GEOLOGICA BELGICA (2010) 13/4: 319-332

EARLY-MIDDLE FRASNIAN (EARLY LATE DEVONIAN) SEDIMENTOLOGY AND MAGNETIC SUSCEPTIBILITY OF THE ARDENNES AREA (BELGIUM): IDENTIFICATION OF SEVERE AND RAPID SEA-LEVEL FLUCTUATIONS

Anne-Christine DA SILVA[1], Johan YANS[2] & Frédéric BOULVAIN[1]

(8 figures)

[1]*Pétrologie sédimentaire, B20 ,Université de Liège, Sart Tilman, B-4000 Liège, Belgium, e-mail : ac.dasilva@ulg.ac.be*
[2]*Département de Géologie, FUNDP, UCL-Namur, 61 rue de Bruxelles, 5000 Namur, Belgium*

ABSTRACT. This paper focuses on the early and middle Frasnian stratigraphic interval from the Ardennes area in Belgium, with a multidisciplinary and high-resolution study, including detailed sedimentology and magnetic susceptibility study, to identify the main paleoenvironmental changes affecting this interval. Three mud mound levels are observed, in stratigraphic order, the Arche, La Boverie and Lion mounds, surrounded and separated by shales. The three mounds are characterized by the same facies and relatively similar facies evolution through time. The base of the mounds shows deep mound facies (mud, stromatactis, crinoids) and the upper part of the mounds shallow mound facies (lagoonal facies, laminites). The mound succession is interpreted as related to the following events: the base corresponds to transgressive and high stand system tracts; overlain by a sharp transition with shallow facies that correspond to a main regression; followed by the next transgressive system tracts, which corresponds to the upper part of this mound and the lower part of the next mound. Then, again a sea-level drop occurs below the top of this lithostratigraphic unit and is followed by the next transgressive stage etc. A similar transgressive-regressive history is interpreted for all three mounds. As the La Boverie mound is only 35 to 45 m-thick, compared to the 100 m-thick Arche and Lion mounds, the two sea-level fluctuations occurring at the base and top of the La Boverie mound are considered as very severe and rapid, occuring within 1 My. An important transgression is interpreted as occurring during the global negative carbon excursion, the *punctata* Event, recorded worldwide (synthesis in Racki et al., 2008). During this interval, strong and sharp variations are also recorded in the magnetic susceptibility curve.

KEYWORDS: Early – Middle Frasnian, *punctata* Event, carbonate mounds, eustatic fluctuations, magnetic susceptibility.

1. Introduction

The early and middle Frasnian (early Late Devonian) interval was a time of a globally warm (greenhouse) climate (for a recent review see Joachimski et al., 2009) and of high sea level (Vail et al., 1977). The combination of these environmental conditions allowed an extremely intense reef development (Kiessling et al., 1999). Recently, isotopic studies focused on the early to middle Frasnian interval and Yans et al. (2007) presented new high-resolution carbon isotopic curves from the Ardennes (Belgium) and the Holy Cross Mountains (Poland). They identified a global carbon cycle perturbation, the Early-Middle Frasnian Event (EMFE): a positive carbon isotope excursion, initiated late in the early Frasnian *transitans* conodont Zone, which was followed by a negative shift within the early middle Frasnian *punctata* Zone (from 5.9‰ to −1.2‰), with the negative shift called the "*punctata* Event" by the authors. The major long-lasting positive $\delta^{13}C$ isotope excursion is recognized in Belgium (Yans et al., 2007), South China (Ma et al., 2008), Poland (Pisarzowska et al., 2006; Racki et al., 2004; Yans et al., 2007), Czech Republic (Geršl & Hladil, 2004), Western Canada (Śliwiński et al., this volume) and Nevada (Morrow et al., 2009). A special issue of Acta Palaeontologica Polonica proposed a spectrum of biotic responses to the EMFE (Balinski et al., 2006) and a special issue of Palaeogeography, Palaeoclimatology and Palaeoecology proposed a thematic issue to highlight the diversity of geochemical results and additional approaches (Racki et al., 2008).

In the Ardennes type-area, three levels of carbonate mounds are known in the Frasnian of the southern border of the Dinant Synclinorium (Maillieux, 1908, 1913). These are in stratigraphic ascending order the Arche, Lion and Petit-Mont Members belonging respectively to the Moulin Liénaux, Grands Breux and Neuville Formations (Boulvain et al., 1999). The Arche and Lion buildups are located in the vicinity of Frasnes which is the historical stratotype of the Frasnian (d'Omalius d'Halloy, 1862). Recently, Boulvain et al. (2005) documented two outcrops (La Boverie quarry and Moulin Bayot sections) and at both locations an additional buildup was recognized between the Arche and Lion Members. It has been called the La Boverie Member. The presence of this additional

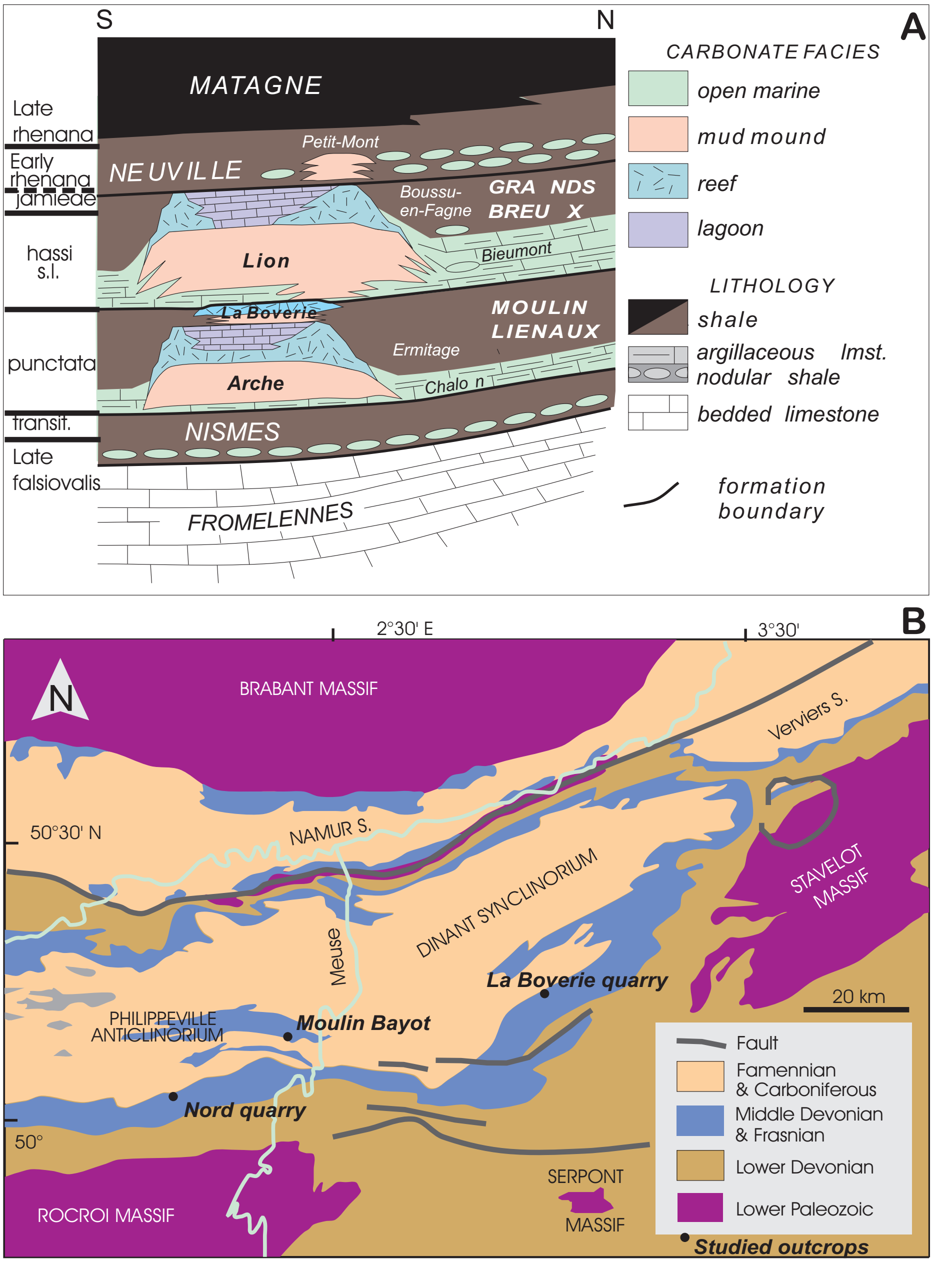

Figure 1. A. Schematic cross-section and lithostratigraphic subdivisions of the Frasnian from the southern border of the Dinant Synclinorium before Variscan tectonic deformation, using the conodont zonation from Bultynck and Dejonghe (2001) and Gouwy and Bultynck (2000). B. Schematic geological map of southern Belgium with location of the studied quarry outcrops and boreholes.

buildup along all of the south side of the Dinant Synclinorium is now supported by its occurrence in four boreholes drilled in the Nord quarry at Frasnes (Boulvain & Coen-Aubert, 2006). This additional mound level occurs within the *punctata* conodont Zone (Gouwy & Bultynck, 2000; Fig. 1). The present paper documents the sedimentology and magnetic susceptibility of the La Boverie Member.

