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From palaeosols to carbonate mounds: facies and environments of the middle Frasnian platform in Belgium

Anne-Christine DA SILVA and Frédéric BOULVAIN

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This paper provides a synthetic sedimentological overview of the middle Frasnian carbonate platform of Belgium and associated carbonate mounds. Carbonate mounds started usually in a relatively deep, quiet subphotic environment with a crinoid-coral-sponge assemblage, then reached the fair-weather wave base and the euphotic zone with an algal-microbial facies. The upper parts of the mounds are characterised by lateral facies differentiation with the algal-microbial facies protecting a central sedimentation area with a dendroid stromatoporoids facies and fenestral limestone. The lateral facies reflect different kinds of input of reworked mound material in the proximal area, from transported fine-grained sediment to coarse-grained fossil debris. On the platform, environments range from the outer zone (crinoidal facies) to stromatoporoid-dominated biostromes and to the lagoonal area of the inner zones (subtidal facies with *Amphipora* floatstone, algal packstone, intertidal mudstone and laminated peloidal packstone and palaeosols). These facies are stacked in metre-scale shallowing-upward cycles. The larger scale sequential organisation corresponds to transgressions and regressions, whose cycles are responsible for differentiating a lower open-marine biostrome dominated unit from an upper lagoonal unit. The last regression-transgression cycle, responsible for the platform-scale development of lagoonal facies, can be correlated with an atoll-stage evolution of the carbonate mounds belonging to the Lion Member.

Anne-Christine da Silva and Frédéric Boulvain, U. R. Pétrologie sédimentaire, B20, Université de Liège, Sart Tilman, B-4000 Liège, Belgium; e-mail: fboulvain@ulg.ac.be, acdasilva@ulg.ac.be *(received: December 16, 2003; accepted: March 11, 2004).*

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INTRODUCTION

During the mid-part of the Frasnian (from the *punctata* to the *jamieae* conodont zones; Gouwy and Bultynck, 2000), a ~5000 km^2 carbonate platform developed in Belgium, showing environments ranging from restricted shallow-water lagoons and supratidal areas to a relatively deep outboard ramp with carbonate mounds (Figs. 1 and 2). This carbonate platform is especially instructive because of a combination of extraordinary exposures ("marble" quarries with large sawn sections) and a long history of palaeontological study which has led to a refined stratigraphic framework (Boulvain *et al*., 1999; Gouwy and Bultynck, 2000). Carbonate mounds have been the subject of intense investigation carried out by several generations of geologists (Tsien, 1975; Boulvain, 2001) but relatively few of these studies focused on the shallow-water part of the platform (Dumoulin *et al*., 1999; Préat *et al*., 1999; da Silva and Boulvain, 2002, 2003). This paper provides the first synthetic sedimentological overview of the Belgian middle Frasnian carbonate platform and the associated carbonate mounds.

GEOLOGICAL SETTING

Southern Belgium belongs to the northern part of the Rhenohercynian fold and thrust belt. Frasnian carbonates and shales are exposed along the borders of the Dinant, Verviers and Namur Synclinoria and in the Philippeville Anticlinorium (Fig. 1). The platform can be divided into three main depositional areas characterised by different facies associations, carbonate production rates and styles of sedimentary evolution (Figs. 2 and 3).

The most distal part of the platform ("southern belt"), located along the southern border of the Dinant Synclinorium, is characterised by carbonate mound sedimentation with associated flank and off-mound facies. Two separate levels of carbonate mounds are recognised in the middle part of the Frasnian, the lower Arche (Fig. 4B) and the succeeding Lion members (Figs. 2, 3 and 4A). In the Philippeville Anticlinorium ("intermediate belt"), the carbonate mound-bearing levels are replaced by bedded limestone, consisting of open-marine facies and biostromes. Along the northern border of the Dinant Synclinorium ("north-

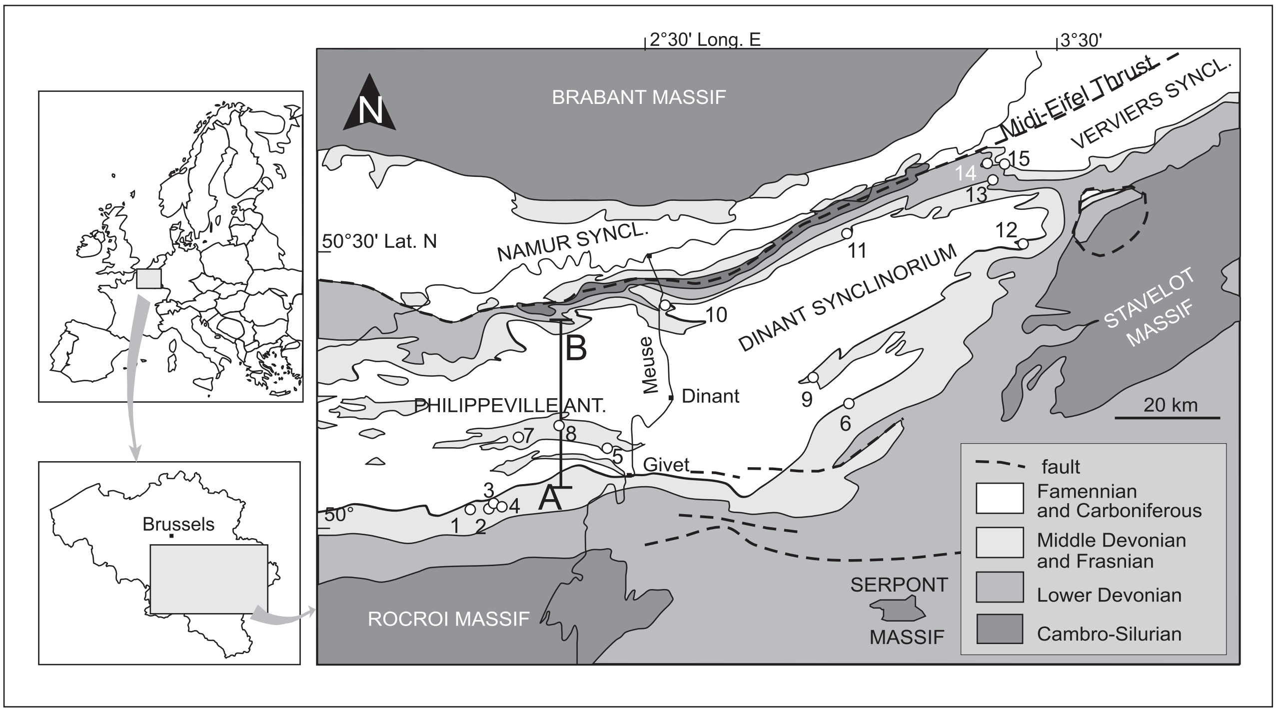

Fig. 1. Geological map of Belgium with location of the studied sections

A–B — line of cross-section; explanations of section numbers are in Table 1

ern belt"), the middle Frasnian consists of bedded limestones, exhibiting a distinct proximal aspect with biostromes alternating with lagoonal facies.

