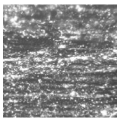
Sedimentology and magnetic susceptibility of Mississippian (Tournaisian) carbonate sections in Belgium

CAPUCINE BERTOLA, FRÉDÉRIC BOULVAIN, ANNE-CHRISTINE DA SILVA & EDDY POTY



Magnetic susceptibility (MS) and biostratigraphy have been used to correlate better the reference sections of the Belgian Tournaisian, the Rivage road and railway sections and the Gendron-Celles railway section. These 200 m thick time-equivalent sections are about sixty kilometres apart and belong to two different sedimentation areas: a shallow ramp setting for Rivage (Condroz Sedimentation Area) and a subsiding area for Gendron (Dinant Sedimentation Area). The sedimentological model shows that both sections are characterized by a carbonate-dominated sedimentation (crinoids-peloids-algae assemblages), interrupted by more argillaceous facies related to rapid sea-level rises (crinoids-brachiopods-bryozoans assemblages). Accommodation space was significantly higher in the DSA and allowed the development of Waulsortian buildups during the Ivorian. Variations of magnetic susceptibility (MS) seem to be related to fluctuations in detrital input and carbonate productivity. MS evolution with palaeogeography can be integrated in the previously published model for the Devonian ramp system: external ramp settings have low carbonate productivity, low water agitation and high MS, whereas more proximal environments are characterized by higher carbonate productivity, higher water agitation and lower MS. MS curves are in general agreements with the 3^{rd}-order sequence interpretation. Lowstand system tracts (LST) show the highest MS values while transgressive system tracts (TST) are characterized by decreasing values and highstand system tracts/falling stage system tracts (HST/FSST) by the lowest values. • Key words: magnetic susceptibility, Mississippian, limestone, facies, ramp, Belgium.

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Changes in magnetic susceptibility (MS) of sedimentary successions are considered to be related to sea level variations (Devleeschouwer 1999, Ellwood *et al.* 1999). This inferred relationship led to the proposal to use MS for high-resolution global correlation of marine sedimentary rocks (*e.g.* Crick *et al.* 1997). The major influence of sea level on the MS signal is related to the strong link between MS and detrital components and the assumption that the detrital input is generally controlled by eustasy (Crick *et al.* 2001). In this way, a sea-level fall increases the proportion of exposed continental area, increases erosion and leads to higher MS values, whereas rising sea level decreases MS (Crick *et al.* 2001). However, climatic variations influence MS through changes in rainfall (high rainfall increases erosion and MS), glacial–interglacial periods (glacial periods involve glacial erosion and marine regression and both effects increase MS) and pedogenesis (formation of magnetic minerals in soils: Crick *et al.* 2001).

In addition to subaqueous delivery, different authors considered that magnetic minerals in carbonate sediments could also be supplied from aeolian suspension and atmospheric dust (Hladil 2002; Hladil *et al.* 2006, 2010). Furthermore, early and late diagenesis can be responsible for MS variation through mineralogical transformations, dissolution or authigenesis (Rochette 1987, McCabe & Elmore 1989, Zegers *et al.* 2003).

A few studies proposed a link between MS and depositional environment (Borradaile *et al.* 1993, Da Silva & Boulvain 2006, Da Silva *et al.* 2009a, b). These studies presented different MS/depositional environment responses in different platform types, suggesting that sea-level changes leading to variation in detrital input are not the only parameter controlling average MS values. Other primary or secondary processes probably also influenced magnetic mineral distribution. Primary processes such as water agitation and carbonate production during deposition

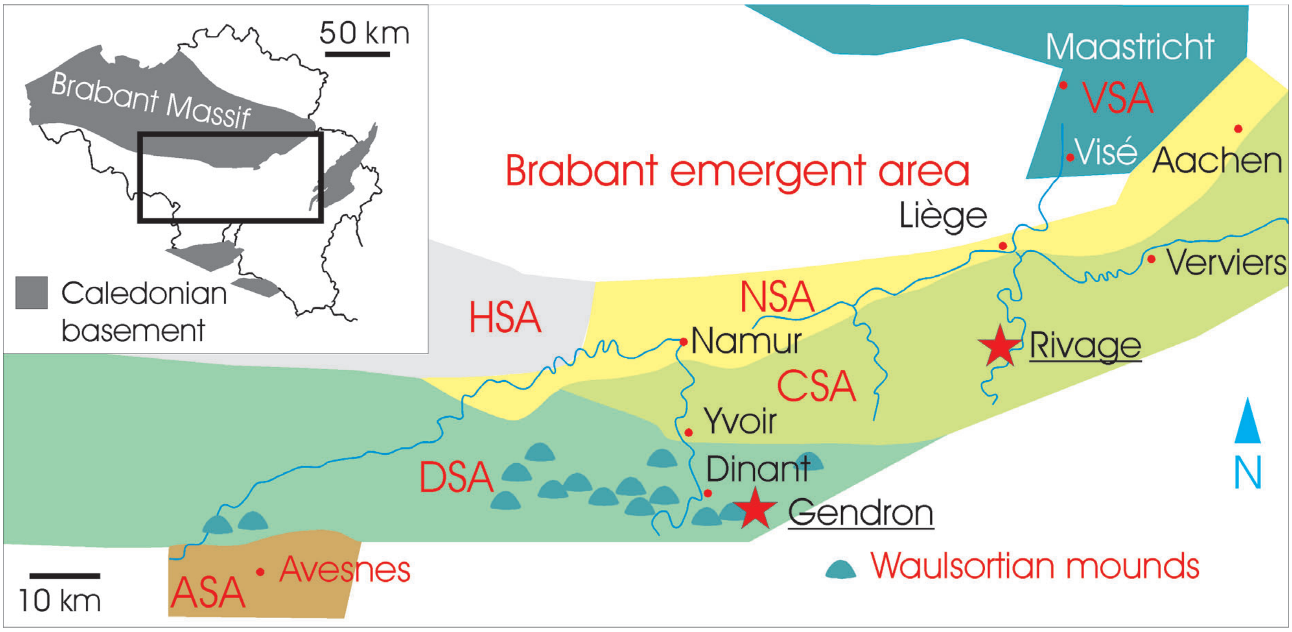

Figure 1. Sedimentation areas for the Tournaisian of Belgium, with location of the studied sections. Abbreviations: VSA – Visé Sedimentation Area; NSA – Namur Sedimentation Area; HAS – Hainaut Sedimentation Area; CSA – Condroz Sedimentation Area; DSA – Dinant Sedimentation Area; ASA – Avesnes Sedimentation Area. After Hance *et al.* (2001). Location of studied sections Gendron and Rivage indicated.