The magnetic susceptibility (MS) technique has been frequently used to correlate and reconstruct paleoclimatic changes in recent sediments (e.g. Robinson, 1993; Curry et al., 1995; Lean & McCave, 1998). More recently, the magnetic susceptibility method was also applied to the correlation of Palaeozoic carbonate platforms (Crick et al., 1997, 2000; Ellwood et al., 1999, 2000; Hladil et al., 2005, 2009; Da Silva & Boulvain, 2006; Da Silva et al., 2009a, 2009b). According to these authors, the magnetic susceptibility signal is mainly related to detrital inputs (magnetic minerals like magnetite and clay as opposed to non-magnetic minerals like carbonates). After Crick et al. (1997), lithogenic inputs are mainly controlled by sea-level variations, but climate and tectonics can also have an influence. If no climatic or tectonic changes are recorded during a studied interval, a sea-level rise will be associated with decreasing MS and a sea-level fall will produce a MS peak (Crick et al., 1997). This relationship between MS and sea level allows correlations that are potentially intercontinental, facies independent and of a higher precision than biozones (Crick et al., 2000).

The main purpose of this paper is to provide a detailed sedimentological analysis of the mound succession, with a special focus on the early-middle Frasnian interval. The combination of sedimentology and MS study allows lateral correlations, as well as identification of relationships between the EMFE, MS evolution and main sedimentological events, in order to better document the

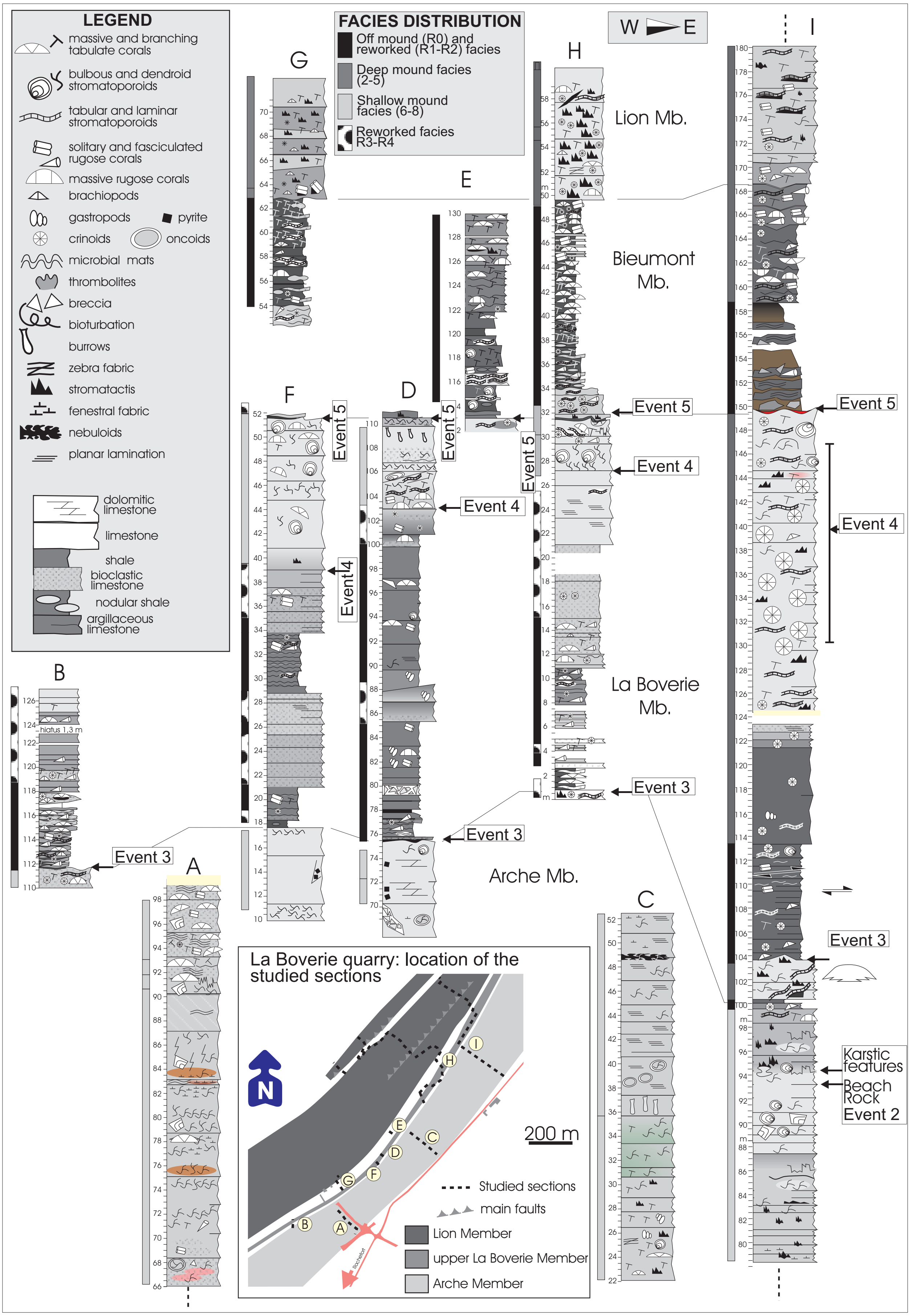

Figure 2. Location of studied sections, lithologic successions of the La Boverie quarry near Rochefort (with weathering profile), facies evolution and main sea-level changes (events 2 to 5, from Fig. 8). Grey box in upper left contains legend for lithologic symbols used in all figures. Logs A-H from Boulvain et al. (2005).

EMFE Event and to identify the main parameters controlling the development of this additional mound level.

2. Geological setting

The Upper Devonian (Frasnian) limestones studied here belong to the Rhenohercycnian fold and thrust belt and crop out at the boundary of the main synclines and anticlines (Fig. 1B). During the middle part of the Frasnian, an extended carbonate platform developed in Belgium (Da Silva & Boulvain, 2004). In the more distal part of the platform (in southwestern Belgium, southern border of the Dinant Synclinorium), a succession of carbonate mound levels separated by shales is observed, consisting of the Moulin Liénaux (Arche and La Boverie mounds) and Grands Breux (Lion mound) Formations (Boulvain, 2001). In the intermediate part of the basin (Philippeville Anticlinorium), argillaceous, crinoidal and biostromal facies (Pont-de-la-Folle and Philippeville Formations) developed and in the proximal part of the basin (northern border of the Dinant Synclinorium, Vesdre Synclinorium and southern border of the Namur Synclinorium), stromatoporoid biostromes and lagoonal facies of the Lustin Formation are observed (Boulvain et al., 1999).

This paper deals with the more distal area of the Belgian carbonate platform (Fig.1A), along the southern border of the Dinant Synclinorium. We studied the mound succession Arche, La Boverie and Le Lion, with a focus on the La Boverie mound. Three main localities were selected for this study: (1) The La Boverie quarry is located at the southeastern edge of the Dinant Synclinorium. The series of buildups exposed in the quarry is nearly 220 m thick and extends for at least 3.5 km laterally. Nine sections were studied at La Boverie quarry (Fig. 2). (2) The Moulin Bayot sections are situated in the southeastern part of the Philippeville Anticlinorium (Fig. 1B). The buildup unit extends laterally for approximately 3.5 km and is more than 150 m thick. Five sections were investigated by Boulvain et al. (2005) on both sides of the Hermeton River. (3) The Nord quarry is located 500 m west of Frasnes, at the southern edge of the Dinant Synclinorium and four boreholes (FR1, FR2, FR3 and FR5, Fig. 3) were drilled in the bottom of the quarry.

Previous observations document the biostratigraphic framework of the Ardennes (Gouwy & Bultynck, 2000; Bultynck & Dejonghe, 2001). The Moulin Liénaux Formation comprises the upper part of the *transitans* conodont Zone and the *punctata* Zone. The lower part of the Lion mound is in the lower part of the *hassi* Zone (Fig. 1A). However, mud mounds are characterized by a small abundance of conodonts leading to difficulties in building conodont biostratigraphy. To get around this problem, Gouwy & Bultynck (2000) used 85 conodont taxa, 48 coral taxa, 29 brachiopod taxa and one stromatoporoid taxon to build a regional Ardennes composite and to produce a chronostratigraphic framework, providing a higher resolution than what could be obtained solely by conodonts.

3. Methods

Detailed sedimentological descriptions and sampling were complemented by magnetic susceptibility analyses.