FACIES AND MICROFACIES

Data comes from the detailed study of more than 3000 thin sections from 15 outcrops from the Dinant and the Verviers Synclinoria and the Philippeville Anticlinorium (Fig. 1 and Table 1). The textural classification used to characterise the microfacies follows Dunham (1962) and Embry and Klovan (1972). The term "coverstone" was suggested by Tsien (1984) to characterise microfacies where laminar organisms cover mud and debris. The classification of stromatoporoid morphology follows that employed by Kershaw (1998). In the following description, microfacies are ordered from the most distal to the most proximal according to textural criteria and comparisons with classical sedimentological models (e.g. Wilson, 1975; Hardie, 1977; Flügel, 1982; James, 1983) and with other

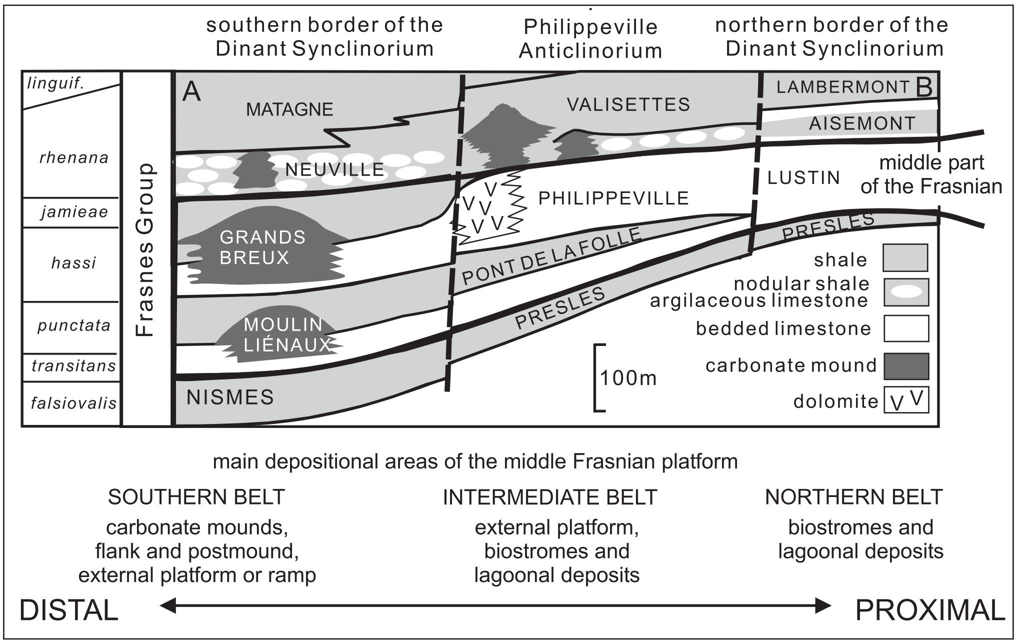

Fig. 2. N–S cross-section through the Belgian Frasnian sedimentary basin prior to Variscan tectonism (corresponds to the line A–B on Figure 1)

Names of formations are capitalised

Devonian platforms specifically (May, 1992; Machel and Hunter, 1994; Méndez-Bedia *et al*., 1994; Pohler, 1998; Wood, 2000; Chen *et al*., 2001). However, this order is not always effective, due to lateral variations, especially in the more proximal parts of the platform. Table 2 compiles sedimentological and bathymetric interpretations for the various microfacies (after Embry and Klovan, 1972; Wilson, 1975; Flügel, 1982).

CARBONATE MOUNDS (M)

The Arche and Lion members are relatively large buildups, 150–200 m thick and 600–1000 m in diameter (Fig. 4A). Seven bioconstructed facies, each one characterised by a specific range of textures and organism associations, are recognised. The components are essentially autochthonous and directly reflect the influence of oceanographic controls such as water agitation and light intensity. Three other facies, corresponding to the lateral time-equivalent sediments, are also defined. Unlike bioconstructed facies, lateral facies include a large amount of transported material originating in the nearby mounds, and their biotic assemblages do not directly reflect the depositional environment.

The analogy between closely related facies in stratigraphically distinct buildups was highlighted by Boulvain *et al*. (2001) who employed the same facies designation, i.e. a number following a specific letter for the member name (for example: A2 and L2, corresponding to nearly equivalent facies in the Arche and Lion members). In this more synthetic paper, the facies numbers are simply preceded by "M" for "mound". The facies description sequence used below depicts a shallowing trend.

Table 1

Location and distribution of the studied sections

No.	Sections	Formations/members	Location	Thickness [m]
		Southern belt		
1	Lompret	Bieumont	SBDS	60
2	Arche	Arche	SBDS	60
3	Nord	Lion	SBDS	130
4	Lion	Lion	SBDS	150
5	Moulin Bayot	Arche–Lion	PA	>130
6	La Boverie	Arche–l'Ermitage–Lion–Boussu–Neuville	SBDS	250
		Intermediate belt		
7	Neuville	Philippeville	PA	70
8	Villers-le-Gambon	Philippeville	PA	105
9	Netinne	Philippeville	SBDS	50
		Northern belt		
10	Tailfer	Lustin	NBDS	105
11	Barse	Lustin	NBDS	46
12	Aywaille	Lustin	EBDS	120
13	Tilff	Lustin	EBDS	90
14	Colonster	Lustin	VS	33
15	Prayon	Lustin	VS	20

No.— number of the section corresponding to the exposure located on Figure 1; PA — Philippeville Anticline; SBDS, NBDS and EBDS — southern, northern and eastern border of the Dinant Synclinorium; VS — Verviers Synclinorium; for location see Figure 1

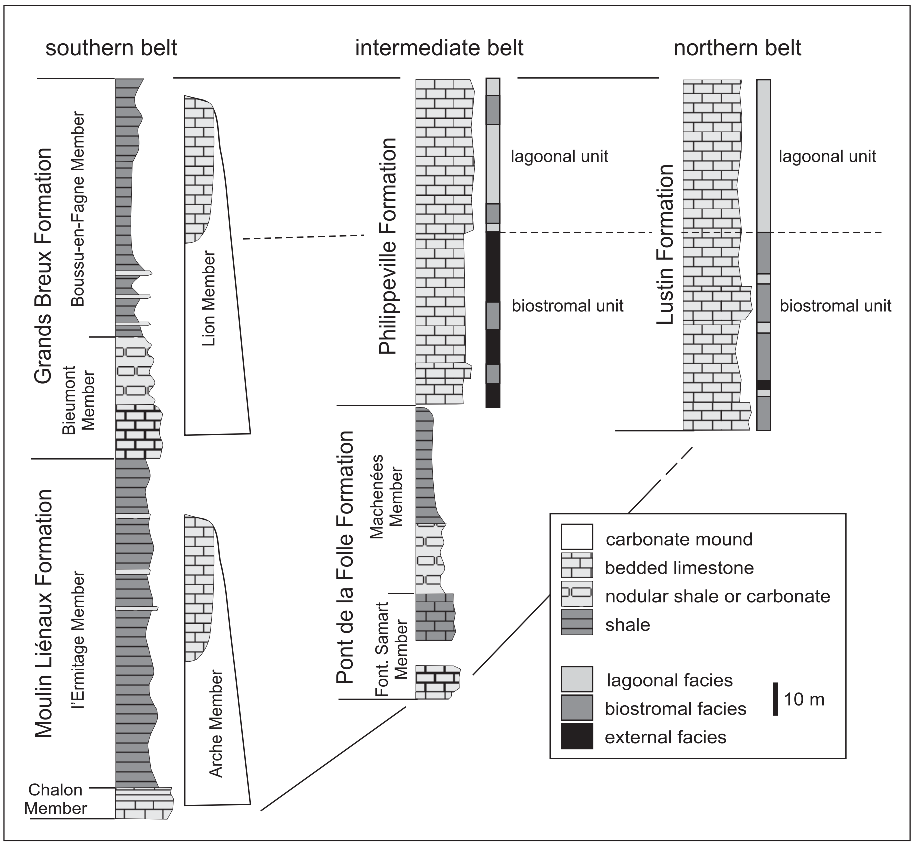

Fig. 3. Correlation of synthetic sections across the middle Frasnian carbonate platform in Belgium, with lithostratigraphic units and facies types

