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Influence of sedimentary setting on the use of magnetic susceptibility: examples from the Devonian of Belgium

A.-C. DA SILVA, C. MABILLE and F. BOULVAIN
Pétrologie sédimentaire, B20, Université de Liège, Sart Tilman, 4000 Liège, Belgium (E-mail: ac.dasilva@ulg.ac.be)

ABSTRACT

Bulk magnetic susceptibility measurements on sedimentological samples from all geological periods have been used widely in the last two decades for correlations and as a proxy for sea-level variations. This paper explores the link between magnetic susceptibility, depositional setting and environmental parameters. These environmental parameters include distal–proximal transects, microfacies successions and fourth-order trends on different carbonate platform types (platform, ramp, carbonate mound or atoll) during different Devonian stages (Eifelian, Givetian and Frasnian). Average magnetic susceptibility values over a distal–proximal-trending facies succession vary markedly with depositional setting. On carbonate platforms, average magnetic susceptibility generally increases towards the top of shallowing-upward sequences. On a distal–proximal transect, average magnetic susceptibility is intermediate for the deepest facies, decreases for the reef belts and increases to a maximum in the back-reef zone. In ramps and atolls, magnetic susceptibility trends clearly differ; average magnetic susceptibility generally decreases towards the top of shallowing-upward sequences and is highest in the deepest facies. The strong relationship between magnetic susceptibility, facies and sequences implies a strong environmental influence. However, the different responses in the different platform types suggest that sea-level changes leading to variation in detrital input is not the only parameter controlling average magnetic susceptibility values. Other primary or secondary processes also probably influenced magnetic mineral distribution. Primary processes such as carbonate production and water agitation during deposition are probably key factors. When carbonate production is high, the proportion of magnetic minerals is diluted and the magnetic susceptibility signal decreases. High water agitation during deposition will also selectively remove magnetic minerals and will lead to low average magnetic susceptibility values. These parameters explain the lowest values observed on the reef platform, inner ramp and atoll crown, which are all in areas characterized by higher carbonate production and greater water agitation during deposition. The lowest values observed in the lagoon inside the atoll crown can be related to detrital isolation by the atoll crown. However, other parameters such as biogenic magnetite production or diagenesis can also influence the magnetic signal. Diagenesis can change magnetism by creating or destroying magnetic minerals. However, the influence of diagenesis probably is linked strongly to the primary facies (permeability, amount of clay or organic matter) and probably enhanced the primary signal. The complexity of the signal gives rise to correlation problems between different depositional settings. Thus, while magnetic susceptibility has the potential to be an important correlation tool, the results of this investigation indicate that it cannot be used without consideration of sedimentary processes and depositional environments and without strong biostratigraphical control.

Keywords Atoll, Belgium, carbonate mound, carbonate platform, Devonian, magnetic susceptibility, ramp.

INTRODUCTION

Quantitative magnetic susceptibility (MS) measurements have become widely used in the sedimentological study of Palaeozoic rocks. However, many questions still remain regarding the origin of MS variations. In the absence of strong tectonic controls, MS in marine strata is thought to be related mainly to sea-level variation and possibly climatic variation (Ellwood *et al.*, 2000). This relationship was proposed because of the strong link between MS and detrital components and the supposition that the detrital input generally is controlled by eustasy (Crick *et al.*, 2001). A sea-level fall increases the proportion of the continental area exposed, increases erosion and leads to higher MS values, whereas rising sea-level decreases MS (Crick *et al.*, 2001). Climatic variations influence MS through changes in rainfall (high rainfall increases erosion and MS), glacial–interglacial periods (glacial periods are related to glacier erosion and to marine regression and both effects increase MS) and pedogenesis (magnetic minerals form in palaeosols; Crick *et al.*, 2001). In addition to subaqueous delivery, different authors considered that magnetic minerals in carbonate sediments can also be supplied from aeolian suspension and atmospheric dust (Hladil, 2002; Hladil *et al.*, 2006). Furthermore, early and late diagenesis can be responsible for MS variations through mineralogical transformations, dissolution or authigenesis.

The relationship between MS and lithogenic inputs led to the use of MS for high-resolution, global correlation of marine sedimentary rocks (Crick *et al.*, 2001). This technique is called magnetosusceptibility event and cyclostratigraphy or the MSCE method (described in Crick *et al.*, 2001, 2002; Ellwood *et al.*, 2000, 2006). These correlations were assumed to be facies-independent and of better precision than biozones. The MSCE, as developed since the mid-1990s, covers important sedimentological and stratigraphic boundaries generally characterized by condensed carbonate strata which were subject to distinct sedimentological changes (Crick *et al.*, 2001, 2002). The application of MS on well-bedded Palaeozoic carbonate sediments (Hladil, 2002; da Silva & Boulvain, 2002, 2006; Hladil *et al.*, 2006; Mabille & Boulvain, 2007a,b, 2008) has shown the potential of this technique for correlating more continuously deposited sedimentary sequences. Furthermore, MS has been used to reconstruct sea-level variations (Devleeschouwer, 1999; Zhang *et al.*, 2000; Racki *et al.*, 2002; da Silva & Boulvain, 2002, 2003, 2006) and climatic variations (Curry *et al.*, 1995; Arai *et al.*, 1997).

The purpose of this paper is to apply the MS technique to different carbonate platform types (carbonate platform, mixed platform, ramp and carbonate mound or atoll) from different periods. These comparisons will help to: (i) identify the main sedimentological parameters controlling average MS values in each platform type; (ii) compare the relative influence of these parameters in each type of platform; and (iii) test the effectiveness of the technique in correlating between these different depositional settings. To this end, this paper will present a comparison of MS data and sedimentary environments. Mean MS values will be compared with microfacies, sequences and main lithofacies changes, in order to quantify the link between MS and sea-level variations. Although this paper is focused mainly on sedimentary processes related to MS variations, a review of diagenetic processes that could change the primary signal is also discussed.

GEOLOGICAL SETTING

Southern Belgium has well-exposed Palaeozoic limestones that are historical stratotypes for several stages of the Devonian. This setting provides a unique opportunity to test the MS technique on different carbonate depositional settings that have been studied intensively (palaeontology and stratigraphy).

This work integrates data from: (i) a Frasnian shallow-water carbonate platform; (ii) an Eifelian-Givetian mixed siliciclastic-carbonate platform; (iii) an Eifelian-Givetian ramp; and (iv) Frasnian carbonate mounds and atolls (Table 1). These sections have been the subject of detailed

Table 1. Studied sections.

