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From mud to limestone: birth and growth of a giant reef in the Eifelian (Middle Devonian) of S Belgium.

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Abstract:

The Wancennes reef is a giant bioherm 3000 m-large and 300 m-high that developed during the early Eifelian *partitus* to *costatus* conodont zones. The basal banks are formed by an accumulation of crinoid debris stabilised by lamellar stromatoporoids forming a coverstone, with a typical pioneer fauna. A micritic core, mostly formed by coral bafflestone, forms the first relief of the reef and evolved laterally and upwards to coral-stromatoporoid bafflestone and framestone that form the bulk of the reef and corresponds to the diversification phase of building and non-building organisms. The reef-crest is dominated by massive stromatoporoids and subordinate tabulate corals whereas the back-reef accumulation of debris is very rich in organisms (climax phase). The development of the reef is strongly influenced by sea level variations. Two third-order eustatic sequences are recorded in the reef. The first one corresponds to the basal banks and micritic core (transgressive systems tract) and lower part of the skeletal framestone (highstand systems tract) ending with an emersion. The second sequence is recorded in the upper part of the framestone (transgressive systems tract) and reef-crest and associated facies (highstand systems tract). The final emersion of the reef marked its termination followed by the deposition of fine-grained siliciclastics. The bathymetry, light penetration and hydrodynamism are assessed by the facies and faunal associations. All point to shallow-water, high-energy environment at the base and top of the reef, with deeper and quieter conditions during the development of the micritic core.

A

1. Introduction

Based on the abundance and wide latitudinal distribution of the stromatoporoid and coral reefs, from 45°N to 45°S (Kiessling, 2001), the Middle Devonian has often been considered as a 'supergreenhouse' period (Copper and Scotese, 2003). The Givetian recorded a peak in skeletal reefs both in terms of amount and volume (Kiessling et al., 1999; Jakubowicz et al., 2019), but the Eifelian reefs are not less interesting. Indeed, the Eifelian age was a time of transition between an Early Devonian world with rare and singular reefs, and the Givetian marked by the acme of the skeletal reefs in the Paleozoic (Burchette, 1981; Copper, 2002). The poor development of reefs during the Early Devonian is tentatively explained by the decline of the stromatoporoid diversity at the end of the Silurian and their long recovery extending up to the end of the Pragian (Stearn, 2001; May and Rodríguez, 2012), associated with unfavourable climatic conditions, large inputs of siliciclastics and low sea level (Antoshkina and Konigshof, 2008¨ ; May, 2022).

The end of the Emsian corresponds to both a climatic amelioration and an increase in sea level (Copper and Scotese, 2003). In parallel, the Late Emsian-Eifelian corresponds to a peak of diversity among the tabulate and rugose corals (Scrutton, 1999) and the high sea level allowed a better communication between platforms, and therefore a higher cosmopolitanism of fauna (Oliver, 1977; Fagerstrom, 1983; Stock, 1990; Pedder, 2010). All conditions were met to trigger a global proliferation of reef-building organisms (Kiessling, 2009; Zapalski et al., 2017a; Bridge et al., 2022).

In Western Europe, Eifelian reefs are usually described as smaller than the Givetian ones (Mendez-Bedia, 1976´ ; Pelhate and Plusquellec, 1980; Hladil, 1988; M´endez-Bedia et al., 1994; Fernandez-Martínez ´ et al., 2010). Exceptions exist, with large reefs like the Wancennes reef, subject of this paper, which outpaces many other Middle Devonian reefs in size and complexity. The reason of this development is to be searched in the complexity of the environments and long-living conditions profitable to the reef-building organisms (Tsien, 1979; Burchette, 1981; Flügel and Flügel-Kahler, 1992).

Though bioherms (isolated reefs with limited horizontal development and significant elevation) have been described in Eifelian strata, they are far less common than biostromes (sheet-like reefs with low elevation). These bioherms are often observed on outer shelf or form isolated platforms offshore (Wolosz, 1992a; Pohler, 1998; Pohler et al., 1999; Jakubowicz et al., 2019) whereas biostromes are typical of platforms (Faber, 1980; Galle et al., 1995; Salerno, 2008; Huang et al., 2022). The Wancennes bioherm is therefore remarkable for its size and age, being lower Eifelian whereas most Eifelian bioherms are younger in age (late Eifelian or crossing the Eifelian-Givetian boundary).

2. Geological and stratigraphical settings

During the Devonian, the Namur-Dinant Basin – which is part of the Rhenohercynian Fold and Thrust Belt of the Variscan Orogen – was situated along the southeastern margin of Laurussia on the Rhenohercynian Ocean under southern tropical latitude. The Namur-Dinant Basin acted as a shallow basin with more proximal facies northwards (Old Red Sandstone facies). Southwards, along the southern limb of the Dinant Synclinorium, the facies, though more distal, are still shallow- water. The Namur-Dinant Basin passes south-eastwards to the Eifel area where similar depositional conditions are known in the northern synclines of the Eifel Synclinorium. Note that no through with deep- water facies is known in Belgium as it is in southern Eifel and Harz (Struve, 1982).

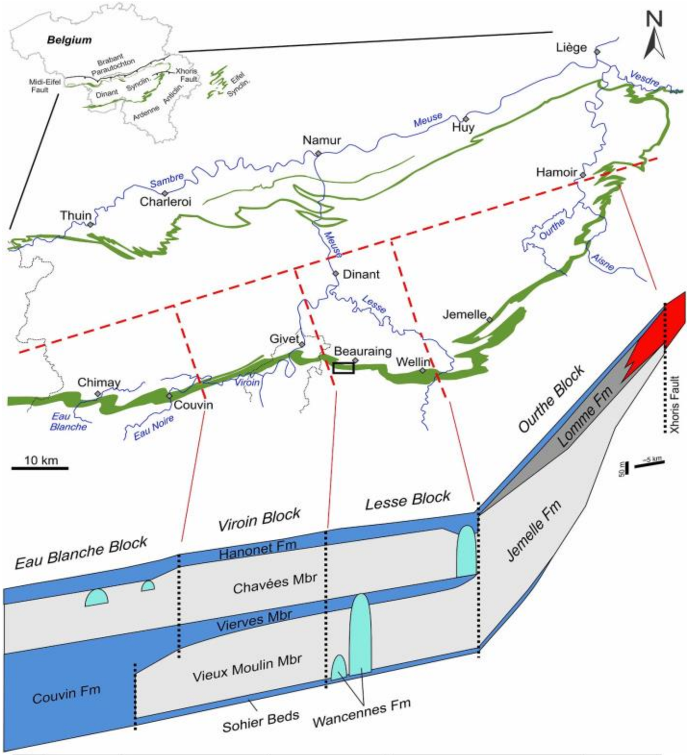
The end of the Early Devonian is characterised, in southern Belgium by the onset of the 'carbonate factory' that culminated in the Givetian. The first part of the Middle Devonian is also a time marked by the development of very diverse reefs, varying from stromatoporoids parabiostromes to small patch-reefs in siliciclastic environment to micritic mounds and to large skeletal bioherms (see Denayer, 2019). The aim of this paper is to document these large reefs.

Along the southern limb of the Dinant Synclinorium (Fig. 1), from west to east, the lower part of the Eifelian succession is represented by shallow-water limestone very renown in the Couvin area (classical type area of the former Couvinian stage, Lecompte, 1958; Bultynck, 1970), that thins eastwards within a more shaly succession of the Jemelle Formation (Vieux Moulin Member, Fig. 2). In the Beauraing area, east of the Meuse river valley, a thick limestone body occurs within the Jemelle Formation. Curiously, it has been overlooked for decades – not a single mention in the classic papers by Lecompte (1958, 1961) and Tsien (1971, 1979). Hence it is necessary to go back to Gosselet (1888) to have an accurate description of this limestone. Denayer (2019) recently described it, recognised its reefal nature and introduced the name Wancennes Formation for it.

Two bioherms are known in the Beauraing area: the Wancennes reef, type locality of the eponymous formation is a very large limestone body

Fig. 1. The Eifelian strata in southern Belgium with a cross section along a W-E-NE line exposing the geometrical relationships of the lithostratigraphic units and the boundaries of the tectonic blocks. In blue, the carbonate-dominated units, in grey the siliciclastic-dominated units, in red the littoral red beds. Abbreviations: Fm: Formation, Mbr: Member,

Syncl.: Synclinorium. Modified after Denayer (2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



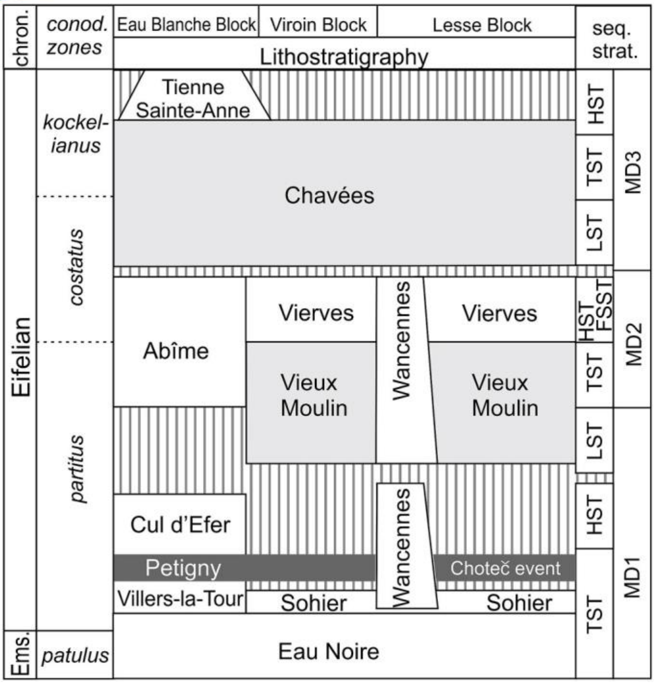


Fig. 2. Chronostratigraphic, biostratigraphic (conodonts) and sequence stratigraphic scheme of the lithostratigraphic succession of the Eifelian strata along the southern limb of the Dinant Synclinorium. Abbreviations: chron.: chronostratigraphy, conod.: conodont, Ems.: Emsian, FSST: Falling-stage systems tract, HST: highstand systems tract, LST: lowstand systems tract, TST: transgressive systems tract, seq. strat.: sequence stratigraphy, Villers-la-T.: Villers-la- Tour Member, Petigny, Cul d'Efer and Abîme Members form the Couvin Formation, the Vieux Moulin and Chavées Members form the Jemelle Formation. Light grey shade indicates the shaly and silty units, the dark grey line indicates the Choteč event. Modified after Denayer (2019).

3000 m-long and up to 300 m-thick (from 50°05'47”N 4°57'50"E to 50°06'03”N 4°59'44"E); the Dion reef is a small lenses c. 300 m-long and 100 m-thick (50°06'27”N 4°53'46"E).

The reef of the Wancennes Formation is the oldest build-up in the Devonian sequence of the Namur-Dinant Basin. Attempts to date the limestone with conodonts from the reefal facies has failed but biostratigraphically-dated horizons are found both at the base and the top of the reef, allowing the correlation with the better-dated time- equivalent Couvin Formation lying to the west (Figs. 1, 2). The Sohier Beds (Fig. 2), a thin carbonate unit below the Jemelle Formation and correlated with the base of the Wancennes Formation yielded a conodont fauna indicating the lower *partitus* zone (Bultynck and Godefroid, 1974). The Vierves Member, a carbonate unit capping the shale and siltstone of the Vieux Moulin Member of the Jemelle Formation and correlated with the top of the Wancennes Formation also yielded the conodont *Bipennatus montensis*, a local marker of the *costatus* zone (Bultynck and Godefroid, 1974; Dumoulin and Blockmans, 2008). The rugose corals also suggest a clear correlation. A yet undescribed species of *Sociophyllum* occurs at the base of both the Couvin and Wancennes formations (Denayer, 2019). Similarly, *Fasciphyllum varium* (= *Beugniesastraea varia* sensu Coen-Aubert, 1988) which is only known in the upper part of the Abîme and Vierves members in the Couvin area (Coen- Aubert, 1988) also occurs in abundance in the upper part of the Wancennes reef. The Wancennes Formation is therefore bracketed within the *partitus* and *costatus* conodont zones (Fig. 2).

