GEOLOGICA BELGICA (2003) 6/3-4: 81-96

SEDIMENTOLOGY, MAGNETIC SUSCEPTIBILITY AND CORRELATIONS OF MIDDLE FRASNIAN PLATFORM LIMESTONE (TAILFER AND AYWAILLE SECTIONS, BELGIUM)

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(6 figures, 1 table and 2 plates)

ABSTRACT. The Tailfer (northern border of the Dinant Synclinorium) and Aywaille sections (eastern border of the Dinant Synclinorium) expose Middle Frasnian shallow-water calcareous deposits corresponding to the Lustin Formation. A petrological, sequence stratigraphy and magnetic study of these sections has been carried out. The petrological analysis leads to the definition of three lithofacies and 14 microfacies, to the construction of a microfacies curve and to the identification of fourth order sequences grouped in sedimentological units and in systems tracts. The crinoidal lithofacies (A) was deposited in the storm wave zone. The biostromal lithofacies (B) is composed of an ideal vertical microfacies succession grading from the storm wave zone to the normal wave zone. Finally, the lagoonal lithofacies (C) is characterized by bedded and brecciated limestones and mudstone grading from the sub- to the supratidal zone. Both sections were divided into two main sedimentological units: the lower part, called biostromal unit is composed of biostromal and crinoidal lithofacies with episodic lagoonal interruptions. This biostromal unit is followed by a regressive surface and by the second unit, constituted by lagoonal lithofacies only. The magnetic susceptibility (MS) curve depends on the abundance of ferromagnetic minerals, which is related to lithogenic supplies and to the proximity of landmasses (Crick *et al.*, 1994). This proximity could be related to eustatism or to other parameters like tectonic or climatic variations. Magnetic susceptibility curves lead to fourth order correlation between the two sections and confirm the bathymetric reconstruction. The first unit shows low MS values related to the distal position of landmasses. After the regression, the susceptibility strongly increases due to a higher amount of lithogenic supplies, which is related to the relative proximity of the continent.

KEYWORDS: Frasnian, Belgium, carbonate platform, sedimentology, magnetic susceptibility, correlation

1. Introduction

The Tailfer (Tsien *et al.*, 1973 and Coen-Aubert & Coen, 1975) and Aywaille sections (Coen, 1968) were subjects of paleontological studies, but neither of these works presents a sedimentological interpretation. Very recently, da Silva & Boulvain (2002) proposed a first sedimentological study of the Tailfer section.

This paper proposes a sedimentological analysis of the two sections, together with a facies model, a reconstruction of facies evolution and a discussion on sequence stratigraphy. The sedimentological study is complemented by magnetic susceptibility (MS) data. MS was previously mainly used for correlations (Crick *et al.*, 1994) and as a paleoclimatic indicator (Curry *et al.*, 1995). Recently, these data were used for reconstruction of sea level curves (Devleeschouwer, 1999; Crick *et al.*, 2001 and da Silva & Boulvain, 2002).

2. Geological setting

The Tailfer quarry (N100°E/50°S) is located on the northern border of the Dinant Synclinorium (Fig.1a) (IGN: 47/8 Lambert co-ordinates X: 186.450; Y: 119.700) and exposes the Lower Frasnian Presles Formation shales and the Middle Frasnian of Lustin Formation limestones that are concerned by this study (the study starts just at the base of the Lustin Formation). The Aywaille (Dieupart) quarry (N75°E/70°N) is located at the eastern border of the Dinant Synclinorium (IGN: 49/3 Lambert co-ordinates X: 243.500, 130.00) and shows the Lustin Formation except for their lowermost and uppermost parts, which are inaccessible (IGN).

In the Philippeville anticline, the distal equivalents of the Lustin Formation (Fig.1b) are the shale-dominated Pont de la Folle Formation followed by the Philippeville Formation where crinoidal lithofacies are better developed

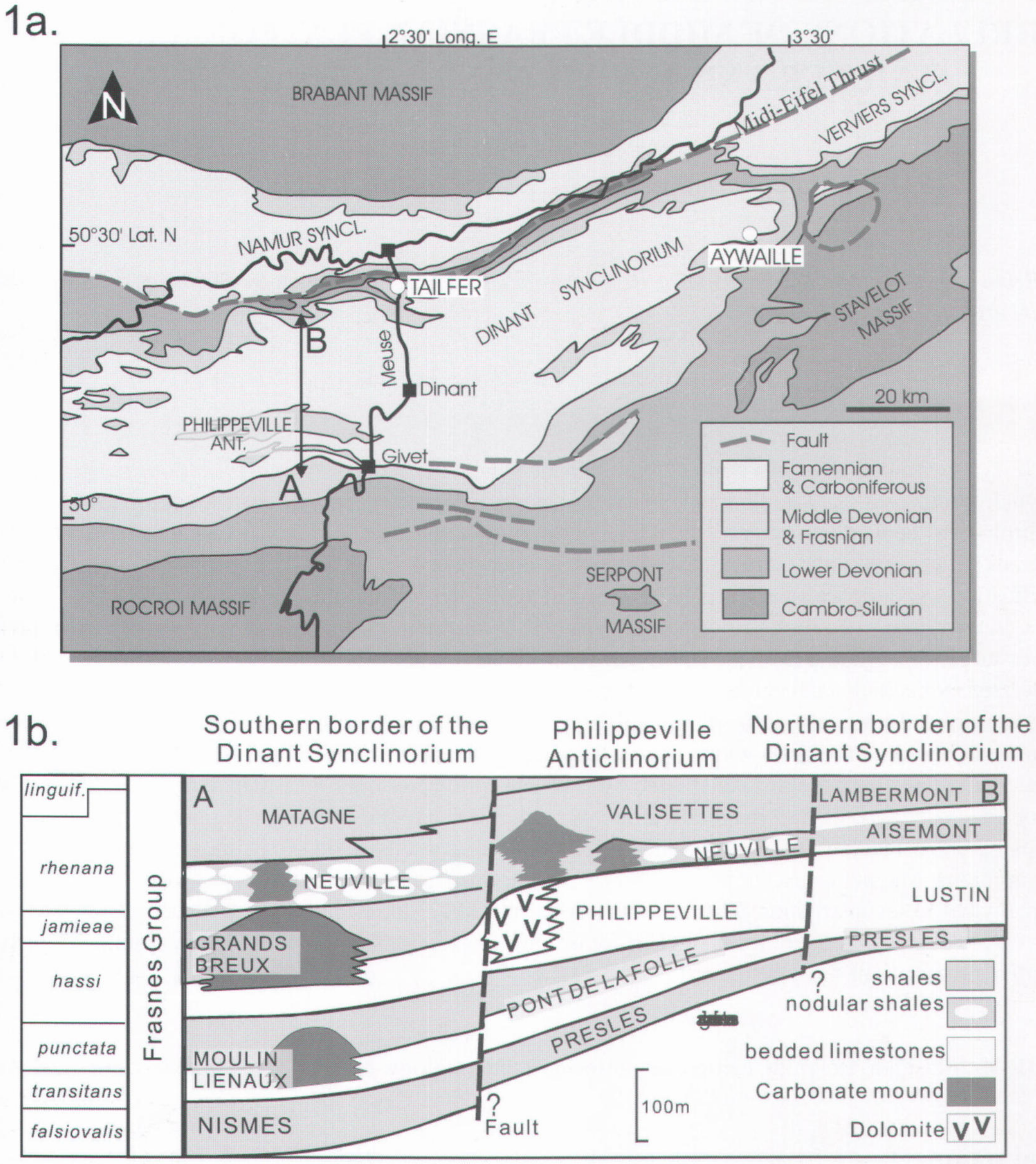


Figure 1.a. Geological setting and location of the studied sections.
Figure 1.b. N-S section in the Belgian Frasnian sedimentation basin before Variscan structuration. Conodont zonation after Gouwy & Bultynck (2000).

than in the Lustin Formation. At the southern border of the Dinant Synclinorium, the time-equivalent Moulin Liénaux and Grand Breux Formations are characterized by carbonate mounds included in shales and bedded argillaceous limestones (Boulvain *et al.,* 1999).

