FRASNIAN REEFS, MOUNDS AND ATOLLS FROM BELGIUM: SEDIMENTOLOGY AND MAGNETIC SUSCEPTIBILITY – A FIELDTRIP GUIDEBOOK

Frédéric BOULVAIN & Anne-Christine DA SILVA

(17 figures, 2 tables)

Département de Géologie, Pétrologie sédimentaire, Bât. B20, Université de Liège, Sart Tilman, B-4000 Liège, Belgium, e-mails : fboulvain@ulg.ac.be, ac.dasilva@ulg.ac.be

1. Introduction

During the Frasnian, a 5000 km^2 carbonate platform developed in Belgium, showing environments ranging from restricted shallow-water lagoons and supratidal areas to a relatively deep external ramp with carbonate mounds. This carbonate platform is especially instructive because of a combination of extraordinary outcrops ("marble" quarries with large sawn sections) and a long history of paleontological study which has led to a refined stratigraphic framework (Boulvain et al., 1999). Carbonate mounds have been the subject of intense investigation carried out by generations of geologists (e.g. Lecompte, 1959; Tsien, 1975; Boulvain, 2007) but a few of these studies focused on the shallow-water part of the platform (Da Silva & Boulvain, 2004).

2. Geological setting

Southern Belgium belongs to the northern part of the Rhenohercynian fold and thrust belt. Frasnian carbonates and shales are exposed along the borders of the Dinant, Vesdre and Namur Synclinoria and in the Philippeville Anticline (Fig. 1). The platform can be divided in three main depositional areas characterized by a different facies association, carbonate production rate and sedimentary evolution.

During the Middle Frasnian, the most distal part of the platform ("southern belt") is located along the southern border of the Dinant Synclinorium, the "intermediate belt" corresponds mainly to the Philippeville Anticline

and the "northern belt" -the shallower- crops out in the northern part of the Dinant Synclinorium, the Namur Synclinorium and the Vesdre area.

2.1. The southern belt

The southern belt is characterized by carbonate mound sedimentation with associated flank and off-mound facies. Since the classical studies by Mailleux (1913), three levels of carbonate mounds were known. These are in ascending order the Arche, Lion and Petit-Mont Members, belonging respectively to the Moulin Liénaux, Grands Breux and Neuville Formations (Fig. 2). The famous Arche and Lion buildups are located in the vicinity of Frasnes, historical stratotype of the Frasnian. Recently, Boulvain et al. (2005) gave information about a set of outcrops located some distance from Frasnes: the La Boverie quarry, close to Rochefort, and the Moulin Bayot sections, close to Vodelée. At both locations, it was possible to study the whole middle Frasnian succession, starting near the base of the Arche Member and ending within the Lion Member. Moreover, at both locations, an additional buildup was recognized between the Arche and Lion Members. The presence of this additional buildup along all the south side of the Dinant Synclinorium is now supported by its occurrence in boreholes drilled in the Nord quarry at Frasnes. The name of La Boverie Member was introduced by Boulvain & Coen-Aubert (2006), as a subdivision of the Moulin Liénaux Formation, for the carbonate deposits lying between the Arche and Bieumont Members.
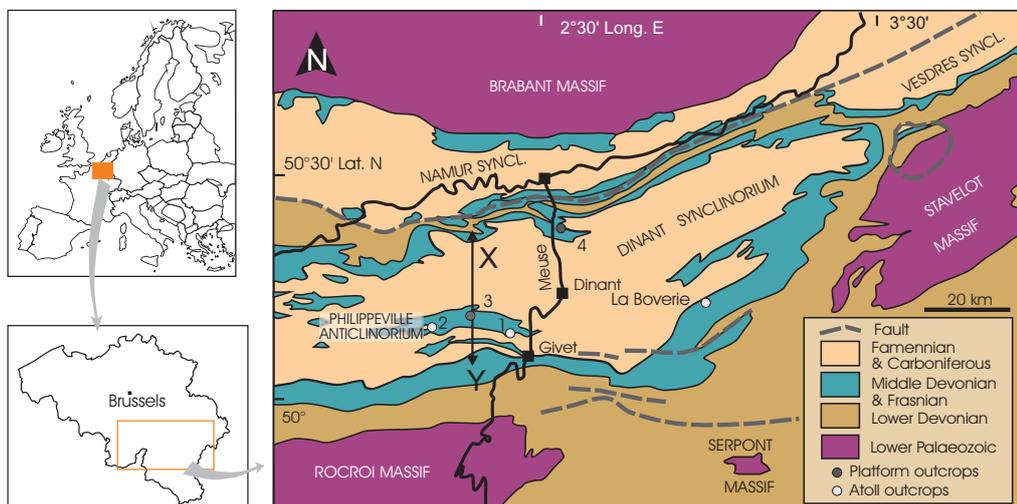
Figure 1. Geological map of southern Belgium with location of stops.
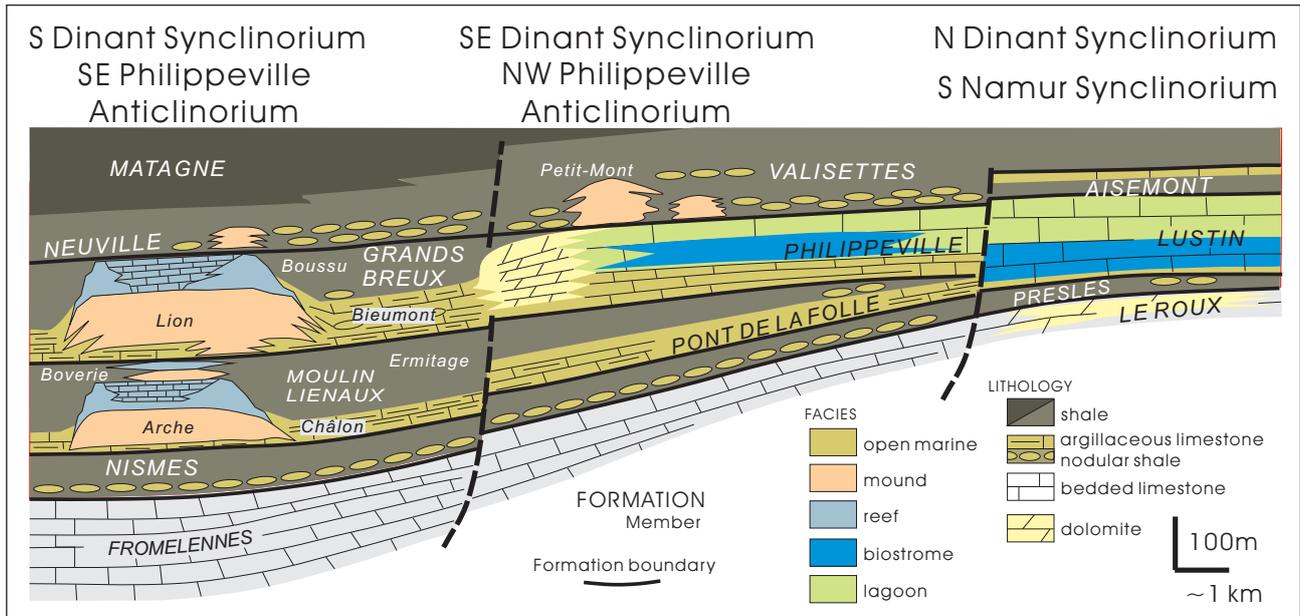
Figure 2. Cross-section in the Belgian Frasnian sedimentary bassin, prior to Variscan tectonism (this section corresponds to the line X-Y on Fig. 1).

2.2. The intermediate belt

In the Philippeville Anticline, the carbonate mound-bearing levels were replaced by shales and argillaceous limestones (Pont de la Folle Formation) followed by bedded limestone consisting of open-marine facies and biostromes (Philippeville Formation).

2.3. The northern belt

Along the northern border of the Dinant Synclinorium ("northern belt"), the Middle Frasnian consists of bedded limestones, exhibiting a distinct proximal aspect with biostromes alternating with lagoonal facies followed by palaeosoils and lagoonal deposits.