RED LIMESTONE WITH STROMATACTIS AND SPONGE SPICULES (M1)

Large stromatactis (dm-m scale) are abundant in this facies. They are interpreted as cavities resulting from sponge collapse (Bourque and Boulvain, 1993). Red pigment originates from microaerophilic iron bacteria (Boulvain *et al*., 2001). This sponge-iron bacteria consortium developed in very quiet suboxic and aphotic waters (Boulvain, 2001)

RED, GREY OR PINKISH LIMESTONE WITH STROMATACTIS, CORALS AND CRINOIDS (M2)

This facies is characterised by the occurrence of decimetre-sized stromatactis together with platy tabulate corals and crinoids (Fig. 4D). Supported cavities filled with radiaxial cement typically occur below laminar organisms. Smaller fenestrae are filled with an equant cement. Two kinds of matrix are distinguished: a first, darker, locally cohesive "primary mud" and a second, lighter, more neomorphosed internal sediment.

The M2 facies, characterised by a poorly diversified fauna (corals and

Table 2

Description of facies from middle Frasnian platform and carbonate mounds

Facies	Color / texture / structure	Autochthonous and allochthonous biota	Preservation transport	Energy	Interpretation	Bathy-metry [m]
1	2	3	4	5	6	7
Carbonate mound facies (M)						
M2. Stromatactis, corals and crinoids	red or pinkish mudstone, floatstone	sponges, corals, crinoids and iron bacteria	preservation ↑ transport ↓	very low	aphotic, below SWAZ	80–100
M3. Stromatactis, corals and stromatoporoids	grey, pinkish or greenish, floatstone, (rudstone)	corals, crinoids, brachiopods, bryozoan and stromatoporoids	preservation ↑ transport ↓	low, episodically moderate	subphotic, close to SWAZ	60–80
M4. Corals, peloids and dasycladales	grey grainstone, rudstone	corals, stromatoporoids, dasycladales, cyanobacteria	preservation ~ transport ~	moderate	euphotic, close to FWWAZ	30–60
M5. Microbial limestone	grey, bindstone bafflestone	corals, cyanobacteria and stromatoporoids	preservation ↓ transport ~	moderate	euphotic, close to FWWAZ	30–60
M6. Dendroid stromatoporoids	grey, rudstone, m-thick beds	dendroid stromatoporoids and cyanobacteria	preservation ↑ transport ↓	high	in the FWWAZ	0–30
M7. Loferites	grey, laminar, grainstone-wackestone	dendroid stromatoporoids and palaeosiphonocladales	preservation ~ transport ↓	low	intertidal	0
M8. Bioturbated limestone	grey, dm-thick, wackestone-mudstone	palaeosiphonocladales and calcispheres	preservation ↑ transport ↓	low	subtidal	5–10
Lateral facies (M)						
M9. Microbioclastic packstone	dark grey, dm-thick, bedded packstone	corals, brachiopods, ostracods bryozoans	preservation ↓ transport ↑	low	below SWAZ	80–100
M10. Bioclastic packstone, grainstone	dark grey, dm-thick, bedded packstone-grainstone	corals, brachiopods, ostracods bryozoans and stromatoporoids	preservation ↓ transport ↑	low, episodically moderate	close to SWAZ	60–80
M11. Peloids and intraclastic packstone and grainstone	dark grey, dm-thick, bedded packstone-grainstone	stromatoporoids, corals, brachiopods and bryozoans,	preservation ↓ transport ↑	low, episodically moderate	close to SWAZ	60–80
External platform or ramp facies (E)						
E1. Crinoidal packstone and wackestone	dark grey dm beds, packstone to wackestone	crinoids, ostracods	preservation↓ transport↑	low	under SWAZ, external deposits	~35
E2. Intraclastic grainstone	dark dm beds	clasts, crinoids, ostracods	preservation↓ transport↑	low , episodically moderate	under SWAZ, slope deposits	20–30
Biostromal facies (B)						
B1. Laminar stromatoporoids	light grey, plurim. beds, coverstone to rudstone	laminar stromatoporoids, ostracods and brachiopods	preservation↑ transport↓	episodical	under or in SWAZ, biostromes	10–20
B2. Low domical stromatoporoids	grey, metre to plurim. beds, rudstone	low domical stromatoporoids, crinoids	preservation↓ transport↕	high	in SWAZ, biostromes	5–10
B3. Dendroid stromatoporoids	light grey, pluridm.to plurim. beds, floatstone to bindstone	dendroid stromatoporoids, ostracods, clotted matrix	preservation↑ transport↑	mainly low, episodical agitation	SWAZ	±15

1	2	3	4	5	6	7
Internal platform facies (I)						
I1. *Amphipora*, palaeosiphono-cladales and peloids	light grey, metric beds floatstone to wackestone	*Amphipora*, palaeosiphono-cladales and peloids	preservation ↑ transport ↓	low	subtidal, restricted	1–15
I2. *Umbella* wackstone	grey, metric beds, heterogeneous, subnodular	*Umbella*, clasts, crinoids,	preservation ~ transport ↓↑	moderate	subtidal to intertidal, channels	3–10
I3. Mudstone	decimetric to metric dark grey beds	ostracods, palaeosiphonocladales	preservation ↑ transport ↓	low	intertidal, local emersion features	0–5
I4. Laminated limestone	dark dm beds, with undulated lamination	mainly peloids	preservation ↑ transport ↓	low to moderate	intertidal, local emersion features	0–2
I5. Brecciated limestones, palaeosols	pluridm beds, light grey, with pink staining	palaeosiphonocladales	preservation ↑ transport ↓	low	supratidal, emerged	>0

SWAZ — storm wave action zone; FWWAZ — fair-weather wave action zone; arrows — high when pointing upwards and low when pointing downwards; ~ — "moderate"

crinoids), without algae or evidence for wave action, is interpreted as having developed in a low-energy, slightly suboxic environment below the photic zone.

GREY, PINKISH OR GREENISH LIMESTONE WITH STROMATACTIS, CORALS AND STROMATOPOROIDS (M3)

These wackestones and floatstones show decimetre-long stromatactis and centimetre-long stromatactoid fenestrae with abundant branching tabulate corals, brachiopods and crinoids (Fig. 4C). Bulbous or laminar (rarely dendroid) stromatoporoids, bryozoans, peloids, and fasciculate rugose corals are locally present. Some subordinate cricoconarids, palaeosiphonocladalean algae and calcispheres are present. Coatings (by *Sphaerocodium*) are poorly developed. Many fenestrae correspond to growth or shelter cavities (Fig. 4F). Through episodic reworking and concentration of bioclasts by storm action, this facies grades into bioclastic rudstones.

The M3 facies developed close to the storm wave base in a subphotic environment.

GREY LIMESTONE WITH CORALS, PELOIDS AND DASYCLADALES (M4)

This facies marks the first occurrence of green algae together with the development of very thick and symmetrical coatings. It is characterised by rudstones, grainstones and floatstones with peloids, intraclasts, branching tabulate corals coated by *Sphaerocodium*, brachiopods, some crinoids, dendroid stromatoporoids, radiospheres and calcispheres. Occasional Udotaeaceae are observed. Stromatactoid fenestrae or stromatactis are present.