3. Material and methods

The present study is based on the field mapping of the lithofacies of the Wancennes and Dion reefs and the building of composite sections presented in Fig. 3. The facies and palaeoecological analyses is based on the observation of c. 350 thin sections and 40 polished slabs. The palaeontological material is curated at the University of Liège (Belgium).

4. Facies, architecture and development of the reef

The underlying strata of the reef are not well exposed in Wancennes and Dion but crop out discontinuously nearby. These are crinoidal and bioclastic floatstone to rudstone with an argillaceous matrix and rich in large solitary rugose corals (cystimorphic solitaries and *Acanthophyllum* spp.) and bulbous or hemispheric *Favosites* colonies. These facies constitute the top of the Eau Noire Formation (Sohier Beds). Other fossils frequent in these beds are brachiopods (large atrypids), platycerid gastropods, fenestellid bryozoans, ostracods and trilobites fragments.

4.1. Basal banks

The base of the reef is made of coarse-grained crinoidal rudstone with abundant debris of stromatoporoids and tabulate corals (Fig. 4A). They form decametric lenses in which irregular bedding are regarded as hummocky crossed-stratifications. Unlike the underlying beds, this rudstone is rather pure and whitish or beige, with very few argillaceous seams. Immediately above, the rudstone becomes richer in stromatoporoids and chaetetid sponges either as centimetric to pluri-centimetric clasts or as entire lamellar colonies in living position or overturned. Isolated branches of ramose rugose corals are also frequent, together with brachiopod shells (usually broken) and ostracods.

The proportion of stromatoporoids and tabulate corals over crinoidal rudstone tends to increase upwards where some beds are entirely made of alternation of thick lamellar stromatoporoids, forming a coverstone. The stromatoporoids are commonly stained in pink by ferruginous pigments disseminated in the coenosteum. In parallel, the rudstone is richer in large bioclasts of brachiopods, gastropods, ostracods, trilobites and rugose corals. In Wancennes, this lower unit is c. 20 m-thick.

A second unit, 40 m-thick, is similar in facies but differs by the morphology of the stromatoporoids that are more commonly bulbous or hemispheric. The stromatoporoids, abundant but poorly diverse, are dominated by *Stromatopora* spp. and *Clathrodictyon* spp. and rare broken branches of *Stachyodes* spp. The *Clathrodictyon* spp. colonies are usually associated with syringoporids tabulate corals forming caunoporid symbiotic associations. Occasional hemispheric colonies of heliolitid form a monospecific assemblage of *Heliolites porosus*. Ramose tabulate corals are locally abundant as broken branches. Auloporids and fragmented branched of *Coenites* spp. occur sporadically. Lamellar colonies of chaetetid sponges (*Pachytheca stelimicans*) are common only in the upper part of this unit where they usually cover stromatoporoids and corals. Rugose corals are uncommon in the lower part and the first remarkable appearance is that of small dendroid colonies of *Sociophyllum* sp. in the crinoidal rudstone. *Lyrielasma* sp. and *Fasciphyllum* sp. are the major component of the coral fauna in the upper part of the stromatoporoid- crinoid banks.

Cavities between and below the stromatoporoids are commonly filled up with fine-grained bioclastic wackestone or mudstone and blocky calcite. Some of these cavities are decimetric in size and often contain clusters of brachiopods (Fig. 4C) and scutellid trilobite pygidia.

The upper 20–25 m of this unit is almost entirely made up of large stromatoporoids (thick lamellar and bulbous colonies, Fig. 4E) with some chaetetid sponges. The matrix is usually a rudstone or floatstone in which fragments of coenitid tabulate corals and heliolitids occur.

4.2. Micritic core

The core facies is very poorly exposed in Wancennes but is well documented from the small reef in Dion where it starts on the top of the crinoidal rudstone with lamellar stromatoporoids. The abundance of fine-grained carbonate and the radically different fauna distinguish these facies from what is observed in the underlying basal banks. Firstly, the stromatoporoids are lacking or only present as small clasts and the crinoids are smaller in size and less abundant.

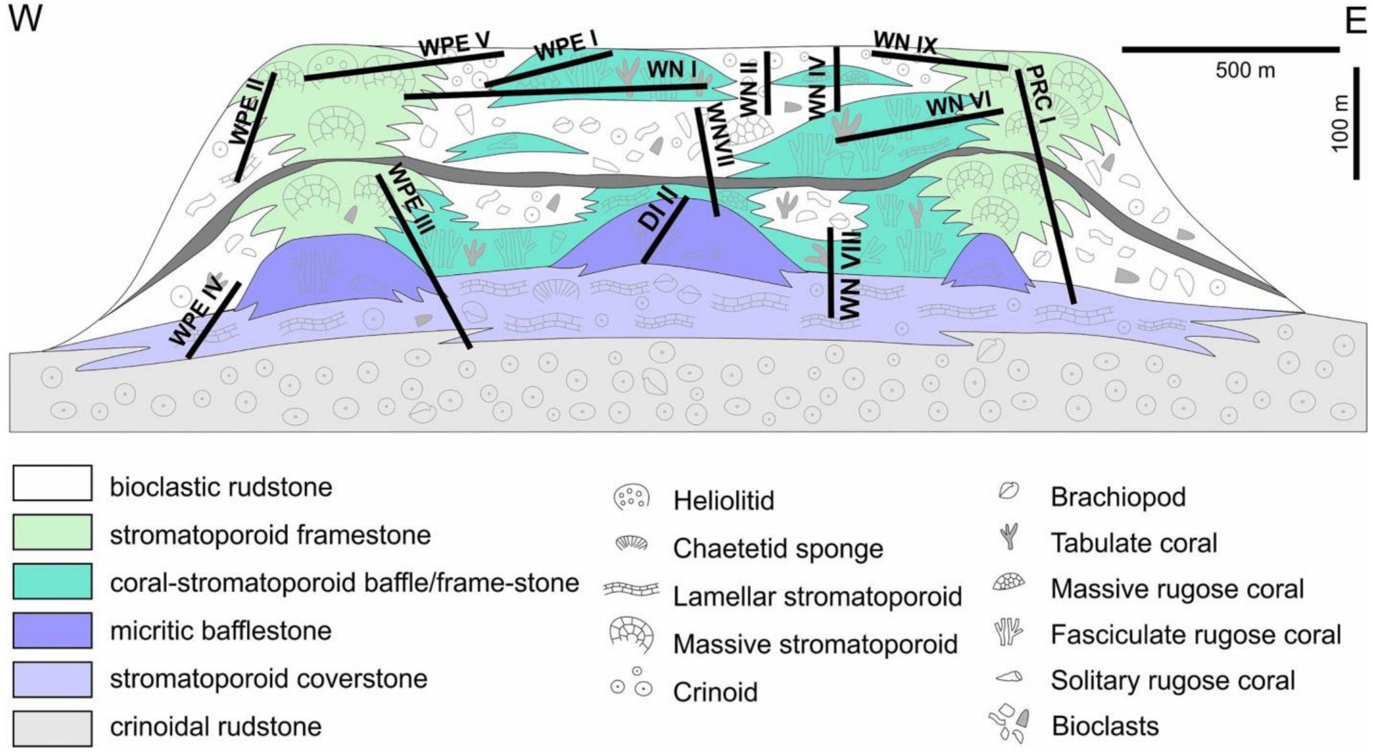


Fig. 3. Schematic diagram of the Wancennes reef with location of the major facies, building stages and sequence stratigraphy interpretation. WPE I-IV, WN I-IX, PRC I, DI II indicate the sections and sampled transects through the reef. Note that the morphology and symmetry of the reef is speculative as based on discontinuous data.

The dominant facies is a fine-grained, wackestone or floatstone, in which the fasciculate rugose corals *Thamnophyllum* sp. is frequent. Atrypid brachiopods are less abundant than previously but systematically bivalved and filled in with geopetal cement (Fig. 5B). Ramose treptostome bryozoans are scattered in the matrix. Tabulate corals are dominated by syringoporids (*Syringocystis* s.l., Fig. 6D) and fragments of coenitids and *Hillaepora* spp. The rugose corals are not more diverse, with only *Cystiphylloides* sp. and abundant small dendroid colonies of *Thamnophyllum* sp. (Fig. 6G). Except for the ramose tabulate corals and stromatoporoids that are clearly fragmented and allochthonous, the other organisms seem to be in life position.

The sediment is usually yellowish due to a certain amount of dispersed ferriferous dolomite crystals. Local accumulations of larger- sized bioclasts forms floatstone patches. Locally, the sediment is absent and the inter-corallite space in the coral colonies is filled in by several generations of radiaxial calcitic cement, which shades vary from dark to light grey (Fig. 6E). The space left after the coalescence of the cement layers in the colonies are filled in by white blocky calcite. The same phenomenon is observed, at a smaller scale between thin sheets of fenestellid bryozoans (Fig. 4B) and between individuals in brachiopod clusters. The abundance of radiaxial-fibrous calcitic cement forms biocementstone in some colonies (Fig. 5A). Despite the proportion of mud in the matrix, there is very few micritic structure that can be attributed to calcimicrobes (Fig. 6B). Thin sheets of *Sphaerocodium* arounds clasts are the only observed microbial structure. Irregular cement-filled cavities, though not stromatactoid, are present (Fig. 6A, C).

The volume of the core is not easy to estimate. In Dion, it seems to occupy the entire limestone mass as this small reef probably drown before the deposition of any other facies. Hence the core is at least 50 m- thick. In Wancennes, this facies does not crop out properly but isolated samples collected in various part of the cropping area suggest that the core facies might form more than one mass within the reef (Fig. 3).

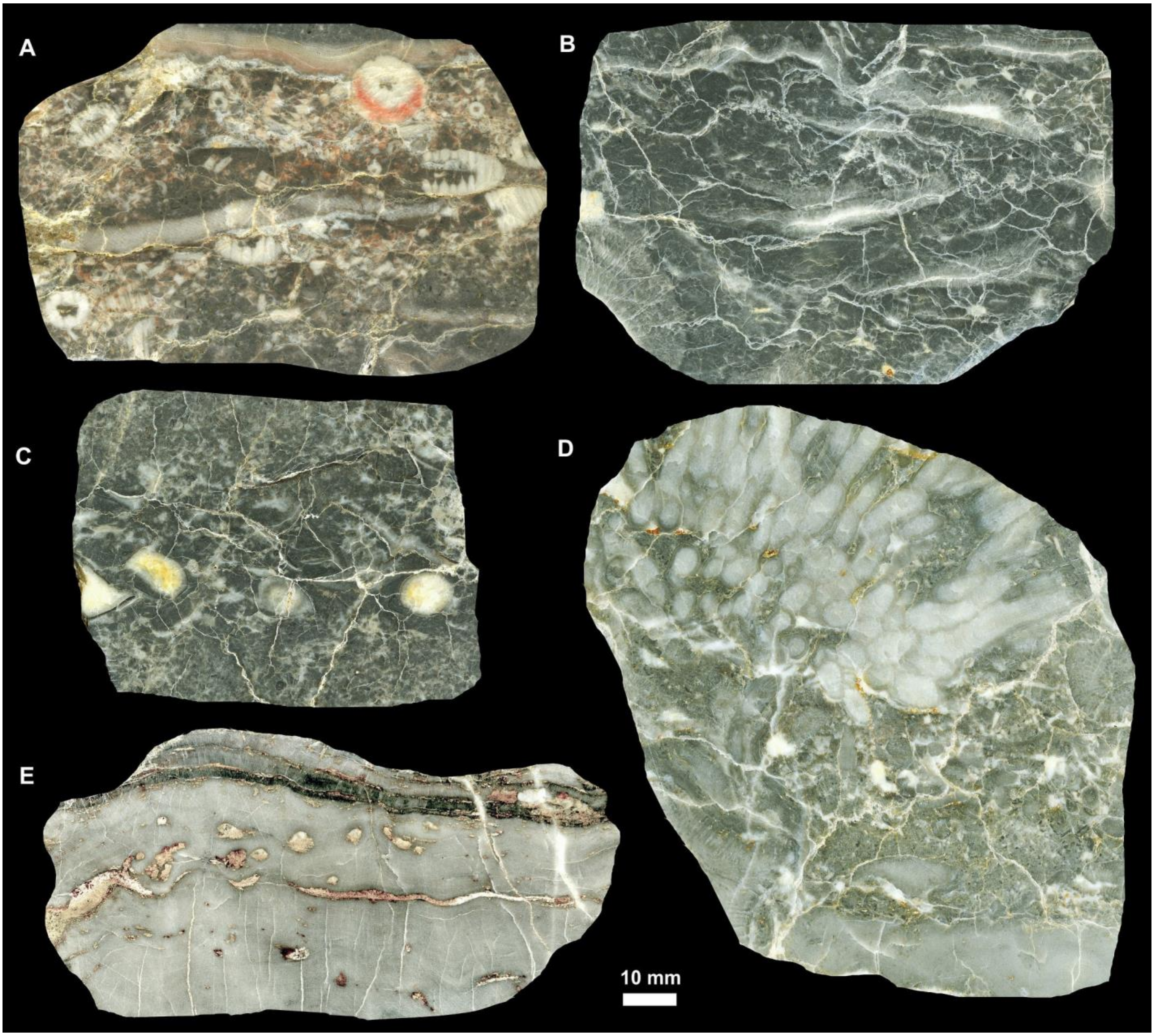


Fig. 4. Lithofacies of the basal banks (A-C, E) and skeletal complex (D) of the Wancennes reef. A. Crinoidal rudstone with thin laminar stromatoporoids (polished slab WPE III.H3). B. Fine-grained bioclastic wackestone with elongated shelter-void cavities below stromatoporoid laminae and laminar bryozoans, filled-up with radiaxial-fibrous calcitic cement and blocky calcite (WPE III.H5). C. Bioclastic rudstone with brachiopod clusters and cement-filled shelter-void cavities (WPE III.F3). D. Bioclastic rudstone with large stromatoporoid fragments and *Fasciphyllum* colonies (WPE III.B4). E. Stromatoporoids and chaetetid coverstone (PRC I.6).