No.	Outcrop	Facies model	Age	Samples	Th (m)
Platform					
1	Villers-le-Gambon	(a) Frasnian carbonate platform	Frasnian	242	105
2	Tailfer	(a) Frasnian carbonate platform	Frasnian	268	105
3	Aywaille	(a) Frasnian carbonate platform	Frasnian	261	120
4	Barse	(a) Frasnian carbonate platform	Frasnian	120	46
5	Couvin	(b) Eifelian–Givetian mixed platform	Eifelian	679	400
6	Villers-la-Tour	(b) Eifelian–Givetian mixed platform	Eifelian	139	53
7	Baileux	(b) Eifelian–Givetian mixed platform	Eifelian–Givetian	460	192
Ramp					
8	Couvinoise	(c) Eifelian–Givetian mixed ramp	Eifelian–Givetian	235	85
Atoll					
9	La Boverie	(d) Frasnian carbonate mound and atoll	Frasnian	195	440
10	Le Lion	(d) Frasnian carbonate mound and atoll	Frasnian	133	445
11	Moulin Bayot	(d) Frasnian carbonate mound and atoll	Frasnian	187	118
12	Lompret	(d) Frasnian carbonate mound and atoll	Frasnian	77	48
13	Nord	(d) Frasnian carbonate mound and atoll	Frasnian	375	375
Total:				3371	2447

No., section number corresponding to the exposure located on Fig. 1; Outcrop, names of the sections; Facies model (a), (b), (c) or (d), corresponding facies model; Age, age of the studied interval; Samples, number of samples used for sedimentological analysis and MS study; Th (m), thickness of the section in metres.

sedimentological studies (see below) which provide environmental interpretations and identification of sea-level variations in different palaeogeographical contexts.

During Eifelian to Late Frasnian, Southern Belgium was located close to the palaeoequator, under a tropical humid climate (Copper, 2002; Hladil *et al.*, 2006). These conditions favoured the expansion of well-developed reef carbonates. Eifelian to Frasnian carbonates and shales are exposed along the borders of the Dinant, Vesdre and Namur Synclinoria and in the Philippeville Anticlinorium in the northern part of the Rhenohercynian fold and thrust belt (Fig. 1A).

The most distal part of the platform (southern belt) is located along the southern border of the Dinant Synclinorium and the intermediate belt outcrop is located in the Philippeville Anticlinorium. The shallowest facies are exposed along the northern border of the Dinant Synclinorium (northern belt).

During the Eifelian (Fig. 1B) a mixed siliciclastic–carbonate ramp developed. In the southern belt, biostromes (Couvin Formation) were surrounded by sandy shales (Jemelle Formation) and overlain by the Hanonet Formation, a well-bedded carbonate unit. In the northern belt, the Eifelian consists of a littoral succession (Riviere Formation) overlying mostly red conglomerates (Burnot Formation) (Bultynck, 2006). At the boundary between the Eifelian and the Givetian, a large carbonate platform or ramp (Hanonet Formation) succeeded the mixed Eifelian deposits.

During the Middle Frasnian, an extensive carbonate platform developed in Belgium (Fig. 1B) (Boulvain *et al.*, 1999). In the more distal part, there is a succession of three carbonate mound and atoll packages separated by argillaceous intervals (Arche and La Boverie mounds in the Moulin Liénaux Formation and Lion mound in the Grands Breux Formation) (Boulvain & Coen-Aubert, 2006). In the intermediate part of the basin, argillaceous, crinoidal and biostromal facies (Pont-de-la-Folle and Philippeville Formations) are present and, in the proximal part of the basin, stromatoporoid biostromes and lagoonal facies developed (Lustin Formation).

The sections studied in this paper (Fig. 1) are Villers (Philippeville Formation), Tailfer, Aywaille and Barse (Lustin Formation) from Frasnian shallow-water and intermediate carbonate platform settings. Couvin, Villers-la-Tour (Couvin Formation) and Baileux (Hanonet Formation) represent the Eifelian–Givetian platform. La Couvinoise section (Hanonet Formation) corresponds to the Eifeilan–Givetian ramp setting. La Boverie (Arche, La Boverie and Lion Members), Le Lion (Grand Breux Formation), Moulin Bayot (Arche Member), Lompret (Grand Breux Formation) and Nord (Arche, La Boverie and Lion Members) sections are distal mound and atoll related deposits (Table 1).

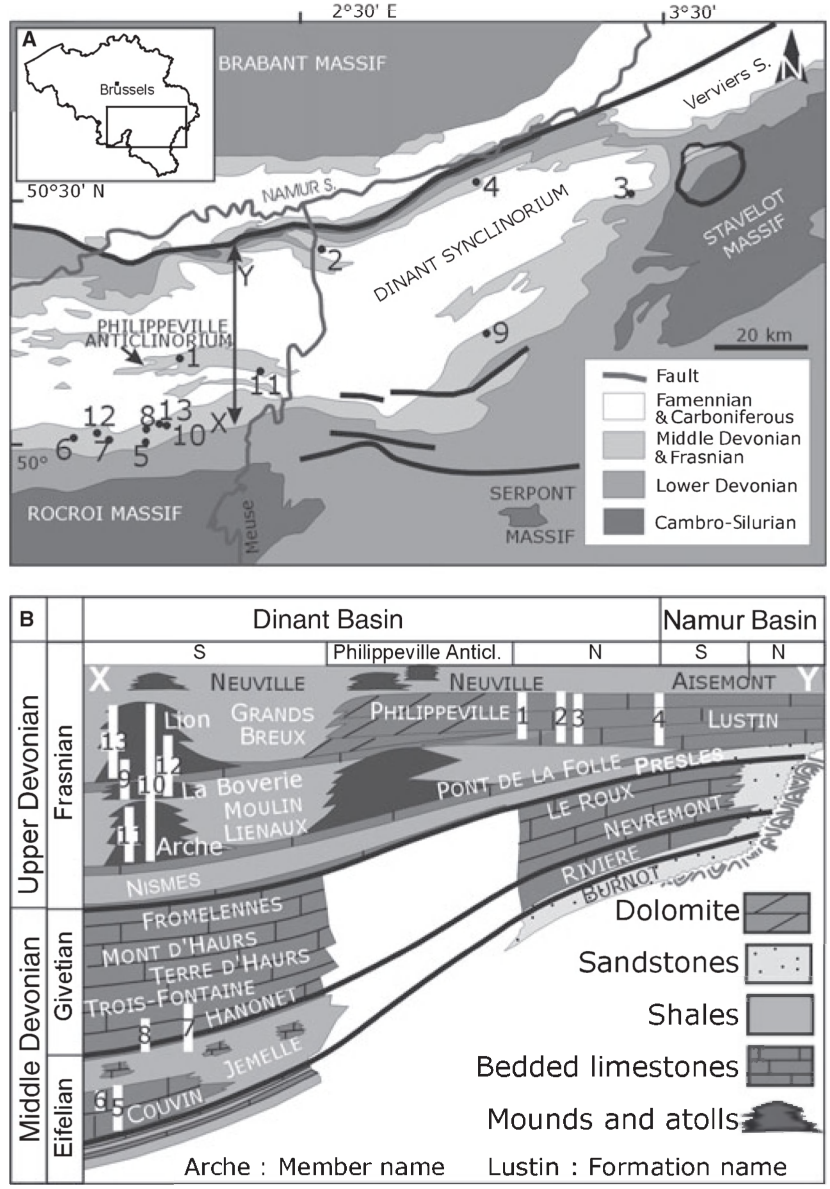

Fig. 1. Geological setting. (A) Geological map of Southern Belgium and location of the different studied sections. (B) North–south section through the Belgian Middle and Upper Devonian sedimentary basin, before Variscan deformation. An explanation of the numbered sections studied is given in Table 1.