3. Lithofacies and microfacies

Lithofacies were defined according field observations and microfacies were based on thin sections. The textural classification used to describe microfacies follows Dunham (1962) and Embry & Klovan (1972). The term "coverstone" was suggested by Tsien (1984) to characterize microfacies with laminar organisms covering mud and debris. Classification of stromatoporoid morphology follows Kershaw (1998). In the following description, microfacies are ordered from the most distal to the most proximal environment according to textural criteria and comparisons with models from Wilson (1975), James (1983), Hardie (1977) and Flügel (1982). However, this order is not always effective, considering possible lateral juxtaposition of environments. Table 1 compiles interpretations and proposes indicative bathymetry for the different microfacies (after Embry & Klovan, 1972; Wilson, 1975 and Flügel, 1982).

Microfacies and lithofacies	Interpretation	m
Crinoidal lithofacies		
1 Floatstone with crinoids, brachiopods and reef-builders	Fore-reef deposits, influenced by biostromes	20-30
Biostromes		
2 Laminar stromatoporoids with muddy matrix	"Reef-mound" like. Weak agitation, under the NWB	20
3 Laminar stromstromatoporoids with reefal bioclasts	"Reef-mound like". Intermittent agitation, medium to weak	15
4 Laminar stromatoporoids with crinoids, brachiopods	"Reef". Medium to high agitation, near the NWB	10
5 Massive stromatoporoid rudstone	"Reef". Medium to high agitation, above the NWB	5-10
6 Stachyodes bindstone to back-reef transition	Subtidal, medium agitation, photic zone. "Reef"	10
7 Stachyodes floatstone to back-reef transition	Subtidal, weak agitation, photic zone. "Reef"	15
Lagoonal lithofacies		
8 Amphipora floatstone	Subtidal, very weak agitation, protected	12
9 Paleosiphonocladales packstone	Subtidal, protected, very weak agitation	10
10 Peloidal packstone	Subtidal, weak agitation	7
11 Umbellina – rich packstone	Channels crossing inter- to subtidal zone, weak to medium agitation	3-10
12 Mudstone	Intertidal, very weak agitation	5
13 Laminar peloidal grainstone to packstone	Inter- to supratidal, occasional emersions, medium to weak agitation	2
14 Brecciated limestone	Supratidal, often emerged	0

Table 1. Tailfer and Aywaille sections, Middle Frasnian limestones : compilation of microfacies interpretation and estimation of water depth.

3.1. Lithofacies A: crinoidal lithofacies

Dark argillaceous dm-thick beds, with crinoids, brachiopods and broken reef-builders.

Microfacies 1: Packstone-floatstone with crinoids, brachiopods and broken reef-builders.

Description: Packstone to floatstone with subordinate grainstone layers. Massive, branching or laminar stromatoporoids, tabulate and rugose corals are often broken and/or strongly encrusted by *Girvanella*, *Sphaerocodium* or stromatoporoids. Crinoids, brachiopods, *Girvanella* and mud clasts are dominant, with subordinate trilobites, cricoconarids, bryozoans, ostracods, sponge spicules, foraminifers and gastropods. Sorting is very low (0,1mm to several cm) and organisms preservation is poor. Argillaceous layers and bioturbations are present.

Interpretation: Poor sorting and coarse nature of the sediment and mud clasts are common characteristics of fore-reef deposits. The dominant organisms (crinoids, brachiopods and cricoconarids…) validate the distal position. The high proportion of reef-builders suggests that this sediment was deposited close to a reefal structure and *Girvanella* abundance imply a shallow-water environment, in the photic zone (up to 50 m after Brett *et al.*, 1993). A lot of storm deposits (shells and grainstone layers, …) confirm the position in the storm wave zone.

3.2. Lithofacies B: 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 sedimentary 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 in this work to accumulations of *Stachyodes*, massive and laminar stromatoporoids, tabulate and rugose corals.

3.2.1 Biostromes with laminar stromatoporoids (Fig.2. and Pl. 1/1)

Biostromes with mostly laminar or tabular stromatoporoids, exceptionally "low domical" or anastomosing, with some branching and massive tabulate corals (*Alveolites*), and fasciculate (*Disphyllum*), massive (*Hexagonaria*) or solitary rugose corals. In Tailfer section, stromatoporoids are mainly laminar but in the Aywaille section, they are high domical and bulbous, with only some tabular stromatoporoids.

Microfacies 2: Laminar stromatoporoids coverstone with muddy matrix

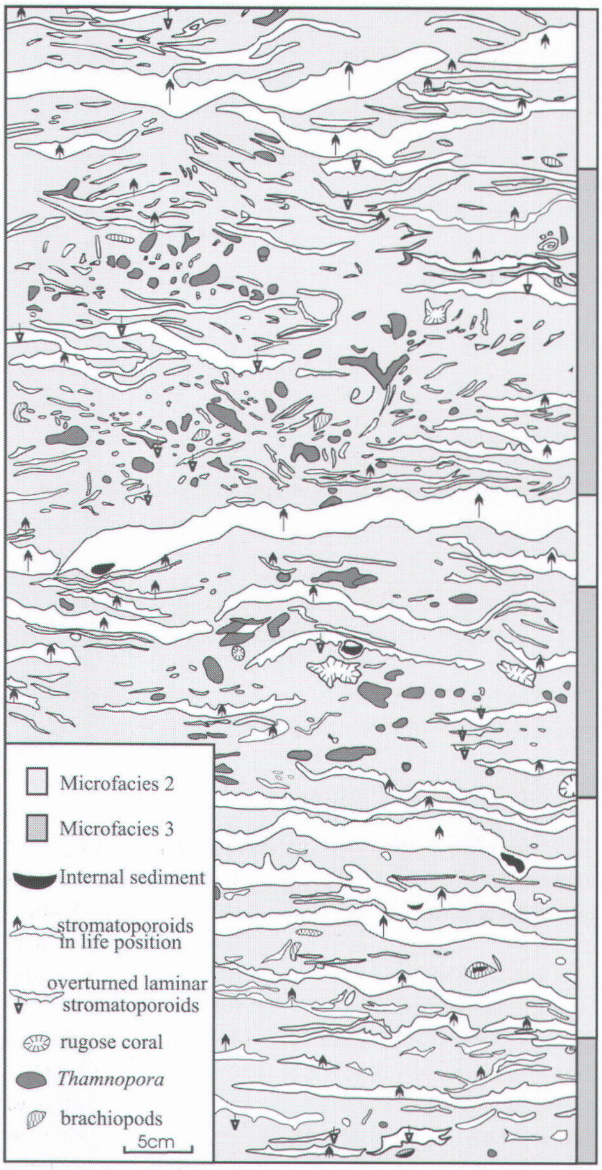


Figure 2. Laminar stromatoporoids coverstone with muddy matrix (microfacies 2) alternating with reefal bioclastic floatstones (microfacies 3). Drawing on a wire-cutted surface from the Tailfer section, 47 m above the base of the section.

