Frasnian carbonate mounds from Belgium: sedimentology and palaeoceanography

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Abstract: The facies architecture, sedimentary dynamics and palaeogeographic evolution were reconstructed for a number of middle–late Frasnian carbonate mounds from the south side of the Dinant Synclinorium (Belgium). Nine facies were recognized in the buildups, each characterized by a specific range of textures and assemblage of organisms: spiculitic wackestone with stromatactis (facies Pm1), which becomes progressively enriched in crinoids and corals (Pm2); grey or pinkish limestone with stromatactis, corals and stromatoporoids (A3–L3, Pm3); grey limestone with corals, peloids and dasycladales (A4–L4, Pm4); grey, microbial limestone (A5–L5, Pm5); grey limestone with dendroid stromatoporoids (A6–L6); grey, laminar fenestral limestone, (A7–L7); and grey, bioturbated limestone (A8–L8). Sedimentological evidence suggests that facies Pm1 and Pm2 correspond to iron bacteria–sponge-dominated communities, developing in a quiet aphotic and hypoxic environment. A3–L3 developed between storm and fair-weather wave base, in an oligophotic environment. Facies A5–L5 developed close to fair-weather wave base. Facies A6–L6 and the fenestral limestone A7–L7 correspond to an environment with slightly restricted water circulation. Facies A8–L8 developed at subtidal depths in a quiet, lagoonal environment. The main differences between the middle and late Frasnian mounds concern facies architecture, and are a consequence of different palaeoceanographic settings. The large flattened middle Frasnian Arche and Lion buildups show limited vertical differentiation, large-scale progradation features, extensive exportation of material towards off-reef environment and development of inner lagoonal facies. They grew offshore from a well-developed carbonate platform with a healthy carbonate factory. Middle Frasnian sea-level fluctuations were relatively mild, and sedimentation was able to keep up with sea-level rise. At the opposite extreme, during the late Frasnian, severe eustatic rises, together with rising oceanic hypoxic conditions, were responsible for frequent collapses of the carbonate factory, drowning of the middle Frasnian carbonate platform, and development of buildups with relatively limited lateral extension, high vertical facies differentiation, low potential for material exportation and high content in microaerophilic iron bacteria.

Among the various Palaeozoic carbonate mounds known throughout the world (e.g. Bosence & Bridges 1995; Monty 1995; Pratt 1995; Bourque 1997), the Frasnian carbonate mounds of Belgium are probably the earliest studied. This remarkable interest carried by generations of geologists derives from the number and quality of outcrops: currently 75 carbonate mounds are known, and the majority have been actively quarried since Roman time. The combination of extraordinary outcrop exposure and a well-documented Devonian stratigraphy makes Frasnian carbonate mounds in Belgium of international significance (e.g. Tsien 1975). This paper is devoted to the middle Frasnian Arche and Lion buildups and the late Frasnian Petit-Mont Member. It illustrates various facies architectures, interprets mound palaeoenvironments, and assesses the possible relationship between evolution of carbonate mounds and changes in palaeoceanographic setting of the sedimentary basin.
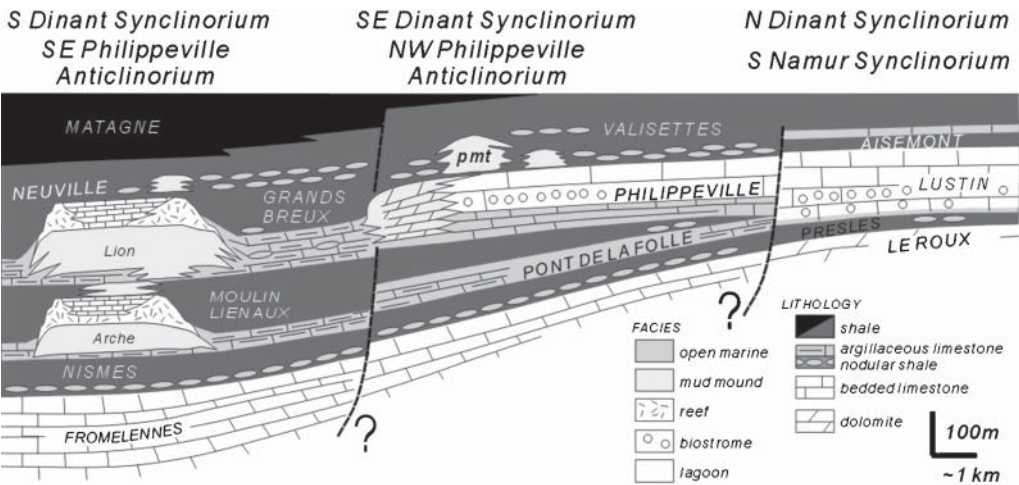
Location and geological context

The Belgian Frasnian lithostratigraphy has been revised recently (Boulvain *et al.* 1999). Three main levels of carbonate mounds are recognized in the Frasnian of the southern border of the Dinant Synclinorium (Figs 1 & 2), which is a large-scale unit of the West-European Variscan fold-and-thrust belt. These are, upsection, the Arche, Lion 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 & Boulvain 2002, 2004).

The best-known middle Frasnian Arche and Lion buildups are located in the immediate neighbourhood of Frasnes: the Nord quarry
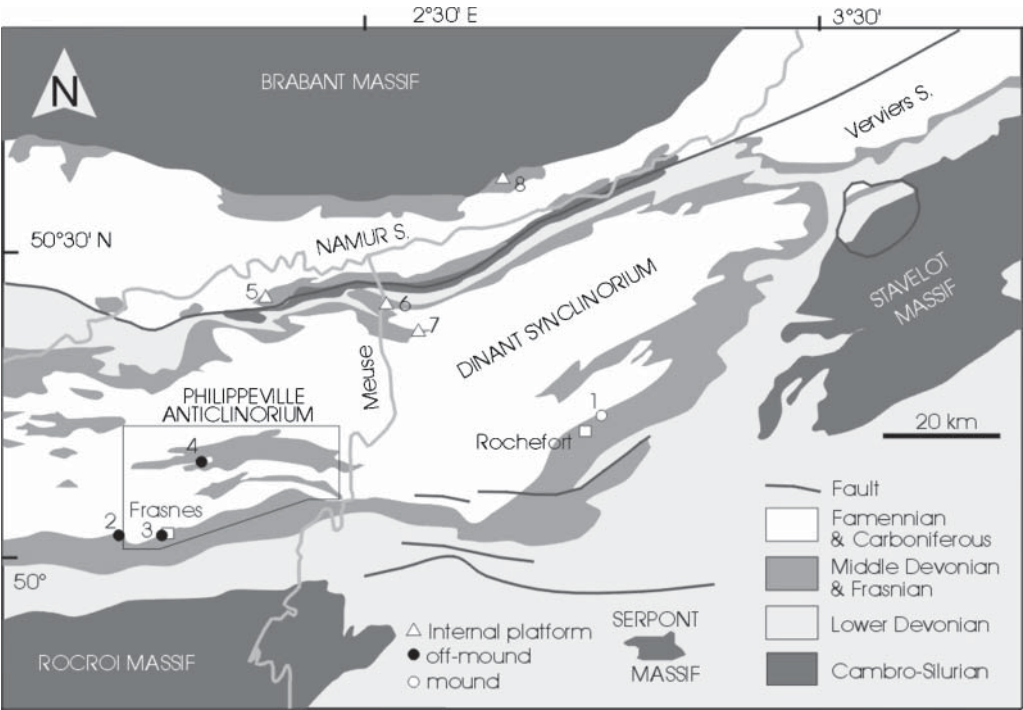
Fig. 1. Schematic geological map of southern Belgium, with location of main outcrops. 1, La Boverie quarry and Humain section; 2, Lompret quarry; 3, Frasnes railway section; 4, Neuville railway section; 5, Aisemont quarry; 6, Lustin and Tailfer sections; 7, Crupet section; 8, Huccorgne section. See Figure 3 for a detailed map of the Frasnes–Philippeville area (framed).

