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Sedimentology, Magnetic Susceptibility and Isotopes of a Middle Frasnian Carbonate Platform: Tailfer Section, Belgium

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KEYWORDS: SEDIMENTOLOGY - CARBONATE PLATFORM - BIOSTROMES - LAGOON - PALEOSOILS - MAGNETIC SUSCEPTIBILITY - BELGIUM - FRASNIAN

Summary

The Tailfer section (Belgium, northern border of the Dinant Synclinorium) exposes Middle Frasnian shallow-water limestones. This paper proposes a sedimentological analysis based on classical petrology, which leads to the identification of 19 fourth order sequences, forming three third order system tracts. This sedimentological analyses is complemented by carbon isotopic and magnetic susceptibility (MS) data (based on the relation between MS and lithogenic input). Each system tracts is characterised by a particular evolution of the isotope and MS curve:

-- **Biostromal Unit**: the biostromes are built by lamellar and branching stromatoporoids and massive metazoans. MS values are weak, in relation with the important distance from landmasses and lesser amounts of lithogenic contribution. The carbon isotope values are close to Frasnian seawater values.

-- **Lagoonal Unit**: it corresponds to a lagoonal facies succession, from inter- to supratidal zones, rich in *Amphipora*, paleosiphonocladales, *Umbella*, and pellets, alternating with paleosoils. MS values are high, related to landmass proximity and high lithogenic input. The carbon isotopic curve shows strongly negative values, close to -7 ‰, resulting probably from a continental influence.

-- **Lagoonal and biostromal Unit**: it consists of a lagoonal succession with some biostromal interruptions. MS values are lower than in the lagoonal unit and the isotopic values are higher (close to 0 ‰), related to an increase in distality.

1 INTRODUCTION

Devonian was a period of intense reefal proliferation. The major centres of reefal development were situated in Canada (Alberta), Russia (Siberian platform and Timan-Pechora Province), Central Europe, Morocco, South China and Australia (Kiessling *et al.*, 1999). These reefs were characterised by a relatively low diversity (Kiessling *et al.*, 1999); they were constructed mainly by stromatoporoids, rugose and tabulate corals, calcareous algae and cyanobacteria (Pohler, 1998). Studies concerning reef facies are very numerous (Burchette, 1981; Hladil, 1986; Weller, 1991; Shen and Zhang, 1997; Pohler, 1998), but papers dealing with contemporaneous back-reef facies are rare (Machel and Hunter, 1994; Wood, 2000). Proposing a reconstruction of Frasnian shallow-water carbonate facies could therefore be of interest.

The sedimentological study is complemented by carbon isotopes and magnetic susceptibility data. Magnetic susceptibility data had been previously used mainly for correlations (Crick *et al.*, 1994) and as a paleoclimatic indicator (Curry *et al.*, 1995). Recently, these data have been used for reconstruction of sea level curves (Devleeschouwer, 1999; Crick *et al.*, 2001).

2 GEOLOGICAL SETTING

The Tailfer outcrop is located at the northern border of a major Variscan structure, the Dinant Synclinorium (Belgium, Fig.1.a.). In detail, the section corresponds to the northern flank of an E-W syncline and the direction and dip of strata is N100°E/50°S. The section belongs to the Middle Frasnian Lustin Formation (Fig. 1b.), characterised by carbonate platform deposits. In the Philippeville Anticlinorium, the distal equivalents of the Lustin Formation are the argillaceous Pont-de-la-Folle Formation, followed by the Philippeville Formation, where biostromes are better developed than in the Lustin Formation. At the southern border of the Dinant Synclinorium, the time-equivalent Moulin Liénaux and Grands Breux Formations expose carbonate mound episodes included in shales (Boulvain *et al.*, 1999).

The Tailfer section was the subject of paleontological studies (Tsien *et al.*, 1973; Coen-Aubert and Coen, 1974), but neither of these works presents a sedimentological interpretation. This paper proposes a sedimentological description of the section, a facies model and a reconstruction of Frasnian platform limestone evolution in this area.

3 METHODS AND EQUIPMENT

3.1 Stable isotope analysis

Rock samples were extracted from the polished samples with a millimetre dental-drill. The sampling was realised on

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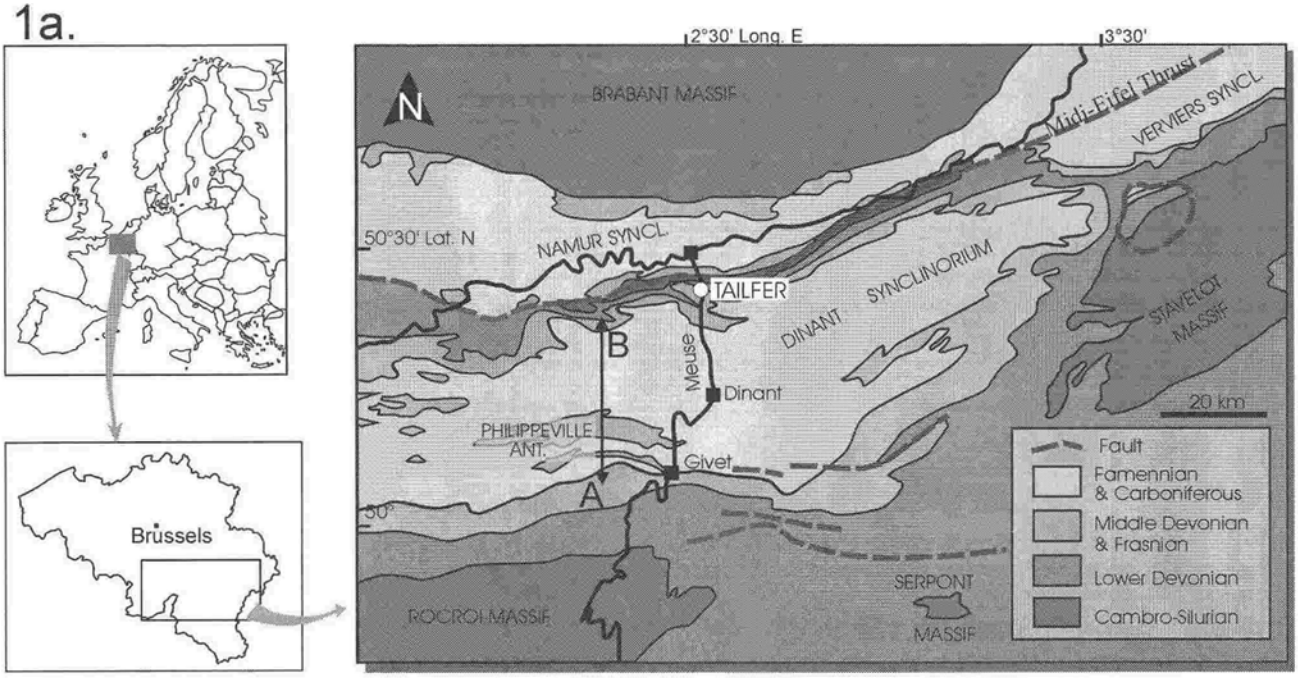