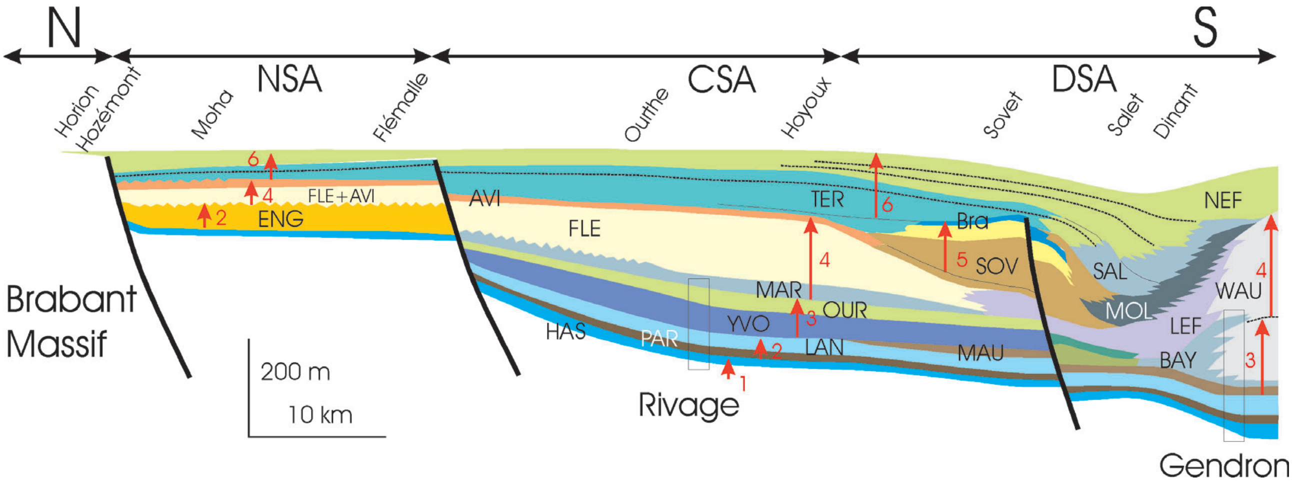

Figure 2. Schematic cross-section in the Tournaisian sedimentary basin, with sedimentary sequences (1–6) and location of the Rivage and Gendron sections. Abbreviations: HAS – Hastière Fm.; PAR – Pont d'Arcole Fm.; LAN – Landelies Fm.; MAU – Maurenne Fm.; YVO – Yvoir Fm.; OUR – Ourthe Fm.; MAR – Martinrive Fm.; BAY – Bayard Fm.; WAU – Waulsort Fm.; LEF – Leffe Fm. After Hance *et al.* (2001).

seem to be important factors (Da Silva *et al.* 2009b, Bábek *et al.* 2010).

MS studies on Tournaisian successions in the world are relatively uncommon, by comparison with general stratigraphic and sedimentological studies. Zhang *et al.* (2000) published a study comparing the MS evolution with sea level variations for Tournaisian platform limestones from the Guizhou province in China. A very detailed study of the MS evolution and its link with paleoenvironments by Bábek *et al.* (2010) focused on sections encompassing the Tournaisian-Viséan boundary in Ireland, England, Belgium and Germany.

The aim of this paper is to apply magnetic susceptibility studies to the thick Belgian Mississippian (Tournaisian) limestone successions. In the general context outlined above, the main goals of this paper are as follow: (1) to test the reliability of the correlations obtained with MS techniques on large scale successions in different settings; (2) to identify the link between MS, environmental parameters and sequence stratigraphy; and (3) to test the impact of parameters such as water agitation during deposition and carbonate production in a ramp setting, where these parameters have important impacts on the sedimentation.

Methods

The MS measurements were made on a KLY-3 Kappabridge device (*cf.* Da Silva & Boulvain 2006). Three measurements were made on each sample weighed with a precision of 0.01 g. The sampling interval for the MS curves is around 1 m. To identify some of the MS carriers, calcareous shale from the Pont d'Arcole Formation (Rivage section) was crushed, and treated with 0.1 M acetic acid.

Petrographic analysis comes from the detailed bed-by-bed study of outcrops and careful observation of 450 thin sections. Microfacies were defined according to textures, sedimentary structures and fossil assemblages. The textural classification used to characterise microfacies follows Dunham (1962). Microfacies were reported along a ramp profile with three main facies belts: outer ramp, mid ramp and inner ramp (Read 1985, Burchette & Wright 1992).

Geological setting

The Early Carboniferous of Southern Belgium belongs to the Rhenish Variscan fold and thrust belt (Fielitz & Mansy 1999). During the Early Carboniferous, the sedimentary context corresponds to a carbonate ramp, with a prominent North-South bathymetric gradient, the more proximal environments and the less complete successions developing northwards.

The Early Carboniferous sedimentation south of the London-Brabant Massif was related to an extensional regime. Common thickness variations of the deposits were the result of normal synsedimentary faulting (Poty 1997). This synsedimentary faulting was responsible for different accommodation rates and for lateral differentiation in sedimentation areas showing different lithostratigraphy and sedimentological evolution through time (Fig. 1) (Poty 1997). This work focuses on two sedimentation areas, the Condroz Sedimentation Area (CSA) and the Dinant Sedimentation Area (DSA) (Figs 1, 2).

The CSA is characterized by relatively proximal facies, interrupted eastwards by sedimentary hiatuses, but becoming more continuous towards the SW. The DSA (equivalent to the "Auge dinantaise", Paproth *et al.* 1983) records deeper and more continuous series, locally influenced by the development of Waulsortian mounds during the upper part of the Tournaisian (Lees *et al.* 1985, Lees 1997; Fig. 2).

The Early Carboniferous sedimentation in Belgium is also constrained by sea-level variations, recorded in 3rd order sequences, as proposed by Hance *et al.* (2001). These sequences are integrated in an overall transgressive cycle, covering progressively the shores of the London-Brabant Massif and dramatically shifting facies belts towards the North.

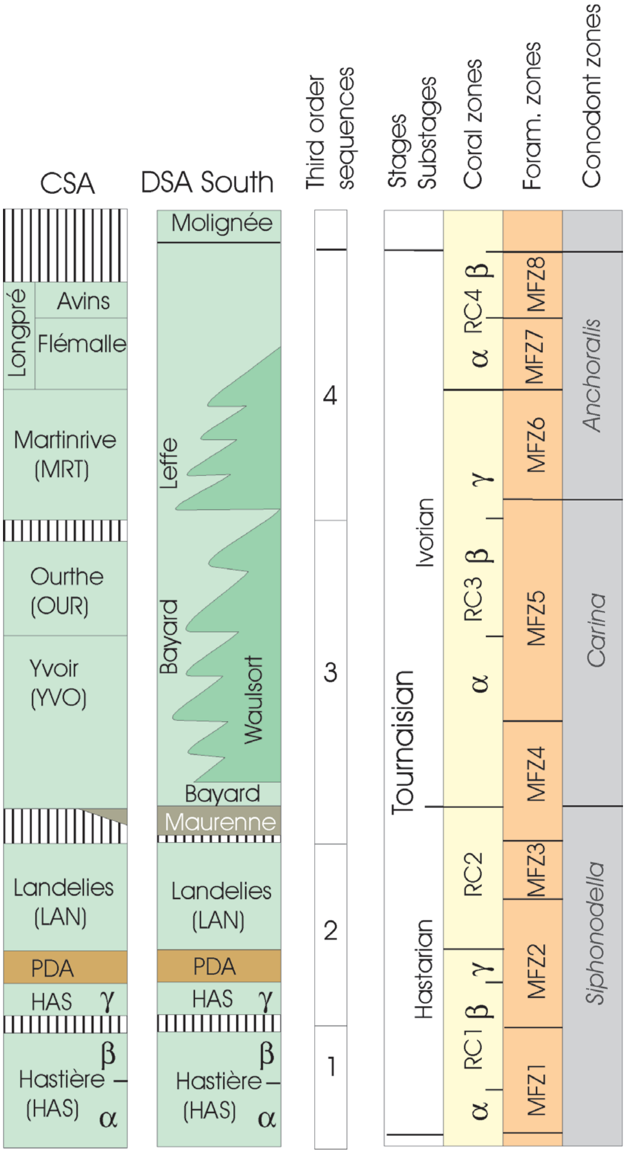

Figure 3. Lithostratigraphy, biostratigraphy and sequence stratigraphy of the DSA and CSA sedimentation areas. After Poty *et al.* (2006, 2011).