During the Upper Frasnian, a general northern shift or retrogradation of the platform is observed: the southern belt extends into the Philippeville Anticline with spectacular development of Petit Mont Member mounds and the intermediate belt shifts to the Northern border of the Dinant Synclinorium. This belt is characterized by shales with two carbonate levels dominated by rugose corals or oncoids (Aisemont Formation) (Boulvain, 2001) (Fig. 2).

3. Facies and microfacies

Data comes from the detailed study of more than 5000 thin sections from 20 outcrops from the Dinant, Namur and Vesdre Synclinoria and from the Philippeville Anticline. In the following descriptions, microfacies are ordered from the most distal to the most proximal, or from the deeper to the shallower. However, this order is not always effective, due to lateral variations, especially in the more proximal parts of the platform. Microfacies are grouped in 4 main facies belts : carbonate mounds and flank deposits (M), external platform or ramp (E), biostromes (B) and internal platform (I) (Fig. 3). Tables 1 & 2 compile detailed sedimentological characteristics and bathymetrical interpretations for the different microfacies.

3.1. Carbonate atolls and mounds (M, southern and intermediate belts, Figs 4 & 5)

The analogy between closely related facies in stratigraphically distinct buildups was highlighted by Boulvain et al. (2001) who employed the same facies designation, i.e. a number following a specific letter for the member name (for example: A2 and L2, corresponding
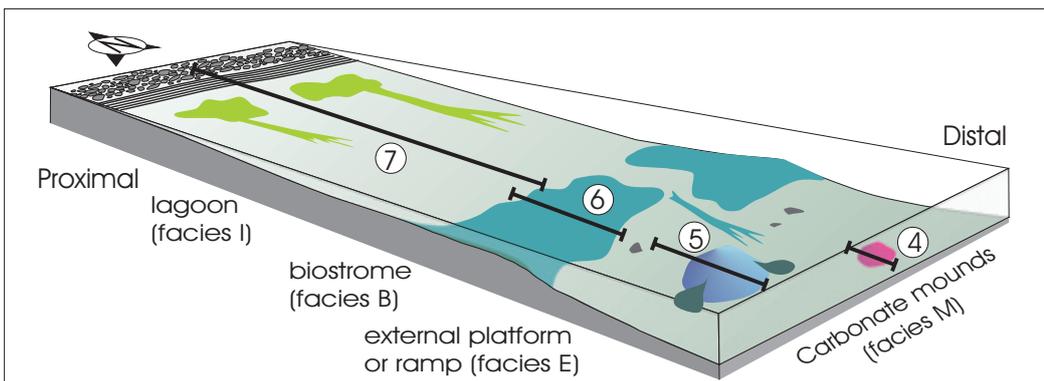
Figure 3. General organization of Frasnian sedimentation domains. 4-7 refer to Figs 4 to 7 (sedimentary models).

Carbonate mound facies (M)

FACIES/ASSOCIATION	COLOR / TEXTURE / STRUCTURE	AUTOCHTONOUS AND ALLOCHTONOUS BIOTA	PRESERVATION / TRANSPORT	ENERGY	INTERPRETATION	BATHY-METRY
M1. Stromatactis, sponges	Red mudstone or wackestone	Sponges and iron bacteria	Preservation ↑ Transport ↓	Very low	Aphotic, below SWAZ	100-150m
M2. Stromatactis, corals and crinoids	Red or pinkish mudstone, floatstone	Sponges, corals, crinoids and iron bacteria	Preservation ↑ Transport ↓	Very low	Aphotic, below SWAZ	80-100m
M3. Stromatactis, corals and stromatoporoids	Grey, pinkish or greenish, floatstone, (rudstone)	Corals, crinoids, brachiopods, bryozoan and stromatoporoids	Preservation ↑ Transport ↓	Low, episodically moderate	Subphotic, close to SWAZ	60-80m
M4. Corals, peloids and dasycladales	Grey grainstone, rudstone	Corals, stromatoporoids, dasycladales, cyanobacteria	Preservation ~ Transport ~	Moderate	Euphotic, close to FWWAZ	30-60m
M5. Microbial limestone	Grey, bindstone bafflestone	Corals, cyanobacteria and stromatoporoids	Preservation → Transport ~	Moderate	Euphotic, close to FWWAZ	30-60m
M6. Dendroid stromatoporoids	Grey, rudstone, m-thick beds	Dendroid stromatoporoids and cyanobacteria	Preservation ↑ Transport ↓	High	In the FWWAZ	0-30m
M7. Loferites	Grey, laminar, grainstone-wackestone	Dendroid stromatoporoids and paleosiphonocladales	Preservation ~ Transport ↓	Low	Intertidal	0m
M8. Bioturbated limestone	Grey, dm-thick, wackestone-mudstone	Paleosiphonocladales and calcispheres	Preservation ↑ Transport ↓		Subtidal	5-10m

Lateral facies (M)

FACIES/ASSOCIATION	COLOR / TEXTURE / STRUCTURE	AUTOCHTONOUS AND ALLOCHTONOUS BIOTA	PRESERVATION / TRANSPORT	ENERGY	INTERPRETATION	BATHY-METRY
M9. Microbioclastic packstone	Dark grey, dm-thick, bedded packstone	Corals, brachiopods, ostracods bryozoans	Preservation → Transport ↑	Low	Below SWAZ	80-100m
M10. Bioclastic packstone, grainstone	Dark grey, dm-thick, bedded packstone-grainstone	Corals, brachiopods, ostracods bryozoans and stromatoporoids	Preservation → Transport ↑	Low, episodically moderate	Close to SWAZ	60-80m
M11. Peloids and intraclastic packstone and grainstone	Dark grey, dm-thick, bedded packstone-grainstone	Stromatoporoids corals, brachiopods and bryozoans,	Preservation → Transport ↑	Low, episodically moderate	Close to SWAZ	60-80m

Table 1. Main characteristics of the carbonate mound facies.

to nearly equivalent facies in the Arche and Lion members). In this more synthetic fieldtrip guidebook, the facies numbers are simply preceded by "M" for "mound".

Eight facies were recognised in the buildups (Table 1), each characterized by a specific range of textures and assemblage of organisms (Boulvain, 2007): spiculitic wackestone with stromatactis (facies M1), which becomes progressively enriched in crinoids and corals (M2); grey or pinkish limestone with stromatactis, corals, and stromatoporoids (M3); grey limestone with corals, peloids and dasycladales (M4); grey, microbial limestone (M5); grey limestone with dendroid stromatoporoids (M6); grey,

FACIES	COLOR / TEXTURE / STRUCTURE	AUTOCHTONOUS AND ALLOCHTONOUS BIOTA	PRESERVATION / TRANSPORT	ENERGY	INTERPRETATION
External platform or ramp facies (E)					
E1. Crinoidal packstone	Dark grey dm beds, packstone to wackestone	Crinoids, ostracods	Preservation ↓ Transport ↑	Low	Under SWAZ, external deposits
E2. Lithoclastic packstone to grainstone	Dark dm beds	Clasts, crinoids, ostracods	Preservation ↓ Transport ↑	Low, episodically moderate	Under SWAZ, slope deposits
Biostromal facies (B)					
B1. Laminar stromatoporoids	Light grey, plurim. beds, coverstone to rudstone,	Laminar stromatoporoids, ostracods and brachiopods	Preservation ↑ Transport ↓	Episodical	Under or in SWAZ, biostromes
B2. Low domical stromatoporoids	Grey, plurim. beds, rudstone	Low domical stromatoporoids, crinoids	Preservation ↓ Transport ↕	High	In SWAZ, biostromes
B3. Dendroid stromatoporoids	Light grey, pluridm to plurim. beds, floatstone to bindstone	Dendroid stromatoporoids, ostracods, clotted matrix	Preservation ↑ Transport ↑	Mainly low, episodical agitation	SWAZ
Internal platform facies (I)					
I1. *Amphipora*, dasycladales and peloids	Light grey, metric beds floatstone to wackestone	*Amphipora*, dasycladales and peloids	Preservation ↑ Transport ↓	Low	Subtidal, restricted
I2. *Umbella* packstone	Grey, metric beds, heterogeneous, subnodular	*Umbella*, clasts, crinoids,	Preservation ~ Transport ↓↕	Moderate	Subtidal to intertidal, channels
I3. Mudstone	Decimetric to metric dark grey beds	Ostracods, dasycladales	Preservation ↑ Transport ↓	Low	Intertidal, local emersion features
I4. Laminated limestone	Dark dm beds, with undulated lamination	Mainly peloids	Preservation ↑ Transport ↓	Low to moderate	Intertidal, local emersion features
I5. Paleosols	Pluridm beds, light grey, with pink staining	Dasycladales	Preservation ↑ Transport ↓	Low	Supratidal, emerged

Table 2. Main characteristics of the external, biostromal and internal facies.

laminar fenestral limestone, (M7); grey, bioturbated limestone (M8).

