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Upper Devonian carbonate platform correlations and sea level variations recorded in magnetic susceptibility

Anne-Christine da Silva *, Frédéric Boulvain

Laboratoire de Pétrologie sédimentaire, B20, Université de Liège, Sart Tilman, 4000 Liège, Belgium

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Abstract

This paper concerns the analysis of four outcrops in the Frasnian (Upper Devonian) of Belgium. We compare the results of a precise sedimentological analysis with magnetic susceptibility (MS) data. This comparison allows us to improve stratigraphic correlations and to test the relationship between magnetic susceptibility and sea level changes.

Considering the sedimentological study, different microfacies have been identified, from the external belt dominated by relatively argillaceous open marine facies with crinoids, to the biostromal and the lagoonal belt dominated by algae-rich muddy facies. Fourth- and third-order sequences have also been identified and are probably related to sea level variations.

Magnetic susceptibility data provides us very good fourth-order correlations and the link between magnetic susceptibility and different sedimentological parameters is obvious. More precisely, MS appears to be related to fourth- and third-order sequences and to microfacies.

Keywords: Sedimentology; Magnetic susceptibility; Sequences; Carbonate platform; Frasnian

1. Introduction

Magnetic susceptibility (MS) was applied to perform correlation of unlithified Recent sediments and to identify climatic variations. In these studies, MS signal was interpreted to be related to lithogenic inputs which are a proxy for climatic variations and Milankovitch cycles (Robinson, 1993; Curry et al., 1995; Arai et al., 1997; Lean and McCave, 1998).

Recently, the use of MS has become more and more widespread in the study of Paleozoic lithified sediments. Some authors used MS for correlations and they claim that these correlations are intercontinental, facies independent and of a better precision than biozones (Crick and Ellwood, 1997; Crick et al., 1997; Ellwood et al., 1999; Crick et al., 2000; Ellwood et al., 2000). They proposed the assumption that MS is related to lithogenic inputs, mainly in relation with sea level variations. According to these authors, a marine regression produces an increase of continental erosion and this will increase the detrital input in the sea and ocean (Crick et al., 1997; Racki et al., 2002).

Application of magnetic susceptibility is now widespread, but there are still many questions remaining on the origin and on the nature of the parameters, which influence the MS signal. The aim of this study is to test the supposed relationship between sea level and magnetic susceptibility by the integration of a detailed sedimentological study and magnetic susceptibility

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* Corresponding author. Tel.: +32 4 3662258; fax: +32 4 3662921.
E-mail address: ac.dasilva@ulg.ac.be (A.-C. da Silva).

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results. We first describe the microfacies and the sedimentological evolution of a carbonate platform and then compare this sedimentological evolution with magnetic susceptibility. In ancient sediments, magnetic susceptibility correlations have been mainly applied to important sedimentological boundaries like Pridolian–Lochkovian (Crick et al., 2001) Eifelian–Givetian (Crick et al., 1997, 2000), Frasnian–Fammennian (Crick et al., 2002) and Cretaceous–Tertiary (Ellwood et al., 2003) boundaries. These special periods are subject to drastic sedimentological changes and so are probably easier to correlate. We test MS on a classical carbonate platform during the Middle Frasnian, which is not subject to major environmental changes. We also compare different kinds of paleoenvironments within the carbonate platform (external zone, biostromes and internal area) to test the validity and the limits of the technique and to identify the main parameters controlling the MS signal evolution.

2. Materials and methods

2.1. Sedimentology

Microfacies analysis came from the detailed bed-by-bed study of four outcrops (Villers, Tailfer, Aywaille and Colonster, Fig. 1) and more than 900 thin sections. The maximum interval between two samples is 1 m. For each sample, the microfacies was determined and magnetic susceptibility measurements were performed. The textural classification used to characterise the microfacies follows Dunham (1962) and Embry and Klovan (1972). Classification of stromatoporoid morphology follows that proposed by Kershaw (1998). In the following description, microfacies are ordered from the most distal to the most proximal according to textural criteria and comparisons with classical sedimentological models (e.g. Wilson, 1975; Hardie, 1977; Flügel, 1982; James, 1983) and with other Devonian platforms specifically (May, 1992; Machel and Hunter, 1994; Méndez-Bedia et al., 1994; Pohler, 1998; Wood, 2000; Chen et al., 2001a).

2.2. Magnetic susceptibility

Magnetic susceptibility (MS) is a measure of the material response to an applied magnetic field (Borradaile, 1988). Volume magnetic susceptibility (k) is defined as the ratio of induced magnetization intensity (M) per unit volume of a substance, to strength of the applied magnetic field (H) inducing the magnetisation: $k=M/H$. It is important to note that what we measure here is induced magnetization as opposed to residual (or fossil) magnetization related to Earth magnetic field. That means that the measurements performed here are bulk results from unoriented samples.

Magnetic susceptibility of a rock depends on the mineralogical composition of the rock and proportion of each mineral. There are three main magnetic behaviours: diamagnetic minerals show extremely weak negative values of MS (carbonates and quartz), paramagnetic minerals show weak positive values (clay minerals, particularly chlorite, smectite, illite and glauconite, ferromagnesian silicates, iron and manganese carbonates, pyrite), and ferromagnetic minerals show high and positive values (mainly magnetite, pyrrhotite and maghémite) (Walden et al., 1999).

The MS signal in marine sedimentary rocks is carried mainly by detrital minerals (mainly ferromagnetic and paramagnetic minerals) whose concentration is related to the lithogenic fraction (continental contribution) that are related to eustatic, climatic and tectonic variations (Ellwood et al., 2000). Thus, the magnetic susceptibility curve increases during a sea level drop 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. Tectonic variations can change the source of magnetic minerals. These links of MS with different environmental parameters are theoretical.

The measurements performed in our lab correspond to mass-specific magnetic susceptibility (which is k multiplied by a reference volume of 1 m^3 and divided by the sample mass) expressed in m^3/kg. Measurements were performed on the KLY-2 kappabridge of the University of Lille and on the KLY-3S kappabridge of the University of Liège. Three measurements are made on each sawn samples (max. 2.5–2.5 cm) weighed with a precision of 0.01 g.