Fig. 2. Schematic N–S cross-section and main lithostratigraphic subdivisions of the Frasnian sedimentary basin before the Variscan orogeny.
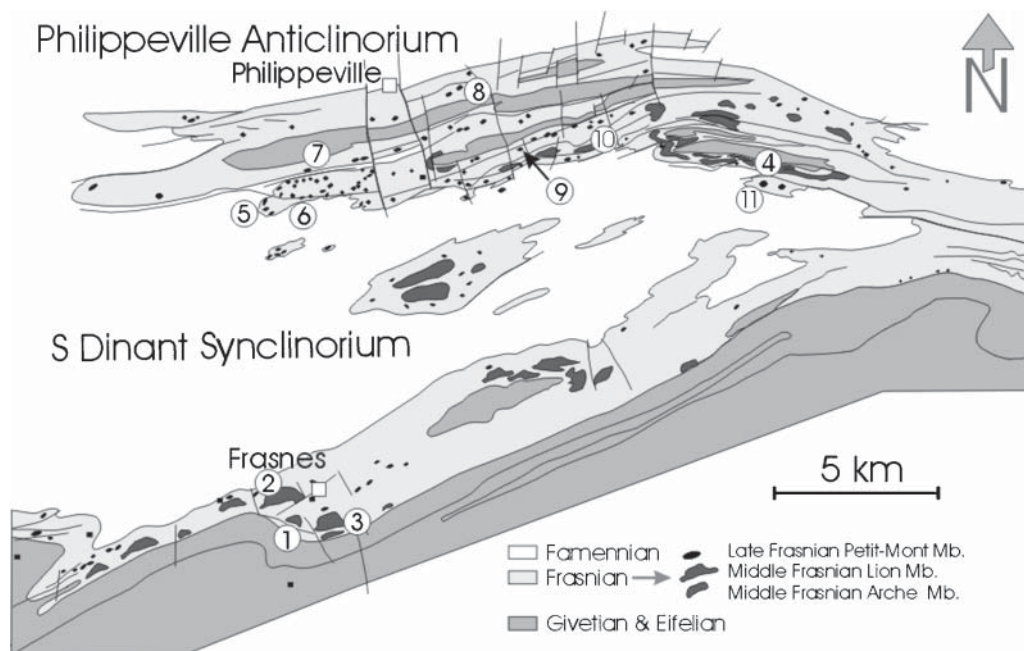
Fig. 3. Detailed geological map of the Frasnes–Philippeville area with location of some Frasnian carbonate mounds. 1, Arche quarry; 2, Nord quarry; 3, Lion quarry; 4, Moulin Bayot sections; 5, Beauchâteau quarry; 6, Tapoumont quarry; 7, Les Bulants quarry; 8, Les Croisettes quarry; 9, Les Wayons quarry; 10, Rochefontaine quarry; 11, Hautmont quarry.

(Lecompte 1954; Boulvain *et al.* 2004), the Lion quarry (Boulvain *et al.* 2004) and the Arche quarry (Lecompte 1954; Boulvain *et al.* 2004); the first two are in the Lion Member, the third is in the Arche Member (Fig. 3). Very recently, Boulvain *et al.* (2005) brought information about a set of outcrops located some distance from Frasnes: the La Boverie quarry close to Rochefort (Fig. 4) and the Moulin Bayot sections close to Vodelée (Fig. 1). At both locations, it was possible to study a series of buildups, starting from the Arche Member and ending with the Lion Member.

Among the 69 late Frasnian carbonate mounds currently listed (Fig. 3), seven buildups from the Philippeville Anticline were examined: Beauchâteau, Les Bulants, Les Wayons (Fig. 4), Rochefontaine, Hautmont, Les Croisettes and Tapoumont (Boulvain 2001).

Several sections in each buildup were described bed by bed, and more than 3000 thin sections were produced. Polished slabs were examined under a binocular microscope. Sections were also studied in peri- and off-mound environments at the southern border of the Dinant Synclinorium (Frasnes, Chimay:

Humblet & Boulvain 2001; Boulvain *et al.* 2004) and in the Philippeville Anticline (Neuville railway sections: Boulvain 2001). Coeval sections were also examined in the internal zones of the Frasnian platform, at the northern border of the Dinant Synclinorium (Lustin, Crupet, Tailfer: Boulvain 2001; Da Silva & Boulvain 2002), at the southern border of the Namur Syncline (Aisemont) and at the northern border of the Namur Syncline (Huccorgne: Boulvain 2001) (Fig. 1).

Previous work

Dewalque (1868) first recognized the 'reefal' character of Belgian Frasnian mounds. After stratigraphic subdivision by Maillieux (1913 1926), Delhaye (1913) recognized a distinct vertical succession of lithofacies within these mounds, but it was Dumon (1932) who related this succession to bathymetric variation. Lecompte (1936, 1959) realized that the Frasnian buildups developed in relatively deep water under conditions of subsidence. His facies zonation (successively lower red zone with corals and stromatactis;
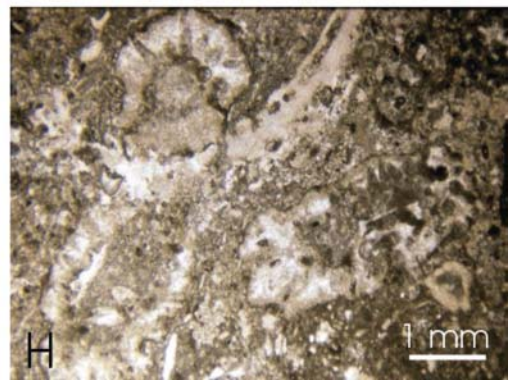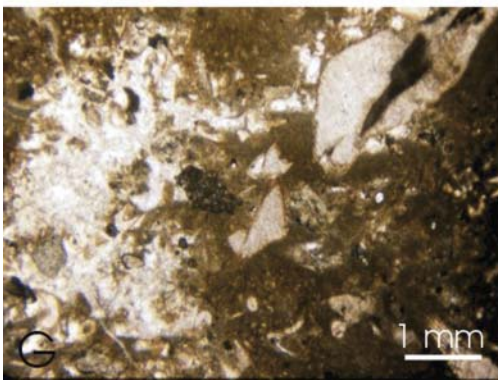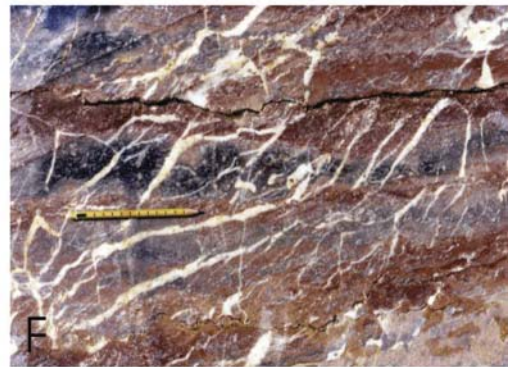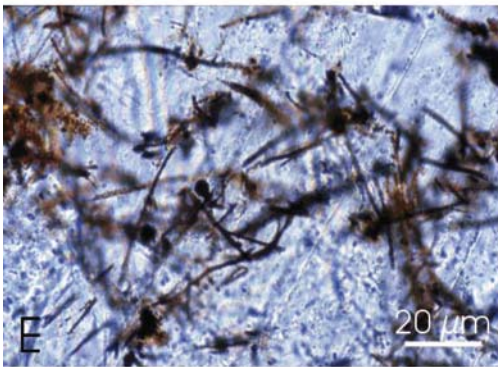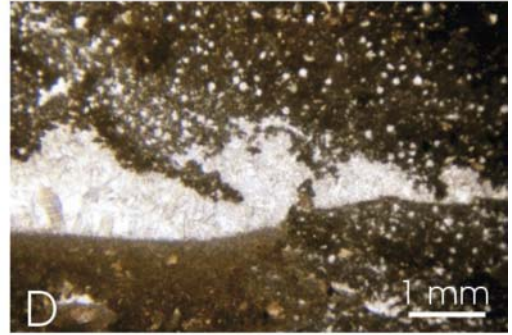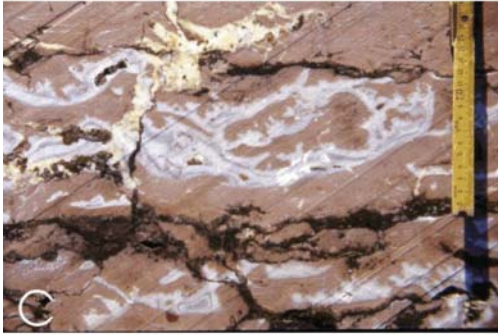
median pink or grey zone with corals, brachiopods, crinoids, stromatoporoids and algae; and upper red zone with corals) was focused on bathymetric and hydrodynamic criteria (below turbulent zone for the red zones and within turbulent zone for the grey or pink zone). According to Tsien (1975, 1980), reefal biofacies were built in the wave action zone (red and pink limestone with corals and cyanobacteria; red and pink limestone with corals and stromatactis; grey limestone with corals and cryptalgal structures), whereas others formed below the wave action zone (red limestone with stromatactis; pink limestone with *Renalcis*). Tsien (1980) also showed that the slopes of buildups were partly oversteepened by differential compaction between buildup limestone and argillaceous non-biohermal sediments. Monty *et al.* (1982) and Monty & Van Laer (1988) asserted that the majority of cavity cements, like the micrite in buildups, were of bacterial origin, and that the presence of microbial gel allowed the development of steep slopes and significant relief. They concluded that the buildups developed below wave base and below the photic zone.