Description: The stromatoporoids are several mm- to several cm- thick and can be subordinate (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 laminar 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. Fenestrae are very numerous and are filled by sparry calcite, dolomite or saddle dolomite. In the clotted matrix, the fenestrae are irregular and mm-thick while under the laminar stromatoporoids, they are cm-thick, with shelter morphology.

Interpretation: Water energy was weak considering the muddy fraction, preservation of clotted matrix, low amount of bioclasts, good preservation of laminar 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 2 developed under variable clay input and that these inputs, as long as they were not too important, did not control the development of the community. 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). Variable matrix characteristics, with probable automicrite (clotted or pelloidal) and detrital matrix (rich in bioclasts) could suggest a mound-like system for this unit (Wolf, 1965 and Reitner *et al.*, 1995). This interpretation, strengthened by the abundant occurrence of fenestrae, has to be developed by careful study of geometry and textural characteristics.

Microfacies 3: Laminar stromatoporoids floatstone with reefal bioclasts (Fig. 2. and Pl. 1/1)

Description: Between laminar stromatoporoids (40 to 50 % of the rock and mm- to cm- thick) and tabulate corals, the matrix consists of reef-derived, bioclast-rich packstones (stromatoporoids, branching tabulates and rugose corals debris), with some paleosiphonocladales, trilobites, bryozoans, ostracods, gastropods, *Nanicella*, crinoids and brachiopods. Astrorhizal mamelons face upwards as well as downward, corresponding to life-position and overturned stromatoporoids. Sorting is weak and preservation state is variable for laminar organisms and low for crinoids, brachiopods and gastropods.

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, transport was weak, as laminar stromatoporoids are often intact. All these characteristics indicate a medium to weak water energy. It must be noted that laminar stromatoporoids are less developed (thinner) in this microfacies because their growth was repeatedly interrupted by higher energy events.

The two laminar stromatoporoids microfacies with tabulate corals (3) and mud (2), alternate in dm-scale units (Fig. 2.). 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, as indicated by good preservation of fossils.

Microfacies 4: Laminar stromatoporoids rudstone with crinoids and brachiopods
Description: These laminar and tabular stromatoporoids rudstones include branching tabulate corals and stromatoporoids as well as 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. Locally, this facies shows an erosive surface at its base. The interstitial bioclasts are well sorted. Preservation is usually low. However, local mud accumulations and well-preserved bioclasts are observed. These deposits always correspond to protected sediment between two superposed laminar stromatoporoids.
Interpretation: Erosive surface at the base of the units and low preservation indicate a relatively sudden deposit, which could either be a tempestite, a transgressive or a destruction phase facies. Fossils are generally broken, suggesting significant water energy, with some protected areas between well-preserved stromatoporoids. The presence of clay material is compatible with thicker tabular stromatoporoids (in comparison with the previous laminar stromatoporoids), as they are supposed to get thicker when sedimentation rate increases (Kershaw, 1998).

3.2.2 Biostrome with massive stromatoporoids

Microfacies 5: Rudstone with massive stromatoporoids, crinoids and brachiopods (Pl. 1/2)
Description: Rudstone to floatstone with massive reef-builders (up to 70%) like stromatoporoids, rugose (*Hexagonaria*) or tabulate corals (*Alveolites*), associated with fasciculate and/or branching rugose corals (*Disphyllum*), branching and encrusting stromatoporoids (*Stachyodes*) and branching tabulate corals (*Alveolites* and *Thamnopora*). Massive stromatoporoids are "high domical", they are generally broken and may be encrusted by other stromatoporoids, tabulate corals or algae. Massive organisms are included in a bioclast-rich rudstone to packstone (crinoids, brachiopods, or bryozoans and broken reef-builders). Rhomboedric brownish dolomite crystals (0.1 to 0.2 mm) locally replace the micritic matrix and clay is locally abundant. Preservation is poor; 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 stromatoporoids seems to correspond to medium water energy (Cornet, 1975; Machel & Hunter, 1994). Reef-builders are broken, but not rounded, suggesting a relatively short transport. Well-developed and regular encrusting organisms indicate high water energy and low sedimentation rate (Machel & Hunter, 1994; James, 1983). The presence of local undisturbed structures and protected sediment suggests 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 storms.

3.2.3. Biostromes with *Stachyodes*

Microfacies 6: Grainstone with *Stachyodes* and Udoteacean algae
Description: Grainstone with *Stachyodes* encrusted by other stromatoporoids and with abundant Udoteacean algae. *Amphipora* are also locally observed. This facies is strongly recristallised.
Interpretation: This grainstone looks very similar to the floatstone (microfacies 7) according the same abundance of *Stachyodes* and Udoteacean algae and the gradual transition from one to the other. However, well-developed and regular encrustations should be related to more significant water energy and low sedimentation rate (Machel & Hunter, 1994; James, 1983). This microfacies appears only in the lower part of the Tailfer section and could be related to the local development of *Stachyodes*-Udoteacean patch-reefs (as a lateral variation of microfacies 7).

Microfacies 7: Floatstone with *Stachyodes*, calcispheres and algae (Pl. 1/3)
Description: Floatstone with *Stachyodes* scattered into a micritic or a clotted matrix. *Stachyodes* (approximately 20%) are accompanied by Udoteacean algae, paleosiphonocladales, calcispheres and ostracods with subordinate gastropods, sponge spicules, solitary rugose corals, laminar stromatoporoids, *Sphaerocodium* and foraminifers. *Girvanella*, *Codiaceae*, *Keega*, tabulate corals or stromatoporoids locally encrust *Stachyodes*. Encrustations are generally irregular and most developed on one side. Preservation is usually excellent, some fossils are still in life position and sorting is poor (cm-scale *Stachyodes* with foraminifers and calcispheres). Locally, this microfacies is more argillaceous with some

brachiopods, crinoids and trilobites. It also shows a continuum with the *Amphipora* microfacies (9) with an increase of *Amphipora* and a decrease of crinoids and brachiopods, and with microfacies 6 with an increase of *Stachyodes* and Udoteacean algae and a disappearance of other organisms.

Interpretation: *Stachyodes* are usually described in shallow-water environments where water energy was moderate and sedimentation rate intermediate (Cornet, 1975; James, 1983; Machel & Hunter, 1994; Wood, 2000). Present Udoteacean algae are shallow water tropical organisms limited to the upper 50m of the water column, 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 locally clotted nature of the matrix could be related to a microbial origin (cf. microfacies 2). Udoteacean algae, paleosiphonocladales and calcispheres are common in the lagoonal zone. However, brachiopods, crinoids and trilobites accumulations are characteristic of the open marine environment. This facies could be transitional between the biostromal zone (with an open-marine input of crinoids, brachiopods, ….) and the lagoonal zone (with paleosiphonocladales, *Amphipora*, …), within moderately agitated environment, protected from the normal waves and in the photic zone.