A complete bio- and lithostratigraphical scale for the Tournaisian-Viséan of Belgium was published by Paproth *et al.* (1983). Recent developments in biostratigraphy and application of sequence stratigraphy allowed Hance *et al.* (2001) and Poty *et al.* (2001, 2006, 2011) to propose an improved stratigraphic canvas for the Tournaisian of the DSA and CSA (Fig. 3). The base of the Carboniferous (Tournaisian) is defined at the first appearance of the conodont *Siphonodella sulcata*. As the taxon has not been discovered in Belgium, the base of the Tournaisian is still not precisely defined in the studied sections, but is possibly situated close to the base of the Hastière Formation.

Poty (1985) described four coral zones (RC1–RC4) in the Tournaisian. Foraminifera were first studied by Conil *et al.* (1977) and revised by Hance (*in* Poty *et al.* 2006).

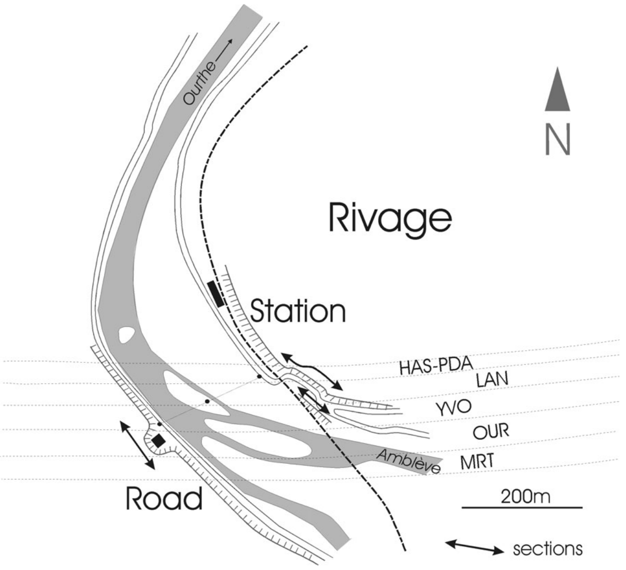

Figure 4. Location of the two parts of the Rivage section. Abbreviations: HAS – Hastière Fm.; PDA – Pont d'Arcole Fm.; YVO – Yvoir Fm.; OUR – Ourthe Fm.; MRT – Martinrive Fm.

This author defined eight foraminifer zones in the Tournaisian (MFZ1–MFZ8). Three conodont zones were recognized by Groessens (1975): *Siphonodella*, *Carina*, *Anchoralis* (Fig. 3).

Lithostratigraphic description of the Gendron and Rivage sections

In the Ardennes, Variscan tectonism affected the Devonian-Carboniferous platform and most sections are folded and faulted (see Fig. 5B). Two sections (Rivage and Gendron-Celles) were chosen on the basis of their outstanding outcrop quality and different palaeogeographic setting. One of the sections, Rivage, is a composite succession based on two outcrops correlated by the boundary between two lithostratigraphic units (Fig. 4), this boundary corresponding to a major facies change (transition from Landelies to Yvoir formations).

In the two areas (DSA and CSA), sedimentation is dominated by dark grey massive or stratified limestones, with some minor argillaceous beds or seams, and subordinate thicker shales or argillaceous limestone units. The CSA section encompasses the uppermost Famennian Comblain-au-Pont Formation and the Tournaisian Hastière, Pont d'Arcole, Landelies, Yvoir, Ourthe and Martinrive formations. For the DSA Gendron section, the succession corresponds to the uppermost Comblain-au-Pont, Hastière, Pont d'Arcole, Landelies, Maurenne, Bayard and Waulsort formations. The Pont d'Arcole and Maurenne formations are the most argillaceous units and Waulsort Formation corresponds to a carbonate mound (Lees *et al.* 1985).

Whereas secondary dolomitisation may affect all units in each section, pervasive dolomitisation is mainly observed in the Landelies and Waulsort formations.

Rivage section

The well-known Rivage section (Conil 1964, Groessens 1975, Conil *et al.* 1986, Devuyst *et al.* 2005, Poty *et al.* 2011) is located along the north-eastern border of the Dinant Synclinorium, in the CSA (Figs 1 and 5A). The railway section (N85°E-68°S to N91°E-71°S) is complemented by another section situated on the other side of the Ourthe River, along the Esneux-Comblain main road (N86°E-70°S).

The last beds of the Comblain-au-Pont Formation correspond to decimetre-to-metre-thick dark grey crinoidal limestone including beds with lamellar stromatoporoids. The Hastière Formation (19 m) starts with well-bedded cm- to m-thick dark grey grainstone-packstone beds showing poor macrofauna, followed by crinoidal limestone and ending with more argillaceous limestone with crinoids, brachiopods and sparse rugose corals. The Pont d'Arcole Formation (10.7 m) is a greenish grey crinoid and brachiopod-rich (*Spiriferina peracuta*) shale and argillaceous limestone, with some bryozoans and rugose corals. The Landelies Formation (27 m) starts with relatively argillaceous dm-m-thick grey packstones with crinoids, brachiopods and corals (*S. rivagensis* and *Uralinia* sp.) and ends with more massive dolomitic limestone (Royseux beds). The Yvoir Formation corresponds to light grey cherty limestone with crinoids. The upper part of the Yvoir Formation and the next units crop out along the road. The Ourthe Formation (34 m) is a thick-bedded (1–2 m) light grey crinoid-rich limestone and is followed by the Martinrive Formation, a dark grey dm-m-thick argillaceous limestone unit with crinoids, brachiopods and cherts.

Gendron-Celles section

Gendron-Celles is located in the most distal part of the DSA, in the Dinant Synclinorium (Figs 1 and 5B; Conil 1968, Groessens 1975, Lees *et al.* 1985, Conil *et al.* 1988, Van Steenwinkel 1993, Devuyst *et al.* 2005, Poty *et al.* 2011). The section (N90°E-89°N) crops out along the Dinant-Bertrix railway, close to the station. Beds are affected by local faults and folds, especially in the vicinity of a Waulsortian mound.

