*. Delicate branching, fasciculate to arborescent growing forms also withstand increased sediment influx, since less sediment can settle on the colonies (Chappell, 1980). One insightful study (Sanders and Baron-Szabo, 2005) mentioned that almost continuous sedimentation–turbidity stress results in impoverished coral assemblages dominated by solitary and weakly integrated phaceloid and dendroid forms that feed largely or entirely heterotrophically. Finally, reduced light intensity, in greater depths or turbid, shallow waters, lowers the photosynthesis rate of zooxanthellae and subsequently constrains

coral growth (Chappell, 1980). The same holds true for turbidity, including sedimentation on coral polyps, which increases the amount of metabolic energy needed for sediment rejection and lowers the uptake of particulate food (Sanders and Baron-Szabo, 2005). Again, growth of more delicate species will be favoured in such settings. It has to be stressed though that rugose corals are not considered to have been zooxanthellate (Coates and Jackson, 1987; see also review by Wood, 1999). Nonetheless, Wells (1963) and Johnson and Nudds (1975) had earlier demonstrated diurnal growth banding in Carbon-iferous rugosans and calculated lower growth rates in siliciclastic-dominated environments. Therefore, apparently, an indirect relation-ship to light existed, e. g. by different availability of food due to variable phytoplankton production or, more generally, by the interdependent ecological factors outlined above. In that context, Nudds and Day (1997) described dwarfed ecophenotypes of *Sipho-nodendron*, which are phenotypic homeomorphs of descendant

species, which originated from a combination of factors such as described above: lowered light levels, sediment-loaded waters, and an imbalance in nutrient supply.

The data outlined above now allow the reconstruction of the following scenarios for the development of the *Siphonodendron* biostromes in time and space, although the subtle factors governing their rise and decline are still mostly unknown and interpretations are more speculative.

4.1.1. Pauciradiale biostrome

The *pauciradiale* biostrome grew in mostly "middle platform settings", in water depths probably less than 40–50 m (Somerville et al., 2009), in the zone between fair-weather wave-base and storm wave-base, indicated by numerous tempestite beds. Differentiation into three facies (Streedagh, O'Donnell's Rock and Bricklieve facies) demonstrates a general landward–seaward zonation with the most landward, possibly shallowest environments, in the northwestern part of the study area. The Streedagh biostromes might be interpreted as deposits within a mud-rich, open marine, moderately calm water middle to inner platform ("shelf lagoon" of Wilson, 1975), frequently interrupted by storms, and sheltered by the intrabasinal rise of the Ox Mountains (Figs. 2, 10, stage II; Ox-Ballyshannon High of Philcox et al., 1992; see also Somerville et al., 2009, fig. 24). This interpretation is supported by the excellent preservation of the *S. pauciradiale* colonies with up to 50% of the colonies upright and in situ, as well as the relatively fine-grained textures. However, in the Serpent Rock section there is much more coral debris; especially the more dendroid open-branching *S. martini* and *S. sociale* colonies are affected, which are smaller in size compared to those in the *martini* biostrome.

The mud-rich Streedagh facies is considered to result from the intrabasinal rise of the Ox Mountains or from active faults like the Grange Fault (see fig. 24 in Somerville et al., 2009), which dammed terrestrial influx from the Laurussian continent. The mud hampered coral growth due to the lack of attachment surfaces. Moreover, suspended sediment suffocated the corals or rapid influx buried them alive. The most common solitary rugose coral *Siphonophyllia* seemed to be specially adapted (Fig. 5F). They are interpreted as almost completely buried mudstickers like present-day Ceriantharia (tube-dwelling anemones). Most were exhumed by storms and concentrated on bedding planes. Note that Hubbard (1970) had previously concluded an upright, mud-sticking way of life in an environment with high sedimentation rate, indicated by the large calices of the caninioids, and concentration of the specimens on bedding planes through winnowing. Further indication of storms and at least temporarily significant current patterns, include commonly inverted coral colonies, patches with concentrated debris of smaller organisms, and rare cross-stratification in rocks of silt-sized grains. In the upper part of the Streedagh Point section, the increasing amount of broken skeletal debris provided sufficient attachment areas for increasing number of coral thickets. Thus, the initial phases of biostromal development may be seen when the distances between *Siphonodendron* clusters become closer, although the episodic influx of mud prevented further development (Fig. 5E). Note that Frost and Langenheim (1974: 329–331) described an almost identical succession in the Oligocene of Chiapas, Mexico. Sanders and Baron-Szabo (2005: fig. 5.4) characterized such thin 'coral marls', up to a few tens of metres thick, with local bioconstructions composed of a few stacked corals or (reworked) coral thickets and abundant solitary corals as inner shelf deposits.

The peculiar *Solenodendron*-rich O'Donnell's Rock facies (Fig. 10, stage II) delineates a special biofacies belt. *So. furcatum* is a colonial species with very small-sized corallites and dwelled preferentially in more argillaceous limestone beds (Fig. 5B). The invariably transported colonial corals indicate relatively shallow water in the proximity of the pre-existing rise of the Ox Mountains, with tempestitic reworking similar to that at Serpent Rock. These storms would have alternated

with quiescent periods when mud drapes formed. The tiny corallites seem to contradict establishment in shallower waters, but the obviously increased sediment influx and the coherent ecological restrictions described above favoured that growth form (see Chappell, 1980 for modern environments and Nudds and Day, 1997 for the Mississippian).

The laterally adjacent Bricklieve facies ('biostromal reef complex' of Aretz, 2002) is characterized by the generation of coral debris from local sources, rapid facies shifts, and substantial thicknesses. As indicated by the mixture of grain- and mud-supported textures, the absence of indicators for very shallow water, (e.g. abundant green algae, ooids and fenestral micrites), the amount of coral debris, and the almost autochthonous source of the debris, the Bricklieve facies developed below fair-weather wave-base, but above the storm wave-base in a middle platform setting (Aretz and Herbig, 2003a; Somerville et al., 2009). The repeated destruction is primarily attributed to the effect of storms. The absence of a substantial coral framework was caused to a great extent by the limited ability of these delicate small fasciculate rugose corals to initiate framework building without the support of encrusting organisms that enhance the original fragile and wide open framework bioconstruction (Aretz, 2002; Aretz and Chevalier, 2007). This also explains the lack of a coral horizon of significant height (e.g. more than 1 m). In fact, most *pauciradiale* colonies develop to heights of c. 20–30 cm.