3. Geological setting

The Upper Devonian (Frasnian) limestones studied here belong to the Rhenohercynian fold and thrust belt. Tectonics is responsible for discontinuous outcropping across the platform, making correlations difficult. During the Middle part of the Frasnian, an extended carbonate platform developed in Belgium (Boulvain et al., 1999). In the more distal part (SW of Belgium, southern border of the Dinant Synclinorium), a succession of two carbonate mound levels separated by argillaceous episodes is observed (Moulin Liénaux

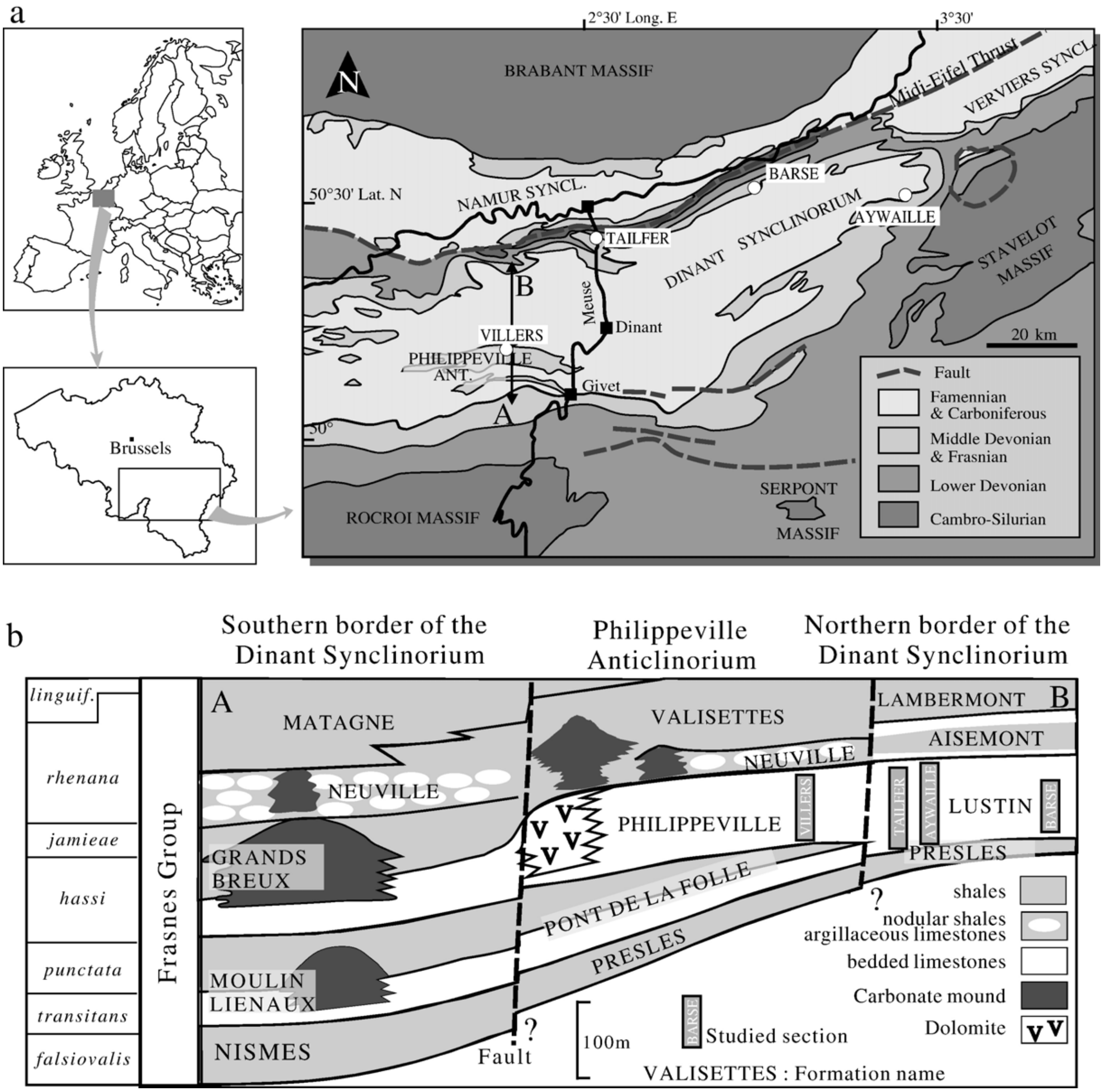


Fig. 1. (a) Geological map of Belgium, with location of the studied sections. (b) NS section through the Belgian Frasnian sedimentary basin, before variscan structuration. Letters A and B correspond to the line A–B on (a).

and Grand Breux Formations) (Boulvain et al., 2004). In the intermediate part of the basin (Philippeville Anticline), argillaceous, crinoidal and biostromal facies dominate (Pont-de-la-Folle and Philippeville Formations), and in the proximal part of the basin (northern border of the Dinant Synclinorium, Vesdre Synclinorium and southern border of the Namur Synclinorium), the development of stromatoporoid biostromes and lagoonal facies is widespread (Lustin Formation) (Fig. 1b). Biostratigraphically, the rocks studied here belong to the *transitans* to *lower rhenana* conodont zones (Gouwy and Bultynck, 2000).

The studied sections are located in Villers, Tailfer, Aywaille and Barse. The Villers section is situated in the Philippeville Anticlinorium and belongs to the Philipeville Formation, the Tailfer and Barse sections are located in the northern part of the Dinant Synclinorium and belong to the Lustin Formation, and the Aywaille section is situated in the eastern part of the Dinant Synclinorium and belongs to the Lustin Formation. The Tailfer outcrop is the more beautiful and complete section, so it is used here to describe the general sedimentological and magnetic susceptibility evolution. A preliminary study on this section and magnetic susceptibility data has been published (da Silva and Boulvain, 2002).

4. Sedimentology

A precise description of the carbonate platform is not the purpose of this paper; we will only propose a summary of facies. The complete sedimentological description of this platform is given by da Silva and Boulvain (2004). The facies described here are sorted from the more distal to the more proximal. For each facies belt, the description concerns mainly the macroscopic features and for microfacies, mainly microscopic features.

4.1. Facies, microfacies and palaeoenvironments

External belt (1–2): decimetric dark calcareous beds, with some argillaceous levels. The main bioclasts are crinoids but there are also some brachiopods, stromatoporoids, rugose and tabulate corals.

(1) Microfacies rich in crinoids and sponge spicules (Plate IA), with uncommon brachiopods, peloids and silicified and broken tabulate corals. Silicification can be common with some chert levels. The texture is a packstone and lamination is defined by sponge spicules, grainstone levels and peloid accumulations. This facies had been only observed in the Villers section and seems to correspond to condensed levels, with very low carbonate production rate (da Silva, 2004).

The high micritic content and fine-grained texture are pointing to a quiet environment, under the fair-weather wave base (FWWB) but within storm weather wave base (SWWB) considering the grainstone layers. The scarcity of reef builder organisms and their strong alteration is probably related to an important distance from the biostromal belt (facies 3–5, see below), considered as the source area.

(2) Packstone or wackestone with crinoids and ostracods (Plate IB) and with subordinate brachiopods, foraminifera, bryozoans, peloids, stromatoporoids and rugose or tabulate corals. Almost all fossils are strongly altered and grains are well sorted. Crinoids, brachiopods and bryozoans all originate from the open area of the platform.

The high proportion of micrite points to an environment located below FFWB. The presence of reefal debris suggests a stronger influence of the biostromal belt.

Biostromal belt (3–5): Biostromes mainly built up by stromatoporoids with different morphologies.

(3) Laminar stromatoporoids biostromes (Plate IC) with some tabular stromatoporoids and rugose or tabulate corals with different morphologies. The matrix is a fine-grained mud, with some peloids or clotted structures. They are also some brachiopods, ostracods, crinoids, bryozoans, paleosiphonocladales and sponge spicules. All these fossils are well preserved. Numerous centimetric size fenestrae, cemented by equant spary calcite or by dolomite are observed mainly under the stromatoporoids.

