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SEDIMENTOLOGY AND MAGNETIC SUSCEPTIBILITY OF THE COUVIN FORMATION (EIFELIAN, SOUTH WESTERN BELGIUM): CARBONATE PLATFORM INITIATION IN A HOSTILE WORLD

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(8 figures and 2 plates)

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ABSTRACT. The Eifelian of Belgium is mainly characterised by a mixed siliciclastic-carbonate sedimentation on a ramp profile. In this context, the Couvin Formation is the more important and remarkable exception. It represents a carbonate platform initiation in a hostile environment. This work is mainly based on the stratotype, corresponding to two stratigraphic sections located in Couvin, along the southern border of the Dinant Synclinorium. These sections are the Eau Noire and Falaise de l'Abîme sections. Unfortunately, they are discontinuous. To allow a better understanding of the sedimentary dynamics, the data are complemented by a shorter but continuous section located in Villers-la-Tour (3.5 km West of Chimay).

Petrographic study leads to the definition of 14 microfacies which are integrated in a palaeogeographical model. It corresponds to a platform setting where the reef complex is mainly constituted by an accumulation of crinoids, stromatoporoids and tabulate corals. The microfacies evolution is interpreted in terms of bathymetrical variations. It shows a general shallowing-upward trend encompassing the vertical succession of fore-reef settings, reef development, back-reef and then lagoon environment. This interpretation is supported by trends in mean magnetic susceptibility data, providing a better understanding of the sedimentary dynamics. Moreover, these data show positive correlation with concentrations of detritic minerals, but an inverse relationship with well washed skeletal limestones.

The comparison of the three studied sections leads to considerations concerning the lateral variability in the Couvin Formation indicating more agitated conditions in the Abîme Member in Villers-le-Tour section.

KEYWORDS: Eifelian, Couvin Formation, type area, carbonate platform initiation.

1. Introduction

Placing the Couvin Formation in its geological context is important to understand the interest of the present work. In fact, at the Eifelian-Givetian boundary, a large carbonate platform developed throughout northern Europe (Fig. 1A). Studying the Eifelian is consequently interesting to understand this important palaeoenvironmental and ecological event.

This work details the sedimentology and the magnetic susceptibility data on the stratotype of the Couvin Formation cropping out at the southern flank of the Dinant Synclinorium between Macon to the west and Dion to the east of the Meuse River (Fig. 1B). The thickness of this formation is estimated to about 380m between Couvin and Nismes but rapidly decreases to the east.

In this context, the Couvin Formation is a case study because it represents a first start of the carbonate factory in a mixed siliciclastic dominated environment (Fig. 2).

1.1. Short history

The first definition of the "Calcaire de Couvin" was made by Gosselet (1860) and refers to the most important mass of Eifelian limestone cropping out from Couplevoie to Nismes. This limestone was thought to be a fringing reef (Gosselet, 1888). Then, Mailleux introduced a new way to name the devonian formations (Mailleux, 1910). This nomenclature (see Fig. 2) was slightly modified by various authors, and by Mailleux himself. Following the key of the Belgian geological map, the term "Cobm" was introduced to refer to the basal limestone of the Couvinian stage with stromatoporoids and corals (*Heliolites porosa*, *Favosites polymorpha*) (Mailleux, 1912). Then, "Co2b" was proposed for the same lithostratigraphic interval (Mailleux & Demanet, 1929) and later replaced by "Co2a + Co2b" (Bultynck, 1970), "Co2a" referring to *Euryspirifer intermedius* zone and "Co2b" to the stromatoporoid limestone. This author recognized three biostromal units separated by subsidence phases. The term "Calcaire de Couvin" was reintroduced by Bultynck & Godefroid (1974) and by Tsien (1974). The Couvin Formation name was finally officialised by Bultynck *et al.*, (1991) and two members were defined (in stratigraphical order): the Foulerie Member and the Abîme Member.