Facies differentiation and the increasing thickness of the *pauciradiale* biostrome towards the Bricklieve Mountains (Figs. 2, 10) probably result from enhanced subsidence creating more accommodation space linked to the activity of the Belhavel and Curlew synsedimentary faults (Somerville et al., 2009, fig. 23), at the southern margin of the Slisgarrow–Drumkeeran Trough. Further deepening and/or quiescence towards the southeast is emphasized by the fact, that in the Cavetown section, about 20 km southeast of the Bricklieve Mountains, virtually all *S. pauciradiale* colonies are in growth position (Somerville et al., 2009); this suggests deposition below storm wave-base. At the Rock of Curry, a further 65 km southeast of Cavetown, at the eastern margin of the upper Viséan carbonate platform, the *pauciradiale* biostrome becomes thinner and is accompanied by gigantoproductoid beds in growth position (Somerville et al., 2009).

The onset of extensive coral growth is not fully understood. It may well be connected to shallowing to a certain threshold water depth. After a rapid transgressive deepening event above the Mullaghmore Sandstone Formation, shallowing is recorded from the Benbulben Shale Formation/Lisgorman Shale Formation throughout the lower Glencar Limestone/lower Bricklieve Formation passing up through the *pauciradiale* biostrome and culminating later in the *martini* biostrome (Fig. 10; Somerville et al., 2009) (see Section 4.1.2). Decline of the *pauciradiale* biostrome growth might result from further shallowing, closing the "*pauciradiale* biostrome window', which is characterized by the predominance of relatively delicate corals in environments below fair-weather wave-base (Figs. 11, 12). In fact, more abundant foraminiferans, local concentrations of massive colonial corals (*Lithostrotion;* Fig. 12A) and more abundant grainstones above the *pauciradiale* biostrome level in the Bricklieve facies indicate deposition in more turbulent conditions above fair-weather wave-base.

4.1.2. Martini biostrome

Regional shallowing continued until the formation of the *martini* biostrome, which, especially in Carrane Hill, originated in an inner platform setting. Here polyspecific para- to autoparabiostromes resulted from repeated impact of tempestites and successive resedimentation of more or less autochthonous coral debris (Aretz and Herbig, 2003a). In the Bricklieve Mountains it is considered to have been formed in middle platform environments (Somerville et al., 2009). The *martini* biostrome is not recorded in the Carrick Syncline (Cavetown section), but may be represented by a biostrome rich in *S. sociale* (Somerville et al., 2009). This is the species with one of the
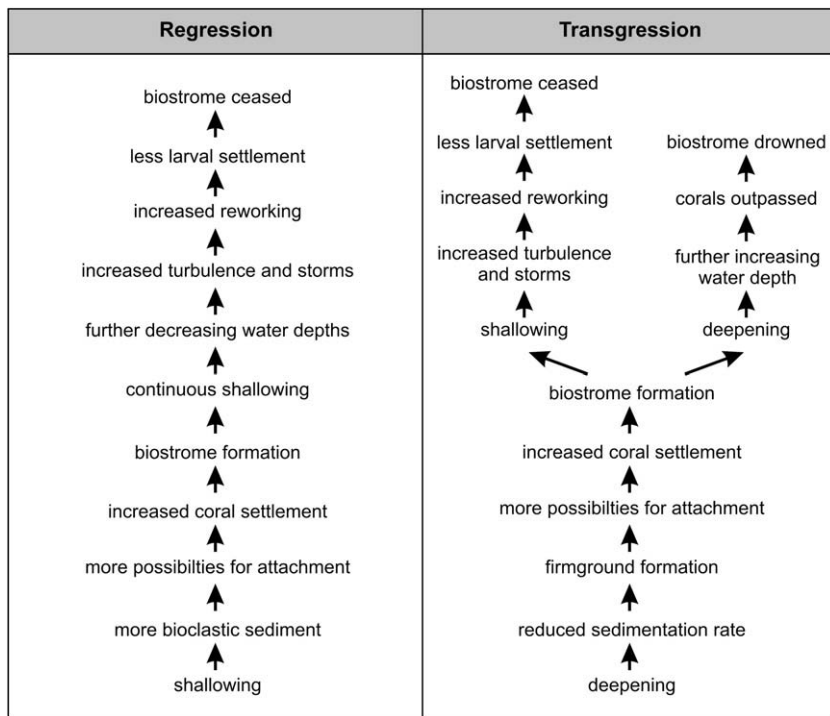
Fig. 11. Simplified causal chains for biostrome formation under regressive and transgressive conditions.

largest corallite diameters within the genus recorded in the study region and together with similar biostrome thicknesses (5–10 m) throughout the study area indicated a quite level platform (Fig. 10, stage III). The shallow-water setting above fair-weather wave-base of the *martini* biostrome (Aretz and Herbig, 2003a) is not only recorded by the general carbonate facies signatures (the common micritisation