4.3. Skeletal complex

The dominant facies of the Wancennes reef, observed at least on a thickness of 80 m is a light grey massive limestone forming a complex assemblage of various facies. The most frequent facies is a framestone with lamellar and domal stromatoporoids and heliolitids, lamellar and dome-shaped tabulate corals (favositids) and rugose coral colonies frequently growing within massive stromatoporoids (Fig. 6A, C). The framestone passes to a bafflestone with ramose tabulate corals and fasciculate rugose corals (Fig. 4D, 6B, 7A-C). Beside the bafflestone and framestone, a large volume of this facies is made of accumulated fragments of stromatoporoids, corals, brachiopods, crinoids, etc. (Fig. 8). The matrix, locally very abundant, is dominantly a bioclastic packstone-grainstone (Fig. 4F). Skeletal debris are mostly crinoids and tabulate and rugose corals, brachiopods, ramose bryozoans, gastropods and trilobites. The fragments size varies from millimetre to decimetre and large colonies can reach several tens of centimetres across and lay overturned or simply toppled in the sediment. The sediment is well-washed and there is no obvious bioturbation preserved. Cemented cavities and radiaxial-fibrous calcitic cement layers around corallites are common but less developed than in the core facies (Fig. 4C). Pendant bothryoidal cement masses are frequent in small cavities (Fig. 6E).

Despite the lack of continuous section, indirect evidence — such as blocks emerging from ploughed fields and signature of clayish content in aerial photographs taken during drought (see Denayer, 2019) — allows the recognition of a 10–20 m-thick unit of fine-grained, argillaceous limestone in the middle part of the succession. The dominant facies is a dark greyish, slightly argillaceous wackestone usually rich in *Fasciphyllum* sp., *Calceola sandalina* and ramose tabulate corals suggesting depositional settings less hydrodynamic, and — or — an influx of fine- grained siliciclastics. Fine-grained (50 µm) detrital quartz grains occur sporadically in this facies.

Above this darker and more argillaceous interval, the same light grey framestone and bafflestone is visible over a thickness of 70 m to 80 m. The matrix is similar to the one of the previous unit. The coral fauna is extremely abundant and diverse. Some massive rugose corals colonies reach 50 cm in diameter whereas some ramose tabulate coral colonies are up to 60 cm-high. These ramose colonies with coalescent branches are close to *Thamnopora*

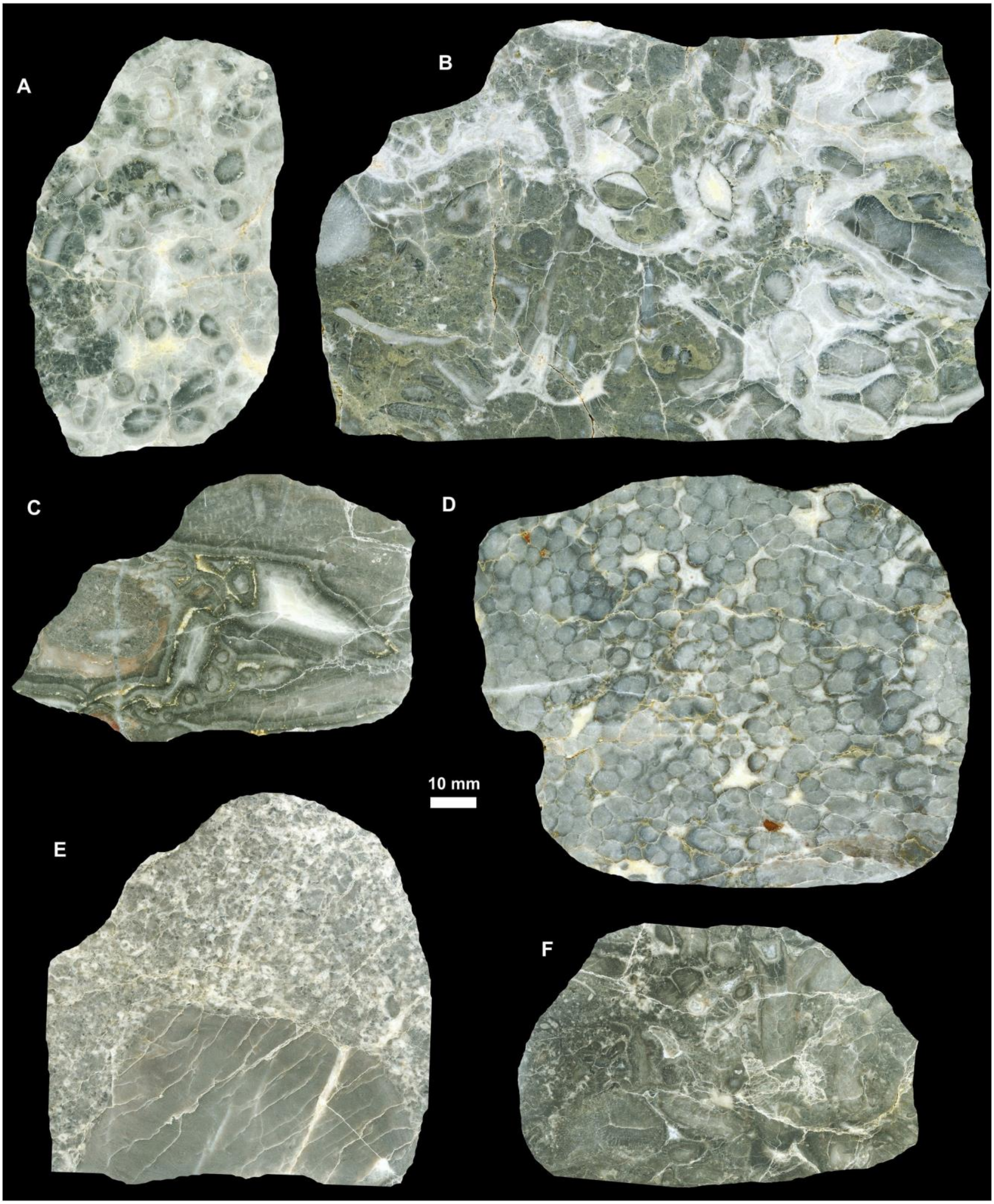


Fig. 5. Lithofacies of the micritic core (A-B), base of the skeletal reef-complex (C-D) and reef-crests (*E*-F) of the Wancennes reef. A. Biocementstone around a *Thamnophyllum* colony (polished slab Di II.12). B. Bafflestone with cement-filled cavities and bioclastic accumulations of stromatoporoid fragments and brachiopods (Di II. A). C. Large cavity under a stromatoporoid fragment, with a complex infilling of radiaxial-fibrous calcitic cement and bryozoan sheets (WPE III.G1). D subcerioid colony of *Fasciphyllum* with inter-corallite space filled with radiaxial-fibrous cement and blocky calcite (PRC I.4). E Crinoidal rudstone with large fragments of stromatoporoid (WPE III.H4). F. Bioclastic rudstone with large fragments of tabulate and rugose corals cemented by radiaxial-fibrous calcitic cement (WN I.B3).

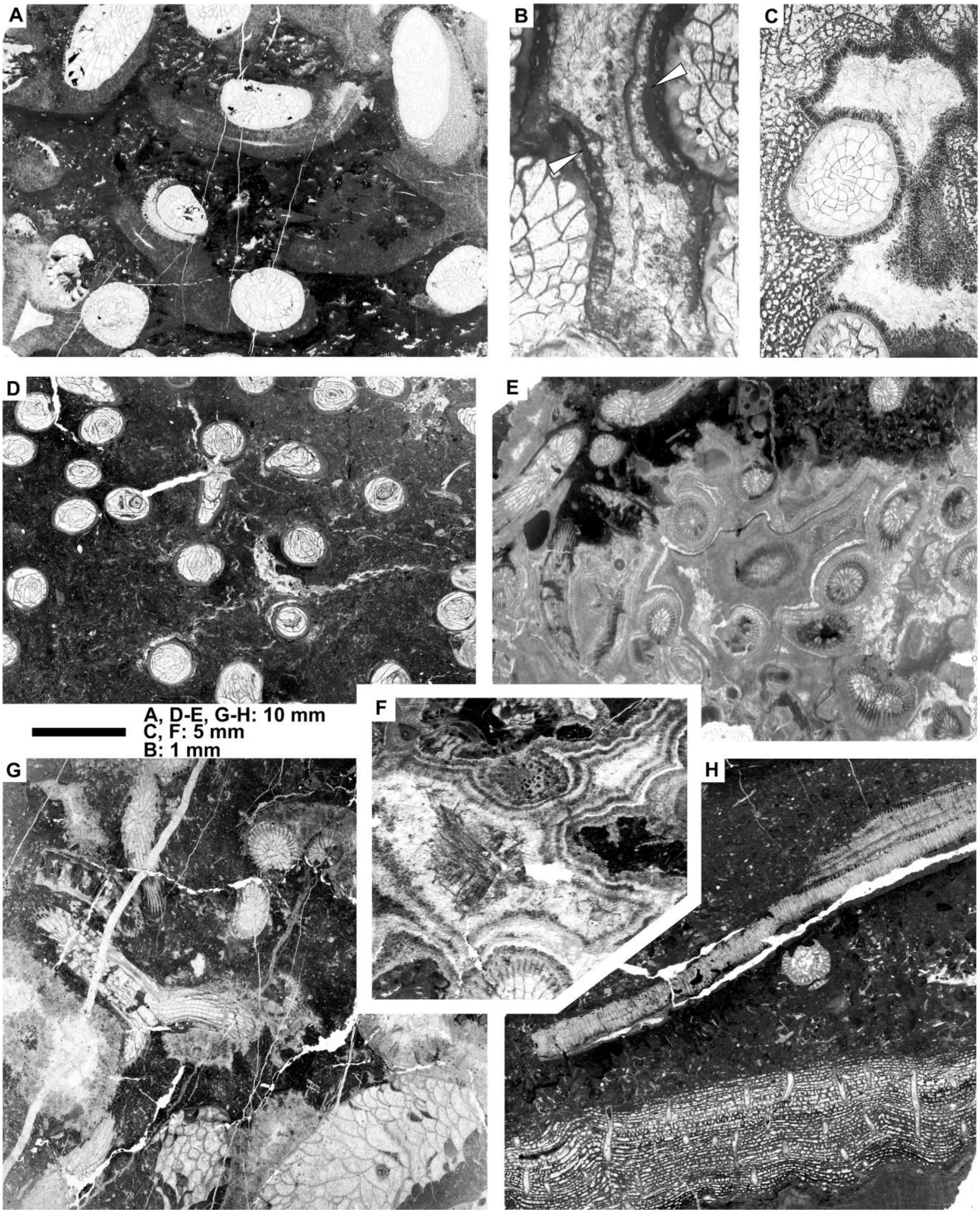


Fig. 6. Microfacies of the micritic core of the Wancennes reef. A. *Fasciphyllum* bafflestone with micritic matrix where small stromatactoid-like cavities are developed besides larger shelter-void cemented cavities (thin section WPE III.8). B. Vesicular lamina of putative microbial origin coating *Fasciphyllum* corallites (WN VI.2). C. Thin radiaxial-fibrous calcitic cement crust in an inter-corallite space cavity (PRC I.4). D. *Syringocystis* wackestone with abundant sponge spicules (WN I.19). E. *Thamnophyllum* bafflestone passing to biocementstone with multiple generations of radiaxial-fibrous calcitic cement and large cavities filled up with blocky calcite and dolomitic calcite appearing yellowish (Di II.12). F close-up view of E showing alternations of with radaxial-fibrous calcitic cement and dark micritic layers. G. *Thamnophyllum* bafflestone with cystimorphic rugose corals (WPE II.4). H. Wackestone with stromatoporoids and chaetetids (*Pachytheca stellimicans*) (WPE I.4).