TECHNIQUES

Microfacies analysis was based on the detailed bed-by-bed study of 13 outcrops and petrographic observations of more than 3300 thin sections. For each sample, the microfacies was determined and MS measurements were performed. Sample spacing was from a minimum of one sample every 2 or 3 m to in excess of two samples per metre (Table 1). No preferential selection was made when choosing the samples for MS measurements, except that large fossils were avoided.

Magnetic susceptibility measurements were performed on the KLY-2 Kappabridge (AGICO, Brno, Czech Republic) at the University of Lille and on the KLY-3S Kappabridge at the University of Liège. Magnetic susceptibility is expressed in $m^3 kg^{-1}$. Three measurements were made on each sample weighed to a precision of 0·01 g and the data represent an average of the three measurements.

SEDIMENTOLOGY

Sedimentological models were proposed for the Frasnian shallow-water platform (da Silva & Boulvain, 2002, 2003, 2004), Frasnian carbonate mounds and atolls (Humblet & Boulvain, 2000; Boulvain *et al.*, 2004; Boulvain, 2007) and the complete Frasnian platform (da Silva & Boulvain, 2004). Eifelian–Givetian platform sedimentology was described by Mabille & Boulvain (2007a,b, 2008). These facies models are summarized here in order to place the MS data in a proper sedimentological context.

Carbonate platform

The Frasnian platform depositional model (facies model a; Fig. 2A) incorporates a distal zone with

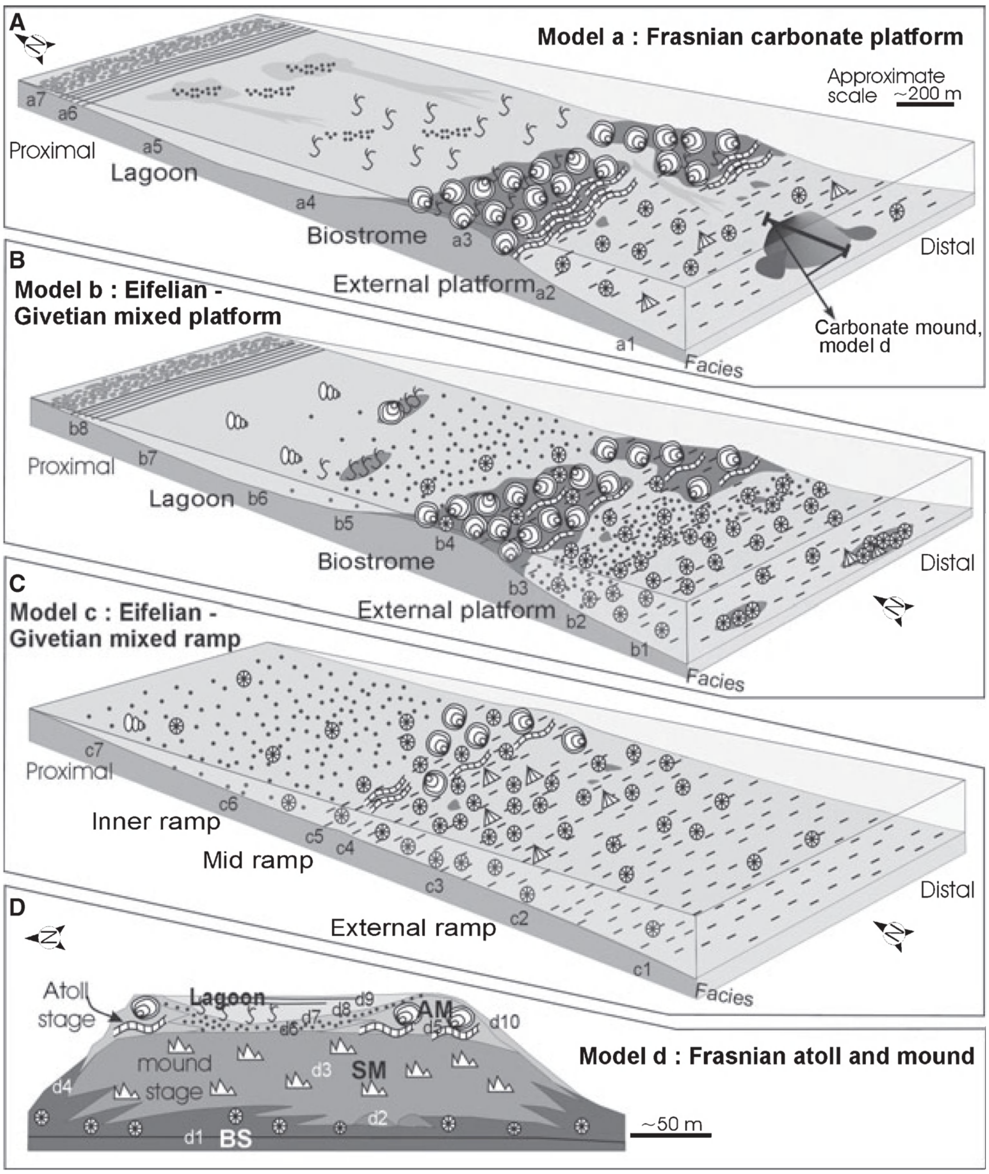

Fig. 2. Sedimentological models developed on the basis of the different studied sections. (A) Model a: Frasnian carbonate platform (a1) dark crinoidal argillaceous beds with sponge spicules; (a2) dark crinoidal argillaceous beds; (a3) biostromes with stromatoporoids; (a4) floatstone with *Amphipora*; (a5) peloidal and algal wackestones and packstones; (a6) mudstones and stromatolites; and (a7) palaeosols. (B) Model b: Eifelian and Eifelian–Givetian boundary mixed platform (b1) argillaceous wackestone with crinoids; (b2) argillaceous packstone with crinoids; (b3) crinoidal and peloidal grainstone; (b4) biostrome with stromatopores; (b5) peloidal grainstone and packstone; (b6) floatstone–packstone with ostracods and gastropods; (b7) floatstone with branching corals; and (b8) laminated peloidal grainstone. (C) Model c: Eifelian–Givetian mixed ramp (c1) argillaceous mudstone with crinoids; (c2) argillaceous wackestone with crinoids; (c3) argillaceous packstone with crinoids; (c4) rudstone with tabulate corals; (c5) coverstone with laminar stromatoporoids; (c6) packstone–grainstone with peloids; and (c7) grainstone with peloids. (D) Model d: Frasnian carbonate atoll and mound. Basinal facies (BS): (d1) basinal microbioclastic packstone–wackestone; skeletal mound (SM): (d2) red stromatactis wackestone; (d3) red stromatactis packstone; (d4) reworking of skeletal mound (flank); algal mound (AM): (d5) coral and peloid rudstone; (d6) algal boundstone; lagoon: (d7) floatstone with dendroid stromatoporoids; (d8) loferites; (d9) bioturbated wackestone, (d10) reworking of lagoonal deposits. Legend is on Fig. 3C.