of bioclasts, the abundance of grainstones, the rudstone character of many beds, and presence of dasyclad algae), but also in the coral biofacies. It is characterized by high diversity and occurrence of most of the large *Siphonodendron* species (*martini-sociale* group) (Table 1), which are better adapted to higher energy levels (Figs. 10, 12). *S. martini* colonies developed two growth strategies to survive in this
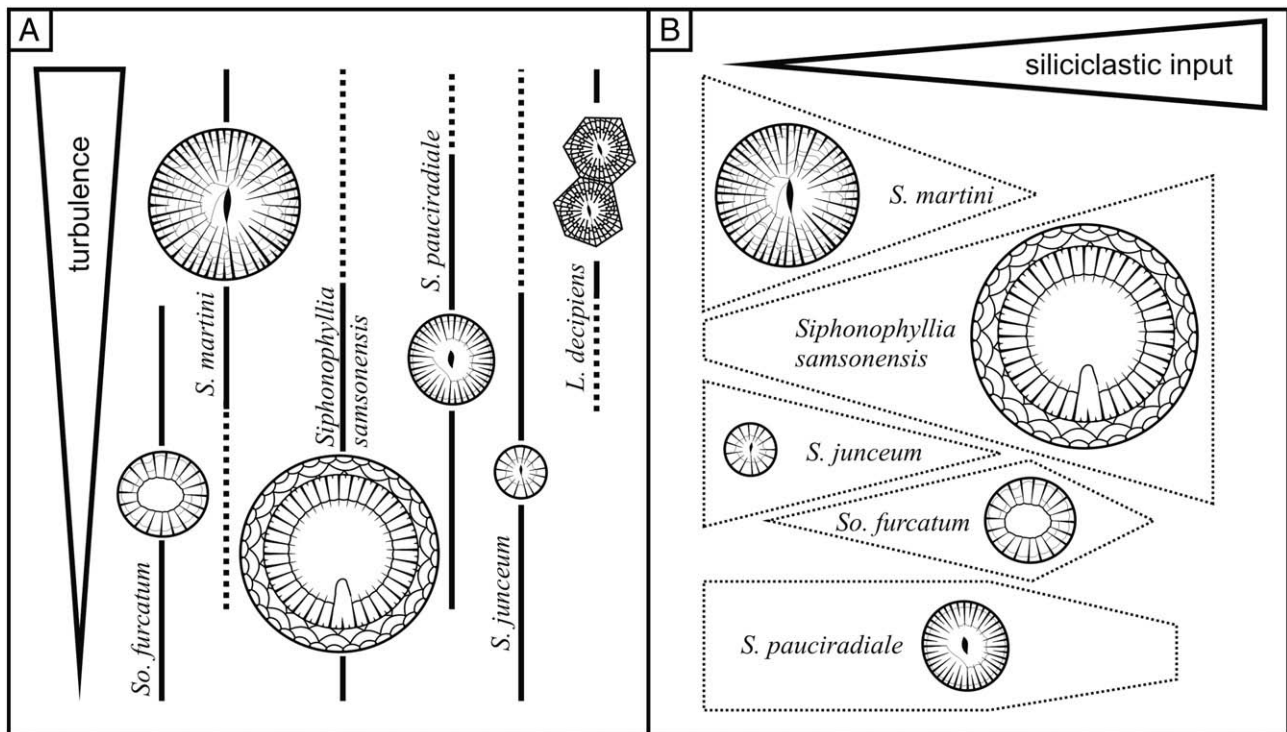

Fig. 12. Sketch illustrating the distribution of the dominant coral species influenced by (A) turbulence and (B) siliciclastic input. Note that turbulence must not be equated with absolute depth. A: solid lines indicate abundant occurrence, dotted lines low abundance; B: rectangles indicate abundance. [*S.* = *Siphonodendron*; *So.* = *Solenodendron*; *L.* = *Lithostrotion*].

turbulent environment. The fragility of the coral is somewhat reduced by peripheral growth resulting in a flat colony shape or, alternatively by strong axial growth resulting in a compact colony shape (see Scrutton, 1998).

Although the rise of the *martini* biostrome may be a consequence of shallowing, its decline, however, appears to be related to drowning, linked to the global late Asbian sea-level rise (Ross and Ross, 1985, 1987; Herbig, 1998), which reached its acme during the late Cf6γ subzone (Figs. 2, 10, stage IV).

The facies at Carrane Hill indicates a major sedimentary change, e.g. a deepening event above the *martini* biostrome. Corals and associated cross-laminated and graded bedding disappear suddenly and are replaced by spicule-bearing, chert-rich micritic limestone facies, which is also recorded in other sections of the upper Bricklieve Limestone Fm. A rapid increase in the water depth after formation of the *martini* biostrome is also recorded in the southern Sligo Syncline, where close to the base of the lower Dartry Limestone Fm mudbank growth was initiated (Warnke, 1994). MacDermot et al. (1996) reconstructed a relief of up to 120 m for some of these banks, thus clearly showing there deeper water origin. (Fig. 10, stage IV). In addition to the global late Asbian sea-level rise, this exaggerated deepening seems to have been triggered by tectonic activity along the Ox Mountains–Pettigoe Fault, which resulted in a half-graben geometry of the Sligo Syncline (Fig. 1; see also Somerville et al., 2009).

4.1.3. Junceum biostromes

The biofacies characteristics of the *junceum* biostrome at O'Donnell's Rock, of the 1st and 3rd *junceum* biostrome in the Bricklieve Mountains (Maelahoo section and Doonaveeragh section, respectively), and of the single biostrome in Cavetown all suggest an increase in water depth in a quiet water, low-energy platform setting (Fig. 10, stages IV and VI; Fig. 12). These biostromes show predominantly upright growth of the most delicate narrowest diameter species of *Siphonodendron* in very thin horizons (typically 1–2 m thick, but up to four-metre thick in Cavetown) and have an almost monospecific composition. These are typical autobiostromes (Aretz and Herbig, 2003a). Analogous modern examples include dwarfed and low growing phaceloid corals from deeper water environments of the Red Sea (Fricke and Schuhmacher, 1983), and generally widespread delicate branching forms among modern azooxanthellate deep water corals.

At O'Donnell's Rock the corals of the *junceum* biostrome settled on top of a firmground formed by an intensively burrowed horizon below. The burrows of the 'Thalassinoides' type are preserved as an intricate network of elongated and partly branched chert nodules showing some comparison to burrows found in the Upper Cretaceous chalk (Bromley, 1996). This may indicate a low sedimentation rate in deeper water and an accompanying sedimentary break (Aretz and Herbig, 2003a).