Laterally to the buildup facies, thin-bedded bioclastic and intraclastic facies are observed, most elements of which underwent a certain transport. Frequent sorting and rounding of their elements characterize these facies. They are ordered according to their content and grain-size: microbioclastic, often argillaceous packstones with ostracodes, trilobites and cricoconarids (M9); bioclastic packstones, grainstones and rudstones with intraclasts (M10) and packstones, grainstones and rudstones with peloids and intraclasts (M11).

Sedimentological evidence suggests that facies M1 and M2 correspond to iron bacteria-sponge-dominated
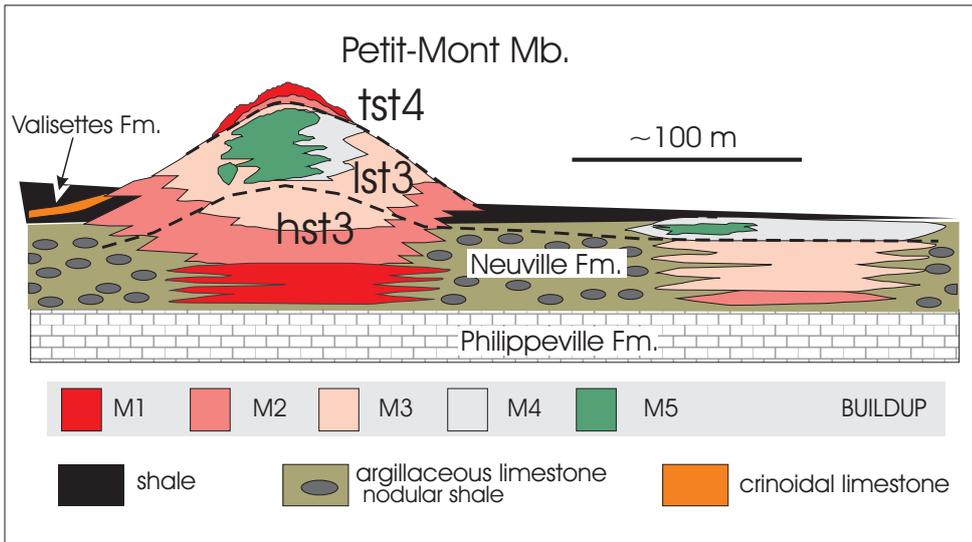
Figure 4. Sedimentary model of Late Frasnian Petit-Mont Member mounds in the Philippeville Anticline.

communities, developing in a quiet aphotic and hypoxic environment (Bourque & Boulvain, 1993; Boulvain et al. 2001). M3 developed between storm wave base and fair weather wave base, in an oligophotic environment. Facies M5 developed close to fair weather wave base. Facies M6 and the fenestral limestone M7 correspond to an environment with slightly restricted water circulation. Facies M8 developed at subtidal depths in a quiet, lagoonal environment.

Microbioclastic packstones (M9) are characterized by an open-marine facies with brachiopods, bryozoans and crinoids, whereas bioclastic rudstones (M10) and intraclastic packstones or grainstones (M11) show a clear mound influence as most of the bioclastic and intraclastic material is derived from these buildups. (Humblet & Boulvain, 2001).

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
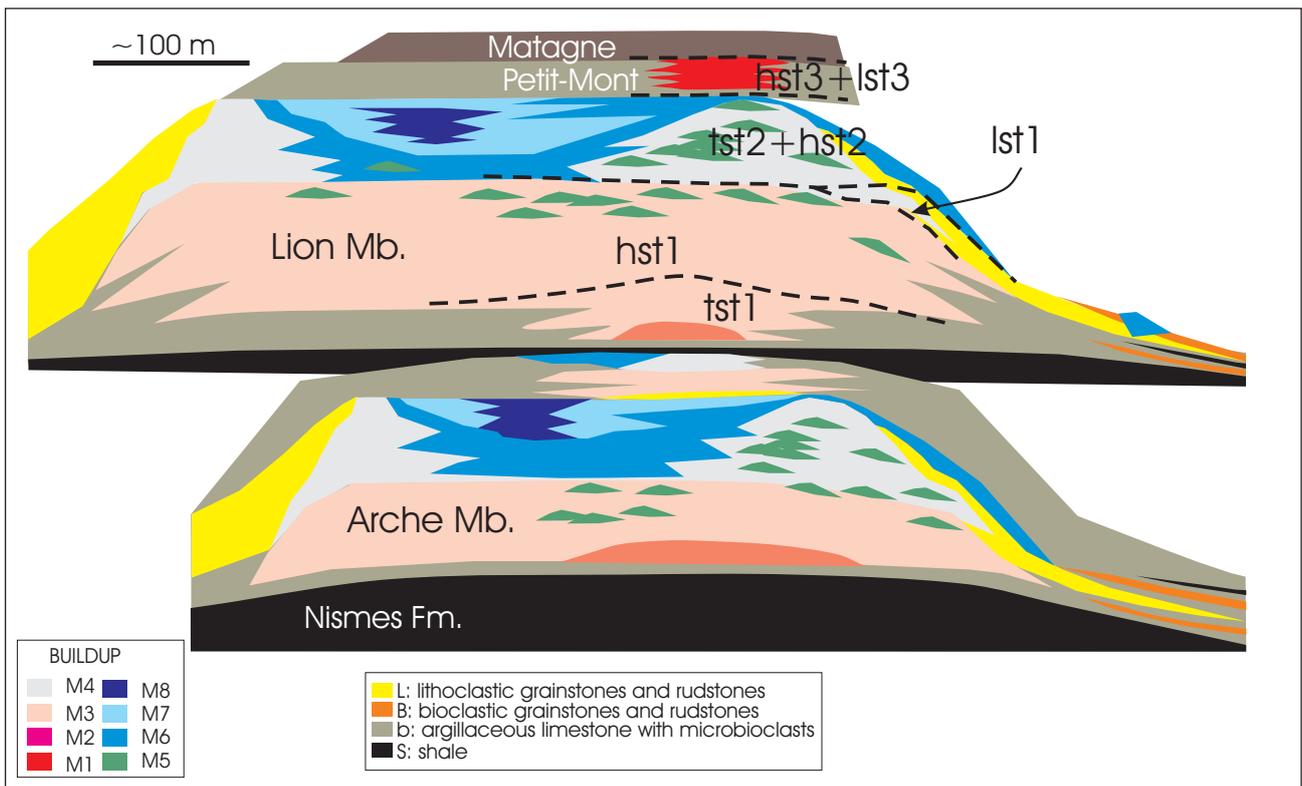
Figure 5. Sedimentary models of Middle to Late Frasnian mounds along the Southern border of the Dinant Synclinorium.
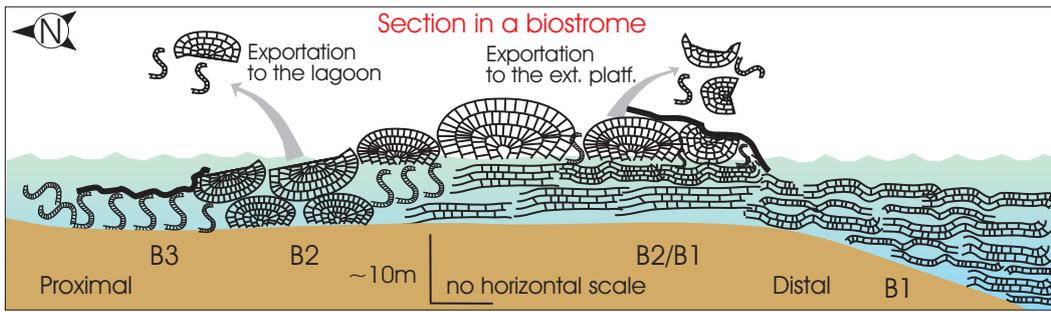
Figure 6. Facies model of Middle Frasnian biostromes. Explanation of symbols, see Fig. 7.

mild, and sedimentation was able to keep-up with sea-level rise (Boulvain, 2007). Reef initiation occurs during a transgression with the development of mud or skeletal mound facies (M2-3). During the subsequent lowstand, reef growth was restricted to a downslope position, resulting in the development of a circular reef margin (atoll crown). During the following transgressive stage, algal and microbial mound facies with stromatoporoids, corals and peloids were deposited (M4-6). The occurrence of relatively restricted facies (M7-8) inside this crown is possibly the result of a balance between sea-level rise and reef growth. During the regression which causes the emersion of the top of the reef and the displacement of the facies downslope, some flank deposits are developed corresponding to the dismantling of the top of the mounds (M10-11).