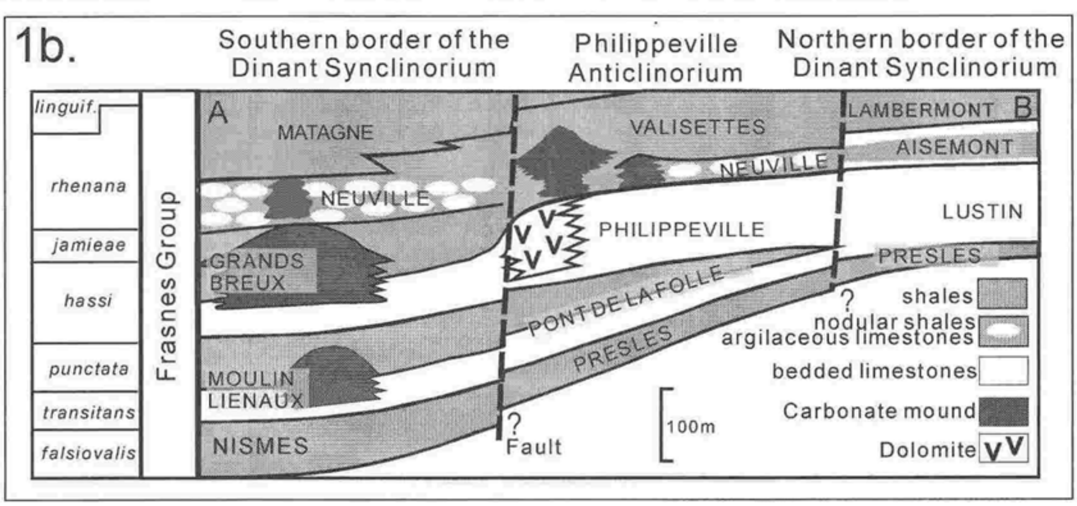


Fig. 1a. Geological setting and location of the studied section. Fig. 1b. N-S section in the Belgian Frasnian sedimentation basin, before Variscan structuration. The first column is the conodont zonation, after Gouwy and Bultynck (2000).

fine-grained carbonate mudstone, with a minimal quantity of skeletal grains, clays and veins.

The analyses were performed at the Institute of Geology and Mineralogy of the University of Erlangen (Germany). The carbonate powders were reacted with 100% phosphoric acid (density >1.9, Wachter and Hayes, 1985) at 75°C in an online carbonate preparation line (Carbo-Kiel - single sample acid bath) connected to a Finnigan Mat 252 masspectrometer. Results were reported in ‰ relative to V-PDB by assigning a $\delta^{13}C$ value of +1.95‰ and a $\delta^{18}O$ value of -2.20‰ to NBS19. Reproducibility was checked by replicate analysis of laboratory standards and is better than ± 0.1‰.

3.2 Magnetic susceptibility

Measurements were performed on limestone blocks, approximately 5cm in length, at the University of Lille (Laboratoire des Sciences de la Terre), with the Kappabridge KLY-2 device. The values of magnetic susceptibility are calculated on basis of sample mass.

4 MICROFACIES

The textural classification used to characterise the microfacies follows Dunham (1962) and Embry and Klovan (1972). The term "coverstone" was suggested by Tsien (1984) to characterise microfacies where lamellar organisms cover mud and debris. Descriptions are based on field observations, polished samples and thin sections. Classification of stromatoporoids morphology follows Kershaw (1998).

In the following description, microfacies are ordered from the most distal to the most proximal according to textural criteria and comparisons with models from the

Microfacies abbreviation	Interpretation	m
Biostromes		
1 Lamellar strom. - muddy matrix	Weak agitation, under the NWB	20
2 Lamellar strom. - reefal biocl.	Intermittent agitation, medium to weak	15
3 Lamellar strom. - crinoids, brach.	Medium to high agitation, near the NWB	10
4 Massive metazoans rudstone	Medium to high agitation, above the NWB	5-10
5 *Stachyodes* bindstone	Subtidal, medium agitation, photic zone	10
6 *Stachyodes* floatstone	Subtidal, weak agitation, photic zone	15
Lagoonal facies		
7 *Amphipora* floatstone	Subtidal, very weak agitation, above the SWB	12
8 Paleosiphonocladales – pack.	Subtidal, above the SWB, very weak agitation	10
9 Heterogeneous pack. with pellets	Subtidal, weak agitation	7
10 *Umbella* – rich packstone	Channels crossing inter- to subtidal zone, weak to medium agitation	3-10
11 Mudstone	Intertidal, very weak agitation	5
12 Homogeneous grainst. with pellets	Intertidal, medium agitation	3-4
13 Laminar peloidal microfacies	Inter- to supratidal, occasional emersions, medium to weak agitation	2
Paleosoils		
14 brecciated limestone	Supratidal, often emerged	0

Table 1. Tailfer section, Middle Frasnian limestones : Compilation of microfacies interpretation and estimation of water depth.

literature (Wilson, 1975; James, 1983; Hardie, 1977; Flügel, 1982). However, this order is not always effective, considering lateral variations. Table 1 compiles interpretations and proposes indicative depths for the different microfacies (after Embry and Klovan, 1972; Wilson, 1975 and Flügel, 1982).

4.1 Biostromes

The term "biostrome" has different meanings according to authors (Kershaw, 1994). To avoid confusion, the definition used in this study is provided. The term was introduced by Cumings (1932), for "purely bedded structures, ... consisting of and built mainly by sedentary organisms, and not swelling into moundlike or lenslike form". This broad sense is applicable to all "layered organic deposits". The definition of biostrome by Link (1950) is more accurate: "accumulations of materials similar or equivalent to those found in bioherms or reefs, but arranged in layers or strata that do not attain a significant vertical relief above see floor. This latter definition will be preferred and applied to accumulations of *Stachyodes*, massive metazoans and lamellar stromatoporoids.

4.1.1 Biostromes with lamellar stromatoporoids (Fig. 2. and Pl. 16/1)

Biostromes with mostly lamellar or tabular stromatoporoids, exceptionally "low domical" or anastomosing, usually with some branching and massive tabulate corals (*Alveolites*), and fasciculate (*Disphyllum*), massive (*Hexagonaria*) or solitary rugose corals.

Microfacies 1: Lamellar stromatoporoids coverstone with muddy matrix

Description: The stromatoporoids are several mm- to several cm- thick and can be minor (some %) or almost the unique rock-forming organism. Locally, they develop astrorhizal mamelons, and they are generally well preserved, in life position. Matrix is generally light grey and rich in small-scale bioclasts (0.01mm) or shows a clotted aspect, even locally peloidal.

After lamellar stromatoporoids, the most frequent organisms are brachiopods and ostracods. They are accompanied by well-preserved crinoids, branching stromatoporoids and tabulate corals, paleosiphonocladales, calcispheres and sponge spicules.

Interpretation: Water energy was weak considering the muddy fraction, preservation of clotted matrix, low amount of bioclasts, good preservation of lamellar stromatoporoids in life position and finally, presence of non-dissociated brachiopods and ostracods. Astrorhizal mamelons are absent or frequent depending on the particular biostrome, indicating that microfacies 1 developped under variable clay input and that these inputs, as long as they were not too important, did not control the facies.