The composite 2nd *junceum* biostrome in the Bricklieve Mountains, which consists of three individual *junceum* horizons, differs by the occurrence of very sparse additional solitary and colonial rugosans (Maelahoo section) and a quite diverse red algal association including a single accompanying palaeosiphonoclad green algal species (Cózar et al., 2005). Especially noteworthy is the occurrence of gigantoproductoid-rich beds associated with the highest *junceum* horizon of the biostrome (Cózar et al., 2005; Somerville et al., 2009). These above features, along with the presence of *Lithostrotion* colonies, occasional grainstone beds, and the abundance of foraminifers in the biostromes compared to enclosing strata, implies occasional reversals of the deepening trend, with short-lived establishment of shallower environments above storm wave-base (Fig. 10, stage V). However, the *S. junceum* colonies are preferentially in growth position and the red algal association could suggest possible dysphotic conditions. Also, the presence of gigantoproductid-rich beds are not necessarily indicative of shallow-water, as seen by their occurrence in the *pauciradiale* biostrome at the Rock of Curry at the distal edge of the platform (Somerville et al., 2009), but they are also recorded with the *pauciradiale* biostromes at Streedagh Point (Somerville et al., 2009). Bourque et al. (1995) and Madi et al. (1996) described the occurrence of productoid brachiopod beds in spicule-rich limestone from the dysphotic zone between fair-weather wave-base and storm wave-base and, at the same depth, their association with fasciculate lithostrotionid thickets and red algae.

A deeper water setting for the *junceum* biostromes was already proposed by Aretz and Herbig (2003a) and later supported by Somerville et al. (2009), who envisaged a tranquil setting below storm wave-base in middle to outer platform settings. Moreover, Aretz and Herbig (2003a) postulated a connection with the maximum flooding phase of the upper Asbian transgression. The individual *junceum* horizons represent short-lived bioevents. They might be connected with the cessation of both production and influx of allochem grains and carbonate mud during repeated phases of maximum sea level, enabling settling of larvae on hard substrate. This also would explain the connected firmground formation in the O'Donnell's Rock section.

However, strata above the *junceum* biostromes show increasing shallowing with the presence of coated grains, ooids, dasyclad algae and pedotubes recorded below the sedimentary break at the Asbian–Brigantian and Formation boundary (Fig. 10; Somerville et al., 2009).

The single discovery of a *Siphonodendron* colony in the succeeding Brigantian Meenymore Fm (Brandon and Hodson, 1984) expresses the unfavourable conditions for corals in the succeeding widespread intertidal-supratidal evaporitic facies (West et al., 1968).

4.2. Limiting factors and causal chains for the bioevents

The presented scenarios help to identify key factors and causal chains for the described bioevents (Fig. 11). As demonstrated above, water depth is one key factor for the development and composition of the individual biostrome. In this context it is important to note that according to the litho- and biofacies the depths gradient in NW Ireland is rather large; between just above fair-weather wave-base and below storm wave-base. The corallite diameters of the *Siphonodendron* species correlate well with facies (Fig. 12). The largest forms occur in the more turbulent waters, which correlates with the need of skeletal stability and robustness. The smallest species, *S. junceum*, is opportunistic and preferentially adapted to deeper water, fading out in turbulent environments. As evidenced by the continuous record of corals in the Asbian carbonates of NW Ireland, *Siphonodendron* species can occur along rather wide depth gradients, but proliferation and biostrome formation are bound to specific conditions.

The *pauciradiale* biostrome can be used to describe and discuss a causal chain during shallowing (regression), whereas the *junceum* biostrome at O'Donnell's Rock illustrates the formation during transgressive conditions (Fig. 11). Biostrome initiation requires increased possibilities for larval settlements and therefore the provision of a hard substrate resulting from increased provision of allochems or firmground formation is essential. Biostrome development stops during a cascade of factors related to changing water depths. The thickness of the biostrome depends on the speed a particular species needs to cross the "biostrome window". Thus, it strongly depends on the specific ecological requirements of the species, but ultimately is controlled by rates of subsidence and sea-level change. In certain cases, the "biostrome window" might be rather prolonged and either a thick biostrome or a stacked pattern of thin biostromes might develop as evidenced by the *pauciradiale* biostrome.

4.3. Comparisons

Aretz (2002) listed only two 'biostromal reef complexes' from the European Mississippian, namely (1) the NW Irish *pauciradiale* biostrome, and (2) the *Siphonodendron* Limestone of SW Spain (Rodríguez et

al., 1994; Rodríguez, 1996). Common to both is the abundance of fasciculate colonial corals belonging to the genus *Siphonodendron*, but distinct differences arise from the development of the Spanish *Siphonodendron* Limestone in shallower water settings, marked among others by purer limestone facies. Also, its pronounced cyclicity and concomitant ecological changes are not developed in the *pauciradiale* biostrome. The absence of laterally continuous biostrome growth in the latter is a further obvious difference. Finally, the diversity of the Lithostrotionidae in the *pauciradiale* biostrome is somewhat higher than in the Spanish *Siphonodendron* Limestone, where in addition to the dominant *S. martini* only *S. irregulare* occurs (Rodríguez et al., 1994).

A less complex, but advanced type of biostromes is the polyspecific para- to autobiostromes, which mostly show a certain ecological zonation, as seen in the upper Asbian of Royseux, Belgium (Aretz, 2001). In NW Ireland, an ecological zonation is missing within the *martini* biostrome, quite possibly due to periodic and complete reworking of its top.

Low height, monospecific biostromes represent the opportunistic basic type of biostromes, forming in very different facies. They have been described from the Middle Viséan of Belgium (Aretz, 2002) and from the Brigantian and Serpukhovian of the Montagne Noire (Aretz, 2002; Aretz and Herbig, 2003b). They can be compared with the single coral horizons of the *junceum* biostromes. Characteristic for all the above-mentioned examples is the dominance of one species and the low height of the structure. However, all grew in different sedimentary regimes, even in calcareous muddy bottoms (Aretz, 2002).

In the lower Brigantian of the Carlow area, SE Ireland high diversity coral biostromes occur (Somerville et al., 2007). The high diversity is at least partly due to the appearance of new taxa in the Brigantian, especially the cerioid genera *Actinocyathus* and *Palastraea* (Rodríguez and Somerville, 2007), which are unknown in NW Ireland. The Carlow biostromes, although dominated by *S. pauciradiale* colonies, differ from those in NW Ireland by having a higher proportion of in situ colonies in close proximity to each other, and showing evidence of less fragmentation and abrasion. They also demonstrate a close association with horizons of gigantoproductid brachiopods. Overall, the Carlow biostromes are interpreted as forming in much shallower water settings (Somerville et al., 2007).