The high amount of fine-grained matrix as well as the well preserved fossils and clotted matrix point to a quiet environment (below FWWB).

(4) Rudstone made by bulbous and high domical stromatoporoids and rugose and tabulate corals (Plate ID). These builders are often highly abraded and/or overturned. They are accompanied mainly by crinoids, brachiopods and bryozoans. The matrix is often micritic or dolomitized.

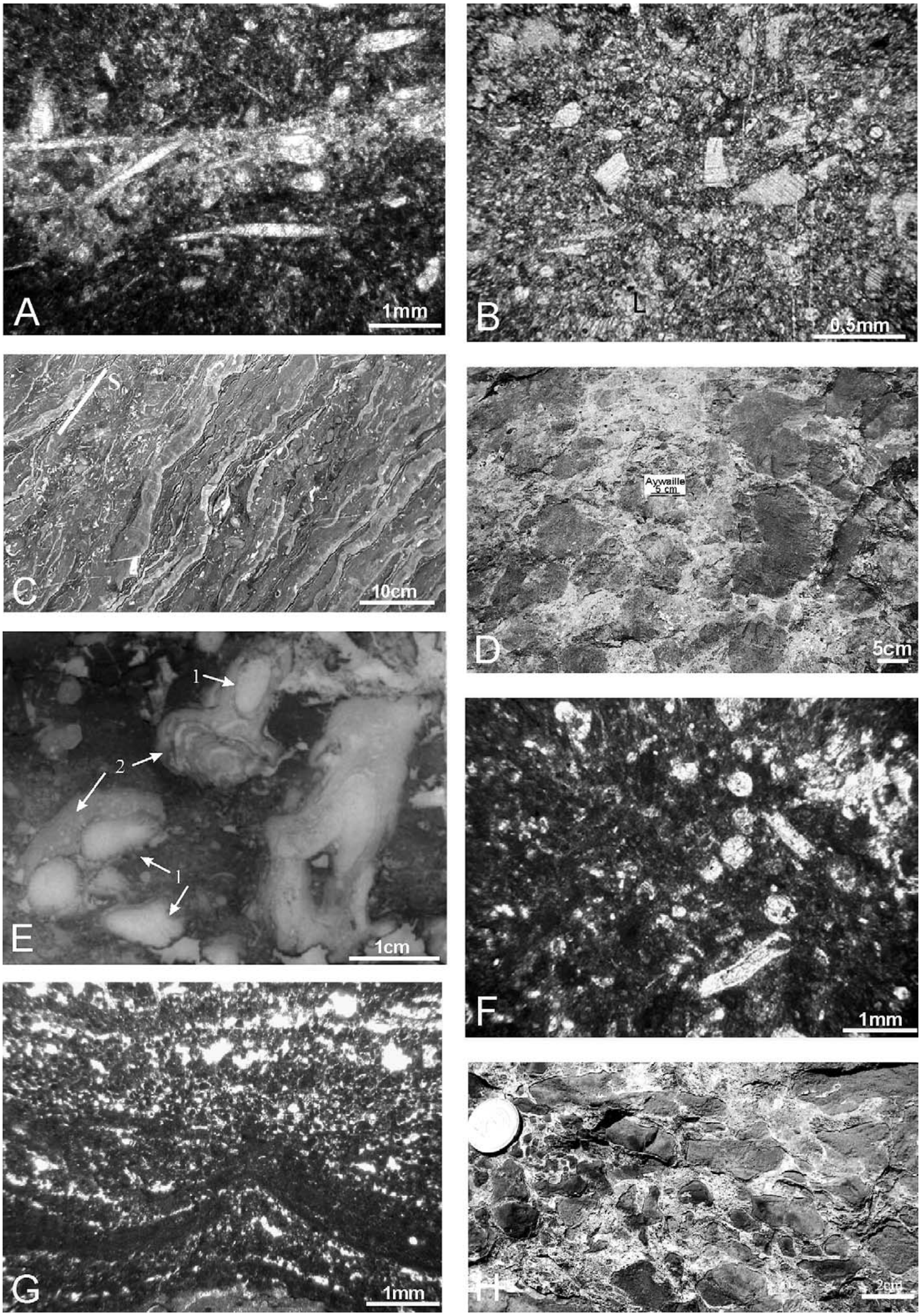
The massive morphology of reef-builders seems to correspond to medium-strength water turbulence (Cornet, 1975; Machel and Hunter, 1994). Stromatoporoids, rugose and tabulate corals are broken, but not rounded, suggesting a limited transport. This microfacies is interpreted as being developed in moderate to strong wave energy, close to the FWWB where sediment was episodically reworked by storms.

(5) Dendroid stromatoporoid biostromes (floatstone) (Plate IE), with *Stachyodes*, paleosiphonocladales, peloids, calcispheres, udoteacean algae, *Amphipora* and ostracods. The stromatoporoids are often irregularly encrusted by other stromatoporoids, codiacea or

Plate I. Illustration of the microfacies from the Frasnian carbonate platform from Belgium. (A) Microfacies rich in crinoids and sponge spicules (1), external belt. Villers outcrop, thin section from sample V47d, normal light, Philippeville Formation. (B) Packstone or wackestone with crinoids (2), external belt. Villers outcrop, thin section from sample V30, normal light, Philippeville Formation. (C) Laminar stromatoporoid biostrome (3), biostromal belt. Tailfer outcrop, field picture, bed number 53, Lustin Formation. Note that stratification is not horizontal and is indicated by S_0. (D) Biostrome with bulbous stromatoporoids (4), biostromal belt. Aywaille outcrop, field picture, bed number 71, Lustin Formation. (E) Dendroid stromatoporoids biostrome (5), biostromal belt. Tailfer outcrop, scanning of thin-section L13, Lustin Formation. (1) Dendroid stromatoporoids (*Stachyodes*) and (2) encrusting stromatoporoids. (F). Packstone with paleosiphonocladales (7), internal belt. Villers outcrop, thin section from sample V123, normal light, Philippeville Formation. (G) Laminated grainstone with peloids (11), internal belt. Aywaille outcrop, thin section from sample A153, normal light, Lustin Formation. (H) Brecciated limestone, paleosol (12), internal belt. Tailfer outcrop, field picture, bed number 74, Lustin Formation.

Girvanella. Fossils are well preserved (not broken) and some are in life position in a classical micritic matrix or in a clotted matrix.

Stachyodes has usually been reported from shallow water zones, where energy is moderate and sedimentation intermittent (Cornet, 1975; James, 1983; Machel and



Hunter, 1994; Wood, 2000). Living 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 preservation of fossils locally in life position, presence of udoteaceae and clotted microstructure suggest weak water energy. This facies developed near the boundary between the biostromal zone and the lagoonal area, under the FWWB.

Internal belt (6–12): The subtidal zone (6–8).