Facies models

Six buildup facies can be defined in the Arche ('A') and Lion ('L') members (facies A3–L3 through to A8–L8) and five (facies Pm1–Pm5) in the Petit-Mont Member, each facies being characterized by a specific range of textures and organic assemblages. Three other facies ('flank facies') can also be defined; these bedded bioclastic and lithoclastic facies being the lateral time-equivalents of the buildup facies. The components in the buildup facies are essentially autochthonous and directly reflect the influence of water parameters such as agitation and light intensity. By contrast, the flank facies contain large amounts of transported material, much of

it derived from nearby buildups (Humblet & Boulvain 2001). The organic assemblages found in the flank facies therefore do not necessarily reflect the environments in which those facies were deposited.

The logic behind the coding scheme used here for designating the buildup facies is the same as that used by Boulvain *et al.* (2001): identical facies are given identical facies numbers, even when they are in buildups at different stratigraphic levels (e.g. A3, L3, respectively, for middle Frasnian Arche and Lion members). This scheme also facilitates comparison with the mounds of the late Frasnian Petit-Mont Member (facies Pm1–Pm5), which have been described in this way (Boulvain 2001). The following descriptions of the buildup facies are organized bathymetrically, from deep to shallow, according to textures and fossil assemblage.

Buildup facies: late Frasnian Petit-Mont Member

Red limestone with stromatactis (facies Pm1). The intense red pigmentation of this facies is the consequence of a hematite content up to 5% Fe_2O_3 (Fig. 4C, E, F). The occurrence of stromatactis is variable. Stromatactis may be grouped in metre-scale beds forming a reticulate structure and exceeding 50% of the rock. Stromatactis may exceed 50 cm in length, but generally diminish in size towards more argillaceous zones. Stromatactis are cemented by inclusion-rich radiaxial calcite. The cement surmounts various types of internal sediment (laminar microspar; microspar with vermiform texture of Pratt 1982; peloids and pseudosparite; microbial mats; ooids with a microsparitic cortex). A strict geometrical relationship between spicular networks and stromatactis does not exist: spicules can overlie, penetrate or form concentrations below stromatactis. In addition to stromatactis,

Fig. 4. (A) Upper part of the Beauchâteau mound, near Senzeilles, late Frasnian Petit-Mont Member, Philippeville Anticlinorium. The height of the outcrop is 30 m. (B) Lower part of the Les Wayons mound, near Merlemont; late Frasnian Petit-Mont Member, Philippeville Anticlinorium. Log of the mound, see Figure 6. (C) Red limestone with stromatactis (facies Pm1); Les Croisettes quarry, Vodecée, late Frasnian Petit-Mont Member, Philippeville Anticlinorium. (D) Stromatactoid fenestra surrounded by a spicular network (facies Pm1); thin section HMC17, normal light; Hautmont quarry, late Frasnian Petit-Mont Member, Philippeville Anticlinorium. (E) Iron bacteria in sparite; thin section RFX, normal light; Rochefontaine quarry, Villers-le-Gambon, late Frasnian Petit-Mont Member, Philippeville Anticlinorium. (F) Pink limestone with corals, crinoids, brachiopods, stromatactis, fenestrae, stromatoporoids and nebuloids (grey horizontal beds) (facies Pm3); Les Bulants quarry, late Frasnian Petit-Mont Member, Philippeville Anticlinorium. (G) Wackestone with stromatactoid fenestrae, crinoids, fenestellids and peloids (facies Pm3); thin section TP 44, normal light; Tapoumont quarry, late Frasnian Petit-Mont Member, Philippeville Anticlinorium. (H) Packstone with peloids and *Trelonella* (facies Pm4); thin section TPG2a, normal light; Tapoumont quarry, late Frasnian Petit-Mont Member, Philippeville Anticlinorium.

millimetre-scale fenestrae with granular sparitic cement are common (Fig. 4D). Sponges are abundant (e.g. tetractinellids, hexactinellids and other non-rigid demosponges with a simple monaxone assemblage of spicules: Termier *et al.* 1981). Matrix is microsparitic–pseudosparitic.

Red limestone with stromatactis, lamellar corals, crinoids (facies Pm2). This facies differs from the former by the addition of crinoids and lamellar corals such as *Alveolites* and *Phillipsastrea*. Decimetre-scale stromatactis and centimetre-scale stromatactoid fenestrae (see Neuweiler *et al.* 2001) with granular cement are abundant. Supported cavities filled with radiaxial cement typically occur below lamellar organisms.

Pink limestone with corals, crinoids, brachiopods, stromatactis and lamellar stromatoporoids (facies Pm3). This facies shows decimetre-scale beds rich in millimetre-scale stromatactoid fenestrae, crinoids, brachiopods, and other bioclasts intercalated with beds containing sparse fenestrae, corals and subordinate stromatoporoids. Corals are generally tabular (*Alveolites, Phillipsastrea, Thecostegites*), branching (*Thamnopora, Senceliaepora*) or fasciculate (*Thamnophyllum*); solitary rugose corals are also present. *Receptaculites* is locally abundant. This facies is locally interbedded with more argillaceous bioclastic units rich in crinoids, coral fragments and brachiopods. Enigmatic structures consisting of decimetre-thick pockets or beds of dark grey radiaxial cement containing brachiopods and crinoids occur (Fig. 4F). These particular structures (called 'nebuloids', cf. Boulvain 2001) may pass laterally by reduction in the proportion of cement, into a network of centimetre-scale stromatactis or fenestrae. *Girvanella* and *Rothpletzella* (here interpreted as cyanobacteria) form partial coatings around particles, and peloids are common and irregular.

Grey limestone with algae, fenestrae, branching tabulate corals and brachiopods (facies Pm4). This facies is devoid of stromatactis. Microfacies are characterized by common peloids and encrusting cyanobacteria. Coatings are generally composite, consisting of an association of various algae and bryozoans. Green algae (*Trelonella, Radiosphaeroporella*) are abundant (Mamet & Boulvain 1992) (Fig. 4H).