The last beds of the Comblain-au-Pont Formation consist of an alternation of dm-m-thick light grey limestone and subordinate shale with crinoids and brachiopods. The Hastière Formation (24 m) shows firstly grey dm-m-thick

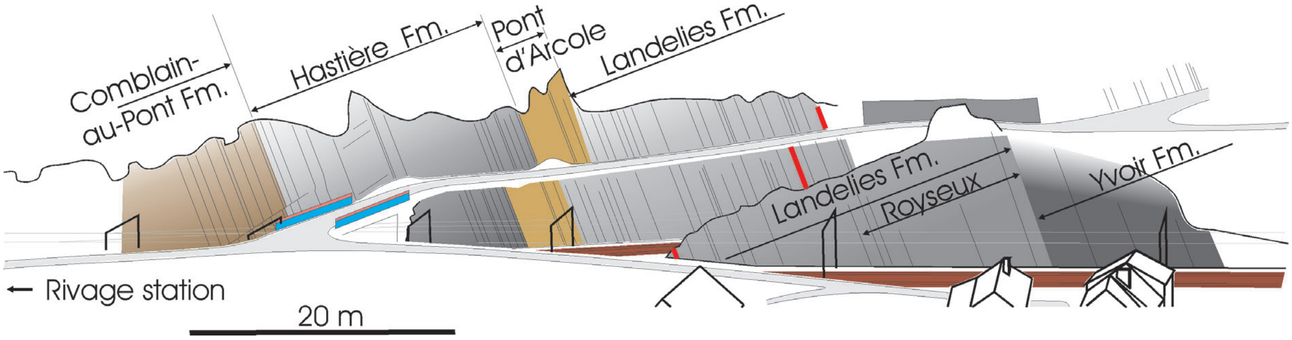

Figure 5A. The Rivage railway section.

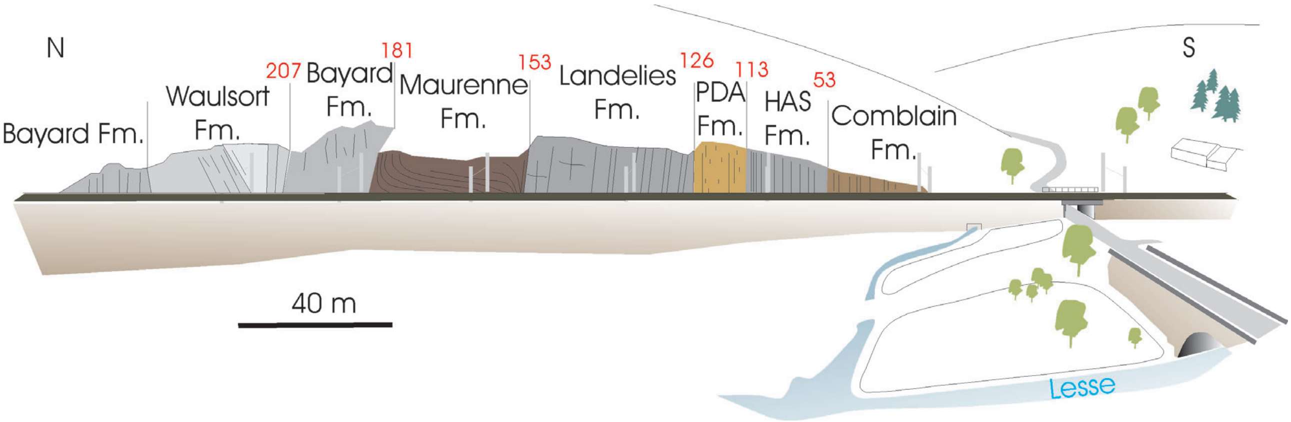

Figure 5B. The Gendron-Celles railway section.

grainstone beds with sparse crinoids and brachiopods, then thicker beds richer in fauna and finally, more argillaceous dm-m-thick dark grey limestone. The shale of the Pont d'Arcole Formation (15 m) contains crinoids, corals, bryozoans and brachiopods and passes progressively upwards to the Landelies Formation (42 m) characterized by light grey well-bedded m-thick grainstone-packstone with crinoids, brachiopods and corals. The Maurenne Formation (~15 m) is a dark grey dm-thick argillaceous wackestone unit with local storm-generated thin coquina beds. The next two units are interbedded: the Bayard Formation represents the sole and flanks of a Waulsortian mound, whereas the Waulsort Formation corresponds to the mound itself. The Bayard Formation is represented by light grey dm–m-thick crinoid-rich beds with cherts. The Waulsort Formation shows light grey dolomitized wackestone with bryozoans and crinoids.

Description of microfacies

Microfacies are reported here from the most distal to the most proximal environment. Microfacies are similar in both sections, but slight differences are mentioned where required.

Shale (MF1)

This facies is constituted by argillaceous, calcareous or dolomitic shale. Rounded and sorted detrital quartz (0.04–0.1 mm) is locally observed, especially in the Gendron section. Bioturbation is uncommon. Some bioclasts, often partially dissolved, are present. Crinoids, brachiopods and bryozoans are still recognizable. Pyrite crystals are present.

Argillaceous mudstones-wackestones with crinoids and brachiopods (MF2)

This often nodular limestone is characterized by an argillaceous microsparitic matrix. Some thin sections show alternating argillaceous and carbonate layers with numerous pressure-solution seams. Poorly rounded quartz grains (0.01–0.1 mm) are locally abundant (up to 30%). Rare horizontal burrows are observed. Bioclasts are often concentrated in thin (mm-thick) graded beds; they are commonly poorly preserved, but some crinoids, brachiopods, ostracods, trilobites, bryozoans, coral fragments, sponge spicules and cyanobacteria (*Girvanella* sp.) are still recognizable.

Wackestones-packstones with crinoids and ostracods (MF3)

These wackestones and packstones with local thin grainstone lenses have a micritic or a microsparitic matrix, often rich in tiny bioclasts. Rounded quartz (0.01–0.05 mm) grains are locally abundant. Some horizontal and vertical burrows are observed. Bioclasts consist of crinoids, ostracods, bryozoans, gastropods, brachiopods, sponge spicules, trilobites and uncommon foraminifers, calcispherids, *Girvanella* and palaeosiphonocladales.

Packstones-grainstones with crinoids (MF4)

Crinoids (mm–cm) are the major constituent of this unit and are associated with other bioclasts such as brachiopods, bryozoans and corals. Grainstones show sparry cement (syntaxial and/or equigranular xenomorphic calcite), and packstones have a micritic or microsparitic matrix.

Packstones-grainstones with peloids and algae (MF5)

These microsparitic packstone-grainstones include 20–60% peloids (0.1–0.4 mm), and poorly preserved crinoids, brachiopods, gastropods, trilobites, ostracods, foraminifers, *Girvanella* and palaeosiphonocladales. Vertical burrows are observed.

Grainstones with crinoids and peloids (MF6)

This facies is characterized by relatively well-sorted grainstones with crinoids and rounded peloids (0.01–0.1 mm). Other bioclasts include palaeosiphonocladales, *Girvanella*, foraminifers, calcispherids, brachiopods, gastropods and ostracods. Many of the bioclasts are micritized.

