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ORIGINAL ARTICLE

F. Boulvain · Pierre Cornet · Anne-Christine da Silva · Gwenaël Delaite · Bernard Demany · Marc Humblet · Marjorie Renard · Marie Coen-Aubert

Reconstructing atoll-like mounds from the Frasnian of Belgium

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Abstract A succession of Frasnian mounds on the southern border of the Dinant Synclinorium (Belgium) was investigated for their facies architecture, sedimentary dynamics and palaeogeographic evolution. Seven mound facies were defined from the Arche (A) and Lion (L) members, each characterized by a specific range of textures and association of organisms (A2/L2: red or pink limestone with stromatactis, corals and crinoids; A3/L3: grey, pink or green limestone with stromatactis, corals and stromatoporoids; A4/L4: grey limestone with corals, peloids and dasycladaceens; A5/L5: grey microbial limestone; A6/L6: grey limestone with dendroid stromatoporoids; A7/L7: grey laminated limestone with fenestrae; and A8/L8: grey bioturbated limestone). Laterally equivalent sediments include substantial reworked material from the buildups and background sedimentation. Textures and fossils suggest that A2/L2 and A3/L3 facies developed close to storm wave base, in a subphotic environment. Facies A4/L4, occurring near fair weather wave base in the euphotic zone, includes lenses of A5/L5 with stromatolitic coatings and thrombolithes. A6/L6 corresponds to a slightly restricted environment and shows a progressive transition to fenestral limestone of A7/L7. This facies was deposited in a moderately restricted intertidal area. A8/L8 developed in a quiet lagoonal subtidal environment. The mounds started with A2/L2 or A3/L3 in which microbial lenses and algal facies A4/L4 became progressively more abundant upwards. Following 20 m of laterally undifferentiated facies, more restricted facies occur in the central part of the buildups. This geometry suggests the initiation of restricted sedimentation, sheltered by bindstone or floatstone facies. The facies interpretation shows that after construction of the lower part of the mounds during a transgression and a sea-level highstand, a lowstand forced reef growth to the margin of the buildups, initiating the development of atoll-like crowns during the subsequent transgressive stage. The persistence of restricted facies results from the balance between sea-level rise and reef growth.

Keywords Frasnian · Belgium · Carbonate mounds · Reefs · Atolls · Facies · Eustasy

Introduction and aim of the work

As a result of the outstanding exposures developed by wire-cut quarrying, the well-documented regional Devonian stratigraphy, and the fact that the puzzling stromatactis structure common in and characteristic of many mud-mounds was first described in Belgian Frasnian mud-mounds (Dupont 1881), the latter have acquired international significance (e.g. Tsien 1975; Bourrouilh and Bourque 1995). More recent sedimentological studies have been mainly devoted to the Late Frasnian Petit-Mont Member (Boulvain 2001). Despite their good outcrop conditions, the Middle Frasnian Arche and Lion members have not yet been submitted to a detailed analysis. Together with new data on these buildups, a sedimentological interpretation of the Lompret quarry and the Frasnes railway section is provided in order to improve our knowledge of the proximal fore-mound and the off-mound areas.

F. Boulvain (✉) · A.-C. da Silva · G. Delaite · B. Demany · M. Humblet · M. Renard
U.R. Pétrologie sédimentaire, B20,
Université de Liège, Sart Tilman,
4000 Liège, Belgium
e-mail: fboulvain@ulg.ac.be
Tel.: +32-4-3662252
Fax: +32-4-3662921

P. Cornet
TotalFinaElf Exploration and Production Géosciences,
Projets Nouveaux 2 place de la Coupole-La Défense 6,
92078, Paris, France

M. Coen-Aubert
Département de Paléontologie,
Institut royal des Sciences naturelles de Belgique,
29 rue Vautier, 1000 Bruxelles, Belgium

Location and geological context

The Belgian Frasnian lithostratigraphy has been revised recently (Boulvain et al. 1999). Three different levels of carbonate mounds are recognized in the Frasnian of the southern border of the Dinant Synclinorium (Figs. 1 and 2), which is a large-scale unit of the West-European Variscan fold-and-thrust belt. These are upsection, the Arche (Fig. 3B), Lion (Fig. 3C), and Petit-Mont members. In the Philippeville Anticlinorium, mounds occur only in the Petit-Mont Member, the other mound-bearing levels being replaced landwards by bedded limestone, locally with back-reef characters. At the northern border of the Dinant Synclinorium and in the Namur Synclinorium, the entire Frasnian consists of bedded limestone and argillaceous strata (da Silva and Boulvain 2002). This paper deals with the first two mound levels in the southern part of the Dinant Synclinorium. The best known Arche and Lion buildups crop out along the southern border of the Dinant Synclinorium, from the vicinity of Trélon towards the west to Marche-en-Famenne in the east (Fig. 1). All the sections studied in the present paper are located close to the village of Frasnes, except the Lompret quarry, which is close to the city of Chimay (Table 1).

Previous work

The first detailed faunal investigation of the Arche and Nord mounds was made by Lecompte (1954). He interpreted the lower red facies from the Arche mound as deeper than the upper grey unit forming the top of the Arche mound and the bulk of the Nord and Lion quarries. According to Lecompte, the grey facies developed into the wave zone. Cornet (1975) presented a very precise description of the three buildups, focusing on the nature

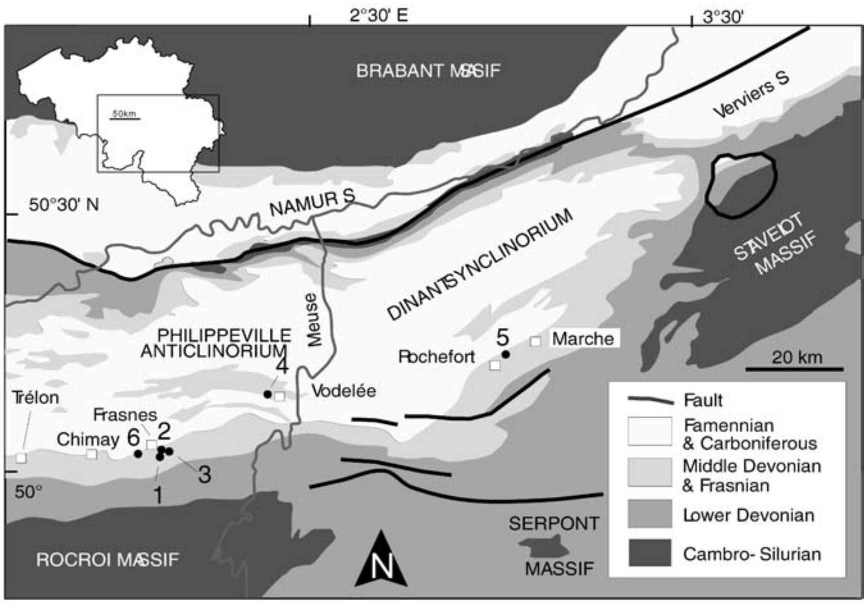

Fig. 1 Schematic geological map of southern Belgium with location of the outcrops (*1* Arche quarry; *2* Nord quarry; *3* Lion quarry; *4* Moulin Bayot sections; *5* La Boverie quarry; *6* Lompret quarry; *7* Frasnes railway section)

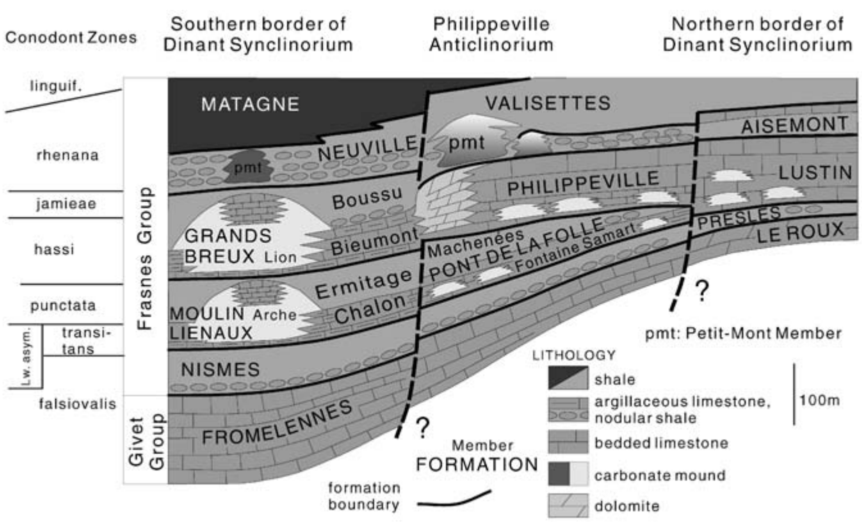

Fig. 2 Schematic N–S cross section and main lithostratigraphic subdivisions of Frasnian sedimentary basin before the Variscan Orogeny