Grey limestone with corals, stromatoporoids, microbial mats, thrombolites (facies Pm5). This facies forms massive limestone with stylolites. Decimetre- to metre-scale growth cavities cemented by granular spar are abundant. Breccia is locally present. The fauna is dominated by subspherical coral colonies (*Hankaxis, Phillipsastrea, Alveolites*), *Thamnopora*, brachiopods and subordinate dendroid stromatoporoids (*Amphipora*). *Renalcis* is locally abundant. Thrombolitic structures and microbial mats are present. Within thrombolites, *Renalcis* is associated with *Palaeomicrocodium* (Mamet & Boulvain 1992). All thrombolites and stromatolites appear as a canvas made up of irregular peloids set in a yellowish pseudosparitic cement (the 'structure grumeleuse' of Cayeux 1935). Irregular peloids and fragments of microbial mats are abundant. Most organisms (including *Palaeomicrocodium*) are strongly encrusted by *Rothpletzella, Girvanella, Wetheredella* and microbial mats.

Buildup facies: middle Frasnian Arche and Lion members

Like that from late Frasnian mounds, the following descriptions of the middle Frasnian buildup facies are organized bathymetrically, from deeper to shallower environments.

Grey, pinkish or greenish limestone, with stromatactis, corals and stromatoporoids (facies A3 and L3). This facies is composed of wackestones and floatstones showing decimetre-scale stromatactis and centimetre-scale stromatactoid fenestrae, with abundant branching tabulate corals, brachiopods and crinoids (Fig. 5C, F). Locally, there are massive or tabular (rarely dendroid) stromatoporoids, bryozoans, peloids and fasciculate rugose corals. Some subordinate cricoconarids, palaeosiphonocladale algae and calcispheres are present. Coatings (*Rothpletzella*) are rarely developed. Many of the fenestrae correspond to cavities situated below a lamellar organism (umbrella effect) or to growth cavities. Local reworking and concentration of bioclasts by storm action might result in this facies evolving into a bioclastic rudstone. This facies resembles late Frasnian Pm3, but with less hematitic pigment.

Grey limestone with algae, fenestrae, branching tabulate corals, stromatoporoids and brachiopods (facies A4 and L4). This facies is composed of rudstones, grainstones and floatstones, with peloids, lithoclasts (fragments of coating), branching tabulate corals coated by *Rothpletzella*, brachiopods, some crinoids, dendroid stromatoporoids, radiospheres and calcispheres. Locally, some Udotaeacea occur. Stromatactoid fenestrae and stromatactis are present. This facies corresponds to the first occurrence of Udotaeacea, together with the development of

very thick and symmetrical coatings. This facies is similar to Pm4.

Grey microbial limestone (facies A5 and L5). This facies is composed of thrombolitic and stromatolitic bindstones and bafflestones, with *Renalcis*, stromatoporoids, tabulate corals, some Udotaeacea, brachiopods, bryozoans and rugose corals (Fig. 5G). Thick coatings of *Rothpletzella* alternate with encrusting microbial laminae rich in peloids. This facies is commonly found associated with facies A3–L3 or A4–L4, as isolated or coalescent metre-scale lenses. This facies is similar to Pm5

Grey limestone with dendroid stromatoporoids (facies A6 and L6). This facies is composed of rudstones, floatstones or grainstones that are rich in peloids, lithoclasts and dendroid stromatoporoids (mainly *Amphipora*) (Fig. 5H). These latter components are thickly coated by *Rothpletzella* or microbial laminae; the coatings are symmetrical. Calcispheres, palaeosiphonocladales (*Issinella, Proninella*) and Udotaeacea (*Trelonella*?) occur. Branching tabulate corals, gastropods and crinoids are present in places. Irregular fenestrae occur in matrix-rich zones.

Grey laminar fenestral limestone (facies A7 and L7). This facies is composed of grainstones and wackestones, with peloids, lithoclasts, calcispheres and palaeosiphonocladales. There are abundant millimetre-length fenestrae scattered throughout the sediment, bedding-parallel (Fig. 5E, I). Locally, there are dendroid stromatoporoids, which are commonly thickly coated.

Bioturbated grey limestone (facies A8 and L8). This facies is composed of wackestones and mudstones with palaeosiphonocladales, calcispheres and peloids. There is commonly evidence of bioturbation: open, vertical burrows filled by pseudosparitic–sparitic cement. Branching tabulate corals, stromatoporoids, ostracods and gastropods are present.

Off-mound and flanking facies

The following descriptions of the off-mound and flanking facies are organized according to content and to grain size.

Shale, nodular shale and argillaceous limestone. This facies includes green–brown shale with sporadic limestone nodules. Nodules are of centimetre–decimetre scale and commonly are irregular. In some cases, nodules coalesce to produce irregular beds of greenish-grey argillaceous limestone containing brachiopods and crinoids. Sponges (lyssakine hexactinellids, and tetractinomorph demosponges) are locally abundant.

Microbioclastic packstones. This facies is composed of thin-bedded, dark, commonly argillaceous, fine-grained (*c.* 100 µm) bioclastic packstones, containing brachiopods, crinoids, rugose corals, tabulate corals, fenestellids, ostracods, trilobites, peloids and cricoconarids. Locally, there are laminar stromatoporoids. Deformative bioturbation is commonly intense. The development of microsparite in the matrix is typically more intense than in all other facies and seems to be related to a higher clay content.

Crinoidal packstones and grainstones. This dark grey limestone with crinoids and bioclasts forms decimetre-thick lenses or beds, with a slightly undulating planar upper surface and an erosive lower surface. Upper surfaces locally were used as substrates by corals.

Bioclastic packstones and grainstones. This facies is composed of dark, centimetre to decimetrethick beds of rudstones, packstones and grainstones. It forms isolated lenses within the microbioclastic facies or within shales. The bioclasts are the same as in the microbioclastic facies, but are coarser grained (*c.* 500 µm). Some lithoclasts, radiospheres and calcispheres are present. Hummocky cross-lamination is developed in places.

Packstones and grainstones with peloids and lithoclasts. This facies is composed of packstones and grainstones. It differs from the last facies in containing abundant and commonly sorted peloids and lithoclasts, with some subordinate crinoids, fragments of corals and stromatoporoids, brachiopods and bryozoans. The grain size is approximately 300 µm.

