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MAGNETIC SUSCEPTIBILITY CORRELATION OF KM-THICK EIFELIAN–FRASNIAN SECTIONS (ARDENNES AND MORAVIA)

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(6 figures, 1 table)

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ABSTRACT. After briefly introducing the sedimentology of two Eifelian-Frasnian carbonate sections in Belgium and Moravia, this paper focuses on the comparison of the magnetic susceptibility (MS) curves. The Ardennes section shows highly variable facies, with an alternation of ramp, platform and mound environments. Detrital inputs are locally very important. Time-equivalent facies in the area of the Moravian Karst correspond to rather pure carbonate platform facies, mostly composed of *Amphipora* beds. The first analysis of long-term trends in Devonian MS in Belgium and Moravia shows a remarkable similarity, despite a very different background of palaeogeographical setting, facies, sedimentary rate and retrogradation-progradation history. However, a relative independence of the MS and the distal-proximal curves, deduced either from the microfacies record (Ardennes) or from shoreline shifts (Moravia) is observed. This questions the nature of the forcing mechanisms that must at least be active at the inter-regional scale. Moravia and the Ardennes are located along the same palaeolatitude, perhaps suggesting some climatically driven mechanisms, responsible for the input of the detrital fraction responsible for the MS in these sediments. Trade winds are potentially responsible for transportation of dust and its widespread distribution in intertropical areas.

KEYWORDS: Devonian limestone, magnetic susceptibility, Moravian karst, Ardennes.

1. Introduction

Changes in magnetic susceptibility (MS) in sedimentary successions are attributed to sea level variations (Ellwood et al., 1999). Based on this relationship, Crick et al. (1997) proposed using MS for high-resolution, global correlation of marine sedimentary rocks. The major influence of sea level on the MS signal is related to the strong link between MS and detrital components and the supposition that the detrital input is generally controlled by eustasy or climate (Ellwood et al., 2010). In this way, a sea-level fall (regression) increases the proportion of exposed continental area, increases erosion and leads to higher MS values, whereas rising sea level (transgression) 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 (formation of magnetic minerals in soils; e.g., Tite & Linington, 1975). 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; Ellwood et al., 2006; Hladil et al., 2006 and this volume). Furthermore, early and late diagenesis can be responsible for MS variations through mineralogical transformations, dissolution or authigenesis (Rochette, 1987; McCabe & Elmore, 1989; Zegers et al., 2003).

In Palaeozoic rocks, most of the magnetic susceptibility studies have been conducted on condensed (~40 m covering ~25 myr, Ellwood et al., 1999) or relatively short sections (5th to 3rd order sequences - one to tens of meters, Hladil et al., 2002; Da Silva & Boulvain, 2002, 2006; Da Silva et al., this volume; Devleeschouwer et al., this volume). A few studies have proposed a link between MS and the depositional environment (Borradaile et al., 1993; Da Silva & Boulvain, 2006; Da Silva et al., 2009a, b). These studies present different MS/depositional environmental responses as a function of different platform types, suggesting that sea-level and climatic changes leading to variations in detrital input are not the only controls on the MS values observed. Other primary or secondary processes probably also influenced the magnetic mineral distribution. Primary processes such as water agitation and carbonate production during deposition (Da Silva et al., 2009b) as well as winnowing effects during storms (Ellwood et al., 2006) also seem to be important factors in controlling the final MS values observed.

The aim of this paper is to apply MS at a larger scale, on hundreds of meters succession (2nd order). We intend to test the reliability of correlations on large scale non-

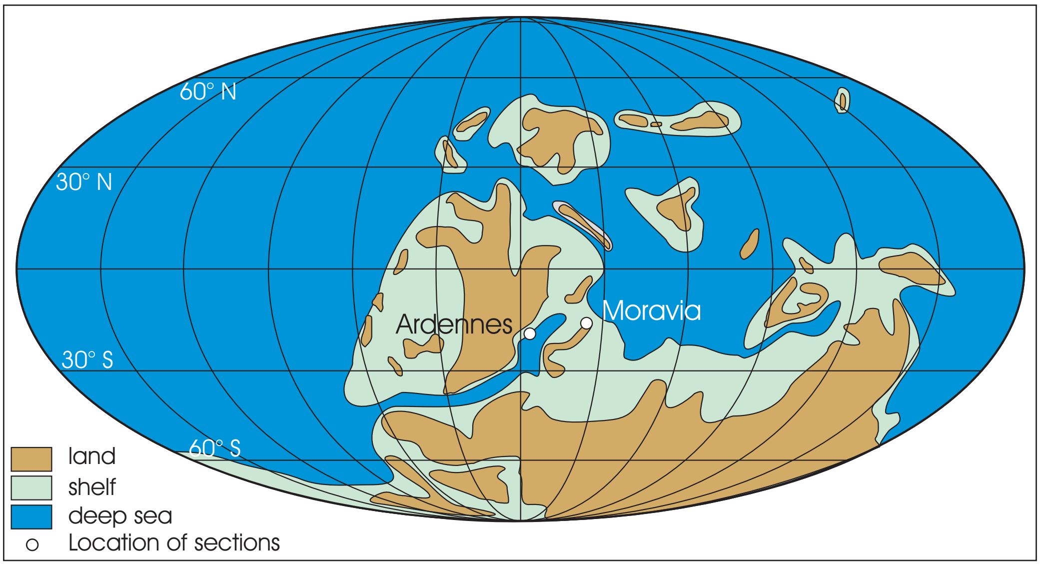

Figure 1. A simplified palaeogeographic sketch showing the approximate locations of the Ardennes and Moravia during the Middle to Upper Devonian.