(6) Floatstone with *Amphipora* in a micritic matrix, with some paleosiphonocladales, *Stachyodes*, ostracods, calcispheres, gastropods and peloids. The fossils are well preserved but *Amphipora* are never in life position.

Amphipora are described as organisms living in shallow water quiet zones, like lagoonal area (James, 1983; Pohler, 1998). The other organisms like calcispheres, paleosiphonocladales and ostracods are also common in the lagoonal zones.

The abundance of *Amphipora* in the previous facies (5) and the abundance of *Stachyodes* in this facies (facies 6) suggests that they were closely associated. This facies was deposited in a quiet environment, in the subtidal lagoonal zone.

(7) Packstone with well preserved paleosiphonocladales (Plate IF) with *Amphipora*, ostracods, gastropods, foraminifera and peloids.

The micritic matrix suggests quiet environmental conditions and the gradation with the previous facies suggests their vicinity.

(8) Packstone with peloids (0.1 to 0.5 mm, sharp edge and well rounded) with paleosiphonocladales, *Amphipora*, ostracods, calcispheres and foraminifera. This facies is very well sorted but is inhomogeneous mainly because of abundant bioturbation.

This facies is laterally adjacent to the facies 7, deposited in the upper part of the subtidal zone.

The intertidal zone (9–11).

(9) Wackstone with *Umbella* and heterogeneous texture, sorting, preservation and nature of bioclasts. The matrix is dark micritic, rich in peloids and millimetre-scale intraclasts, but grainstones lenses are also present. Locally, concentrations of clasts (millimetric), clay and detrital quartz (0.05 mm) are observed. Sorting is poor, as a consequence of textural heterogeneity and variable size of fossils. *Umbella* are accompanied by gastropods, palaeosiphonocladales, foraminifera, ostracods, crinoids and brachiopods. *Umbella* are well preserved (not broken) and crinoids and brachiopods are well preserved or broken. Desiccation cracks and bioturbation are common.

According to Mamet (1970), *Umbella* was significant in littoral environment of excessive salinity. Other fossils originated from lagoonal areas. Desiccation cracks were caused by occasional emersion. Unbroken fossils, muddy matrix and clay suggest a quiet environment. Presence of fossils that are usually not associated (palaeosiphonocladales, *Umbella*, calcispheres originating from lagoon and crinoids and brachiopods derived from open sea) could be related to a channel system starting in the intertidal area, crossing the lagoon and connected with the open sea, resulting in a mixed of biotic assemblage.

(10) Mudstone with ostracods, paleosiphonocladales, fenestreae (millimetric, horizontal or vertical, filled with sparitic or vadose cement) and desiccation cracks.

Texture, nature and non-fragmented character of fossils are related to a quiet environment. Desiccation cracks and vadose cement indicate an environment subjected periodically to emersion. Horizontal fenestrae are the result of sheet cracks or decay of microbial mats (Grover and Read, 1978). This microfacies developed in a lagoonal environment in the intertidal zone, with very low energy.

(11) Laminated grainstone with peloids (Plate IG) (0.05–0.1 mm, sharp to diffuse rims) (70–90% by volume) and fenestrae. The lamination originates from packstone–grainstone–mudstone alternations, variable abundance of fenestrae or bird's eyes, local microbioclastic or intraclastic layers, clay or detrital quartz accumulations, or fining-upward sorting.

Abundant fenestrae, local presence of algal tubes as well as irregularity of laminae are the main characters of this microfacies and seem to correspond to microbial mats (Aitken, 1967). However, cross-stratification, fining-upward sorting, planar lamination, bioclastic concentrations and relief-compensating laminae suggest local mechanical reworking of these microbial mats (Aitken, 1967). Microbial 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).

The Supratidal (12).

The last facies (12) is characterized by strongly brecciated metre-thick intervals (Plate IH), accompanied by micritic or dolomitic planar beds cut by desiccation cracks. The clasts (centimetre- to decimetre-size) are generally elongated in the direction of stratification; they are composed of mudstone or wackestone with palaeosiphonocladales and pellets 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. Pyrite and hematite crystals are abundant and sometimes follow the stratification.

According to Wright (1994), brecciation is a common characteristic of paleosols. Presence of pendant vadose cement, desiccation cracks, circum-granular cracks, hematite, pyrite and glaebules are also well-known characteristics of pedogenesis. So this facies correspond to the supratidal zone, with well developed paleosoil horizons.

4.2. Sedimentological evolution

The Frasnian platform deposits are stacked into small-, medium- and large-scale sequences. This kind of stacking pattern is very common during the Frasnian (McLean and Mountjoy, 1994; Brett and Baird, 1996; Elrick, 1996; Garland et al., 1996; Whalen et al., 2000; Chen et al., 2001b).

4.2.1. Small-scale sequences

The small-scale sequences correspond to a few beds (1 to 5 beds, decimetres to metres thick) and show mainly a shallowing upward trend. In this work, the sampling interval was more or less 50 cm, so the small-scale sequences were only identified in the field but not on the microfacies curve. For this reason, we will only consider the medium- and large-scale sequences in this paper.

4.2.2. Medium-scale sequences

The medium-scale sequences (example on the Tailfer section, Figs. 2 and 3c) are constituted by the stacking of small-scale sequences; they are metres thick and they show transgressive and regressive trends. They are mainly asymmetric with the regressive tendency, which is usually predominant. These sequences are identified on the microfacies curve (Fig. 3c and e) and in the field.

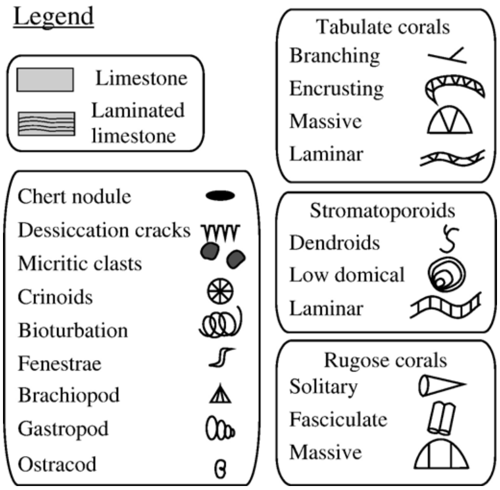


Fig. 2. Legend of lithological column of Figs. 4–6.