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 (Boulvain, 2001). In this context, the main part of the Petit-Mont mounds developped as a catch-up sequence (M1-3) during a highstand while the shallowest algal-microbial facies (M4-5) were the consequence of a sea-level drop.

3.2. Carbonate platform (E, B, I, intermediate and northern belts, Figs 6 & 7)

The ideal shallowing-upward facies succession starts with open-marine deposits corresponding to crinoidal packstones (E1). They are followed by biostromes with laminar stromatoporoids (B1), overturned and broken massive stromatoporoids (B2) and dendroid stromatoporoids (B3). Then, biostromes are overlain by subtidal lagoonal facies with *Amphipora*, paleosiphonocladales and peloids (I1), followed by mudstone (I3) and laminated peloidal facies (I4) in the intertidal zone. The subtidal and intertidal zones were cut by channels filled by *Umbella* and intraclasts (I2). The supratidal zone was characterized by paleosols (I5) (Da Silva & Boulvain, 2004) (Table 2).

An important sedimentological observation concerning platform evolution (intermediate and southern belts) is the apparent division seen in all the sections between an upper and a lower unit (Da Silva & Boulvain, 2002) (Figs 10 & 13). The lower unit is dominated in the intermediate belt by ramp facies with some biostromal interruptions, and in the northern belt by biostromes with lagoonal interruptions. The upper unit (lagoon) consists of an alternation of biostromes and lagoonal facies in the intermediate belt and of lagoonal facies (with paleosol) in the northern belt.

Within these sedimentological units, facies are stacked into metre-scale cycles, showing mainly shallowing-
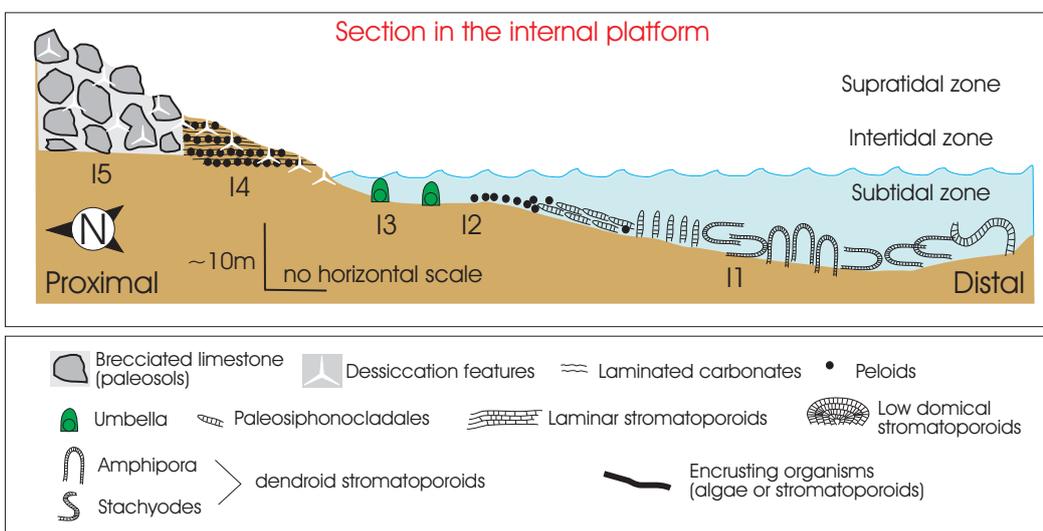
Figure 7. Facies model of the Middle Frasnian internal platform. Explanation of symbols for Figs 6 & 7.

Figure 8. Drowning of the Hautmont mound. Vodelée, Petit-Mont Member.
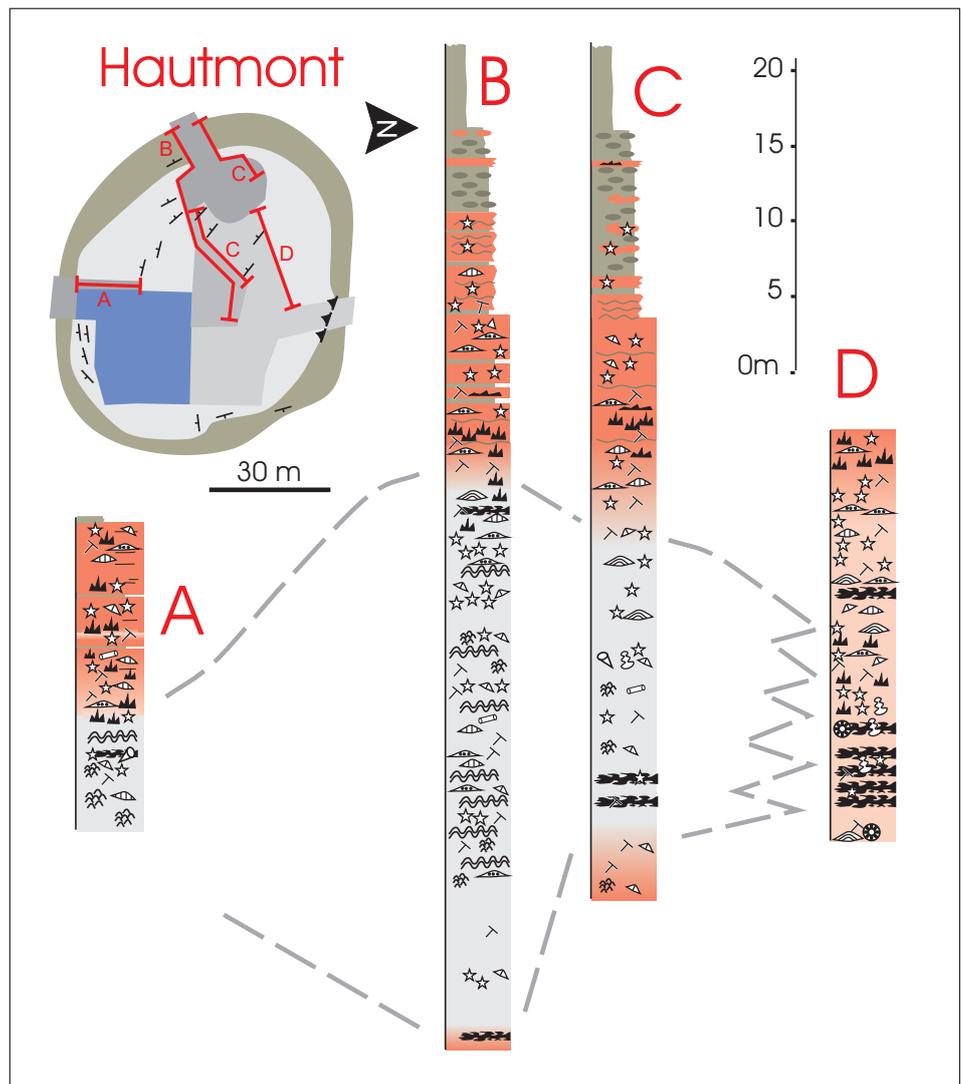
Figure 9. Logs of sections in the Hautmont quarry. Vodelée, Petit-Mont Member.

upward trends. Such cyclicity is common in Devonian shallow-water carbonates. Different kinds of cycles however, are identified here.