condensed successions and to identify the link between MS and environmental parameters at this larger scale. We evaluate this here for the Middle and Upper Devonian limestone sequences collected in the Ardennes (Belgium) and in the Moravian Karst (Czech Republic).

2. Geological context

During the Devonian period, the Ardennes and Moravia were both located in the Rheic Ocean, south of the Old Red Sandstone Continent, at approximately the same latitude (Fig. 1). Both areas belong to the Variscan Rhenish sedimentary facies and tectonic belt and were thrust over their northern forelands (e.g. Franke, 1995; Fielitz & Mansy, 1999). Despite this, the Ardennes and Moravia sedimentary basins and environments were significantly different. The close vicinity of the mainland was responsible for increased detrital inputs in the Ardennes. The delivery of originally riverine and coastal marine aquatic suspensions of this material into carbonate ramp and slope environments was significant (e.g. Chamley et al., 1997; Mabille & Boulvain, 2008) but was probably also mediated by dust storms and 'Old-Red-Continent' atmospheric dust in general (e.g., the trajectories according to spore dispersals, Hladil & Bek, 1999). On the other hand, the former Moravian block was distant and separated from the mainland, encircled by deep seas and covered by platform limestones with numerous *Amphipora* lagoons (Hladil, 2002). The riverine and coastal inputs of detrital material were very low due to distant source areas, and small amounts of impurities in these limestones relate mostly to sedimented dust. Actually, long-distance dust transport predominated (Hladil et al., 2006 and this volume).

The present work integrates sedimentological and MS data from the Upper Eifelian into Late Frasnian limestones collected along the southern border of the Dinant Synclinorium in Belgian and French Ardennes. An 800 m-thick composite section was assembled from four outcrops (Fig. 2), which were the subject of detailed sedimentological studies that provide a good knowledge of facies (environmental interpretation and evolution) and of sea level variations. The lower part of the composite section corresponds to samples from La Couvinoise quarry (Upper Eifelian-Lower Givetian; Mabille &

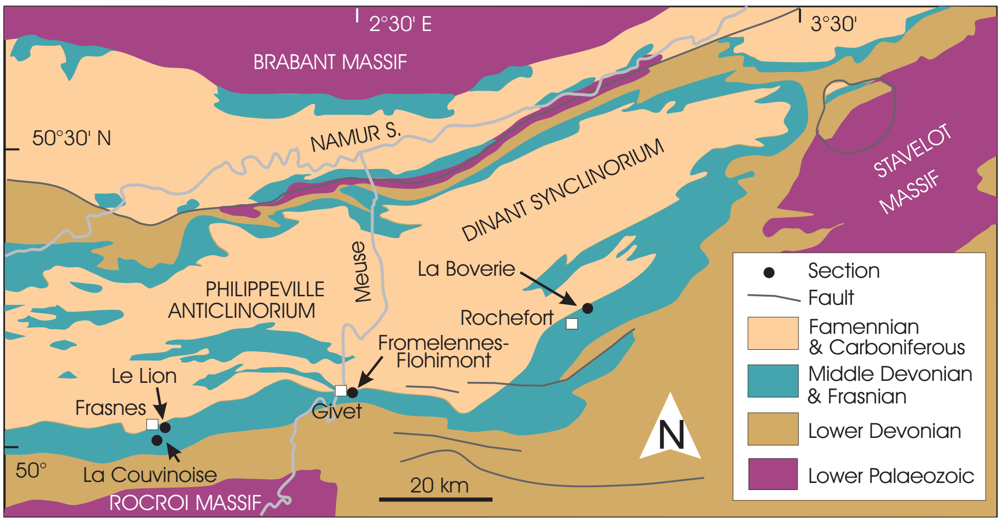

Figure 2. Geological context and location of Belgian sections in the Ardennes.

Boulvain, 2007), the middle part to samples from the Fromelennes-Flohimont road section (Givetian; Boulvain et al., 2009), and the upper part to samples from the La Boverie and Lion quarries (Frasnian; Boulvain et al., 2005). Connections between these four sections were made using important sedimentological changes that represent formation boundaries.