The clotted nature of the matrix was probably related to a microbial origin, as suggested by the laminar aspect of this sediment, its locally encrusting character and the abundance of mm-scale fenestrae. These characteristics are typical of mats and not of mechanical accumulations (Aitken, 1967).

Microfacies 2: Lamellar stromatoporoids floatstone with reefal bioclasts (Fig. 2. and Pl. 16/1)

Description : Between lamellar stromatoporoids (40 to 50 % and mm- to cm- thick) and tabulate corals, matrix is a reefal bioclast-rich packstone (stromatoporoids, branching tabulate and rugose coral debris), with some paleosiphonocladales, trilobites, bryozoans, ostracods, gastropods, *Nanicella*, crinoids and brachiopods. Astrorhizal mamelons face upwards as well as downward, corresponding to in life-position and overturned stromatoporoids. Sorting is weak and preservation state is variable for lamellar organisms and low for crinoids, brachiopods and gastropods.

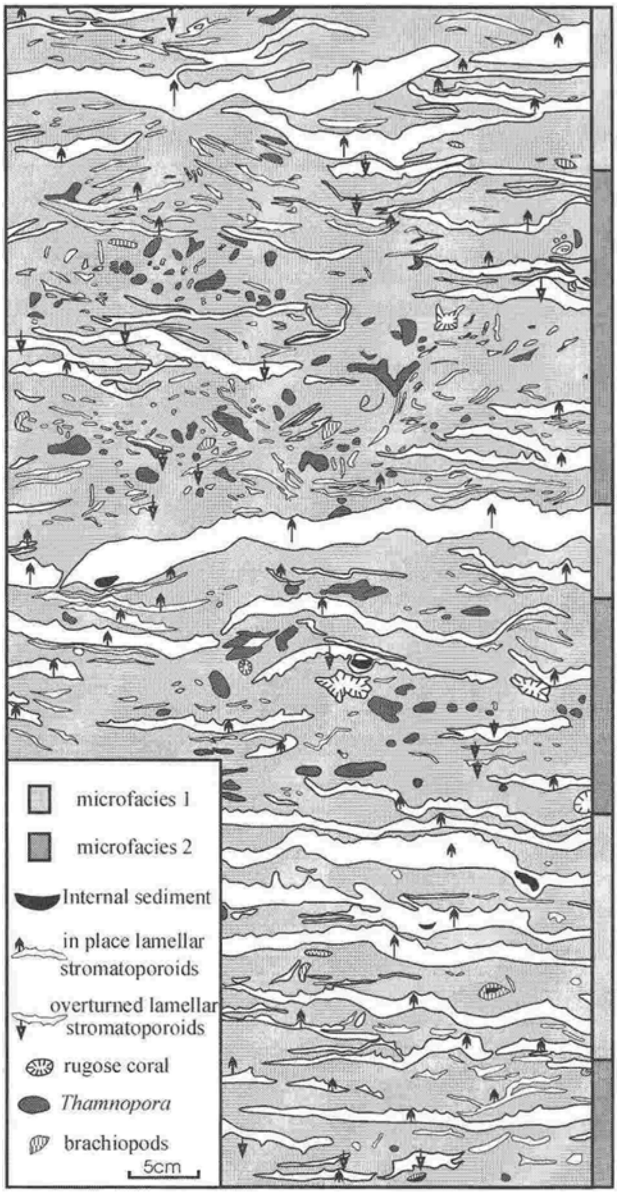


Fig .2. Lamellar stromatoporoids coverstone with muddy matrix (microfacies1) alternating with reefal bioclasts floatstones (microfacies2). Drawing on a sawn surface in the Tailfer section. 47 m above the base of the section.

Interpretation: The interstitial matrix is very rich in tabulate corals and small debris of crinoids, brachiopods, bryozoans and stromatoporoids. Water energy had to be sufficient to produce this debris. However, transportation was weak, as lamellar stromatoporoids are often intact. All these characteristics indicate a medium to weak water energy. It must be noted that lamellar stromatoporoids are less developed in this microfacies because their growth was repeatedly interrupted by higher energy events.

Microfacies 3: Lamellar stromatoporoids rudstone with crinoids and brachiopods

Description: These lamellar and tabular stromatoporoids rudstones include branching tabulate corals and stromatoporoids and massive and fasciculate rugose corals. The matrix is a bioclasts-rich packstone, with crinoids and brachiopods, associated with subordinate bryozoans, ostracods, paleosiphonocladales, trilobites and gastropods. The stromatoporoids (10-20%) are often broken and generally develop astrorhizal mamelons (clay may be an important component). Locally, this facies shows an erosive surface at its base. The interstitial bioclasts are well sorted. Preservation is usually low. However, local muddy accumulations and well-preserved bioclasts are observed. These deposits always correspond to protected sediment between two superposed lamellar stromatoporoids.

Interpretation: Erosive surface at the base of the units and low preservation indicate a relatively sudden deposit, which could be either a tempestite or a transgressive facies. Fossils are generally broken, indicating significant water energy, with some protected areas between well-preserved stro-

Plate 16 Facies from the Tailfer section, Belgian Middle Frasnian carbonate platform.