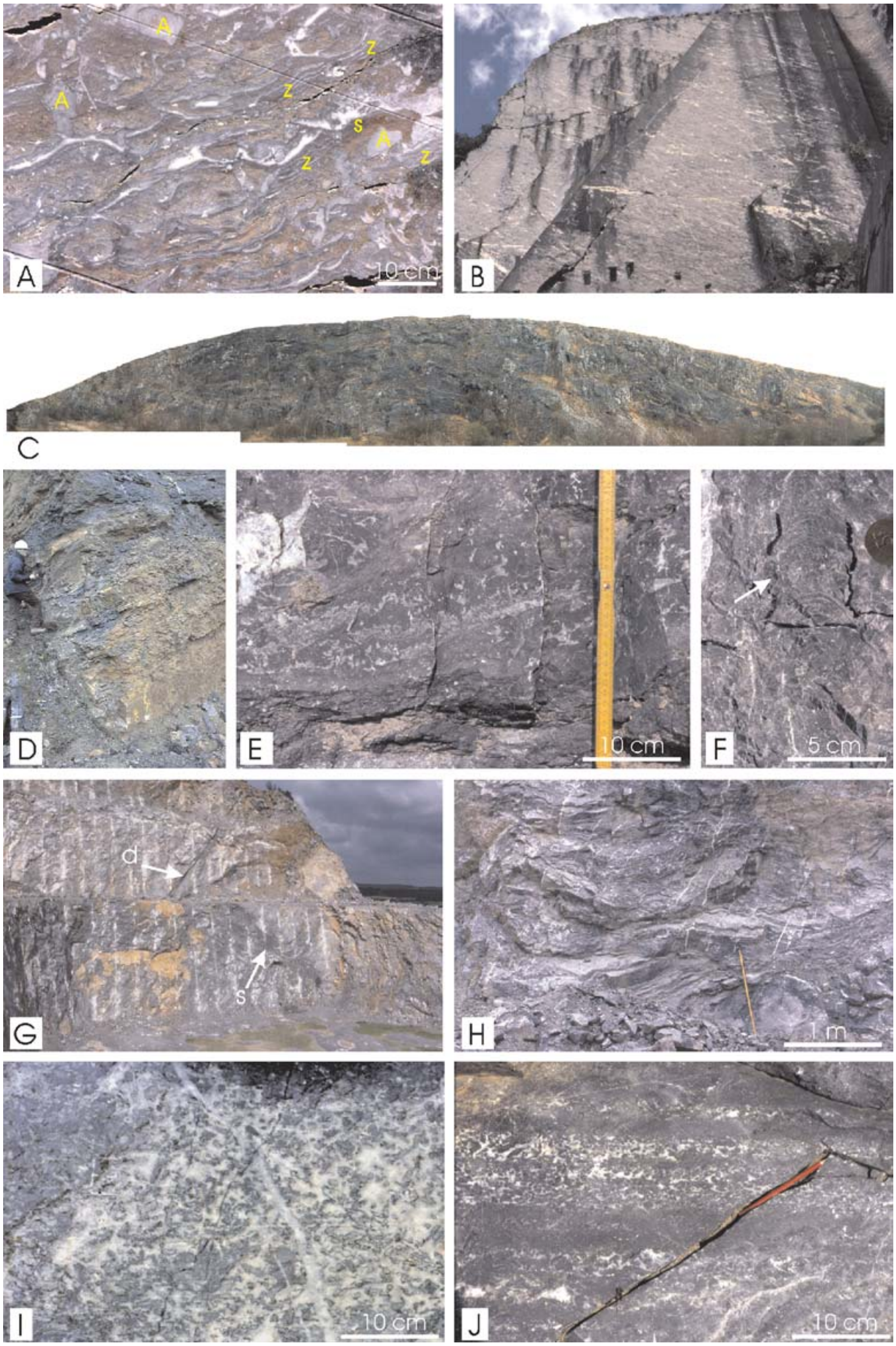

Fig. 3 Facies from the Middle Frasnian Arche and Lion carbonate mounds and lateral sediments. **A** Lower part of the Arche carbonate mound (Arche quarry, Frasnes), characterized by red floatstones with stromatactis and shelter cavities (*s*), zebra (*z*), tabulate corals (*A*), crinoids, brachiopods and stromatoporoids (A3). **B** Middle part of the Arche carbonate mound (Arche quarry, Frasnes), showing grey algal and microbial bindstones and bafflestones (A4-A5). The stratification is nearly horizontal and the quarry wall is 20 m high. **C** 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 above the floor. The sketch of Fig. 7 is made from this mosaic. **D** Bedded argillaceous limestone (lateral facies of a Lion Member mound) in the Lompret quarry, Bieumont Member, Chimay. **E** Grey limestone with stromatactis, corals and crinoids (L3) from the Nord quarry (Lion Member, Frasnes). Bed 31, section A. **F** Grey microbial and algal limestone (L5) with a columnar stromatolite (*arrow*). Nord quarry (Lion Member, Frasnes). Bed 37, section A. **G** Upper part of section A in the Nord quarry (Lion Member, Frasnes). *S* stratification (*dipping to the right*); *d* synsedimentary neptunian dyke. **H** Lower part of the A section in the Nord quarry (Lion Member, Frasnes) showing zebra structures related to synsedimentary slumping. **I** Grey rudstone with dendroid stromatoporoids (*Amphipora*) (L6). Upper part of the Lion quarry, Frasnes. **J** Grey laminar fenestral limestone (L7). Section C from the Nord quarry, Lion Member, Frasnes

and morphology of the stromatoporoids in relation to their palaeoenvironment. His studies were used later by Tsien (1980) for a palaeogeographic model of the Frasnian platform. More recently, the Nord quarry was investigated bed-by-bed by Boulvain and Coen-Aubert (1997) together with descriptions of rugose corals and a preliminary facies model. However, as the Nord quarry is located on the back part of the mound, data were missing for developing a comprehensive sedimentological model. Two other groups of sections are presently being studied by Boulvain et al. (in press) in the Philippeville Anticlinorium (Moulin Bayot, Fig. 1) and the southeastern part of the Dinant Synclinorium (La Boverie, Fig. 1).

Despite several stratigraphical and palaeontological investigations (Vandelaer et al. 1989; Coen-Aubert 1994), the Frasnes railway section has never been studied sedi-

Table 1 Studied sections: number: number of the section corresponding to the outcrop located on Fig. 1; Section: corresponding name of the section; Formations: formations exposed at each section; Location: *PA*: Philippeville Anticline; *SBDS*: southern border of the Dinant Synclinorium; and Thickness: thickness of each section

Nr.	Sections	Formations/members	Location	Thickness (m)
Mounds				
1	Arche quarry	Arche	SBDS	60
2	Nord quarry	Lion	SBDS	130
3	Lion quarry	Lion	SBDS	150
4	Moulin Bayot sections	Arche-Lion	PA	>130
5	La Boverie quarry	Arche-Ermitage-Bieumont-Lion-Boussu-Neuville	SBDS	250
Lateral facies				
6	Lompret	Bieumont	SBDS	60
7	Frasnes railway section	Bieumont-Boussu	SBDS	120

mentologically. The first facies description of the Bieumont Member in the Frasnes section was published recently by Humblet and Boulvain (2001) together with a detailed study of the Lompret quarry.

Methods

The bed-by-bed descriptions and sampling were carried out between 1991 and 2002. Samples collected by Cornet from the Lion quarry in 1975 were used for making a new set of thin sections. Petrographic studies were based on collections of 266 thin sections from the Lion quarry, 81 thin sections from the Nord quarry and 136 thin sections from the Lompret and Frasnes sections.

Mound and lateral facies

Seven bioconstructed facies (Table 2), each one characterized by a specific range of texture and organism associations, are defined in the Arche and Lion members (A2/L2 to A8/L8). In these facies, the components are mostly autochthonous and directly reflect the influence of oceanic controls such as water agitation and light intensity. Three other facies (b, B and L), corresponding to the lateral equivalent sediments, are also defined. Unlike bioconstructed facies, these lateral facies include material transported from the adjacent buildups, and their assemblages do not directly reflect the depositional environment.