The Upper Eifelian to Lower Givetian portion of the composite section is characterized by mixed detrital-carbonate ramp sediments, followed by a well-developed Givetian carbonate platform with environments ranging from crinoidal facies to stromatoporoid-dominated biostromes and to lagoonal facies. After the demise of the carbonate factory at the beginning of the Frasnian and the generalization of argillaceous sedimentation, the Middle Frasnian is characterized by a severe backstepping of the facies belts and a succession of three carbonate mound levels, starting in quiet, relatively deep aphotic water and ending in relatively shallow waters.

The Moravian section encompasses very pure carbonate facies of a large reef-rimmed carbonate platform complex, which is documented by many boreholes (e.g. Hladil, 1994, 2002). Large outcrops for sampling are rare, and are concentrated mainly in the area of the Moravian Karst (Fig. 3). Stratal successions are dominated by dark-grey, thin-bedded and rhythmically deposited *Amphipora* banks, which alternate with lighter and thicker intervals built by stromatoporoid–coral banks (Hladil, 1983, 1994). The concentrations of non-carbonate impurities do not exceed 3 wt.% (often much less). Almost all this material was originally eolian dust and was delivered over broad, very shallow platform–lagoon areas from distant sources (Hladil et al., 2006). Other argillaceous or clayey sediments are absent and detrital rims around few and gradually sediment-covered cliffs of crystalline basement rocks are rare. The major vertical accretion marked by biohermal shoals developed during the Frasnian.

The appropriate parts for the composite Moravian section used in this paper, have been chosen based on the quality of rock preservation. The section was, therefore, assembled from three long sections in relatively unfaulted blocks of limestone, where the lower (Eifelian-Givetian) part is the Celechovice Statni quarry (NE of the Moravian Karst, near Olomouc; Galle & Hladil 1991; Hladil et al. 2002), the middle part (Givetian) is represented by the Josefov-Barova section (central Moravian Karst, N of Brno; Zukalova, 1971) and the upper part (Givetian-Frasnian) by the Mokra Quarry West (SE of Brno; Gersl & Hladil 2004). The connections among these three parts were made using the complementary sections in the Josefov-Pila (lower/middle connection) and Mokra quarries (middle/upper connection).

The main parts of the Moravian Karst composite section (Celechovice, Josefov-Barova and Mokra; Hladil et al., 2006) were selected with respect to their sedimentological and bathymetric characteristics. These sections are in *Amphipora*-dominated facies, with less disturbed stratal successions (without bioherms, major gaps or slope sediment incursions), and correspond to depths of sedimentation that can be estimated as from a few metres to several tens of metres as a maximum. Therefore, the Moravian composite section represents strong facies and bathymetric homogeneity.

3. Methods

The MS measurements were made using KLY-2, -3 and -3S Kappabridge devices (see Da Silva & Boulvain, 2006; Hladil et al., 2006). Three measurements were made on each sample weighed with a precision of 0.01g. Sampling interval for the Ardennes MS curve is ~1 m. Hiatuses were encountered near 420 m and from 500 to 530 m. The interval for the Moravian MS curve is ~ 0.5 m and data were derived from smoothed curves (average of samples situated in a 0.5 m window) (Fig. 4).

A special difficulty arises when trying to compare the huge amounts of sedimentological information from Moravia and Belgium. However, the relative homogeneity in time and space of the Moravian facies (Hladil et al., 2006) and the availability of numerous subsurface data sets makes it possible to build a "platform shoreline shift"

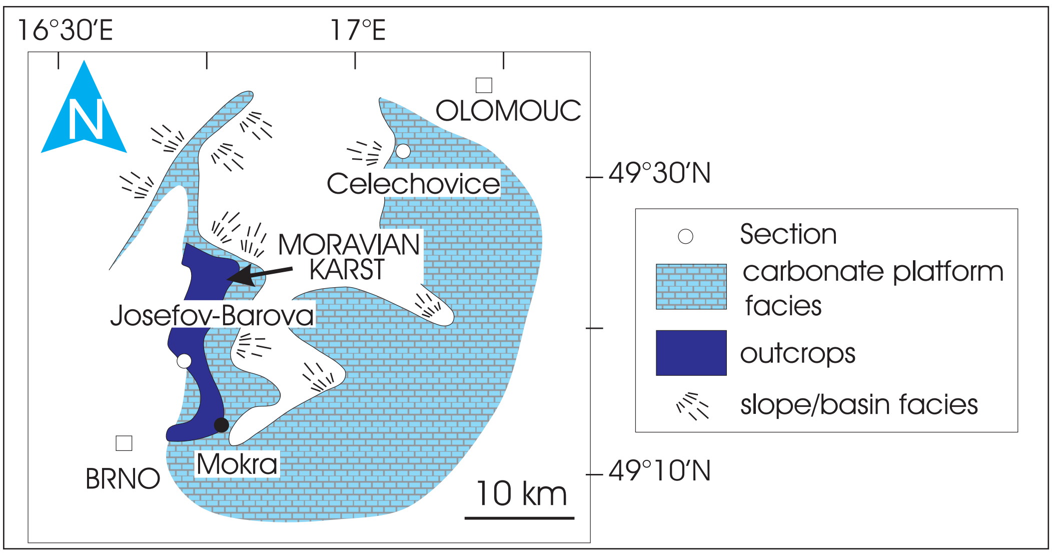

Figure 3. Location of the three elements of the Moravian composite section.