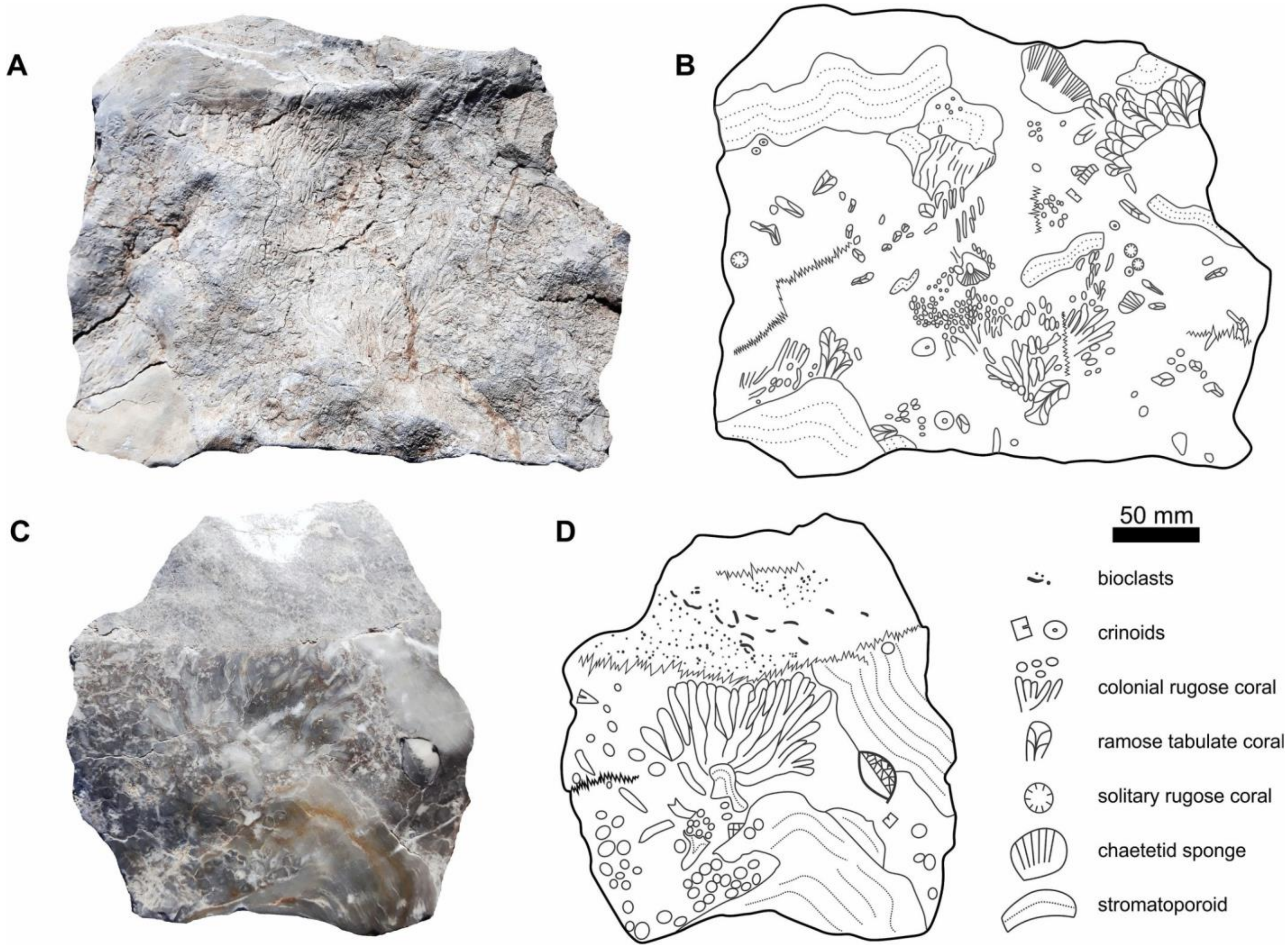


Fig. 7. Examples of reefal lithofacies of the Wancennes reef. A-B. *Fasciphyllum-Thamnopora* bafflestone with abundant matrix and numerous large debris of stromatoporoids, chaetetids and crinoids (block WN VI.A). C-D. stromatoporoid-coral framestone separated from a crinoidal rudstone patch by stylolithes (polished block WN VI.B).

lagoon surrounded by the reef- *tumefacta* but display slightly larger corallites (F. Tourneur, pers. com. January 2023, Fig. 7).

Multiple generations of radiaxial-fibrous calcitic cement separated by very thin dark micrite — probably microbial in origin — filled up shelter voids, cavities and inter-corallite space in colonies and locally forms large part of the limestone (Fig. 6E-F). Though the origin of this calcite is debated, it is a typical component observed in reef-margin and reef-flat environment (Shen et al., 2008).

4.4. Reef-crests

The reef-crests are dominated by large (up to 1 m in diameter) bulbous stromatoporoids (*Stromatopora* spp. and *Clathrodictyon* spp.) associated with *Heliolites porosus* colonies forming a framestone with a very low proportion of bioclastic matrix. Hemispheric or bulbous colonies of *Favosites* also occur. The accumulation of large colonies forms a massive unit that can be traced for a hundred metres on both sides of the reef. Laterally to the stromatoporoid framestone, up to 25 m-thick accumulations of whitish, relatively well sorted, crinoidal rudstone is observed. This crinoidal rudstone commonly displays a syntaxial cement around the crinoid fragments when the latter are not mud-coated. Other skeletal elements are fragments of ramose tabulate corals and centimetric clasts of stromatoporoids (Fig. 4E, 10C-D). Even in the central part of the reef top, there is no stromatolitic or bid-eyes mudstone that would have deposited in quiet settings. Hence, there is no evidence for a crest.

The top of the reef is not exposed but it seems to be very clear-cut and overlaid by the shale of the Chavees Member of the Jemelle Formation as suggested by the shaly debris appearing in crops immediately above of the last limestone crest.

4.5. Fore-reef and flanks

The eastern flank of the Wancennes reef is discontinuously exposed along a small path. The facies is bioclastic and crinoidal, with clasts of corals and stromatoporoids, usually badly-washed and with yellowish ferruginous stains. The fauna is abundant but strongly fragmented and seemingly re-deposited. Besides the limited occurrence of these flank facies, no fore-reef structure has been observed. However, the outcropping conditions preclude a good observation of this part of the reef structure.

The Wancennes Formation is embedded in the shale and siltstone of the Vieux-Moulin Member but the latter is known to be deposited after the limestone (see 6.2.) and thus is not contemporaneous with the reef. However, debris from the reefs seem to have been scattered laterally in the shale when the latter deposited.

5. Succession of ecological communities

As in many Devonian reefs, the ecological spectrum varies laterally and vertically during the growth of the reef, resulting in a lateral and vertical distribution of ecological niches occupied by various ecological communities (Burchette, 1981; Copper, 1988; Wood, 1998). In the Wancennes reef, the faunal succession forms a continuum throughout the major facies (Fig. 11).

5.1. Colonisation phase

The pioneer reef-building organisms to appear in Wancennes are the stromatoporoids that grew directly in the crinoid carpet at the base of the reef. Their generic diversity has not been explored in detail, but it seems that the generalist genera *Stromatopora* and *Clathrodictyon* are dominant. Chaetetid sponges are the second reef-building organisms in term of abundance. As stated above, their morphology is dominantly lamellar and tabular, and often encrusting each other. Tabulate (mostly *Thamnopora* spp.) and rugose corals (unidentifiable solitaries) are not significantly contributing to the reef structure at the base of the basal banks, and both appear mostly as isolated fragments. During this early stage of reef-growth, the main carbonate producers are the crinoids.

After the colonisation phase by the stromatoporoids, a more diverse fauna settled. The stromatoporoids are still the dominant frame-builders but tabulate corals and chaetetid sponges start to diversify. Auloporids are frequent encrusters of the stromatoporoids and other corals, together with the chaetetid sponge *Pachytheca stellimicans*. *Sociophyllum* sp. is the first colonial rugose coral to appear in the rudstone facies. *Lyrielasma* sp. and *Fasciphyllum* sp. first appear in the crinoid-stromatoporoid beds where they form delicate colonies encrusted by *Clathrodictyon* spp. and *Rhaphidopora* spp. A sub-cerioid trend is often observed in these colonies. Ramose coenitids tabulate corals and the ramose stromatoporoids *Stachyodes* spp. are also present as fragments.

The brachiopods also display an increase in diversity from the crinoid carpet where only fragments of gypidulids are identifiable, to a more variegated fauna of gypidulids, atrypids, athyridids, rhynchonellids and spiriferids in the crinoids-stromatoporoids beds. As stated above, many of them occur in clusters of several (tens) of individuals that seemingly occupied cavities. They might represent a cryptic fauna but this is not easily demonstrated.

A second colonisation phase is recorded by the settlement of a fauna adapted to the fine-grained, quiet environment that reigned during the development of the micritic core. The chaetetids and stromatoporoids are very rare in this facies, as it is often the case in fine-grained sediments, and usually reduced to thin laminae covering coralla. The tabulate corals (ramose coenitids and auloporids) are poorly diverse as well. Conversely, this facies recorded the proliferation of cystimorphic rugose corals (*Cystiphylloides* sp., rare *Mesophyllum* sp.) and of the colonial corals *Thamnophyllum* sp. and *Fasciphyllum* sp. (Fig. 6A, E, G). Both genera form small (10–15 cm-high and -wide) phacelloid colonies with cylindrical corallites well separated from each other. The coralla are occasionally covered with thin sheets of calcimicrobes (Fig. 6B). In absolute number, this facies is less diverse than the underlying basal banks but they display a rather distinct fauna. This is obviously linked to the sediment type.

5.2. Diversification phase

The diversification phase occurs during the development of the stromatoporoid-coral framestone-bafflestone occupying the largest part of the skeletal complex. Above the micritic core, the stromatoporoids and the massive tabulate corals (alveolitids) recolonises the reef together with crinoids. *Stromatoporella* spp. and *Actinostroma* spp. are dominant whereas *Clathrodictyon* spp. seems rarer, as is *Stachyodes* spp. The tabulate corals are dominated by small ramose coenitids and *Thamnopora* spp., whereas heliolitids and chaetetids sponges are still uncommon.

Above an interval of dark limestone beds with abundant solitary rugose corals (*Calceola sandalina*, *Acanthophyllum* spp., cystimorphic solitaries) and colonies of *Thamnophyllum* sp., the development of the bafflestone takes over, with the same fauna as described above.

5.3. Climax phase

The abundance of fasciculate and sub-cerioid colonies of the rugose coral *Fasciphyllum* is very remarkable (Fig. 7B, G). Colonies growing within stromatoporoids – or stromatoporoids growing around coralla – are common, expressing complex symbiotic relationships (Fig. 9A, C). With large colonies of ramose *Thamnopora* spp., also intergrowing with stromatoporoids, they form a bafflestone that trapped a bioclastic matrix. In the upper part of the reef, hemispheric and columnal stromatoporoids, heliolitid and favositid tabulate corals form a framestone together with massive colonies of the rugose corals *Xystriphyllum* sp., *Spongophyllum* sp., *Cyathophyllum* sp. (Fig. 10A) and the unexpected *Taymirophyllum* sp., *Australophyllum* sp. and cf. *Carlinastraea* sp. All of them are usually encrusted by stromatoporoid laminae. The solitary rugose corals reach their maximum diversity in the upper part of the reef, with abundant *Cystiphylloides* spp. (including pseudo-colonies of gregarious individuals), *Mesophyllum* spp. (some specimens are up to 12 cm in diameter), *Acanthophyllum* spp., *Stringophyllum* spp., *Dohmophyllum* sp., *Lekanophyllum* sp., etc.