Facies interpretation

Below all the carbonate mounds was a soft argillaceous bioturbated substrate that was colonized by sponges, corals, branching bryozoans and some crinoids (Figs 5D & 6). The environment was situated below the photic and wave zones. Sediment had an oxic character (Boulvain 1993). This type of substrate is rather surprising if compared with published reports in which crinoidal sands (Burchette 1981), hardgrounds (Walker & Alberstadt 1975), lamellar corals (Maurin *et al.* 1981) or breccia (Mountjoy & Riding 1981) are common mound substrates.
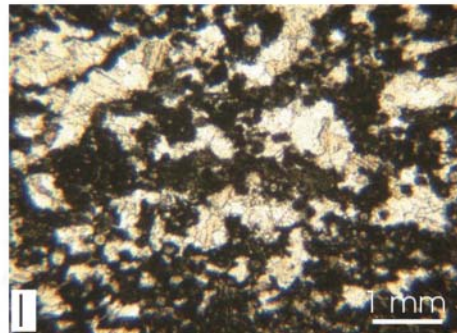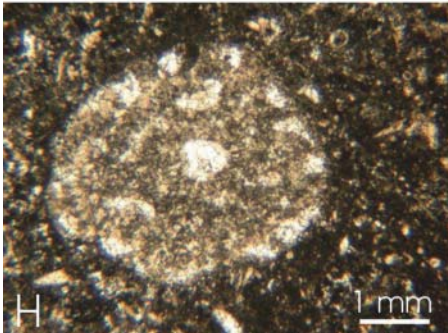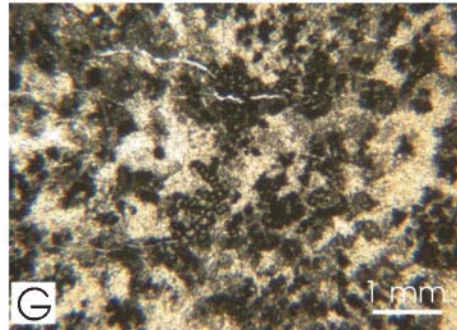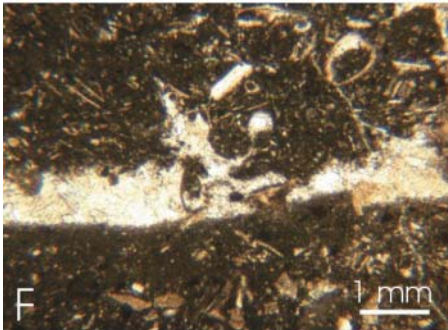
The deepest mound facies is red limestone with stromatactis (Pm1). Bourque & Boulvain (1993) concluded that stromatactis formed from sponge degradation in a relatively coherent, gel-like sediment. Cavities left after degradation evolved within sediment by collapse of the upper part and internal sedimentation on the base (Wallace 1987). It seems noteworthy that, in spite of the presence of sponges in argillaceous limestone below the carbonate mounds, no stromatactis were observed.
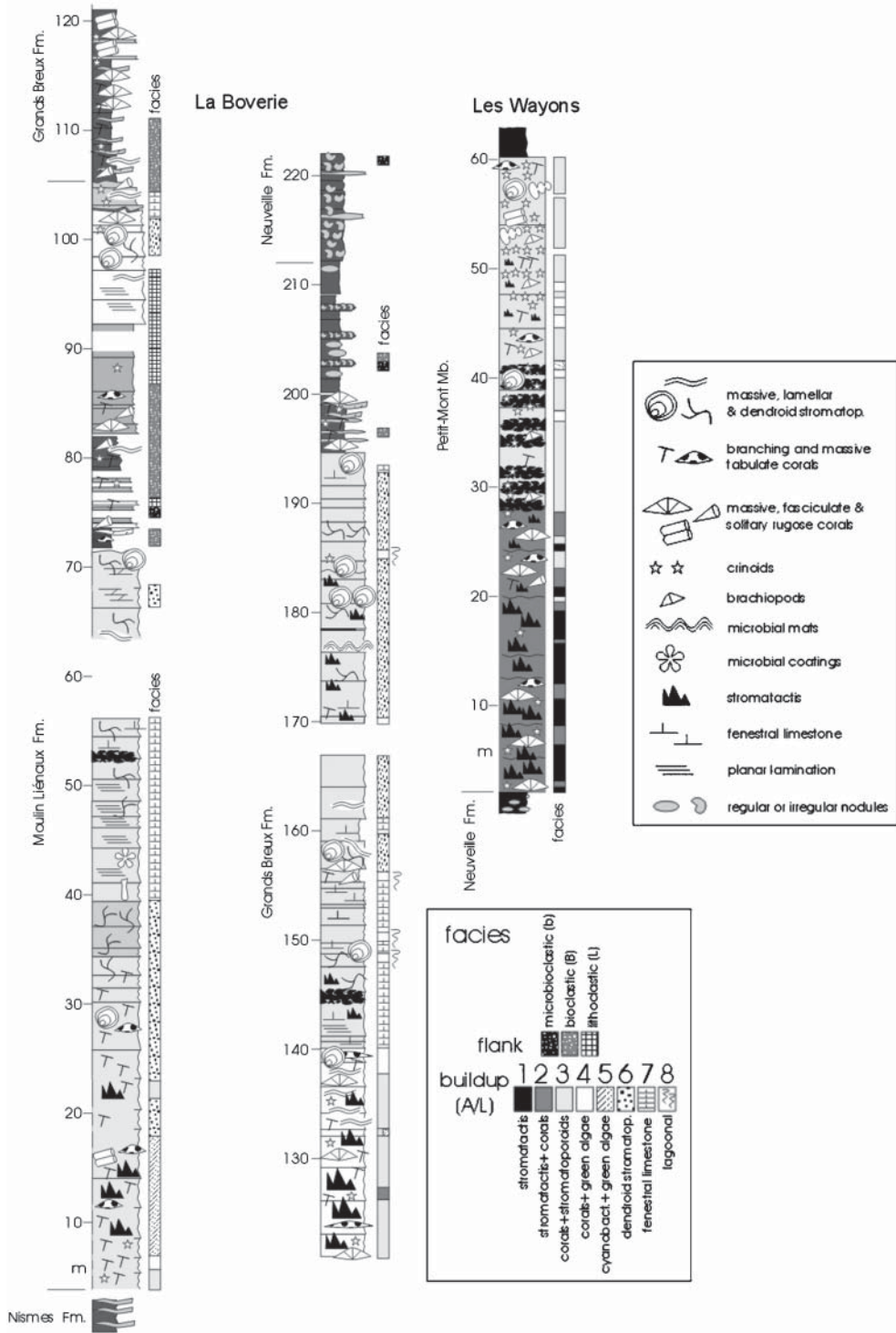
In the late Frasnian Petit-Mont Member, the intensity of pigmentation decreases gradually from the red limestone with stromatactis (Pm1) to grey microbial limestone (Pm5). The surrounding argillaceous facies are devoid of ferruginous pigment and are low in pyrite. Two hypotheses are possible to account for the presence of this pigment: (1) trapping of hematite detrital particles on the carbonate mounds (Lecompte 1936); or (2) local production, possibly of microbial origin (Monty et al. 1982; Boulvain et al. 2001). In the red matrix, a micrometre-scale hematitic pigment occurs among crystals of microspar. In early cemented cavities, the pigment forms possibly organically precipitated coccoids 5–10 μm in diameter and threads 1–3 μm in diameter (Fig. 4E). These structures can be referred to Siderocapsa-like and Sphaerotilus–Leptothrix-like iron bacteria (Boulvain et al. 2001). It is likely that iron-oxidizing bacteria also were present in the matrix, but that they were later partially destroyed during matrix neomorphism. The ecology of recent iron-oxidizing bacteria is well-known (Van Veen et al. 1978; Ghiorse 1984). They develop in environments where iron is available in reduced form, but where the redox potential is sufficiently high so that oxidation can occur. This is the case for oxygen-poor sediment or water (Pringsheim 1952; Nealson 1983). It can also be related to microenvironments (e.g. within pellets) where iron-bacteria are associated with other micro-organisms that maintain a low O_2 concentration (Cowen & Silver 1984).

No lateral zonation of buildups occurred during the development of Pm1 (Fig. 7). This suggests a certain isotropy of the sedimentary environment (few currents, no significant vertical gradient). Absence of algae and the prevalence of muddy facies indicates a quiet environment located below photic and wave action zones. The transition between the argillaceous limestone below the mounds and this facies is abrupt and is accompanied by a reduction in biological diversity. However, the establishment of the stromatactis facies was not associated with any change in laterally equivalent facies. The development of Pm1 facies could point to a local hypoxic environment, perhaps following a strong increase in organic productivity. This hypothesis is supported by decreasing bioturbation in red limestone with stromatactis. The elimination of endofauna suggests locally reducing sediment. The ubiquitous organisms present below the mounds would be replaced by a sponge–microbe community whose only fossilized representatives would be stromatactis and iron-oxidizing bacteria. Byers (1977) indicated that sponges can live hypoxically.