3.3. Lithofacies C: Lagoonal

Field observations show that lagoonal lithofacies is characterized by locally laminar and brecciated limestones, mudstone to wackestone or floatstone with *Amphipora*. The different microfacies are closely related and do not show clear boundaries, suggesting a continuum.

Microfacies 8: 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 usually 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, foraminifers, paleosiphonocladales and *Amphipora*). *Amphipora* is described as an organism colonizing shallow-water, quiet, lagoonal, generally hypersaline and turbid environments (Cornet, 1975; Pohler, 1998; James, 1983). Water energy was weak (protected normal waves) because of abundant carbonate mud, clay and asymmetrical encrustations. However, the local presence of grainstone lenses with pellets and bioclasts could be related to storms. This facies seems closely related to the paleosiphonocladale microfacies (9). This microfacies is characteristic of a restricted subtidal zone, protected from normal waves and affected only by storm waves.

Microfacies 9: Packstone-wackestone with paleosiphonocladales (Pl. 1/4)

Description: Paleosiphonocladales are accompanied by microbioclasts, branching stromatoporoids (*Amphipora* and *Stachyodes*), solitary rugose corals, *Umbellina*, ostracods, gastropods, foraminifers, clasts and pellets, *Vermiporella*, *Sphaerocodium*, and *Bisphaera*, together with subordinate crinoids, bryozoans, cricoconarids and brachiopods. Paleosiphonocladales (*Kamaena* and *Issinella* mainly) are well preserved, ostracods are generally not dissociated, but crinoids, brachiopods and bryozoans are broken. Bioturbations are frequent. Usually, this microfacies shows three end members characterized 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 this microfacies looks heterogeneous due to fossil distribution and bioturbations. This microfacies shows a continuum with mudstones (12).
- 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 (10).

Interpretation: fauna or flora (*Umbellina*, gastropods, *Amphipora*, pellets) are mainly restricted.

- Wackestone end member: presence of micrite and of well-preserved fossils indicates a very quiet environment, protected from the normal waves.
- Packstone end member: abundance of well-preserved paleosiphonocladales and presence of micrite and clay suggest a quiet environment protected from the normal waves. Presence of broken *Stachyodes*, rugose and tabulate corals and of strongly broken crinoids and brachiopods indicates external episodic sediment inputs. The packstone could be derived from reworking of paleosiphonocladale "bafflestone"
- Pellets end member: presence of mud between the pellets suggests a low energy environment, with possible influence of storms, as suggested by grainstones layers.

Microfacies 10: 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, foraminifers, *Umbellina*, ostracods, *Girvanella* and bro-

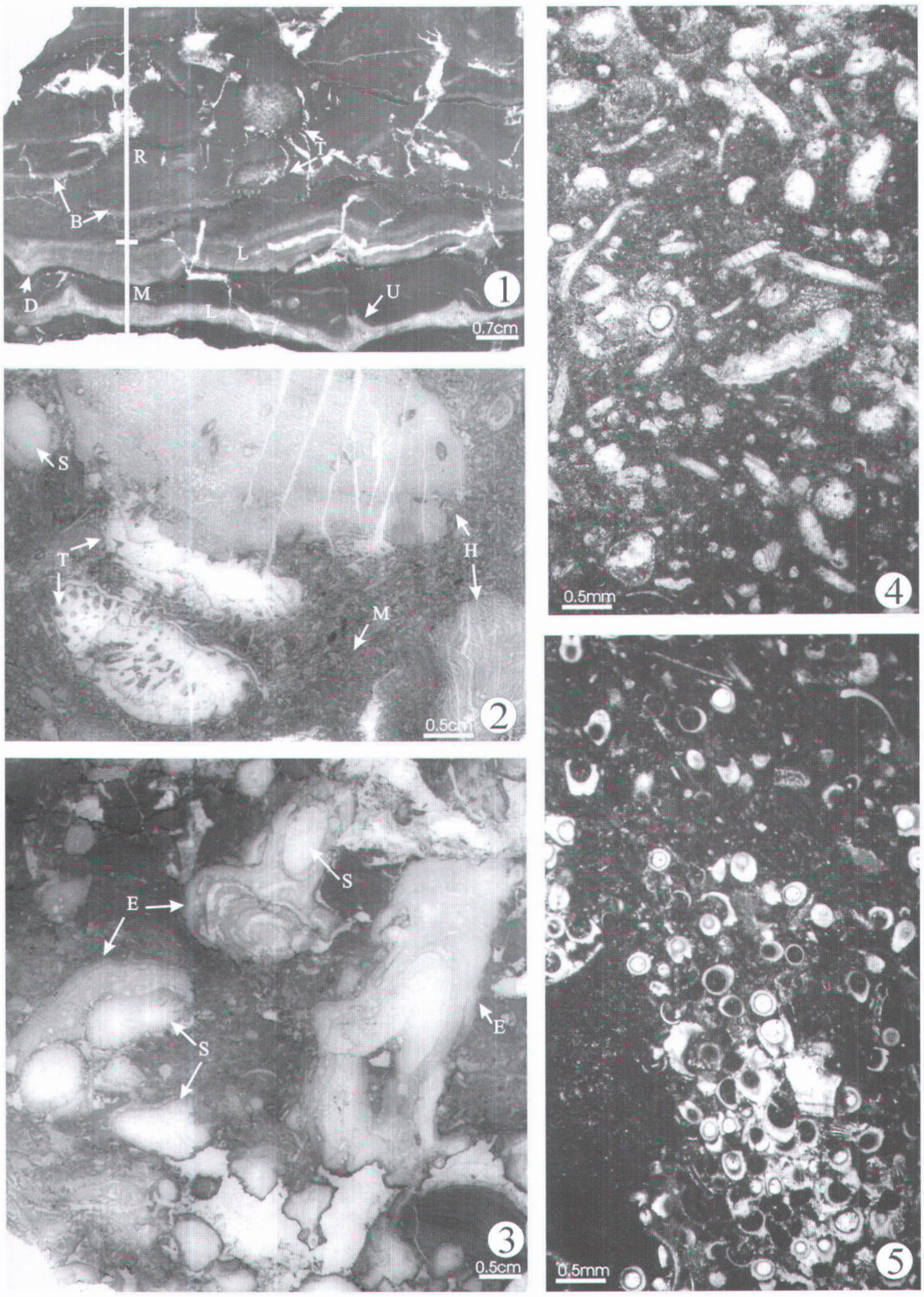


PLATE 1

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

1.1. Laminar stromatoporoids coverstone with muddy matrix (microfacies 2) alternating with reefal bioclasts floatstone (microfacies 3). Laminar stromatoporoids (L) 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 laminar stromatoporoids (B) and tabulate corals (T). Tailfer section, scan of sample 53C, 48m above the base of the section.

1.2. Rudstone with massive stromatoporoids (microfacies 5). The "high domical" or bulbous 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.

1.3. Floatstone with *Stachyodes* (microfacies 7). *Stachyodes* (S) are often encrusted by other stromatoporoids (E). These encrusted stromatoporoids are in life position. Tailfer section, scan of thin section 13, 6m above the base of the section.