5. Conclusions

1. The rugose coral biostromes in upper Viséan (Asbian) platform carbonates in NW Ireland are approximately synchronous regional bioevents. They resulted from punctuated environmental changes that induced special, short-lasting ecological conditions. The biostromes differ in the geometry of the colonies, their thickness, internal construction mode and taxonomic composition. They can be used as regional marker beds.
2. All biostromes are dominated by species of the phaceloid colonial rugosan genus *Siphonodendron*: a lower *S. pauciradiale* biostrome is followed by a *S. martini* biostrome and one to three *S. junceum* biostromes formed higher in the Asbian succession.
3. The *pauciradiale* biostrome is the thickest, laterally most persistent and most variable of all biostromes. Three distinct facies types are recognized from NW to SE; the Streedagh facies (NW) developed in a mud-rich, open marine, moderately calm water platform frequently interrupted by storms. It is characterized by the giant solitary caniniid *Siphonophyllia*, which lived as a mudsticker, much like modern Ceriantharia. Up-section, increasing bioclastic debris allowed settlement of small coral thickets, which constitute the *pauciradiale* biostrome. The O'Donnell's Rock facies developed in proximity to the Ox Mountains also with tempestitic reworking of the biostrome. It is unique for the local abundance of the delicate fasciculate genus *Solenodendron* in more argillaceous limestones. The apparent paradox of a delicate, branched taxon in relatively shallow water is explained by increased turbidity/sediment influx,

which hampered *Siphonodendron* growth. The up to 50 m- thick Bricklieve facies (SE) with common coral boundstones developed in deeper water but still above the storm wave-base. In fact, in all three facies, the *pauciradiale* biostromes formed below fair-weather wave-base and above storm wave-base.
4. The *martini* biostrome grew on a levelled carbonate platform, as deduced from comparable thicknesses (c. 5–10 m) throughout the study area. High degrees of colony abrasion and fragmentation and characteristic allochems (ooids, cortoids, micritised grains and rare dasyclad algae) indicate deposition above fair-weather wave-base. This biostrome has a high coral diversity throughout the study area and the predominance of larger more robust species of *Siphonodendron*.
5. The three *junceum* biostromes are the thinnest, decimetre to several metres thick, and least persistent horizons. In the southern Ballymote Syncline there are three *junceum* biostromes, but in the O'Donnell's Rock area and the Carrick Syncline only a single one is recognized. The thicker biostromes are composite, consisting of several thinner coral horizons and intervening allochem facies. The *junceum* coral horizons are monospecific to oligospecific autobiostromes with only minor abrasion and fragmentation and coral colonies predominantly in situ. In the Bricklieve Mountains gigantoproductid brachiopod beds are associated with the highest *junceum* horizon of the 2nd *junceum* biostrome. Associated red algae and both exceptionally rare green algae and solitary dissepiment-bearing corals suggest local shallowing, but still deposition may have occurred in the dysphotic conditions. Also, the extremely delicate growth form of *S. junceum* and the prevailing upright growth suggest formation of the biostromes on a deeper water platform, mostly below storm wave-base.
6. According to facies and in comparison with modern scleractinian growth forms, sea-level variation exerted a significant control on the rise and decline of the *Siphonodendron* biostromes. The *pauciradiale* biostrome formed during an extended shallowing-upward cycle in a depth interval involving the acme of the small species. The cycle ended with the development of the *martini* biostrome in shallower water, characterized by the predominance of large species of *Siphonodendron*. Its demise may be associated with drowning during the global late Asbian sea-level rise. The thin *junceum* biostromes indicate deposition in deeper water, probably when low supply of allochems enabled formation of a firmground and thus settlement of coral larvae. Coral growth ceased almost completely after formation of the *junceum* biostromes during the falling sea level of the latest Asbian, leading to subaerial exposure and erosion.
7. Comparison of growth forms of rugose corals and modern scleractinians demonstrate that siliciclastic mud input and resulting turbidity/sedimentation, as well as turbulence, are important ecological constraints independent from light. Turbidity and turbulence result in a complex cascade of ecological constraints simulating apparent depth, which is one of the major controls on the succession of different biostromes in the Asbian of NW Ireland. Another important factor is tectonic control, with synsedimentary faulting and differential subsidence creating local variation in water depths and lateral facies changes.
8. Lithostrotionids occur in a relatively wide depth range, down into dysphotic conditions, with considerable overlap of species (Fig. 12). Thereby increased turbidity mimics greater depth. Mass occurrences of delicate species indicate deeper water (*S. junceum* and *S. pauciradiale*) or more turbid conditions (*Solenodendron furcatum*) on the platform. Mass occurrences of species with large corallites (*S. martini*) and compound lithostrotionids (*Lithostrotion* ssp.) indicate a shallow water platform setting, mostly above fair-weather wave-base. The very large solitary coral *Si. samsonensis* lived as a mudsticker preferentially in calm, very turbid waters. Since it is lacking in most *junceum* biostromes, it obviously is not adapted to dysphotic deeper water conditions.

Appendix A. Studied sections in the Ballymote and Sligo synclines

Syncline	Area	Formation	Locality	National Grid Reference	Other publications
Ballymote	Bricklieve Mountains	lower Bricklieve Limestone	Kesh Corann Cavern	G 707122	Caldwell and Charlesworth (1962)
Ballymote	Bricklieve Mountains	lower Bricklieve Limestone	Carnaweeleen	G 716131	Caldwell and Charlesworth (1962)
Ballymote	Bricklieve Mountains	lower Bricklieve Limestone	Lough Labe (W. side)	G 725122	Caldwell and Charlesworth (1962)
Ballymote	Bricklieve Mountains	lower Bricklieve Limestone	Murhy	G 717121	Caldwell and Charlesworth (1962)
Ballymote	Bricklieve Mountains	lower Bricklieve Limestone	Top Corann	G 712127	Caldwell and Charlesworth (1962)
Ballymote	Bricklieve Mountains	upper Bricklieve Limestone	Carrowkeel	G 755117	Caldwell and Charlesworth, (1962)
Ballymote	Highwood	upper Bricklieve Limestone	Lough Arrow	G 801154	Dixon (1972)
Ballymote	Carrane Hill	lower Bricklieve Limestone	Carrane Hill I	G 819192	Cózar et al. (2005)
Ballymote	O'Donnell's Rock	Glencar Limestone	Western scarp	G 881353	Jones, 1975
Ballymote	O'Donnell's Rock	Glencar Limestone	Hill 280	G 882348	
Ballymote	O'Donnell's Rock	Dartry Limestone	Roadside Quarry	G 881347	Somerville et al. (2009)
Ballymote	O'Donnell's Rock	Dartry Limestone	Larkfield	G 885350	Jones (1975)
Ballymote	Tobercurry	lower Bricklieve Limestone	Knocknashee	G 557191	
Sligo	Coastal sections	Glencar Limestone	Streedagh Point	G 631510	Hubbard (1966, 1970), Dixon (1970)
Sligo	Coastal sections	Glencar Limestone	Serpent Rock	G 565463	Hubbard (1966)