Magnetic susceptibility (volume magnetic susceptibility = k) is a measure of the material response to an applied magnetic field. In this paper, we use mass-

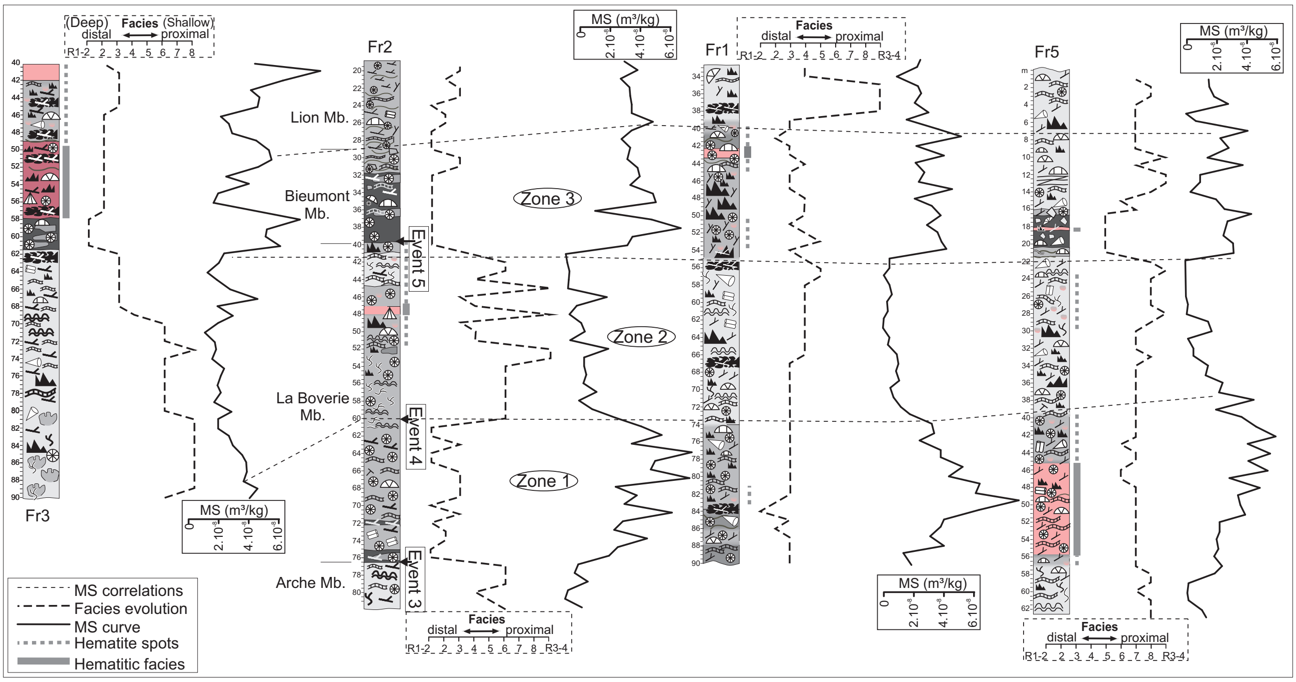

Figure 3. Lithologic successions of the boreholes drilled in the Nord quarry at Frasnes, with facies evolution (dotted lines), magnetic susceptibility curves (MS) and main sea-level changes (events 3 to 5, from Fig. 8). Legend is in Figure 2.

specific magnetic susceptibility, which is k multiplied by a reference volume of $1m^3$ and divided by the sample mass and expressed in m^3/kg. Measurements were carried out with the KLY-3S Kappabridge of the University of Liège (Belgium). In the boreholes of the Nord quarry, sample stratigraphic spacing was one meter and for each sample the microfacies was identified and magnetic susceptibility was measured. Three measurements are made on each sawn sample (max. 2.5x2.5 cm) weighed with a precision of 0.01 g. After Ellwood et al. (1999), for samples weighing more than 10 g, the precision of the device is around $1x\ 10^{-10}\ m^3/kg$.

The magnetic susceptibility of a rock depends on the mineralogical composition of the rock and the proportion of each mineral. The three main magnetic behaviours are: diamagnetic minerals (such as carbonates and quartz) showing extremely weak negative MS values; paramagnetic minerals (e.g., clay minerals, particularly chlorite, smectite, illite and glauconite, ferromagnesian silicates, iron and manganese carbonates, pyrite) showing weak positive values, and ferromagnetic minerals (mainly magnetite, pyrrhotite and maghemite) showing strong positive values.

4. Sedimentology

4.1. Facies and communities

The Arche, La Boverie and Le Lion mounds have similar facies (and relatively similar facies evolution as well), each facies being characterized by a specific range of textures and organic assemblages. The logic behind the coding scheme used here for designating the mud mound facies is the same as used by Boulvain (2007): identical facies are given identical facies numbers, even when they are in buildups at different stratigraphic levels. This scheme facilitates comparison between the mounds. The observed facies were very similar to those described from other laterally equivalent sections (Boulvain, 2001, 2007), with only a few differences. As a result, our detailed facies descriptions and interpretations follow closely those proposed by Boulvain (2001, 2007).

The buildup facies are divided into deep mound facies and shallow mound facies. They both are mainly autochthonous deposits and are interpreted in terms of bathymetry, which indicates environments ranging from deep-aphotic and sub-wave base to shallow intertidal (Boulvain, 2007). In addition to these buildup facies, four reworked facies (by storms or debris flows on the flank) were described, composed of bedded bioclastic and lithoclastic lithologies. Facies 1 was observed in the upper Frasnian Petit mont mound but not in these outcrops, so facies 1 is not described here (for description, refers to Boulvain, 2001).

- Deep mound facies:

Facies 2: red or pink limestones composed of stromatactis, corals and crinoids (Fig. 4A). This facies is characterized by decimeter-sized stromatactis and smaller stromatactoid fenestrae (Neuweiler et al., 2001), platy thin tabulate corals and crinoids. These carbonates are coloured in red or pink by hematite derived from iron bacteria as already observed in other Frasnian mounds in Belgium (Boulvain, 2001).

Facies 3: relatively similar to facies 2 but with a grey or pink colour and with abundant laminar stromatoporoids, branching tabulate corals, brachiopods and crinoids (Fig. 4B).

Facies 4: grey limestone with corals, peloids and Udotaeaceae (Fig. 4C). This facies is composed of rudstones, grainstones and floatstones, with peloids, coated grains, branching tabulate corals with *Sphaerocodium*, brachiopods, crinoids, dendroid stromatoporoids, radiolarians and calcispheres.

Facies 5: grey microbial limestone (Fig. 4D), which is composed of thrombolitic and stromatolitic boundstones and bafflestones, with *Renalcis*, stromatoporoids, tabulate corals, Udotaeaceae, brachiopods, bryozoans and rugose corals.

Facies 2 and 3 correspond to the carbonate mounds sensu stricto, and are developed in the deepest environment. Both were deposited in a low-energy environment, below the storm wave base, in a subphotic area. Facies 4 and 5 developed in the photic zone (first appearance of green algae), close to the fair-weather wave base (Boulvain, 2007).

- Shallow mound facies:

Facies 6: grey limestone with dendroidal stromatoporoids (Fig. 4E). This facies is composed of peloidal rudstones, floatstones or grainstones with lithoclasts and dendroid stromatoporoids (dominantly *Amphipora*).

Facies 7: grey laminar fenestral limestone composed of grainstones and wackestones, with peloids, lithoclasts, calcispheres, palaeosiphonocladales and millimeter-scale fenestrae (parallel to the bedding) (Fig. 4F).

Facies 8: bioturbated grey limestone. 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 to sparitic cement. Branching tabulate corals, stromatoporoids, ostracods and gastropods are present.

Facies 6, 7 and 8 correspond to the inner lagoon deposits. Facies 6 developed above the fair weather wave base in a moderate to high-energy setting, facies 7 developed in a very shallow quiet intertidal area and facies 8 in a quiet subtidal lagoon environment.

- Reworked and off mound facies:

The reworking facies are organised according to fossil content and grain size:

Off mound facies R0: Shale, nodular shale and argillaceous limestone (R0), green–brown shale with sporadic limestone nodules. Nodules are of centimeter–decimeter scale and are commonly irregular.

Reworked facies R1: microbioclastic packstones (Fig. 4G). This facies is composed of thin-bedded, dark, often