1.4. Packstone - wackestone with paleosiphonocladales (mainly *Issinella*) (microfacies 9). Tailfer section, thin section 47d, 41m above the base of the section, ordinary light.

1.5. Bioturbated packstone with *Umbellina* (microfacies 11). Tailfer section, thin section 87c, 71m above the base of the section.

ken brachiopods and crinoids. The heterogeneous aspect is related to bioturbations or to low 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 bioturbations or low energy conditions, which do not allow sorting. it corresponds to the upper limit of the subtidal zone, with moderate water energy.

Microfacies 11. Heterogeneous packstone-wackstone with *Umbellina* (Pl. 1/5)

Description: texture, sorting, preservation and nature of bioclasts are heterogeneous. Locally, concentrations of clasts, clay and detrital quartz (0.05mm) are observed. Main texture is a wackestone with dark micritic matrix rich in pellets and mm-scale intraclasts. *Umbellina* (more than 40%) are accompanied by gastropods, paleosiphonocladales, foraminifers, ostracods, crinoids, brachiopods, bryozoans and scarce *Amphipora*. Preservation is relatively variable, with well-preserved or completely broken organisms in the same thin section. Desiccation cracks are common.

Interpretation: According to Mamet (1970), *Umbellina* were significant in littoral and abnormal salinity environments. The fossils are a mixture of open marine fauna (crinoids, bryozoans and brachiopods) and lagoonal fauna (paleosiphonocladales, calcispheres,...). Intense bioturbation is related to a relatively weak sedimentation rate and presence of desiccation cracks gives evidence of occasional emersions. Muddy matrix and clay suggest a quiet environment. This very heterogeneous microfacies would be the result of the development of a brecciated channel system, originating in the intertidal zone in *Umbellina*-rich environments and eroding the lagoonal sediments in intertidal and subtidal zones. These channels crossed the biostromes and were probably connected with open marine environment. It should be noted that, n the two sections, after a third order regression (cf chapter 5), 5 to 10 meters of *Umbellina* layers could be related to a strong reworking of sediments.

Microfacies 12: Mudstone with ostracods and calcispheres

Description: Mudstone with ostracods, calcispheres, paleosiphonocladales, foraminifers, pellets, *Umbellina* 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 pseudomorphs confirms the non-evaporitic, tropical humid nature of climate, close to the Bahamas model (Hardie, 1977; Purser, 1980) with which the comparison is made to allow interpretation. Bioturbations indicate low sedimentation rate, desiccation cracks and vadose cement suggest an environment subjected to periodical emersions (intertidal zone, Read, 1985). The horizontal fenestrae are the result of sheet cracks or decay of algal mats (Grover & Read, 1978). This microfacies is developed in the intertidal zone of a lagoonal environment, with very low water energy.

Microfacies 13: Laminar grainstone to packstone with pellets and fenestrae

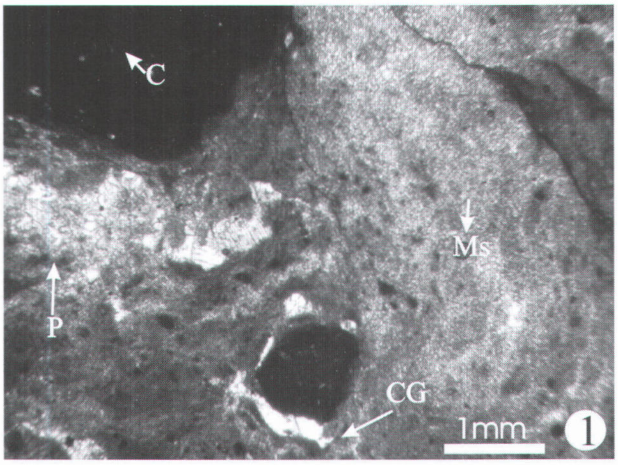
Description: This microfacies is mainly constituted by an accumulation of pellets (0.05-0.1mm, 70-90%) with sharp or diffuse rims. The lamination originates from packstone-grainstone-mudstone alternations, variable abundance of fenestrae or bird's eyes, local microbioclastic or intraclastic beds, clay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

Interpretation: Abundant fenestrae, occasional presence of algal sheaths 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 local mechanical reworking of these algal mats (Aitken, 1967). These 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.

Microfacies 14: Brecciated limestone (Pl. 2/1-2/2)

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 constituted by wackestone with paleosiphonocladales, pellets or mudstone and are surrounded by microspar cement, dolomite and argillaceous infiltrations. Granular cement is often present within the cavities and under the clasts, forming brownish irregular pendant cements. Pellets (glaebules) concentrations are observed. Pyrite and hematite crystals are frequent and sometimes follow stratification.

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



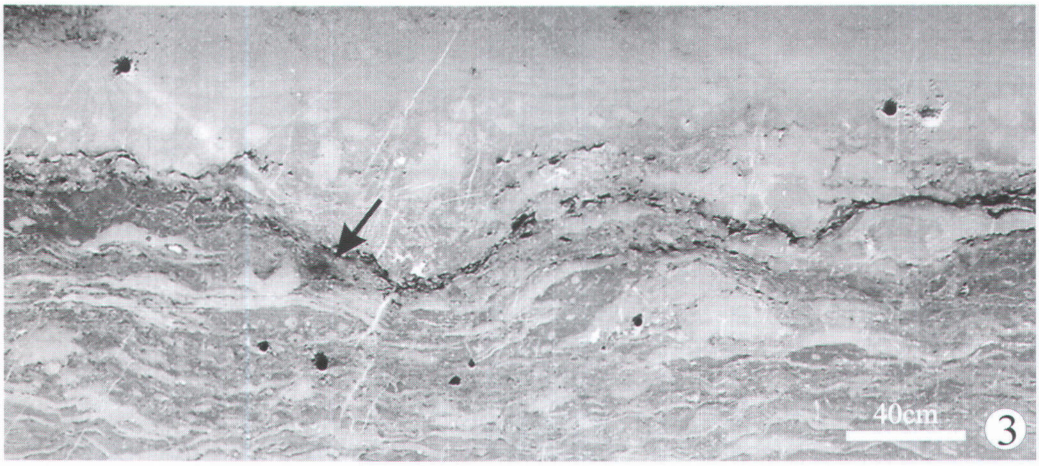


PLATE 2

Facies from the Tailfer section, Belgian Middle Frasnian carbonate platform

1.1. Brecciated limestone (microfacies 14) interpreted as paleosoils. Tailfer section, thin section 72, 63m above the base of the section. (C) Micritic clast (P) pendant vadose cement (CG) Circum granular cracks (Ms) Microspar cement.

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

1.3. Third order downward shift (arrowed), separating a laminar stromatoporoids biostrome and a lagoonal unit. Tailfer section, field photograph, 49 m above the base of the section.