As used in Boulvain et al. (2001), closely related facies in stratigraphically distinct buildups are referred to the same facies number following a specific letter for the member name (for example: A2 and L2, correspond to nearly equivalent facies in the Arche and Lion members). A comparison is also possible with the Petit-Mont Member carbonate mounds (Pm1-Pm5) whose description follows a similar classification (see Boulvain 2001). The bioconstructed facies description used below depicts a shallowing upward trend.

Red, greenish or pinkish mudstones and floatstones with stromatactis, corals and crinoids (A2/L2)

This facies is characterized 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 a granular cement. Two kinds of matrix are easily observed: an early darker, locally cohesive “primary mud” and a later lighter, more neomorphosed internal sediment. Unlike in the Late Frasnian Petit-Mont Member (Bourque and Boulvain 1993; Boulvain 2001), stromatactis are not always related to the vicinity of sponge spicules network.

Grey, pinkish or greenish floatstones with stromatactis, corals and stromatoporoids (A3/L3)

These wackestones and floatstones show decimetric stromatactis and centimetric stromatactoid fenestrae with abundant branching tabulate corals, brachiopods and crinoids (Fig. 3A, Fig. 4E). Bulbous or laminar (rarely dendroid) stromatoporoids, bryozoans, peloids, and fasciculate rugose corals are locally observed. Some subordinate cricoconarids, palaeosiphonocladale algae and calcispheres are present. Coatings (*Sphaerocodium*) are poorly developed. Many fenestrae correspond to growth or shelter cavities (Fig. 3A). Through reworking and bioclast concentration by storm action, this facies may evolve into bioclastic rudstones.

Grey rudstones and grainstones with corals, peloids and dasycladaceens (A4/L4)

This facies marks the first occurrence of dasycladaceens and Udotaeacea, together with the development of very thick and symmetrical microbial coatings upon bioclasts. It corresponds to rudstones, grainstones and floatstones with peloids, lithoclasts, branching tabulate corals coated by *Sphaerocodium*, brachiopods, some crinoids, dendroid stromatoporoids, radiospheres and calcispheres (Fig. 4F). Occasional Udotaeacea are observed (Mamet and Boul-

Table 2 Description of facies from Middle Frasnian carbonate mounds. *SWB* storm wave base; *FWWB* fair-weather wave base. *Arrows* mean "high" when pointing upwards and "low" when pointing downwards; ~ means "moderate"

Facies	Color/texture/ structure	Autochthonous and allochthonous biota	Preservation/ transport	Energy	Interpretation	Bathymetry
Carbonate mound facies (A/L)						
A2/L2. Stromatactis, corals and crinoids	Red, greenish or pinkish mudstone, floatstone	Spongs, corals, crinoids and iron bacteria	Preservation ↑ Transport ↓	Very low	Aphotic, below SWB	80–100 m
A3/L3. Stromatactis, corals and stromatoporoids	Grey, pinkish or greenish floatstone, (rudstone)	Corals, crinoids. brachiopods, bryozoan and stromatoporoids	Preservation ↑ Transport ↓	Low, episodically moderate	Subphotic, close to SWB	60–80 m
A4/L4. Corals, peloids and dasycladaceens	Grey grainstone, rudstone	Corals, stromatoporoids. dasycladaceens. cyanobacteria	Preservation ~ Transport ~	Moderate	Euphotic, close to FWWB	30–60 m
A5/L5. Microbial limestone	Grey bindstone bafflestone	Corals, cyanobacteria and stromatoporoids	Preservation ↑ Transport ~	Moderate	Euphotic, close to FWWB	30–60 m
A6/L6. Dendroid stromatoporoids	Grey rudstone, m-thick beds	Dendroid stromatoporoids and cyanobacteria	Preservation ↑ Transport ↓	High	Above the FWWB	0–30 m
A7/L7. Fenestral limestone	Grey laminated, grainstone-wackestone	Dendroid stromatoporoids and paleosiphonocladales	Preservation ~ Transport ↓	Low	Intertidal	0 m
A8/L8. Bioturbated limestone	Grey, dm-thick, wackestone-mudstone	Paleosiphonocladales and calcispheres	Preservation ↑ Transport ↓	Low	Subtidal	5–10 m
Lateral facies						
b. Microbioclastic packstone	Dark grey, dm-thick, bedded packstone	Corals, brachiopods, ostracods bryozoans	Preservation ↑ Transport ↓	Low	Below SWB	80–100 m
B. Bioclastic packstone, grainstone	Dark grey, dm-thick, bedded packstone-grainstone	Corals, brachiopods, ostracods bryozoans and stromatoporoids	Preservation ↑ Transport ↓	Low, episodically moderate	Close to SWB	60–80 m
L. Intraclastic packstone and grainstone	Dark grey, dm-thick, bedded packstone-grainstone	Stromatoporoids corals, brachiopods and bryozoans	Preservation ↑ Transport ↓	Low, episodically moderate	Close to SWB	60–80 m

vain 1992). Stromatactoid fenestrae and stromatactis are present.

Grey microbial bindstones and bafflestones (A5/L5)

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 laminae. Thrombolites and stromatolites (Fig. 3F) are characterized by a canvas-like structure made up of irregular peloids in a yellowish pseudosparitic cement ("structure grumeleuse" of Cayeux 1935). This A5/L5 bioconstructed facies is commonly geometrically associated with A3/L3 or A4/L4, in the form of metre-scale lenses growing in bioclastic sediment. This microbial facies is locally developed in large synsedimentary fractures, as incrustations on the walls, interlayered with fibrous cement.

Grey rudstones with dendroid stromatoporoids (A6/L6)

These rudstones, floatstones and grainstones are very rich in peloids, lithoclasts and dendroid stromatoporoids (*Amphipora, Stachyodes*), strongly coated by *Sphaerocodium* or microbial laminae (symmetrical coatings) (Figs. 3I and 4H). Calcispheres, palaeosiphonocladales and Udotaeaceae are observed. Locally, branching tabulate corals, gastropods and crinoids are present. In some matrix-rich facies, irregular fenestrae are observed.

Grey laminated grainstones to wackestones with fenestrae (A7/L7)

These grainstones and wackestones with peloids, lithoclasts, calcispheres and palaeosiphonocladales show abundant millimetre-length fenestrae scattered in the sediment or marking the stratification (Figs. 3J and 4I). Locally, some dendroid stromatoporoids, often strongly coated by *Sphaerocodium*, are present.

Grey bioturbated wackestones and mudstones (A8/L8)

These sediments contain palaeosiphonocladales, calcispheres and peloids and are often bioturbated (open vertical burrows filled by pseudosparitic to sparitic cement). Some branching tabulate corals and dendroid stromatoporoids, ostracodes and gastropods are also observed.

Laterally to this massive bioconstructed facies (A2/L2-A8/L8), thin-bedded bioclastic and lithoclastic facies are observed, most elements of which underwent transport. Frequent sorting and rounding of the grains characterize these facies. They are listed below according to their content and grain-size.