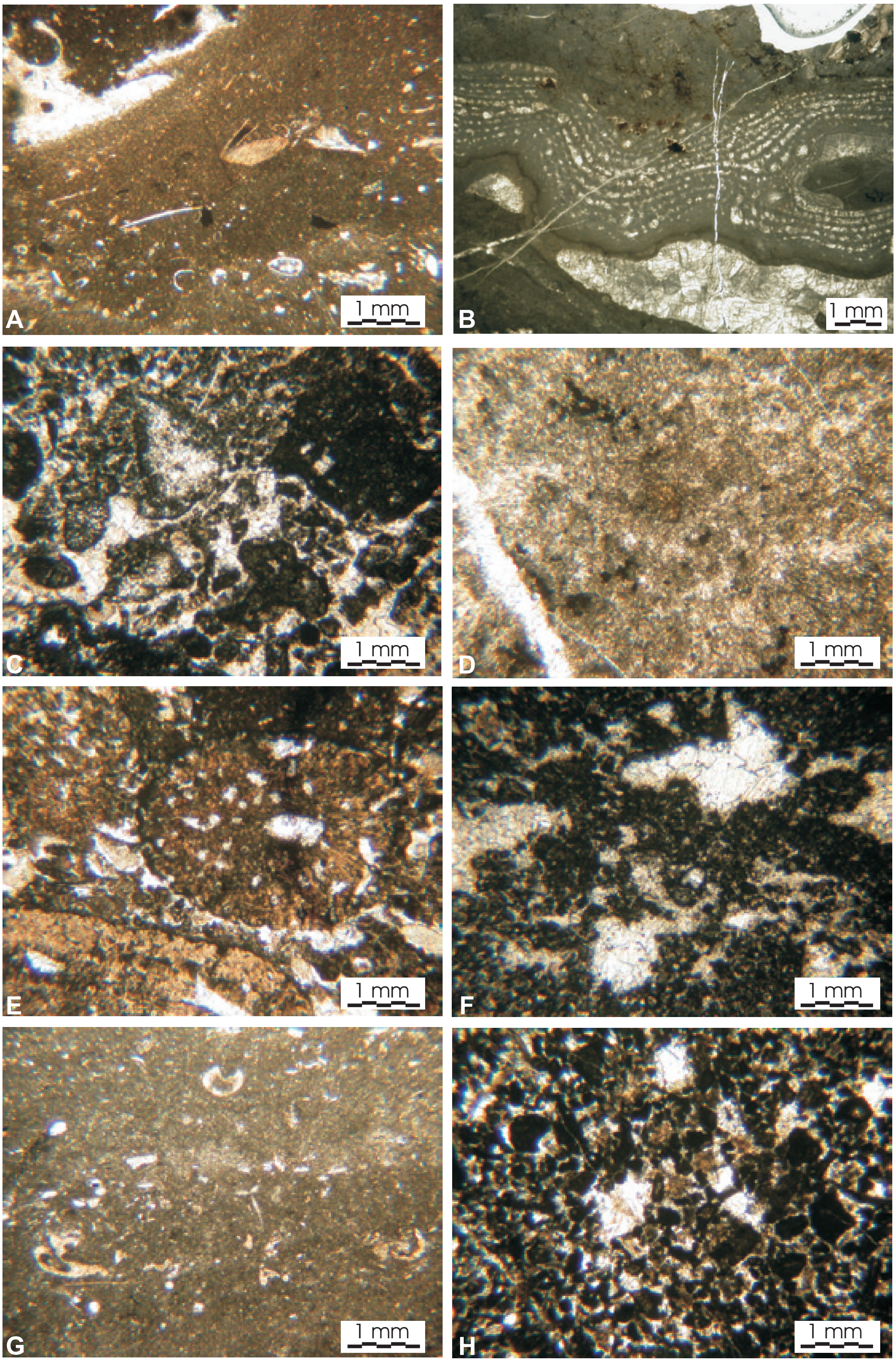

Figure 4. Photomicrographs of the different microfacies in plane-polarized light, from the Nord and La Boverie quarries, Frasnes. A: wackestone with stromatactoid fenestrae, crinoids and microbioclasts. Facies 2, base of the mound, Nord quarry, thin section FR3-50 m. B: stromatoporoid with fenestrae. Facies 3, lower part of the Arche mound, 1 m from the base of section La Boverie I (Fig. 2). C: grainstone with fragments of microbial coatings, codiaceae-udoteaceae and peloids. Facies 4, upper part of the mound, Nord quarry, thin section FR3-33 m. D: bafflestone with thrombolites and *Renalcis*. Facies 5, upper part of the mound, Nord quarry, thin section FR3-16 m. E: rudstone with dendroid stromatoporoids. Facies 6, upper part of the mound, Nord quarry, thin section FR2-86 m. F: grainstone with peloids, lithoclasts and irregular fenestrae. Facies 7, upper part of the mound Nord quarry, thin section FR2-94 m. G: microbioclastic wackestone with crinoid fragments. Facies R1, distal flank of the mound, Nord quarry, thin section FR3-59 m. H: lithoclastic grainstone. Facies L, upper flanks of the mound, Nord quarry, thin section FR1-15 m.

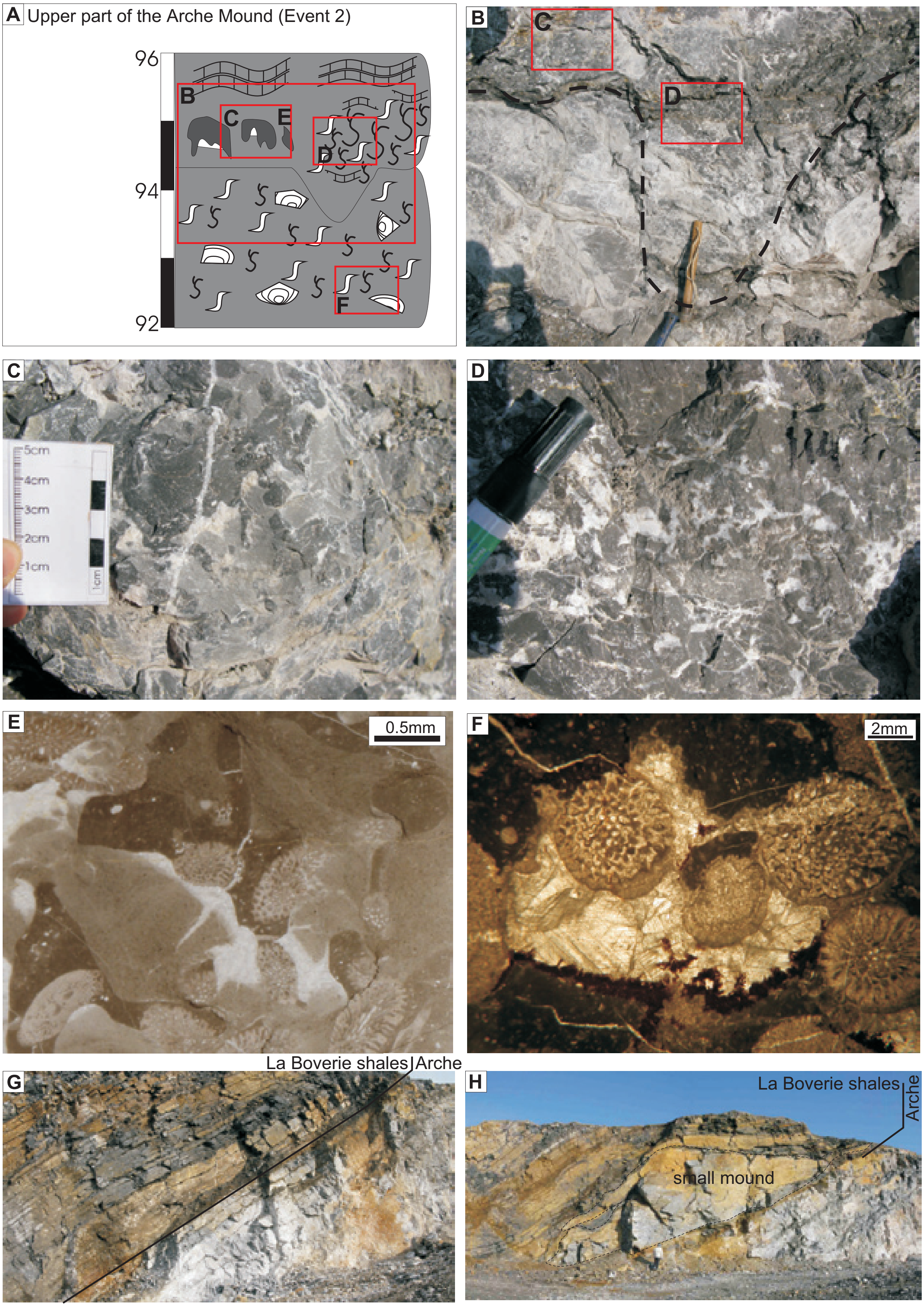

Figure 5. Illustration of some of the observed main events (synthesis on Fig. 8) from the La Boverie quarry (section I, Fig. 2). A. Part of the lithologic column from the La Boverie section I, upper part of the Arche Member, Event 2 (see Fig. 8). Red rectangles correspond to the location of pictures B-F). B. Karstic surface (dashed line). C. Karstic features (magnified in picture E). D. fenestral facies. E. Karstic features, rounded dissolution features. F. Brecciated facies (R4) with tabulate corals and pendant cement. G. Event 5, sharp transition between the Arche Member and the La Boverie shales. H. Sharp transition between the Arche Member and the La Boverie shales, with 1 m of shales, followed by a small mound (maximum of 5 m-thick, local, only observed in this section).

argillaceous, fine-grained (~100 µm) bioclastic wackestones to packstones, with brachiopods, crinoids, rugose corals, tabulate corals, fenestellids, ostracods, trilobites, peloids, and cricoconarids.

Reworked facies R2: bioclastic packstones and grainstones. This facies consists of dark-coloured centimeter- to decimeter–scale thickly bedded bioclastic packstones and grainstones with isolated hummocky cross stratification. The facies occurs as local lenses within argillaceous limestone or shale. The ~300 µm-diameter bioclasts include brachiopods, crinoids, rugose and tabulate coral fragments, laminar stromatoporoids, fenestellids, ostracods, trilobites, peloids and cricoconarids. Locally, some lithoclasts, palaeosiphonocladales, radiospheres and calcispheres are present.

Reworked facies R3: packstones and grainstones, locally breccia, containing abundant and commonly sorted peloids and redeposited lithoclasts (Fig. 4H).

Reworked facies R4: bioclastic breccias and rudstones, with centimetre- to decimetre-scale broken stromatoporoids, or tabulate corals and rugose corals. This facies occurs commonly as normally graded lenses, overlying a lower erosive surface. Between the clasts, a cement or matrix are observed, with clasts, peloids and small debris of crinoids and brachiopods. The cement is mostly a sparite, dolomite or microdolomite. Locally a pendant cement can also be observed (Fig. 5E).

Off mound facies R0 is the common facies surrounding the mounds probably mostly related to very low energy sedimentation with a few more energetic events. Flanking facies R1 and R2 are characterized by open marine fauna and correspond to the base of the mounds or to flank deposits, and are always observed associated with the deepest mound facies. They were probably deposited in relatively deep environments, the influence of the mounds being low in facies R1 and increasing in facies R2.

Facies R3 and R4 correspond to reworked bioclastic and intraclastic material derived from the buildups. The reworking was probably related to a marine regression which was responsible for an exposure of the mounds (Boulvain, 2007); these microfacies are interpreted as the shallowest. The possible occurrence of pendant cements in facies R4 (Fig. 5E) points to a beach rock environment.