6. Discussions

6.1. Comparing Wancennes with other reefs

Reefs have been often described or simply reported from the Eifelian strata (Tsien, 1971; Hladil, 1988; Kiessling et al., 1999; Shen et al., 2008; Jakubowicz et al., 2019). They represent a large spectrum of build-ups, including many examples of coral thickets and biostromes up to large bioherms. The Wancennes reef, with its own particularities, is here compared to other published build-ups (Table 1).

The time-equivalent carbonate deposits of the Wancennes reefs are to be found in the Couvin Formation that develops west of the Meuse river valley, on the Eau Blanche Block, some 30 km west of Wancennes (Fig. 1). The Couvin Formation is the *stratum typicum* of the disused Couvinian substage (Lecompte, 1958; Bultynck, 1970; Tsien, 1971). It is partly reefal. Its lower part (Villers-la-Tour Member) — *premier biostrome* or 'Co2aI' of the old literature (e.g. Bultynck, 1970) — is composed of an alternation of crinoidal rudstone and stromatoporoid- tabulate corals coverstone with rugose corals and chaetetid sponges. They represent the time-equivalent of the basal banks of the Wancennes reefs and share with them many characters. The dominance of lamellar stromatoporoids as the main frame-builder is obvious in both cases, as well as the development of the basal crinoid carpet. The main difference resides in the cyclic arrangement of these alternations in the Villers-la- Tour Member (see Denayer, 2019), which has not been observed in Wancennes. In Couvin, this first unit passes upwards to fine-grained, organic-rich dark limestone with few dysoxic fauna of the Petigny Member (Fig. 2, see 6.6.).

Above comes a second episode of biostrome in the Cul d'Efer Member – *second biostrome* or 'Co2aIII' of the old literature. The latter starts with the same crinoidal rudstone and stromatoporoid coverstone alternations and passes upwards to bulbous stromatoporoids and heliolitids alternating with coarse-grained bioclastic rudstone with big cystimorphic rugose corals, arranged in sequential parabiostromes. These sequences, very characteristic in the lower part of the member, are thinning- upwards and finning-upwards. Again, the sequential character is very strong in Couvin but not expressed in the Wancennes reef.

The upper member of the Couvin Formation – Abîme Member or 'Co2aIV-V' in the old literature – starts with stromatoporoid beds similar to those known in the underlying member. It then includes a unit of darker finer-grained and slightly argillaceous limestone rich in fauna. Theses beds can be correlated with the darker facies known in the middle part of the Wancennes reef. Above come stromatoporoids biostromes alternating with accumulations of broken small

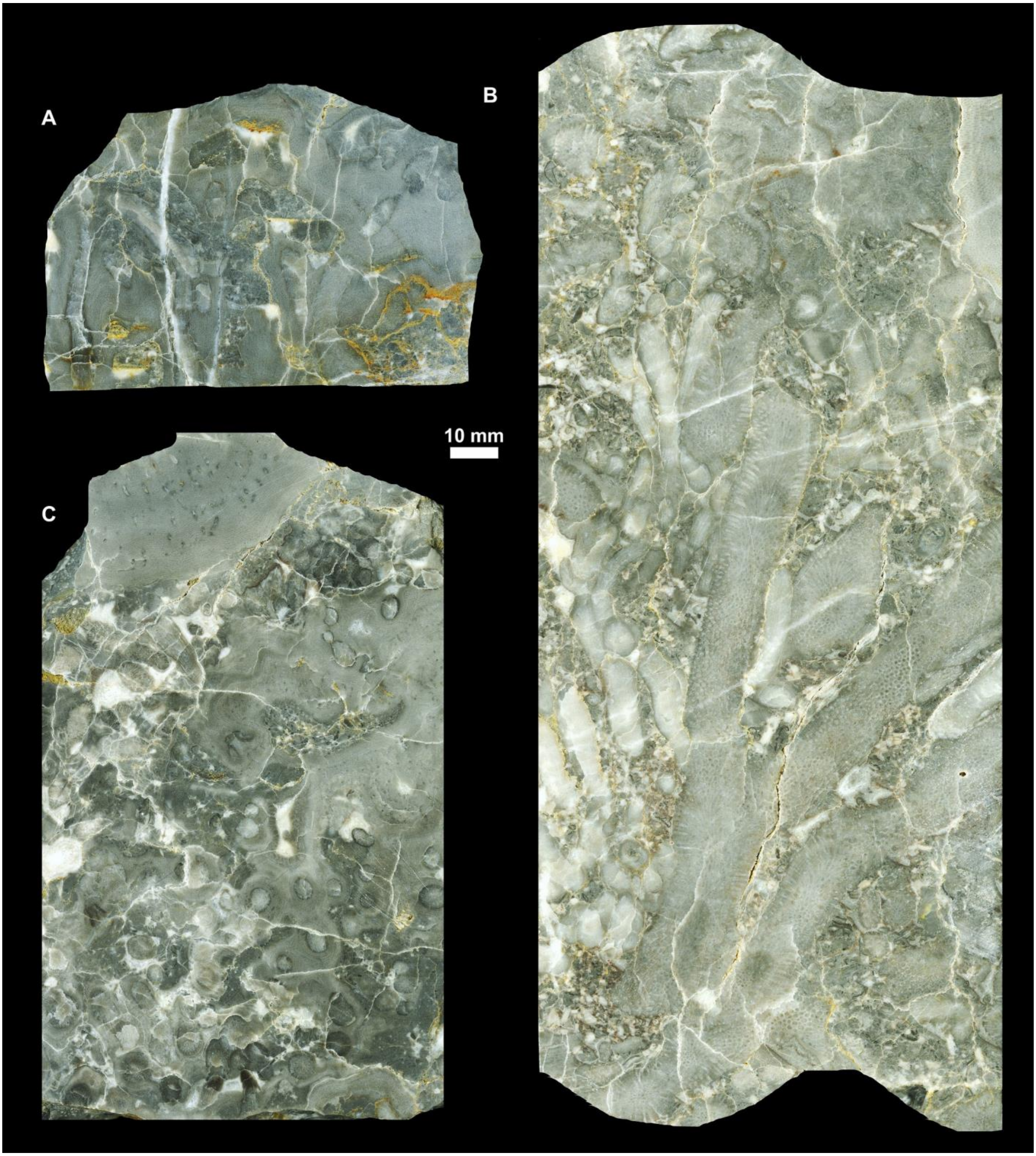


Fig. 8. Lithofacies of the skeletal complex of the Wancennes reef. A stromatoporoid-rugose coral coverstone (polished slab WN VI.5). B. Stromatoporoid-fasciculate rugose coral symbiotically intergrowing forming a framestone with cement-filled cavities (WN VI.2). C. *Thamnopora-Fasciphyllum* bafflestone with a bioclastic grainstone-rudstone matrix (WN IV.1).

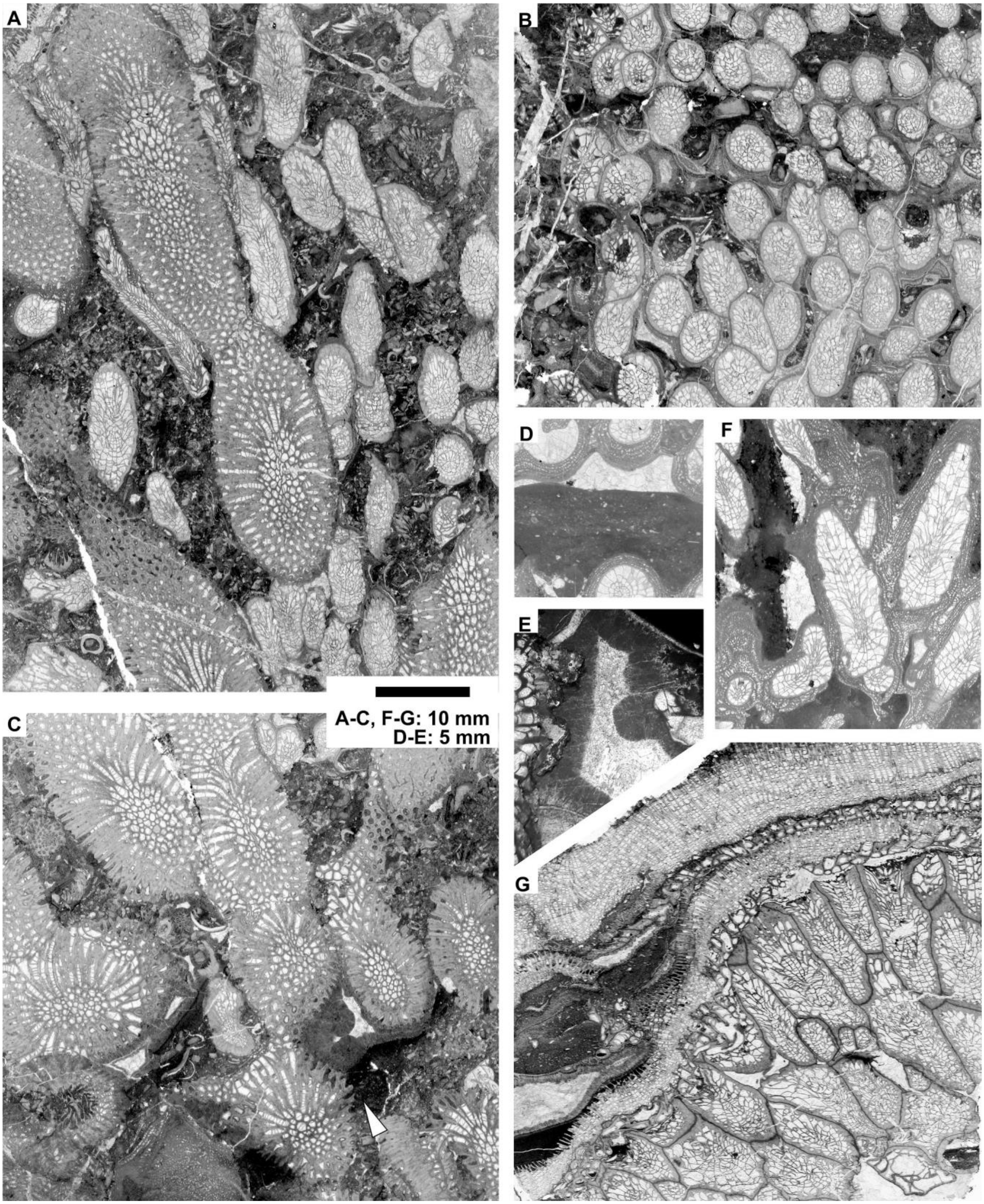


Fig. 9. Microfacies of the skeletal complex of the Wancennes reef. A, C. *Thamnopora-Fasciphyllum* bafflestone with a bioclastic grainstone-rudstone matrix and inter- corallite space filled up with radiaxial-fibrous calcitic cement showing bothryoids (arrow) (thin section WN IV.1). B. *Fasciphylum* baffestone with corallite encrusted by thin stromatoporoid laminae (WPE II.7). D. Close-up view of a cavity between *Fasciphyllum* coralites, filled-up with dark micritic material and blocky calcite (WN VI.21). E. Close-up view of a cavity with cement bothryoids (WN V.2). F. Stromatoporoid-fasciculate rugose coral intergrowth forming a framestone (WN VI.21). G. framestone made of a sub-cerioid colony of *Fasciphyllum* (down-right) encrusted by several generations of auloporid tabulate corals, chaetetid sponges and micritic layers of putative microbial origin (WPE III.C1).