Facies M4, characterised by the first occurrence of common green algae and cyanobacterial coatings, developed close to the fair-weather wave base in a photic environment.

GREY MICROBIAL LIMESTONE (M5)

These thrombolitic and stromatolitic bindstones and bafflestones include *Renalcis*, stromatoporoids, tabulate corals, some Udotaeaceae, brachiopods, bryozoans and rugose corals (Fig. 4G). Thick coatings of *Sphaerocodium* alternate with encrusting microbial mats. Thrombolites and stromatolites are characterised by a clotted micro-structure made up of irregular peloids in a yellowish pseudosparitic cement ("structure grumeleuse" of Cayeux, 1935).

This bioconstructed M5 facies is often closely associated with M3 or M4, in the form of metric lenses in bioclastic sediment. This microbial facies also developed in some large synsedimentary fractures, as parietal encrustations, interlayered with fibrous cement.

GREY LIMESTONE WITH DENDROID STROMATOPOROIDS (M6)

These rudstones, floatstones or grainstones are especially rich in peloids, intraclasts and dendroid stromatoporoids (*Amphipora*, *Stachyodes*), thickly and more or less isopachously coated by *Sphaerocodium* or microbial mats (Fig. 4H). Calcispheres, palaeosiphonocladales and Udotaeaceae are present, locally along with branching tabulate corals, gastropods and crinoids. In some matrix-rich zones, irregular fenestrae were observed.

The M6 facies is characterised by its intraclastic character, the abundance of dendroid stromatoporoids and the dominant grainstone texture. It corresponds to an environment located above the fair-weather wave base. This *Amphipora*-rich facies is also observed in debris flows deposited on the flanks of carbonate mounds, especially in the fore-mound location.

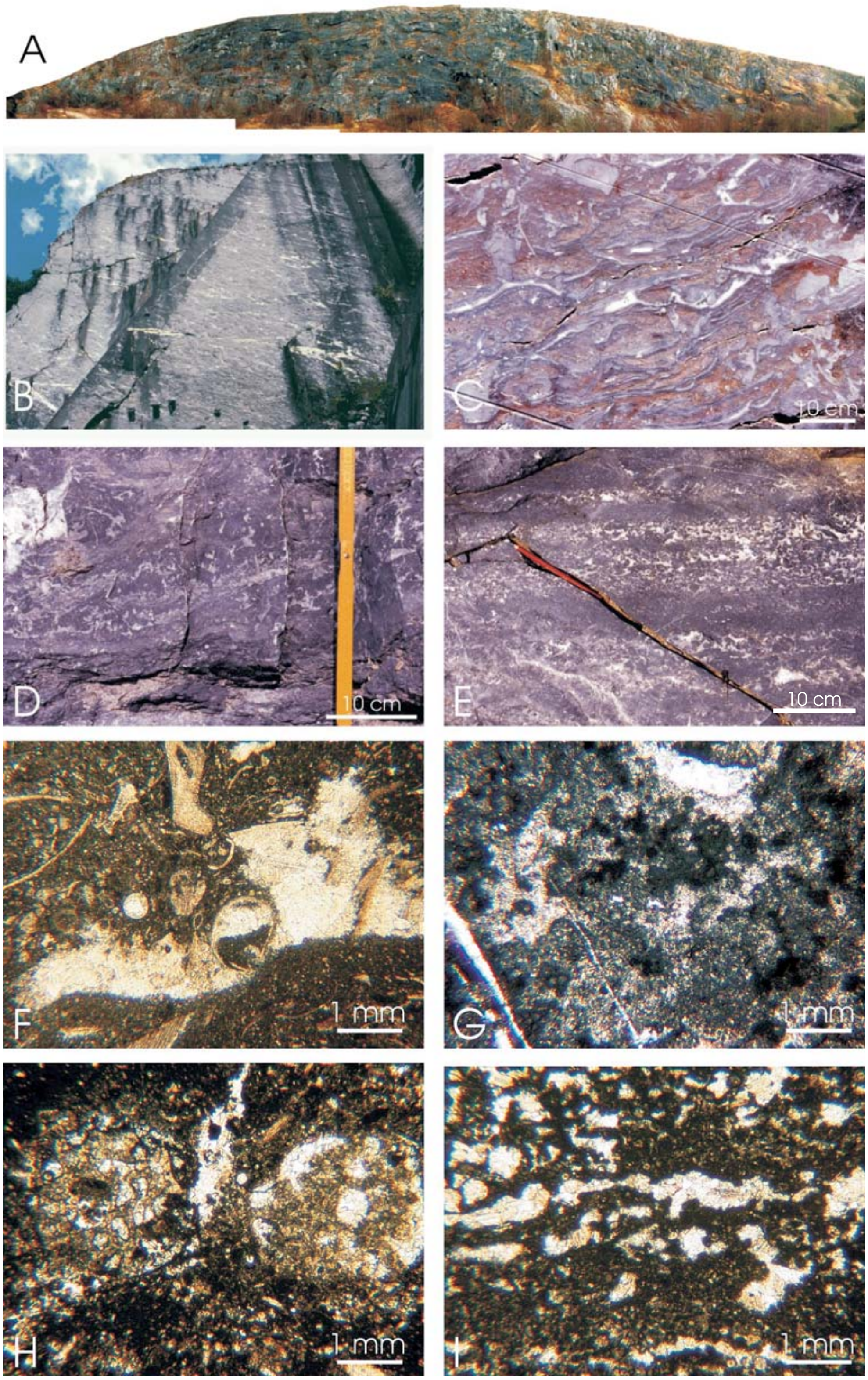

Fig. 4. **A** — photo mosaic giving a complete NE–SW panorama of the Lion mound (Lion quarry, Frasnes), the highest point of the quarry is nearly 40 m high; **B** — middle part of the Arche carbonate mound (Arche quarry, Frasnes), showing grey algal and microbial bindstones and bafflestones (facies M4–M5), the stratification is nearly horizontal and the height of the quarry wall reaches 20 m; **C** — lower part of the Arche carbonate mound (Arche quarry, Frasnes), characterised by red coverstones with stromatactis and shelter cavities, zebra, tabulate corals, crinoids, brachiopods and stromatoporoids (facies M3); **D** — grey limestone with stromatactis, corals and crinoids (facies M2) from the Nord quarry (Lion Member, Frasnes); **E** — intraclastic limestone with birdseyes and fenestrae or loferites (facies M7), La Boverie quarry, Jemelle, Lion Member; **F** — wackestone with stromatactoid fenestra, crinoids and brachiopods (facies M3); thin section B209, normal light, La Boverie quarry, Jemelle, Arche Member; **G** — bafflestone with thrombolites and *Renalcis* (facies M5); thin section H31, normal light; Humain section, Lion Member; **H** — floatstone with dendroid stromatoporoids (facies M6), thin section B407b, normal light, La Boverie quarry, Jemelle, Lion Member; **I** — intraclastic packstone with birdseyes or loferites (facies M7) thin section B46, normal light, La Boverie quarry, Jemelle, Lion Member

GREY LAMINATED FENESTRAL LIMESTONE (LOFERITES, FISCHER, 1964) (M7)

These grainstones and wackestones with peloids, intraclasts, calcispheres and palaeosiphonocladales show abundant millimetre-long fenestrae (birdseyes) scattered within the deposit or imparting the stratification (Fig. 4E and 4I). Locally, some dendroid stromatoporoids, often strongly coated, are present.