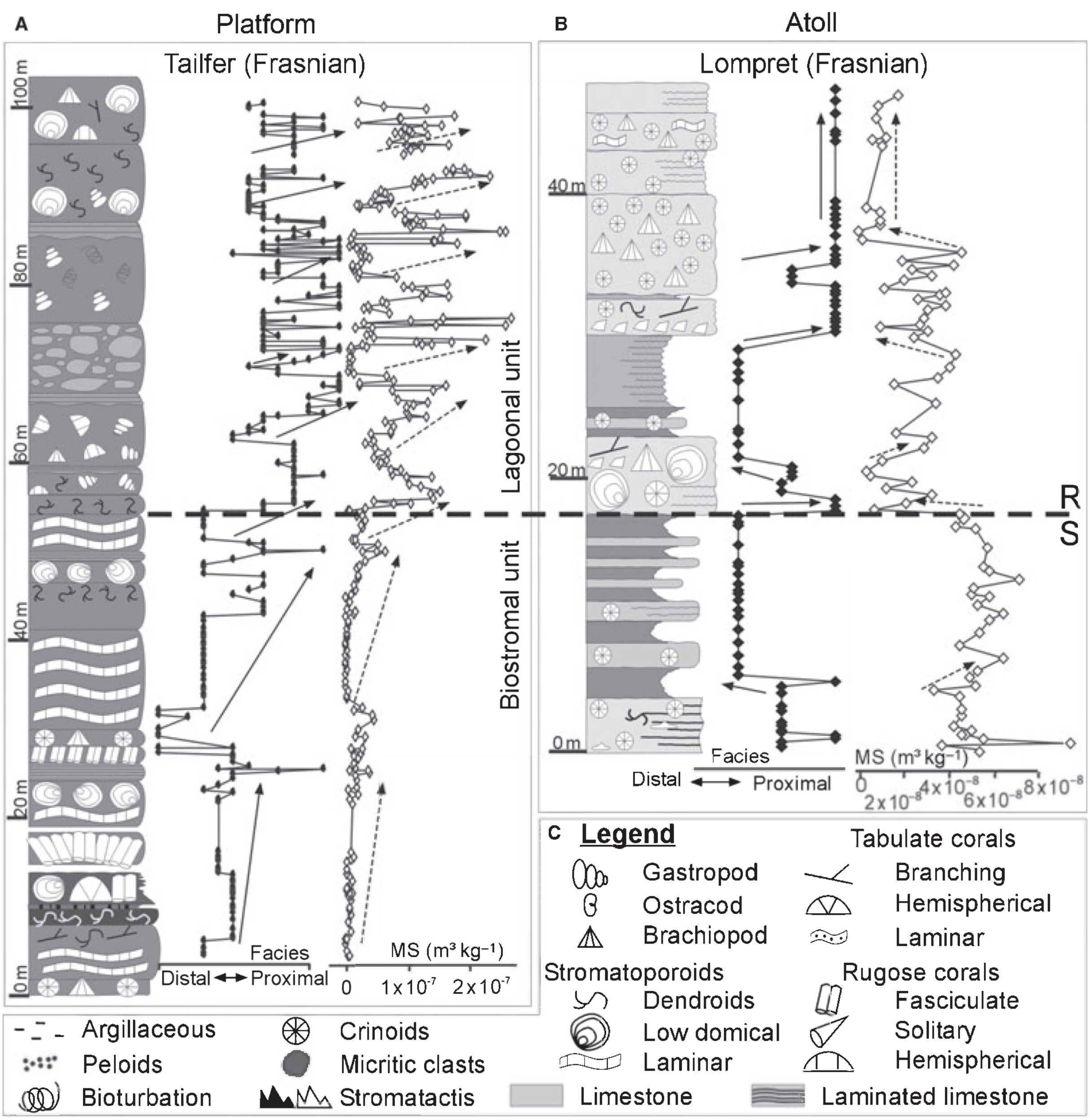

Fig. 3. Magnetic susceptibility evolution compared with environmental variations through time (distal to proximal) based on microfacies change in the platform and atoll. Magnetic susceptibility trends are underlined by dotted arrows and facies trends by black arrows. (A) Tailfer section, Frasnian carbonate platform. (B) Lompret, Frasnian carbonate atoll and mound. This figure shows that for the carbonate platform, MS is related directly to facies trends and sequences, with an MS increase during shallowing-upward trends. RS corresponds to the regressive surface. (C) Legend for Figs 2, 3 and 4. Stromatoporoid classification comes from Kershaw (1998).

dark crinoidal beds and argillaceous intervals (facies a1 to a2); the biostromal zone was built mainly by stromatoporoids (facies a3) and the back-reef or lagoonal zone is characterized by floatstones–wackestones to packstones–grainstones with branching stromatoporoids (facies a4, subtidal zone), calcareous algae and peloids (facies a5, subtidal zone), mudstone and stromatolites (facies a6, subtidal to intertidal lagoon) and palaeosols (facies a7, supratidal). All Frasnian platform sections can be divided into two units which are built up by shallowing-upward sequences (Fig. 3). The first unit (lower 50 m, biostromal unit) presents the stacking of sequences made by distal or biostromal deposits (facies a1 to a3) followed by lagoonal deposits (facies a4 to a6). The second unit (upper 50 m, lagoonal unit) is dominated by lagoonal deposits

