Sedimentology and magnetic susceptibility of the Upper Eifelian–Lower Givetian (Middle Devonian) in SW Belgium: insights into carbonate platform initiation

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Abstract: The major part of the Hanonet Formation is deposited on a mixed siliciclastic–carbonate detrital ramp, whereas the top is dominated by carbonate-rimmed shelf-related sedimentation. The transition corresponds roughly to the Eifelian–Givetian boundary. This work is based on two stratigraphic sections located in the southern part of the Dinant Synclinorium. Petrographic study leads to the definition of 11 microfacies, which demonstrate important sedimentological differences existing between the sections. A curve showing microfacies evolution is interpreted in terms of changing bathymetry. An environmental model depicts the lateral transition from a multiclinal carbonate ramp (to the east) to a fore-reef setting (to the west). Magnetic susceptibility was used to establish accurate stratigraphic correlations between the two sections. It also leads to an appreciation of the relative importance of eustatic sea-level change and local sedimentation rate. The combined interpretation of the microfacies curves and the magnetic susceptibility provides a new view of the sedimentary dynamics of the studied sections and, in a more general way, a better understanding of the processes responsible for magnetic susceptibility variations in carbonate rocks.

Limestones in the Upper Eifelian–Lower Givetian of SW Belgium provide an instructive means to investigate the initiation of a carbonate platform. This leads to fundamental questions about the mechanisms responsible for the transition from a mixed siliciclastic–carbonate detrital ramp during the Eifelian to a rimmed carbonate shelf near the Eifelian–Givetian boundary, and thus insight into the start of the 'carbonate factory' to understand the parameters that influence the carbonate production. Although the La Couvinoise quarry has already been studied several times in the past, it has never been the subject of detailed sedimentological work, and nothing has ever been published on Les Monts de Baileux. This first use of magnetic susceptibility to obtain accurate stratigraphic correlations and information about the sedimentary dynamic of the sections is also a test for the use of magnetic susceptibility in multiclinal ramp, containing a series of cliniforms (La Couvinoise) and fore-reef settings (Les Monts de Baileux).

Location and geological context

The Hanonet Formation is on both sides of the Eifelian–Givetian boundary. At this time, a large carbonate platform developed throughout northern Europe (Fig. 1a) and overcame the mixed siliciclastic–carbonate ramp.

The two studied sections are located along the southern flank of the Dinant Synclinorium, in the area of Couvin (Fig. 1b). The Dinant Synclinorium is part of the Rhenohercynian fold-and-thrust belt.

Studying the Eifelian–Givetian in Belgium is of crucial importance to understand this rapid and dramatic transition. The Hanonet Formation, then, forms the link between the Jemelle Formation (the last ramp-related unit of the Eifelian) and the Trois-Fontaines Formation (the first carbonate platform-related unit of the Givetian) (Fig. 2).

The first section (La Couvinoise) is located near the railway station in Couvin (400 m to the NW). Although the basal contact with the underlying Jemelle Formation is lacking, it exposes 85 m of the Hanonet Formation, up to the base of the biostromal unit of the Trois-Fontaines Formation.

Les Monts de Baileux quarry is located to the NE of the 32nd kilometre marker along the N66 road between Couvin and Baileux. The first 6 m of outcrop are part of the Jemelle Formation. Data were collected over 113 m up to the base of the biostromal unit of the Trois-Fontaines Formation.

Previous work and historical context

The biostratigraphy of the Eifelian at the southern flank of the Dinant Synclinorium is well established for the rugose corals (Coen-Aubert 1989, 1996, 1997, 1998), brachiopods (e.g.

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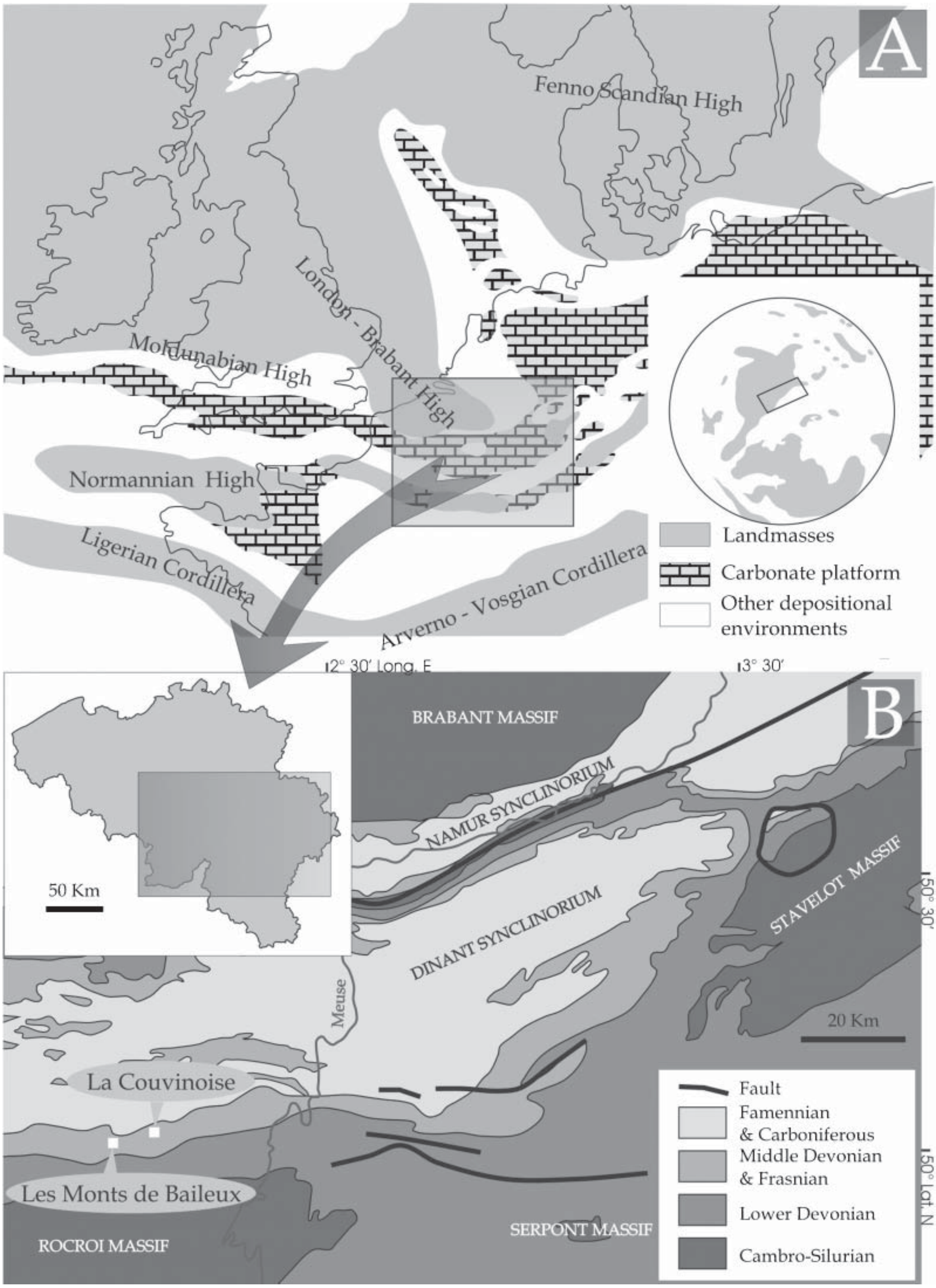


Fig. 1. (**a**) Palaeogeographic setting at the Eifelian (390 Ma), after Ziegler (1982) and McKerrow & Scotese (1990) showing the large carbonate platform that develops throughout northern Europe and overcomes the mixed siliciclastic–carbonate ramp. (**b**) Geological setting and location of the studied sections at the southern flank of the Dinant Synclinorium.