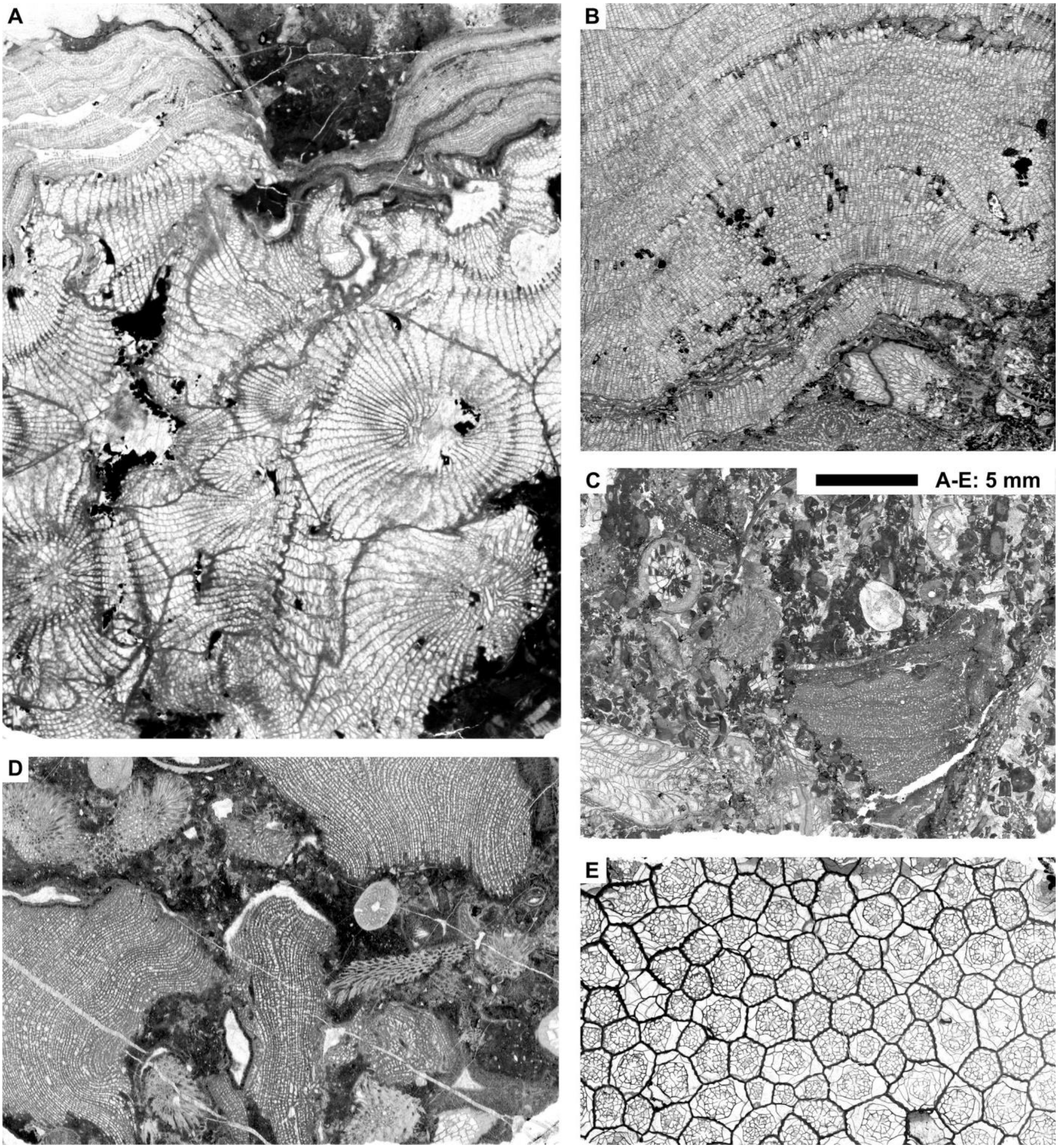


Fig. 10. Microfacies of the reef-crests (A, C, E) and back-reef (B, D). A. Massive *Cyathophyllum* covered with stromatoporoids (thin section WN I.31). B. Chaetetid sponge interfingered with stromatoporoid laminae (WN III.1). C. Crinoidal rudstone with large fragments of corals, stromatoporoids and brachiopods (PRC I.15). D. Coarse-grained bioclastic rudstone with stromatoporoids, tabulate and rugose corals (WN VI.15). E. Cerioid colony of *Fasciphyllum* (WPE V.1).

branches of rugose and tabulate corals and amphiporid stromatoporoids. These cyclic deposits are interpreted as shallowing-upwards parasequences, some being capped by mud-cracks. The contemporaneous development of the Couvin Formation biostromes and Wancennes bioherm recorded different depositional conditions, notably the accommodation space and responses to changes in eustacy and energy (see 6.3.). Hence the resulting geometry is very different, as are their respective faunal assemblages.

Within the Abîme Member, a singular bioherm occurs in the Nismes locality (Roche Trouee Facies in ´ Denayer, 2019), c. 50 m in diameter and 20 m in height. This small reef is very rich in bulbous and columnar stromatoporoids, large colonies of fasciculate rugose corals and ramose tabulate corals with patches of bioclastic matrix. The bioherm passes laterally to bioclastic rudstone beds with corals and stromatoporoids debris and is capped by bedded bioclastic limestone mostly made of an accumulation of small branches of coenitid tabulate corals and amphiporid stromatoporoids. This last unit is the time-equivalent of the upper part of the Wancennes reef and is very similar in facies but lacks the abundant and diverse rugose coral fauna. This lack is tentatively explained by a position of the small bioherm closer to the platform and, possibly, by a shorter time of development.

Bioherms of the Tienne Sainte-Anne Member of the Jemelle Formation occur in the upper Eifelian in the Couvin-Chimay area as well as near Wellin (Fig. 1). They typically start on a crinoid-ramose tabulate coral rudstone similar to the crinoid carpet of Wancennes but reduced in thickness. Stromatoporoids stabilising the rudstone form a coverstone that passes upwards to a floatstone and bafflestone rich in brachiopods and small ramose tabulate corals. This micritic core is rich in chaetetid sponges and brachiopods, with a limited covering role by stromatoporoids. Cement-filled cavities are frequent either below large bioclasts of chaetetid sheets (shelter voids), or within the matrix. No reef-crest facies have been observed but large colonies of *Heliolites porosus* and *Cyathophyllum multicarinatum* suggest a more hydrodynamic environment in the upper part. Like the Wancennes reef, the Tienne Sainte-Anne bioherms are embedded in shale and siltstone of the Jemelle Formation, but in both cases, these siliciclastics deposited after the growth of the reef (Denayer, 2019).

Outside the Namur-Dinant Basin, Eifelian reefs have been described in the neighbouring Eifel Synclines (Pohler et al., 1999; Brühl, 1999; Salerno, 2008 for recent summary) where each reef has its own characteristics. Whereas the upper Eifelian – Lower Givetian cyclic stromatoporoids-corals biostromes are very similar to the cyclic biostromal units of the Couvin Formation, the Weineberg bioherm is more similar to the Wancennes reef. In both cases, a basal crinoidal siltstone with local accumulation of tabulate corals and stromatoporoids initiated the carbonate production. The bioherm – described as 'mud mound' is a 10–15 m-thick massive unit of grey limestone rich in stromatactoid cavities. The matrix is a bioclastic wackestone-packstone rich in bryozoans and sponge spicules, where laminar tabulate corals (including *Platyaxum* spp.), chaetetid sponges (*Pachytheca stellimicans*) and rugose corals (*Thamnophyllum* sp.) occurs. Crinoids and stromatoporoids are uncommon in this facies but form the rudstone unit capping the reef. Contrarily to Wancennes, the Weinberg reef displays a limited range of facies and associated fauna, suggesting that the ecological climax phase was never attained. In fact, the facies and ecological characters of the Weinberg reef are closer to those observed in the Tienne Sainte-Anne bioherms of S Belgium than to the Wancennes reef.

In Cantabria (N Spain), an Upper Emsian – lower Eifelian bioherm was described at Arnao by Mendez-Bedia (1976)´ . This reef starts on bioclastic beds stabilised by lamellar stromatoporoids. Massive stromatoporoids and alveolitid tabulate corals are the main frame-builders from the base to the top of the reef. The facies are mostly framestone and coverstone with a significant bioclastic component and subordinate *Thamnopora* and rugose coral bafflestone. No micritic core has been detected. Facies and fauna point to a high energy shallow-water environment. In that regard, it resembles the upper part of the Wancennes reef.

Similarly, the initiation of the Aferdou el Makrib reef of the Moroccan Ani-Atlas (Kaufmann, 1998; Jakubowicz et al., 2019; Majchrzyk et al., 2022) was triggered by the deposition of a crinoidal carpet that served as anchor for the development of a micritic core. Noticeably, the shift from crinoidal rudstone to micritic limestone with cystimorphic rugose corals is progressive and no stromatoporoid-dominated stage has been reported. This quasi-absence of stromatoporoids and abundance of foliose colonies of coenitid tabulate corals (*Platyaxum* and *Roseoporella*) are interpreted as evidence for mesophotic conditions (Majchrzyk et al., 2022). This, together with the scarcity of stromatactoid cavities in Wancennes suggest that the latter developed in conditions of shallower water compared to Aferdou el Makrib. Both reefs recorded the spreading and colonisation of the fine-grained facies by the coral *Thamnophyllum*. The *Thamnophyllum* bafflestone grades into a ramose tabulate- dominated rudstone then to a debris-dominated facies towards the reef-front in Aferdou el Makrib but in Wancennes, the dominant bafflestone- and framestone-builders are not the tabulate corals but the very abundant rugose coral *Fasciphyllum* associated with massive stromatoporoids, *Heliophyllum* and *Favosites*. Again, it suggests that Wancennes recorded a much more hydrodynamic environment that culminated within the fair-weather wave zone.

Bioherms occurring in the Eifelian Onondaga Formation of Ontario and New York (Wolosz and Paquette, 1988; Wolosz, 1992a) display a very peculiar development, with a core composed of bafflestone erected either by phacelloid rugose corals ('eastern facies' in Wolosz, 1992b); by delicate dendroid cladoporid tabulate corals (LeRoy reef, Wolosz and Paquette, 1988); or by stromatoporoids (Formosa reef, Fagerstrom, 1983). In both cases, the micritic core lacks stromatactoid cavities. The top of the core is marked by an erosive surface suggesting emersion, followed by the deposition of bioclastic

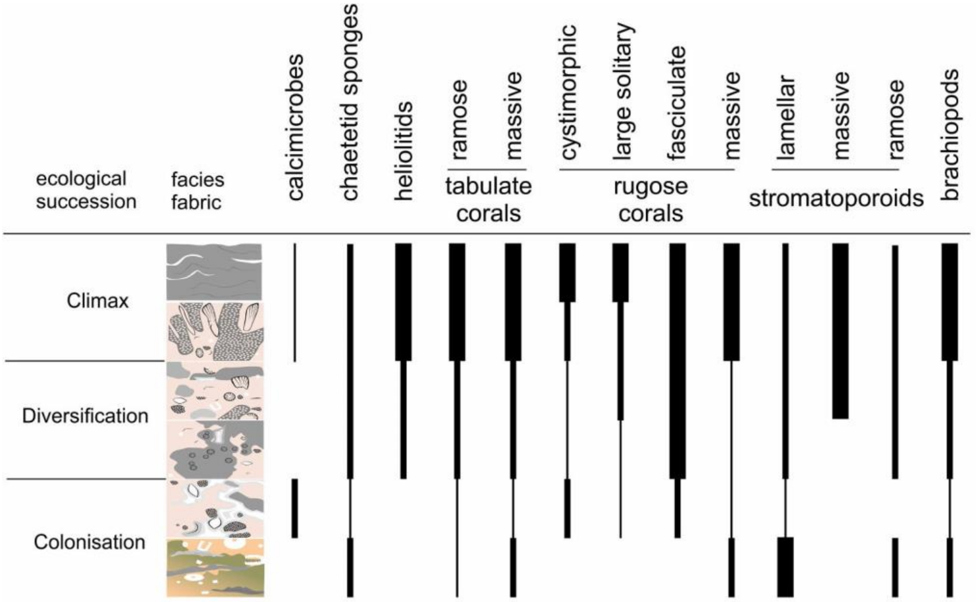


Fig. 11. Ecological succession and relative abundance of selected biota during the development of the Wancennes reef as reconstructed herein.

rudstone ('protocapbeds') then by a diverse community of tabulate and rugose corals forming a bafflestone ('flank beds'). Like in Wancennes, the development of the reef is controlled by eustacy and two sequences, separated by an emersion surface, are recorded. Besides the limited size of the Onondaga reefs, the major difference is the monospecific character of the building community.