In the biostromal unit from the intermediate belt, sedimentation is mainly acyclic with the stacking of 10 cm-thick crinoidal beds, probably due to the deeper environment being less sensitive to minor relative sea-level variations.

In the lagoonal unit, the cycles are characterized by biostromes followed by lagoonal deposits and capped by intertidal laminites. In the northern belt, the biostromal unit shows one or few metres-thick cycles, with crinoid beds (the colonisation stage) followed by massive biostromes and lagoonal deposits and capped by intertidal laminites. The lagoonal unit is characterized by restricted subtidal and intertidal facies covered by, or transformed into paleosols. These cycles are not always complete.

4. Stops

4.1. Stop 1: Hautmont quarry, Vodelée, Petit-Mont Member

This stop is dedicated to a very spectacular Late Frasnian carbonate mound (Petit-Mont Member): the Hautmont mound near Vodelée. This active quarry is located on the SE end of the Philippeville Anticline. The central part of the mound is in nearly horizontal position. The top of the mound is well accessible and all stages of mound drowning are visible (Figs 8 & 9). The upper central part of the mound shows a core of grey microbial, coral stromatoporoid limestone (M5). 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 often associated with *Palaeomicrocodium*.

4.2. Stop 2: Beauchâteau quarry, Senzeilles, Petit-Mont Member

This abandoned marble quarry, located near the village of Senzeille in the SW part of the Philippeville Anticline, is the most spectacular outcrop of a Late Frasnian carbonate mound in Belgium. The mound is standing in subhorizontal position and large sawn sections expose facies ranging from the middle part of the mound (M3) to its top (M4 and 5). The upper central panel shows interfingering between grey massive microbial facies and pink bedded bioclastic flank sediments. The left part of the quarry shows crinoid-rich argillaceous flank sediments.

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 (M5) and the sharp distinct character of some fractures indicate early lithification. Conversely,

plastic deformation of the sediment, presence of overturned coral colonies (very spectacular in the lower central panel of the quarry), 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 (stromatactis) 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.
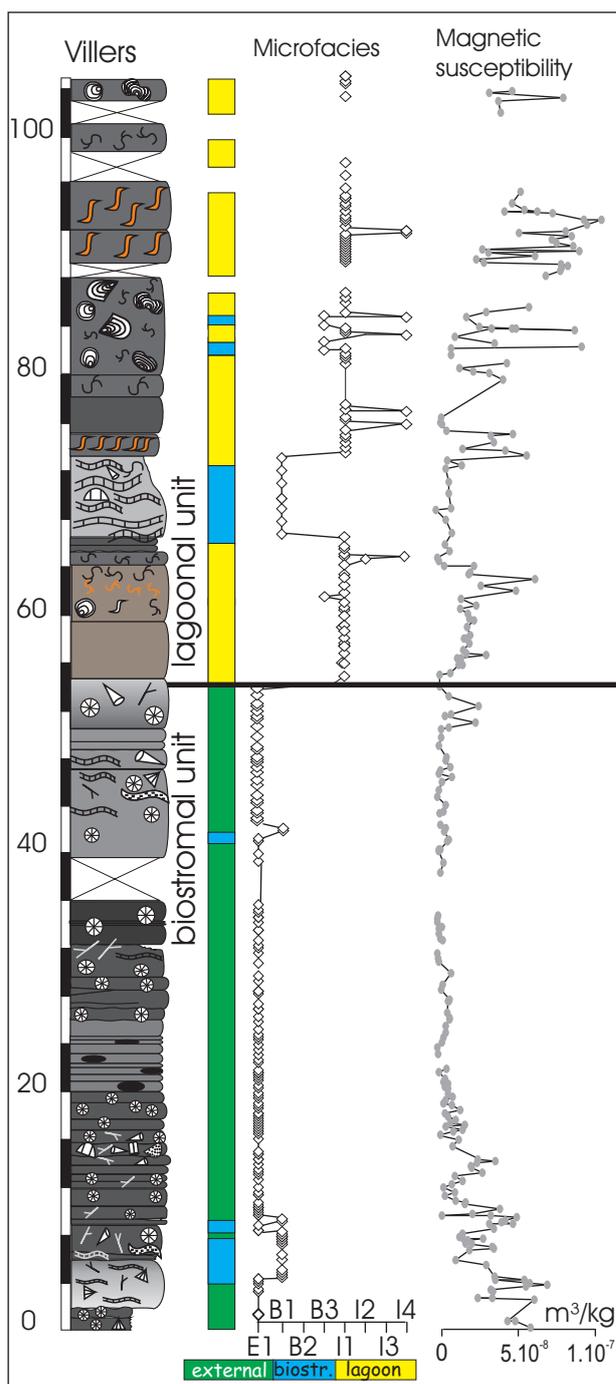
Figure 10. Log of the Villers-le-Gambon section with microfacies and magnetic susceptibility.

4.3. Stop 3: Villers-le-Gambon section, Philippeville Formation

This section along a disused railway (Fig. 10) is located in the S of the Philippeville Anticline. It is one of the rare section exposing almost completely the Philippeville Formation. The lower 50 m are dominated by dark argillaceous crinoidal limestones (E1) with some biostromal beds and chert intercalations. The upper 50m are characterized by biostromal facies with well-developed massive stromatoporoids alternating with fenestral mudstones (I1) or branching stromatoporoids (I3) rudstones.

4.4. Stop 4: Tailfer quarry, Lustin Formation

Located along the Meuse river, the Tailfer section is part of the northern flank of a major anticline, close to the Northern border of the Dinant Synclinorium. The first part of the section starts along the main road with oolitic hematitic beds alternating with dark shales (Lower Frasnian, top of Presles Formation, Fig. 11). Carbonate production starts with crinoidal beds (boundary with the Lustin Formation) and development of biostromes. These biostromes are dominated by massive or laminar stromatoporoids. The succession continues in the Tailfer quarry with a splendid sawn section of a lamellar stromatoporoids biostrome (Fig. 12). This is followed by an alternation of lagoonal deposits and well-developed paleosols (Fig. 13).