4.2. Facies succession and sedimentological model

Mound thickness of the La Boverie Member varies little. Values of mound thickness range from 34 m in the La Boverie quarry in Rochefort to 36 m or locally 45 m in the Nord quarry at Frasnes (Boulvain and Coen-Aubert, 2006). The sizes of the Arche and Lion mounds differ significantly from that of the La Boverie mound. In Frasnes, the Lion mound is 800 x 400 m in area and 150 m thick. In La Boverie quarry, the Lion Member is 3.5 km long and more than 80 m thick and the Arche Member is about 100 m thick.

All the mounds are composed of the same facies association (off mound, deep mound, shallow mound and reworked facies, Fig. 2). Furthermore, facies succession is

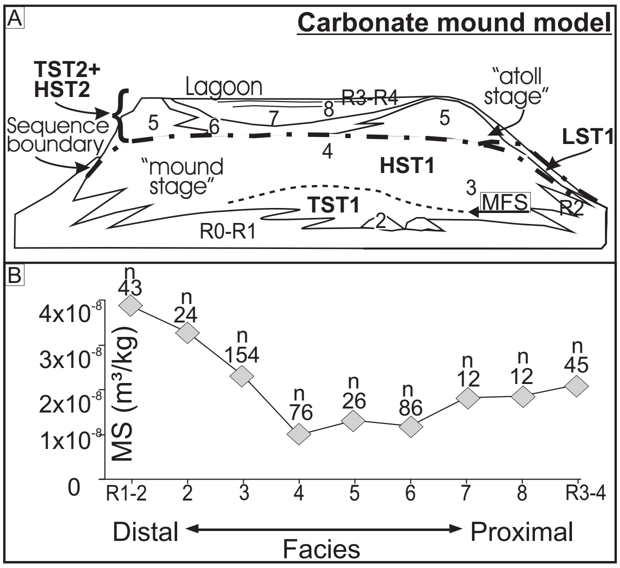

Figure 6. A. Geometry, facies model and sequence stratigraphy of a mound (Boulvain, 2007). B. Mean magnetic susceptibility values (n=number of for data for each facies) the mound facies. Highest values are observed for the deepest facies (facies 2-3 and R1-2), lowest for the mound facies (4-5) and intermediate values for the shallow water reworked deposits (facies 6-7 and R3-4). Legend is in Figure 2.

similar in all of the mounds. The Lion and Arche buildups begin with grey or pinkish/reddish floatstones containing stromatactis, corals and crinoids (facies 2 and 3, Boulvain and Coen-Aubert, 1998; Boulvain et al., 2004). After about 40 to 70 m of this facies forming the bulk of the mounds, a grey "algal" facies began to develop (facies 4 and 5), including microbial boundstone or bafflestone lenses that tend to coalesce upwards. The mound ends up with very shallow water facies (facies 6 to 8), occurring in the central part of the buildups. This geometry suggests the development of an area of relatively restricted sedimentation (inner shallow lagoon) sheltered by the bindstone or floatstone facies of the mound margin (atoll crown) (Boulvain, 2007).

After the growth of the lower part of the mounds during a transgression, with a short episode of low oxygen conditions locally revealed by the presence of iron bacteria (Boulvain et al. 2001), a clear lateral progradation (increasing of the mound diameter) is recorded by the fore-mound sedimentation of reworked material (facies R3-4). Then, a lower sea level restricts the reef growth to occur only downslope, culminating in the development of a circular reef margin (atoll crown) during the following transgressive stage. Therefore, the occurrence of relatively restricted facies inside this crown is possibly the result of a balance between sea-level rise and reef growth (see model in Fig. 6A).

Given the geometry and the bathymetry of the sedimentary bodies, a sequence stratigraphic of the buildups and their lateral sediments is proposed (see synthesis in Fig. 6, 8). Considering system tracts definitions, the sequential model is built mostly on the basis of: stratigraphic succession (aggradation, retrogradation, progradation) and geometry (extension or restriction of the mound). However, in this mud mound system and outcrop quality, remarkable surfaces are very rarely observed. Considering these arguments, it is possible to develop a sequence sequence stratigraphic succession on a theoretical model but it is very difficult to precisely identify the surfaces on outcrops. This kind of theoretical model (without precise position of surfaces) was already partly proposed in different papers for the Upper Frasnian Lion mound (Boulvain, 2007; da Silva et al., 2009b). 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 a strong progradation associated with reduced accommodation space occurring during the HST. The mound development during the following lowstand systems tract (LST) was restricted to the margin of the buildups. The subsequent development of an atoll-like margin corresponds to a new TST with a significant lateral facies differentiation between fore-mound and mound lagoon (Boulvain, 2007).

Facies succession observations of the La Boverie Member are relatively similar (Figs 2, 3) with an evolution from stromatactis coral facies (2 and 3) at the base, towards shallow water algal-microbial-stromatoporoid facies (4, 5, 6 and 8) at the top. However, the shallow water facies are not observed in all the La Boverie mound sections (for example, they are not observed in La Boverie, section I, Fig. 2).

5. Magnetic susceptibility (MS)

Based on 371 samples taken from the Nord quarry at Frasnes, MS values range from -2 x 10^{-9} m³/kg to 8.8 x 10^{-8} m³/kg, with a mean value of 2 x 10^{-8} m³/kg. Variations in the magnetic susceptibility signal correlate with significant facies changes (Figs 3 and 6), with highest MS values corresponding to the deepest facies (flanking facies R1-R2 and buildup facies 2 and 3). A transition from shallow to deeper facies corresponds to MS increase.

Good correlations (Fig. 3) were made using sharp MS increases (from low values around 0 m³/kg up to high values around 6 x 10^{-8} m³/kg). Three main MS trends are observed in and around the La Boverie Member. The first, located at the base of the Member, begins at low values (0.1 x 10^{-8} m³/kg) that increase to reach high values (5.8 x 10^{-8}m³/kg, Fig. 3, zone1) and corresponds to the transition from the Arche Member (shallow water facies) to the base of the La Boverie mound (deep lower mound facies). Then, MS decreases and remains low, around 0.002 x 10^{-8} m³/kg (Fig. 3, zone 2) in the upper part of the La Boverie mound corresponding to shallow mound facies. The last excursion is located at the transition between the La Boverie and Bieumont Members and begins at negative values (-0.09 x 10^{-8} m³/kg values, from zone 2) which tend to increase towards high values (4.2 x 10^{-8} m³/kg, Fig. 3, zone 3), corresponding to the deep facies of the Bieumont and base of the Lion Members.

Considering the La Boverie quarry (Fig. 7), the magnetic susceptibility curve of the whole succession can be divided in three main parts. A first part, corresponding to the Arche Member presents very low MS values (Fig.

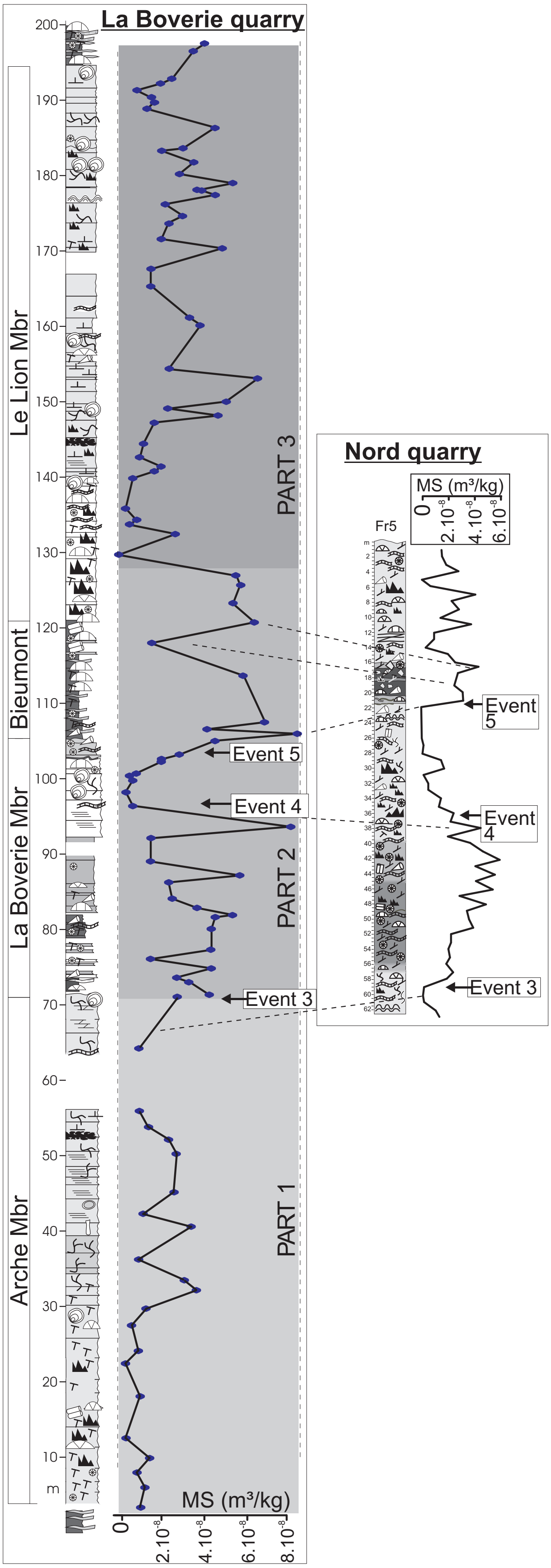

Figure 7. La Boverie quarry, sections C (lower 56 m) and H (upper part) (see Fig. 2) and MS curve (left column), correlated to the MS curve at Nord quarry core Fr5 (right column). Log after Boulvain et al. (2005). Legend is in Fig. 2.