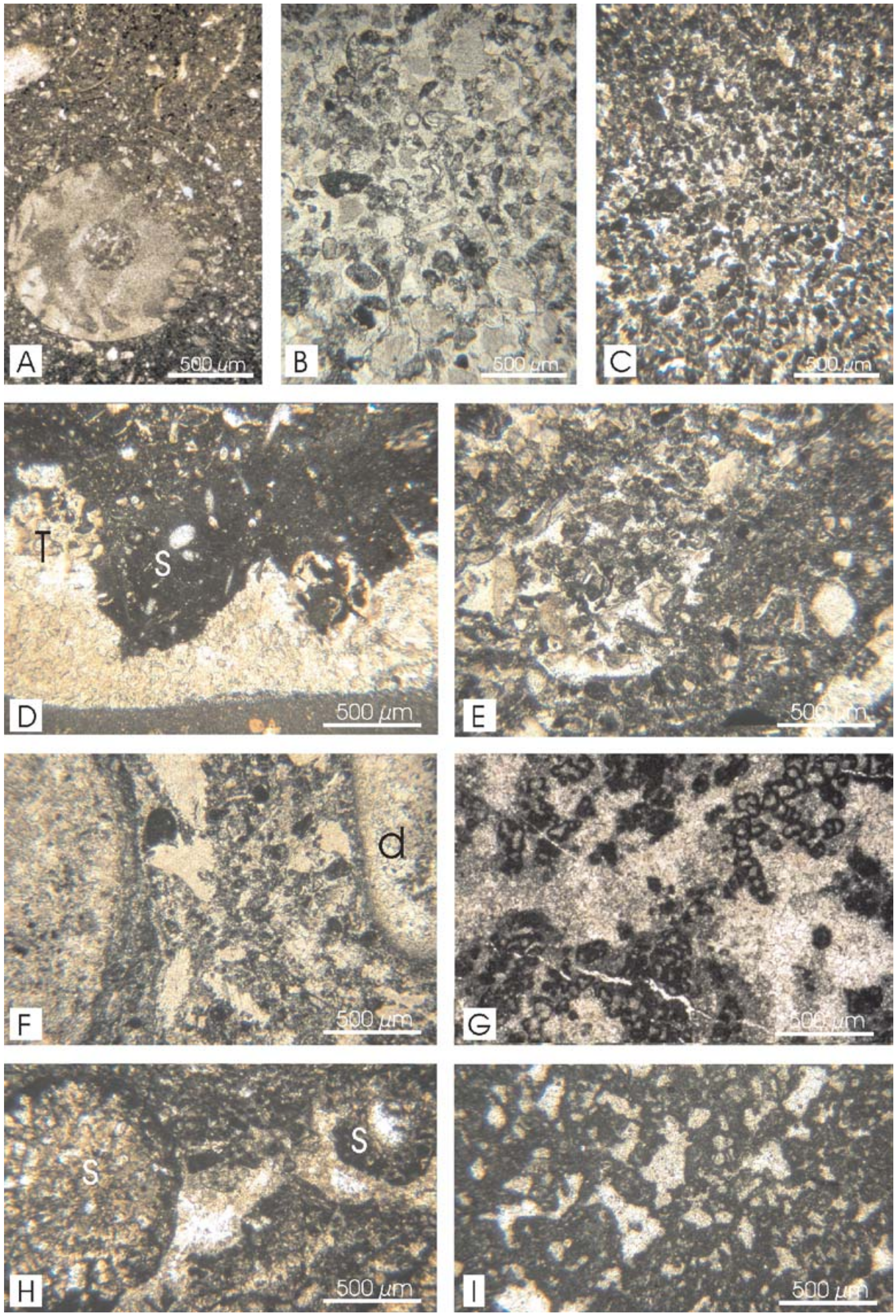

Fig. 4 Microfacies from the Middle Frasnian Arche and Lion carbonate mounds and lateral sediments. **A** Microbioclastic wackestone with highly bioeroded crinoid ossicle (facies b). Bieumont Member, Frasnes railway section. **B** Bioclastic grainstone (facies B) rich in crinoid fragments and lithoclasts. Sample N13b, Nord quarry, Lion Member, Frasnes. **C** Lithoclastic grainstone with crinoids, fragments of corals and brachiopods (facies L). Sample 418, Lion quarry, Frasnes. **D** Wackestone with stromatactis, sponge spicules (*S*) and branching tabulate corals (*Trachypora*, T) (L2). Sample N32, section A, Nord quarry, Lion Member, Frasnes. **E** Wackestones with stromatactoid fenestrae and abundant corals, brachiopods and crinoid fragments (L3). Sample N6A, section A, Nord quarry, Lion Member, Frasnes. **F** Packstone with peloids, lithoclasts, branching tabulate corals coated by *Sphaerocodium*, brachiopods, crinoids, dendroid stromatoporoids and dissolved green algae (*d*) (L4). Sample N35, section A, Nord quarry, Lion Member, Frasnes. **G** Microbial bafflestone with thrombolites and *Renalcis*. Sample N46b, section A, Nord quarry, Lion Member, Frasnes. **H** Rudstone with dendroid stromatoporoids (*s*) and microbial coatings (L6). Sample L102, Lion quarry, Lion Member, Frasnes. **I** Packstone with peloids, lithoclasts and fenestrae (L7). Sample L304, Lion quarry, Lion Member, Frasnes

Microbioclastic packstones (b)

These thin-bedded dark, often argillaceous, fine-grained (<100 µm) bioclastic packstones include some larger brachiopods, crinoids, fragments of rugose and tabulate corals, fenestellids, ostracodes, trilobites, peloids and cricoconarids (Fig. 4A). Locally, some laminar stromatoporoids and palaeosiphonocladales are present. Bioturbation is often intense. Microspar is typically better developed than in other facies and may be related to a higher clay content (Longman 1977).

Bioclastic packstones, grainstones and rudstones (B)

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, but coarser-grained (~300 μm). Some lithoclasts, radiospheres and calcispheres are present (Fig. 4B). Hummocky cross stratification is locally observed.

Packstones, grainstones and rudstones with peloids and lithoclasts (L)

This facies differs from facies B by the greater abundance of peloids and lithoclasts with some subordinate crinoids, fragments of corals and stromatoporoids, brachiopods and bryozoans (Fig. 4C). This facies is usually well-sorted, with grain-size varying from 50 to 300 μm.

Description of sections

The Arche quarry

The disused Arche quarry is located close to the village of Frasnes and is cut into a 450×250 m limestone buildup belonging to the Arche Member (Figs. 5, 3B). Some stratified beds located just below the base of the mound show a strike of N145°E with a dip of 30°N. The thickness of the mound is estimated to 120 m. Bed-by-bed description and sampling was carried out in the NE excavation, from the bottom of the quarry to the top of the hill (Figs. 5, 6).

The exposed base of the buildup consists of nodular shales and lenses of argillaceous limestone containing large amounts of broken and aligned *Disphyllum* corallites accompanied by crinoids, brachiopods, platy tabulate corals and solitary corallites of *Macgeea rozkowskae*. The last bed below the mound is very rich in vermiform structures (Pratt 1982) attributed to sponges. The buildup starts sharply with pink floatstone showing abundant zebra, shelter fenestrae and stromatactis (Fig. 3A). The fauna includes *Alveolites, Thamnopora*, laminar stromatoporoids, crinoids, brachiopods, bryozoans and solitary rugose corals (A3). This facies continues to a height of 31 m, where the colour of the sediment becomes progressively lighter and A4 facies alternates with A3. In this unit, the macrofauna is composed of crinoids, brachiopods and branching tabulate corals. Peloids and microbial coatings become progressively more abundant upwards. From 42 m to the top of the section, the limestone (grainstone, bindstone) fades into grey with alternating A4 and A5 facies. The macrofauna includes dendroid and laminar stromatoporoids, gastropods, brachiopods, crinoids and branching tabulate corals. Petrographically, this last unit is rich in microbial laminites, peloids and dasycladaceens.

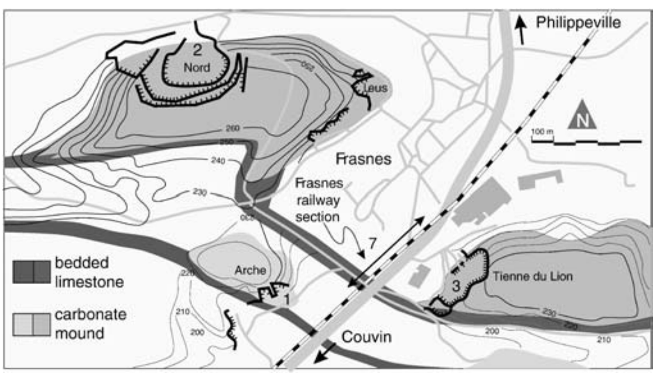

Fig. 5 Detailed geological map of the Frasnes area with location of carbonate mounds and sections

The Lion quarry

This large old quarry lies 750 m SE of Frasnes, close to the Couvin-Charleroi main road (Fig. 5). Bioclastic beds situated near the south end of the quarry show a strike of N90°E with a dip of 35°N. The Lion hill is nearly 800×400 m in area and the suggested thickness of the buildup reaches 150 m. The front wall of the quarry is about 280 m wide and 50 m high, giving a spectacular SW–NE section of the buildup (Fig. 7, Fig. 3C). Knowing the general palaeogeography of the Frasnian platform (Tsien 1980), this SW–NE section corresponds roughly to a fore-mound/ mound core transect.

The geometry of the bedding planes shows a very clear progradation in the form of 50-m-high sigmoidal beds in the southern part of the quarry and nearly horizontal bedding in the northern area (Fig. 7). These well-bedded zones are separated by a more massive zone in the central part of the quarry. Samples were collected from 30 vertical sections, with a sampling interval varying from decimetre to metres (Cornet 1975; Fig. 8).