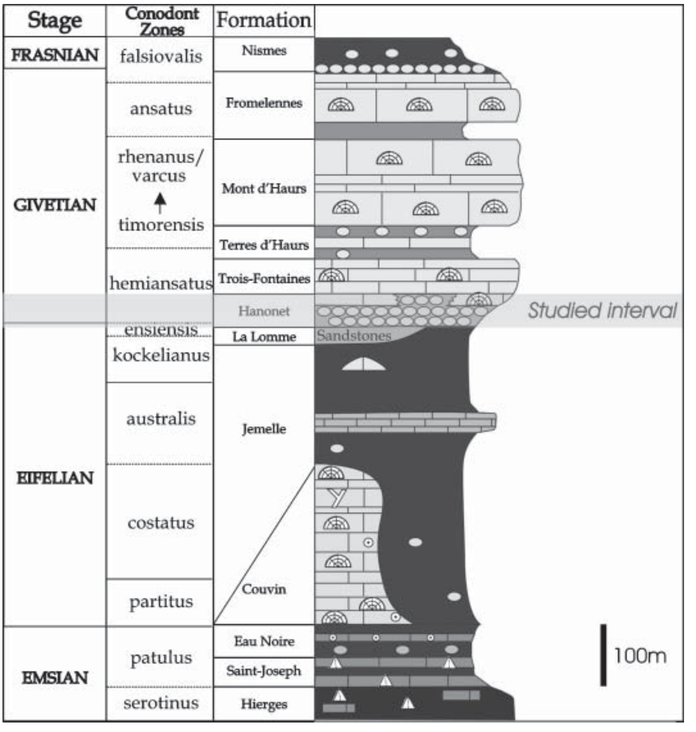


Fig. 2. Generalized lithostratigraphic section of Middle Devonian formations at the southern border of the Dinant Synclinorium, after Bultynck & Dejonghe (2001). The studied interval corresponding to the Hanonet Formation in located at the boundary between the Eifelian (ramp-related sedimentation) and the Givetian (carbonate platform-related sedimentation). Same legend as in Figure 3.

Godefroid 1995) and conodonts (e.g. Bultynck 1970).

The base of the Eifelian is now defined by the appearance of *Polygnathus costatus partitus* (Werner 1982). This species was found in Belgium above the basal limit of the old Couvinian stage. Moreover, the upper limit of the Eifelian, marked by the rising of *Polygnathus hemiansatus*, is below the upper limit of the Couvinian, which was placed at the top of the Hanonet Formation. Thus, the Eifelian and the Couvinian do not represent strictly the same stratigraphic interval, and the Eifelian is now regarded as the official name for the lower part of the Middle Devonian.

For the *Co2d* interval, the formal name of the Hanonet Formation, the stratotype was established in La Couvinoise quarry (Bultynck 1970) and the actual name Hanonet Formation was introduced by Tsien (1973).

The first sedimentological study of La Couvinoise quarry (Préat 1989) led to the definition of six microfacies. From these microfacies, three distinct environments were defined: external ramp, middle ramp and inner ramp. The stratigraphic succession of these environments corresponds to a general shallowing-upwards trend. A palaeoecological approach based on the ostracods (Casier *et al*. 1992) confirms this trend in La Couvinoise quarry from the top of the Hanonet Formation to the base of the Trois-Fontaines Formation.

A more detailed study of the Eifelian–Givetian transition led to the definition of 10 major microfacies and several submicrofacies deposited on a mixed siliciclastic–carbonate detrital ramp (Préat & Kasimi 1995; Kasimi & Préat 1996).

Methods

Bed-to-bed description and sampling were carried out in 2003 and 2004. From the samples, 550 thin sections were prepared. The textural classification used to characterize the microfacies follows Dunham (1962) and Embry & Klovan

(1972). The term 'coverstone' characterizes microfacies where laminar organisms cover mud and bioclastic debris (Tsien 1984). This led to the definition of 11 major microfacies and four submicrofacies, and to the establishment of a two-dimensional sedimentological model. These microfacies are compared to those defined for other Eifelian sections in Belgium (Préat 1989; Préat & Kasimi 1995). Then, each sample was submitted to magnetic susceptibility measurements with a KLY-3 (Kappabridge). Each sample was measured three times and weighed with a precision of 0.01 g. These operations allow the definition of the mass-calibrated magnetic susceptibility of each sample and the drawing of magnetic susceptibility curves for both sections.

Description of sections

La Couvinoise quarry

Five lithological units were defined (Fig. 3). The lowest consists of 39 m of dark very argillaceous limestone interbedded with subnodular beds of limestone. Brachiopods and crinoids that are often well preserved dominate the fauna. Some rugose corals, domical tabulate corals, *Receptaculites* and *Orthoceras* are also present near the top of the unit.

The second unit (from 39 to 50 m) starts with the first development of laminar stromatoporoids and branching tabulate corals. This unit is also characterized by enrichment in rugose corals, whereas the brachiopods are less abundant. Some gastropods, laminar tabulate corals and *Orthoceras* are also found. This limestone is less argillaceous but some centimetre-thick argillaceous interbeds are present.

The third unit (from 50 to 61 m) begins with pure limestone followed by slightly argillaceous limestone. The top of this unit is characterized by pure and very massive limestone in metre-thick beds. Crinoids, laminar stromatoporoids, rugose corals and branching tabulate corals dominate the fauna, but some domical stromatoporoids and tabulate corals are also present.

The fourth unit (from 61 to 77 m) is similar to the second one, in terms of the presence of argillaceous limestone and joints. The faunal assemblage is also similar, except for the replacement of the laminar stromatoporoids by laminar tabulate corals about 2 m above the base of this unit.

The uppermost unit (from 77 to 85 m) is composed of centimetre- to decimetre-thick beds of almost pure limestone interbedded with very argillaceous limestone. Crinoids dominate the fauna, whereas brachiopods, tabulate corals, rugose corals, gastropods and laminar stromatoporoids are less abundant. This unit corresponds to the first part of the Trois-Fontaines Formation defined as 'bedded argillaceous crinoidal limestones' (Bultynck & Dejonghe 2001).

Les Monts de Baileux quarry

Eight units are observed in this section.

The lowest lithological unit (A) is 6 m thick, and is composed of very argillaceous limestone with a sparse fauna of crinoids and brachiopods. At the top of the unit some lenticular decimetre-sized beds of slightly argillaceous limestone are present. This unit corresponds to the top of the Jemelle Formation.

A more abundant fauna and enrichment in gastropods characterize the B unit (from 6 to 26 m). This unit consists in an interbedding of several metre-thick sets of beds of purer limestone with more argillaceous limestone. Shaly interbeds are common.