In the Tamworth Best (New South Wales), three bioherms occurring at the same stratigraphic level are described (Pohler, 1998). They all start on an accumulation of *Stachyodes* branches or on coarse-grained bioclastic rudstone. Stromatoporoids are the dominant reef-building organisms but the proportion of *Stachyodes* spp. and rugose corals (*Sociophyllum* sp. and *Xystriphyllum* sp.) allow to differentiate three communities in the three bioherms. Like in Wancennes, the build-ups all have a significant bioclastic component and the bafflestone- and framestone-builders are not evenly distributed within the reef. Interestingly, laterally to the Tamworth bioherms are developed a series of biostromes dominated by stromatoporoids and tabulate corals that are rhythmically arranged. A similar pattern is observed in Wancennes and Couvin, though in Tamworth, rhythmic deposits are also observed within the framestone where nodular limestone occur repeatedly and alternates with stromatoporoids and tabulate corals. Theses alternations are explained as eustatic oscillations by Pohler (1998). Their top is marked by a red sediment-filled cavities that points to a karstic origin and the emersion of the limestone mass at the end of the Eifelian. The reefs are overlaid by siliciclastic or mixed sediments that suggest a change in the carbonate factory after the emersion of the reefs.

In conclusion, the Wancennes reef is most similar in geometry and size to the Aferdou al Makrib bioherm but differs from the latter by the large dominance of stromatoporoids as main builders (Table 1). These differences probably reflect differences in the transparency of water (due to sediment influx or depth). The Arnao bioherm is comparable to the Wancennes reef in term of faunal composition as both are dominated by stromatoporoids and tabulate corals with an important participation of rugose corals and chaetetid sponges, though taxonomic differences are observed. The latter is explained by the older age of the Arnao reef and by its development on inner shelf settings

6.2. Reef growth and eustacy

The initiation of the Wancennes bioherm was triggered by the deposition of an extensive crinoid carpet that runs not only in Wancennes but on several tens on kilometres along the southern limb of the Dinant Synclinorium. This unit – Sohier Beds – runs laterally both to the Wancennes and Couvin Formations below the shale of the Jemelle Formation (Fig. 2). Both in Wancennes and Couvin, the Sohier Beds are rather thick (10 m) and coarse-grained, with a dominance of the rudtsone-grainstone facies. Such accumulation might result from storm deposits as suggested in other Middle Devonian reefs (Krebs, 1971, 1974; James and Bourque, 1992; Eichholt and Becker, 2016; Low et al., ¨ 2022). Laterally, this unit tends to be thinner (5 m), finer-grained (floatstone, wackestone) and more argillaceous, and passes to nodular limestone in the Jemelle area. The thickening of the crinoid carpet below the reefs could be interpreted either as a cause – the presence of a thicker crinoid accumulation triggered the reef growth – or a consequence – where reefs grew, the carpet was preserved whereas in area without reef, the sediment was scattered and micritised. Since reef development is often associated to palaeotopographic highs (Copper, 1988; Gischler, 1995; Kiessling et al., 1999; Jakubowicz et al., 2019), the first hypothesis seems credible but the second one cannot be discarded. Nevertheless, the formation of the crinoid carpet was the first change in the background sedimentation – as known elsewhere – and triggered a localised shallowing which certainly was beneficial to the benthic association. The lithostratigraphical succession changes immediately east of the Wancennes reef and it is used by Denayer (2019) to place the boundary between the Viroin and Lesse Blocks and the possible presence of a synsedimentary fault. Although a palaeotopographic high might have contributed to the reef initiation, the structural evidence is not obvious.

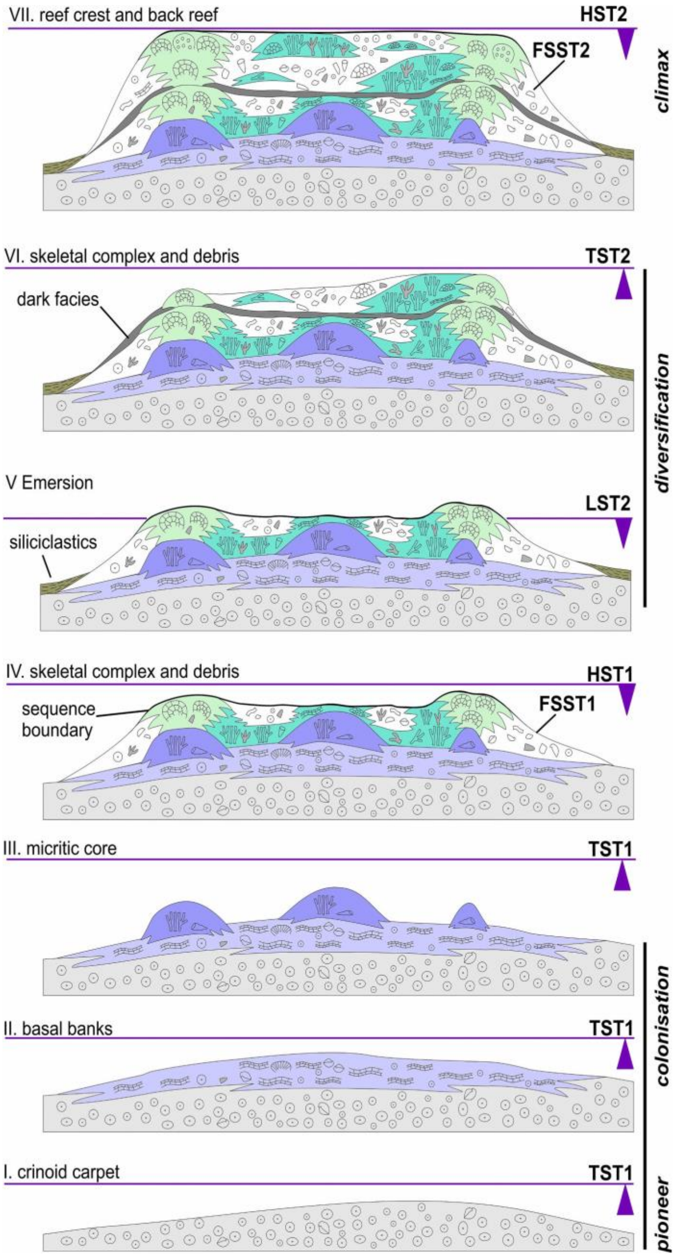


Fig. 12. Idealised growth of the Wancennes reef and its relationships with the sea level oscillations of third-order sequences MD1 and MD2 of Denayer (2019). Terms in italics refer to the ecological phases. Abbreviations: FSST: falling-stage systems tract, HST: highstand systems tract, LST: lowstand systems tract, TST: transgressive systems tract.

Table 1
Comparison of characteristics of the Wancennes reef with other Eifelian reefs of S Belgium and with other Eifelian bioherms (the list is not exhaustive and based on best described reefs).

Locality	Reef geometry	Age	Size	Thickness	Position	Dominant fabric	Dominant building organism	Micritic core	Cyclicity	Diveristy	Diversity of algae and calcimicrobes	reference
Wancennes	Bioherm	Early Eifelian	3.000 m	300 m	Isolated shelf	Framestone-bafflestone	Stromatoporoids, tabulate corals	*Thamnophyllum*-cystimorph bafflestone	Not detected	High	Very low	This paper
Couvin	Biostromes	Early Eifelian	10.000 m	80 m (individual biostromes +m)	Mid-outer shelf	Coverstone	Stromatoporoid	none	Strong	Medium	Low	Denayer, 2019
Roche Trouée	Bioherm	Early Eifelian	50 m	20 m	Outer-shelf	Bafflestone, framestone	Stromatoporoid, rugose corals	None	Not detected	High	Very low	Denayer, 2019
Tienne-Sainte-Anne	Bioherm	Late Eifelian	100 m	100 m	Isolated	Coverstone	Stromatoporoids	Tabulate coral bafflestone	Not detected	Medium	Medium	Denayer, 2019
Weinberg	Bioherm	Late Eifelian	400 m	35 m	Outer shelf	Micritic	Calcimicrobes, bryozoans	Stromatactoid wackestone	Not detected	Low	Medium	Pohler et al., 1999
Arnao	Bioherm	Late Emsian-early Eifelian	>100 m	100 m	Inner shelf	Framestone, coverstone	Stromatoporoids, tabulate corals	None	Not detected	High	Low	Méndez-Bedia, 1976
Aferdou al Makrib	Bioherm	Late Eifelian	1.000 m	200 m	Offshore	Bafflestone, coverstone	Tabulate corals	*Thamnophyllum*-cystimorph and stromatactis bafflestone	Not detected	High	Low	Jakubowicz et al., 2019
Tamworth	Bioherm	Eifelian	>100 m	+10 m	Outer shelf	Bafflestone, framestone	Stromatoporoids, rugose corals	none	Rhythmic alternations	High	Low	Pohler, 1998
LeRoy	Bioherm	Eifelian	100 m	10 m	Outers shelf	Bafflestone	Tabulate and rugose corals	*Cladopora*-bafflestone	Not detected	Very Low	Low	Wolosz, 1992a, 1992b
Nahanni	Barrier	Eifelian	10.000 m	300 m	Shelf margin	Framestone	Stromatoporoids, rugose corals	None	Not detected	Unknown	High	Noble and Ferguson, 1971

Once the benthic association settled on the crinoid carpet, the stromatoporoids quickly became the dominant building-organism and contributed to enhance the local topography. The change from stromatoporoid-dominated community to stromatoporoid-coral assemblage in the early stage of reef formation (upper part of the basal banks) has been observed in many Devonian reefs (Corlett and Jones, 2011; Königshof and Kershaw, 2006). They are not mutually excluding (e.g. 'Facies zone 1' in Salerno, 2008) and might simply represent a change in bathymetry during the transgressive phase of the third-order eustatic sequence MD1 (Denayer, 2019, Fig. 12).

Judging from the crinoidal facies and morphology of the stromatoporoids, it is plausible to interpret this first phase as taking place within the storm-wave activity zone (see 6.4.). As the early Eifelian transgression progressed, the bathymetry decreased slowly as the carbonate production was high enough to follow the increase in sea level. The maximum depth was probably reached at the time the micritic core formed as it witnesses more quiet depositional conditions. Hence, the micritic part – though not continuous laterally within the bioherm – correspond to the maximum flooding interval of the third-order sequence MD1 (Denayer, 2019). When the sea-level increase started to slow down, the carbonate production was sufficient to catch-up, and the bathymetry decreased consequently. Hence, the sedimentation above the micritic core is typical of a shallow-water hydrodynamic environment.

The distinct age of the carbonate facies (Couvin and Wancennes Formations) and the surrounding siliciclastic deposits (Vieux-Moulin Member of the Jemelle Formation, Fig. 2-3) is demonstrated by conodont and brachiopods (see Denayer, 2019). Hence, it means that while the limestone deposited, no or very little sediment deposited laterally and that the siliciclastics of the Vieux-Moulin Member came much later than the Wancennes reef. Conversely, the Vieux-Moulin Member siliciclastics deposited in the topographic lows when the reef was out of water at the sequence boundary and during the lowstand of the next sequence (MD2, Fig. 12). It suggests that the reef grew when the background sedimentation rate was very low, with very little to no siliciclastic influx. The second conclusion is that the exportation of the carbonate sediment produced on the reef was also very low around the reef and decreasing to zero away from it. In consequence, the reef should have created an important relief on the seafloor that may have reach >100 m – a part of the Vieux-Moulin siliciclastics were already deposited when the reef reached its full growth of 300 m.

The darker, more argillaceous facies observed in the middle part of the reef is interpreted as the transgressive systems tract overlying a first highstand systems tract represented by the first unit of the skeletal complex (Fig. 12). The outcropping conditions precludes the observation of a subaerial erosive surface that would have recorded the emersion of the reef at the end of the first sequence (MD1), but the presence of a sequence boundary is not rejected regarding the contrast of facies. The second unit of the skeletal complex above the darker facies represents the second sequence (MD2). It displays a shallowing-upward trends that culminates with the deposition of the crinoidal rudstone in back-reef facies and in the flanks (possibly as the falling-stage systems tract as it progrades, Fig. 12). The latter seemingly indicate the emersion of the reef at the end of its growth (Fig. 3). Or, to say it in the other way round: the emersion ended the reef development. Nevertheless, there are no traces of subaerial sedimentation such as pendulous cement or karstification, which might indicate that the emerged part of the reef was entirely removed by erosion.