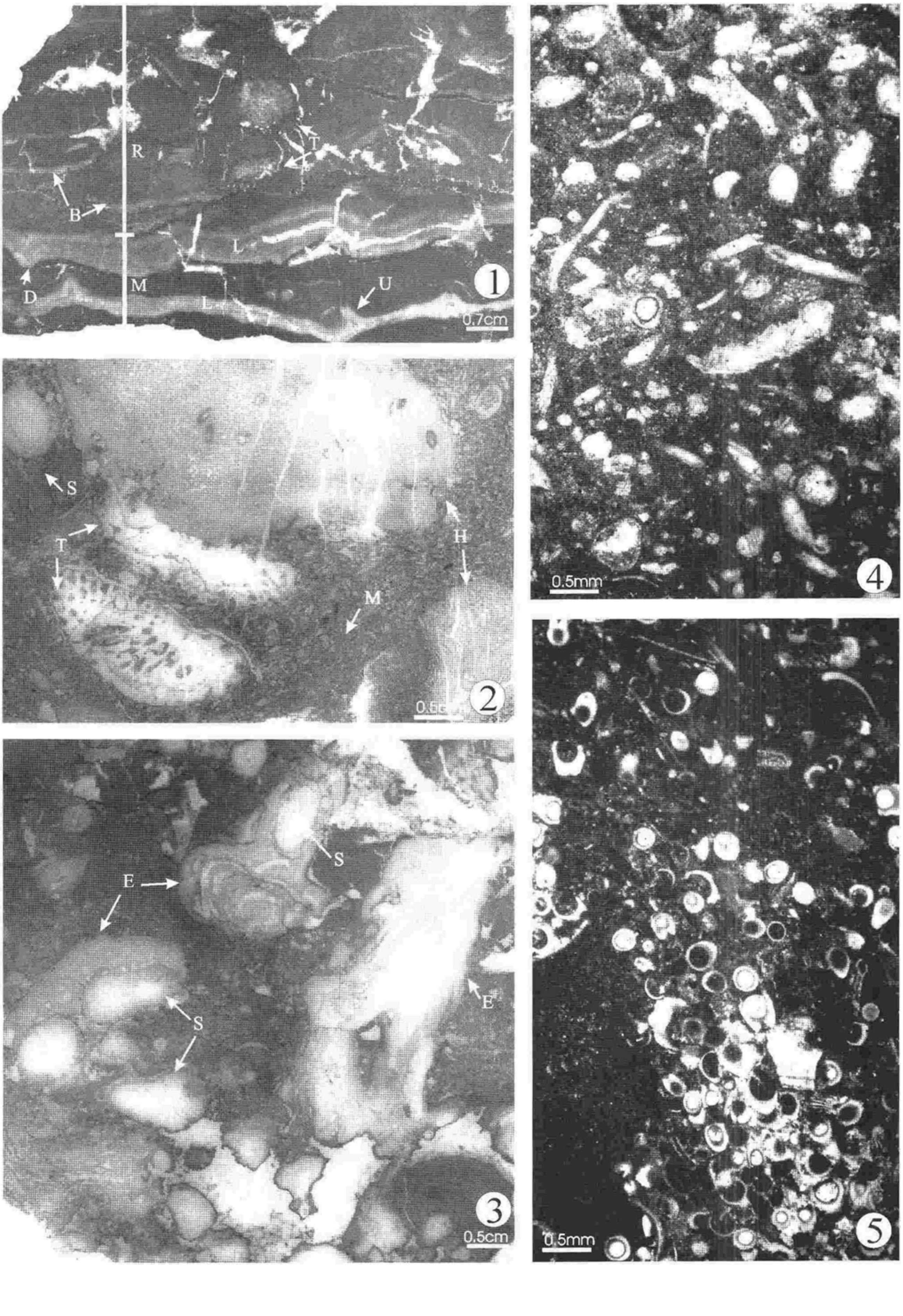
Fig. 1. Lamellar stromatoporoids coverstone with muddy matrix (microfacies 1) alternating with reefal bioclasts floatstone (microfacies 2). Lamellar stromatoporoids show upwards facing (U) and downwards facing (D) astrorhizal mamelons, corresponding respectively to in life-position and overturned organisms. Muddy matrix (M) alternates with reefal bioclasts-rich matrix (R) including broken lamellar stromatoporoids (B) and tabulate corals (T). Tailfer section, scan of sample 53C, 48m above the base of the section.

Fig. 2. Rudstone with massive metazoans (microfacies 4). The high domical broken stromatoporoids (H) are accompanied by *Stachyodes* (S) and tabulate corals (T). These organisms are included in a bioclasts-rich rudstone to packstone with dolomitized matrix (M). Tailfer section, scan of thin section 24, 10m above the base of the section.

Fig. 3. Floatstone with *Stachyodes* (microfacies 6). *Stachyodes* (S) are often encrusted by stromatoporoids (E). These encrusted stromatoporoids are in life position. Tailfer section, scan of thin section 13, 6m above the base of the section.

Fig. 4. Packstone - wackestone with paleosiphonocladales (mainly *Issinella*) (microfacies 8). Tailfer section, thin section 47d, 41m above the base of the section, ordinary light.

Fig. 5. Bioturbated packstone with *Umbella* (microfacies 10). Tailfer section, thin section 87c, 71m above the base of the section.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5

matoporoids. Clay material is present. This is compatible with thicker tabular stromatoporoids (in comparison with the previous lamellar stromatoporoids). Indeed, according to Kershaw (1998), stromatoporoids get thicker when sedimentation rate increases.

Biostromes edification (Fig. 2.) by lamellar stromatoporoids corresponds to the following ecological sequence: microfacies 3 characterised the colonisation phase, and was developped during relatively high energy events. Then, the two lamellar stromatoporoid facies with tabulate corals (2) and mud (1), alternate in dm-scale units. 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 3), as indicated by good preservation of fossils.

4.1.2 Biostrome with massive metazoans

Microfacies 4: Rudstone with massive metazoans (Pl. 16/2)

Description : Rudstone to floatstone with massive metazoans (up to 70%) as stromatoporoids, rugose corals (*Hexagonaria*) or tabulate corals (*Alveolites*), locally associated with fasciculate and/or branching rugose corals (*Disphyllum*), branching stromatoporoids (*Stachyodes*) and branching tabulate corals (*Alveolites* and *Thamnopora*). The massive stromatoporoids are "high domical"; they are generally broken and may be encrusted by stromatoporoids, tabulate corals or algae. Massive organisms are included in a bioclast-rich rudstone to packstone (crinoids, brachiopods, or bryozoans and broken metazoans). Rhomboedric dolomite crystals (0.1 to 0.2 mm) locally replace the matrix. Preservation is poor; the bioclasts are broken and oriented in all directions. Sorting is medium and bimodal (dm-scale macrofossils and mm- to cm-scale bioclasts).

Interpretations : The interstitial corpuscles (crinoids, brachiopods and bryozoans) originated from open sea. The massive morphology of metazoans seems to correspond to medium water energy (Cornet, 1975; Machel and Hunter, 1994). Metazoans are broken, but not rounded, suggesting a relatively short transport. The presence of local undisturbed structures and of protected sediment suggest episodical low energy periods. Some beds show a fining-upward sorting and an erosive basal surface, which is characteristic of storm deposits (Aigner, 1985).

This microfacies is interpreted as biostromes formed in moderate to strong water energy, episodically reworked by storm.

4.1.3 Biostromes with *Stachyodes*

Microfacies 5: Bindstone with *Stachyodes*, encrusting stromatoporoids and Udoteacean algae

Description : Bindstone with *Stachyodes* encrusted by stromatoporoids. *Amphipora* and numerous Udoteacean algae are locally observed. This facies is strongly recrystallised.

Interpretation : This bindstone looks very similar to the floatstone (microfacies 6), by abundance of *Stachyodes* and Udoteacean algae and by gradual transition from one to the other. However, encrustations as well as grainstone texture would be related to more significant water energy. Well-developed and regular encrusting organisms indicate high water energy and low sedimentation rate (Machel and Hunter, 1994; James, 1983).

Microfacies 6: Floatstone with *Stachyodes*, calcispheres and Udoteacean algae (Pl. 16/3)

Description : Floatstone with *Stachyodes* scattered into a micritic or a clotted matrix. *Stachyodes* (approximately 20%) are locally accompanied by Udoteacean algae, paleosiphonocladales, calcispheres and ostracods together with gastropods, sponge spicules, brachiopods, solitary rugose corals, lamellar stromatoporoids, *Sphaerocodium* and foraminifera. *Girvanella*, *Codiaceae*, *Keega* or stromatoporoids locally encrust *Stachyodes*. Encrustations are generally irregular and are most developed on one side. Preservation is usually excellent and some fossils are still in life position. Sorting is poor (cm-scale *Stachyodes* with foraminifera and calcispheres).