In the C unit (from 26 to 41 m) the fauna become more diverse with the first development of domical stromatoporoids (up to 50 cm in diameter), laminar stromatoporoids and branching, domical and laminar tabulate corals. Crinoids are again present whereas brachiopods and gastropods are less abundant. This third unit is composed of variably argillaceous limestone.

The beginning of the D unit (from 41 to 57 m) is marked by an important faunal change. Although crinoids and domical tabulate corals are still present, domical stromatoporoids and branching tabulate corals disappear. As laminar skeletons of stromatoporoids and tabulate corals become less common, brachiopods and gastropods are more abundant. Finally, the first appearance of rugose corals and trilobites is observed. Lithologically, the limestone is less argillaceous even though some argillaceous interbeds are present.

The E unit (from 57 to 67 m) starts with a distinctive metre-thick tempestite with brachiopods, crinoids and gastropods. The unit is composed of slightly argillaceous limestone. The fauna includes crinoids, rugose corals, and laminar and domical stromatoporoids and tabulate corals.

The F unit (from 67 to 95 m) is characterized by argillaceous limestone becoming less argillaceous upwards. This unit resembles unit C. Some differences can be noted: rugose corals are present and some bioclastic decimetre-sized lenses are present.

The beginning of the G unit (from 95 to 101 m) is marked by a 5 cm-thick shale bed. The lower half of this unit is more argillaceous than

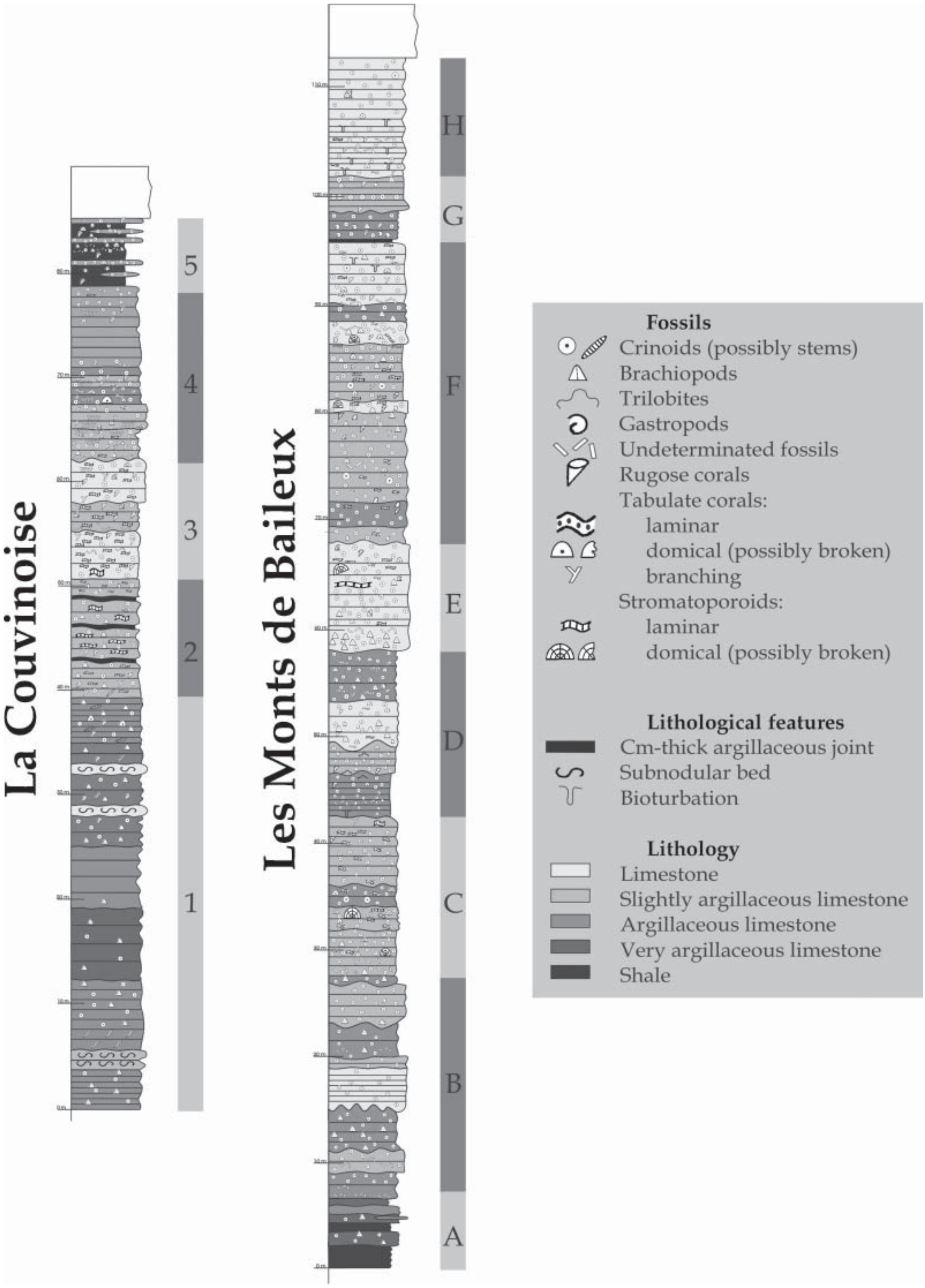


Fig. 3. Sedimentological log of the two studied sections showing the lithological units. These units are numbered from 1 to 5 for La Couvinoise section and from A to H for Les Monts de Baileux section. Both sections end at the base of the biostromal unit of the Trois-Fontaines Formation.

the upper half. The fauna consists of gastropods, crinoids, brachiopods, rugose corals and domical tabulate corals. Two decimetre-thick crinoidal grainstone beds are present; the first with an erosive base and the second lenticular.

Finally, the H unit (from 101 to 113 m) consists of bioturbated, slightly argillaceous limestone. Crinoids dominate the fauna but some tabulate corals (laminar, domical and branching), rugose corals, stromatoporoids (laminar and domical) and gastropods are also present. This eighth unit corresponds to the base of the Trois-Fontaines Formation defined previously as locally coral-rich crinoidal limestone (Bultynck *et al.* 1991).

Description of microfacies

The marked differences between the two sections lead to the use of two sets of microfacies: seven microfacies for La Couvinoise (MFC1–MFC7) and four microfacies for Les Monts de Baileux (MFB1–MFB4). Microfacies present in both sections (MFC5a and MFC6) are only described for La Couvinoise. For each section, the microfacies are described in order of increasing proximality (see Fig. 4).

La Couvinoise quarry

MFC1: slightly argillaceous mudstone with sparse fauna. Fossils are uncommon but characterize an open-marine environment: trilobites, crinoids, brachiopods, ostracods and bryozoans. These organisms are well preserved. Detrital quartz (up to 10%), framboidal pyrite and micas are present. Pressure-solution seams are also present.

MFC2: slightly argillaceous wackestone with crinoids and brachiopods. The dominant bioclasts are trilobites, crinoids, brachiopods, ostracods and bryozoans with some reef-building organisms and algae. Moreover, well-preserved ostracods, brachiopods, bryozoans and crinoids are common. Detrital quartz, framboidal pyrite and pressure-solution seams are present whereas micas become less common than in MFC1.