In the upper central parts of the mounds, facies M6 shows a progressive transition to loferites rich in peloids, calcispheres and palaeosiphonocladales (M7). This very shallow facies developed in a quiet intertidal area.

BIOTURBATED GREY LIMESTONE (M8)

These wackestones and mudstones with palaeosiphonocladales, calcispheres and peloids are commonly bioturbated (open vertical burrows filled by pseudosparitic to sparitic cement). Branching tabulate corals and dendroid stromatoporoids, ostracodes and gastropods are also present.

The M8 facies is very fine-grained and was deposited in a quiet lagoonal subtidal environment.

Laterally to the buildup facies, thin-bedded bioclastic and intraclastic facies were observed, most elements of which underwent a certain transport. Frequent sorting and rounding of their elements characterise these facies. They are ordered below according to their content and grain-size.

MICROBIOCLASTIC PACKSTONES (M9)

These thin-bedded, dark, often argillaceous, fine-grained (<100 μm) bioclastic packstones include some recognisable brachiopods, crinoids, fragments of rugose and tabulate corals, fenestellid bryozoans, ostracodes, trilobites, peloids and cricoconarids. Locally, some laminar stromatoporoids and palaeosiphonocladales are present. Bioturbation is often intense. Recrystallisation of micrite to microspar is typically more developed than in other facies and seems to be related to the higher clay content.

BIOCLASTIC PACKSTONES, GRAINSTONES AND RUDSTONES (M10)

These dark centimetre- to decimetre-thick beds of rudstones, packstones and grainstones form isolated lenses within the preceding facies or within shales. The bioclasts are the same as in the microbioclastic facies M9, but coarser-grained (typically 300 μm in size). Some intraclasts, radiospheres and calcispheres are present. Hummocky cross-stratification was locally observed.

PACKSTONES, GRAINSTONES AND RUDSTONES WITH PELOIDS AND INTRACLASTS (M11)

This facies differs from the previous one by the dominance of peloids and intraclasts with subordinate crinoids, fragments of corals and stromatoporoids, brachiopods and bryozoans. This facies is usually well-sorted, with grain size varying from 50–300 μm.

This bedded bioclastic-intraclastic facies results from the input of eroded material exported directly from the buildups or from the reworking and sorting of already-deposited material by storm waves (Humblet and Boulvain, 2001). Microbioclastic packstones (M9) are characterised by an open-marine facies with brachiopods, bryozoans and crinoids, whereas bioclastic rudstones (M10) and intraclastic packstones or grainstones (M11) show a clear carbonate mound influence as most of the bioclastic and intraclastic material is derived from these buildups.

EXTERNAL PLATFORM OR RAMP (E)

This area is characterised by dark limestone or argillaceous limestone in decimetre-thick beds.

CRINOIDAL PACKSTONES AND WACKSTONES (E1)

Packstone to wackstone including small (0.2 mm) bioclasts, mainly of crinoids and ostracods, with some sponge spicules, brachiopods, reefal debris, trilobites, bryozoans, peloids and calcareous algae (Fig. 5A). Sorting is good and fossils are not well preserved (broken bioclasts and crinoids affected by "pitting").

The fine-grained matrix suggests a quiet depositional environment and the dominant biotic elements, such as crinoids, sponge spicules, trilobites and bryozoans, point to open-marine environments. The sporadic presence of palaeosiphonocladales is probably related to inputs from the inner platform. This facies is formed under the fair-weather action zone, with some bioclastic material transported from the biostromes or the lagoonal area.

INTRACLASTIC GRAINSTONE (E2)

Grainstone to packstone mainly formed by accumulation of micritic intraclasts (0.2–0.5mm), crinoids and ostracods, with some sponge spicules, brachiopods, gastropods, reefal debris, trilobites, bryozoan, peloids and algae (Fig. 5B). The clasts are sub-rounded and moderately well sorted. Preservation is low and some grains are coated.

The coarse nature of the clasts and the grainstone texture are related to a slightly agitated environment. Abundance and mixing of reworked material from different sources suggest flank setting or channels originating from the biostrome or the lagoon. This facies is very similar to packstones, grainstones and rudstones with peloids and intraclasts from the adjacent mudmound facies (M11).

BIOSTROMES (B)

The facies described here are considered to be biostromes because of the abundance, grain size, growth form and organisation of stromatoporoids. Their compositions are similar or identical to that found in bioherms or reefs, but arranged in layers or strata that do not attain a significant vertical relief above the sea floor.

LAMINAR STROMATOPOROIDS COVERSTONE (B1)

Coverstone, floatstone and rudstone with mostly laminar or tabular stromatoporoids, exceptionally "low domical" or anastomosing, usually with some branching, and massive tabulate corals (*Alveolites*), and fasciculate (*Disphyllum*), massive (*Hexagonaria*) or solitary rugose corals (Fig. 5C). Other common organisms are brachiopods and ostracods, which are accompanied by crinoids, dendroid stromatoporoids and branching tabulate corals, palaeosiphonocladales, calcispheres and sponge spicules. The matrix is generally light grey and rich in small bioclasts (0.01mm) or shows a clotted, even locally peloidal aspect.

The environment was low-energy, considering the muddy fraction, preservation of clotted matrix, low amount of bioclasts, preservation of laminar stromatoporoids in life position and presence of articulated shells of brachiopods and ostracods. The clotted nature of the matrix is probably related to a microbial origin, as is also suggested by the laminated and