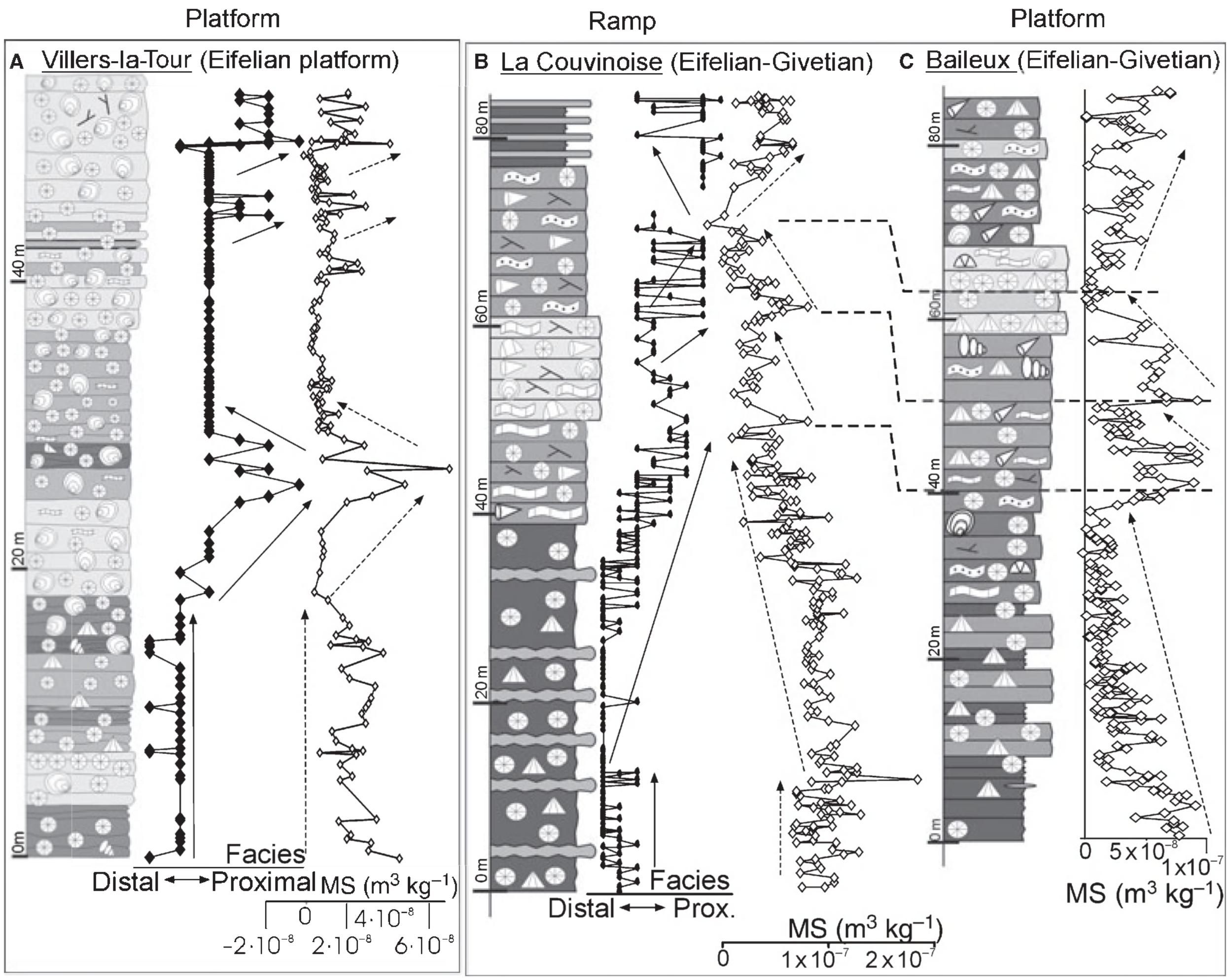

Fig. 4. Magnetic susceptibility evolution compared with environmental variations through time (distal to proximal) based on microfacies change between platform and ramp. Magnetic susceptibility trends are highlighted by dotted arrows and facies trends by black arrows. (A) Villers-la-Tour section, Eifelian mixed platform. (B) La Couvinoise section, Eifelian-Givetian mixed ramp. (C) Baileux, Eifelian-Givetian distal platform. For the carbonate shallow-water platform (Fig. 4A), MS is related directly to facies trends and sequences, with an MS increase during shallowing-upward trends. For the mixed ramp (B) and distal platform (C) mean MS increases during transgressive trends and decreases during shallowing-upward trends. This parallel evolution allows relatively good correlations (dotted lines). Legend is on Fig. 3C.

(facies a4 to a7) where sequences start with subtidal lagoonal deposits (a4 to a5) and end with intertidal (a6) to supratidal (a7) deposits.

The Eifelian–Givetian platform differs from the Frasnian platform mainly in the higher detrital fraction (mixed platform), more frequent occurrence of grainstones (indicating greater water agitation during deposition) and shows less well-developed sequences (but some larger scale sequences are still observed; see Villers-la-Tour section; Fig. 4A). Two successive platforms developed, first in the lower part of the Eifelian (Couvin and Villers-la-Tour sections) and later at the boundary between the Eifelian and the Givetian (Baileux section). The two platforms show similar deposition profiles and are represented by a single platform model (model b; Fig. 2B). In the distal zone, argillaceous packstones and wackestones with crinoids developed (facies b1 and b2), followed by crinoidal and peloidal grainstones (facies b3). The biostromal zone is composed mainly of stromatoporoids (facies b4). In the internal zone, at the contact with the biostromes, water agitation was still high and favoured deposition of peloidal grainstones and packstones (facies b5). In the subtidal internal zone, wackestones, floatstones and packstones with ostracods, gastropods and branching corals (facies b6 and b7) were deposited, whereas in the intertidal zone agitation increased, leading to laminated peloidal grainstones (facies b8).

Mixed carbonate ramp

The Eifelian–Givetian mixed carbonate ramp (model c; Fig. 2C), studied in the La Couvinoise section, can be subdivided into the outer ramp, mid-ramp and inner ramp (ramp classification after Burchette & Wright, 1992). The outer ramp succession ranges from argillaceous mudstones to wackestones and packstones with crinoids and brachiopods (facies c1 to c3). The mid-ramp is composed of rudstones with debris of stromatoporoids and tabulate and rugose corals (facies c4 and c5). The inner ramp shows packstones and grainstones with peloids (facies c6 and c7). Some prograding, aggrading and retrograding facies stacking patterns are observed (see La Couvinoise section; Fig. 4B).

Carbonate atoll

The deepest facies observed in the mounds (model d; Fig. 2D) correspond to a microbioclastic packstone and wackestone (d1, basinal facies, BS) followed by mud or skeletal mound facies characterized by red stromatactis coral and ammonoid wackestone or floatstone (SM, facies d2 to d4). These facies were developed below the photic zone. The first occurrence of green algae occurred in algal and microbial mound facies (AM), corresponding to rudstone with corals and peloids (d5) and algal–microbial boundstone (d6). These facies developed in the photic zone, close to the fair-weather wave base. Lagoonal deposits are also observed, with floatstone with dendroid stromatoporoids (d7); fenestral limestone (d8); and bioturbated wackestone (d9). Reworking deposits are also observed, characterized by grainstone, packstone and rudstones with bioclasts and lithoclasts (d10).

Development of the mound is related closely to sea-level changes: reef initiation occurred during transgression with development of the deepest facies and flank deposits (d1 to d4; Fig. 2D). A subsequent fall in sea-level restricted reef growth to downslope locations and led to the development of a circular reef margin (atoll 'corona') during the following transgressive stage (algal and microbial mound facies, AM, d5 and d6). Therefore, the occurrence of relatively restricted facies (lagoon) inside this corona is possibly the result of a balance between sea-level rise and reef growth (d7 to d9). During the major regression that caused emergence of the top of the reef and lateral displacement of facies downslope some flank deposits developed, corresponding to sediment reworking at the top of the mounds (d10). The main regression which exposed the top of the Lion mound corresponds to the boundary between the biostromal and lagoonal units on the Frasnian platform (Fig. 3).

MAGNETIC SUSCEPTIBILITY RESULTS

Carbonate platform

Magnetic susceptibility evolution is similar in all the Frasnian platform sections (see the example of Tailfer section, Fig. 3A). The lower part of the section (biostromal unit) has very low (close to $0\ m^3\ kg^{-1}$) MS values. The upper part of the section (lagoonal unit) presents high average MS values (mean of $6{\cdot}62 \times 10^{-8}\ kg\ m^{-3}$ for Tailfer section). The shallow-water carbonate platform in the Tailfer section shows a close correspondence between facies variations and average MS values (Fig. 3A). Generally, in shallowing-upward sequences (black arrows) average MS increases towards the top. Average MS therefore is related to facies successions and fourth-order sequences and increases at the main regressive surface (da Silva & Boulvain, 2006).