Biostrome edification by lamellar stromatoporoids (Facies B1) corresponds to the following ecological sequence (Fig.12): lamellar stromatoporoids rudstone with crinoids, brachiopods and packstone matrix characterises the colonisation phase (B1/3, Fig.12B), and developed during relatively high energy events. Then, two other lamellar stromatoporoids facies with tabulate
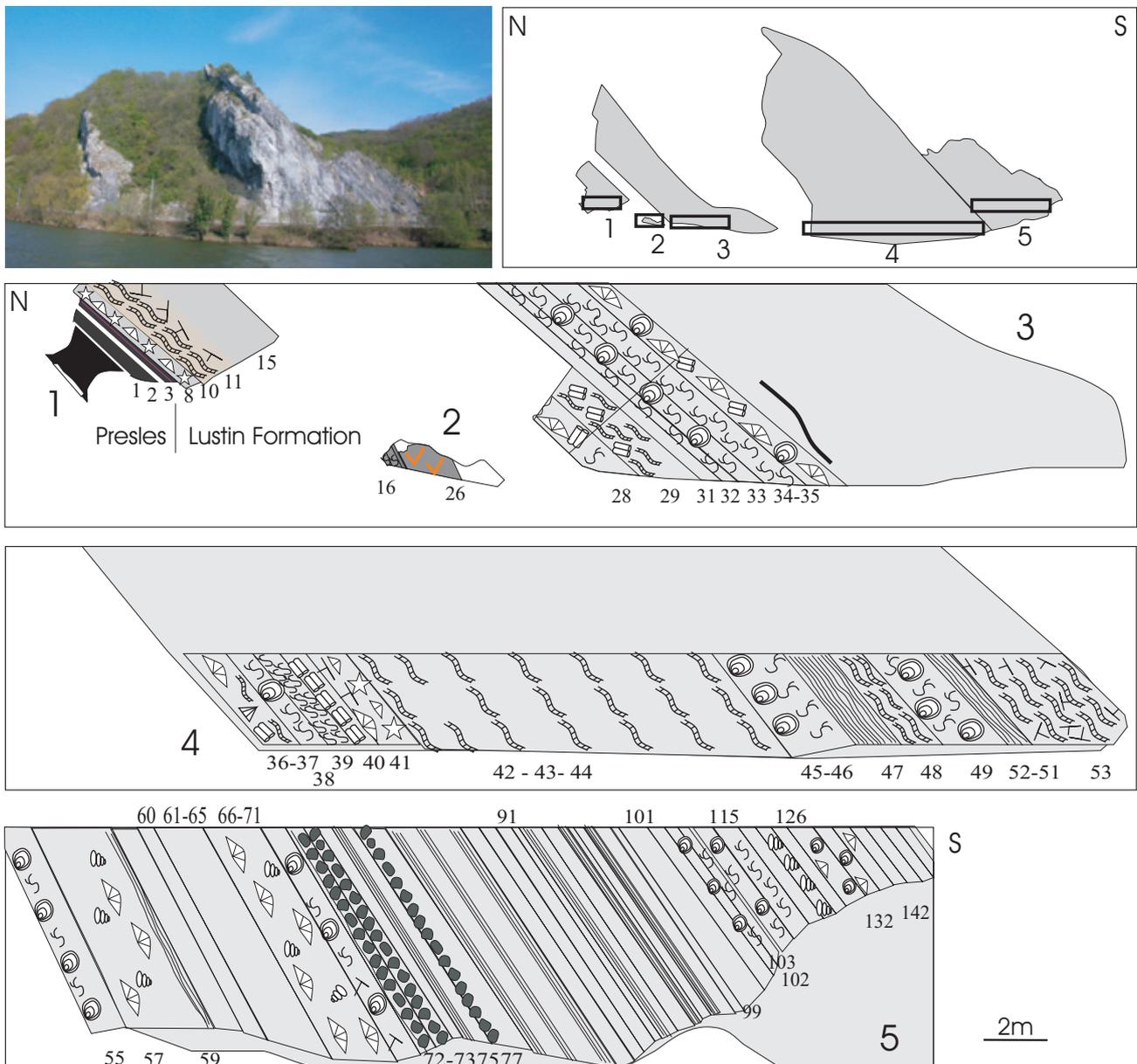
Figure 11. Tailfer section. Presles and Lustin Formations.
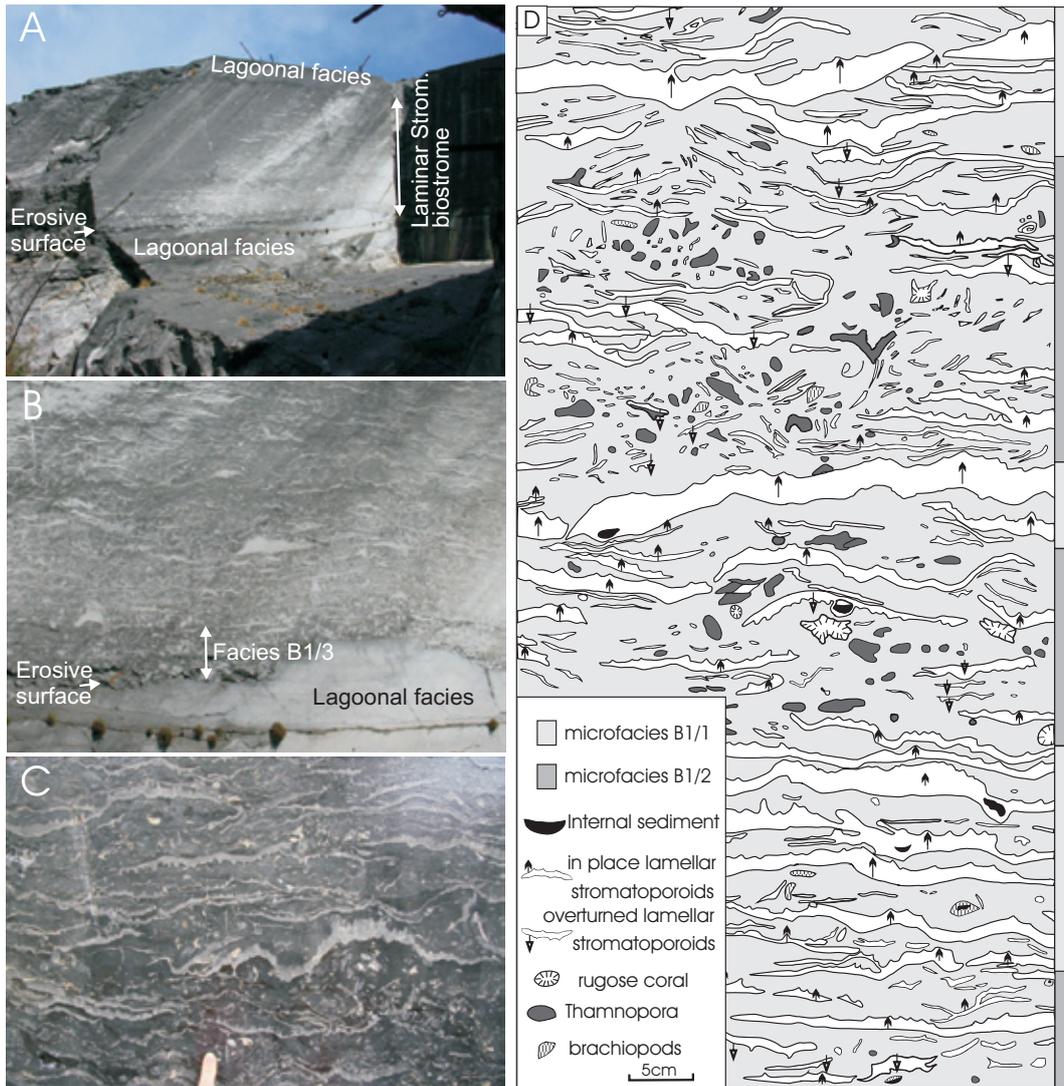
Figure 12. Lamellar stromatoporoids biostrome, Tailfer quarry, Lustin Formation.
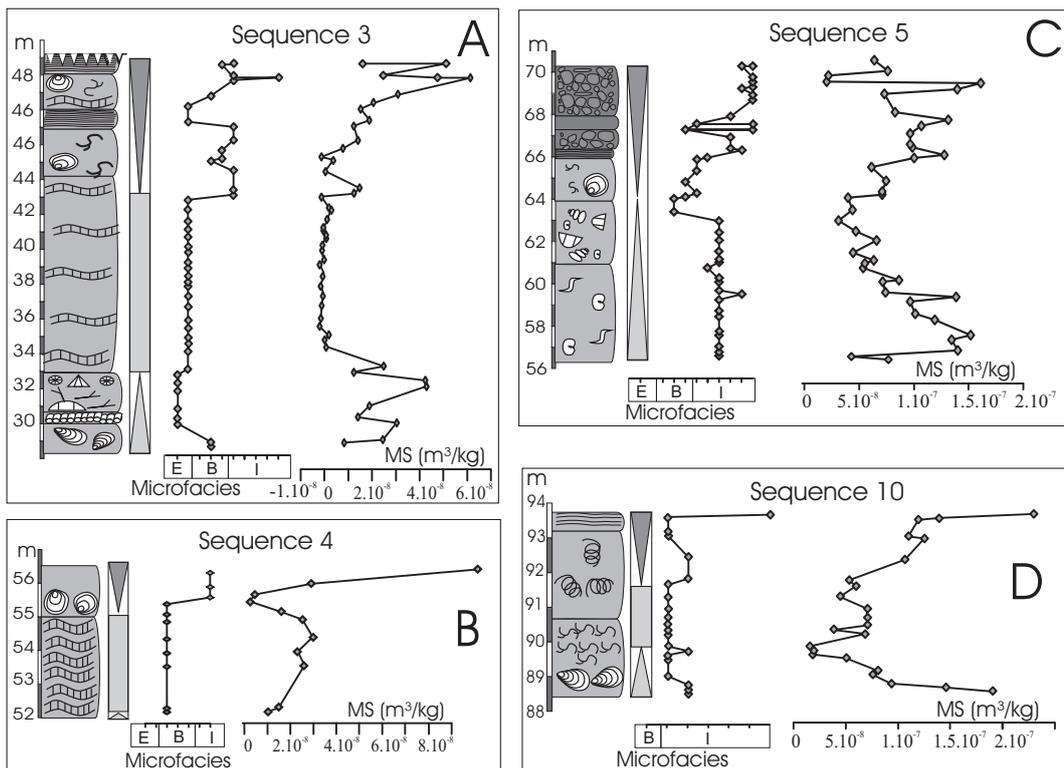
Figure 14. MS evolution with sequence evolution, close up from Fig. 13.
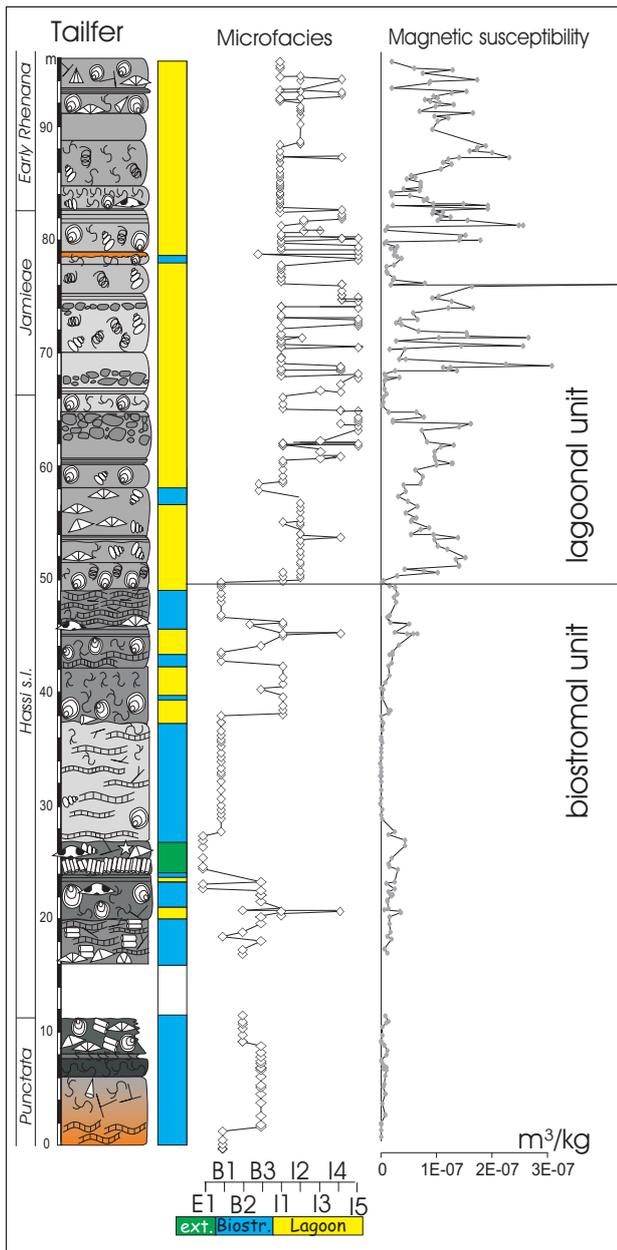
Figure 13. Log, microfacies and magnetic susceptibility of the Tailfer section, Lustin Formation. Northern border of the Dinant Synclinorium.