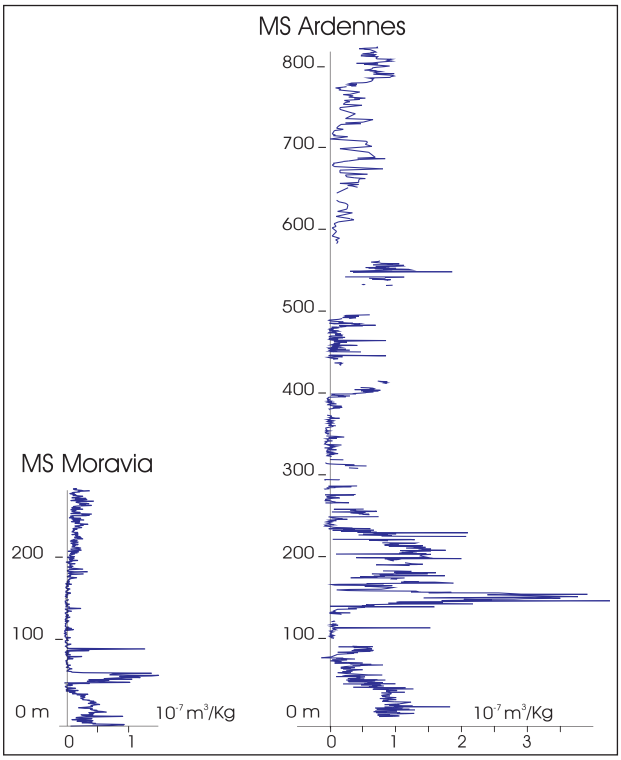

Figure 4. MS curves from Moravia and the Ardennes.

curve, which is probably the most direct way to represent local bathymetric variations and transgressive-regressive patterns.

In the Ardennes, the Variscan tectonism folded the Devonian platform and buried most of it under more recent sediments. As no subsurface data are available, all sedimentological information comes from a narrow outcrop belt that runs approximately perpendicular to the palaeogeographic gradient, cropping out along the southern border of the Dinant Syncline (Fig. 2). Therefore, the best way to represent this information is through a facies evolution curve through time. In this study, microfacies analysis comes from the detailed bed-by-bed study of outcrops and petrographic observation of more than 1000 thin sections. For easy comparison of depositional environments through the entire composite sequence, all the microfacies were reported along a platform profile that exposes three main facies belts: external ramp and platform with reef mounds; mid-ramp and platform, and restricted internal platform (Table 1).

4. Results

4.1. Ardennes

The mixed carbonate ramp of the Eifelian – Givetian transition beds (0-90 m) can be divided in different environments ranging from a mid-ramp to a fore-reef facies (Mabille & Boulvain, 2007), corresponding to a succession of argillaceous mudstones to packstones with crinoids and brachiopods (mid-ramp, facies 11-13, Table 1), rudstones with stromatoporoids debris, tabulate and rugose corals, followed by packstones and grainstones with peloids (fore-reef, facies 14, 16, Table 1). General evolution of mean magnetic susceptibility corresponds to a global decrease of values (Fig. 5, a).

Givetian interval corresponds to a succession of platform, mid ramp and restricted platform limestone

The external ramp-platform-mound system	**0**	bioclastic-lithoclastic packstones-grainstones (mound flank)
	1	mudstones with stromatactis (sponges) (mound)
	2	wackestones with sponges, corals and crinoids (mound)
	3	wackestones-packstones with corals and stromatoporoids (mound)
	4	algal-peloidal packstones-grainstones (mound)
	5	algal microbial bindstones (mound)
	6	rudstones with dendroid stromatoporoids (mound)
	7	fenestral packstones-grainstones (mound lagoon)
	8	algal wackestones (mound lagoon)
The mid-ramp platform system	**11**	argillaceous mudstones
	12	argillaceous bioclastic wackestones
	13	argillaceous packstones with brachiopods and crinoids
	14	floatstones and rudstones with reefal debris
	15	bindstones with stromatoporoids
	16	packstones-grainstones with peloids
	17	grainstones with peloids and crinoids
	18	floatstones with stromatoporoids and corals
The internal restricted platform system	**21**	rudstones with dendroid stromatoporoids
	22	algal wackestones
	23	wackestones with *Umbella*
	24	oolithic grainstones
	25	grainstones with calcispherids and peloids
	26	paleosols

Table 1. Main facies belts with microfacies from Devonian limestone sequences of the Ardennes (after Da Silva & Boulvain, 2004 ; Mabille & Boulvain, 2007 ; Boulvain et al., 2009).