The Eifelian platform (see Villers-la-Tour section; Fig. 4A) also presents a close correspondence between facies evolution and MS, with increasing MS towards the top of shallowing-upward sequences. Graphs of mean MS values for each microfacies (Fig. 5) present a similar trend for the Frasnian (facies model a; Fig. 5A) and for the Eifelian–Givetian (facies model b; Fig. 5B; see also synthesis of values on Table 2). Mean MS values for distal deposits decrease from the deepest facies to the biostrome. Mean MS values for lagoonal deposits increase from the biostrome to the shallower facies with the exception of the shallowest facies.

Mixed carbonate ramp

Comparison of MS and microfacies evolution curves for La Couvinoise Eifelian–Givetian ramp section (Fig. 4B) shows an inverse relationship. A shallowing-upward trend generally corresponds to a decrease of average MS values. The general evolution of mean MS with microfacies (facies model c; Fig. 5C, Table 2) corresponds to a decrease in MS from the outer to the inner ramp.

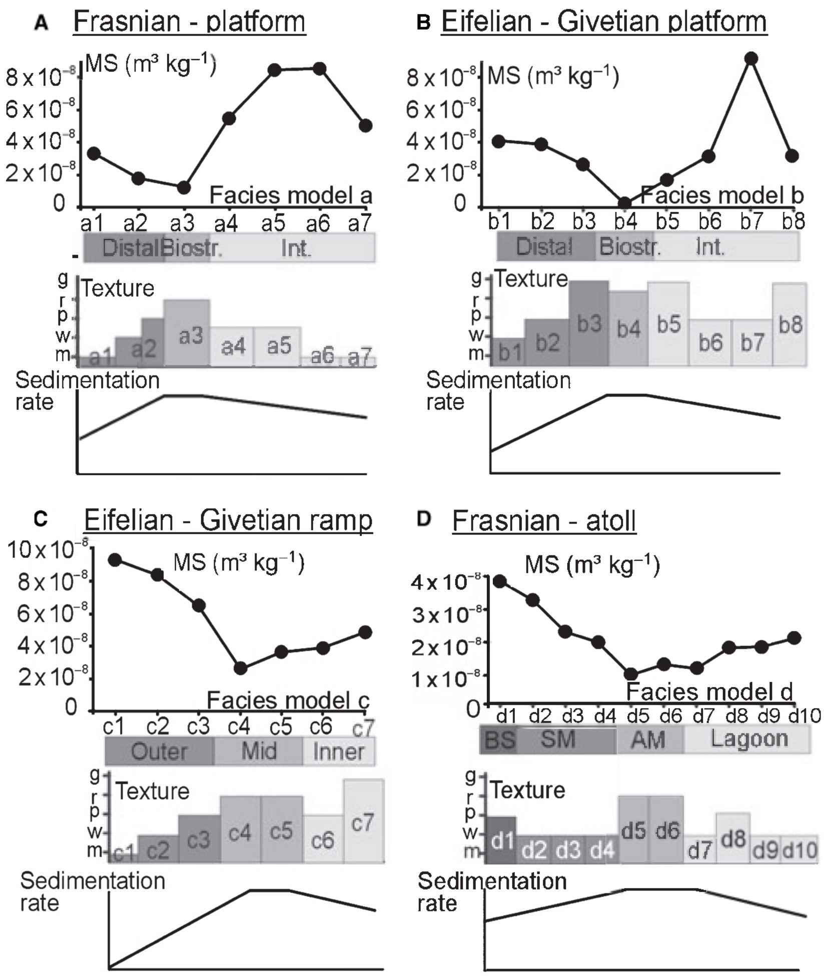

Fig. 5. Mean MS values on relative proximity transects with corresponding textures and sedimentation rates. (A) Frasnian carbonate platform, facies model a. (B) Eifelian and Givetian mixed platform, facies model b. (C) Eifelian–Givetian mixed ramp, facies model c. (D) Frasnian carbonate mound and atoll, facies model d. Textures are ordered from lower to higher water energy during deposition: m, mudstone; w, wackestone–floatstone; p, packstone; r, rudstone; g, grainstone and boundstone. Abbreviations are: Distal, distal facies; Biostr., biostromal facies; Int., internal facies; Outer, outer ramp; Mid, mid-ramp; Inner, inner ramp; BS, basinal and flank facies; SM, mud or skeletal mound facies; AM, algal and microbial mound facies; Lagoon, lagoonal facies inside the crown. For facies explanations, see legend of Fig. 3C or text in *Sedimentology* section. Sedimentation rates correspond to a compilation from literature data (Reitner & Neuweiller, 1995; Yamano *et al.*, 2002; Quiquerez *et al.*, 2004; McNeill, 2005).

Table 2. Mean MS values for the most distal, intermediate and proximal facies for each depositional profile (platform, ramp and atoll).

Platform		Ramp		Mound and atoll	
Facies	MS (m^3 kg^{-1})	Facies	MS (m^3 kg^{-1})	Facies	MS (m^3 kg^{-1})
Deepest		*Outer ramp*		*Deepest mound*	
a1	$3{\cdot}3 \times 10^{-8}$	c1	$9{\cdot}3 \times 10^{-8}$	d1	$3{\cdot}5 \times 10^{-8}$
b1	$4{\cdot}1 \times 10^{-8}$				
Biostrome		*Mid ramp*		*Algal mound*	
a3	$1{\cdot}2 \times 10^{-8}$	c4	$2{\cdot}6 \times 10^{-8}$	d5	1×10^{-8}
b4	$2{\cdot}1 \times 10^{-8}$				
Lagoon		*Inner ramp*		*Lagoon*	
a6	$8{\cdot}6 \times 10^{-8}$	c7	$4{\cdot}8 \times 10^{-8}$	d10	$1{\cdot}8 \times 10^{-8}$
b7	$9{\cdot}3 \times 10^{-8}$				

For facies number legend, see section *Sedimentology*.

Furthermore, the mid-ramp typically has slightly lower values than the inner ramp. In this mixed carbonate ramp example, average MS evolution is opposite to the carbonate platform trend, with MS decreasing towards the top of shallowing-upward sequences.

Carbonate atoll

When comparing average MS with the main atoll microfacies (facies model d; Fig. 5D, Table 2), the deepest facies (BS, facies d1), mud or skeletal mound facies (SM, facies d2 to d4) have the highest values, decreasing from facies d1 to d4. Algal and microbial mound facies (AM, facies d5 and d6) and lagoonal deposits with branching stromatoporoids (facies d7) have lower values. The shallower lagoonal deposits (facies d8 and d9) and the facies resulting from dismantling of the mound (facies d10) also have relatively low intermediate values. The average MS trend in the carbonate atolls (Fig. 3B) is relatively similar to that observed in the carbonate ramps and is the reverse of the one observed in the carbonate platforms.