Interpretation : *Stachyodes* are usually described in shallow-water zones, where energy is moderate and sedimentation rate intermediate (Cornet, 1975; James, 1983; Machel and Hunter, 1994; Wood, 2000). Present Udoteacean algae are shallow water tropical organisms (below 50 m after May, 1992). According to Roux (1985), Devonian Udoteacean algae were found in open-sea environments, lagoons and reef fronts at depths lower than 10 m. The good preservation of fossils (locally in life-position), presence of Udoteacean algae and preservation of clotted structure suggest very weak water energy. The clotted nature of the matrix may be related to a microbial origin (cf. microfacies 1).

4.2 Lagoonal facies

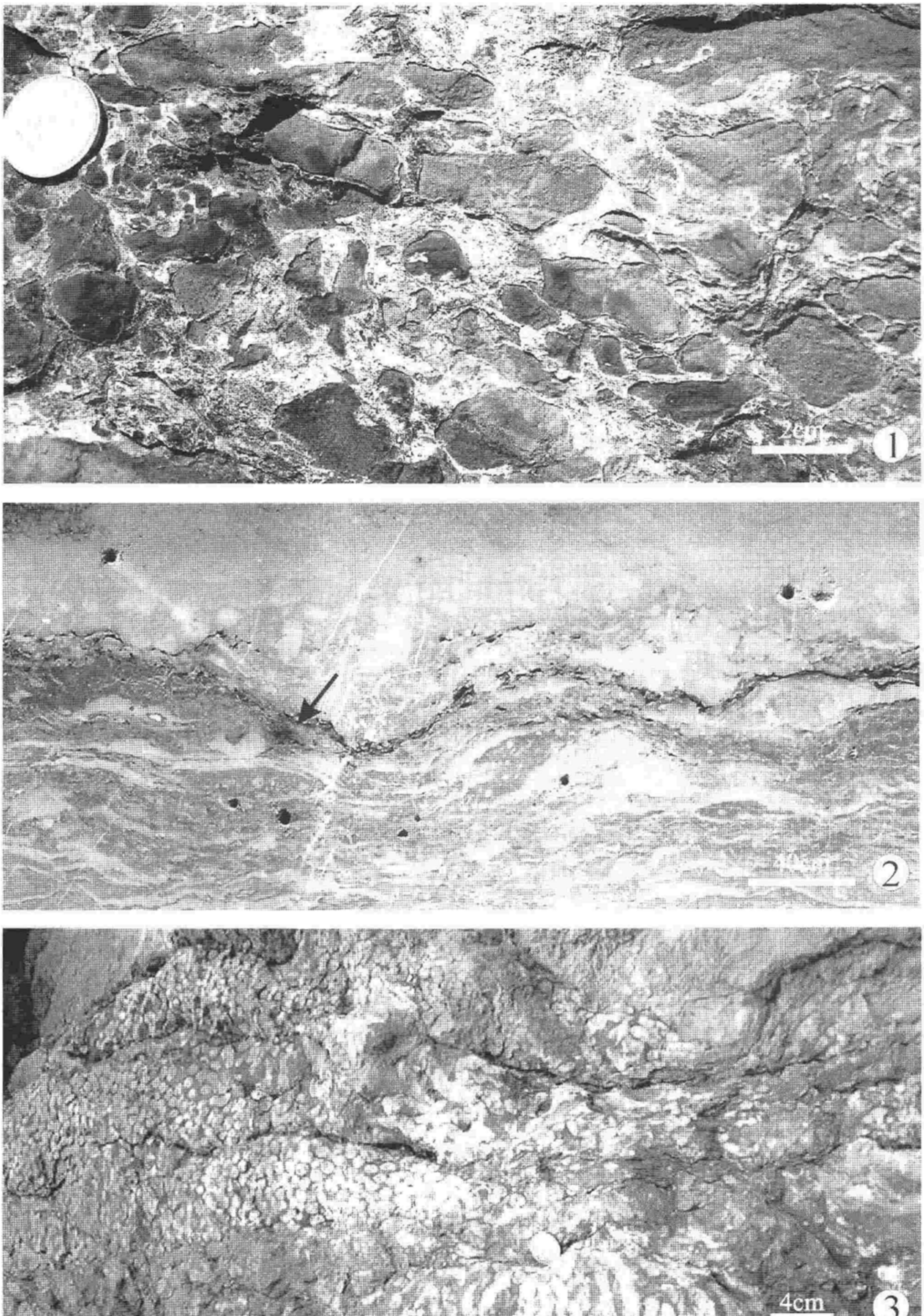
Field observations show that lagoonal facies are characterised by locally laminar mudstone to wackestone or floatstone with *Amphipora*. The different microfacies are

Plate 17 Facies from the Tailfer section, Belgian Middle Frasnian carbonate platform

Fig. 1. Brecciated limestone (microfacies 14) interpreted as paleosoils. Tailfer section, field photograph, 63m above the base of the section.

Fig. 2. Third order regression surface (arrowed), separating a lamellar stromatoporoids biostrome and a lagoonal unit. Tailfer section, field photograph, 49 m above the base of the section.

Fig. 3. Bed 38 made up almost exclusively by *Disphyllum goldfussi*. Tailfer section, field photograph, 25 m above the base of the section.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closely related and do not show clear boundaries, suggesting a continuum.

Microfacies 7: Floatstone
with *Amphipora* and paleosiphonocladales

Description: Wackestone, packstone and floatstone with *Amphipora* and branching tabulate corals, accompanied by solitary rugose corals, nodular stromatoporoids (cm-scale) and paleosiphonocladales with subordinate ostracods, Udoteacean algae. *Vermiporella*, *Girvanella*, *Keega* and stromatoporoids encrust the *Amphipora*. These encrustations are irregular and more developed on one side. Preservation is good; only brachiopods and gastropods are broken and sorting is poor.

Interpretation: Organisms mainly originate from a restricted area (calcispheres, ostracods, foraminifera, paleosiphonocladales, *Amphipora*). *Amphipora* is described as an organism inhabiting shallow-water, quiet, lagoonal, generally hypersaline and turbid environments (Cornet, 1975; Pohler, 1998; James, 1983). Water energy had to be weak (below normal wave base, NWB) because of abundant carbonate mud, clay and asymmetrical encrustations. However, the local presence of pellets- and bioclasts-rich grainstone lenses could be related to storms. This facies seems very close to the paleosiphonocladale microfacies (8).

This microfacies is characteristic of a restricted subtidal zone, in the storm wave action zone.

Microfacies 8: Packstone-wackestone with paleosiphonocladales (Pl. 16/4)

Description: The paleosiphonocladales are accompanied by microbioclasts, branching stromatoporoids (*Amphipora* and *Stachyodes*), rugose solitary corals, *Umbella*, ostracods, gastropods, foraminifera, clasts and pellets, *Vermiporella*, *Sphaerocodium*, and *Bisphaera*, together with subordinate crinoids, bryozoans, tentaculitids and brachiopods. Paleosiphonocladales (*Kamaena* and *Issinella* mainly) are well preserved, ostracods are generally not dissociated, but crinoids, brachiopods and bryozoans are broken. Bioturbation is frequent. Usually, this microfacies shows three end members characterised by different textures and fossil proportions, without a clear separation.