The base of the mound is not visible in the quarry and the bulk of the buildup consists of grey floatstone with stromatactis, branching tabulate corals, brachiopods, crinoids, bulbous or tabular (rarely dendroid) stromatoporoids and fasciculate rugose corals (L3). The north-east end of the Lion quarry, corresponding to the highest part of the mound, shows a transition between facies L3 and the algal facies L4, with lenses of microbial facies L5. These facies are capped in the northernmost part of the quarry by fenestral peloidal limestone (L7, see sections 1 to 5, Fig. 8). The southern sections show alternations of bioconstructed facies L3 and reworked bioclastic material (B). The upper south-west flank of Lion quarry (upper part of sections 21–25, Fig. 8) is characterized by debris flows of lithoclastic material and sediment rich in dendroid stromatoporoids. This material is thought to have been eroded from the central part of the mound.

The Nord quarry

This active quarry is located 500 m west of Frasnes, where it is cut into a 1200×600 m hill (Fig. 5). The thickness of the buildup is close to 150 m, as in the Lion mound. Well-bedded facies located near the base of the mound show a strike of N70°E and a dip of 25°N. The A,

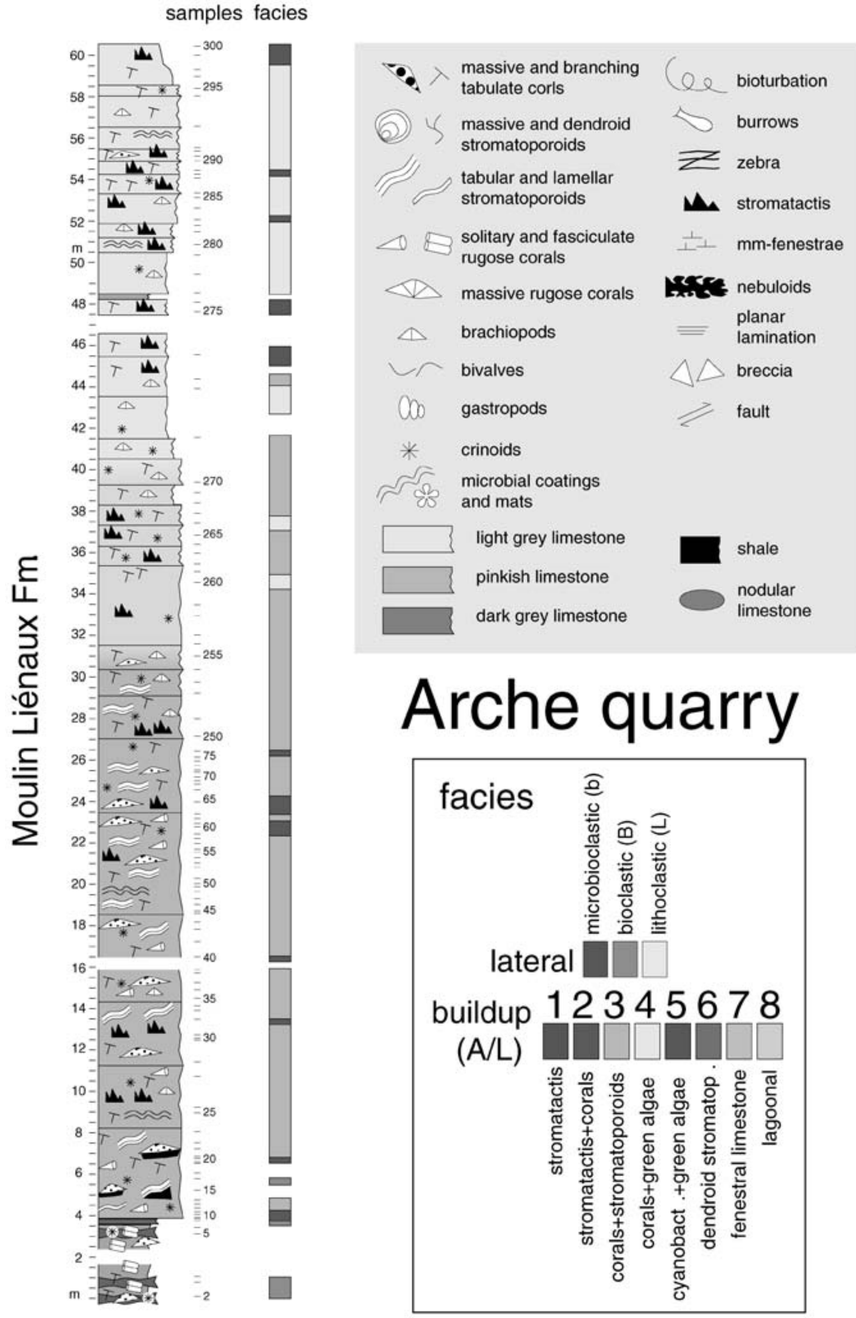

Fig. 6 Log and facies of the Arche buildup (Arche Member, Frasnes) and explanation of symbols

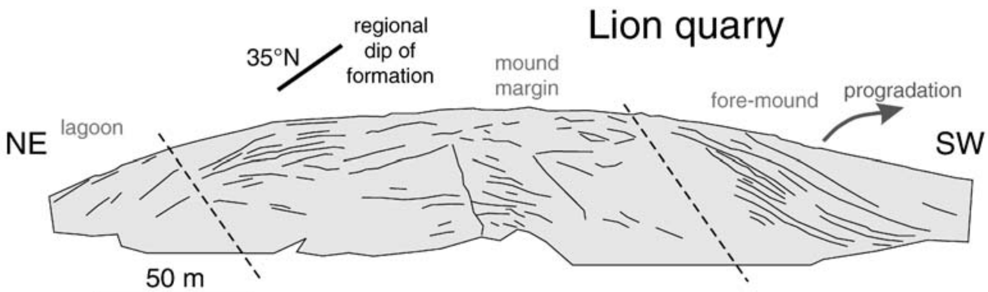

Fig. 7 Front view of the Lion Member at the Lion quarry, Frasnes with the stratification highlighted

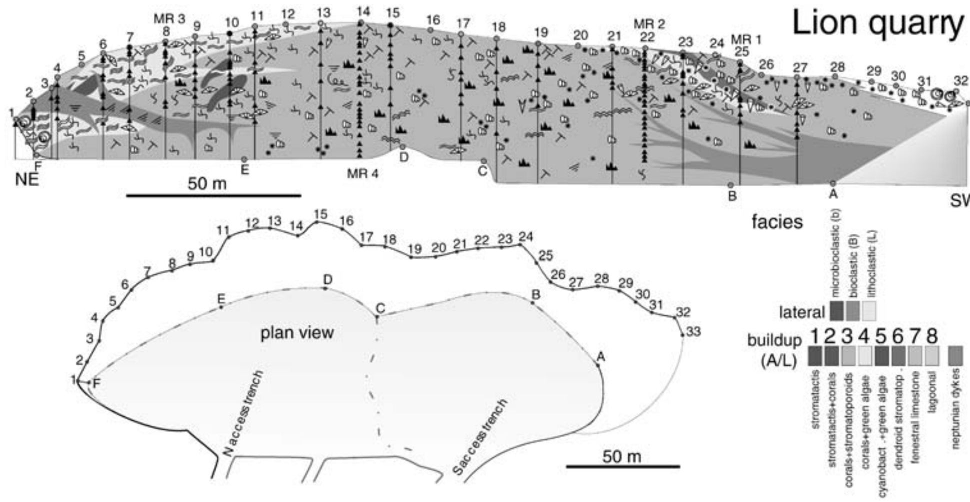

Fig. 8 Logs and facies of the Lion buildup (Lion Member, Frasnes)

B, C and D sections correspond to the main quarry and a complementary section was studied in an old abandoned quarry (Leus quarry) lying at the eastern edge of the hill (Fig. 5).

Section A is the most complete (Figs. 9, 10); it starts from the bottom of the quarry and continues towards the west, then to the north until it reaches the top of the mound at the north-western end of the quarry (Fig. 3G). The section starts with 2 m of red floatstone rich in branching tabulate corals, laminar stromatoporoids, crinoids and stromatactis (L2 and L3). From 2 to 9 m, the colour changes rapidly to light grey with no evident faunal change. Subhorizontal fractures with spar balls (Playford 1984) and zebra calcite (Fig. 3H) are observed. From 9 to 26 m, floatstones with tabulate corals, tabular stromatoporoids, crinoids and stromatactis (L3) alternate with nebuloids (flattened decimetre-thick lenses of brachiopods cemented by marine fibrous cement, interpreted to be tempestites; Boulvain 2001). The next unit, from 26 to 31 m, is richer in microbial coatings, peloids and dendroid stromatoporoids (L4 and L6). From 31 to 52 m, the facies L3 is again present and is locally interbedded with minor bioclastic grain flows (B).