Grainstones with crinoids, lithoclasts and peloids (MF7)

Crinoids, lithoclasts and peloids are the major constituents of this facies. Crinoids are micritized, peloids are rounded or irregular, from 0.1 to 1 mm. Lithoclasts (mm–cm) are micritic or of algal-microbial origin.

Grainstones with peloids and ooids (MF8)

Rounded peloids (~0.2 mm) are abundant. Some lithoclasts are also observed. Most ooids (~0.4 mm) are bahamites. Rare partly micritized crinoids, ostracods, brachiopods and bryozoans are seen.

Depositional model

The microfacies from the Tournaisian of the DSA and CSA show the following characteristics: (1) sedimentation could be assigned to a carbonate-dominated system with subordinate siliciclastic units; (2) there is a continuous facies succession from deep to shallow environments; (3) no barrier reefs were developed; (4) there are no extensive lagoonal or restricted sediments; (5) storm sedimentation is widespread (see below), and (6) there are no slope sediments (slumps, turbidites). These characteristics point to a ramp, rather than a shelf setting (Read 1985, Burchette & Wright 1992, Herbig & Weber 1996). Taking this into account, facies can be easily interpreted in the Burchette & Wright (1992) carbonate ramp model. This model can be applied either to a homoclinal or a distally-steepened ramp (Flügel 2004). The inner ramp is the zone between the shoreline and the fair-weather wave base. The mid-ramp encompasses the zone between the fair-weather wave base and the storm wave base and the outer ramp is located below the normal storm wave base. Most microfacies are carbonate-rich, with full open marine influence marked by the abundance of crinoids and brachiopods. However, supply of detrital silt to sand-sized quartz is locally observed, mainly in Gendron. From MF3 to MF8, the scarcity of lamination or other sedimentary structures is regarded as the result of intense bioturbation (Sepkoski *et al.* 1991).

The MF1 shale makes up the bulk of the Pont d'Arcole Formation. The fine-grained character of the sediment, lack of bioturbation and rare open-marine fossils suggest a quiet environment, probably locally dysoxic, situated below the storm wave base (Flügel 2004). Facies MF2 occurs sporadically in the Pont d'Arcole Formation and frequently in the Maurenne Formation. This argillaceous limestone was deposited in a quiet environment, below the normal storm wave base. Some bioclasts-rich graded beds correspond to distal storm deposits (Reineck & Singh 1972, Guillocheau & Hoffert 1988) that may record exceptional events. MF3 is sporadically represented in nearly all formations. The presence of numerous small transported bioclasts and of minor grainstone levels suggests an environment located close to the storm wave base (Aigner 1985).

An important sedimentological change, corresponding to the transition between outer ramp and mid ramp, is recorded with MF4. This facies is mainly observed in the Ourthe, Bayard and Yvoir formations. It results from the dismantling of crinoid meadows by storms within the storm wave zone (Van Steenwinkel 1980, 1988; Préat & Kasimi 1995). MF5, mainly observed in the Hastière and

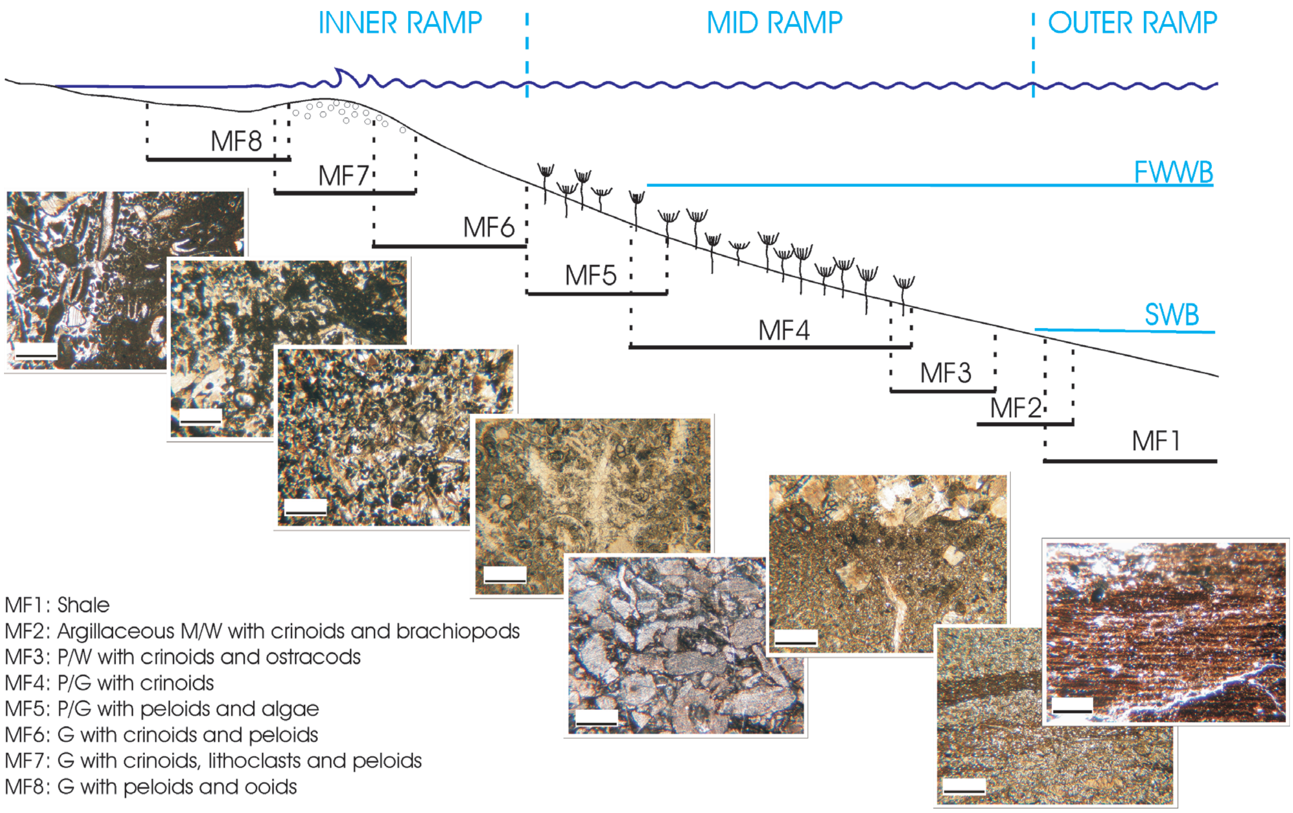

Figure 6. Sedimentological model and microfacies from the Belgian Tournaisian. Scale bar: 1 mm.

Landelies formations, is rich in peloids together with various bioclasts of mixed open-marine (crinoids, brachiopods, trilobites) and proximal character (palaeosiphonocladales, *Girvanella*). The origin of peloids can be diverse: faecal, micritized grains, direct algal origin, and intraclasts (Tucker & Wright 1990). Even if the micritization of bioclasts is proven by local preservation of relics within larger peloids, other origins cannot be excluded. Some grainstone levels within MF5 can be interpreted as proximal tempestites (Aigner & Reineck 1982). This corresponds in fact to the amalgamation of storm deposits with erosion of the major part of a classical storm sequence, leading to the preservation and repetition of truncated sequences (Van Steenwinkel 1980, 1988).