1.2. Location of sections

The three studied sections are located in the Chimay-Couvin area, southwestern Belgium (Fig. 3). The first one, the Eau Noire section, crops out along the west side of the Eau Noire River. The starting point of sampling and

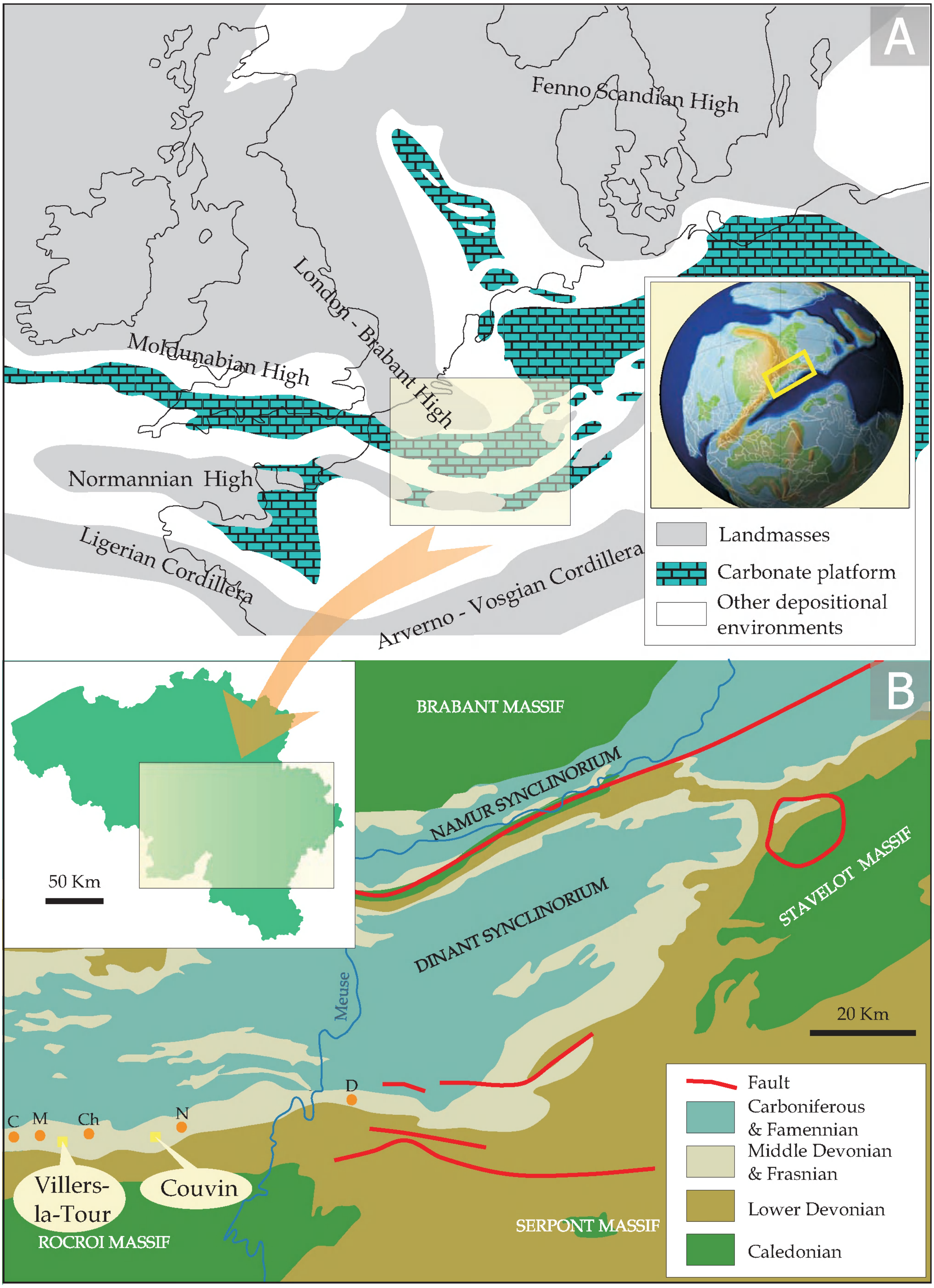


Figure 1: A: Palaeogeographic setting at the Eifelian (390 Ma), after Ziegler (1982) and McKerrow & Scotese (1990) showing the large carbonate platform which develops throughout northern Europe and overcomes the mixed siliciclastic-carbonate ramp.
B: Geological setting and location of the studied sections at the southern flank of the Dinant Synclinorium. C: Couplevoie, M: Macon, Ch: Chimay, N: Nismes, D: Dion.

description is located behind the swimming pool in the Foulerie locality. The base of the section (Pl. 1A) corresponds to the base of the Couvin Formation as defined as the first succession of thick-bedded limestones overlying the last thick bed of calcareous shales of the Eau Noire Formation (Bultynck *et al.*, 1991). Although the first 80 and last 50 metres of section are more or less continuous (Pl. 1B), the middle interval of 160 metres is poorly exposed. So, even if the studied interval has an approximate thickness of 285 metres, only 135 metres of outcrop are really present. The section ends behind the houses in the Rochettes Street (Pl. 1C).

The second section corresponds to the cliff above the "Trou de l'Abîme" cavern, on the east side of the Eau Noire River (Pl. 1D). This section has a thickness of 33 metres. The stratigraphic gap between the two sections can be approximately estimated to 85 metres after Bultynck (1970) and from the geological map (Marion & Barchy, 1999). In the present work, the total thickness of the Couvin Formation is estimated to 400 m. This value is to be compared with the classical estimation of 380 metres in Couvin (Bultynck & Dejonghe, 2001). The difference can easily be explained by gaps in the Eau Noire section, presence of faults, various estimations made for gaps between the two sections, etc.