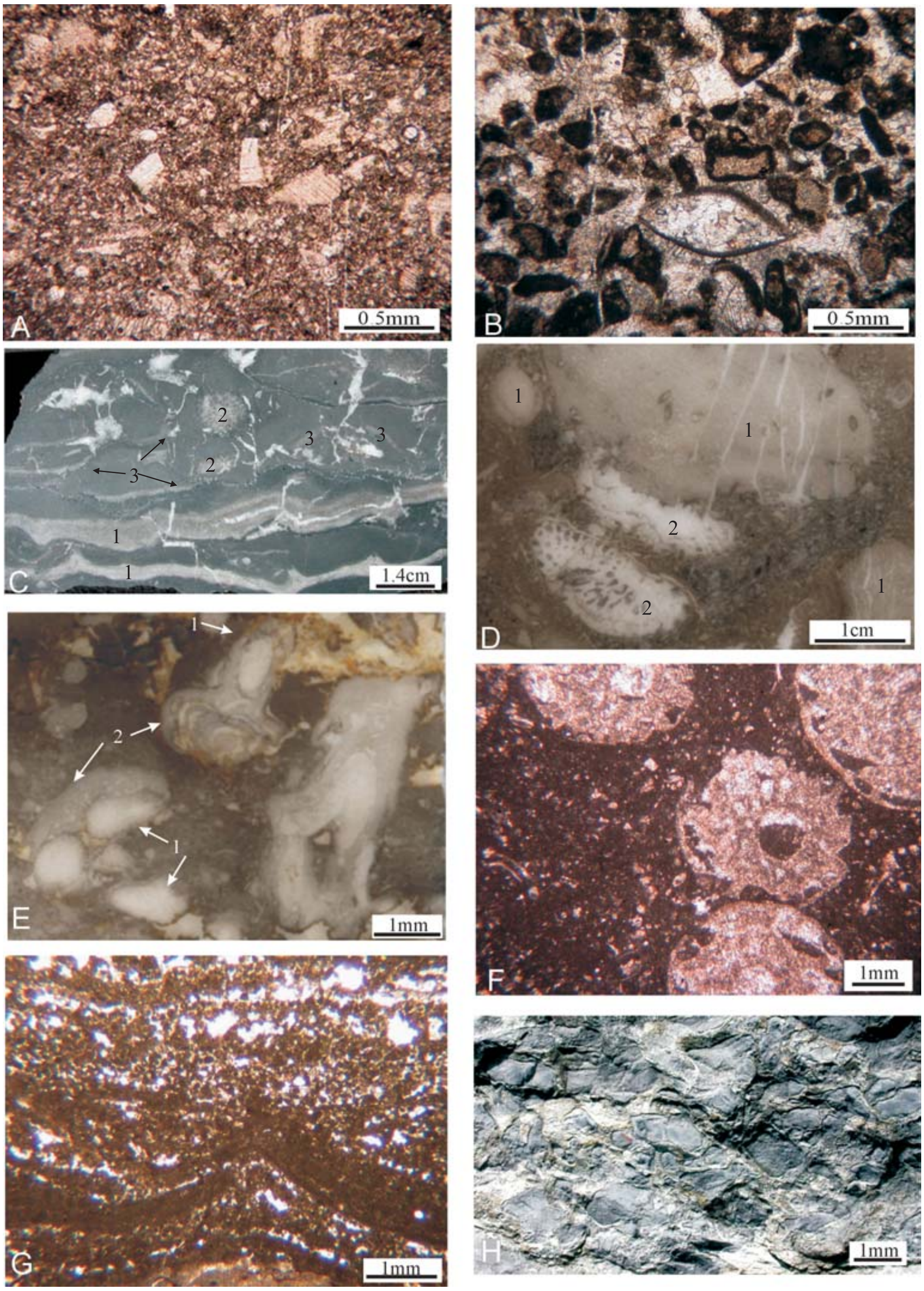

Fig. 5. **A** — microbioclastic crinoidal packstone (facies E1) thin section V30, normal light, Villers-le-Gambon section, Philippeville Formation; **B** — intraclastic and bioclastic grainstone (facies E2), thin section V48, normal light, Villers-le-Gambon section, Philippeville Formation; **C** — laminar stromatoporoids coverstone (facies B1): 1 — laminar stromatoporoids, 2 — tabulate corals and 3 — broken laminar stromatoporoids, scanning of sawn sample L53b, Tailfer section, Lustin Formation; **D** — low domical stromatoporoids rudstone (facies B2): 1 — broken low domical stromatoporoids and 2 — branching tabulate corals, thin section L24, Villers-le-Gambon section, Philippeville Formation; **E** — dendroid stromatoporoids floatstone (facies B3): 1 — dendroid stromatoporoids (*Stachyodes*) and 2 — encrusting stromatoporoids, scanning of thin section L13, Tailfer section, Lustin Formation; **F** — *Amphipora* and palaeosiphonocladales packstone (facies I1), thin section V123, normal light, Villers-le-Gambon section, Philippeville Formation; **G** — laminar grainstone and packstone with peloids and fenestrae (facies I4), thin section A153, normal light, Aywaille section, Lustin Formation; **H** — brecciated limestone, palaeosol (facies I5), field picture, bed 74, Tailfer section, Lustin Formation

locally encrusting character of the sediment and the abundance of millimetre-scale fenestrae. These characteristics are absent in mechanical accumulations (Aitken, 1967). This facies is located in the storm wave action zone.

LOW DOMICAL STROMATOPOROIDS RUDSTONE (B2)

Rudstone to floatstone with massive organisms (up to 70%) such as stromatoporoids, rugose (*Hexagonaria*) or tabulate corals (*Alveolites*), locally associated with fasciculate and/or branching rugose corals (*Disphyllum*), dendroid stromatoporoids (*Stachyodes*) and branching tabulate corals (*Alveolites* and *Thamnopora*). The massive stromatoporoids are "high domical"; they are generally broken and may be encrusted by other stromatoporoids, tabulate corals or calcareous algae (Fig. 5D). These massive organisms are in a bioclast-rich rudstone to packstone (crinoids, brachiopods, or bryozoans and broken stromatoporoids, rugose and tabulate corals). Preservation is poor, fossils are often broken; the bioclasts are oriented in all directions and sorting is medium and bimodal (decimetre-size macrofossils and millimetre-size to centimetre-size bioclasts).

Other organisms (crinoids, brachiopods and bryozoans) originated from the open sea. The massive morphology of reef-builders seems to correspond to medium-strength water turbulence (Cornet, 1975; Machel and Hunter, 1994). Stromatoporoids, rugose and tabulate corals are broken, but not rounded, suggesting a relatively limited degree of transport. The presence of fossils in life position suggests episodic low energy periods.

This microfacies is interpreted as biostromes that developed in moderate to strong wave energy, episodically reworked by storms, close to the fair-weather wave action zone.

DENDROID STROMATOPOROIDS FLOATSTONE (B3)

This facies consists of floatstone with *Stachyodes* scattered in a micritic or clotted micrite matrix (Fig. 5E). The *Stachyodes* (approximately 20% by volume) is locally accompanied by udoteacean algae, palaeosiphonocladales, calcispheres and ostracods with subordinate gastropods, sponge spicules, brachiopods, solitary rugose corals, laminar stromatoporoids and foraminifera. *Girvanella*, Codiaceae or stromatoporoids locally encrust *Stachyodes*. Encrustations are generally irregular and asymmetrical. Fossils are well preserved (not broken) and some fossils are in life position. Sorting is poor (centimetre-scale *Stachyodes* with foraminifera and calcispheres).

Stachyodes skeletons have been usually reported from shallow-water zones, where energy is moderate and sedimentation rate intermittent (Cornet, 1975; James, 1983; Machel and Hunter, 1994; Wood, 2000). Living udoteacean algae are shallow-water tropical organisms (above 50 m after May, 1992), and according to Roux (1985), Devonian udoteacean algae were found in open-sea environments, lagoons and reef fronts at depths lower than 10 m. The preservation of fossils locally in life-position, the presence of Udotaeaceae and the clotted microstructure suggest low ambient wave energy. The clotted nature of the matrix may be related to a microbial origin (as in microfacies M5 and B1). This facies developed near the boundary between the biostromal zone and the lagoonal area, under the fair-weather wave action zone.

INTERNAL PLATFORM OR LAGOON (I)

Lagoonal facies are characterised by limestones ranging from laminated mudstone to wackestone or floatstone with *Amphipora*. The various microfacies are closely related and do not show clear boundaries, suggesting a continuum.

FLOATSTONE AND PACKSTONE WITH *AMPHIPORA*, PALAEOSIPHONOCLADALES AND PELOIDS (I1)

Bioturbated packstone and floatstone with *Amphipora*, palaeosiphonocladales and peloids, are characterised by the dominance of one of these three types of grains (Fig. 5F). This facies shows subordinate branching tabulate corals, solitary rugose corals, bulbous stromatoporoids (centimetre-size), ostracods and udoteacean algae. *Girvanella* and stromatoporoids encrust *Amphipora*. These encrustations are irregular and asymmetrical. Preservation is good and sorting can be high.

The organisms (calcispheres, ostracods, foraminifera, algae, *Amphipora*) mainly originate from a restricted area. *Amphipora* is considered as inhabiting shallow-water, quiet, lagoonal, generally hypersaline and turbid environments (Cornet, 1975; James, 1983; Pohler, 1998). Wave energy had to be low, because of abundant carbonate mud, clay and asymmetrical encrustations. This microfacies is characteristic of a restricted subtidal zone in an internal platform or lagoon, with low to moderate wave energy.