The transition to the inner ramp is observed with MF6, frequent in the Hastière and Landelies formations. This facies is dominated by transported peloids and crinoids mixed with some algae. Many of the grains are micritized and most of the peloids originate from completely micritized grains. Relatively good sorting and grainstone texture suggest a location above the fair weather wave base. MF7, observed in the Landelies Formation, is relatively similar to MF6, with a higher percentage of micritized grains. High micritization indicates a longer exposure of bioclasts to wave action and biodegradation before burial. Large lithoclasts are probably reworked from algal-microbial mats or from fine-grained sediments deposited in pools in littoral setting (Tucker & Wright 1990, Préat & Kasimi 1995). MF8 is observed only at the base of the Hastière Formation, in the Gendron section. This highly micritized ooid and peloid-rich microfacies probably corresponds to tidal channels in a littoral environment (Loreau & Purser 1973). Fig. 6 shows the bathymetric distribution of microfacies along the Burchette & Wright (1992) carbonate ramp model.

Sedimentary evolution and sequence stratigraphy

The sequence stratigraphic canvas used in the present study is based on the studies by Hance *et al.* (2001), Devuyst *et al.* (2005) and Poty *et al.* (2006, 2011), who defined four third-order sequences in the Tournaisian. The first of these corresponds to the Comblain-au-Pont Formation and the first two members of the Hastière Formation (TST1–HST1). In the Rivage section (Fig. 7), facies are dominated by MF6 and 7 (inner ramp). In the Gendron section, the first beds of the Hastière Formation record MF8 and MF2, passing upwards to MF5, MF6 and MF7, typical of mid- and inner ramp settings.

The second sequence starts with the upper member of the Hastière Formation, and includes the Pont d'Arcole and Landelies formations. The last member of the Hastière Formation is characterized by a deepening event (MF6-5-4-3-2), which is relatively progressive in Gendron but more rapid in Rivage. The bulk of the Pont d'Arcole Formation (TST2) accumulated on an outer ramp (MF1–MF3) while the Landelies Formation (HST2–FSST2) (*cf.* Plint & Nummedal 2000) shows a progressive shallowing upwards from an outer to an inner ramp (MF3–MF7).

The third sequence encompasses the Yvoir and the Ourthe formations in the CSA and the Maurenne, Bayard and Waulsort (partim) formations in the DSA. The Yvoir Formation (TST3) was deposited on a mid ramp (MF4–MF6) while the Maurenne Formation (LST3) corresponds to a protected area on a mid or inner ramp (MF2). The Ourthe Formation, a thick crinoidal unit (MF4), is deposited on a mid-ramp (HST3–FSST3?). The crinoid-rich Bayard Formation (MF6–MF4) and the lower part of a Waulsortian mound (MF3) are related to the TST3-HST3-FSST3.

The fourth sequence (TST4) starts with a recurrence of the Bayard Formation in Gendron and with the Martinrive Formation (MF4–MF3) in the CSA.

A comparison of microfacies through all the sections correlated by biostratigraphy and sequence stratigraphy (Fig. 7) highlights the shallower character of the Rivage section when compared with the Gendron section. This is especially true for the Hastière Formation, dominated by MF7 in Rivage and by MF6 in Gendron.

Magnetic susceptibility

MS values for Rivage and Gendron range from near zero to 14×10^{-8} m^3/kg. These relatively low MS values are consistent with published values from Frasnian platform limestone (between 0 and 32×10^{-8} m^3/kg: Da Silva & Boulvain 2002), Eifelian ramp argillaceous limestone (from –2 to 12×10^{-8} m^3/kg: Mabille & Boulvain 2007), or Givetian platform limestone (–1 to 43×10^{-8} m^3/kg: Boulvain *et al.* 2010; Fig. 8).

When comparing the MS values of the two sections, similar trends and events are observed (Fig. 7). These are considered as isochronous and correlatable (see Ellwood *et al.* 1999). The MS curves will now be shortly described, in relation to the sequence stratigraphy units previously defined by Hance *et al.* (2001) and Poty *et al.* (2006, 2011).

TST1 is characterized by a progressive lowering of MS values (from 10×10^{-8} m^3/kg to 2×10^{-8} m^3/kg) in Rivage and oscillations between these values in Gendron. HST shows very low MS values in Rivage and a rapid decrease in Gendron. In both sections, TST2 shows a significant MS increase up to 10×10^{-8} m^3/kg followed by oscillating values between 8×10^{-8} m^3/kg and 12×10^{-8} m^3/kg. Again, HST2–FSST2 shows decreasing values, from 14×10^{-8} m^3/kg to 0 or slightly negative values. Higher MS values (around 12×10^{-8} m^3/kg) for LST3 are observed in Gendron but not in Rivage. TST3-HST3-FSST3 is characterized again by low MS values and finally, TST4 shows slightly higher MS values (4×10^{-8} m^3/kg).

Discussion

The relationships between the MS signal and different sedimentological characteristics of the two sections will now be addressed: these characteristics include lithostratigraphic units, lithology, sequence stratigraphic units and facies. Fig. 9 represents the mean MS values for each formation in Rivage and Gendron. Some formations are represented in both sections (Hastière, Pont d'Arcole, Landelies) while others are observed only in one section (Yvoir, Maurenne, Ourthe, Bayard, Waulsort, Martinrive) because the paleogeographic differentiation between CSA and DSA was increasing during the Tournaisian (Poty 1997). A first observation is that mean MS values decreased through time, except for the shaly Pont d'Arcole Formation. This could indicate a progressive long-term lowering of the MS carrier input into the basin. Actually, a parallel decrease of the detrital input is also visible by a reduction in the number and thickness of the argillaceous beds from the Hastière Formation to the upper Tournaisian. Another interesting observation is that the Gendron formations show systematically higher MS values than the Rivage ones. Following the same interpretation, this suggests a higher MS-carrier input in Gendron than in Rivage. As stated previously, detrital silt and sand-sized quartz is also more abundant in Gendron than in Rivage.

It is interesting to note that magnetite was extracted from shale of the Pont d'Arcole Formation using a permanent magnet (confirmed by X-ray diffraction). A relatively high proportion of magnetite suggests that the MS signal is dominated by the ferromagnetic minerals, as already proposed by Devleeschouwer *et al.* (2010).