The organic community in red limestone with stromatactis, corals and crinoids (Pm2) is more diverse than that in the underlying facies. Pm2 facies was primarily muddy and the presence of delicate branching forms and some partial encrustations indicates low energy. Sponges were abundant, but large stromatactis are rare. The less homogeneous character of the facies could explain the replacement of the large cavities by networks of small stromatactis in the zones richest in grains. Cemented cavities located under lamellar corals could have played the role of keystones, vertically limiting the collapse of the roof of the cavities left by the degradation of sponges. This facies does not show any lateral zonation. A low-energy environment below the photic zone is suggested.

Fig. 5. (A) Photo mosaic giving a complete NE–SW panorama of the middle Frasnian Lion mound (Lion quarry, Lion Member, Frasnes). The highest point of the quarry is nearly 40 m high. **(B)** Middle part of the middle Frasnian Arche mound (Arche quarry, Frasnes), showing grey algal and microbial bindstones and bafflestones (facies A4–A5). The stratification is nearly horizontal and the high of the quarry wall reaches 20 m. **(C)** Lower part of the middle Frasnian Arche carbonate mound (Arche quarry, Frasnes), characterized by red coverstones with stromatactis and shelter cavities, zebra, tabulate corals, crinoids, brachiopods and stromatoporoids (facies A3). **(D)** Large amounts of Disphyllum corallites in shale, forming the substrate of the Arche mound (middle Frasnian Arche Member, Frasnes). **(E)** Laminar fenestral limestone (facies L7); La Boverie quarry, Jemelle, middle Frasnian Lion Member. **(F)** Wackestone with stromatactoid fenestra, crinoids and brachiopods (facies A3); thin section B209, normal light; La Boverie quarry, Jemelle, middle Frasnian Arche Member.
(G) Bafflestone with thrombolites and Renalcis (facies L5); thin section N46b, normal light; Nord quarry, middle Frasnian Lion Member. **(H)** Floatstone with dendroid stromatoporoid (facies L6); thin section B407b, normal light; La Boverie quarry, Jemelle, middle Frasnian Lion Member. **(I)** Fenestral intraclastic packstone (facies L7); thin section B46, normal light; La Boverie quarry, Jemelle, middle Frasnian Lion Member.

Fig. 6. Simplified logs of the middle Frasnian Arche and Lion members in the La Boverie quarry and of the late Frasnian Petit-Mont Member in the Les Wayons quarry.
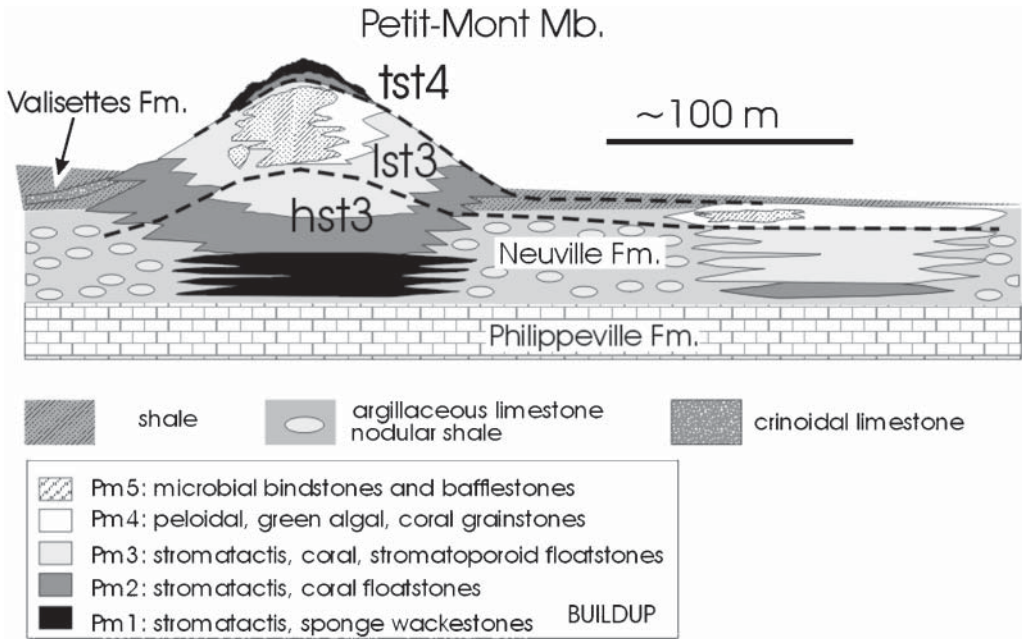
Fig. 7. Sedimentological model of the late Frasnian Petit-Mont mounds in the Philippeville Anticlinorium, with third-order sequential canvas.
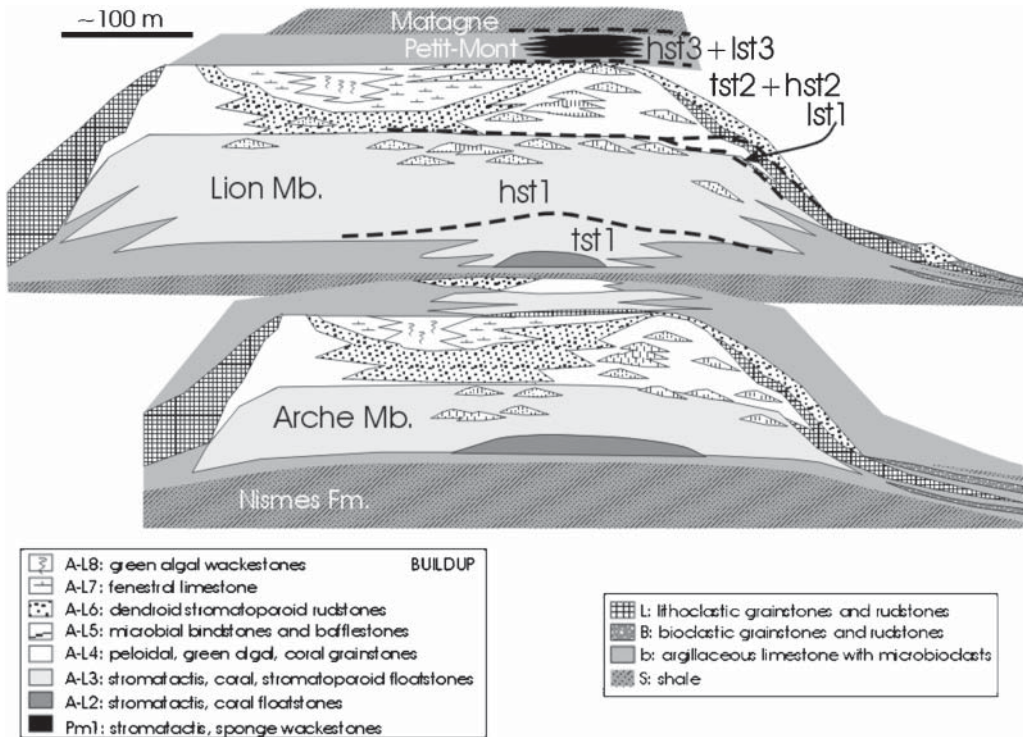

Fig. 8. Sedimentological model of the middle Frasnian Arche and Lion mounds along the south side of the Dinant Synclinorium, with third-order sequential canvas for the Lion Member.

The pink or grey limestone with corals, crinoids, brachiopods, stromatactis, fenestrae and stromatoporoids (Pm3 and A3–L3) is faunally more diverse than the surrounding lateral facies. The presence of cyanobacteria suggests deposition close to the photic zone. The sediment is essentially microsparitic, but locally packstone and rudstone pockets occur, indicating temporary increases in turbulence (Fig. 4F).

Grey limestone with algae, fenestrae, branching tabulate corals and brachiopods (Pm4 and A4–L4) contains the most diverse organic community. Green algae, algal peloids and symmetrical coatings are common. Intraclasts indicate synsedimentary lithification. The coarse texture and presence of green algae indicate a shallow environment, in the photic and wave action zones. The total disappearance of hematite (Fig. 5B) could be related to better oxygenation of water, suppressing iron-oxidizing bacteria communities.