4. Sedimentological model

The ideal regressive facies sequence starts with open marine facies corresponding to the crinoidal packstones (1). The crinoidal lithofacies (A) is followed by the biostromal lithofacies (B) : laminar stromatoporoids with micrite (2) alternating with frequently overturned laminar stromatoporoids and tabulate corals (3), are overlaid by strongly broken and overturned laminar stromatoporoids and massive stromatoporoids with crinoids and brachiopods (4 and 5) and then by *Stachyodes* and Udoteacean algae (6 and 7). Biostromal microfacies (B) are followed by lagoonal lithofacies (C) from subtidal zone with *Amphipora*, paleosiphonocladales and pelloidal microfacies (8, 9, 10), to intertidal zone with mudstone and laminated pelloidal facies (12 and 13). The subtidal and intertidal zones are cut by channels filled by *Umbellina* and clasts (11). Supratidal zone is characterized by paleosoil microfacies (14). The sequences are never complete.

Microfacies distribution changes from one section to the other (Fig. 3.): within biostromes, stromatoporoids morphology is clearly dominated by laminar forms (and tabulate and rugose corals) at Tailfer, while branching and bulbous organisms are prevailing at Aywaille. The Aywaille section includes more *Amphipora* and paleosiphonocladales-rich microfacies and less paleosoils than the Tailfer outcrop.

Microfacies interpretation, distribution of microfacies in the two sections leads to propose a sedimentological model for the Lustin Formation platform sediments (Fig. 4). This model has to be complemented by further studies on lateral time-equivalent sections. Tailfer and Aywaille sections can be divided in two different sedimentological units on the basis of the main lithofacies :

- BIOSTROMAL UNIT : first unit, dominated by biostromal lithofacies, episodically interrupted by lagoonal episodes.
- LAGOONAL UNIT : second and last unit, constituted only by lagoonal facies.

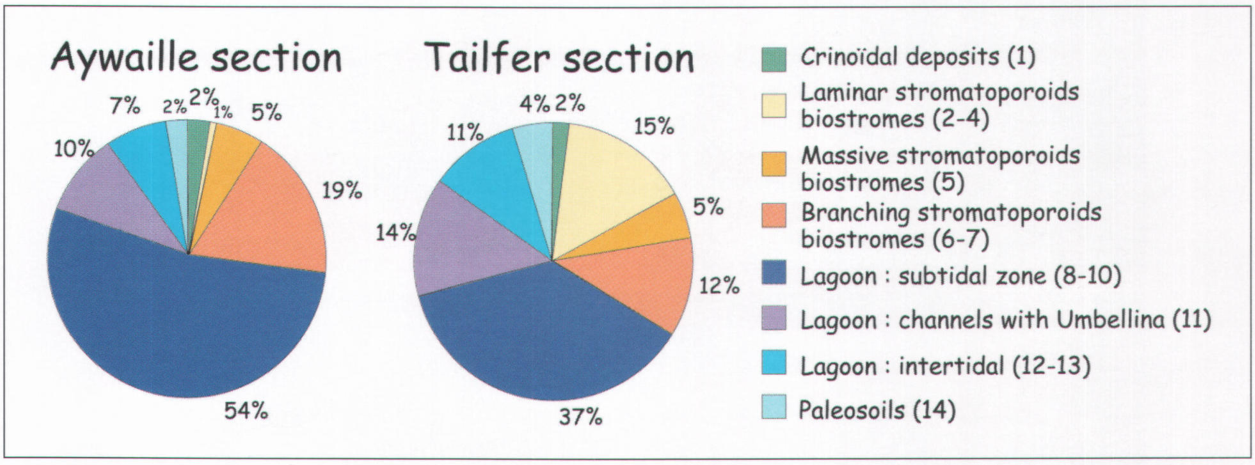
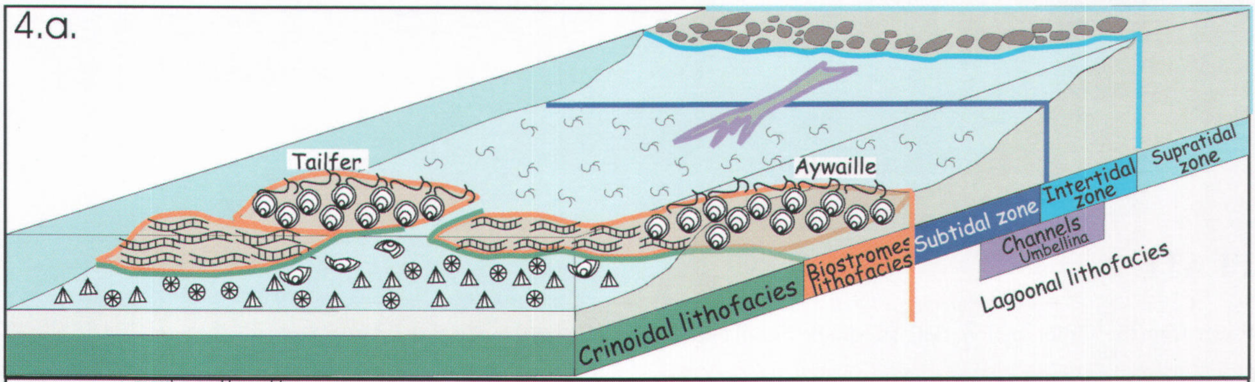


Figure 3. Microfacies proportion in Aywaille and Tailfer sections.



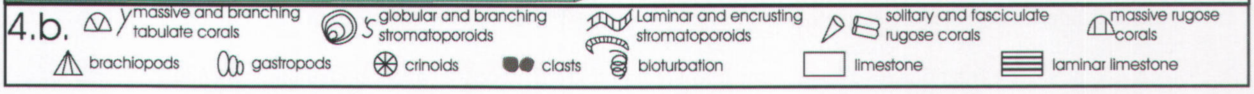


Figure 4.a. Model of the Middle Frasnian platform (Lustin Formation) in Belgium.
Figure 4.b. Legend figures 4, 5 and 6.