Figure 15. Mean MS evolution with microfacies on the carbonate platform from Belgium.
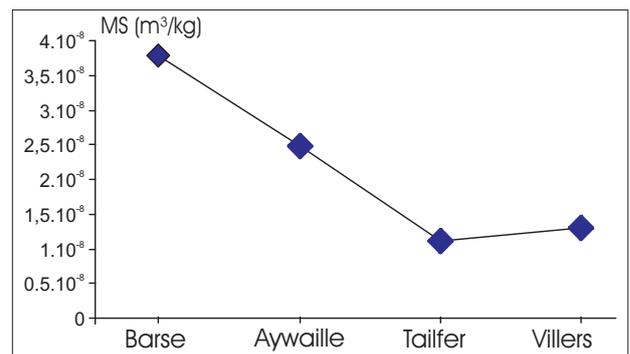
Figure 16. Mean MS evolution for platform sections, from more proximal zone of the platform (Barse), to the more distal zone (Villers).

corals (B1/2) and mud (B1/1), alternate in dm-scale units (Fig.12C-D), probably in relation with short term higher energy events. Muddy microfacies settled in quiet to very quiet water (immediately below the storm wave zone) while reef bioclasts-rich microfacies corresponded to higher energy periods. Water energy however remained relatively weak (in comparison with microfacies B1/3), as indicated by good preservation of fossils.

5. Magnetic susceptibility and platform sediments

The trends in the MS signature are similar for all described stratigraphic sections. We will use the Tailfer section as a reference to describe the relationship between facies

change and MS signature. Detailed results were published in Da Silva & Boulvain (2002, 2006, 2009a & b)

MS evolution seems to be related to different parameters. We will illustrate the relationship between MS and fourth (a), third (b) order sequences, with microfacies (c) and with the position of the section in the basin.

a) The first trend is a correlation between the cycles identified on the MS curve and the fourth order sequences. Each regressive trend corresponds to a MS peak on the MS evolution curve. On Fig. 14, the detail of some of these trends at the scale of fourth order sequences is presented and the link between MS and sequence evolution is obvious. Concerning the sequence 3 (Fig. 14), the first trend is a short transgressive event, with biostromal facies (facies B3) grading to external crinoidal deposits (facies E1). This transgressive phase corresponds to decreasing MS values. The second trend is an aggrading biostrome, mainly built by lamellar stromatoporoids (facies B1) that
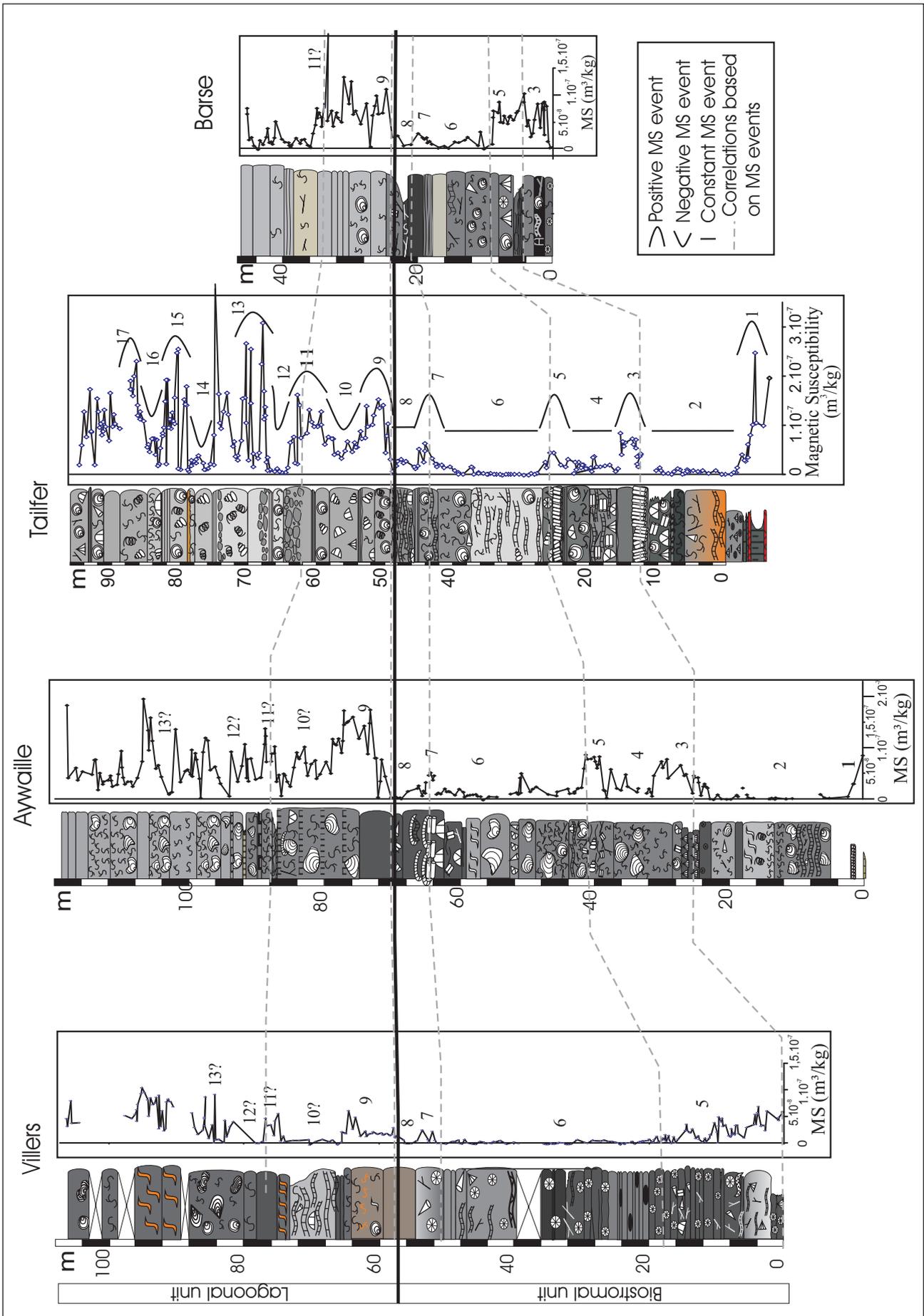
Figure 17. MS curves and correlations for 4 sections from the carbonate platform of Belgium.