MFC3: slightly argillaceous packstone with crinoids and brachiopods. This microfacies is associated with MFC2 and MFC3 at the base of the section. At the top, it constitutes decimetre- to metre-thick beds. The fauna is dominated by trilobites, crinoids, ostracods and bryozoans, but is more diversified: gastropods, stromatoporoids, tabulate corals and some algae (mainly palaeosiphonocladaleans). Some fossils are well preserved (e.g. brachiopods, bryozoans, ostracods or trilobites). Detrital quartz reaches 7.5%, cubes of pyrite and micas are locally present.

MFC4: slightly argillaceous floatstone and rudstone with stromatoporoids and tabulate corals. This facies corresponds to centimetre-sized fragments of rugose corals, tabulate corals (domical, laminar and branching) and stromatoporoids (laminar and domical) in a slightly argillaceous micritic matrix. Other organisms such as crinoids, brachiopods, bryozoans, ostracods and trilobites are present. The degree of preservation of reef-building organisms is higher than that of other fossils. The detrital quartz become less abundant (<1%) and cubes of pyrite are observed.

MFC5: stromatoporoidal coverstone.

– *MFC5a: coverstone with reworked stromatoporoids in a slightly argillaceous matrix.* This microfacies is dominated by laminar stromatoporoids. They are well preserved, and some reach more than 1 m in diameter and 20 cm in thickness. The matrix is slightly argillaceous, and textures range from packstone to mudstone. Crinoids, ostracods and brachiopods dominate the fauna. However, other reef-building organisms (like domical tabulate corals and stromatoporoids and branching tabulate corals) and algae are locally present. Peloids (spherical or ovoidal and from 0.2 to 0.5 mm in diameter) are only present in Les Monts de Baileux quarry.

– *MFC5b: coverstone with* in situ *stromatoporoids in a microsparitic matrix.* These coverstones are similar to those described in MFC5a. The only difference is that they include *in situ* laminar stromatoporoids and a microsparitic non-argillaceous microsparitic matrix. This matrix, by its relative cohesiveness, is favourable to the preservation of shelter porosity corresponding to synsedimentary cavities under stromatoporoids (Boulvain 2001).

MFC6: microsparitic packstone and poorly sorted peloidal grainstone rich in bioclasts. The peloids represent 20–30% of the thin-section surfaces. Two different types are observed: similar to those described above (for MFC5a) or larger (0.5–1 mm) and irregular. They can be related to the micritization of bioclasts, as suggested by local relics of the original fossil. This microfacies is rich in bioclasts: crinoids, brachiopods, bryozoans, ostracods, algae (*Girvanella*, dasycladaleans, udoteaceans and palaeosiphonocladaleans) and gastropods in order of decreasing abundance. Detrital quartz can reach up to 10% in the La Couvinoise quarry.

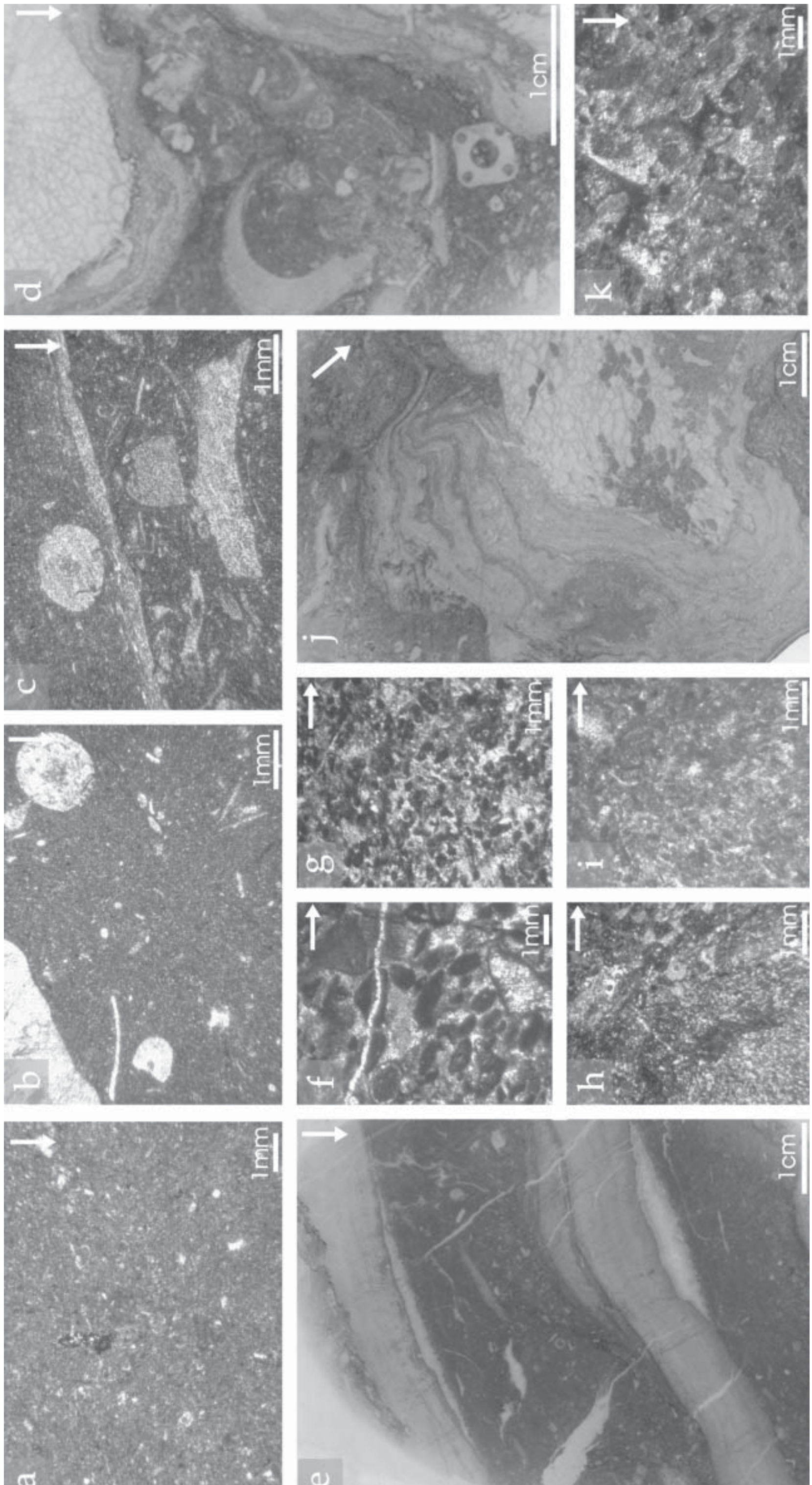


Fig. 4. Microfacies of the Hanonet Formation (arrows indicate bottom). See text for more explanations. (**a**) MFC1: locally argillaceous mudstone with poor fauna. (**b**) MFC2: locally argillaceous wackestone with crinoids and brachiopods. (**c**) MFC3: locally argillaceous packstone with crinoids and brachiopods. (**d**) MFC4: slightly argillaceous floatstone and rudstone with stromatoporoids and tabulate corals bioclasts. (**e**) MFC5b: coverstone with non-reworked stromatoporoids in a microsparitic matrix. (**f**) MFC6: microsparitic packstone and poorly sorted peloidal grainstone rich in bioclasts. (**g**) MFC7: well-sorted peloidal grainstone. (**h**) MFB1: mudstone with high terrigeneous content. (**i**) MFB2: peloidal wackestone with micritic matrix. (**j**) MFB3: floatstone with stromatoporoids and tabulate corals bioclasts in a peloidal matrix. (**k**) MFB4: crinoidal grainstone and packstone.