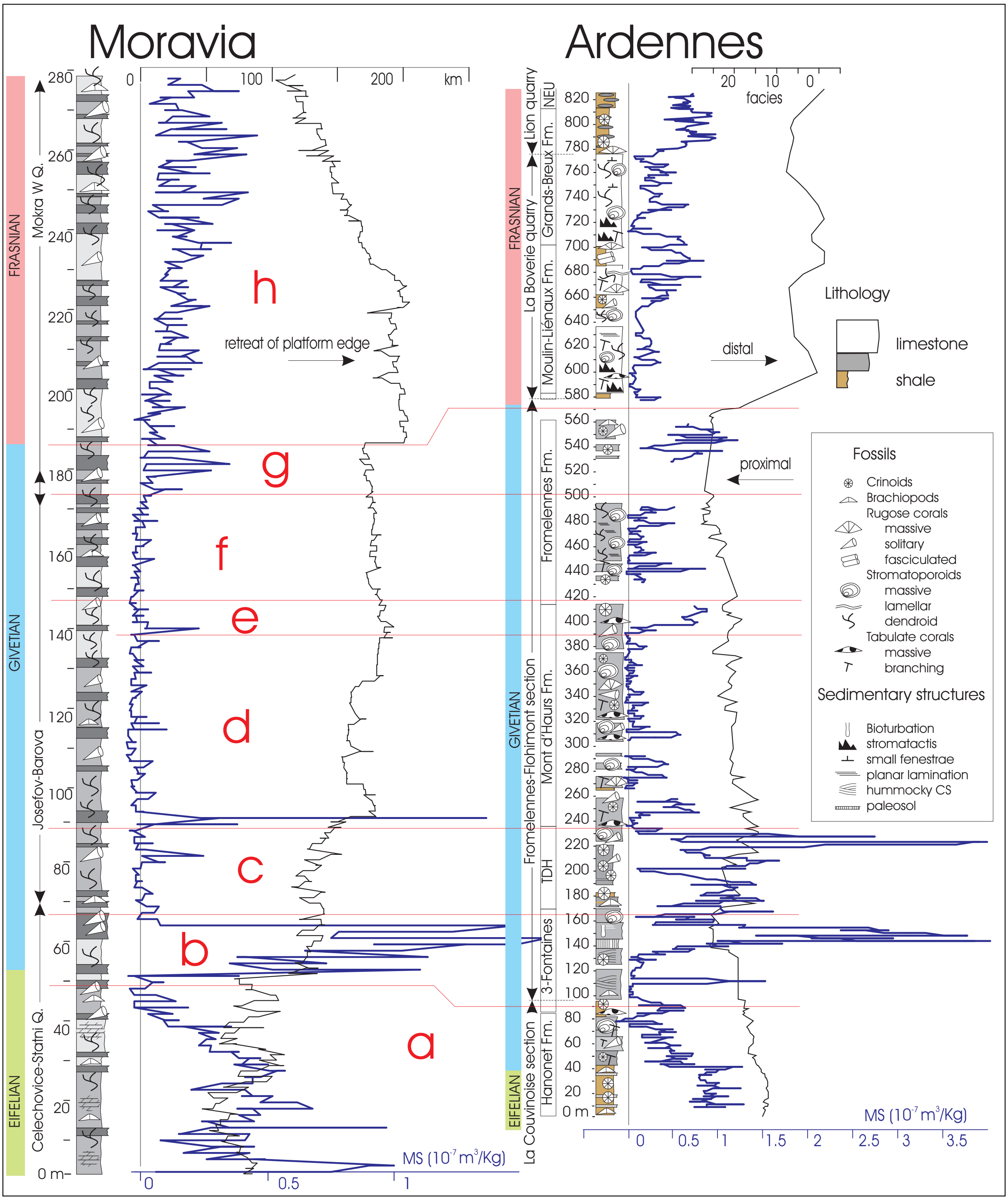

Figure 5. Logs, MS (blue line) and bathymetric (black line) curves from Moravia and Ardennes. a to h: MS units. Note the different MS and metric scales between the two sections.

settings (Boulvain et al., 2009). It starts with peloidal grainstones showing frequent hummocky cross stratification (100-143 m), topped by five levels of paleosols (facies 16, 26, Table 1). This ramp environment shows very low MS values except for the paleosols. The next unit (143-165 m) is characterized by wackestones with poorly diversified fauna and flora, from restricted lagoonal environment (facies 22, 25, Table 1). MS first shows very high values, then decreases towards relatively low values through this interval (Fig. 5, b).

The lower part of the next unit (165-237 m) is dominated by argillaceous wackestones with crinoids and brachiopods in a mid-ramp environment, followed by alternating crinoidal wackestones and coral-stromatoporoid floatstones (facies 12-14, Table 1). The MS signal rises to, and then oscillates around relatively high values (Fig. 5, c).

The next unit (237-390 m) shows a background of open-marine crinoidal wackestones interrupted by coral-rich debris flows. The upper part of the unit presents more shallow facies (Fig. 5, d), before a final deepening upwards trend (390-415 m). The MS signal is low but rises towards the top of the unit (Fig. 5, e).