A major sedimentary break at 52 m is characterized by the darkening of the last two beds (0.7 m) together with the presence of a thin black coating of manganese oxides-hydroxides, covering all fenestrae walls. Moreover, a concomitant faunal change is marked by a spectacular enrichment in the planktic foraminiferan *Nanicella* and considerable bioturbation. Above a centimetre-thick, dark clay seam, the dips of the strata increase and facies L2 with abundant stromatactis, crinoids and brachiopods represents the first carbonate sediment above the discontinuity. From 59.5 to 62 m, floatstone with stromatactis, rugose and tabulate corals (L3) is observed. This grades upwards (62–89 m) into microbial bindstone and bafflestone (L5) alternating with grainstone rich in fragments of microbial coatings (L4). From 89 m to the end of the section, the algal-microbial facies alternates with dendroid stromatoporoid rudstone (L6). The upper 12 m of the buildup are characterized by the local reappearance of facies L3.

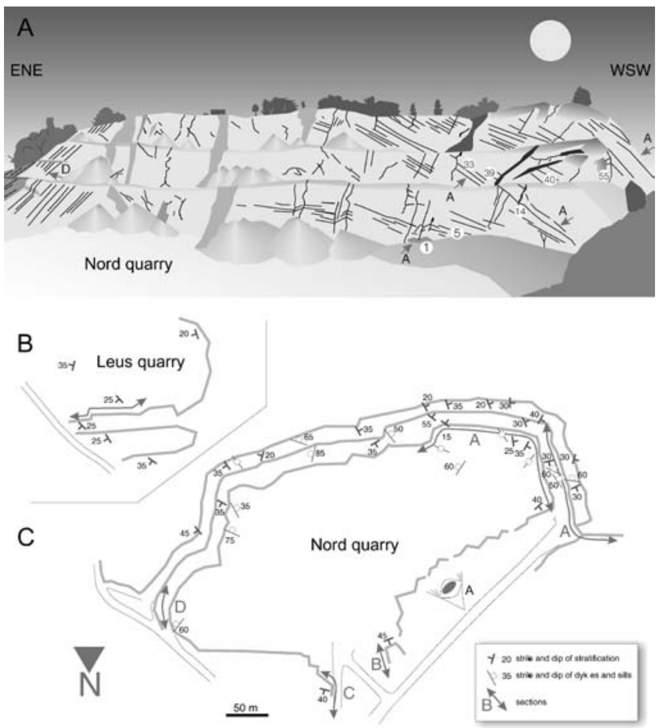

Fig. 9 A Front view of the Nord quarry, with location of sections *A* and *D* and selection of bed numbers. B Map of the Leus quarry with location of section. C Map of the Nord quarry with location of sections and geometry of stratification and synsedimentary fractures

The B, C and D sections are located at the back side of the mound, near its northern end. They are characterized by light grey wackestone to grainstone with lithoclasts, fenestrae and calcispheres (L7). This facies constitutes the top of the mound and passes upwards into the Boussu-en-Fagne Shale showing centimetre-thick bioclastic limestone lenses (first rich in corals and crinoids, then in brachiopods) and local oolitic grainstone.

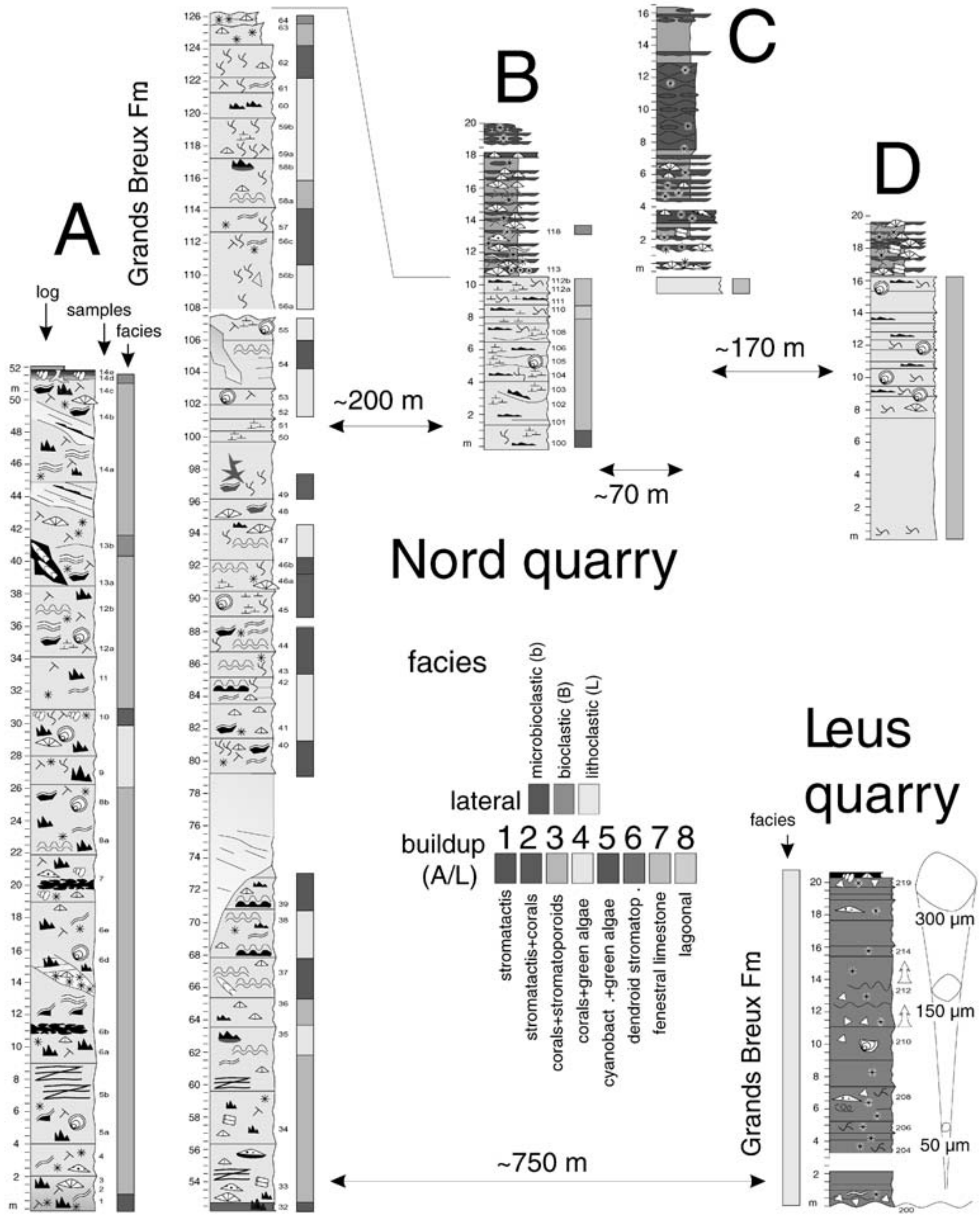

Fig. 10 Logs and facies of the Nord buildup (Lion Member, Frasnes)

The Leus section shows the transition between the Nord buildup and the off-mound facies of the Frasnes railway section (Fig. 5). Given the landward location of the section with respect to the main part of the buildup, it could represent the back-mound flank. The Leus section is very monotonous and shows 20 m of lithoclastic-bioclastic grainstones and packstones rich in palaeosiphonocladal algae, calcispheres, degraded crinoids and *Amphipora*. The section as a whole is graded bedded: the lithoclast diameter increases from 50 μm near the base to 300 μm at the top of the section (Fig. 10).

The Lompret quarry

The Lompret quarry lies close to the village of Lompret, 5.5 km NE of Chimay. The quarry is located in bedded limestone belonging to the Bieumont Member (Fig. 3D). The studied section is located at the east end of the quarry. It is an old working face with a roughly north-south direction. The base of the Bieumont Member is not exposed. The strike of the strata is N 105° E with a dip of 22°N.