MFC7: well-sorted peloidal grainstone. Small ovoidal peloids (cf. MFC5a) dominate this microfacies (up to 50%). The other elements are very uncommon: algae (mainly *Girvanella*), crinoids and ostracods.

Les Monts de Baileux quarry

MFB1: mudstone with high terrigeneous content. These mudstones, locally laminated, are particularly rich in detrital quartz and/or clay with local presence of micas flakes. Oxidized iron is often abundant, giving a yellowish–reddish colour to the rock. The fauna is very rare and poorly diversified (crinoids and brachiopods). Locally, it includes broken bryozoans, ostracods, tabulate corals, palaeosiphonocladaleans, trilobites and echinoid spines. Peloids range from rare to abundant. Millimetre-thick lenticular wackestones or packstones are also present.

MFB2: peloidal wackestone with micritic matrix. Bioclasts of trilobites, brachiopods, crinoids, ostracods and bryozoans dominate the fauna. Small peloids (cf. MFC5a) are also present. Green algae are locally present (palaeosiphonocladaleans and dasycladaleans). These bioclasts are poorly preserved, except for those located in some packstone lenses. Note that dolomitized thin sections with replacement of matrix by euhedral dolomite crystals and less common preserved fossils (trilobites, brachiopods, crinoids, ostracods, bryozoans and palaeosiphonocladales) are considered as MFB2.

MFB3: floatstone with stromatoporoids and tabulate coral bioclasts in a peloidal matrix. Between domical tabulate corals, solitary rugose corals, laminar stromatoporoids and tabulate corals, matrix is peloidal and rich in calcareous algae: dasycladaleans, palaeosiphonocladaleans, udoteaceans and *Girvanella*.

MFC5a: coverstone with reworked stromatoporoids in a slightly argillaceous matrix. This is the same microfacies as that in La Couvinoise.

MFB4: crinoidal grainstone and packstone. Crinoids dominate the fauna, whereas peloids and bioclasts, such as trilobites, ostracods, bryozoans, brachiopods and some calcareous algae (palaeosiphonocladaleans and dasycladaleans), are less common. The crinoids are well sorted and locally surrounded by syntaxic cement.

MFC6: microsparitic packstone and poorly sorted peloidal grainstone. This is the same microfacies as that in La Couvinoise. However, two submicrofacies are distinguished in Les Monts de Baileux.

– *MFC6a: microsparitic packstone and poorly-sorted peloidal grainstone with trilobites.* Calcareous algae and reef-derived debris are very rare, whereas the open-marine fauna (trilobites, brachiopods, crinoids, ostracods and bryozoans) is well represented.

– *MFC6b: microsparitic packstone and poorly sorted peloidal grainstone with calcareous algae and reef-building organisms.* Whereas calcareous algae and reef-derived debris (solitary rugose corals, domical tabulate corals and stromatoporoids and laminar tabulate and stromatoporoids) corals are common, trilobite bioclasts are lacking.

Microfacies interpretation

Different criteria are available to interpret the palaeoenvironmental setting of each microfacies. Faunal association and depositional texture directly reflect the level of energy and agitation. Two major sets of organisms have been described: open-marine fauna (trilobites, bryozoans, crinoids, brachiopods and ostracods); and reef-building organisms (rugose corals, tabulate corals and stromatoporoids). Calcareous algae (abundance and nature) and peloids are also significant constituents. Other criteria like sorting, terrigeneous content, nature of matrix and degree of preservation of bioclasts are also relevant. Moreover, a comparison with other microfacies defined in the literature for Eifelian rocks is made when possible. Every microfacies described here above may be interpreted in terms of degree of distality and relative bathymetry.

La Couvinoise quarry

The major difference between MFC1, MFC2 and MFC3 is texture, which ranges from mudstone to wackestone and packstone. However, they are similar in terms of faunal assemblage, nature of matrix, and detrital quartz and mica content. They were deposited in a similar environment and the faunal assemblage suggests an open-marine setting. The presence of packstone lenses within mudstones and wackestones can be interpreted as relatively distal storms deposits (Dott & Bourgeois 1982), such that MFC3 may represent storm deposits within MFC1 and MFC2. Thus, these microfacies correspond to an open-marine environment located below fair-weather wave base (FWWB) but above storm wave base (SWB). This is also the interpretation made for similar microfacies of the Eifelian–Givetian boundary interval in the Dinant Synclinorium (Préat & Kasimi 1995). A study of ostracod fauna from La Couvinoise quarry (Casier *et al.* 1992) determined a dysaerobic environment for this microfacies.

MFC4 includes debris coming from a reefal environment, but open-marine conditions still prevailed. Their more agitated nature, as shown by the floatstone/rudstone textures, points to an environment situated close to the FWWB. The same interpretation was made for similar microfacies (Préat 1989; Préat & Kasimi 1995).

The development of laminar stromatoporoids characterizing MFC5 corresponds to favourable conditions in terms of bathymetry, substrate and sufficiently low detrital input (see, for example, Kershaw 1998). These favourable conditions may correspond to a lowering of detrital input from the nearby landmasses. In La Couvinoise, the first stromatoporoids are observed simultaneously with a lithological change from very argillaceous limestone to less argillaceous limestone, indicating a lowering in detrital input. In MFC5a some stromatoporoids are overturned, suggesting a higher influence of storms and a location near the FWWB (Kershaw 1980). This environment may be regarded as a potential source for part of the debris in MFC4 but another source, probably a biostromal unit, is needed for domical stromatoporoids and tabulate coral debris.

The main characteristic of MFC6 is the abundance of peloids. They probably have a shallow-water, low-energy origin like a lagoon or a back-reef area (see, for example, Tucker & Wright 1990). Moreover, in other Eifelian sections studied in Belgium, the presence of peloids is also linked to the development of reefal settings (Préat & Kasimi 1995; Mamet & Préat 2005). This proximal environment might also be responsible for the production of calcareous algal debris. It is noticeable that there is a mixing between the two kinds of sediment (open-marine bioclasts and peloids + calcareous algae). This suggests that the proximal material (supplied by storm deposits or debris flow) and the open-marine bioclasts (supplied by storm deposits) are deposited in the same environment and then mixed by bioturbation. The grainstone texture suggests a location within the FWWB.

The MFC7 shows a higher influence of the peloidal source than the MFC6 and the good sorting involves a more continuous degree of agitation. This microfacies is considered as the most proximal one.

Les Monts de Baileux quarry

MFB1 represents the deepest microfacies of both sections. The primary sedimentation mechanism process is slow accumulation of suspended mud and minute debris, but small wackestone and packstone lenses probably represent distal storm deposits. This suggests that this microfacies was located just above the SWB (Préat & Kasimi 1995).