The lower part of the Fromelennes Formation (415-500 m) is characterized by alternating dendroid stromatoporoid-rich carpets and other restricted facies (facies 21-26, Table 1). MS is low but oscillating (Fig. 5, f). In the upper part of the Fromelennes Formation (532-561 m) more open-marine conditions are associated with a rise in MS (Fig. 5, g) (see also Devleeschouwer et al., this volume).

The La Boverie quarry shows a nearly complete Frasnian section (580-825 m). The general context is an external platform with a succession of three mound levels (Boulvain & Coen-Aubert, 2006; Da Silva et al., this volume). MS shows oscillations, with the highest values found in the deepest mound facies (facies 1-3, Table 1) (Fig. 5, h). The last unit, (811-825 m) varies from shale to argillaceous wackestones, typical of an external platform setting, with relatively high MS values.

4.2. Moravian Karst

The Ardennes time-equivalent facies in the area of Moravian Karst corresponds to a pile of rather pure carbonate platform facies rocks, mostly associated with inner platform *Amphipora* beds (Hladil et al., 2006).

A typical transgressive cycle for the East Moravian platform consists of; (1) slightly developed paleosol/protosol or erosion base; (2) laminated (locally intraclastic) carbonate sediments, sometimes with relict fabrics after evaporates (dissolved or replaced by calcite); (3) lenses and wedging beds with pioneer colonization (e.g. also with worms, gastropods, some brachiopods); (4) *Amphipora*-banks; (5) *Amphipora* and boundstone (stromatoporoid - coral) banks, alternate layers; and (6) boundstone/rudstone banks, cracked (also *Entobia* sponge-bored) layers containing surfaces filled with vadose silt etc., and the uppermost coral heads (and clasts/pebbles) that locally contain silicified micro-debris (scattered and small, mm-sized "cauliflowers" or microgeodes). Other characteristics of these cycles are that; (a) the phases with *Amphipora* correspond to the thickest units; (b) a dark grey to light grey limestone transition occurs between (4) and (5), or in (5); (c) the uppermost part of (6), and mainly (1) (2) and (3) are often associated with increased MS values although the light grey (5) together with a significant lower part of (6) are marked, quite often, by low or lowest MS values; and (d) although there are numerous modifications to this basic cyclic pattern, at least some of the main features can be found almost universally across these platform facies.

The cyclic pattern on the East Moravian platform (including the alternation of dark and light grey colours of limestones and erosional gaps between the cycles) are best seen on slightly domical highs of the platform or at the platform margins. This type of section is however, not appropriate for building of MS stratigraphic, regional or inter-regional correlation standards, being precluded by large degree of lithological change together with increased lacunae and irregularities in record. On the other hand, the platform parts selected for this purpose, with more rapidly subsiding basement (dominated by long-lasting lagoonal facies), show slight or no biohermal insertions, and rather moderate or slightly expressed hiatuses or condensations at cycle boundaries. It substantiates the reason why these parts with *Amphipora* limestone facies were preferred for construction of the Moravian composed MS section.

5. Comparison of MS and facies between Moravia and the Ardennes

When examining the MS curves from the Ardennes and Moravia composite sections, a clear resemblance appears: a progressive lowering of the MS signal during the end of Eifelian-beginning of Givetian, a series of high values during Lower Givetian, a low MS signal during the main part of the Givetian, an increase of MS near the Givetian-Frasnian boundary and relatively high and increasing values during the Frasnian. These MS trends are roughly similar to those observed for equivalent aged sections in Morocco and elsewhere (Ellwood et al., 2006; Ellwood et al., in press). Peaks and main trends are used for correlations (Fig. 5).

During the Upper Eifelian/Lower Givetian, both MS curves are decreasing. The Moravia composite records a progressive retrogradation and the Ardennes a progradation together with the first development of the Givetian carbonate platform (Fig. 5, a). The major MS rise (Fig. 5, b) occurring at the beginning of the Givetian corresponds to a rapid progradation in the Ardennes, with development of paleosols and restricted facies, and a rapid retrogradation in Moravia, with many transgression/deepening related signs, e.g., bryozoans, crinoids, rare cephalopods, dacryoconarids and other open sea organisms mixed into shallow coral-stromatoporoid banks. The low MS values in Moravia at c (Fig. 5) correspond to a second transgression, also visible in the Ardennes with the drowning of the platform and the generalization of external mid ramp facies. MS values remain high in the Ardennes. The next unit (Fig. 5, d), after a short transgression, is characterized by regression in both Ardennes and Moravia, with decreasing and low MS values. The MS peaks (Fig. 5, e) correspond in Belgium to the drowning of the Mont d'Haurs platform with detrital inputs, but are not associated with any sedimentological event in Moravia. The low MS values (Fig. 5, f), corresponding to the restricted Fromelennes *Amphipora* limestone in Belgium, are similar in Moravia, with equivalent facies. This is the only unit showing a strict parallelism of facies in the two areas. During this time, MS values are rising in Belgium and Moravia (Fig. 5, g), before a major transgression everywhere and the end of high MS values. This corresponds to the basal Frasnian flooding event. The

Frasnian MS curves (Fig. 5, h) show similar high amplitude oscillating MS values, in very different settings: external platform with mounds in the Ardennes, and a rapidly prograding internal platform in Moravia.