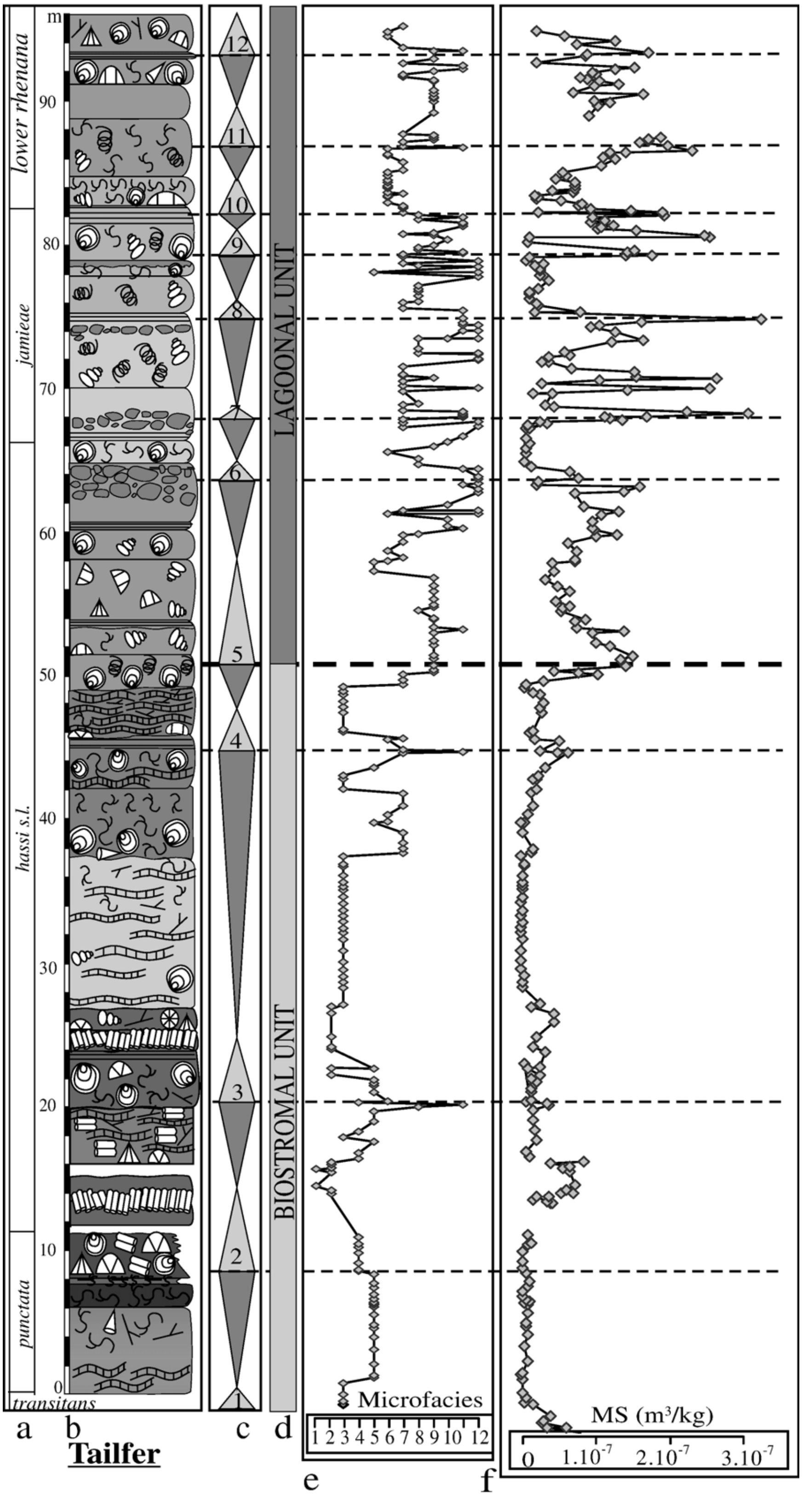
During the *jamiaea* conodont zone (0.45 My after Tucker et al., 1998), two or three medium-scale sequences are observed and during the *hassi* conodont zone (1.25 My after Tucker et al., 1998), four of these sequences are recorded. Using these data, the medium-scale sequences have a theoretical duration of 150 to 300 ky, which correspond to the fourth order (Vail et al., 1977; Goldhammer et al., 1993).

These kinds of fourth-order sequences are very common in carbonate platforms and are theoretically generated by different mechanisms:

(1) Autocyclic tidal flat progradation (Ginsburg, 1971; James, 1984) appears during continuous regional subsidence and relative sea level rise. It corresponds to tidal flat progradation implying a decrease of the area and eventual cessation of carbonate production. Because the platform is continually subsiding, it allows the re-establishment of carbonate production. This mechanism generates regressive-prone, tidal flat-capped cycles. In our case, the fact that some sequences have a transgressive base and some are not capped by tidal flat facies is not in good agreement with the autocyclic tidal flat progradation model (Osleger, 1991; Elrick, 1995). The abundance of pedogenetic structures is also in opposition with this theory (Elrick, 1995), because they require a relative sea level drop below the platform surface.

(2) Episodic tectonic subsidence (Cloetingh, 1988), corresponding to periodic subsidence of tectonic blocks by synsedimentary faults. The fact that it is possible to correlate almost all the fourth-order sequences across the platform and that the pedogenetic structures imply uplift (rather than sown-dropping) are strong arguments against this hypothesis.

(3) Eustatic variations (Elrick and Read, 1991; Goldhammer et al., 1993) with low amplitude sea level fluctuations. Transgressive–regressive cycles, subtidal cycles and subaerial exposure can be readily explained by eustatic variations. The correlation of the cycles all around the platform is also in agreement with this hypothesis. During icehouse intervals, eustatic variations are usually related to glacio-eustasy, but the Frasnian is well known as a greenhouse period. For explaining the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LAGOONAL UNIT
BIOSTROMAL UNIT
Microfacies
1 2 3 4 5 6 7 8 9 10 12
MS (m³/kg)
0 1.10⁻⁷ 2.10⁻⁷ 3.10⁻⁷
a
b
c
d
e
f
Tailfer

development of eustatic sequences during greenhouse periods, some authors have proposed an influence of Milankovitch cyclicity, with cyclic evaporation of isolated oceanic basin (Donovan and Jones, 1979; Strasser, 1988), geoid deformation or variation in oceanic circulation (Mörner, 1994).

4.2.3. Large-scale sequences

The large-scale sequences are of several tens of metres thick and their theoretical duration is higher than 1 million years, corresponding to the third order (Vail et al., 1977; Goldhammer et al., 1993). The main sedimentological feature is an important facies shift from dominantly biostromal to lagoonal environments (see microfacies curve on Fig. 3d and e). The first unit consists of biostromal and external facies. This is called the "biostromal unit" and the fourth-order sequences that make it up start with biostromal or external deposits followed by lagoonal sediments (subtidal or intertidal). The second unit comprises mainly lagoonal deposits and is called the "lagoonal unit". The medium-scale sequences begin with subtidal deposits followed by intertidal or supratidal sediments. These units are recognized over the entire sedimentary area and are probably related to sea level variations.

Several charts of eustatic fluctuations during the Frasnian have been published (Johnson et al., 1985; Day, 1996; Whalen and Day, 2005). Correspondences between see level variations in another sedimentological basin with our case study can be a good argument to support eustatic origin of our sequences. In the carbonate platforms of western Alberta, Whalen and Day (2005) identified the position of the important sea level change between the eustatic events IIc and IId in the *hassi* conodont zone. This transition could correspond to our boundary between the biostromal and lagoonal unit. In Australia, Playford (2002, Fig. 2, p. 765) identified different sequences and the boundary between sequences 4 and 5 can also correspond to our boundary. Correlation of eustatic events worldwide is difficult considering that conodont zonal boundaries are not always very well constrained. So this coincidence of sea level events between Alberta, Australia and Belgium can be a good argument for eustatic origin of our large scale sequences but the uncertainties in age dating don't permit unequivocal correlation or interpretation of an eustatic origin.