WACKESTONE WITH *UMBELLA* (I2)

Heterogeneous texture, sorting, preservation and nature of bioclasts characterise this microfacies. Commonly it is a wackestone with a dark micritic matrix, rich in peloids and millimetre-scale intraclasts, but grainstones and packstones are also present. Locally, concentrations of clasts, clay and detrital quartz (0.05 mm) were observed. Sorting is poor, as a consequence of textural heterogeneity and the variable size of fossils. Examples of *Umbella* are accompanied by gastropods, palaeosiphonocladales, foraminifera, ostracods, crinoids and brachiopods. The *Umbella* are well preserved (not broken) and crinoids and brachiopods are well preserved or broken. Desiccation cracks are common.

According to Mamet (1970), *Umbella* was significant in littoral environment of high salinity. Other fossils originated from lagoonal areas. Desiccation cracks were caused by occasional emergence. The unbroken fossils, muddy matrix and clay suggest a quiet environment. The presence of fossils that are usually not associated (palaeosiphonocladales, *Umbella*, calcispheres originating from the lagoon, and crinoids and brachiopods derived from the open sea) may have been related to a channel system crossing the lagoon and connecting with the open sea, leading to mixing of biotic assemblage.

MUDSTONE (I3)

This facies is composed of mudstone with ostracods, calcispheres, palaeosiphonocladales, foraminifera, pellets, *Umbella* and subordinate debris of gastropods and brachiopods. Fenestrae, mostly horizontal but locally vertical and irregular and filled with coarse calcitic sparite cement are typical. Some of these cavities show vadose cement. Desiccation cracks are common.

The texture, nature and non-fragmented state of preservation of the fossils are characteristic of a quiet environment. Desiccation cracks and vadose cement indicate an environment subjected to emergence. Horizontal fenestrae are the result of sheet cracks or decay of microbial mats (Grover and Read, 1978). This microfacies developed in a lagoonal environment in the intertidal zone, with very low wave energy.

LAMINATED GRAINSTONE AND PACKSTONE WITH PELOIDS AND FENESTRAE (I4)

This microfacies mainly consists of an accumulation of peloids (0.05–0.1mm) (70–90% by volume) exhibiting sharp to diffuse rims (Fig. 5G). The lamination originates from packstone-grainstone-mudstone alternations, a variable abundance of fenestrae or birdseyes, local microbioclastic or intraclastic layers, clay or detrital quartz accumulations, or fining-upward sorting. Some brachiopods and *Amphipora* are observed.

Abundant fenestrae, the occasional presence of algal tubes as well as the irregularity of the laminae are the main characters of this microfacies and seem to correspond to microbial mats (Aitken, 1967). However, cross-stratification, fining-upward sorting, planar lamination, bioclastic concentrations and relief-compensating laminae, suggest local mechanical reworking of these algal mats (Aitken, 1967). Algal mats are distributed from the upper intertidal zone to the supratidal zone in the humid tropical model of the Bahamas (Wilson, 1975; Hardie, 1977; Purser, 1980).

BRECCIATED LIMESTONES (I5)

These strata comprise strongly brecciated metric-size intervals, accompanied by micritic or dolomitic planar beds cut by desiccation cracks (Fig. 5H). The clasts (centimetre- to decimetre-size) are generally elongated in the direction of stratification, are composed of wackestone with palaeosiphonocladales, pellets or mudstone and are surrounded by microspar, dolomite and argillaceous infiltrations. Granular cement is often present within the cavities and under the clasts, forming brownish irregular pendants. Pellet concentrations were observed. Pyrite and hematite crystals are frequent and sometimes follow the stratification.

According to Wright (1994), brecciation is a common characteristic of palaeosoils. The presence of pendant vadose cement, desiccation cracks, circum-granular cracks, hematite, pyrite and glaebules are also well known characteristics of pedogenesis.

DISCUSSION AND PALAEOENVIRONMENTAL EVOLUTION

THE CARBONATE MOUNDS

The M2 facies developed in a low-energy, slightly suboxic environment below the photic zone. The M3 facies with stromatactis, corals and stromatoporoids developed close to the storm wave base, in a subphotic environment. It includes some M5 cyanobacteria-rich lenses. These lenses became abundant and overlapping when the depth decreased; this shallowing trend was also highlighted by the increasing abundance of green algae, as in the M4 facies. These two facies developed close to the fair-weather wave base in a photic environment. However, no progressive transition between these first three facies and the three following was observed. The M6 facies is characterised by its peloidal character, the abundance of dendroid stromatoporoids and the dominant grainstone texture, with local graded bedding. This facies corresponds to an environment located above the fair-weather wave base, with possible restriction marked by a relatively low faunal diversity. M6 shows a progressive transition to laminated fenestral mudstones rich in peloids, calcispheres and palaeosiphonocladales (M7). This facies developed in a quiet intertidal area. The last facies (M8) accumulated in a subtidal lagoonal environment.

The mounds began with the development of large coral colonies (fasciculate or domical rugose corals) on a muddy sea floor, then came the progressive colonisation of this substrate by sponges, and finally carbonate production in the form of centimetre- to decimetre-sized lenses of micrite. Later, progradation took place by the simple lateral extension of bioconstructed facies over adjacent facies without a colonisation phase of the substrate by corals.

A strong facies similarity between the Arche and Lion members was observed. Moreover, the facies succession and distribution are also very similar (Fig. 6). Indeed, both generations of buildups begin with grey or pinkish limestone with stromatactis, corals and stromatoporoids (M3), with possible local M2 facies. Above about 40–70 m of this facies forming the bulk of the mounds, the grey "algal" M4 facies begins to appear, including microbial limestone lenses (M5). The facies that developed in the central part of both buildups suggest the development of an area of slightly restricted sedimentation, i.e. some kind of inner lagoon, sheltered by the bindstone or floatstone, generating a mound margin environment.

By comparison with recent models of atoll development in response to eustatic variations (Warrlich *et al*., 2002), it is possible to suggest a dynamic interpretation of the geometry and evolution of the Lion and Arche members (Fig. 6). After the growth of the lower part of the carbonate mounds during transgression, possibly with a short episode of low oxygen conditions, as revealed by the local presence of iron bacteria (Boulvain *et al*., 2001), significant progradation is recorded by fore-mound sedimentation of reworked material. Low sea level then forced reef growth along the margin, culminating in the development of an atoll crown during the following transgressive stage. The presence of lagoonal facies is therefore possibly the result of balance between sea level rise and reef growth.

THE CARBONATE PLATFORM

The ideal shallowing-upward facies succession starts with open-marine deposits corresponding to crinoidal packstones (E1) and grainstones (E2). They are followed by biostromes with laminar stromatoporoids (B1), overturned and broken massive stromatoporoids (B2) and then dendroid stromatoporoids (B3). Then, biostromes are overlain by subtidal lagoonal facies with *Amphipora*, palaeosiphonocladales and peloids (I1), followed by mudstone (I3) and laminated pelloidal facies (I4) from the intertidal zone. The subtidal and intertidal zones were cut by channels filled by *Umbella* and intraclasts (I2). The supratidal zone was characterised by palaeosols (I5).

An important sedimentological observation concerning platform evolution (intermediate and southern belts) is the apparent division seen in all the sections between an upper and a lower unit (Fig. 3). The lower unit (biostrome) is dominated in the intermediate belt by ramp facies with some biostromal interruptions, and in the northern belt by biostromes with lagoonal interruptions. The higher unit (lagoon) consists of an alternation of biostromes and lagoonal facies in the intermediate belt and of lagoonal facies (with palaeosols) in the northern belt.