Skeletal organisms in grey limestone with corals, stromatoporoids, thrombolites and microbial mats (Pm5 and A5–L5) display subspherical or encrusting morphologies. Algal and microbial coatings are complex, thick and symmetrical. This is best explained by a more agitated environment. A reduction in organic diversity is also observed. This facies is also characterized by the importance of 'structure grumeleuse'. In the absence of obvious sponges, these structure are generally interpreted as microbial (cf. Pratt 1982; Tsien 1985). Perforations and lithoclasts show that the mats were synsedimentarily cemented.

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 Ancient Wall buildups (Whalen *et al.* 2000). It corresponds to an environment located above fair-weather wave base, 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 of Lion Member mounds, especially in the fore-mound environment (Fig. 8). In the upper central parts of the mounds, 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 & Mountjoy 1975) or to the 'peloidal packstones and grainstones' from the

peritidal facies association of the Miette and Ancient 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.

Flank beds of Petit-Mont Member mounds are rich in crinoidal packstone and grainstone. These crinoids were probably indigenous. This type of community has commonly been reported from the flanks of Palaeozoic mounds (Burchette 1981; Pratt 1982). These communities developed when the mounds had relief; i.e. starting from the base of the upper part of the Petit-Mont mounds. Crinoidal beds with planar tops and undulating bases resulted from the reworking of the bioclastic material and its transport downslope.

The bedded bioclastic–lithoclastic facies of the Lion and Arche members result from the input of eroded material exported directly from the buildups by gravity flows (Stoakes 1980) or from the reworking and sorting of already deposited material by storm waves (Humblet & Boulvain 2001). Microbioclastic packstones are characterized by an open-marine facies with brachiopods, bryozoans and crinoids, whereas bioclastic rudstones and lithoclastic packstones and grainstones 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 & Mountjoy 1975) or from the Miette and Ancient Wall buildups (Whalen *et al.* 2000).

Architecture and sediment dynamics of the buildups

Middle Frasnian Arche and Lion members are relatively large buildups, more than 150 m thick and nearly 1 km in diameter (Fig. 5A). Late Frasnian Petit-Mont mounds are smaller limestone bodies, 60–80 m thick, with a diameter of 150–250 m (Fig. 4A). All the buildups are included in argillaceous limestone, nodular shale or shale.

Contradictory inferences about the initial mechanical state of carbonate mound mud appear to derive from field observations. The persistence of dips as high as 35° on the flanks of several mounds, the presence of lithoclasts in the grey limestone (Pm5, A5–L5) and the sharp distinct character of some fractures indicate early lithification. Conversely, plastic deformation

of the sediment, presence of overturned coral colonies, formation of zebra structures by lateral compression, scarcity of hardgrounds and of sediment borings, and the irregular character of some synsedimentary fractures indicate an absence of early lithification. It appears that the sediment was initially sufficiently ductile to permit synsedimentary deformation, yet sufficiently coherent to have maintained open cavities and significant relief. It is likely that the sediment had a gel-like consistency, probably related to the presence of significant quantities of organic matter.

Late Frasnian Petit-Mont Member

Interpretation of facies succession. The succession of facies in the Petit-Mont Member (Figs 6 & 7) mounds poses an interpretive problem. Two principal models have been proposed to explain the evolution of communities of constructing organisms: the autogenic model of Walker & Alberstadt (1975), and the allogenic model inspired from the work of Lecompte (1959) and Hoffman & Narkiewicz (1977). Lecompte considered that the succession observed in the carbonate mounds of the Petit-Mont Member corresponded to an adaptation of communities to decreasing depth, from intermittent agitation to turbulence. The more general model of Walker & Alberstadt (1975) distinguished a succession of phases in the evolution of mound communities from stabilization of the substrate until domination by some very specialized species. In the case of the Petit-Mont Member, the colonization of the substrate is related to sponges (Pm1). The diversification phase corresponded to the establishment of an assemblage of corals, crinoids, brachiopods, stromatoporoids and cyanobacteria (Pm3), followed by branching tabulate corals, brachiopods and green algae (Pm4). The domination stage is marked by the appearance of grey limestone with corals, stromatoporoids, thrombolites and microbial mats (Pm5), with general encrusting morphology. In off-mound environments, however, no apparent change in facies and assemblages was observed. This appears to exclude the intervention of allogenic processes in the evolution of mound communities, but off-mound communities are mainly made up of generalists of which the sensitivity to variations of oceanic parameters is less than that of more specialized organisms (Walker & Alberstadt 1975). Furthermore, various sedimentological features indicate an increase in turbulence and luminosity when passing from the base of the mounds to grey limestone (Pm5). In the

internal zones of the platform, the shallowing-upwards succession of facies was a response to a relative sea-level fall (Boulvain 1993, 2001). Pm5 development is also accompanied by an increase in the diameter of the mounds and by progradation of lateral facies Pm3 down flanks. These arguments suggest that at least the development of the grey algal–microbial core (Pm5) in late Frasnian Petit-Mont Member mounds was related to a relative sea-level fall.

If ecological evolution (Pm1–Pm5) of the Petit-Mont mounds is related to bathymetry, a similar interpretation for the opposite sequence (Pm5–Pm2), which caps, after a hardground, the largest mounds, could be suggested. This sequence, related to increasing depth, is accompanied by an upwards reduction in the diameter of the carbonate mounds (Fig. 7). A specialized community of corals, stromatoporoids, thrombolites and microbial mats (Pm5) was replaced by a community of sponges, corals and crinoids (Pm2). However, carbonate production was not able to compensate for the rise in sea level, and the last beds of the mounds, already very argillaceous, were covered by argillaceous limestone and nodular shale. This transgressive sequence is marked in the internal zones of the platform by the disappearance of oncoid shoals and overall deposition of argillaceous sediment.

Palaeobathymetry. Grey limestone with fenestrae, branching tabulate corals and brachiopods (Pm4) developed when mounds reached the wave action and photic zones. Depth of the wave action and photic zones may be related to the geometrical characteristics of the basin, and to climatic and other parameters. About 30 m is used here as a base (Flügel 2004). Using this depth of development for facies Pm4, it is possible to estimate the depth of development of red limestone with stromatactis (Pm1) by knowing the average thickness of decompacted sediments separating both facies. An average rate of compaction of 1.5 (Boulvain 1993, 2001) was estimated by the method of Beaudoin *et al.* (1987). Calculation gives a value of about 100–150 m for water depth during deposition of the base of the mounds. In the Upper Devonian of Alberta, Stoakes (1980) related hypoxic to anoxic sediments that result from basin starvation at comparable depths.

Middle Frasnian Arche and Lion members

Lateral facies. Microbioclastic packstones mainly occur in off-mound facies. In this facies the influence of reefs on the sediment budget remains relatively low. On the other hand, the lithoclastic grainstones and bioclastic rudstones

are facies where extensive supply of reefal debris is significant. This reefal input consists of bioclastic–lithoclastic sediment reworked from the mound and deposited by debris flows showing decimetre-deep basal erosion structures (Humblet & Boulvain 2001).

The base of the buildups. The buildups began with the development of large coral colonies (fasciculate rugose corals in the famous Arche quarry) on a muddy sea floor, followed by the progressive colonization of this substrate by sponges and, finally, more intense microbial (?) carbonate production in the form of centimetric–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 (Fig. 5C) the basal mound unit is coloured red owing to the presence of iron bacteria (Boulvain *et al.* 2001), whereas, in other mounds, only several metric–decametric lenses of L2–L3 limestone are red and they 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 (Fig. 8). Much more, the facies succession and their distribution are also very similar. Indeed, the two generations of buildup began with grey or pinkish floatstone containing stromatactis, corals and stromatoporoids (A3–L3). After about 40–70 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. 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 all the buildups, the name of 'atoll-like mound' was suggested for the middle Frasnian Arche and Lion members (Boulvain *et al.* 2004).