5. Magnetic susceptibility results

5.1. Correlations

Correlations are made on basis of magnetic susceptibility peaks (events with the same pattern), which are considered as isochronous (Crick et al., 1997). Third-order to fourth-order correlations are proposed on the basis of MS peaks (Fig. 4).

5.2. MS evolution

The trends in the MS signature are similar for all described stratigraphic sections and we will use the Tailfer section as a reference section to describe the relationship between facies change and the MS signature. We have chosen this section because it is the stratotype of the Lustin Formation, it represents a significant portion of the Frasnian without important hiatus, it is not strongly affected by diagenesis and it is an outstanding quarry with sawn rock faces, which allowed very precise observations.

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

(a) The first trend is a subdivision of the MS curve in two distinct parts (Fig. 3f). The biostromal unit presents very low MS values (mean of $2 \cdot 10^{-8}\,\mathrm{kg/m^3}$). Just above the boundary between the two units, the values are increasing strongly. The upper portion of the curve is characterized by higher values (to mean of $6.62 \cdot 10^{-8}\,\mathrm{kg/m^3}$) and corresponds to the lagoonal unit.

(b) The second trend is a correlation between the cycles identified on the MS curve and the fourth-order sequences. Each regressive trend corresponds to a MS peak on the MS evolution curve. On Fig. 5, the detail of some of these trends at the scale of fourth-order sequences is presented and the link between MS and sequence evolution is

Fig. 3. Main data on the Tailfer section. (a) Conodont zonation on the Tailfer section, after Gouwy and Bultynck (2000). (b) Lithological column of the Tailfer section (for legend, see Fig. 2). (c) Fourth order sequences, light grey pointing-up triangles are transgressive phase and dark grey pointing-down triangles are regressive phase. (d) Sedimentological units. (e) Microfacies evolution curve (microfacies are explained in the corresponding paragraph and are represented on this figure). (f) Magnetic susceptibility curve.

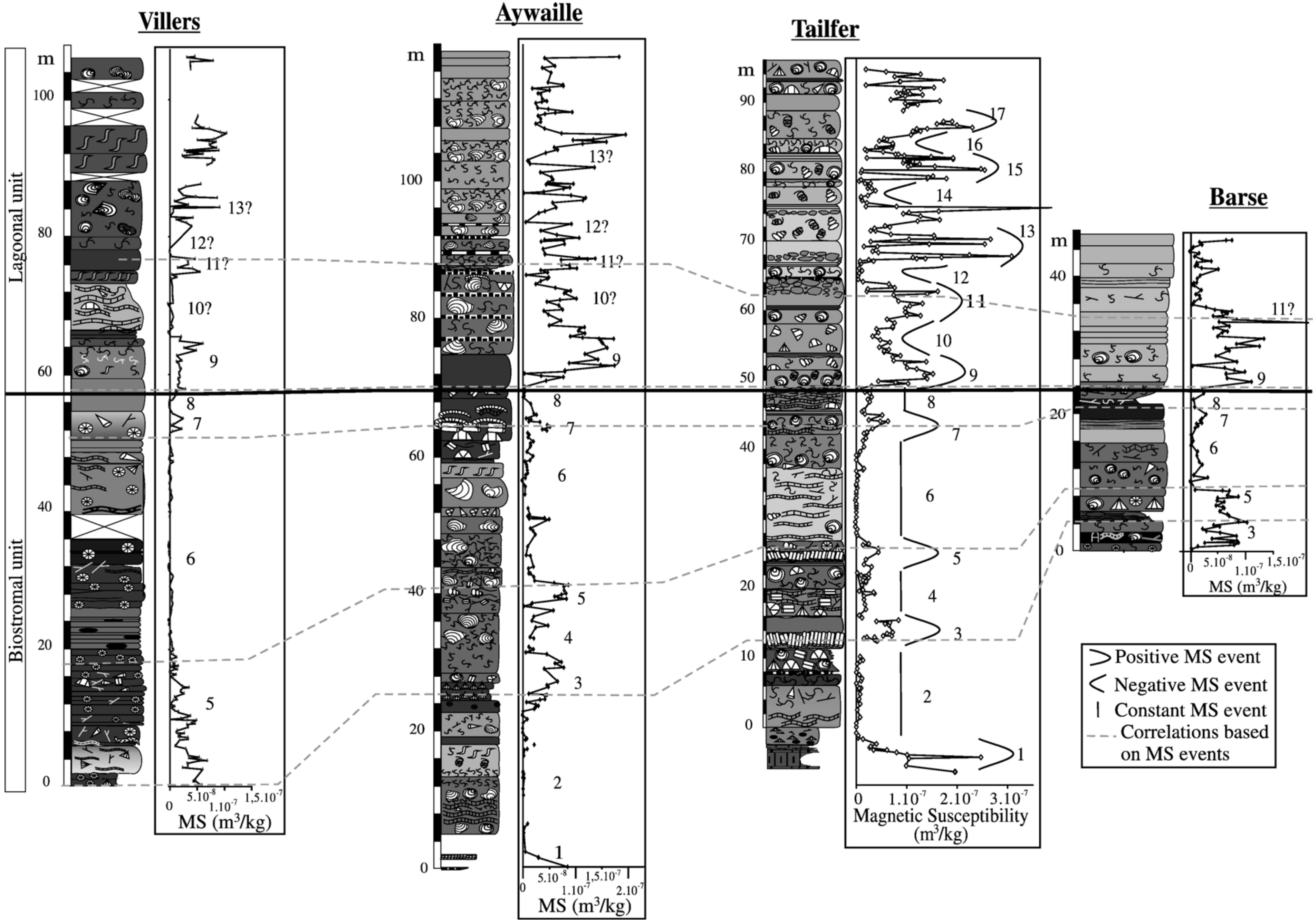

Fig. 4. Correlations of the studied sections with magnetic susceptibility events. For legend, see Fig. 2.