As previously stated, the Hastière and Landelies formations are characterized by alternations of limestone and subordinate shale beds (Conil & Vandenven 1972). This common pattern could be the result of cyclic variations in carbonate productivity or detrital input or even could be a diagenetic effect, by concentration of argillaceous residue by pressure solution (Wanless 1979). Fig. 10 shows that, for a series of limestone and shale beds of the Hastière and Pont d'Arcole formations in Gendron, MS values remain relatively close. This simple observation allows the dismissal of the last hypothesis for the development of the argillaceous beds: if these beds were of diagenetic origin, MS carriers would have been concentrated by pressure solution and shale beds would have

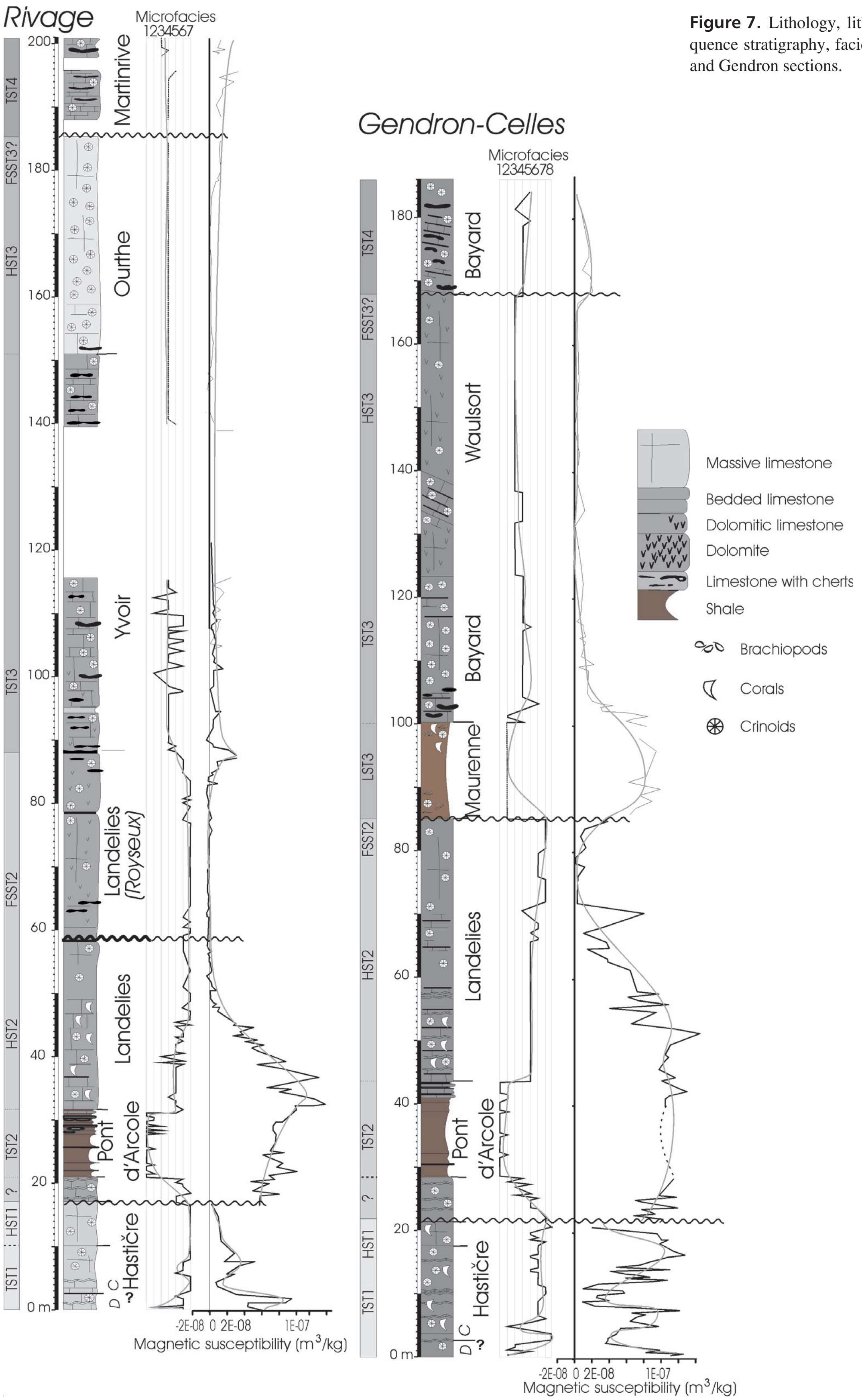

Figure 7. Lithology, lithostratigraphic units, sequence stratigraphy, facies and MS of the Rivage and Gendron sections.

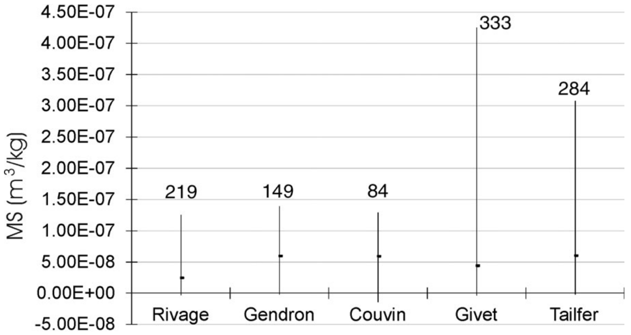

Figure 8. MS values (maximum, minimum, mean and number of samples) from different sections and platform types. Rivage and Gendron – Tournaisian ramp (this paper); Couvin – Eifelian ramp (Mabille & Boulvain 2007); Givet – Givetian platform (Boulvain *et al.* 2010); Tailfer – Frasnian platform (Da Silva & Boulvain 2002).

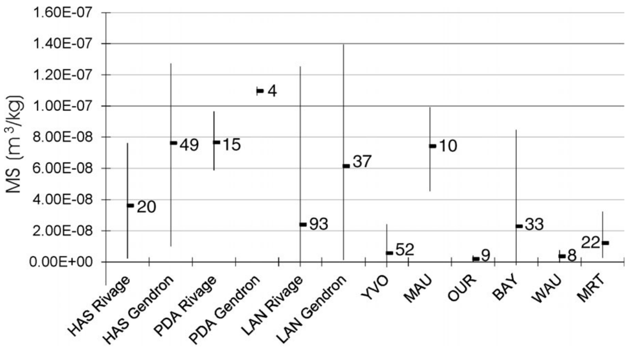

Figure 9. MS values (maximum, minimum, mean and number of samples) for the different formations of the Rivage and Gendron sections. Abbreviations: HAS – Hastière Fm.; PDA – Pont d'Arcole Fm.; LAN – Landelies Fm.; YVO – Yvoir Fm.; MAU – Maurenne Fm.; OUR – Ourthe Fm.; BAY – Bayard Fm.; WAU – Waulsort Fm.; MRT – Martinrive Fm.

higher MS values than their limestone counterparts. This result suggests also that the input of MS-carriers stayed roughly constant during the deposition of the limestone-shale alternation.

At a higher scale, the MS-systems tracts relationships highlighted in this study are relatively consistent and in agreement with the Crick *et al.* (1994) model (Fig. 7): LST show high values while TST are characterized by decreasing values and HST–FSST by the lowest values (excepted for the base of the Landelies Formation). This corresponds to the tendencies previously observed on the Belgian Frasnian platform where one HST shows low MS values (mean of 2×10^{-8} m^3/kg) and the next TST shows higher values (mean of 6.6×10^{-8} m^3/kg) (Da Silva & Boulvain 2006). As already proposed by different authors, the results presented here point to an MS signal probably dominated by lithogenic inputs (Crick *et al.* 1997, 2001; Ellwood *et al.* 2000; Hladil 2002). The proportion of lithogenic inputs seems to be higher during low sea level, when larger portion of continental areas are exposed. 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 the MS of the sediments increases accordingly. This hypothesis is that 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. As suggested by Tite & Linington (1975) for example, pedogenesis can be an important source of magnetite during emersion of internal zones of carbonate platforms. As already proposed by Mabille & Boulvain (2007), the magnetic fraction seems to be hydrodynamically linked to the detrital sand and silt-size quartz fraction.