-- The first end member is a wackestone with well-preserved paleosiphonocladales (near 10%); sorting is medium to poor and the microfacies looks heterogeneous because of fossil distribution and bioturbation. This assemblage shows a continuum with mudstones (microfacies 11).

-- The second end member is a packstone, extremely rich in paleosiphonocladales (up to 60%) and microbioclasts (0.05mm), with rare micritic matrix. Preservation is low and sorting is excellent (0.1-0.2mm).

-- The third end member is a heterogeneous packstone- or grainstone-rich in pellets. It shows a continuum with the unlaminar heterogeneous pellets microfacies (microfacies 9).

Interpretation: Frequent bioturbations indicates a low sedimentation rate and fauna or flora (*Umbella*, gastropods, *Amphipora*, pellets) is mainly restricted.

-- Wackestone end member: presence of micrite and of well-preserved fossils indicate a very quiet environment, under the normal wave base.

-- Packstone end member: abundance of well preserved paleosiphonocladales and presence of micrite and clay suggest a quiet environment, under the normal wave base (NWB). Presence of broken metazoan (*Stachyodes*, rugose and tabulate corals) and of strongly broken crinoids and brachiopods indicate external episodic sediment inputs.

-- Pellets end member: presence of mud between the pellets suggests a low energy, but the grainstone layers would indicate a possible influence of storms.

The packstone assemblage would be characteristic of paleosiphonocladales "bafflestone" within the lagoon, in the sub-tidal zone near the *Amphipora* microfacies. The wackestone assemblage corresponds to the transition with the mudstone (11) and the pellets assemblage with the heterogeneous facies with pellets (9).

Microfacies 9: Heterogeneous packstone and grainstone with pellets and clasts

Description: Heterogeneous packstone and grainstone with pellets and clasts (0.1-0.5mm), broken stromatoporoids or paleosiphonocladales, calcispheres, foraminifera, *Umbella*, ostracods, *Girvanella* and broken brachiopods and crinoids. The heterogeneous aspect is related to bioturbation or to bad sorting. This microfacies often shows irregular fenestrae, filled with pellets, sparite or dolomite.

Interpretation : Bioclasts are characteristic of an internal platform or lagoon. Some bioclastic beds suggest storm deposits. This microfacies is heterogeneous, due to bioturbation or low energy conditions, which do not allow sorting. This microfacies corresponds to the upper limit of the subtidal zone, with moderate water energy.

Microfacies 10: Heterogeneous packstone with *Umbella* (Pl. 16/5)

Description: Heterogeneous texture, sorting, preservation and nature of bioclasts mainly characterise this microfacies. Locally, concentrations of clasts, clay and detrital quartz (0.05mm) are observed. Sorting is poor, as a consequence of textural heterogeneity and variable size of fossils. Main texture is a wackestone with dark micritic matrix, rich in pellets and mm-scale intraclasts. *Umbella* (more than 40%) are accompanied by gastropods, paleosiphonocladales, foraminifera, ostracods and scarce *Amphipora*. Preservation is relatively good and desiccation cracks are common.

Interpretation: According to Mamet (1970), *Umbella* were significant in littoral and abnormal salinity environments. Other fossils originate from lagoonal environments. Intense bioturbation is related to a relatively weak sedimentation rate and presence of desiccation cracks is related to occasional emersions. Good preservation of fossils, muddy matrix and clay suggest a quiet environment. Presence of fossils that are usually not associated (paleosiphonocladales, *Umbella*, calcispheres...) could be related to a channel system crossing the mudstone (11), pellets (9) and paleosiphonocladales (8) facies, leading to clasts and grainstone formation.

This very heterogeneous microfacies would be the result of channels originating in the intertidal zone in *Umbella*-rich environments, and eroding the lagoonal sediments in intertidal and subtidal zones.

Microfacies 11: Mudstone with ostracods and calcispheres

Description: Mudstone with ostracods, calcispheres, paleosiphonocladales, foraminifera, pellets, *Umbella* and subordinate debris of gastropods and brachiopods. This mudstone generally shows some fenestrae, mainly horizontal but locally, vertical and irregular, filled by coarse sparite. Some of these cavities show vadose cement. Desiccation cracks may be frequent.

Interpretation: Texture, nature and good preservation of fossils are characteristic of a quiet, lagoonal environment. Scarcity of gypsum confirms the non-evaporitic, humid–tropical nature of sediments, close to the Bahamas lagoonal model (Hardie, 1977; Purser, 1980) with which the comparison is made to allow interpretation. Bioturbation indicates low sedimentation rate, desiccation cracks and vadose cement indicate an environment subjected to emersion (intertidal zone, Read, 1985). The horizontal fenestrae would probably be the result of sheet cracks or decay of algal mats (Grover and Read, 1978).

This microfacies developed in lagoonal environment in the intertidal zone, with very low water energy.

Microfacies 12: Homogeneous grainstone with pellets and paleosiphonocladales

Description: Very well sorted grainstone, with pellets (0.1mm) and broken paleosiphonocladales. Pellets are subspherical, with sharp rims.

Interpretation : This very well sorted grainstone was formed in medium water energy (because of the small size of the clasts and grainstone texture). This facies is characteristic of the intertidal zone.

Microfacies 13: Laminar grainstone to packstone with pellets and fenestrae

Description : This microfacies is mainly constituted by an accumulation of pellets (0.05-0.1mm) (70-90%) with sharp or diffuse rims. The lamination originates from packstone-grainstone-mudstone alternations, variable abundance of fenestrae or bird's eyes, local microbioclastic or intraclastic beds, clay or detrital quartz accumulations, or fining-upward sorting. Some well-preserved brachiopods and *Amphipora* are observed. This microfacies can also show loferites (Fischer, 1964).

Interpretation : Abundant fenestrae, occasional presence of algal tubes as well as irregularity of laminae are the main characters of this microfacies and seem to correspond to algal mats (Aitken, 1967). However, cross-stratification, fining-upward sorting, regular lamination, bioclastic accumulations and relief-compensating laminae, are characteristic of mechanical reworking of these algal mats (Aitken, 1967). Algal mats are distributed from the upper intertidal zone to the supratidal zone in the humid tropical model of the Bahamas (Wilson, 1975; Hardie, 1977; Purser, 1980). Loferites are also interpreted by Fischer (1964) as intertidal sediments.

4.3 Paleosoils

Microfacies 14: Brecciated limestone (Pl. 17/1)

Description : This microfacies corresponds to strongly brecciated metric units, accompanied by micritic or dolomitic laminar beds and affected by desiccation cracks. The clasts (cm to dm-scale) are generally lengthened according to stratification. They are composed by wackestone with paleosiphonocladales, pellets or mudstone and are surrounded by microspar, dolomite and argillaceous infiltrations. Granular cement is often present within the cavities and under the clasts, forming brownish irregular pendants. Pellets concentrations are observed. Pyrite and hematite crystals are frequent and sometimes follow the stratification.

Interpretation : According to Wright (1994), brecciation is characteristic of paleosoils. Presence of pendant vadose cement, desiccation cracks, circum-granular cracks, hematite pyrite and glaebules are also well known characteristics of paleosoils.