7, part 1), with most of the MS values around 1 x 10^{-8} m^3/kg and with a couple of peaks at the top of the Arche Member to around 4 x 10^{-8} m^3/kg. Then, a second part (Fig. 7, part 2) corresponding to the La Boverie, Bieumont and first ten meters of the Lion Member presents sharp variations with values between 0.2 x 10^{-8} to 8.5 x 10^{-8} m^3/kg. The last part, the base of the Lion Member (Fig. 5, part 3) presents relatively low values (around 1 x 10^{-8}) with one high peak (5 x 10^{-8} m^3/kg), followed by several peaks (around 4 x 10^{-8} m^3/kg).

As observed, the MS curves from the Nord quarry cores (Fig. 3) are easy to correlate, but they are from the same mound. The peaks developed at the La Boverie quarry in the La Boverie Member could be correlated to the Nord quarry cores (Fig. 7), although the two outcrops are 100 km apart, belonging to different mound bodies.

6. Discussion

In this chapter, we will first consider the magnetic susceptibility interpretation. In the light of the MS correlations and facies interpretations, we then propose an integrated reconstruction of the main sedimentary changes occurring during the key EMFE period.

6.1. Magnetic susceptibility and sedimentary dynamics

Da Silva and Boulvain (2002, 2006) applied MS measurements to the Frasnian shallow water carbonate platform in Belgium, which is time equivalent to these mounds. These studies provided precise correlations on the carbonate platform and demonstrated the relationship between MS and facies (MS increases for more proximal facies), and MS and fourth-order sequences (increasing MS at the top of a regressive sequence due to increasing lithogenic inputs).

As described herein, in the carbonate mounds, the link between MS and facies (Figs 3 and 6) works opposite than that predicted by traditional models (Crick et al., 1997), and that observed on the shallow water carbonate platforms (Da Silva and Boulvain, 2006). The highest MS values (around 6x10^{-8} m^3/kg) are observed within the more distal facies which correspond to the surrounding (R1) and mound flank (R2) deposits and deepest mound facies (2-3). All the other facies, corresponding to the shallowest mound facies (4, 5 and 6), the lagoonal sediments (7-8) and the dismantling of the mound (R3-R4) have low values (around 1.5x10^{-8} m^3/kg).

The strong link between MS evolution and facies trends speaks in favour of a strong environmental link. In the present case, we should also consider the possible influence of the microbial hematite in facies 2. These hematitic levels related to the deeper facies occur in the lower part of the La Boverie Member, in the core Fr5, and this zone corresponds to high MS values (Fig.3, zone 1). However, in the cores 1 and 2, within the lower La Boverie Member, the MS values are equally high, but without any hematitic spots. In corresponding stratigraphic intervals, the MS curve has a similar behaviour in hematite-rich levels and levels without occurrence of hematite (Fig. 3).

As we have seen, a strong environmental control on the MS evolution is observed but the logical increase in MS values with regression trend is not observed. In this kind of relatively distal carbonate mounds, sedimentation is mainly controlled by autochthonous processes (e.g., Boulvain et al., 2004). The growth of the mound and the related sedimentation rate is highly variable and will probably influence lithogenic concentration, as well as water agitation during deposition (high water agitation will prevent deposition of detrital particles, but will favour carbonate cementation) and protection (a barrier or reef will protect the sediment from lithogenic inputs). Effectively, the surrounding (R1) and mound flank (R2) deposits and the mound facies 2-3 (which have the higher mean MS values) correspond to a low to moderate sedimentation rate and to the deepest environments, with condensed levels and very low water agitation (below the effect of storm wave base). However, shallow mound facies (atoll crown 4, 5 and 6 and R3-4) and lagoonal facies (7 and 8) are characterized by a higher water agitation on the external side of the atoll crown and protected environment inside the crown, as well as a high sedimentation rate. All these point to low mean MS values (as also observed in Babek et al., this volume).

So in laterally time-equivalent shallow water deposits and carbonate mounds, the processes that are controlling MS peaks work in the opposite way. Effectively, on the shallow water platform, a regression will increase the magnetic susceptibility by increasing the lithogenic inputs (Da Silva and Boulvain, 2006) and in the carbonate mounds, a regression will increase the carbonate production and wave agitation and so will dilute the lithogenic input and will produce a decrease of magnetic susceptibility. These results are very important because it makes it difficult to correlate magnetic susceptibility peaks from different sections if the processes controlling these peaks act in an opposite ways on different parts of the platform.

6.2. Events, sedimentary dynamics and correlations with the EMFE

With the combined sedimentological and MS correlations, it is possible to reconstruct the sedimentary dynamics during the early-middle Frasnian in the Ardennes area and to define several events. The events are corresponding to a sharp transition between unrelated facies or to a karstic surface or a beach rock.

The *punctata* Zone is characterized by a concentration of sharp sea-level changes (see synthesis of sedimentological events in Fig. 2 for the La Boverie quarry, Fig. 3 for the Nord quarry and Fig. 8 for a general model), which define the following events;

- Event 1: middle part of the Arche mound, abrupt shallowing, transition from deep mound facies (2-3) to shallow mound facies (6-8).

- Event 2: upper part of the Arche mound, 6 m below the top of the mound, beach rock (pendant cement, Fig. 5F) and karstic surface (Figs 5A-E).

- Event 3: top of the Arche mound, drowning of the mound. Mound development could not keep up with

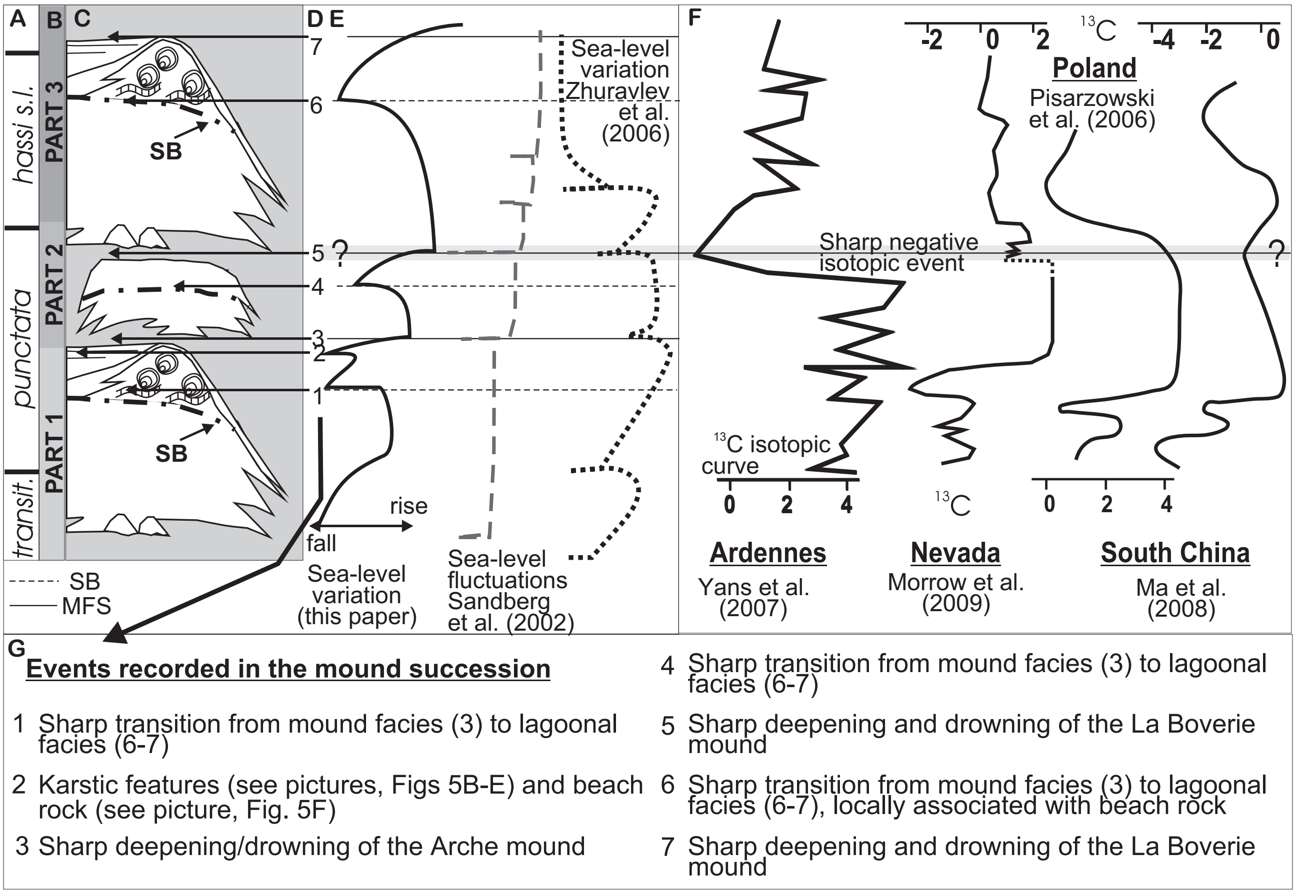

Figure 8. Synthetic model, mound succession and main sedimentological events. A. Conodont zonation from Bultynck and Dejonghe, 2001. B. Main magnetic susceptibility behaviour, based on the MS curve from the La Boverie quarry (see Fig. 7). Part 1 has low values and small variations, part 2 has the highest values of the section and sharp variations and part 3 corresponds to low values with a few variations. C. Mound model and succession, legend in Fig. 2. D. Main events (defined in G) and sedimentological observations. E. Reconstruction of a theoretical sea-level curve, in relation to the main events observed in D, and comparison with some other sea level curves from literature. F. Carbon isotopic curves from literature, dashed interval in Nevada curve denotes undetermined missing stratigraphic section instantaneously removed by Alamo impact event prior to emplacement of the breccia. G. Description of events recorded in column D.

rising sea level and carbonate production stopped, replaced by shales (Fig. 5G). The top of the Arche mound is characterized by very shallow water deposits (including karstic features 6 m below the top, Event 2) and the overlying transition to deep shale deposits is very sharp. After collapse of the carbonate factory, widespread shales are deposited, except in some local areas where small buildups continue (local "survival" mounds, La Boverie section I, Figs 2 and 5H). Above the shales, carbonate production started again and expanded with deep mound facies 2 and 3 corresponding to the base of the La Boverie mound.