The third section is located 3.5 kilometres West of Chimay, in an abandoned quarry in Villers-la-Tour (Pl. 1E). This section shows a 55 m-thick continuous succession of strata.

1.3. Methods

Bed-to-bed description and sampling were carried out in 2002 and 2003 for the Eau Noire and the Abîme sections. The description of Villers-la-Tour section is adapted from the work of Marc Bertrand (Bertrand, 1990; Bertrand *et al.*, 1993). From the samples, 930 thin sections were prepared. The textural classification used to characterize the microfacies follows mainly the textural-structural principles introduced by Dunham (1962) and Embry & Klovan (1972) but also Folk (1959). The description of stromatoporoids is based on morphological classification by Kershaw (1998). The terms used are branching, laminar, domical and bulbous. The term massive (Tucker & Wright, 1990) is used for both domical and bulbous forms when the difference cannot be made (fragments or thin sections). The term "coverstone" characterises microfacies where laminar organisms cover mud and bioclastic debris (Tsien, 1984).

This led to the definition of 14 microfacies, followed by the construction of a sedimentological model, and by the plotting of microfacies curves. These microfacies are compared to those defined for the limestone strata near the Eifelian-Givetian boundary in Belgium and France (Mabille & Boulvain, *in press*; Préat & Kasimi, 1995) and to Standard Microfacies (Wilson, 1975).

The bulk magnetic susceptibility for every sample was measured using a KLY-3 Kappabridge. The magnetic susceptibility response was measured three times and these values were averaged. Resolution of 0.01g was sufficient for determining the sample weight. These operations allow the calculation of the mass-calibrated magnetic susceptibility of each sample.