5 MICROFACIES EVOLUTION AND SEDIMENTOLOGICAL MODEL

In Table 1, microfacies are ordered along a distal to proximal transect that will allow the construction of an evolution curve (Fig.3.C) of environments through time. This curve makes possible to identify different sequence orders:

4th order sequences (m–tens of m, of hundred ky duration) (indicated on the Fig.3. by numbers 1 to 19): The ideal complete regressive sequence begins with biostromal facies, firstly lamellar stromatoporoids with micrite (1), alternating with frequently overturned lamellar stromatoporoids and tabulate corals (2), overlaid by strongly broken and overturned lamellar stromatoporoids and massive metazoan with crinoids and brachiopods (3 and 4), then by *Stachyodes* and Udoteacean algae (5 and 6). Biostromal microfacies are followed by lagoonal microfacies from subtidal zone with *Amphipora* (7), paleosiphonocladales microfacies (8), and *Umbella* (10), followed by microfacies from intertidal zone (11, 12 and 13) and ending with supratidal paleosoil microfacies (14). The sequences are never complete. These fourth order sequences follow each other to form three

3rd order sequences (tens of m-scale, of My duration):

- Biostromal Unit (0-49m), dominated by biostromal facies, episodically interrupted by lagoonal episodes. The boundary with the overlying unit corresponds to a major regression surface (downward shift) (Pl. 17/2).

-- Lagoonal Unit (49-82m), constituted by lagoonal facies and paleosoils. The boundary with the following unit is located at the first biostromal facies and corresponds to an inundation surface.

-- Lagoonal and Biostromal Unit (82-96m): this unit is still dominated by lagoonal facies, but massive metazoans become more frequent.

6 MAGNETIC SUSCEPTIBILITY STUDY

6.1 Principle

Magnetic susceptibility (MS) is a measure of the material response to an applied magnetic field (Borradaile, 1988). Within the sedimentary rocks, ferromagnetic mineral concentration depend of the lithogenic fraction (continental contributions), which is markedly related to eustatism. Thus, the magnetic susceptibility curve increases during a sea level fall and shows high values during low level; it decreases during a rising sea level and shows low values during high level. An increase in the susceptibility curve may also be related to climatic variations such as increasing rainfall or ice sheets.

6.2 Correlations

The link between magnetic susceptibility and lithogenic contributions (climatic and/or eustatic mechanisms) is mainly used for intrabasinal, interbasinal, interregional and intercontinental correlations with higher resolution than that offered by biostratigraphy (Crick *et al.*, 1994, 1997 and 2000; Crick and Ellwood, 1997 and Ellwood *et al.*, 1999, 2000). Correlations are made on basis of magnetic susceptibility peaks, isochronous and facies independent. Thus, MS analyses made for the Tailfer outcrop could, in later studies, be used for correlations (work in progress).

6.3 Sedimentary interpretation and evolution

When comparing the MS curve (Fig.3.D) and the facies evolution curve (Fig.3.E), the same global evolution is observed. The link between the MS curve and sea level changes leads to interpret the MS curve in terms of system tracts (Devleeschouwer, 1999):

-- The biostromal unit shows very low values and indistinct fourth order cycles. This weak signal corresponds well to low lithogenic inputs related to relatively high distance from the continent

-- The lagoonal unit is characterised by an increase in MS values, but also by their higher variability. Increase is related to the marine regression and correlative increase in lithogenic contributions. Variability could be due to the fact that "tidal deposits" are very sensitive to slight environmental variations (Hardie, 1977).

-- In the lagoonal and biostromal unit, MS values decrease slightly, but the persistence of the lagoonal character leads to a still highly variable signal.

It clearly appears that the magnetic susceptibility signal is not related to any particular facies, but rather to the sequences and system tracts. Indeed, the episodic lagoonal deposits within the biostromal unit show very low values (close to $4.10^{-8} m^3/kg$), in agreement with those of the biostromal unit. On the other hand, the same lagoonal facies in the lagoonal unit show relatively higher and variable values, (between 0 and $3.5.10^{-7} m^3/kg$), close to mean lagoonal unit values.

6.4 Environmental reconstructions

Finally, the differences observed between the magnetic susceptibility curve and the microfacies curve (see regressive phase 4) could also provide information about sedimentation. Indeed, if lithogenic variations are not related to marine level changes, they should be related to an important climatic or tectonic change (Devleeschouwer, 1999). The comparison of the two curves shows a significant opposition for sequence 4. Indeed, the microfacies curve shows a transgression and the susceptibility curve is increasing, suggesting a regression. This sequence corresponds to a unique and particular sedimentary environment, represented by a metric bed made up almost exclusively of *Disphyllum goldfussi* (Tsien *et al*, 1973) (Pl. 17/3), commonly overturned, but not dismantled, surrounded by coarse argillaceous dolomite. This bed is found laterally at the same level in a lot of outcrops of the Lustin Formation. The opposition of the two curves suggests some particular conditions for the development of this mono-specific concentration. The increase in the MS curve, without sea level fall, could be related to an increase in the detrital input possibly related to an increase in rainfall.

7 CARBON ISOTOPES CURVE

The geochemical behaviour of carbon is mainly governed by organic processes, in which photosynthesis plays a major role (Moore, 1989). Isotopic variations of $\delta^{13}C$ are directly related to burial of organic matter. Indeed, organic carbon is enriched in ^{12}C isotopes; thereby an increasing burial of organic matter produces an increase in the $^{13/12}C$ of seawater that is reflected in skeletons and inorganic carbonates (Davey and Jenkyns, 1999). On the other hand, an increase in the oxidation rate of organic matter decreases the $\delta^{13}C$. These variations in the C oceanic reservoir may be induced by sea level variations, oceanic circulation changes (Samtleben *et al.*, 2000) or productivity variations on the continent or in the ocean.

The $\delta^{13}C$ of meteoric water, related to the ground gas CO_2, shows values near -20‰ (Moore, 1989). Thus systems submitted to a strong meteoric influence should show a mixing of ground gas with CO_3^{--} derived from marine carbonate dissolution, which leads to intermediate values according to ratios (Moore, 1989).

Isotopic carbon curves have been used to undertake correlations (Samtleben, 2000), identify climatic variations (Arthur *et al*, 1988; Brand, 1989), determine the isotopic composition of seawater (Wadleigh and Veizer, 1992), determine variations of organic matter burial rate (Baud *et al.*, 1989), etc.