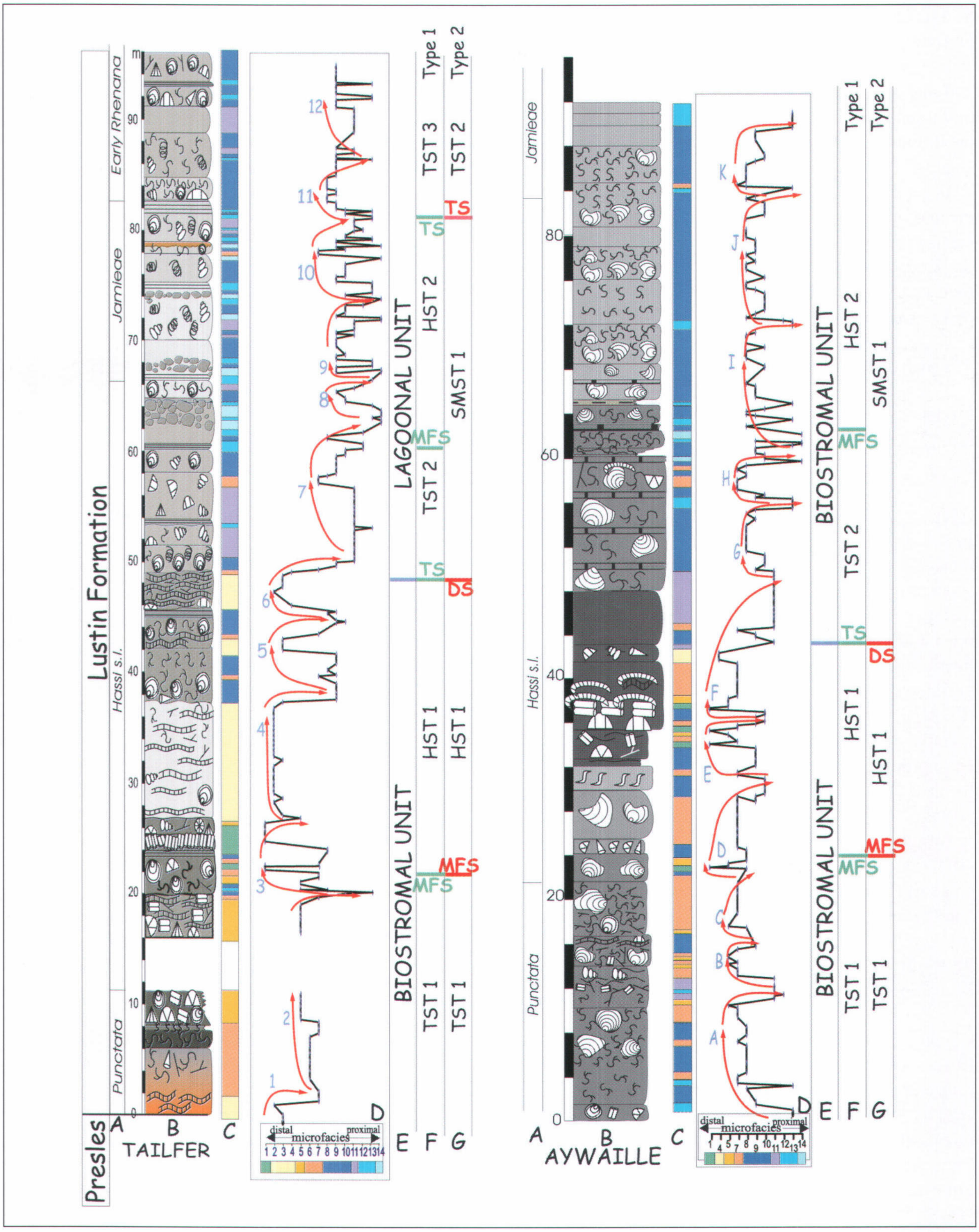


Figure 5. Microfacies evolution in Aywaille and Tailfer sections :

(A) Conodont zonation after Gouwy & Bultynck (2000)
(B) Sedimentological log (from field observations)
(C) Representation by colors of microfacies evolution (see legend on Fig. 3)
(D) Microfacies evolution curve
(E) Sedimentological units
(F) Three order system tracts with type 1 sequences
(G) Three order system tracts with type 2 sequences.

5. Discussion on the sequence stratigraphic framework

In Table 1, microfacies are ordered along a distal to proximal transect; this interpretation allows to reconstruct an evolution curve of environments through time (Fig.5.D).

4th order sequences (m scale, of hundred ky duration) (indicated on Fig.5.D. by numbers 1 to 13 for the Tailfer section, and A to K for the Aywaille section) : fourth order sequences show similar (often regressive) pattern, but facies changes from Tailfer to Aywaille, as stated above, makes sequence correlations relatively difficult.

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

Two different stratigraphic frameworks with type 1 and type 2 sequences (Van Wagoner *et al.*, 1988) are plausible:

- Type 1 sequences (Fig.5.F.) :

In first hypothesis, the biostromal unit correspond to a transgressive system tract (TST 1) followed by a highstand system tract (HST 1) separated by a maximum flooding surface (MFS) characterized by the first occurrence of an open marine crinoidal facies (1). The boundary with the overlying system tract corresponds to a sharp major regression surface (downward shift, DS) in the two sections (Pl. 2/3). In this interpretation, the DS (type 1 sequence boundary) is considered as a major erosion surface, with an important phase of non- deposition and it merges with the next transgressive surface. The lagoonal unit is composed of a TST (2), with the *Umbellina* facies and with reworked fossils (mainly rugose corals), followed by a HST (2) with the paleosoils. The reappearance of massive stromatoporoids characterized a transgressive surface and the base of the TST (3). The TST 3 is dominated by subtidal facies whereas supratidal facies disappear. This TST outcrops only in the Tailfer section while the Aywaille section is interrupted before the transgression.

- Type 2 sequences (Fig.5.G.) :

In this second hypothesis, the BIOSTROMAL unit is interpreted like in the first proposal but the DS is considered as a regression surface without major erosion features and sedimentation gap (type 2 sequence boundary). The LAGOONAL unit is then interpreted as a shelf margin system tract (SMST 1), followed by a transgressive system tract (TST 2, corresponding to TST3 of type 1). The SMST 1, characterized by sub-, inter- and supratidal facies, is followed by a transgressive surface at the reappearance of massive stromatoporoids.

Further investigations are needed to select one of this hypothesis, especially studies of lateral extensions of the platform in more distal sections. We need good correlations between distal and proximal sections to understand if a LST developed in the distal sections without time equivalent deposition on the platform (hypothesis 1), or if no important stratigraphic gap exists between distal and proximal sections (hypothesis 2). Magnetic susceptibility is expected to be a very powerful tool for correlations of distal and proximal sections (cf chapter 6).

6. Magnetic susceptibility study

6.1 Principle

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. Values of magnetic susceptibility were calculated on basis of sample mass. Magnetic susceptibility (MS) is a measure of the material response to an applied magnetic field (Borradaile, 1988). Within sedimentary rocks, ferromagnetic mineral concentration depends on the lithogenic fraction (continental contributions), which is markedly related to eustatism (or tectonism or climate). Thus, the magnetic susceptibility curve increases during a sea level fall and shows high values during low sea level; it decreases during a rising sea level and shows low values during high sea level. An increase in the susceptibility curve may also be related to climatic variations such as increasing rainfall or development of ice sheets (Crick *et al.*, 1994).

6.2. Correlations

The link between magnetic susceptibility and lithogenic contributions (eustatic and/or climatic mechanisms) was mainly used for intrabasinal, interbasinal, interregional and intercontinental correlations with higher resolution than that offered by biostratigraphy (Crick *et al.,* 1994, 1997 and 2000 and Ellwood *et al.,* 1999, 2000). Correlations are made on basis of magnetic susceptibility peaks, which are isochronous and facies independent. On the fourth order level, the MS leads to more precise correlations between the two sections than biostratigraphy and sequence stratigraphy (Fig. 6.H.). These correlations are easier than those made by sequence stratigraphy, because of the individual SM peak pattern, which are different depending on the particular sequence. The correlations between the two sections are underlined on fig 6, by orange arrows and letters a to j.