The section starts with 5 m of dark grey homogeneous argillaceous limestone (Fig. 11). Fauna is not abundant and poorly diversified (unit 1). This unit is overlain by approximately 12 m of alternating pure and argillaceous limestone. Organisms are even less abundant (unit 2). Small brachiopods, trilobites, cricoconarids, gastropods,

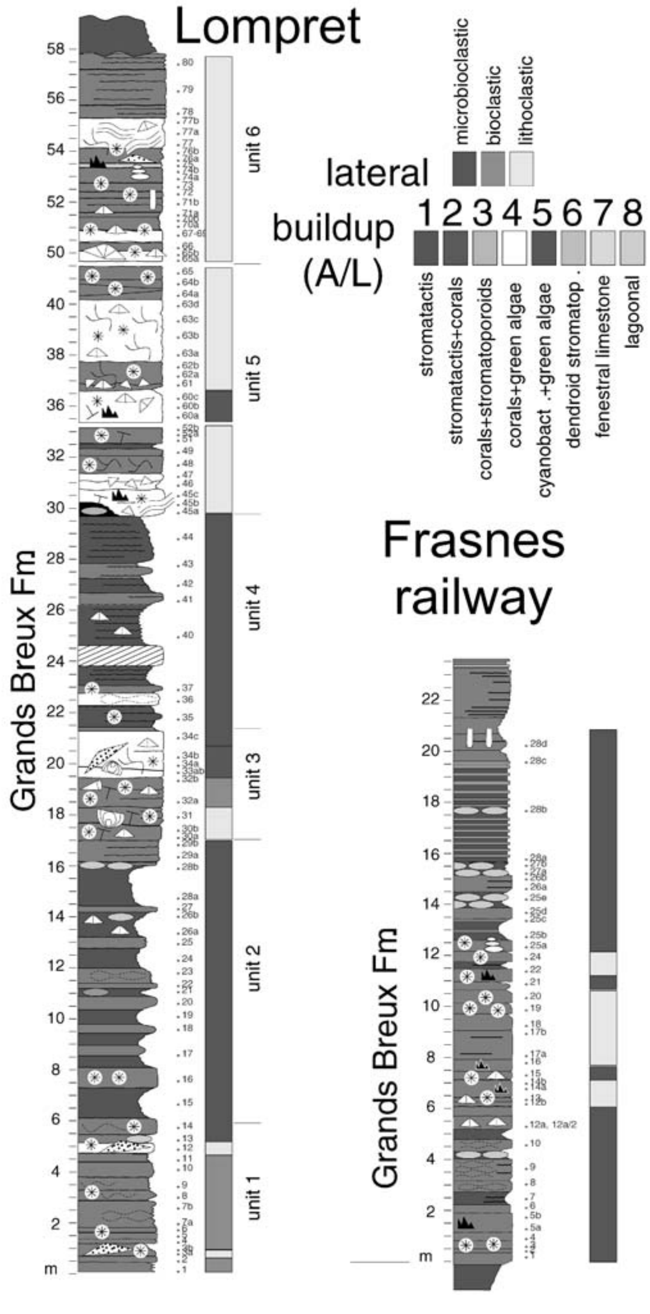

Fig. 11 Logs and facies of the Bieumont Member in the Lompret quarry and Frasnes railway section

ostracodes and crinoids are observed. The small solitary rugosan coral *Metriophyllum*, typical of open-marine facies, is present.

Unit 3 (17–21.5 m) shows a sharp facies change with a much more massive and grainy character. These layers are very rich in bioclasts and locally show fining-upward graded beds suggesting, together with the lenticular geometry, a system of submarine channels. The next unit (unit 4:21. 5–30. 5 m) marks the return to alternating argillaceous and pure limestone. These strata are darker with few reefal fossils. The following unit, the fifth (30.5–40 m), corresponds to a succession of debris flows. After a gap, the last unit consists of darker and finer-grained limestone. However, bioclastic material was still present as indicated by the sporadic presence of thinner and narrower grain-flow beds.

The Frasnes railway section

The stratotype of the Bieumont Member is located in Frasnes, between the Nord and Lion quarries (Fig. 5) along the Charleroi-Couvin railway. Whereas light grey bioclastic or lithoclastic limestone is observed in the Lompret quarry, the Frasnes railway section shows only dark grey fine-grained argillaceous limestone with argillaceous intercalations (Fig. 11). It is possible to subdivide this section into two distinct units (Coen-Aubert 1994): the first 16 m consist of dark fine-grained bioclastic or lithoclastic limestone, relatively argillaceous and locally subnodular, whereas the member ends with 21 m of fine-grained, very argillaceous limestone, with numerous argillaceous intercalations.

Facies interpretation

Textural facies interpretation and nature of fossil assemblages allow to interpret the degree of restriction of the environment and to propose a relative bathymetric scale based on simple reference marks such as the base of the photic zone, storm (SWB) and fair weather wave base (FWWB).

The A2/L2 facies, characterized by a poorly diversified fauna (corals and crinoids), without algae nor evidence for wave action, is relatively rare in the Arche and Lion mounds. In the Late Frasnian Petit-Mont mounds (Boulvain 2001), an equivalent facies (Pm2) was interpreted as developing in a low energy, slightly suboxic environment below the photic zone. Evidence for the suboxic tendencies of the environment was the presence of abundant microaerophilic iron bacteria in the sediment (Boulvain et al. 2001).

The A3/L3 facies with stromatactis, corals and stromatoporoids includes some cyanobacteria and shows episodic reworking by storm waves. It developed close to storm wave base (SWB), in a subphotic environment. It includes A5/L5 lenses, with stromatolitic coatings and thrombolithes rich in *Renalcis*. These lenses become abundant and anastomosing when the depth decreases. This shallowing is also highlighted by the progressive occurrence of green algae, as in facies A4/L4. These two facies developed close to fair weather wave base (FWWB) and in a photic environment. The A6/L6 facies is characterized by its lithoclastic character, the abundance of dendroid stromatoporoids and the dominant grainstone texture, with possible graded bedding. This facies resembles the “*Amphipora* floatstone and rudstone” from the subtidal facies association of the Miette and Ancien Wall buildups (Whalen et al. 2000). It corresponds to an environment located above FWWB, with possible evolution to restricted conditions marked by a relatively low faunal diversity. This *Amphipora* -rich facies is also observed in debris-flow beds deposited on the flanks, especially in the fore-mound environment (Lion quarry, Fig. 8, sections 23 and 25). In the upper central parts of the mounds (Lion quarry, sections 1–5, Fig. 8 and Nord quarry, sections B and D, Fig. 10), facies A6/L6 shows a progressive transition to fenestral limestone rich in peloids, calcispheres and palaeosiphonocladales (A7/L7). This facies is very similar to the "laminite facies" from the reef-flat interior of the classic Frasnian Golden Spike reef complex, Alberta (Mc Gillivray and Mountjoy 1975) or to the "peloidal packstones and grainstones" from the peritidal facies association of the Miette and Ancien Wall buildups (Whalen et al. 2000). For Hopkins (1972), this facies was deposited in a lagoonal environment. In the Belgian buildups, this very shallow facies develops in a moderately restricted intertidal area. The last facies (A8-L8) is very fine-grained and is deposited in a relatively shallow quiet subtidal lagoonal environment.

The bedded bioclastic-lithoclastic facies result 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 (b) are characterized by an open-marine facies with brachiopods, bryozoans and crinoids, whereas bioclastic rudstones (B) and lithoclastic packstones and grainstones (L) show a clear buildup influence through abundant input of bioclastic and lithoclastic material. These flank facies are similar to the bioclastic-lithoclastic fore-reef strata of the Frasnian carbonate buildups from the Leduc Formation (Mc Gillivray and Mountjoy 1975) or from the Miette and Ancient Wall buildups (Whalen et al. 2000).

Geometry of buildups

Lateral facies

Microbioclastic packstones (b) are mainly observed in off-mound facies (Frasnes railway section and units 2 and 4 from the Lompret quarry, see Fig. 11). In this facies, the influence of reefs on the sediment budget remains relatively low. On the other hand, the lithoclastic grainstones and bioclastic rudstones (L and B) are facies where extensive supply of reefal debris is significant. This reefal input is particularly evident in the Lompret section (Fig. 11), where open-marine facies are interrupted by bioclastic-lithoclastic sediment reworked from the mound, deposited by debris flows showing decimetre-deep basal erosion structures (units 3, 5, 6 of Fig. 11). The sections in the southern part of the Lion quarry (Fig. 8, sections 21 to 27) are rather similar, but as they are closer to the main part of the buildup, they show an interbedding with in situ facies L3. Another type of lithoclastic facies is present around the Nord buildup, in the Leus quarry (Fig. 10), where the general coarsening-upward trend reflects the progradation of the mound. As the Leus quarry is located along the back section of the Nord mound and the sediments mainly consist of well-sorted reworked lithoclastic material (L) without any macrofossils, this section is interpreted as a back-mound flank deposit.