Fig.3.E shows that a 4th order signal is obvious, but is

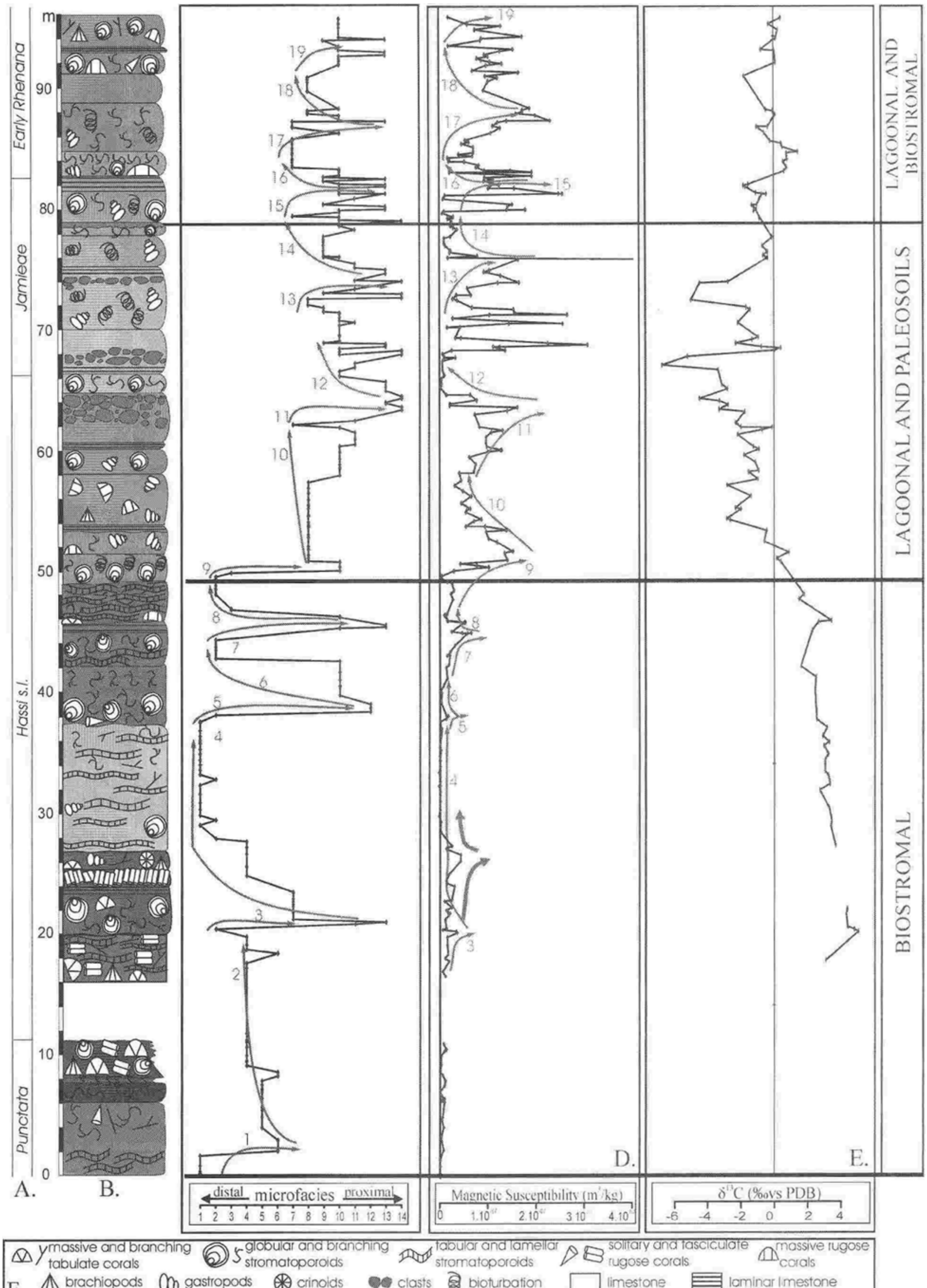

Fig. 3. Compilation of different data from the Middle Frasnian Tailfer section (A) Conodont zonation after Gouwy and Bultynck (2000) (B) Sedimentological log (C) Microfacies evolution curve. (D) Magnetic susceptibility profile (E) Carbon isotope profile (F) Legend of the log.

difficult to interpret in the current research state. On the other hand, a clear third order signal is observed:

- The **biostromal unit** shows decreasing isotopic values from 3.8 to 1 ‰. These values are therefore relatively close to 2, in agreement with Frasnian Sea values ($\delta^{13}C$ between 1.3 and 2.3 ‰, according to Hurley and Lohmann, 1989).

- The **lagoonal unit** shows weak, always negative and strongly variable values. These values seem related to a meteoric and marine fluid mixing or to an increasing influence of soil-derived organic material. Indeed, inter- and supratidal facies show the weakest values, reaching almost -8 ‰ and subtidal sediments have values closer to -2 ‰.

- **The lagoonal and biostromal unit** shows an increase of values that reached 0 ‰, probably related to the lower influence of meteoritic fluids.

As for the magnetic susceptibility signal, it seems that carbon isotopic values are not linked to the facies, but rather to the system tracts.

8 CONCLUSIONS

The Tailfer section (Belgium, northern border of the Dinant Synclinorium) exposes Middle Frasnian shallow-water limestone.

The sedimentological study allows identifying 14 microfacies grouped in fourth order sequences that compose three third order system tracts:

- The **biostromal unit** is mainly characterised by biostromal facies interrupted by lagoonal sediments. The ideal vertical biostromal sequence shows facies grading from the storm wave zone to the normal wave zone, with lamellar stromatoporoids in life position surrounded by micrite, alternating with frequently overturned lamellar stromatoporoids, associated with tabulate corals. This part of the sequence is followed by massive, broken and overturned corals and stromatoporoids and by *Stachyodes* encrusted by stromatoporoids.
- The **lagoonal unit** shows an internal platform facies succession grading from sub- to supratidal zones (in a humid tropical climate of Bahamas type). The subtidal facies are dominated by paleosiphonocladales, pellets and *Amphipora* and the intertidal facies are characterised by mudstone and bedded pelloidal facies showing desiccation cracks and vadose cement. Channels filled mainly with clasts and *Umbella* cut this sub- and intertidal facies. Brecciated limestones paleosoils beds characterise the supratidal zone.
- The **lagoonal and biostromal unit** shows mainly lagoonal facies with some biostromal episodes.

The aspect of the magnetic susceptibility curve suggests different comments :

- High-resolution correlations (Crick *et al.*, 1994) for later studies on Middle Frasnian platform will be available through comparison of the Tailfer section MS curve and other outcrops curves.
- Quick determination of a relative sea level curve, without deeper sedimentological analysis is provided by MS studies. In this study, the fourth and third order sequences are easily identifiable. The biostromal unit shows low values in relation with distal position, the lagoonal unit is characterised by high values in relation with proximity of landmasses.
- Other informations about sedimentation appear from a careful step-by-step comparison of the MS and microfacies curves: differences are related to a parasite signal linked to lithogenic input variation, probably depending from climatic changes.

The carbon isotopic curve brings connection between system tracts and diagenesis. Indeed, the biostromal unit shows values close to Frasnian seawater standards. The lagoonal unit values are strongly negative, related to more significant continental supply. The biostromal and lagoonal unit shows intermediate values, related to the increasing distality.

ACKNOWLEDGEMENTS

A-C. da Silva benefited from a F.R.I.A. grant from the Belgian Fond National de la Recherche Scientifique (FNRS). F. Boulvain acknowledges support through research grant FRFC 2-4501-02 from FNRS. The authors are especially thankful to Olivier Averbuch (University of Lille) for allowing access to the magnetic susceptibility device and to Marc Bertrand and an anonymous reviewer for critical reading of the manuscript. This paper is a contribution to the French CNRS 'Eclipse' Project.

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Manuscript received June 6, 2001
Revised manuscript received December 19, 2001