corresponds to low (around 0 m³/kg) and almost constant MS values. A regressive trend caps the sequence, with high domical stromatoporoids (facies B2) followed by laminar limestones (facies I4) from the intertidal zone; this regressive trend corresponds to increasing MS values. Within sequence 4, the transgressive phase is almost absent and is followed by an important aggradational phase (biostromes with laminar stromatoporoids, facies B1) and a regressive phase (high domical stromatoporoids, facies B2 followed by mudstone, facies 7). The corresponding MS evolution is almost constant during the aggrading phase and is followed by increasing values during the regressive phase. The sequences 5 and 10 (Fig. 14) also show transgressive trends followed by regressive trends with the MS curve respectively decreasing and increasing.

b) The second trend is a subdivision of the curve in two distinct parts (Fig. 13). The biostromal unit presents very low MS values (mean of $2x10^{-8}$ m³/kg). Just above the boundary between the two units, the values are increasing strongly. The upper portion of the curve is characterized by higher values (to means of $6.62x10^{-8}$ m³/kg), and corresponds to the lagoonal unit.

c) Fig. 15 presents the relationship between magnetic susceptibility and microfacies. On the horizontal axis, the microfacies succession is represented, with increasing proximality from the right to the left. The relationship between magnetic susceptibility and microfacies is obvious, with increasing MS related to proximality. Effectively, the external and biostromal microfacies show MS values around $2x10^{-8}$ m³/kg, while the lagoonal facies shows values around $6.7x10^{-8}$ m³/kg, with in details subtidal facies $5.5x10^{-8}$ m³/kg, intertidal facies $8.5x10^{-8}$ m³/kg and supratidal facies $5x10^{-8}$ m³/kg. It appears that paleosols always have lower MS values than intertidal deposits. This can be explained by the fact that these paleosols correspond mainly to subtidal deposits affected by pedogenesis. So the MS signal of the subtidal deposits seems to be preserved during emersion and pedogenesis. MS is related both to microfacies and to third order sequential evolution.

d) If we compare the MS values of the biostromal unit of the different sections (Fig. 16), the mean values are the highest in Barse which is the most proximal section and decrease distally. For the Villers section, the values are a little bit higher, maybe because of a lower sedimentation rate and local condensed intervals.

Correlations are made on basis of magnetic susceptibility peaks (events with the same pattern) which are considered isochronous (Crick et al., 1997). Third order to fourth order correlations are proposed on the basis of MS peaks (Fig. 17).

6. References

BOULVAIN, F., 2001. Facies architecture and diagenesis of Belgian Late Frasnian carbonate mounds (Petit-Mont Member). *Sedimentary Geology*, 145: 269-294.

BOULVAIN, F., 2007. Frasnian carbonate mounds from Belgium: sedimentology and palaeoceanography. *In* Álvaro, J. Aretz, M. Boulvain, F. Munnecke, A. Vachard D. & Vennin, E. (eds) Palaeozoic Reefs and Bioaccumulations: Climatic and Evolutionary Controls. *Geological Society, London, Special Publications*, 275: 125-142.

BOULVAIN, F. BULTYNCK, P. COEN, M. COEN-AUBERT, M. LACROIX, D. LALOUX, M. CASIER, J-G. DEJONGHE, L. DUMOULIN, V. GHYSEL, P. GODEFROID, J. HELSEN, S. MOURAVIEFF, N. SARTENAER, P. TOURNEUR, F. & VANGUESTAINE, M., 1999. Les Formations du Frasnien de la Belgique. *Memoirs of the Geological Survey of Belgium*, 44: 125 pp.

BOULVAIN, F. & COEN-AUBERT, M., 2006. A fourth level of Frasnian carbonate mounds along the south side of the Dinant Synclinorium (Belgium). *Bulletin de l'Institut royal des Sciences naturelles de Belgique, Sciences de la Terre*, 76: 31-51.

BOULVAIN, F. DEMANY B. & COEN-AUBERT, M., 2005. Frasnian carbonate buildups of southern Belgium: the Arche and Lion members interpreted as atolls. *Geologica Belgica*, 8: 69-91.

BOULVAIN, F., DE RIDDER, C., MAMET, B., PRÉAT, A. & GILLAN, D., 2001. Iron microbial communities in Belgian Frasnian carbonate mounds. *Facies*, 44: 47-60.

BOURQUE, P.A. & BOULVAIN, F., 1993. A model for the origin and petrogenesis of the red stromatactis limestone of Paleozoic carbonate mounds. *Journal of Sedimentary Petrology*, 63: 607-619.

CRICK, R.E., ELLWOOD, B.B., EL HASSANI, A., FEIST, R. & HLADIL, J., 1997. Magnetosusceptibility event and cyclostratigraphy (MSEC) of the Eifelian–Givetian GSSP and associated boundary sequences in North Africa and Europe. *Episodes*, 20: 167–175.

DA SILVA, A-C. & BOULVAIN, F., 2002. Sedimentology, magnetic susceptibility and isotopes of a Middle Frasnian carbonate platform: Tailfer section, Belgium. *Facies*, 46: 89-102.

DA SILVA, A-C. & BOULVAIN, F., 2004. From palaeosols to carbonate mounds: facies and environments of the Middle Frasnian platform in Belgium. *Geological Quarterly*, 48: 253-266.

DA SILVA, A-C. & BOULVAIN, F., 2006. Upper Devonian carbonate platform correlations and sea level variations recorded in magnetic susceptibility. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 240: 373-388.

DA SILVA, A.C., MABILLE, C. & BOULVAIN, F., 2009a. Influence of sedimentary setting on the use of magnetic susceptibility: examples from the Devonian of Belgium. *Sedimentology*, 56: 1292-1306.

DA SILVA, A.C., POTMA, K., WEISSENBERGER, J.A.W., WHALEN, M.T., MABILLE, C. & BOULVAIN, F., 2009b. Magnetic susceptibility evolution and sedimentary environments on carbonate platform sediments and atolls, comparison of the Frasnian from Belgium and from Alberta. *Sedimentary Geology*, 214: 3-18.

HUMBLET, M. & BOULVAIN, F., 2001. Sedimentology of the Bieumont Member: influence of the Lion Member carbonate mounds (Frasnian, Belgium) on their sedimentary environment. *Geologica Belgica*, 3: 97-118.

LECOMPTE, M., 1959. Certain data on the genesis and ecologic character of Frasnian reefs of the Ardennes (transl. by P.F. Moore). *International Geological Review*, 1: 1-23.

MAILLIEUX E., 1913. Nouvelles observations sur le Frasnien et en particulier sur les paléorécifs de la plaine des Fagnes. *Bulletins de la Société belge de Géologie*, XXVII: 67-104.

TSIEN, H. H., 1975. Introduction to the Devonian reef development in Belgium. *2nd Symposium international sur les Coraux et récifs coralliens fossiles, Paris, livret-guide exc*. C: 3-43.