The base of the buildups

The buildups began with the development of large coral colonies (fasciculate rugose corals in the Arche quarry) on a muddy seafloor, followed by the progressive colonization of this substrate by sponges, and finally more intense microbial (?) carbonate production in the form of centimetric to decimetric lenses of micrite. Later, lateral progradation operated by the simple extension of the bioconstructed facies without a colonization phase of the substrate by corals. In the Arche quarry, the basal mound unit is coloured red from the presence of iron bacteria (Boulvain et al. 2001), whereas in the Nord quarry, only several metric to decametric lenses of L2–3 limestone are red and there are surrounded by light grey L3 facies.

The internal architecture of the buildups

The first significant observation is the facies similarity between the Arche and Lion members. Much more, the facies succession and their distribution are also very similar (Fig. 12). Indeed, the two generations of buildup began with grey or pinkish floatstone containing stromatactis, corals and stromatoporoids (A3/L3). After about 40 to 70 m of this facies forming the bulk of the mounds, the grey "algal" A4/L4 facies began to develop, including microbial bindstone or bafflestone lenses (A5/L5) which tend to coalesce upwards. More restricted facies developed in the central part of the buildups, as shown by the Lion (1 to 6) and Nord sections (B, C and D). This geometry suggests the development of an area of relatively restricted sedimentation, i.e. some kind of inner shallow lagoon, sheltered by the bindstone or floatstone facies of the mound margin. As the same geometry is observed in the La Boverie quarry (Boulvain et al. 2004), the name of "atoll-like mound" is proposed for the Arche and Lion members.

The nature of the facies and the characteristic geometry of the Arche and Lion buildups are compared with Frasnian carbonate buildups from the Leduc Formation (Alberta, Canada). In these reefs, the fore-reef strata consist of detrital coral and stromatoporoid facies; the reef margin comprises a massive stromatoporoid facies whereas the laminites and *Amphipora* facies represent the main facies in the inner lagoon (Mc Gillivray and Mountjoy 1975; Mountjoy 1980; Whalen et al. 2000). Moreover, the general size of some Alberta mounds, although variable and dependant on the subsidence rate, is similar to that of the Belgian mounds; e.g., the Golden Spike Leduc reef is 3.6 km x 2.4 km in area and 182 m in height, according to Mountjoy (1980). However, an im-

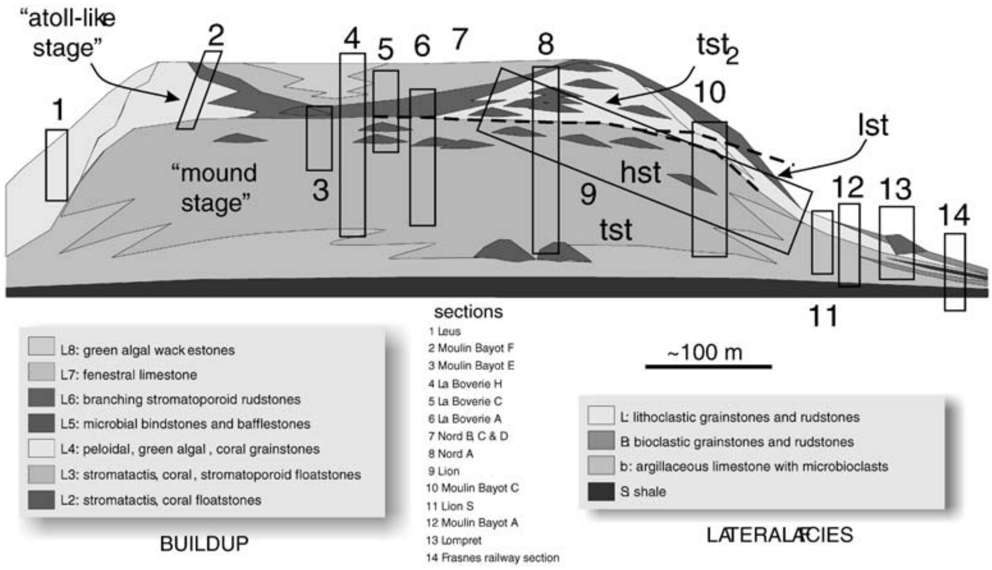

Fig. 12 General sedimentological model of the Frasnian Arche and Lion buildups. Rectangles correspond to the different sections listed in the lower central part of the figure. La Boverie and M. Bayot sections: see Boulvain et al. (2004)

portant difference between Belgian and Alberta buildups lies in the fact that the latter are characterized by a well-developed rim of stromatoporoid biostromes (Whalen et al. 2000), when the Belgian buildups show only mud-rich mound-type facies.

Sediment dynamics

By comparison with recent models of atoll development in response to eustatic variations (Warrlich et al. 2002), a dynamic interpretation is suggested for the geometry and succession of sedimentary units in the Lion and Arche members (Fig. 12). After the growth of the lower part of the mounds during transgression, possibly with a short episode of low oxygen conditions revealed by the presence of iron bacteria (Boulvain et al. 2001), a clear progradation is recorded by fore-mound sedimentation of reworked material, as observed in the southern part of the Lion quarry and the Lompret section. Lower sea level then restricts reef growth to occur only downslope, culminating in the development of a circular reef margin during the following transgressive stage. The presence of relatively restricted facies is therefore possibly the result of a balance between sea-level rise and reef growth.

Knowing the geometry and bathymetry of the sedimentary bodies, a 3rd-order sequence subdivision of the buildups and their lateral sediments is proposed (Fig. 12). The lower and middle parts of the buildups correspond to the succession of a transgressive systems tract (TST) and/or a highstand systems tract (HST) with strong progradation associated with reduced accommodation space occurring during the HST. The mound development during the lowstand systems tract (LST) was restricted to the margin of the buildups, with possible emergence and synsedimentary lithification. This lowering of sea-level was recorded in the internal platform by subsequent widespread development of paleosols in the upper part of the Lustin Formation (da Silva and Boulvain 2002). The development of an atoll-like margin corresponds to the TST2 with significant lateral facies differentiation between fore-mound and mound lagoon.

By comparison, the 3rd order sequence pattern of the Leduc buildups seems more complex, as six depositional sequences were recorded by Whalen et al. (2000) and Van Buchem et al. (2000). However, Leduc buildups cover a time span of 4 conodont zones, from the Early *Hassi* to the Late *Rhenana* Zones. In Belgium, it is the whole Arche and Lion mounds succession that covers 4 conodont zones, from the *Punctata* to the *Jamieae* Zones (Boulvain et al. 1999).Within this succession, at least 4 depositional sequences are recorded.

This overall picture gives rise to the following interpretations: transgressive systems tracts may correspond to various unit types according to the developmental stage of the buildups and perhaps to different rates of sea-level rise. They may correspond to aggrading "deep" mound facies (TST) or to shallow facies developing in a lagoon (TST2). These two TST are keep-up type units (Neumann and Macintyre 1985). The lowstand systems tracts are poorly developed, implying low accommodation space and a temporary emergence of the buildups.

Conclusions

Facies description and interpretation of Frasnian Arche and Lion carbonate mounds lead to the definition of seven buildup facies (A2-A8 or L2-L8) and three lateral facies (b, B and L). Buildups started in a relatively deep, quiet aphotic environment with a sponge-coral-crinoid assemblage (A2/L2), first reached storm wave base and the subphotic zone (A3/L3, stromatoporoid-coral-stromatactis assemblage), and then fair-weather wave base and the euphotic zone (A5/L5). The upper parts of the buildups are characterized by algal-microbial facies (A4/L4 and

A5/L5) protecting a central restricted area of sedimentation with dendroid stromatoporoid facies (A6/L6) and fenestral limestone (A7/L7). The lateral facies range reflects different kind of sediment supply of reworked material, from fine-grained sheet flows to coarse-grained debris flows.

The geometry of the buildups shows two development stages: a first homogeneous mound stage and a later atoll-like stage with significant lateral facies differentiation. The mound stage developed as a transgressive and highstand systems tracts, whereas the atoll-like stage corresponds to a lowstand and transgressive systems tracts.

If this sequence stratigraphic interpretation of Belgian Middle Frasnian buildups supports the presence of transgressive and regressive phases, the existence of complete Exxon cycles of sea-level change (Vail et al. 1977) is not yet proven. For smaller-scale variations (4th and 5th order), observations show that the bioconstructed facies do not reflect a sequence organization, suggesting some kind of biological feedback in relation to variations in oceanic parameters (Boulvain 2001).

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