- Event 4: middle part of the La Boverie mound, transition from deep mound facies (2-3) to shallow mound facies (6-8). This transition is observed in the Nord quarry sections (Fig. 3) and in the La Boverie quarry (Fig. 2) except in section I, where the local absence of shallow water facies could be related to erosion or strong lateral facies variations like a transition to the atoll crown.

- Event 5: top of the La Boverie mound, drowning of the mound. Mound development could not keep up with rising sea level and carbonate production stopped, being replaced by shale deposition. The upper part of the La Boverie mound is characterized by shallow water deposits, sharply overlain by deep water shale deposits. Hard grounds are locally developed on the top of the buildups (section D and I in La Boverie, Fig. 2). The La Boverie mound is followed by shales and then deep water facies of the prograding Lion mound. This event would correspond to the *punctata* Event, although lack of precise conodont biozonation in the mounds does not allow a more precise biostratigraphic correlation.

- Event 6: middle part of the Lion mound, transition from deep mound facies (2-3) to shallow mound facies (6-8). At La Boverie section I, this transition is associated with beach rock features.

- Event 7: top of the Lion mound, drowning of the mound. Mound development could not keep up with rising sea level and carbonate production stopped, being replaced by shale deposition. The top of the Lion mound is characterized by shallow water and the overlying transition to deep shale deposits is very sharp.

It clearly appears that the *punctata* Zone is characterized by five important sea-level changes (events 1 to 5, Fig. 8). It also corresponds to the strongest and sharpest MS variations (part 2 of the magnetic susceptibility curve, Fig. 7). These rapid, but severe fluctuations have also been mentioned by Gouwy and Bultynck (2000, p. 37 and Fig. 16) on the basis of changes in the conodont biofacies. According to these authors, they occur at the top of second major transgressive-regressive cycle for the Ardennes, i.e. above the Arche Member, in the upper part of the Ermitage Member. The sea-level variations therefore are recognized at the basin scale. In addition, similar sea-level changes were also recorded in the synthesis of Sandberg et al. (1992, 2002) and in Poland (Zhuravlev et al., 2006) (Fig. 8).

Carbon isotopic data published by Yans *et al*. (2007) came from various outcrops in the Ardennes area. However, the stratigraphic succession in the present study is similar to that studied by these authors; so it is possible to propose a correlation with the Yans et al. (2007) carbon isotopic curve and with other published works on the EMFE event (Fig. 8, Pisarzowski et al., 2006; Ma et al., 2008; Morrow et al., 2009). The main negative carbon isotope excursion defined by Yans et al. (2007) corresponds to the transgressive pulse and drowning of the La Boverie mound (Event 5) (Fig. 8).

By comparison with the sequence stratigraphic models proposed for the Arche and Lion mounds (Boulvain, 2007), the La Boverie buildups show strong basin-scale sea-level variations at a shorter time interval than that expected for "classic" Arche and Lion mounds. Two periods of collapse of the shallow water carbonate factory (base and top of the La Boverie Member) due to rapid sea-level rises and drops occur in a 34 to 45 m thick interval. It is difficult to determine the duration of these variations but we can estimate it by comparison with the carbonate mounds from Arche and Lion Members. The facies of all the mounds are similar, so the sedimentation rate is probably similar between the different mounds. The Lion and Arche Members are between 100 and 150 m thick so they are two to four times thicker than the La Boverie Member. Considering similar sedimentation rates, the time interval between the strong sea-level fluctuations, which implies the initiation (sea-level rise) and demise (sea-level fall) of the Arche and Lion mounds, is probably two to four times longer than in the La Boverie Member. Considering that the Lion mounds lasted probably between 1 and 2 My (Gouwy and Bultynck, 2000; Kaufmann, 2006) and the Arche Member lasted around 1My, the duration between the main eustatic fluctuations recognized in the La Boverie Member is between 0.25 and 0.5 My. Drowning of the mounds was also very rapid, as observed for example at the top of the Arche Member, that is characterized by karstic features and beach rock, 6 meters below the top of the mound, overlain by the sharp transition to shales (estimated water depth of about 100 m).

7. Conclusions

A new level of Frasnian mound has been recently discovered in the Frasnes area where the historical stratotype of the stage has been defined. It is assigned to the La Boverie Member and lies between the Arche and Bieumont Members, within the early-middle Frasnian interval (Boulvain and Coen-Aubert, 2006). The discovery of this new mound level is very important because it records unusual high amplitude eustatic fluctuations.

From a sedimentological point of view, the La Boverie mound presents the same succession of facies induced by sea-level variations as is recorded in the much thicker Frasnian Arche and Lion mounds. A sea-level drop is observed at the top of the Arche Member, followed by a high-amplitude sea-level rise in the lower part of the La Boverie Member, which is then followed by a second sea-level drop below the top of this lithostratigraphic unit. These sea-level changes are recognized in the whole sedimentary basin of the Ardennes area and in other areas (e.g., Poland). Therefore, these sea-level changes should be regarded as eustatic variations. For the Arche and Lion Members, the time interval between the initiation and the demise of the mounds (i.e., the time-interval between the main sea-level fluctuations) is between 1 and 2 My, but for the new La Boverie mound the time interval is dramatically less. These observations document that rapid, high amplitude sea-level changes characterize the *punctata* Zone. The *punctata* Event, a negative carbon isotopic excursion identified first in the Ardennes and then worldwide corresponds to an important transgressive phase.

In the *punctata* conodont zone, magnetic susceptibility variations are sharp and strong, in relation to the sharp and strong depositional events. However, the MS record is opposite of that expected. Theoretical models propose that MS increases during regression and this trend is obvious in the shallow water platform of Belgium (Da Silva and Boulvain, 2006), with the highest MS recorded for the shallowest facies. In the case of mounds, magnetic susceptibility increases in the deepest facies. This high magnetic susceptibility is probably related to lower sedimentation rates (and condensed levels) rather than to higher lithogenic inputs. In contrast, the low MS values observed in the shallow water mound facies are related to high productivity, greater biogenic sediment production and dilution of magnetic minerals. This observation is important because if the processes controlling magnetic susceptibility on different part of platforms can produce an opposite signal. Then the resulting MS-based correlations across different zones of the platform will be problematic.

8. Acknowledgements

The Carmeuse (O. Swennen) and Lhoist (E. Burnotte) companies gave us all facilities for the field study and investigation of the boreholes drilled in the Nord and La Boverie quarries, respectively. AC Da Silva acknowledges the F.N.R.S. for a position as postdoctoral researcher. This research was supported by the Belgian Fond National de la Recherche Scientifique (Project FRFC n°2-4501-02) and is part of the IGCP-580 project (Application of magnetic susceptibility as a paleoclimatic proxy on Paleozoic sedimentary rocks and characterization of the magnetic signal). Jared Morrow and Ondrej Babek provided critical reviews which strongly improved the paper, as well as Jean-Clair Duchesne for his final Editing work on this paper. We dedicate this work to Michel Coen and Michel Vanguestaine, recently deceased, who were famous contributors to the knowledge of the Frasnian of Belgium.

9. References

BÁBEK, O., KALVODA, J., ARETZ, M., COSSEZ, P.J., DEVUYST, F.X., HERBIG, H. & SEVASTOPULO, G., 2010. The correlation potential of magnetic susceptibility and outcrop gamma-ray logs at Tournaisian-Viséan boundary sections in western Europe. *Geologica Belgica*, this volume.

BALINSKI, A., OLEMPSKA, E. & RACKI, G., 2006. Early-Middle Frasnian global transition : Biotic response to a major perturbation of the global carbon budget. *In* Balinski, A., Olempska, E. & Racki, G. (eds), Biotic aspects of the Early-Middle Frasnian Eventful transition. *Acta Palaeontologica Polonica* 51: 606-608.

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

BOULVAIN, F., 2007: Frasnian carbonate mounds from Belgium: sedimentology and palaeoceanography. *In* Alvaro, J. 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. & COEN-AUBERT, M., 1998. Le monticule frasnien de la Carrière du Nord à Frasnes (Belgique): sédimentologie, stratigraphie séquentielle et coraux. *Service Géologique de Belgique, Professional Paper,* 1997/3, 285 : 1-47.

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. et al., 1999. Les formations du Frasnien de la Belgique. *Memoirs of the Geological Survey of Belgium,* 44 : 1-125.