Again, two sources of debris must be considered to explain the nature of the MFB2 assemblage: an open-marine one (trilobites, bryozoans, crinoids, brachiopods and ostracods) and a transported but proximal one (peloids and calcareous algae, and possibly micrite). The proximal origin of the micrite is uncertain and we are not able to exclude a local production of this micrite. MFB2 was situated within the SWB, the packstone lenses representing storm deposits.

MFB3 possess the same characteristics as MFC4, except that it is influenced by a proximal source supplying peloids and calcareous algae, and perhaps micrite.

MFC5a is similar in both sections, except that in Les Monts de Baileux there was a greater supply of peloids.

MFB4 is mainly characterized by well-sorted crinoidal grainstone and packstone. Such an accumulation of crinoids corresponds to storms deposits around the FWWB. The environment is largely influenced by an open-marine source while material originating from proximal areas is less abundant.

MFC6 includes two submicrofacies. The main difference concerns the relative importance of the two sources of debris. MFC6a is more influenced by the open-marine source, whereas MFC6b is more influenced by the proximal area.

Palaeoenvironmental model

Microfacies interpretation of each section leads to the conclusion that the two depositional environments are different (Fig. 5). La Couvinoise quarry is more influenced by a fine-grained detrital input, whereas Les Monts de Baileux quarry is characterized by a more proximal carbonate

	La Couvinoise	**Les Monts de Baileux**
Setting	Multiclinal ramp	Fore-reef
Reef	None?	Present
Terrigenous input	High	Low
Carbonate input	Low	High
Total input	Lower	Higher

Fig. 5. Summary of main palaeoenvironmental features.

influence. The palaeoenvironmental model proposed here is based on a synthesis of microfacies interpretation and explains the major differences between the two sections (Fig. 6). This model describes the lateral transition from a multiclinal carbonate ramp (La Couvinoise) to a fore-reef environment in a platform setting (Les Monts de Baileux). Without any barrier in La Couvinoise (this absence is perhaps caused by the terrigenous input itself) terrigenous material are allowed to spread, whereas a barrier would have created a more protected environment, potential source of peloids, calcareous algae and lime-mud. In the first case, however, the detrital input was not too great to prevent the development of isolated stromatoporoid bioconstructions in La Couvinoise, whereas in the second situation the input of carbonate detritus was so abundant that the development of stromatoporoids is very poor.

Microfacies curves interpretation

The palaeoenvironmental evolution, highlighted by the microfacies curves, is described lithological unit by lithological unit for each section. This allows a better understanding of the differences existing between them (Fig. 7).

La Couvinoise quarry

The first unit is characterized by MFC1, MFC2 and MFC3 (note that in the second third of the unit, MFC1 is very dominant). Referring to the microfacies interpretation, this unit corresponds to open-marine setting, under the FWWB and above the SWB.

A wide variety of microfacies (MFC2, MFC3, MFC4, MFC5a, MFC5b and MFC6) is present in the second unit. It marks: (1) an increase of storms energy and influence, shown by the apparition of MFC4; (2) the presence of MFC6, which shows that the FWWB is reached at the top of the unit; (3) the development of stromatoporoids (MFC5a and MFC5b); and (4) there is an evolution to more proximal microfacies along this unit.

The microfacies present in the third unit are similar to those present in the second one (except MFC2). The evolution, however, is just the opposite and goes from proximal to distal settings.

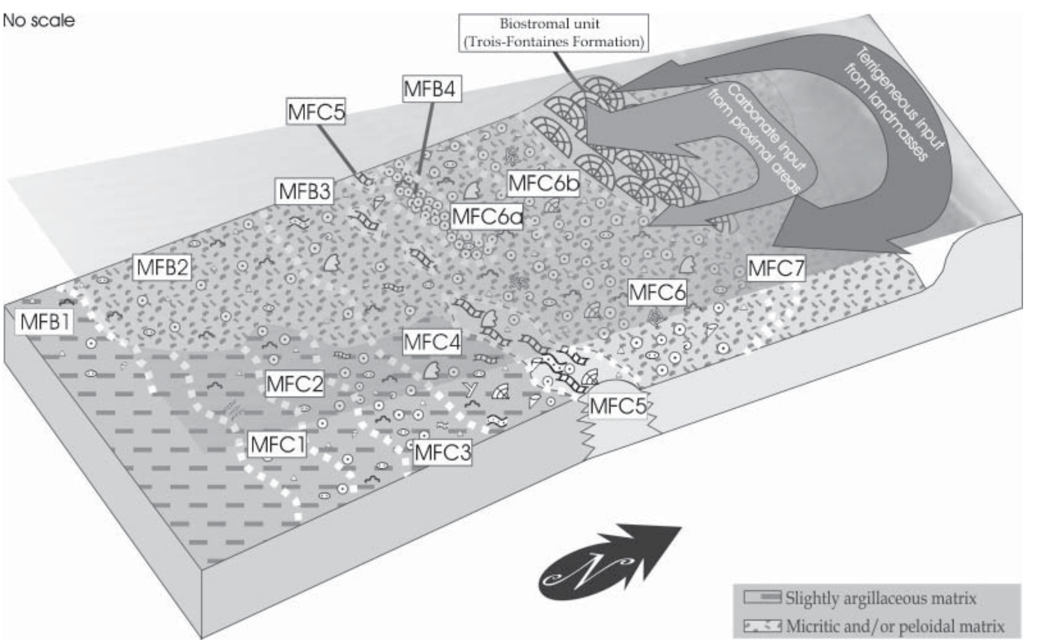


Fig. 6. Proposed palaeoenvironmental model. Same legend as in Figure 3. This model shows the lateral transition from a multiclinal carbonate ramp (La Couvinoise) mainly influenced by a fine-grained detrital input to a fore-reef setting (Les Monts de Baileux) characterized by the major influence of a proximal source of carbonate (peloids and calcareous algae, and possibly micrite).

The fourth unit is characterized by MFC3, MFC4, MFC5a and MFC6 and can be divided in two. The first half is characterized by an oscillating microfacies curve showing a background sedimentation around the FWWB (MFC3, MFC4 and MFC5a) often flooded by peloids, calcareous algae and carbonate input originating from a more proximal area (MFC6). Nevertheless, the second half of the fourth unit shows an evolution from MFC3 to MFC6.

The fifth and last unit is also characterized by an oscillating curve between MFC3 and MFC4, on the one hand, and MFC6 and MFC7, on the other. MFC3 and MFC4 involve a location under the FWWB with a high terrigeneous input (confirmed by the abundance of shale). However, proximal carbonate inputs are also well represented, as shown by MFC6 and MFC7.

Les Monts de Baileux quarry

Except for the A unit, the microfacies curve is characterized by lots of oscillations in Les Monts de Baileux. These oscillations occur between two groups of microfacies. The first group (MFB2, MFB3, MFC5a and MFB4) represents the background sedimentation with a limited but present proximal influence, whereas the second (MFC6a and MFC6b) corresponds to high proximal inputs in carbonate (peloids and calcareous algae, and possibly micrite).

A unit is divided into two parts. The first part is only composed of MFB1, whereas the top is composed of MFB4. This shows a rapid transition from the SWB to the FWWB.