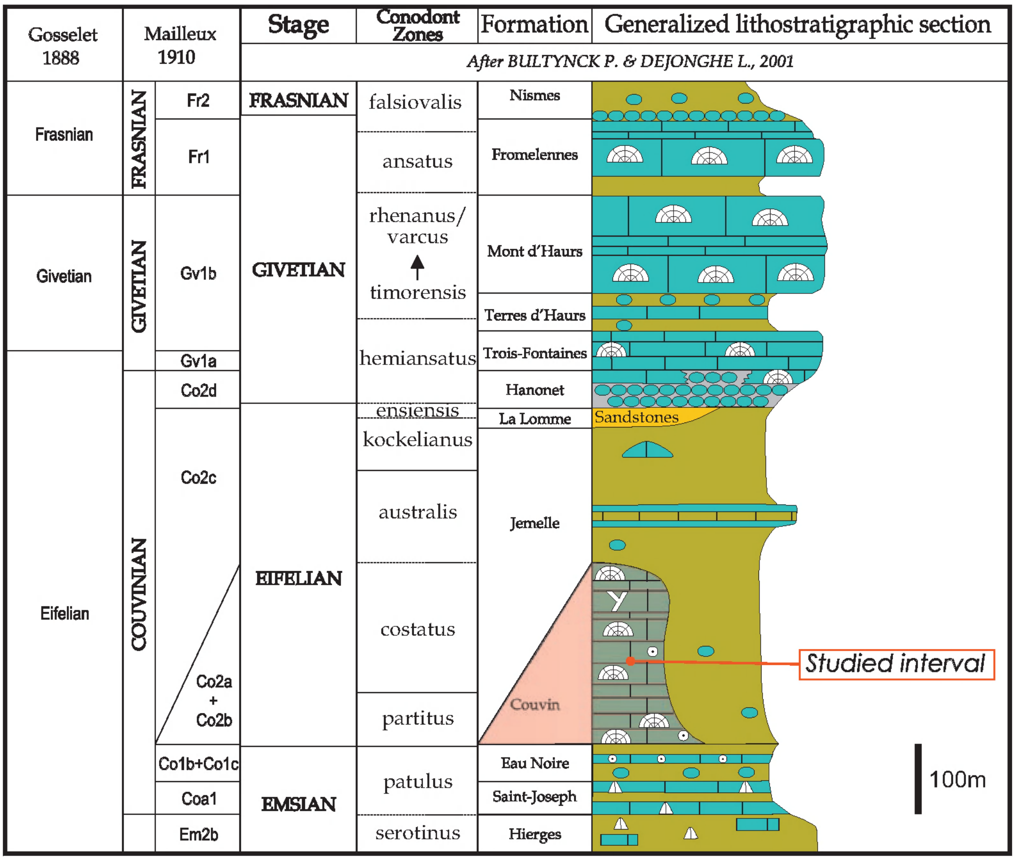


Figure 2: Generalized lithostratigraphic section of Middle Devonian formations at the southern border of the Dinant Synclinorium, after Bultynck & Dejonghe (2001). The studied interval corresponds to the Couvin Formation. It is located under the boundary between the Eifelian (ramp-related sedimentation) and the Givetian (carbonate platform-related sedimentation). The Couvin Formation represents a first start of the carbonate factory in a mixed siliciclastic dominated environment. See Fig. 5 for legend.