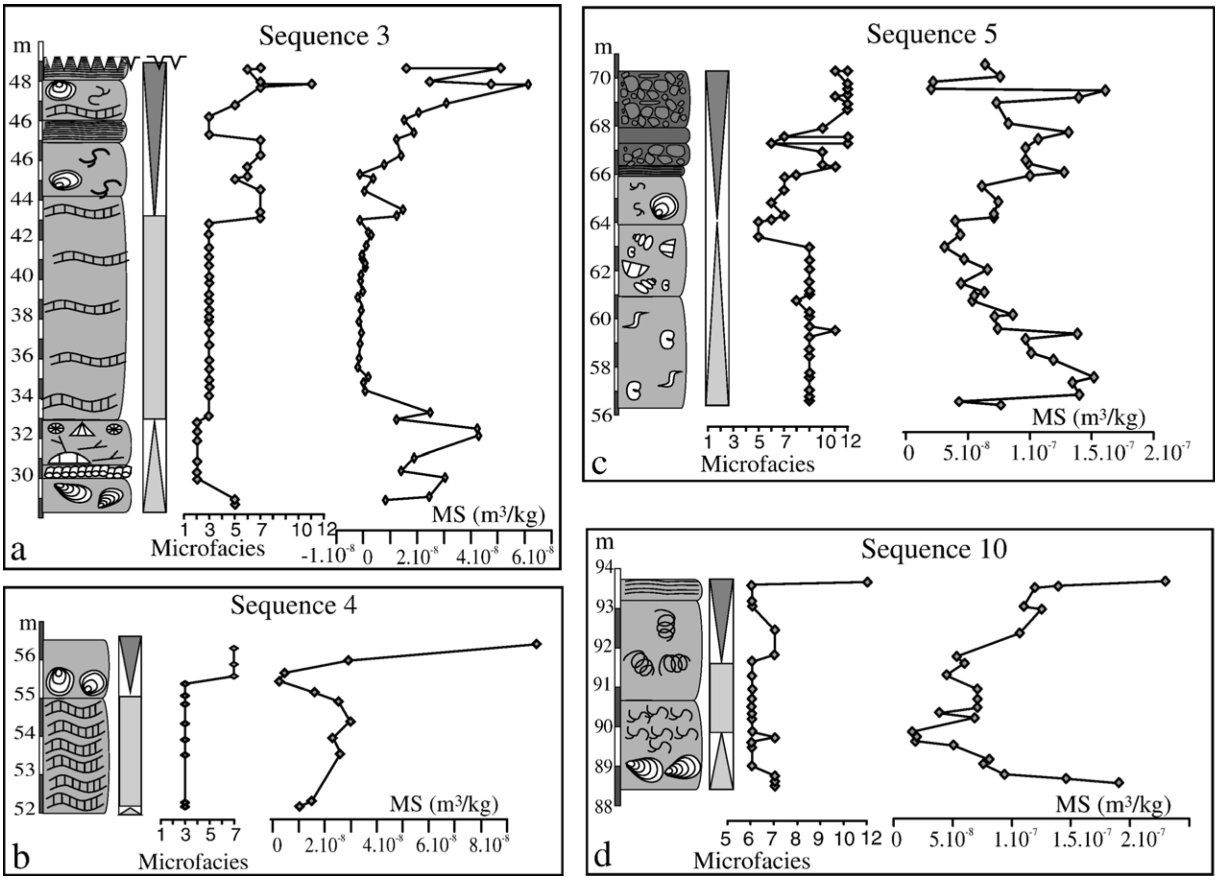

Fig. 5. Examples of fourth order sequences from the Tailfer section (these sequences are represented on the complete lithological column of the Tailfer section on the Fig. 3c and e), with comparison of microfacies evolution curve and magnetic susceptibility evolution curve. For legend, see Fig. 2.

obvious. Concerning the sequence 3 (Fig. 5a), the first trend is a short transgressive event, with biostromal facies (facies 4) grading to external crinoidal deposits (facies 2). This phase corresponds to decreasing MS values. The second trend is an aggrading biostrome, mainly built by lamellar stromatoporoids (facies 3) that corresponds to low (around $0\,\mathrm{kg/m^3}$) and almost constant MS values. A regressive trend caps the sequence, with high domical stromatoporoids (facies 4) followed by laminar limestones (facies 11) from the intertidal zone; this regressive trend corresponds to increasing MS values. Within sequence 4 (Fig. 5b), the transgressive phase is almost absent and is followed by an important aggradational phase (biostromes with laminar stromatoporoids, facies 3) and a regressive phase (high domical stromatoporoids, facies 4 followed by mudstone, facies 7). The corresponding MS evolution is almost constant during the aggrading phase and is followed by increasing values during the regressive phase. The sequences 5 and 10 (Fig. 5c and d) also show transgressive trends followed by regressive trends with the MS curve respectively decreasing and increasing.

(c) Fig. 6a presents the relationship between magnetic susceptibility and microfacies. On the horizontal axis, the microfacies succession is represented, with increasing proximality from the right to the left. The relationship between magnetic susceptibility and microfacies is obvious, with increasing MS related to proximality. Effectively, the external and biostromal microfacies have MS values around $2 \cdot 10^{-8}\,\mathrm{m^3/kg}$, while the lagoonal facies shows values around $6.7 \cdot 10^{-8}\,\mathrm{m^3/kg}$, with in details subtidal facies $5.5 \cdot 10^{-8}\,\mathrm{m^3/kg}$, intertidal facies $8.5 \cdot 10^{-8}\,\mathrm{m^3/kg}$ and supratidal facies $5 \cdot 10^{-8}\,\mathrm{m^3/kg}$. It appears that paleosols always have lower MS values than intertidal deposits. This can be explained by the fact that these paleosols correspond mainly to

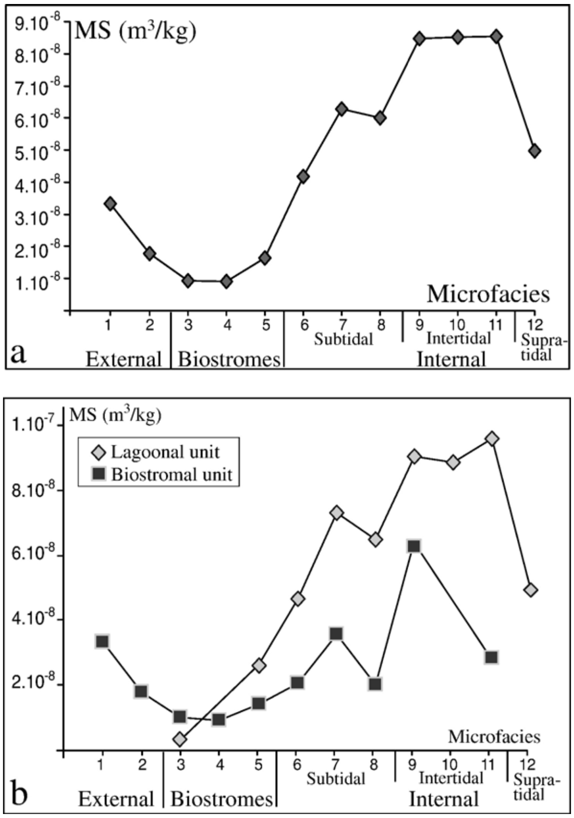

Fig. 6. (a) Microfacies (horizontal axis) versus mean MS values (vertical axis) for Barse, Tailfer, Aywaille and Villers sections. (b) Microfacies (horizontal axis) versus mean MS values (vertical axis) for the biostromal and the lagoonal units, for Barse, Tailfer, Aywaille and Villers sections.

subtidal deposits affected by pedogenesis. So the MS signal of the subtidal deposits seems to be preserved during emersion and pedogenesis. Fig. 6b presents the evolution of mean MS values compared with microfacies for each sedimentological unit. Values from the biostromal unit and from the lagoonal unit are separated. It appears that the evolution of magnetic susceptibility is very similar and is increasing with increasing proximality. For example, mean values of microfacies 8 is around $2\cdot10^{-8}\,\mathrm{m^3/kg}$ for the biostromal unit and around $4.6\cdot10^{-8}\,\mathrm{m^3/kg}$ for the lagoonal unit. This strong difference between the two units has already been observed in the MS evolution curve (point a in this chapter). So MS is related both to microfacies and to third-order sequential evolution.