In the B unit microfacies are MFB2 and MFB4 (Group 1) and MFC6a and MFC6b (Group 2). Moreover, it is remarkable that the interbedding of several metre-thick sets of beds of purer limestone within more argillaceous limestone corresponds, respectively, to parts where group 2 and group 1 are dominant.

C and D units are both characterized by a group 1 represented by MFB2 and MFB3 and a group 2 composed of MFC6a and MFC6b. The first group indicates energetic settings, but still under the FWWB. The difference between C and D consists of the fact that the first group of microfacies dominates the C unit, whereas the second dominates the D unit. This explains why the D unit is composed of more massive limestone.

The E unit is very massive, this is related to the dominance of MFC6b and MFC6a (Group 2). MFB2 is poorly represented.

Oscillations are again observed within the F unit between group 1 (MFB2 and MFB3) and group 2 (MFC6b and MFC6a). The last is still dominant. It is also noticeable that laminar stromatoporoids (MFC5a) are present only in this unit.

Group 1 (MFB2 and MFB3) dominates group 2 (MFC6b and MFC6a) in the G unit. This indicates a lower influence of the proximal carbonate input.

The H unit is dominated by MFC6a at the base and MFC6b at the top. Group 1 (MFB2) is poorly represented.

Microfacies curves: conclusions

There is also a large difference between the two sections that prevents any correlation based on sequence stratigraphy from being made (Fig. 7). In fact, it is possible to plot the bathymetric evolution in La Couvinoise by interpreting the microfacies curves; this interpretation suggests a general shallowing-upwards trend. For Les Monts de Baileux, however, the major process that defines the microfacies curve involves the pulses in the carbonate influx, which were independent of bathymetry. These two distinct sedimentary dynamics explain why no correlation based on sequence stratigraphy can be made.

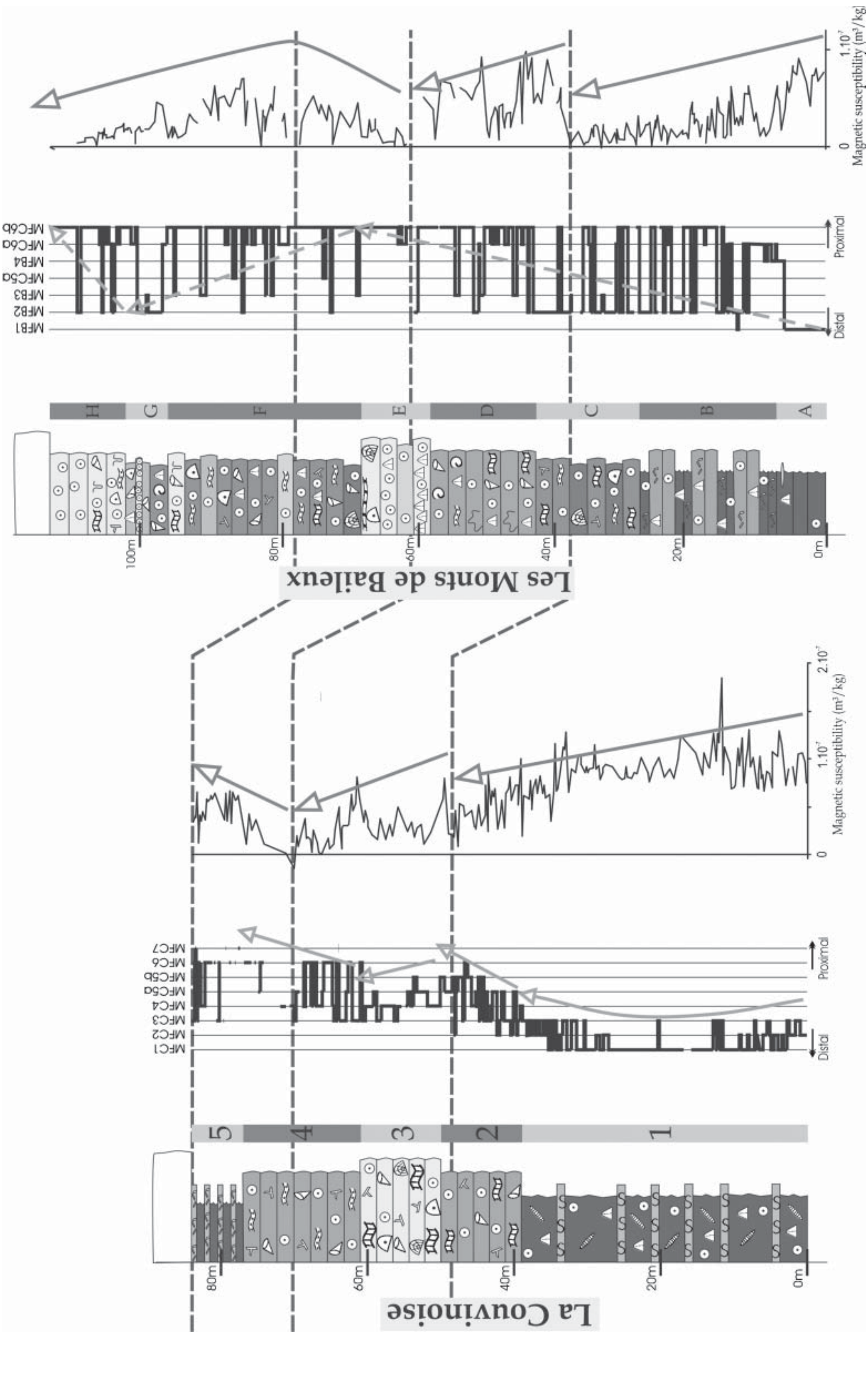
Magnetic susceptibility

Principles

Magnetic susceptibility (MS) is a measure of the sample response to an external magnetic field first employed in the study of Palaeozoic rocks during the 1990s. For sedimentary rocks, the major influence on MS is the terrestrial fraction. This can be linked to eustasy because when the sea level falls, the erosion of exposed continental masses increases and this typically leads to higher MS values. On the other hand, when the sea level rises, MS shows lower values. Thus, MS can be used to obtain accurate correlations with higher resolution than that offered by biostratigraphy (Crick *et al.* 1997; da Silva & Boulvain 2002). It is important to note that other influences like climatic changes (precipitation, ice ages, pedogenesis), tectonism, diagenesis, volcanism, impact ejecta and so on may also influence MS values.