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 those 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 & 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; for example, the Golden Spike Leduc reef is 3.6×2.4 km in area and 182 m in height, according to Mountjoy (1980). However, an important 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), whereas the Belgian buildups show only relatively mud-rich mound-type facies.

Mound types and palaeoceanography

Late Frasnian carbonate mounds from the Petit-Mont Member offer an ideal case study of the architecture of carbonate mounds according to bathymetric evolution. Above a substrate of argillaceous limestone rich in sponges, corals, brachiopods and bryozoans, red limestone with stromatactis (Pm1) initiated mound development. This facies was produced by a community of sponges and iron-bacteria, below the photic and wave action zones, in a hypoxic environment at a depth of 100–150 m. Above this, a transition towards red limestone with stromatactis, corals and crinoids (Pm2), then to pink limestone with corals, crinoids, brachiopods, stromatactis, fenestrae and stromatoporoids (Pm3) occurred. The photic zone was reached for cyanobacteria. Grey limestone with fenestrae, branching tabulate corals and brachiopods (Pm4) developed in the wave action zone. At the same time, grey limestone with corals, stromatoporoids, thrombolites and microbial mats was deposited in the mound core (Pm5), marking the domination of encrusting organisms. This general facies succession records a third-order sequence pattern: a highstand system tract (Pm1–Pm4 facies succession), followed by a lowstand (Pm5) and a rapid transgressive system tracts (Pm3–Pm1 facies succession), responsible for the final drowning of the mounds (Fig. 7). Inshore time-equivalent facies belts are ramp-type sediments, dominated by argillaceous limestone during highstand systems (HST) and transgressive systems tracts (TST) and oncoidal shoals during a lowstand systems tract (LST) (Boulvain 1993, 2001).

The facies of Petit-Mont Member mounds are indicators of palaeobathymetry. They also point to a particular palaeoceanography. They recorded hypoxic environments at relatively shallow depth preceding a large-scale anoxic event: the Lower Kellwasser event (Copper 2002*a*, *b*).
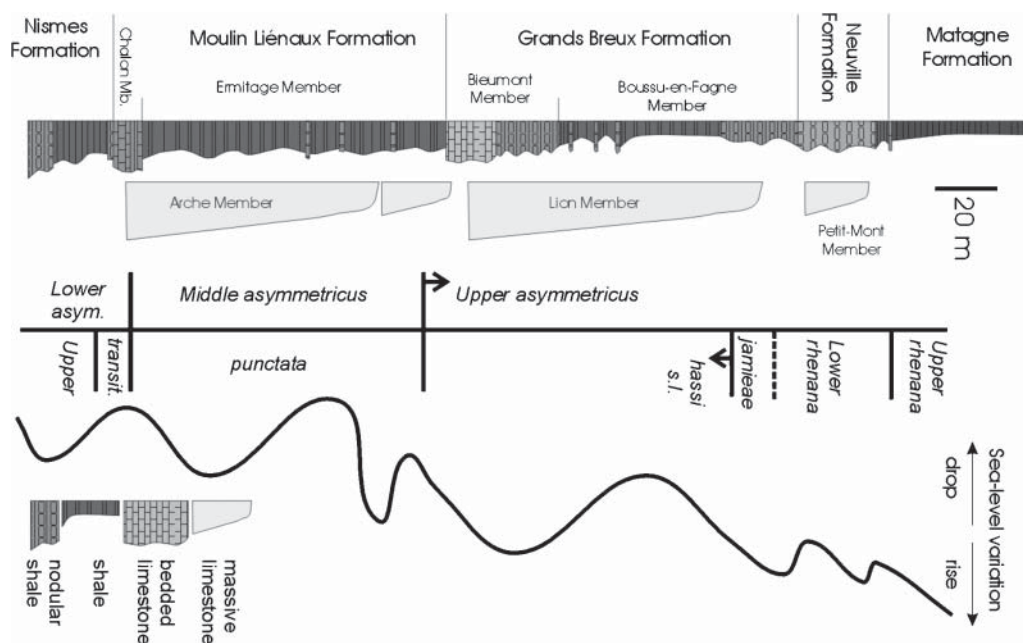
Fig. 9. Schematic log of Frasnian formations along the south side of the Dinant Synclinorium with sea level curve and conodont zonation (after Boulvain *et al.* 1999).

Can we consequently consider this type of carbonate mound as an indicator of hypoxic conditions on a large scale? Other case studies could test this hypothesis.

Palaeotemperature history of the Frasnian shows that this very warm greenhouse climatic period is interrupted by two short-term cooling events, evidenced by positive excursions in $\delta^{18}O$ of conodont apatite in the Late *rhenana* Zone and at the Frasnian–Famennian boundary (Joachimski *et al.* 2004). The first cooling pulse coincides with the Lower Kellwasser and could be contemporaneous with the drowning of the Petit-Mont Member mounds.

On the other hand, middle Frasnian carbonate mounds record different oceanographic conditions. They pass landwards to a 'normal' carbonate platform, with well-developed lagoonal complexes and barrier reefs (Da Silva & Boulvain 2002, 2004). More specifically, 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 middle Frasnian Lion and Arche members. After the growth of the lower part of the mounds during a transgression (Fig. 9), a clear progradation is recorded by fore-mound

sedimentation of reworked material. Lower sea level then restricted reef growth to downslope positions only, 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.

A third-order sequence subdivision of the Lion mounds and their lateral sediments is proposed, based on the geometry and bathymetry of the sedimentary bodies (Fig. 8). The lower and middle parts of the buildups correspond to the succession of a transgressive systems tract (TST1) and/or a highstand systems tract (HST1), with strong progradation associated with reduced accommodation occurring during the HST. The mound development during the lowstand systems tract (LST1) was restricted to the margin of the buildups, with possible emergence and synsedimentary lithification (Sandberg *et al.* 1992). This lowering of sea level was recorded in the internal platform by subsequent widespread development of palaeosols in the upper part of the Lustin Formation (Da Silva & Boulvain 2002). The development of an atoll-like margin corresponds to the TST2, with significant lateral facies differentiation between fore-mound and mound lagoon.

Conclusion

The sequential canvas proposed here for middle and late Frasnian carbonate mounds gives rise to the following observations: TSTs may correspond to various unit types according to the developmental stage of the buildups and to different rates of sea-level rise. They may correspond to aggrading 'deep' mound facies (Lion TST1), to shallow facies developing in a lagoon (Lion TST2) or to give-up type sequences (Petit-Mont TST4) (Neumann & Macintyre 1985). Highstand systems tracts could correspond to catch-up aggrading sequences (Petit-Mont HST3) or to prograding stages with high rates of sediment exportation (Lion HST1). The LSTs could be poorly developed, implying low accommodation and a temporary emergence of the buildups (Lion LST1) or could correspond to the maximum development of the mounds (Petit-Mont LST3).

This overall picture suggests that the main differences between the Arche or Lion members and the Petit-Mont Member are a consequence of different palaeoceanographic setting. The middle Frasnian Arche and Lion members are large flattened buildups showing limited vertical differentiation, large-scale progradation features, extensive exportation of material towards off-reef environment and development of inner lagoonal facies. They grew offshore from a well-developed carbonate platform with a healthy carbonate factory. Middle Frasnian sea-level fluctuations were relatively mild, and sedimentation was able to keep up with sea-level rise. At the opposite end of this spectrum, during the late Frasnian, severe eustatic rises (Johnson *et al.* 1985), together with rising oceanic hypoxic conditions (Copper 2002*a*, *b*), were responsible for collapse of the carbonate factory, drowning of the middle Frasnian carbonate platform and development of Petit-Mont type mounds: buildups with relatively limited lateral extension, vertical facies differentiation, low potential for material exportation and high content in microaerophilic iron bacteria.

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