Within these sedimentological units, facies are stacked into metre-scale cycles, showing mainly shallowing-upward trends. Such cyclicity is common in Devonian shallow-water carbonates (e.g. Préat and Racki, 1993; McLean and Mountjoy, 1994; Brett and Baird, 1996; Elrick, 1996; Garland *et al*., 1996; Whalen *et al*., 2000; Chen *et al*., 2001). Different kinds of cycles however, are identified here. In the biostromal unit from the intermediate belt, sedimentation is mainly acyclic stacking of 10 cm thick crinoidal beds, probably due to the deeper environment being less sensitive to minor relative sea level variations. In the lagoonal unit, the cycles are characterised by biostromes followed by lagoonal deposits and capped by intertidal laminites. In the northern belt, the biostromal unit shows one or few metres-thick cycles, with crinoid beds (the

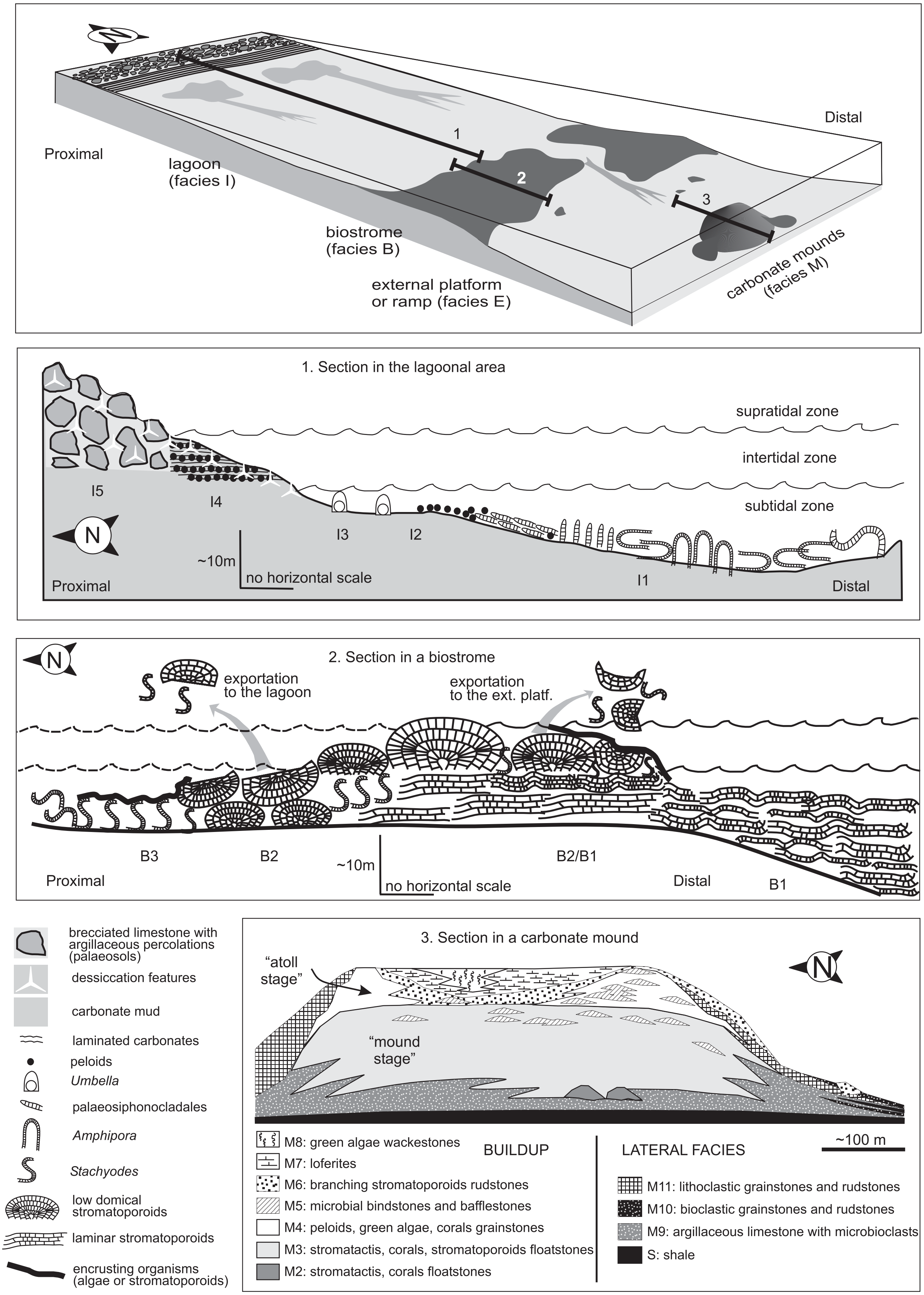

Fig. 6. Proposed models for the development of the middle Frasnian platform of Belgium

colonisation stage) followed by massive biostromes and lagoonal deposits and capped by intertidal laminites. The lagoonal unit is characterised by subtidal and intertidal facies covered by, or transformed into palaeosols. These cycles are not always complete.

CONCLUSIONS

The middle Frasnian carbonate mounds of Belgium can be subdivided into seven buildup facies (M2–8) and three laterally adjacent facies (M9–11). Carbonate mounds started usually in a relatively deep, quiet subphotic environment with a stromatoporoid-coral-sponge assemblage (M3), then reached the fair-weather wave base and the euphotic zone with algal-microbial facies (M4 and M5). The upper parts of the mounds are characterised by lateral facies differentiation with algal-microbial facies protecting a central sedimentation area with dendroid stromatoporoid facies (M6) and fenestral limestone (M7). The lateral facies reflect different kinds of input of reworked mound material into the proximal area, from transported fine-grained sediment to coarse-grained fossil debris.

By delineating the geometry of the sedimentary bodies and their bathymetric interpretation, it is possible to propose a sedimentological subdivision of the mounds and lateral equivalent facies (Fig. 6). The lower and middle parts of the buildups correspond to a succession of a transgression and a sea level stillstand with major progradation associated with reduced accommodation space. Mound development during a succeeding sea level drop was restricted to the edge of the buildup, with possible emergence and lithification from meteoric waters. The atoll crown development corresponds to a transgression resulting in marked lateral facies differentiation between fore-mound and interior lagoon. The demise of mound development was then the consequence of a final transgression associated with the deposition of the Boussu-en-Fagne or l'Ermitage Shale (Fig. 3).

The architecture of the Belgian middle Frasnian platform is classical in that it resembles other Frasnian carbonate platforms with stromatoporoid-dominated facies seen in China, Alberta, Iberia, Australia and so on. Environments range from the outer zone (crinoidal facies) to stromatoporoid-dominated biostromes and the lagoonal area of the inner zones (subtidal facies with *Amphipora* floatstone, algal packstone, intertidal mudstone and laminated peloidal packstone and palaeosols). These facies are stacked in metre-scale shallowing-upward cycles. The larger scale sequential organisation corresponds to transgressions and regressions, whose cycles are responsible for differentiating a lower open-marine biostrome-dominated unit from an upper lagoonal unit. The last regression-transgression cycle, responsible for the platform-scale development of lagoonal facies, can be correlated with the atoll-stage evolution of the carbonate mounds belonging to the Lion Member. These sequential correlations still have to be confirmed by other types of high-precision correlation, such as magnetic susceptibility (da Silva and Boulvain, 2002).

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