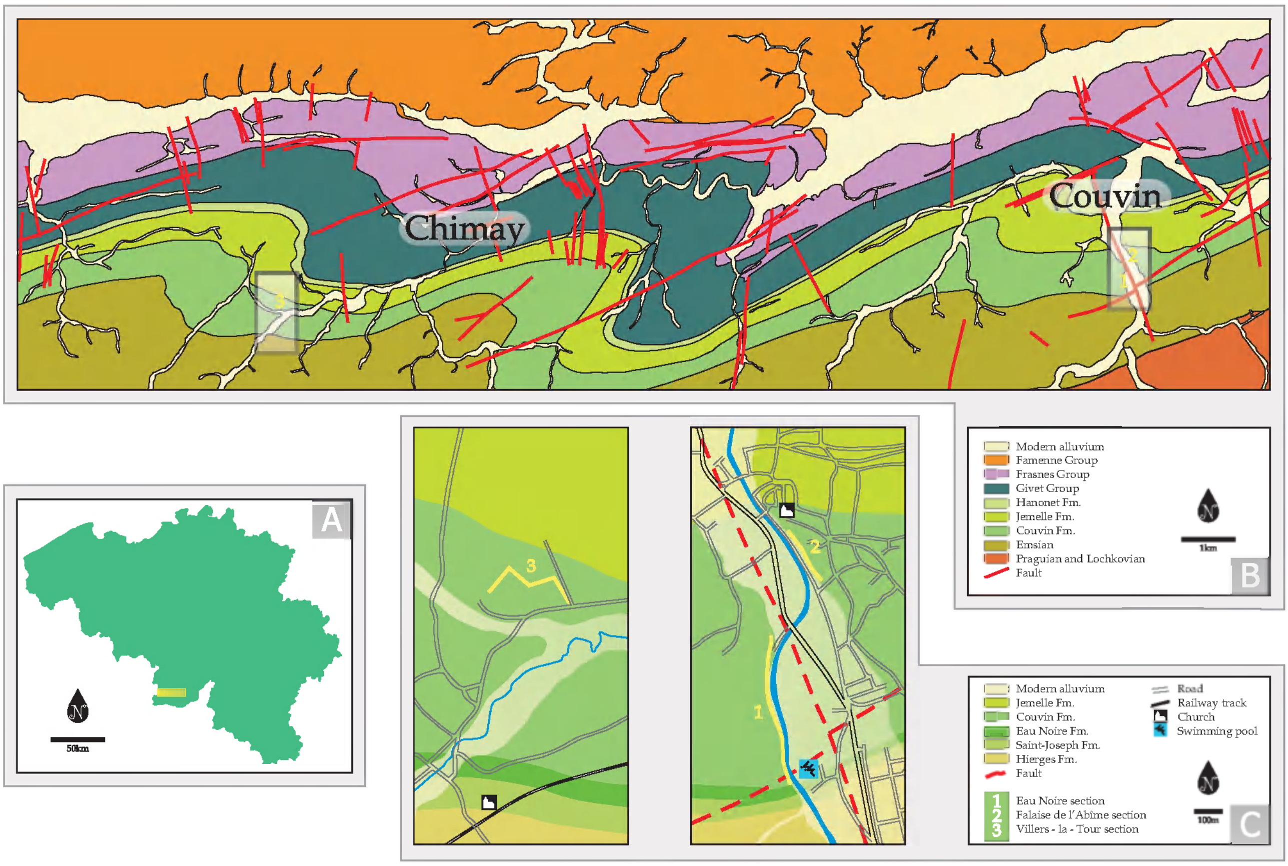


Figure 3: Location of studied sections
A. Location of the Chimay-Couvin area.
B. Geological map of the Chimay-Couvin area. The studied sections are located by two black boxes: Eau Noire (1), Falaise de l'Abîme (2), and Villers-la-Tour (3). The stratotype of the Couvin Formation corresponds to the first two sections.
C. Close up of the studied sections.

2. Description of sections

2.1. Eau Noire and Falaise de l'Abîme sections

The following description is based on field observations (Fig. 4, and see Fig. 5 for legend). A reference is made to units defined by Bultynck (1970). Five lithological units are detailed (1 to 5 on Fig. 4).