6. First interpretation of the origin of the MS signal

This paper represents a first comparison, at the 2nd order scale, of MS curves of Devonian sections located in two different palaeogeographical settings. Interpretations are therefore limited and preliminary.

The Moravian section encompasses pure platform limestone with a slight cyclic pattern. Detrital inputs are very low and environments are commonly restricted inside the open sea platform. The distance from large emerged land areas was great and no river deltas occurred in close palaeogeographic vicinity of this complex. The Ardennes section shows highly variable facies, with an alternation of ramp, platform and mound environments. Detrital inputs are locally very important, and preliminary gamma-ray spectrometric sections indicate general dominance of Th over U in limestone (results are opposite in Moravia, with U>>Th; Hladil et al., 2006). This indicates that argillaceous components dominate in the Belgian sections, in agreement with the palaeogeography at the site (Fig. 1). As an exception, the Upper Givetian shows roughly comparable facies for Ardennes and Moravia.

Together with facies dissimilarities, another important discrepancy between the two sections is the sediment accumulation rate. The thickness of the Ardennes section (820 m) is nearly 3 times higher than that from the equivalent Moravia sequence (280 m) (Fig. 4). This suggests completely different subsidence mechanisms.

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) driven by eustatic, climatic and tectonic variations (Crick et al., 1997). Theoretically, the MS curve increases during a sea level regression, and shows high values at low levels; and decreases during transgressions and shows low MS values during high levels. However, there is also a concurrent, facies-dependent model that takes effect where sea level rise or increased subsidence is not balanced by vertical reef-platform accretion, carbonate production or accommodation space on the slope or in sags. In these cases, the rising proportion of argillaceous material in deeper carbonate-rich environments can produce a trend toward increasing MS values, which may correspond to rising sea levels (e.g., Da Silva & Boulvain, 2004, 2006;