Regionally, these MS results confirm some recent improvements of the sequence stratigraphy framework. The high but decreasing MS values of the upper member of the Hastière Formation are consistent with a TST (Hance *et al.* 2001, Poty *et al.* 2011) rather than a LST (Devuyst *et al.* 2005). Moreover, the sharp contact between low and high MS values in the same formation argues for a sequence boundary with a well-developed erosion surface. Conversely, the lack of high MS values in the Rivage section at the beginning of sequence 3 leads us to question the presence of the LST3, well developed in Gendron. This could be related to the deeper setting of the Gendron section in the DSA, while the CSA was possibly emergent during deposition of LST3.

Available data in the literature (*e.g.* Hladil 2002, Da Silva & Boulvain 2002) support the notion that, generally, proximal microfacies possess higher values of MS than distal ones. This is explained by the relative proximity to the terrestrial source. However, the average MS values of each microfacies in the present study (Fig. 11) show just the opposite trend, with higher MS values for distal microfacies and lower values for proximal ones. The very low mean MS value recorded by MF4 is probably related to the high crinoid content (diamagnetic calcite).

This inverse relationship was already highlighted by Zhang *et al.* (2000) for Tournaisian sections in China and by Bábek *et al.* (2010) for a series of sections around the Tournaisian-Viséan boundary in Ireland, England, Belgium and Germany as well as by Mabille & Boulvain (2007) for a Belgian Eifelian-Givetian ramp section.

This variable MS-facies relationship led Da Silva *et al.* (2009a) to propose 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 ramps. One hypothesis is that, with a constant and homogeneous detrital supply, the MS variations are mainly

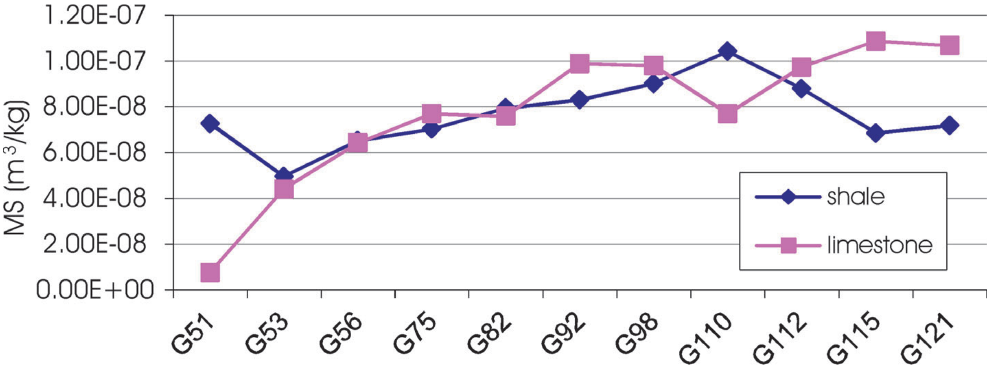

Figure 10. Comparison of MS values from limestone and adjacent shale beds for different samples from Hastière and Pont d'Arcole formations (Gendron section). G51–121: samples.

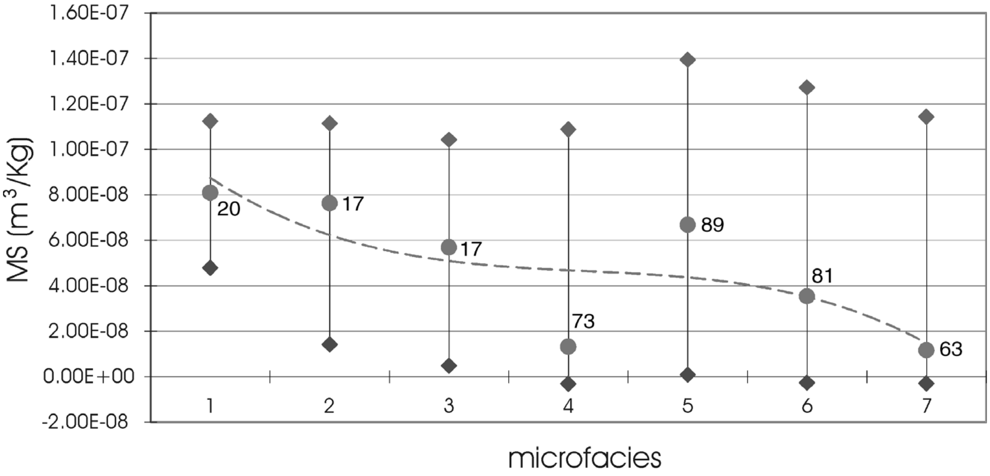

Figure 11. MS values (maximum, minimum, mean and number of samples) from the different facies (1–7).

controlled by water agitation and carbonate productivity which are lower on outer than on inner ramp systems (Mabille & Boulvain 2007, Da Silva *et al.* 2009a, Bábek *et al.* 2010). The present study on Tournaisian ramp deposits confirms this hypothesis. Another explanation proposed by Zhang *et al.* (2000) is that deeper environments tend to form reducing sediments, which promote the development of authigenic minerals like pyrrhotite and siderite. These minerals are paramagnetic and could result in higher MS values.

Conclusions

This sedimentological and MS study is dedicated to two important Belgian Tournaisian reference sections, the Rivage road and railway sections and the Gendron-Celles railway section. These sections belong to two different sedimentation areas; a shallow ramp for Rivage (CSA) and a subsiding area for Gendron (DSA). Both sections are characterized by a carbonate-dominated sedimentation (crinoids-peloids-algae assemblages), interrupted by more argillaceous facies related to rapid sea-level rises (crinoids-brachiopods-bryozoans assemblages). Accommodation space was significantly higher in the DSA and allowed the development of Waulsortian buildups during the Ivorian.

MS curves allow better correlation of the two sections and are in agreement with the 3rd order sequential interpretation. LST show the highest MS values while TST are characterized by decreasing values and HST–FSST by the lowest values. These results again suggest that the MS signal is probably dominated by lithogenic inputs (Crick *et al.* 1997, 2001; Ellwood *et al.* 2000; Hladil 2002) and controlled by magnetite (Devleeschouwer *et al.* 2010, Riquier *et al.* 2010). The proportion of lithogenic inputs seems to be higher during low sea level, when significant parts of continental area are exposed. During low sea level, the base level is lowered and heightened erosion increases the detrital contribution into the marine system. At the facies level, average MS values are higher for distal microfacies and lower for proximal ones, suggesting that, with a constant and homogeneous detrital supply, the MS variations are mainly controlled by water agitation and carbonate productivity which are lower on outer than on inner ramp systems.

As a consequence, variations of MS seem to be related both to fluctuations in detrital input and oceanic parameters. MS evolution with palaeogeography can be integrated in the Da Silva *et al.* (2009a) model for the Devonian: external ramp settings show low carbonate productivity, low water agitation and high MS, whereas more proximal environments are characterized by higher carbonate productivity, higher water agitation and lower MS.

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