INTERPRETATIONS

This study documents that the record of average MS along a proximal–distal profile differs depending on the platform type. Mean MS values increase towards the most proximal facies on carbonate platforms, whereas they increase towards the most distal facies of atolls and mixed ramps. These divergent trends are problematic in terms of using MS for correlation. In this section, a review of the primary (or environmental) and secondary (or diagenetic) processes influencing the magnetic mineral content will be presented. The possible origin of magnetic minerals will be discussed in the light of the results described above.

Primary origin

Variation in terrigenous input is often explained by sea-level oscillations but Crick *et al.* (2001) also considered local tectonic variations and climatic changes as potential factors influencing MS. In the cases studied here, Eifelian–Givetian and Frasnian, the global tectonic and climatic settings remain relatively similar, with no strong tectonic activities in the area and a stable tropical climate (Frakes *et al.*, 1992; Kiessling *et al.*, 2003). The Frasnian carbonate platform examples are lateral time equivalents of the carbonate mounds; however, their MS trends are opposite. Therefore, in this instance, climatic and tectonic changes probably do not have a strong impact on MS.

Sources other than terrigenous input are also proposed to explain MS variations in some settings. Volcanic activity (Crick *et al.*, 2001), hydrothermal vents (Borradaile & Lagroix, 2000) and bolide impacts (Ellwood *et al.*, 2003) can also increase MS (increase of magnetic minerals in suspension) but their impact is considered to be relatively local and instantaneous, with minimal influence on the global signal (Crick *et al.*, 2001). Pedogenetic minerals are also often considered as MS carriers (Tite & Linington, 1975). In the shallow-water Frasnian platform, numerous palaeosol levels are observed but they have a lower mean MS when compared to the other associated lagoonal facies (facies a7; Fig. 5A). Thus it seems that, in this case, pedogenic influence on magnetic mineral distribution is minimal.

Magnetite of biogenic origin is also well-known (Kirschvink & Chang, 1984; Stolz *et al.*, 1986; McNeill *et al.*, 1988), mainly in Recent sediments. Bacterial magnetite is observed mainly in shallow-water and marsh carbonates. Depending on the geochemical regime, this fine-grained magnetite can occur near the surface of modern sediments decreasing strongly with depth because of the loss of the fine-grained component (Stolz *et al.*, 1986; McNeill *et al.*, 1988). In the Devonian sediments of this investigation, diagenetic loss of this kind was probable but further studies are needed to confirm this assessment.

General theory suggests that the main MS controlling parameter is lithogenic input (Ellwood *et al.*, 2000) through riverine or aeolian sources (Hladil, 2002; Hladil *et al.*, 2006). If this is the case, a normal trend in all the models would be increasing average MS from the more distal to the more proximal facies according to the vicinity of landmasses. In fact, this is only the case for the shallower part of carbonate platforms. This contradiction can be explained by carbonate sedimentation which is a complex system, with interactions between hydrodynamic, biological and chemical phenomena. Hydrodynamics (mainly water agitation), sedimentation rate and/or carbonate production probably are key factors controlling magnetic mineral distribution. These two primary parameters can be considered a significant influence on the mean MS trends observed in different platform types: (i) carbonate production can dilute the proportion of magnetic minerals; and (ii) water agitation during sedimentation can prevent magnetic particles from settling.

To test this relationship, the degree of water agitation and sedimentation rate need to be reconstructed. The texture and preservation state of fossils are direct links to water agitation during deposition (increasing water agitation from mudstone to grainstone; Fig. 5). The sediment production rate varies in different areas of the platform and for different carbonate systems (synthesis of carbonate production and water agitation in Fig. 5). In carbonate platforms and ramps, the main trend is a decrease in the carbonate productivity with increasing depth, with maximum carbonate production in the reef zone or in the mid ramp (Quiquerez *et al.*, 2004; McNeill, 2005). In the carbonate mound proper, the atoll crown represents the maximum production rate and the sedimentation rate is slightly lower in the lagoon (Yamano *et al.*, 2002). However, production rate profiles are a simplified view and carbonate production will vary depending on different parameters (such as subsidence, depositional setting, sediment producers and oceanographic influences).

Of all the profiles (platform, Fig. 5A and B; ramp, Fig. 5C; and atoll, Fig. 5D), the MS values are lowest in the biostromal facies, mid-ramp and atoll crown, which are characterized by the highest carbonate productivity and water agitation during deposition. In the ramp profile, MS is lower in the inner ramp than in the outer ramp and this could be related to high water agitation during deposition in the inner ramp, preventing the deposition of magnetic minerals in this area. In the atoll, MS is also lower in the lagoon than in the mound and this could be related to the protection of the atoll (possibly associated with higher sedimentation rate). This model is relatively simple and can explain the values obtained along the different platform profiles but the supply of MS minerals can be very complex and affected by many syn-depositional and post-depositional parameters.

Secondary origin

Different diagenetic processes are able to modify MS after deposition by creating (authigenesis, McCabe & Elmore, 1989; Zegers *et al.*, 2003) or destroying magnetic minerals (Rochette, 1987). Recognition of depositional or early post-depositional remanent magnetism on different areas of a Recent platform can highlight the influence of depositional facies and early diagenesis on the preservation or destruction of magnetic minerals.

In basinal sediments from the Bahamas (ODP leg 166), MS values alternate between weak and diamagnetic values (McNeill & Kislak, 2000) and along the slope of the Queensland Plateau (Australia, ODP leg 133) MS intensity decreases with depth of sediments (McNeill *et al.*, 1993). Carbonate magnetization and preservation are considered highly variable and probably are a function of regional platform geohistory and diagenesis (McNeill, 1993). In shallow-water carbonate sediments, primary MS is related mainly to bacterial magnetite (Bahamas; McNeill *et al.*, 1988) and its preservation decreases with depth of sediments (Queensland plateau; McNeill, 1993). Dolomitization and transformation of aragonite and high magnesium calcite into low magnesium calcite have no detectable effects on magnetic polarities (McNeill *et al.*, 1988; McNeill & Kirschvink, 1993). However, magnetization acquisition and destruction probably are related mainly to the original facies and their original petrophysical properties, which control subsequent diagenesis and the partial oxidation of magnetite into maghaemite (McNeill, 1997).

As observed in Fig. 5, MS is related partly to sedimentary textures (lowest MS values for grainstones, packstones and rudstones). As previously stated, this relationship can be explained by water agitation during sedimentation affecting magnetic mineral deposition but it can also be explained by enhanced diagenesis and dissolution in these highly permeable facies (compared with mudstone and wackestone).