References

Alberstadt, L.P., Walker, K.R., Zurawski, R.P., 1974. Patch reefs in the Carters Limestone (Middle Ordovician) in Tennessee and vertical zonation in Ordovician reefs. Bull. Geol. Soc. of America 85, 1171–1182.
Aretz, M., 2001. The upper Viséan coral-horizons of Royseux — the development of an unusual facies in Belgian Early Carboniferous. Tohoku Univ. Mus. Bull. 1, 86–95.
Aretz, M., 2002. Habitatanalyse und Riffbildungspotential kolonialer rugoser Korallen im Unterkarbon (Mississippium) von Westeuropa. Kölner Forum für Geologie und Paläontologie 10, 1–155.
Aretz, M., Chevalier, E., 2007. After the collapse of stromatoporoid sponge — coral reefs — the Famennian and Dinantian reefs of Belgium: Much more than Waulsortian Mounds. In: Álvaro, J.-J., Aretz, M., Boulvain, F., Munnecke, A., Vachard, D., Vennin, E. (Eds.), Palaeozoic Reefs and Bioaccumulations: Climatic and Evolutionary Controls: Geological Society Special Publications, 275, pp. 163–188.
Aretz, M., Herbig, H.-G., 2003a. Palaeoecology of Late Dinantian coral biostromes from County Sligo, northwestern Ireland. Berichte des Instituts für Geologie und Paläontologie der Karl-Franzens-Universität Graz 7, 6.
Aretz, M., Herbig, H.-G., 2003b. Contribution of rugose corals to Late Viséan and Serpukhovian bioconstructions in the Montagne Noire (Southern France). In: Ahr, W.M., Harris, P.M., Morgan, W.A., Somerville, I.D. (Eds.), Permo–Carboniferous Carbonate Platforms and Reefs, Society for Economic Palaeontologists and Mineralogists Special Publication 78, and American Association of Petroleum Geologists Memoir 83, pp. 119–132.
Aretz, M., Nudds, J., 2005. The coral fauna of the Holkerian/Asbian boundary stratotype section (Carboniferous) at Little Asby Scar (Cumbria, England) and implications for the boundary. Stratigraphy 2, 167–190.
Aretz, M., Nudds, J., 2007. Palaeoecology of the Late Viséan (Dinantian) coral-chaetetid biostrome at Little Asby Scar (Cumbria, Great Britain). In: Hubmann, B., Piller, W.E. (Eds.), Fossil corals and sponges: Schriftenreihe der Erdwissenschaftlichen Kommissionen der Österreichischen Akademie der Wissenschaften, 17, pp. 365–381.
Bernecker, M., Weidlich, O., 2008. Azooxanthellate corals in the Late Maastrichtian–Early Paleocene of the Danish basin: bryozoan and coral mounds in a boreal shelf setting. In: Freiwald, A., Roberts, J.M. (Eds.), Cold-water Corals and Ecosystems. Springer, pp. 3–25.
Bourque, P.-A., Madi, A., Mamet, B.L., 1995. Waulsortian-type bioherm development and response to sea-level fluctuations: Upper Viséan of Béchar basin, western Algeria. J. Sed. Res. B65, 80–95.
Brandon, A., Hodson, F., 1984. The stratigraphy and palaeontology of the late Viséan and early Namurian rocks of north-east Connaught, Dublin. Geol. Surv. Ireland Spec. Pap. 6, 1–54.
Brett, C.E., Baird, G.C. (Eds.), 1997a. Paleontological Events, XV + 604 pp. Columbia University Press, New York.
Brett, C.E., Baird, G.C., 1997b. Epiboles, outages, and ecological evolutionary bioevents: taphonomic, ecological, and biogeographic factors. In: Brett, C.E., Baird, G.C. (Eds.), Paleontological Events. Columbia University Press, pp. 249–284.
Bromley, R.G., 1996. Trace Fossils. Biology, Taphonomy and Applications. Chapman and Hall, London.
Caldwell, W.G.E., 1959. The Lower Carboniferous rocks of the Carrick on Shannon Syncline. Q. J. Geol. Soc. London 115, 163–187.
Caldwell, W.G.E., Charlesworth, H.A.K., 1962. Viséan coral reefs in the Bricklieve Mountains of Ireland. Proc. Geol. Assoc. 73, 359–382.
Chappell, J., 1980. Coral morphology, diversity and reef growth. Nature 286, 249–252.
Coates, A.G., Jackson, J.B.C., 1987. Clonal growth, algal symbiosis and reef formation by corals. Paleobiology 13, 363–378.
Conil, R., Groessens, E., Laloux, M., Poty, E., Tourneur, F., 1991. Carboniferous guide foraminifera, corals and conodonts in the Franco–Belgian and Campine basins: their potential for widespread correlation. Courier Forschungsinstitut Senckenberg 130, 15–30.
Copper, P., 1988. Ecological succession in Phanerozoic reef ecosystems: is it real? Palaios 3, 136–152.
Cózar, P., Somerville, I.D., Aretz, M., Herbig, H.-G., 2005. Biostratigraphical dating of upper Viséan limestones (NW Ireland) using foraminifera, calcareous algae and rugose corals. Irish J. Earth Sci. 23, 1–23.
Cózar, P., Somerville, I.D., Mitchell, W.I., Paula Medina-Varea, P., 2006. Correlation of Mississippian (Upper Viséan) foraminiferan, conodont, miospore and ammonoid zonal schemes and correlation with the Asbian–Brigantian boundary in northwest Ireland. Geol. J. 41 (2), 221–241.
Dixon, O.A., 1970. Variation in the Viséan coral *Caninia benburbensis* from Northwest Ireland. Palaeontology 13, 52–63.
Dixon, O.A., 1972. Lower Carboniferous rocks between the Curlew and Ox Mountains Northwestern Ireland. J. Geol. Soc. London 128, 71–101.
Ernst, G., Schmid, F., Seibertz, E., 1983. Event-Stratigraphie im Cenoman und Turon von NW-Deutschland. Zitteliana 10, 531–554.
Fricke, H., Schuhmacher, H., 1983. The depth limits of Red Sea Stony Corals: an ecophysiological problem (a deep diving survey by submersible). Marine Ecol. 4, 163–194.
Frost, S.H., Langenheim Jr., R.L., 1974. Cenozoic Reef Biofacies. Northern Illinois University Press, De Kalb/Illinois. XI + 388 pp.
George, T.N., 1958. Lower Carboniferous palaeogeography of the British Isles. Proc. Yorks. Geol. Soc. 31, 227–318.
George, T.N., Oswald, D.H., 1957. The Carboniferous rocks of the Donegal Syncline. Q. J. Geol. Soc. London 113, 137–179.
George, T.N., Johnson, G.A.L., Mitchell, M., Prentice, J.E., Ramsbottom, W.H.C., Sevastopulo, G.D., Wilson, R.B., 1976. A correlation of Dinantian rocks in the British Isles. Spec. Rep. of the Geol. Soc. of London 7, 1–86.
Graham, J.R., 1996. Dinantian river systems and coastal zone sedimentation in northwest Ireland. In: Strogen, P., Somerville, I.D., Jones, G.Ll. (Eds.), Recent Advances in Lower Carboniferous Geology: Geological Society Special Publication, 107, pp. 183–206.
Hance, L., Poty, E., Devuyst, F.X., 2001. Stratigraphie séquentielle du Dinantien type (Belgique) et corrélation avec le Nord de la France (Boulonnais, Avesnois). Bull. Soc. Géol. Fr. 172, 411–426.
Herbig, H.-G., 1998. The late Asbian transgression in the central European Culm basins (Late Viséan, cd IIIα). Zeitschrift der Deutschen Geologischen Gesellschaft 149, 39–58.
Hubbard, J.A.E., 1966. Population studies in the Ballyshannon Limestone, Ballina Limestone and Rinn Point Beds (Viséan) of NW Ireland. Palaeontology 9, 252–269.