MS values and correlations

When comparing the MS values of the two sections, similar trends and events are observed (Fig. 7). These are considered as isochronous and facies-independent, and thus correlatable (see also Ellwood *et al.* 1999). Moreover, the average value for each section (6.38×10^{-8} m^3 kg^{-1} for La Couvinoise and 2.92×10^{-8} m^3 kg^{-1} for Les Monts


Les Monts de Baileux
La Couvinoise
Magnetic susceptibility (m³/kg)
Proximal
Distal
MFB1
MFB2
MFB3
MFC5a
MFB4
MFC6a
MFC6b
MFC1
MFC2
MFC3
MFC4
MFC5a
MFC5b
MFC6
MFC7
A
B
C
D
E
F
G
H
1
2
3
4
5
0m
20m
40m
60m
80m
100m

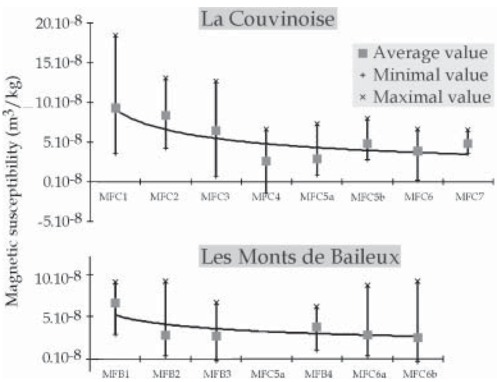


Fig. 8. Average, minimal and maximal MS values plotted by microfacies for each location. These curves show a general decreasing in average values from distal to proximal microfacies in both sections.

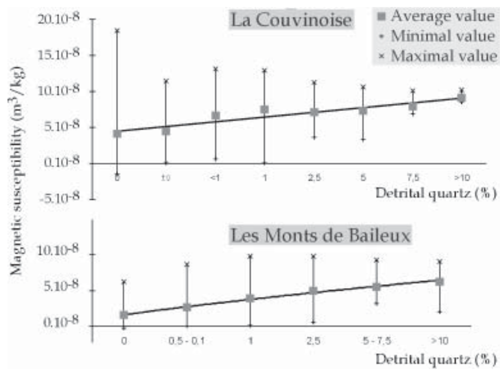


Fig. 9. Average, minimal and maximal magnetic susceptibility values plotted by percentage of detrital quartz for each location. Although quartz is diamagnetic and has a weakly negative magnetic susceptibility signature, and thus does not affect the overall MS values, it is regarded as a good proxy for detrital content.

de Baileux) confirms that the environment in La Couvinoise was subjected to a greater detrital input, accounting for its higher MS values.

Available data in literature (e.g. Hladil *et al.* 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 (Fig. 8) shows just the opposite trend, with higher MS values for distal microfacies and lower values for proximal ones. This can be explained if the environment of deposition of the Hanonet Formation was located sufficiently far from the detrital source to homogenize the detrital supply. In this situation there is no great difference in the terrestrial input for each microfacies. Thus, the major influence on the MS value is the dilution by the carbonate production. So the greater the carbonate productivity, the greater the dilution of the MS signal.

MS interpretation

If the MS response is related to sea-level change, it is surprising to observe such a divergence between it and the microfacies curves (Fig. 7). Published data (da Silva & Boulvain 2002) usually report strong correlation between MS and bathymetric interpretation based on microfacies. This is noticeably the case for La Couvinoise, where the microfacies curve suggests a general shallowing-upwards trend, whereas the MS curve corresponds grossly to a general deepening-upwards trend followed by a (slight) shallowing-upwards trend.

Making a semi-quantitative estimate of detrital quartz content for each thin section, a strong correlation between the abundance of detrital quartz and MS values (Fig. 9) is apparent. While the detrital quartz does not carry the MS signal, it is a good indicator of the detrital input, at least for the two sections studied here. Therefore, it is certain that the MS is correlated to the detrital input.

In other sections, for example Aywaille and Tailfer from the Frasnian of Belgium (da Silva & Boulvain 2003), the MS and microfacies curves are nearly parallel. Each transgressive or regressive trend is registered in both curves. It is quite different for La Couvinoise and Les Monts de Baileux. In fact, in La Couvinoise, the two curves seem to be opposed for the two first lithological units. Then they are more correlated, even if

Fig. 7. Schematic sedimentological log, microfacies curves and magnetic susceptibility curves. Same legend as in Figure 3. Arrows represent trends in curves and dashed lines the correlation lines mainly based on MS features. For microfacies curves, trends are defined lithological unit by lithological unit in La Couvinoise. Note also that the oscillating microfacies curve in Les Monts de Baileux, related to a different sedimentary dynamic, prevents from any reliable trend from being considered. This is why no correlation based on sequence stratigraphy can be made.

there is a kind of time lag in that the same trends are present somewhat later in the MS curve. To understand the different mechanisms or environmental parameters that constrain the different curves, it is necessary to focus on the contrasting depositional environments of the two sections: a carbonate platform for Aywaille and Tailfer; and a ramp and fore-reef setting for La Couvinoise and Les Monts de Baileux.

At the very least, the microfacies curve gives information about the local bathymetric evolution. A hypothesis is that the MS variations, reflecting continental erosion, are correlated to global sea-level change. In this case it corresponds to a general deepening-upwards trend followed by a shallowing-upwards trend, allowing the development of the Trois-Fontaines Formation biostromal unit. It so happens that this is confirmed by the global sea-level curve available in the literature (Johnson *et al.* 1985). If the trends observed for local and global sea-level evolution are not the same, different sedimentation rates may explain these differences.

Here, the shape of the microfacies curves is related to local bathymetry, dependent on both global sea-level fluctuation and the sedimentation rate. Considering local variations in the sedimentation rate, significant differences between the local and global sea-level evolution can be obtained. The different sedimentary dynamics shown by the microfacies analysis can explain the differences between the sedimentation rate in each section. For Les Monts de Baileux, microfacies analysis has already shows that the major influence on the microfacies evolution is the carbonate input, creating a relative independence between the global sea-level curve (shown by MS) and the local sea-level change (shown by the microfacies curve). However, the differences between the local and global sea-level evolution in La Couvinoise can be explained by considering major variations in sedimentation rate provided by strongly contrasting carbonate productivity. Thus, the 'carbonate factory' worked at different rates (owing to ecological parameters) to fill in the free space left by the global sea-level pattern. For example, if the 'carbonate factory' worked faster than the eustatic sea-level rise, it can produce a regressive event that has the appearance of a local sea fall.

Conclusions

For this study of the Hanonet Formation, two sections were considered: La Couvinoise (the stratotype) and Les Monts de Baileux, whose marked differences are evident even in the field.

Petrographic analyses led to the definition of 11 microfacies and four submicrofacies, of which only three are observed in both locations. All these microfacies are integrated to a two-dimensional palaeoenvironmental model depicting the lateral transition from a multiclinal carbonate ramp (La Couvinoise) to a fore-reef setting (Les Monts de Baileux). The former environment is mainly characterized by enhanced terrigenous input, whereas the latter is greatly influenced by back-reef-derived sediment deposition. This also implies a major divergence between both sections in terms of sedimentary dynamics that does not allow suitable high-resolution stratigraphic correlations based on sequence stratigraphy.

However, magnetic susceptibility analyses revealed itself to be a powerful tool to establish accurate stratigraphic correlations between the two sections. The combined interpretation of the microfacies and the magnetic susceptibility curves proved instructive. This interpretation, mostly based on the La Couvinoise quarry, explains the apparent divergence existing between the general shallowing-upwards trend recorded by the microfacies curve and the two deepening-upwards trends followed by a shallowing-upwards trend shown by magnetic susceptibility. This situation can be explained by a difference between the evolution of the local bathymetry and global sea level induced by differences in the rates of sedimentation. In this case, eustasy is reflected in the evolution of the magnetic susceptibility, whereas the microfacies curve records the local relative sea-level evolution.

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