The influence of late diagenesis has been assessed in some studies of Palaeozoic sediments. Late remagnetization or demagnetization can be related to heating or to various chemical influences, mainly those connected with fluid circulation. Magnetite formation may be linked to the special chemical conditions associated with hydrocarbon migration (Elmore *et al.*, 1987; Machel & Burton, 1991). Magnetite replacement of pyrite (Brothers *et al.*, 1996) in organic-rich carbonate sediments was also affected by organic matter maturation. The MS can also increase in relation to burial migration fluids (Schneider *et al.*, 2004) or dolomitization (Bityukova *et al.*, 1998; Shogenova, 1999). The Devonian sediments of this investigation do not seem to be particularly rich in organic matter, no hydrocarbon migration was described and the limestones are not affected by dolomitization.

Magnetite formation can be linked to the transformation of smectite to illite (between 2 and 4 km depth) and the associated iron migration (Jackson *et al.*, 1988; Katz *et al.*, 1998). Zegers *et al.* (2003) identified such processes in some dark clay-rich Givetian limestones from Belgium. Following this previous work, it is proposed that iron released during smectite–illite conversion will partly remain *in situ* in the clay and magnetite will crystallize *in situ* within the clay aggregate, enhancing the primary signal generated by lithogenic inputs.

Diagenetic destruction of MS can be related to the transformation of a strongly magnetic mineral into a lesser magnetic mineral (oxidation of magnetite to maghaemite, Henshaw & Merril, 1980 or transformation of magnetite into pyrite and pyrrhotite, Rochette, 1987) or by dissolution of magnetite (associated with pyritization of organic rich sediments, after Canfield & Berner, 1987). Rochette (1987) showed that the breakdown of magnetite and its transformation into less magnetic minerals, like pyrite and pyrrhotite, corresponds to the anchizone–epizone boundary. In Belgium, metamorphism does not reach this boundary (temperature between 120 and 240 °C, Helsen, 1992; Fielitz & Mansy, 1999).

In this case, the strong relationship between MS and different environmental parameters suggests that the MS signal is probably related to primary factors (lithogenic inputs, hydrodynamic effect and sedimentation rate). However, a diagenetic mechanism enhancing or decreasing the MS primary signal can not be excluded. As previously stated, diagenesis is influenced commonly by the primary facies (e.g. the amount of clay for smectite to illite transformation, petrophysical properties (mainly permeability), the amount of organic matter, sediment oxidation, etc). A complete study of the magnetic minerals and diagenetic history is therefore necessary.

IMPLICATIONS FOR USE OF MAGNETIC SUSCEPTIBILITY

The MS is probably highly influenced by the depositional profile, lithogenic input, sedimentation rate and water agitation during deposition and is possibly affected by diagenesis. These various influences lead to different MS trends along the depositional profile of a carbonate platform, ramp, mound or atoll. To assess the use of MS as a correlative tool, three scenarios are presented: (i) a comparison of results from the same kind of depositional setting; (ii) a comparison of different depositional settings (Frasnian carbonate mounds versus carbonate platform); and (iii) Eifelian–Givetian mixed ramp compared with time-equivalent distal platform deposits.

(1) It was possible to compare different sections, 50 to 200 km apart, that represent the same kind of depositional setting (Frasnian shallow-water platform or carbonate mounds). The MS provides good fourth-order correlation between the sections of the Frasnian shallow-water carbonate platform (da Silva & Boulvain, 2006) and also offers reasonable correlations between the Frasnian mounds (da Silva *et al.*, in press).

(2) The Frasnian carbonate platform sediments and atolls are lateral time-equivalents. Because mean MS variation with facies for the carbonate platform is opposite to that which is recorded for the carbonate mounds, a comparison of the Tailfer section from the shallow-water carbonate platform (da Silva & Boulvain, 2002, 2006) with the Lompret section (Humblet & Boulvain, 2000) from the carbonate mound area is revealing (Fig. 3). In Tailfer, after development of biostromal limestones, a strong regression caused erosion and successive development of lagoonal deposits (da Silva & Boulvain, 2002, 2006). The regression is identified on Fig. 3 by the dotted line and is located 55 m from the base of the Tailfer section. It corresponds to the transition between the biostromal and lagoonal unit. This transition is marked by a major increase in MS above the regressive surface (shift of MS values from 2×10^{-8} to $6{\cdot}6 \times 10^{-8}$ m^3 kg^{-1}). In Lompret, the first unit corresponds to distal deposits (facies a1) that are followed after the main regression (dotted line; Fig. 3) by different levels of reworked material (rudstones, floatstones) and related to re-deposition of eroded material (Humblet & Boulvain, 2000). This transition is marked here by a distinct decrease in MS (MS values from $5{\cdot}2 \times 10^{-8}$ to $2{\cdot}1 \times 10^{-8}$ m^3 kg^{-1}). In this case, the main sea-level variation is recorded in the MS signal for similar depositional settings but in an opposite way.

(3) The Eifelian–Givetian carbonate ramp shows a decreasing mean MS from the more distal to the more proximal facies (example of the La Couvinoise section; Fig. 4B). This section is compared with the time-equivalent Baileux platform section, composed only of distal deposits. For the distal deposits the mean MS trend decreases in both cases from the more distal to the more proximal setting. Figure 4B and C presents a comparison of MS evolution for the La Couvinoise (Fig. 4B) and Baileux (Fig. 4C) sections and it appears that the main trends are rather similar and that, in this case, MS allows effective correlations (indicated by dotted lines).

CONCLUSIONS

This paper offers an important compilation of data on the relationship between magnetic susceptibility (MS), environmental parameters (proximal–distal transect, microfacies evolution trends and fourth-order sequences) and platform types (platform, ramp, atoll or mound) during different Devonian stages (Eifelian, Givetian and Frasnian).

Magnetic susceptibility evolution is different depending on the depositional setting:

1 The MS varies with temporal environmental changes: within carbonate platform deposits, MS increases towards the top of shallowing-upward sequences but, within ramp and atoll deposits, MS increases toward the top of transgressive trends.

2 The MS varies along a distal–proximal transect and this variation depends on the type of depositional profile. For carbonate platforms, mean MS is intermediate in the distal zone, minimum in the biostromes and maximum in the lagoonal area. For carbonate ramps, mean MS is maximum in the outer ramp and minimum in the mid ramp and inner ramp. During the development of the carbonate mounds, MS was relatively high and decreased with the development of the atoll corona and its enclosed lagoon.

These data show that MS is related closely to environmental variations. However, if MS is related only to lithogenic inputs, a normal MS distribution profile would show a decrease of MS in facies further from landmasses. To explain the observed opposite behaviour, it seems that magnetic mineral deposition probably is affected strongly by carbonate production (increased carbonate production dilutes MS) and by water agitation during deposition (high water agitation prevents the deposition of fine-grained magnetic particles). Diagenesis is probably also a factor acting on the MS signal but, as MS reflects trends related to environmental parameters, the diagenetic influence was probably also related to the main facies variations and enhanced the primary signal (through clay proportion, permeability, organic matter, etc.).

Magnetic susceptibility as a correlative method is a very simple, non-destructive technique, the measurements can be performed very fast and it can produce good correlations within similar depositional settings. However, the processes driving the MS signal are highly complex and variable. A strong sedimentological, diagenetic and palaeontological framework is needed, otherwise correlations between sections from different depositional settings can be problematic.

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