Hubbard, J.A.E., 1970. Sedimentological factors affecting the distribution and growth of Viséan caninoid corals in north-west Ireland. Palaeontology 13, 191–209.

Insalaco, E., 1998. The descriptive nomenclature and classification of growth fabrics in fossil scleractinian reefs. Sed. Geol. 118, 159–186.

Johnson, G.A.L., Nudds, J.R., 1975. Carboniferous coral geochronometers. In: Rosenberg, G.D., Runcorn, S.K. (Eds.), Growth Rhythms and the History of the Earth's rotation. Wiley, London, pp. 9–24.

Jones, G. Ll., 1975. Carboniferous rocks of the O'Donnell's Rock area, Co Leitrim, Unpublished BSc Thesis, Queen's University of Belfast.

Kauffman, E.G., Hart, M.B., 1995. Cretaceous bio-events. In: Walliser, O.H. (Ed.), Global Events and Event Stratigraphy in the Phanerozoic. Springer, pp. 285–312. Berlin, Heidelberg, New York.

Kelly, J.G., 1996. Initiation, growth and decline of a tectonically controlled Asbian carbonate ramp, Cuilcagh Mountain area, NW Ireland. In: Strogen, P., Somerville, I.D., Jones, G.Ll. (Eds.), Recent Advances in Lower Carboniferous Geology: Geological Society Special Publication, 107, pp. 253–262.

Legg, I.C., Johnston, T.P., Mitchell, W.I., Smith, R.A., 1998. Geology of the country around Derrygonnelly and Marble Arch, Memoir of the Geological Survey of Northern Ireland, Sheets 44, 56 and 43.

MacDermot, C.V., Long, C.B., Harney, S.J., 1996. Geology of Sligo - Leitrim. A geological description of Sligo, Leitrim and adjoining parts of Cavan, Fermanagh, Mayo and Roscommon, to accompany bedrock geology 1:100,000 scale map series, Sheet 7, Sligo - Leitrim. Dublin. Geological Survey of Ireland.

Madi, A., Bourque, P.-A., Mamet, B.L., 1996. Depth-related ecological zonation of a Carboniferous carbonate ramp: Upper Viséan of Béchar Basin, western Algeria. Facies 35, 59–80.

Mitchell, M., 1989. Biostratigraphy of Viséan (Dinantian) rugose coral faunas of Britain. Proc. Yorks. Geol. Soc. 47, 233–247.

Mitchell, W.I., 1992. The origin of Upper Palaeozoic sedimentary basins in Northern Ireland and relationships with the Canadian Maritime Provinces. In: Parnell, J. (Ed.), Basins on the Atlantic Seaboard, Petroleum Geology, Sedimentology and Basin Evolution: Geological Society Special Publication, 62, pp. 191–202.

Mitchell, W.I., 2004. Carboniferous. Regional Guide to the Geology of Northern Ireland — our Natural Foundation: Geological Survey of Northern Ireland (GSNI), Belfast, pp. 79–116.

Nudds, J., Day, A., 1997. The effects of clastic sedimentation on a fasciculate rugose coral from the Lower Carboniferous of Northern England. In: Perejón, A., Comas-Rengifo, J. (Eds.), Proceedings of the VII International Symposium on Fossil Cnidaria and Porifera, Madrid, Spain, 1995, Volume I: Boletín de la Real Sociedad Española de Historia Natural, 91, pp. 93–97.