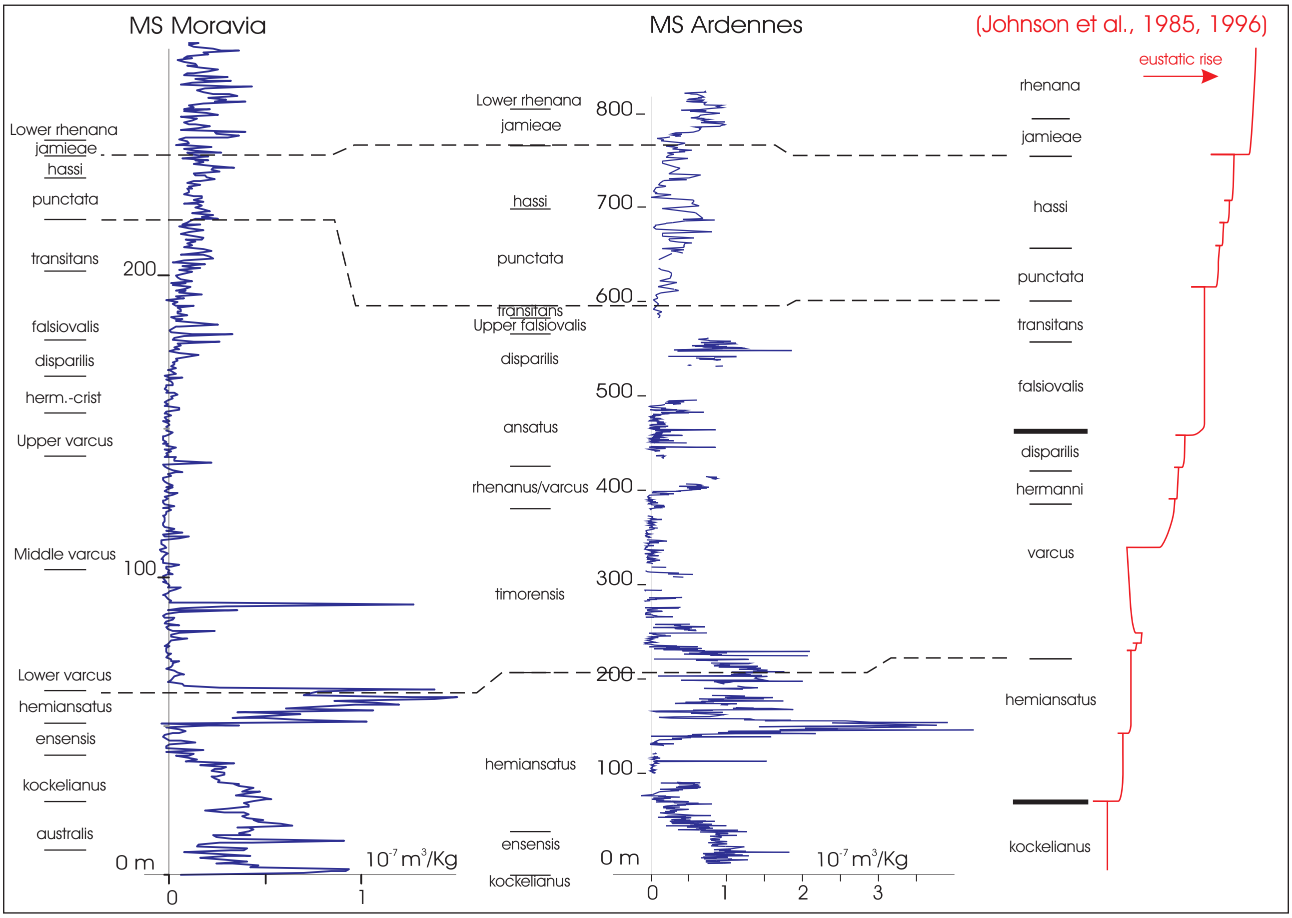

Figure 6. MS curves for Moravia and the Ardennes; conodont-based correlations and comparison with the Johnson et al. (1985) eustatic curve. Belgian conodont zonation after Gouwy & Bultynck (2000) and Préat & Bultynck (2006). Moravian zonation is a result of lateral projection of the conodont data from the drilled slope facies (Hladil, 2002; Hladil et al., 2006).

Babek et al., 2007 and this volume; Da Silva et al., 2009a and this volume).

The present study, covering a large part of the Devonian limestone sequences from two different environmental settings, shows a relative independence of the MS and the distal-proximal curves, deduced either from the microfacies record (Ardennes) or from shoreline shifts (Moravia) (Fig. 5). A noticeable exception corresponds to the Lower Givetian paleosols in the Ardennes that recorded the highest MS values.

The remarkable similarity of the two MS curves with a totally different background of palaeogeographical setting, facies, sedimentation rate and transgression-regression history, shows that observed MS stratigraphic patterns correlate among distant regions much better than is possible to predict from theoretical assumptions (Da Silva et al., 2009b). This implies of course some kind of forcing mechanism at least at the inter-regional scale.

Theoretically, a eustatic control, despite different local bathymetric changes, cannot be ruled out. However, a comparison of the MS curves with eustatic curve of Johnson et al. (1985) (Fig. 6) shows no evident correlation. The best degree of correspondence exists between the most general shape of these Belgian and Moravian local bathymetric curves and the eustatic curve as suggested by Morrow et al. (1995) and Hladil (2002), but significant discrepancies are observed at low scales (e.g., Hladil et al., 2009; Da Silva et al., 2009a, b).

At this point of the study, it seams realistic that more Devonian MS curves in different areas where the sedimentology is well known are necessary. Moravia and the Ardennes are located at the same palaeolatitude (Fig. 1), perhaps suggesting that a climatically driven mechanism is responsible for the detrital fraction and corresponding MS variations observed in these sediments. Trade winds are potential transporting mechanisms of dust, distributed widely through intertropical areas (Hladil et al., 2006).

As for stratigraphic correlation among the two MS curves, both logs must be further re-calibrated to a better defined series of chronological levels. Both the Ardennes and Moravian sections are problematic in detail. The accuracy of biostratigraphic scales is influenced by the intermittency of conodont occurrences in Belgium and a similar intermittency combined with uncertainty from basin-platform correlations in Moravia. A biostratigraphic advantage for the Belgian sections is seen in the fact that these sections are thicker and have more conodont tie points within the sections.

Finally, there are important discrepancies between biostratigraphy and the potential MS correlations among the two composite sections, (Figs 5 & 6), especially around the Eifelian-Givetian boundary (*ensensis/ hemiansatus* conodont zones).

7. Concluding remarks

This first analysis of long-term trends in Devonian MS variations in Belgian and Moravian mainly carbonate composite sequences shows a remarkable similarity, despite having large differences in palaeogeographical setting, facies, sediment accumulation rates and eustatic transgressive-regressive history. This MS similarity among these sequences provides the potentially to re-calibrate some of the biostratigraphical data determined for these sequences.

The similarity of the MS record, combined with a poor correlation to the global eustatic curve of Johnson et al. (1985) suggests a similar MS forcing mechanism, at least at the inter-regional scale, but this mechanism may not be directly connected to sea-level variations.

In this case, we must admit that some “latent, global or latitudinal climatic-eustatic regime” may be responsible for these unified MS changes that exhibit the same or a similar timing. Our reasoning is based on the fact, that the really high sea levels during some significant Givetian and Frasnian intervals correspond to large segments of the record where the MS signal is the lowest. During these times, periods when epeiric seas, microcontinents and islands, and also coastal lowlands, changed to carbonate platforms or carbonate seas, climates may have been “less dusty”, or less affected by continentally derived winds and corresponding dust.

To test our results and conclusions, we are expanding this work to allow us to compare results from the sections reported here to other long-term Devonian MS curves in different paleogeographic settings and palaeolatitudinal settings.

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