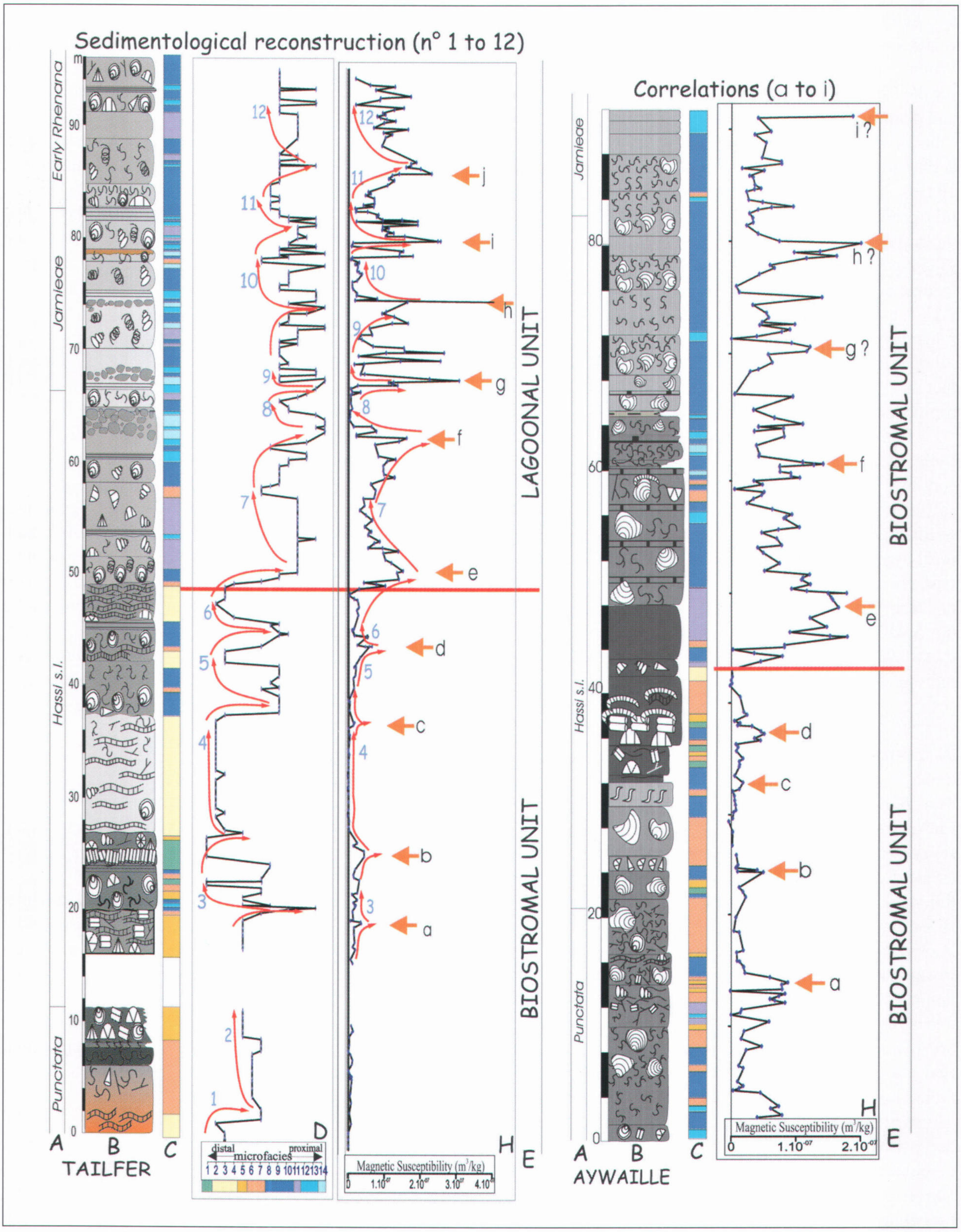


Figure 6. Compilation of different data from the Middle Frasnian Tailfer and Aywaille sections :

(A) Conodont zonation after Gouwy & Bultynck (2000)
(B) Sedimentological log (from field observations)
(C) Representation by colors of microfacies evolution (see legend on Fig. 3)
(D) Microfacies evolution curve
(E) Sedimentological units
(H) Magnetic susceptibility profile

6.3. Sedimentary interpretation and evolution

When comparing MS curve and facies evolution curve for the Lustin section (Fig.6.H.), the same global (units) and detailed (fourth order) evolution is observed.

- the biostromal unit shows very low MS values (from -2.10^{-09} to 6.10^{-08} m^3/kg) and uncontrasted fourth order cycles. This weak signal corresponds well to low lithogenic inputs related to a relatively high distance from the continent
- the lagoonal unit is characterized by an increase in MS values, but also by their higher variability (values from 3.10^{-09} to 3.10^{-07} m^3/kg). This increase is related to the marine regression and correlative higher inputs in lithogenic contributions. Variability could be due to the fact that "tidal deposits" are very sensitive to slight environmental variations (Hardie, 1977).

It clearly appears that for limestones, the magnetic susceptibility signal is not related to any specific facies, but rather to the sequences and particularly to the sedimentological unit. Indeed, the episodic lagoonal deposits within the biostromal unit show very low values (close to $4.10^{-8} m^3/kg$), in agreement with the general distal position. On the other hand, the same lagoonal facies in the SMST show relatively higher and variable values, (between 0 and $3.5.10^{-7} m^3/kg$), probably related to the more proximal position.

7. Conclusions

The Tailfer and the Aywaille sections expose Middle Frasnian shallow-water limestones. The sedimentological study allows to identify 3 lithofacies and 14 microfacies and to divide the sections in two sedimentological units : the ideal regressive lithofacies and microfacies succession ranges from open marine to supratidal environments. Packstone with crinoids and brachiopods were deposited in the storm wave zone. Biostromal lithofacies, with laminar stromatoporoids followed by massive, broken and overturned corals and stromatoporoids and by encrusted *Stachyodes* range from the storm wave zone to the normal wave zone. Lagoonal lithofacies include subtidal facies dominated by paleosiphonocladales, pellets and *Amphipora* and intertidal facies with mudstone and bedded pelloidal facies affected by desiccation and vadose cementation; channels filled mainly with clasts and *Umbellina* reworked this sub- and intertidal facies and brecciated limestone paleosoil beds characterize the supratidal zone. The two sections are divided in two sedimentological units and in fourth order sequences. The first unit is characterized by biostromal lithofacies with short lagoonal interruptions while the second one is constituted only by lagoonal lithofacies. Two stratigraphic canvas are proposed and discussed, with emphasis on the possible presence of a major stratigraphic gap in the second part of the Lustin Formation. The magnetic susceptibility curve (related to lithogenic supplies and among other to sea level) suggests different comments :
- it allows to make high-resolution correlations (fourth order) between the Aywaille and Tailfer sections;
- it allows quick determination of a relative sea level curve, without thorough sedimentological analysis. In this study, the fourth order sequences and the sedimentological units are easily identifiable. The biostromal unit shows low values in relation with distal position; the lagoonal unit is characterized by high values in relation with the proximity of landmasses.

8. Acknowledgements

A-C. da Silva benefited from a F.R.I.A. grant from the Belgian Fonds National de la Recherche Scientifique (FNRS). F. Boulvain acknowledges support through research grant FRFC 2-4501-02 from FNRS. This paper is a contribution to the French CNRS "eclipse" program. The authors are especially thankful to Olivier Averbuch (University of Lille) for allowing access to the magnetic susceptibility device and to Marc Bertrand, Xavier Devleeschouwer, Alain Herbosch et Marie Coen-Aubert for critical reading of this paper and for advice.
Cet article est un hommage à Jean-Marie Graulich, merci pour ta passion infinie …. (Anne-Christine da Silva).

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Manuscript received 29.4.2002 and accepted for publication 18.12.2002.