6.3. Cyclicity

The absence of cyclic or rhythmical deposits in the Wancennes reef is no exception. The phenomenon has been highlighted in other Devonian reefs (Vopni and Lerbekmo, 1972; Eichholt and Becker, 2016; Jakubowicz et al., 2019). As explained above, while the Wancennes reef grew without trace of cyclicity in the sedimentation, the biostromes of the time-equivalent Couvin

Formation, built by stromatoporoids and tabulate corals are typically (auto-)parabiostromes organised in parasequences. Therefore, the absence of cyclicity in Wancennes cannot be explained by the absence of orbital or eustatic control. Salerno (2008) attributed the strong autocyclic pattern of the early Givetian stromatoporoid biostromes of the Eifel Hills to the limited accommodation space available on the platform. In fact, if the subsidence is low, the sediment rapidly fills the available space, producing shallowing-upward sequences. Short eustatic oscillations (probably 5th–6th order) added to the limitation of the accommodation enhanced the effect producing allocyclic parasequences (Brownlaw et al., 1996; Shen et al., 2008).

In Wancennes, the deposition of the reef sediment seems to be mostly organised by third-order transgressive trends enhancing the creation of accommodation space. The recurrence of high-energy events such as tsunamis or hurricanes that destroyed the reefal structure and distributed the sediments over large surfaces might also preclude an autocyclic deposition (Salerno, 2008). Cyclic deposition is possible during long periods of time only in transgressive trends.

6.4. Palaeobathymetry, light, turbidity and nutrient availability

As explained above, there is a clear shallowing-upwards trend throughout the reef succession, interpreted as the result of combined third-order eustatic sequences and accommodation. However, the faunal succession reflects two poles in terms of palaeobathymetry. The 'deep' part, corresponding to the assemblage observed in the micritic core, and the 'shallow' part corresponding to the assemblage observed in the reef crests.

The core facies and palaeoecological assemblage, dominated by the colonial *Thamnophyllum* and cystimorphic solitary rugose corals, where chaetetid sponges and stromatoporoid are almost lacking, suggest deeper facies, most probably below the fair-weather wave base. Nevertheless, the absence of foliose and platy tabulate corals with small corallites such as *Roseoporella* and *Platyaxum* that are typically met in mesophotic environments (Zapalski et al., 2017b; Zapalski and Berkowski, 2019) suggest a limited depth. In Recent tropical clear water, platy colonies of zooxanthellate scleractinian corals dominate the assemblage below 20–25 m whereas above that depth, branching and massive forms are dominant (Baker et al., 2016). If Devonian platy tabulate corals had an ecology similar, if not identical, then, the depth can be extrapolated from the Recent. The distribution of Recent zooxanthellate corals – and probably of Paleozoic corals – is not dictated by depth only but by the light availability (Acevedo et al., 1989; Hallock and Schlager, 1996). In clear water, the light availability decreases with increasing depth but where the water is turbid, the light decreases more rapidly. Hence the corals might show signs of light limitation (i.e. mesophotic communities) even in shallow settings as demonstrated by Zapalski et al. (2017b, 2021)

The base of the storm-influenced zone is assumed to be at c. 20 m- deep (Hubbard, 1992) to 35 m-deep (Scoffin, 1993), which is concordant with the occurrence of broken branches of rugose coral colonies in the micritic core. Though different species occur, the genus *Thamnophyllum* is frequently observed in pre-climax communities adapted to fine-grained sediment settings and soft-substrate in low-energy environments (Jakubowicz et al., 2019). It has been reported from such environment not only in Belgium and Morocco but also in the *Barrandei- kalk* of Austria (Hubmann, 1993) and in the Horní Beneˇsov reef of Czech Republic (Galle et al., 1995). Other phillipsastraeid corals with horseshoe dissepiments are frequent dwellers of these muddy environments (Sorauf, 2007; Jakubowicz et al., 2019), possibly because they acquired the ability to expel the fine-grained sediments from their body by creating an elevated ring around heir calice (Hubbard and Pocock, 1972).

According to Wood (1993), nutrient-rich water tends to produce bafflestones, either in upwelling zones (high probability of reef development according to Kiessling et al., 1999) or due to riverine discharged of nutrient-rich water (Salerno, 2008). The *Thamnophyllum* bafflestone in the micritic core and the *Fasciphyllum* bafflestone in the rest of the reef would therefore plead for eutrophic waters. Conversely, stromatoporoids seem to have preferred low nutrient supply as modern zooxanthelate scleractinian corals (McNeil and Jones, 2008; Kershaw et al., 2018), better adapted to oligothrophic waters than tabulate and rugose corals (Wood, 1998; Copper, 2002). However, corals and stromatoporoids belonged to different ecological feeding guilds (predator versus autotrophic and filtering) that might explain why the stromatoporoid overcome corals in such environment. A change of nutrient influx, combined with changes in bathymetry might be responsible for the switch from stromatoporoid-dominated assemblages of the basal banks to corals-stromatoporoids of the skeletal complex, then to the reef-crests.

In the skeletal complex and reef-crests, the presence of *Stachyodes* spp. and stromatoporoids with a massive or globular habitus indicate very shallow settings (Jakubowicz et al., 2019) and oligotrophic waters. The occurrence of massive *Heliolites porosus* testifies for shallow-water hydrodynamic settings as well (Pohler, 1998; Schroder, 1997¨). The dominance of stromatoporoids and poverty in other corals than heliolitids in the reef-crests indicate a low level of environmental stress with low detrital input and clear waters (Kershaw, 1998; Kershaw et al., 2018).

The abundance of coral and stromatoporoid debris in the skeletal reef-complex is not surprising considering the abovementioned bathymetric and hydrodynamic conditions. Very low grain maturity in the matrix (poor sorting, poor to moderate rounding, little micritisation) suggest a limited exposure time, limited transportation and rapid deposition of the material whereas large unbroken or non-fragmented elements suggest turbulent episodes interrupted by long low-energy periods. The almost complete absence of interrupted growth lines and the rarity of epibionts on the colonies in the skeletal framework and reef crest suggest also a sedimentation rate rather high (Krol et al., 2018´) but most probably not constant. Episodic influxes of sediment that buried the organisms could explained why so few epibionts colonised the corals and stromatoporoids (see Zaton et al., 2018, 2022´). Recurrent high hydrodynamic events are probably hurricanes as S Belgium was situated in the hurricane zone between 10° and 30° of latitude during the Eifelian (Copper and Scotese, 2003).

A very rough estimation of the amount of biodetrital elements – by estimating the proportion of blocks with corals colonies, stromatoporoids or chaetetid sponges and blocks with only matrix in the ploughed field – suggests that >70% of the reef volume is made of coarse-grained broken and reworked material. Though, no lagoon-like structure has been noticed in Wancennes, it is quite clear that most of the reef building-organisms were living on the periphery and the material filling most of the reef results from the mechanic fragmentation of this living fringe, as observed in the Recent atolls (e.g. Repellin and Trichet, 1977; Braithwaite et al., 2000 and references therein). Their rapid accumulation and cementation therefore created cluster reefs or segmented reefs sensus Riding (2002).

6.5. Absence of algae and calcimicrobes

Contrary to the Lower and Upper Devonian reefs, calcareous algae and calcimicrobes are uncommon components of Middle Devonian reefs (Riding, 1979; Hladil, 1995; Shen et al., 2008; Antoshkina and Konigshof, 2008¨ ; Jakubowicz et al., 2019; May, 2022). The cause of this gradual involvement through the Devonian has been frequently questioned (May, 1992; Shen et al., 2008; Edinger et al., 2002; Jakubowicz et al., 2019). Changes in the global oceanic nutrient regime during the Givetian is often given as a cause to the diversification of algae and calcimicrobes and their role in reefal development. It is not entirely satisfactory. In the Wancennes reef, there is very few calcimicrobes (rare *Rothplezella* and *Spaherocodium* sheets around coralla or clasts, Fig. 6B) and a single occurrence of putative udoteacean. In the time-equivalent Couvin Formation that recorded biostromes formed on a platform, algae are more common and more diverse (Mamet and Preat, 1994´) as it is in the Eifelian of Sauerland (May, 1992) and in New South Wales (Mamet and Pohler, 2002). This distribution is tentatively explained by a sedimentary bias as the hydrodynamic conditions reigning on the reef were probably higher than on the platform. The delicate skeleton of the algae might simply have been worn out in Wancennes but better preserved in Couvin.

6.6. Effects of the Chotec event

The Chote ˇc event (Chlupa ´ ˇc and Kukal, 1986) is commonly associated with the development of anoxic sediments in bathyal sections and produced a moderate extinction in the pelagic realm. In the Couvin area, the event is recorded in the Petigny Member of the Couvin Formation (Fig. 2) that is characterised by dysaerobic fine-grained dark and non- bioturbated limestone (Denayer, 2019). Avlar and May (1997), Ernst et al. (2012) and Denayer (2019) suggested that the transgression triggered the invasion of basinal anoxic water on the platform, creating short-living dysaerobic conditions, particularly during the maximum flooding interval when the bathymetry reached its maximum. In the Wancennes reef, this interval is recorded in the micritic core. The fauna in this facies is de facto different from what is known before and after but there is no clue for dysoxia and the fauna might simply reflect the change of facies (from stromatoporoid coverstone to bioclastic wackestone), or a limited increase in bathymetry. Hence, the faunal association before and after this event is identical, precluding the recognition of any extinction, as those commonly observed in the neritic settings (May, 1995, 1997). The rugose corals of the early Eifelian are mostly ecological generalists and ubiquists, being the pioneer taxa colonising the Western Europe carbonate shelves after a siliciclastic-dominated Early Devonian. Such faunas are known to better cope with stressful environments and therefore, have higher chance to survive short-living crisis. In carbonate- dominated Middle Devonian shelves where coral faunas were more specialised, the Chote ˇc event brought significant changes (Pedder, 2010).

7. Conclusions

The Wancennes reef is certainly one of the largest build-ups of the early Eifelian of Western Europe, making it a giant, even compared to Givetian or Frasnian reefs. Its development is parallelised with third- order eustatic fluctuations and by the ecological succession of building-organisms (Fig. 12). Like most Devonian shallow-water reefs, it started to grow when a crinoid carpet accumulated on the sea-floor, providing a hard substrate and a relief profitable for the encrusting organisms such as stromatoporoids. The latter stabilised the crinoid rudstone and built the basal banks of the reef. On top of these banks, when the transgression induced a maximum bathymetry, the stromatoporoid coverstone was replaced by a micritic core baffled by fasciculate corals. When the sedimentation caught-up, stromatoporoids, corals and chaetetid sponges built framestone and bafflestone in a high hydrodynamic environment. After emersion of the reef-flat, the development of deeper water facies started over and quickly gave rise to the reef-crests and back-reef environments with a large variety of habitats and associated sediments where a very diverse fauna settled. The termination of the reef is a consequence of its emersion during a regressive phase, followed by the deposition of fine-grained siliciclastics that hampered the development of reef-building organisms.

Despite a general growth pattern very typical of Devonian reefs, the Wancennes reef displays its own characteristics, notably the apparent lack of mesotrophic communities suggesting a (very) shallow-water environment; the scarcity of microbial structures and green algae suggesting very high-energy conditions; the relative development of flank facies; and its final emersion. The absence of cyclic deposits also suggests a high energy and a constant accommodation space precluding small- scale changes in bathymetry. Both causes also explain the abundance of broken and reworked material in the reef.

To conclude, there is still an aspect that needs to be addressed in a forthcoming paper: the palaeobiogographic signal that bears the coral fauna, notably the surprising presence of the rugose coral *Taimyrophyllum* sp., *Australophyllum* sp. and cf. *Carlinastraea* sp. The first two have never been reported outside Central Asia and Pacific province of Australia and N America whereas the third one is unknown after the Pragian. There is no doubt that their presence, together with the high coral diversity and disparity are related to the reefal facies that are uncommon in the lower Eifelian of Western Europe. The modalities of this unusual palaeobiogeographic singleton has yet to be explained.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

No data was used for the research described in the article.

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