Oswald, D.H., 1955. The Carboniferous rocks between the Ox Mountains and Donegal Bay. Q. J. Geol. Soc. London 111, 167–183.

Philcox, M.E., Baily, H., Clayton, G., Sevastopulo, G.D., 1992. Evolution of the Carboniferous Lough Allen Basin, Northwest Ireland. In: Parnell, J. (Ed.), Basins on the Atlantic Seaboard, Petroleum Geology, Sedimentology and Basin Evolution: Geological Society Special Publication, 62, pp. 203–215.

Poty, E., 1981. Recherches sur les Tétracoralliaires et les Héterocoralliaires du Viséen de la Belgique. Meded. Rijks Geol. Dienst 36, 1–161.

Poty, E., Devuyst, F.-X., Hance, L., 2006. Upper Devonian and Mississippian foraminiferal and rugose coral zonation of Belgium and Northern France: a tool for Eurasian correlations. Geol. Mag. 143, 829–857.

Rodríguez, S., 1996. Development of coral reef-facies during the Viséan at Los Santos de Maimona, SW Spain. In: Strogen, P., Somerville, I.D., Jones, G.Ll. (Eds.), Recent Advances in Lower Carboniferous Geology: Geological Society Special Publication, 107, pp. 145–152.

Rodríguez, S., Somerville, I.D., 2007. Comparisons of rugose corals from the Upper Viséan of SW Spain and Ireland: implications for improved resolutions in late Mississippian coral biostratigraphy. In: Hubmann, B. Piller, W.E. (Eds.), Fossil Corals and Sponges, Proceedings of the 9th International Symposium on Fossil Cnidaria and Porifera, Graz, 2003. Austrian Academy of Sciences, Schriftenreihe der Erdwissenschaftlichen Kommissionen 17; Vienna, 275–305.

Rodríguez, S., Arribas, M.E., Falces, S., Morena-Eiris, E., de la Pena, J., 1994. The *Siphonodendron* Limestone of the Los Santos de Maimona Basin: development of an extensive reef-flat during the Visean in Ossa Morena, Spain. Courier Forschungsinstitut Senckenberg 172, 203–214.

Ross, C.A., Ross, J.R.P., 1985. Late Paleozoic depositional sequences are synchronous and worldwide. Geology 13, 194–197.

Ross, C.A., Ross, J.R.P., 1987. Late Paleozoic sea levels and depositional sequences. Cushman Found. for Foramin. Res. Spec. Pub. 24, 137–149.

Sanders, D., Baron-Szabo, R.C., 2005. Scleractinian assemblages under sediment input: their characteristics and relation to the nutrient input concept. Palaeogeogr. Palaeoclimatol. Palaeoecol. 216, 139–181.

Scotese, C.R., 2002, http://www.scotese.com, (PALEOMAP website).

Scrutton, C.T., 1998. The Palaeozoic corals. II: structure, variation and palaeoecology. Proc. Yorks. Geol. Soc. 52, 1–57 Leeds.

Sevastopulo, G.D., Wyse Jackson, P.N., 2009. Carboniferous: Mississippian (Tournaisian and Visean). In: Holland, C.H., Sanders, I. (Eds.), The Geology of Ireland. Dunedin Academic Press, Edinburgh, pp. 215–268.

Somerville, I.D., 1979. Cyclothems in the early Brigantian (lower D2) limestones east of the Clwydian Range, North Wales. Geol. J. 14, 69–87.

Somerville, I.D., 2008. Biostratigraphic zonation and correlation of Mississippian rocks in Western Europe: some case studies in the late Viséan/Serpukhovian. Geol. J. 43, 209–240.

Somerville, I.D., Cózar, P., Rodríguez, S., 2007. Late Viséan rugose coral faunas from south-eastern Ireland: composition, depositional setting and palaeoecology of *Siphonodendron* biostromes. In: Hubmann, B. Piller, W.E. (Eds.), Fossil Corals and Sponges, Proceedings of the 9th International Symposium on Fossil Cnidaria and Porifera, Graz, 2003. Austrian Academy of Sciences, Schriftenreihe der Erdwissenschaftlichen Kommissionen 17; Vienna, 307–328.

Somerville, I.D., Cózar, P., Aretz, M., Herbig, H.-G., Mitchell, W.I., Medina-Varea, P., 2009. Carbonate facies and biostromal distribution in a tectonically controlled platform in northwest Ireland during the late Viséan (Mississippian). Proc. Yorks. Geol. Soc. 57, 173–200 Leeds.

Vaughan, A., 1905. The palaeontological sequence in the Carboniferous Limestone of the Bristol area. Q. J. of the Geol. Soc. 61, 181–307.

Walliser, O.H. (Ed.), 1986. Global bio-events. Lect. Notes Earth Sci., 8, Springer, Berlin, Heidelberg, p. 442.

Walliser, O.H. (Ed.), 1995. Global Events and Event Stratigraphy in the Phanerozoic. Springer, Berlin, Heidelberg, New York, p. 333.

Warnke, K., 1994. Die unterkarbonischen Mud Mounds in den Counties Sligo und Leitrim, Nordwest-Irland. Documenta Naturae 88, 1–72.

Wells, J.W., 1963. Coral growth and geochronometry. Nature 197, 948–950.

West, I.M., Brandon, A., Smith, M.A., 1968. A tidal flat evaporitic facies in the Viséan of Ireland. J. Sed. Petrol. 38, 1079–1093.

West, R.R., Feldman, H.R., Maples, C.G., 1997. Some Upper Carboniferous (Pennsylvanian) event beds (epiboles). In: Brett, C.E., Baird, G.C. (Eds.), Paleontological Events. Columbia University Press, pp. 425–450.

Wilson, J.L., 1975. Carbonate Facies in Geologic History. Springer, Berlin, New York. XIII + 471 pp.

Wood, R., 1999. Reef Evolution. Oxford University Press, Oxford. XI + 414 pp.

Wright, V.P., Vanstone, S.D., 2001. Onset of Late Paleozoic glacio-eustasy and evolving climates of low latitude areas: a synthesis of current understanding. J. Geol. Soc. 158, 579–582.