(d) If we compare the MS values of the biostromal unit of the different sections (Fig. 7), the mean values are the highest in Barse which is the most proximal section and decrease distally. For the Villers sections, the values are a little bit higher, maybe because of a lower sedimentation rate and local condensed intervals.

6. Discussion

The prominent characteristic of the magnetic susceptibility curve is the relationship between MS and the sedimentological units. The higher values correspond to the lagoonal unit and the lower values to the biostromal unit. The trend related to medium-scale sequences is also obvious, with decreasing values in transgressive phases, constant values in aggradational phases and increasing values in regressive phases. We have seen that these fourth- and third-order sequences are related to sea level variations. If the facies stacking patterns can be interpreted to indicate third- and fourth-order eustatic sea level changes, then the similarity in the microfacies and MS curve implies that the MS trend also records eustatic variations.

These results confirm the idea of Crick et al. (1997, p. 168) that, during phases of low sea level, magnetic susceptibility is high. These authors suggest the following mechanism: during low sea level, the base level is lowered and heightened erosion increases the detrital contribution into the marine system. This material is then dispersed by bottom currents throughout ocean basins and MS of the sediments increases accordingly. This hypothesis is also the most commonly cited to explain MS variations (Borradaile et al., 1993; Robinson, 1993; English, 1999; Ellwood et al., 2000; Stage, 2001). Other mechanisms, also related to sea level change, can be responsible for increase of magnetic materials in sedimentary basins during lowering sea level. After Tite and Linington (1975), pedogenesis can be an important source of magnetite

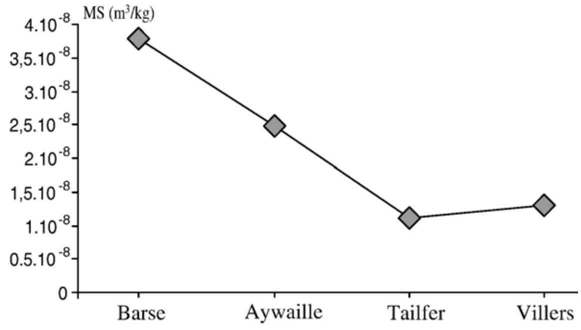

Fig. 7. Mean magnetic susceptibility values from the most proximal section on the right side of the graph (Barse) to the most distal section on the left side (Villers).

and this pedogenesis is related to low sea level. In our case, the increase of mean values in the lagoonal unit could also be explained by an increase of pedogenesis but we have seen that magnetic susceptibility of paleosoils is not higher than the values for subtidal facies. Some authors have also proposed that bacterial magnetite can be an important source of magnetic material in carbonates (Kirschvink and Lowenstam, 1979; McNeill et al., 1988). After these authors, this kind of bacterial magnetite is mainly observed in salt and freshwater peat, bogs, marshes and shallow water carbonates and produces very fine-grained magnetite. An increase of bacterial magnetite production related to widespread restricted environments can also increase magnetic susceptibility in our case. But several authors have shown that this fine-grained magnetite appears only at the surface of actual sediments and decrease strongly with depth because of a loss of the fine-grained component (Blakemore, 1975; Stolz et al., 1986; McNeill et al., 1988). In our lithified sediment, fine-grained magnetite was also probably destroyed by lithification and diagenesis.

We have seen also that magnetic susceptibility is directly related to microfacies. In our case, microfacies evolution is linked with eustatic changes and there are no strong lateral variations of microfacies and no significant differences of sedimentation rates between the different microfacies (higher sedimentation rate could dilute the MS signal). So the evolution of magnetic susceptibility with microfacies is probably directly related to the changes of sea level, but it is probably more valid to compare sections with similar sedimentation rate.

7. Conclusions

The architecture of the Belgian Middle Frasnian platform resembles other Frasnian carbonate platforms with stromatoporoid-dominated facies seen in China, Alberta, Iberia, Australia and so on (Burchette, 1981; Racki, 1992; Machel and Hunter, 1994; Méndez-Bedia et al., 1994; Weissenberger, 1994; Shen and Zhang, 1997; Pohler, 1998; Whalen et al., 2000; Wood, 2000; Chen et al., 2001a; Copper, 2002; George et al., 2002). Environments range from the outer zone (crinoidal facies) to stromatoporoid-dominated biostromes and to the lagoonal area in the inner zones (subtidal facies with *Amphipora* floatstone, algal packstone, intertidal mudstone and laminated peloidal packstone and paleosols). These facies are stacked in metre-scale shallowing-upward cycles and we have demonstrated that these fourth-order cycles are related to sea level variations. The larger scale sequential organization corresponds to transgressions and regressions, whose cycles are responsible for differentiating a lower open-marine biostrome dominated unit (biostromal unit) from an upper lagoonal unit.

In the study of the Frasnian carbonate platform of Belgium, magnetic susceptibility permits very precise correlations, much more precise than those obtained by conodont zonations (Gouwy and Bultynck, 2000).

The magnetic susceptibility evolution is related to the following parameters:

(a) A trend related to large-scale sequences (third order).
(b) A trend related to medium-scale sequences (fourth order) with decreasing values in transgressive phases, constant values in aggradational phases and increasing values in regressive phases. We have seen that these fourth-order sequences are related to sea level variations so the magnetic susceptibility data are also in relation with these eustatic movements.
(c) A facies dependent pattern, with the higher MS values for the proximal facies; this can be explained by the distance to the landmasses, which produce the lithogenic inputs which increase for proximal facies.
(d) And, finally, a decreasing trend from the most distal to the most proximal outcrops.

So, in regards with the fourth points developed above, we can clearly conclude that magnetic susceptibility signal, in the Belgian shallow water carbonate platform is mainly related to sea level variations. The influence of erosion is probably predominant.

The main advantages of magnetic susceptibility techniques are the following: the measurements can be performed very rapidly (150 samples in 1 day), the samples can be of different forms and densities, in powder or in blocks (smaller than 3 cm) and it is a non-destructive technique. The MS provides high resolution correlations for carbonate platforms and can bring information on facies evolution and sea level variations.

The main disadvantages are that MS is still a new technique and many questions remain (for example on the influence of diagenesis and on the minerals, which are carrying the signal and on their origin).

In consideration of these problems, it appears that MS can probably provide very high resolution correlations and information on sedimentological evolution. But it is probably necessary to couple MS with other techniques like sedimentological analysis and with biostratigraphy to provide chronologic control.

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