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

BOULVAIN, F., CORNET, P., DA SILVA, A-C., DELAITE, G., DEMANY, B., HUMBLET, M., RENARD, M. & COEN-AUBERT, M., 2004. Reconstructing atoll-like mounds from the Frasnian of Belgium. *Facies,* 50: 313 - 326.

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: 69-89.

BULTYNCK, P. & DEJONGHE, L., 2001. Devonian lithostratigraphic units (Belgium). *In* Bultynck, P. & Dejonghe, L. (eds), Guide to a revised lithostratigraphic scale of Belgium. *Geologica Belgica,* 4/1: 39-69.

CRICK, R.E., ELLWOOD, B.B., HLADIL, J., 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(3): 167-175.

CRICK, R.E., ELLWOOD, B.B., EL HASSANI, A. & FEIST, R., 2000. Proposed magnetostratigraphy susceptibility magnetostratotype for the Eifelian-Givetian GSSP (Anti-Atlas, Morocco). *Episodes,* 23(2): 93-101.

CURRY, W.B., SCHNEIDER, D.A. & PARTY, L.S., 1995. Ceara Rise sediments document ancient climate change. *EOS,* 76(5): 40-45.

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 paleosols to carbonate mounds: facies and environments of Middle Frasnian carbonate platform in Belgium. *Geological Quarterly,* 48(3): 253-266.

DA SILVA, A.C. & BOULVAIN, F., 2006. Upper Devonian carbonate platform correlations and sea level variations recorded in magnetic susceptibility. *Palaeogeography, Palaeoclimatolology, 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.

D'OMALIUS D'HALLOY, J.G.J., 1862. Abrégé de géologie, 7ème édition (ce compris, celles publiées sous les titres d'éléments et précis de géologie), Bruxelles, Leipzig, Paris, 626 pp.

ELLWOOD, B.B., CRICK, R.E. & EL HASSANI, A., 1999. Magnetosusceptibility event and cyclostratigraphy (MSEC) method used in geological correlation of Devonian rocks from Anti-Atlas Morocco. *The American Association of Petroleum Geologists Bulletin,* 83(7): 1119-1134.

ELLWOOD, B.B., CRICK, R.E., EL HASSANI, A., BENOIST, S.L. & YOUNG, R.H., 2000. Magnetosusceptibility event and cyclostratigraphy method applied to marine rocks: detrital input versus carbonate productivity. *Geology,* 28: 1135-1138.

GERŠL, M. & HLADIL, J., 2004. Gamma-ray and magnetic susceptibility correlation across a Frasnian carbonate platform and the search for "*punctata*" equivalents in stromatoporoid-coral limestone facies of Moravia. *Geological Quarterly,* 48: 283-292.

GOUWY, S. & BULTYNCK, P., 2000. Graphic correlation of Frasnian sections (Upper Devonian) in the Ardennes, Belgium. *Bulletin de l'Institut royal des Sciences naturelles de Belgique, Sciences de la Terre,* 70 : 25-52.

HLADIL, J., GERŠL, M., STRNAD, L., FRANA, J., LANGROVA, A. & SPISIAK, J., 2005. Stratigraphic variation of complex impurities in platform limestones and possible significance of atmospheric dust: a study with emphasis on gamma-ray spectrometry and magnetic susceptibility outcrop (Eifelian-Frasnian, Moravia, Czech Republic). *International Journal of Earth Science*, 95: 703-723.

HLADIL, J., KOPTIKOVA, L., GALLE, A., SEDLACEK, V., PRUNER, P., SCHNABL, P., LANGROVA, A., BABEK, O., FRANA, J., HLADIKOVA, J., OTAVA J. & GERŠL M., 2009. Early Middle Frasnian platform reef strata in the Moravian Karst interpreted as recording the atmospheric dust changes: the key to understanding perturbations in the punctata conodont Zone. *Bulletin of Geosciences,* 84: 75-106.

JOACHIMSKI, M., BREISIG, S., BUGGISCH, W., TALENT, J.A., MAWSON, R., GEREKE, M., MORROW, J.R., DAY, J. & WEDDIGE, K., 2009. Devonian Climate and Reef Evolution: Insights from Oxygen Isotopes in Apatite. *Earth and Planetary Science Letters*, 284: 599-609.

KAUFMANN, B., 2006. Calibrating the Devonian Time Scale: A synthesis of U-Pb ID-TIMS ages and conodont stratigraphy. *Earth-Science Reviews,* 76: 175-190.

KIESSLING, W., FLUGEL, E. & GOLONKA, J., 1999: Paleoreef maps : evaluation of a comprehensive database on Phanerozoic reefs. *The American Association of Petroleum Geologists, Bulletin* 83: 1552-1587.

LEAN, C.M.B. & McCAVE, I.N., 1998. Glacial to interglacial mineral magnetic and palaeoceanographic changes at Catham Rise, SW Pacific Ocean. *Earth and Planetary Science Letters,* 163: 247-260.

MA, X.-P., WANG, C.-Y., RACKI, G. & RACKA, M., 2008. Facies and geochemistry across the Early-Middle Frasnian transition (Late Devonian) on South China carbonate shelf: Comparison with the Polish reference succession. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 269 : 130-151.

MAILLIEUX, E., 1908. Quelques mots sur le récif de marbre rouge de l'Arche, à Frasnes. *Bulletin de la Société belge de Géologie,* 22 : 346-349.

MAILLIEUX, E., 1913. Nouvelles observations sur le Frasnien et en particulier sur les paléorécifs de la plaine des Fagnes. *Bulletin de la Société belge de Géologie, de Paléontologie et d'Hydrologie, Mémoires,* 27 : 67-104.

MORROW, J.R., SANDBERG, C.A., MALKOWSKI, K. & JOACHIMSKI, M.M., 2009; Carbon isotope chemostratigraphy and precise dating of middle Frasnian (lower Upper Devonian) Alamo Breccia, Nevada, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 282 : 105-118.

NEUWEILER, F., BOURQUE, P.-A. & BOULVAIN, F., 2001. Why is stromatactis so rare in Mesozoic carbonate mud mounds? *Terra Nova* 13: 338-346.

PISARZOWSKA, A., SOBSTEL, M. & RACKI, G., 2006. Conodont-based event stratigraphy of the Early-Middle Frasnian transition on the South Polish carbonate shelf. *In* Balinski, A., Olempska, E. & Racki, G. (eds): Biotic aspects of the Early-Middle Frasnian eventful transition. *Acta Palaeontologica Polonica,* 51: 606-608.

RACKI, G., PIECHOTA, A., BOND, D. & WIGNALL, P.B., 2004. Geochemical and ecological aspects of lower Frasnian pyrite-ammonoid level at Kostomłoty (Holy Cross Mountains, Poland). *Geological Quarterly,* 48: 267–282.

RACKI, G., JOACHIMSKI, M.M. & MORROW, J.R. 2008. A major perturbation of the global carbon budget in the Early-Middle Frasnian transition (Late Devonian). *Palaeogeography, Palaeoclimatology, Palaeoecology,* 269: 127-129.

ROBINSON, S.G., 1993. Lithostratigraphic applications for magnetic susceptibility logging of deep-sea sediment cores: examples from ODP Leg 115. *In* Hailwood, E.A. & Kidd, R.B. (eds): High Resolution stratigraphy. *Geological Society Special Publication,* 70: 65-98.

SANDBERG, C.A., ZIEGLER, W., DREESEN, R., & BUTLER, J.L., 1992, Conodont biochronology, biofacies, taxonomy, and event stratigraphy around middle Frasnian Lion Mudmound (F2h), Frasnes, Belgium. *Courier Forschungsinstitut Senckenberg*, 150: 87 p.

SANDBERG, C.A., MORROW, J.R. & ZIEGLER, W., 2002. Late Devonian sea-level changes, catastrophic events, and mass extinctions. *In* Koeberl, C. & MacLeod, K.G. (eds), Catastrophic Events and Mass Extinctions: Impacts and Beyond: Boulder, Colorado. *Geological Society of America Special Paper*, 356: 473–487.

ŚLIWIŃSKI, M., WHALEN, M. & DAY, J., 2010. Trace element variations in the middle Frasnian *punctata* zone (late Devonian) in the Western Canada sedimentary basin – changes in oceanic bioproductivity and paleoredox spurred by a pulse of terrestrial afforestation? *Geologica Belgica*, this volume.

VAIL, P.R., MITCHUM, R.M.J. & THOMPSON, S., 1977. Seismic stratigraphy and global changes of sea level, Part 4: Global cycles of relative changes of sea level. *In* Payton, C. E. (ed.): Seismic stratigraphy - applications to hydrocarbon exploration. *The American Association of Petroleum Geologists, Memoir,* 26: 83-97.

YANS, J., CORFIELD, R.M., RACKI, G. & PRÉAT, A., 2007. Evidence for a major perturbation of the carbon cycle in the Middle Frasnian punctata conodont Zone. *Geological Magazine,* 144: 263-277.

ZHURAVLEV, A.V., SOKIRAN, S., EVDOKIMOVA, I.O., DOROFEEVA, L.A., RUSETSKAYA, G.A., & MALKOWSKI, K., 2006. Faunal and facies changes at the Early-Middle Frasnian boundary in the north-Western East European platform. *In* Balinski, A., Olempska, E., & Racki, G. (eds), Biotic aspects of the Early-middle Frasnian eventful transition. *Acta Palaeontologica Polonica*, 51: 747-758.

Manuscript received 10.12.2009, accepted in revised form 04.05.2010, available on line 25.06.2010