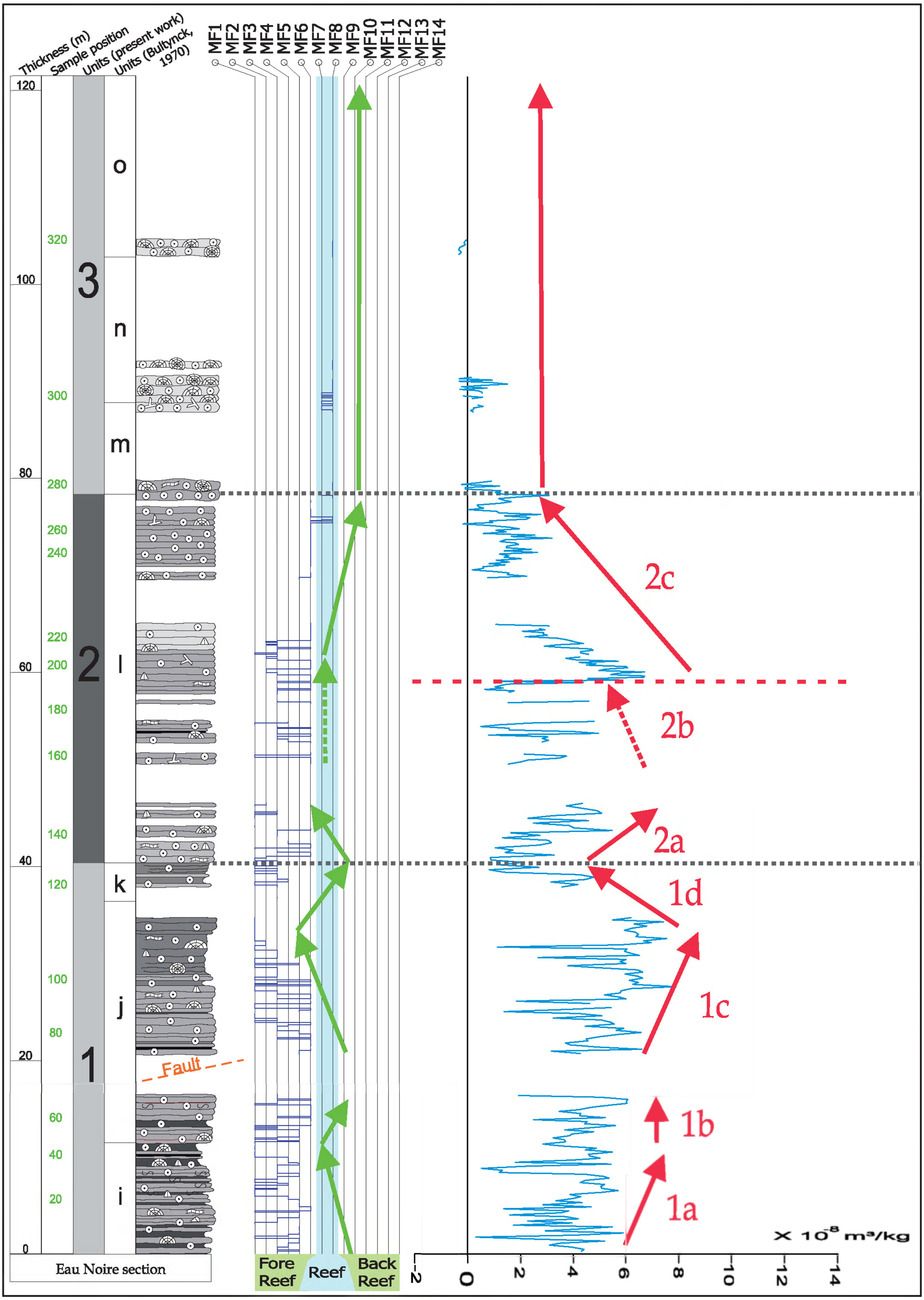
(1) The lowest consists of 41 m of dark argillaceous crinoidal limestones interbedded with calcareous shales. The macrofauna is represented by brachiopods, solitary rugose corals, bulbous and domical stromatoporoids (absent of the underlying Eau Noire Formation, Fig. 2) and some trilobites and gastropods. Laminar stromatoporoids and tabulate corals are also present. The lithology is characterised by subnodular beds interlayed with cm-thick argillaceous interbeds. A fault is observed within the gap between beds 71 and 72, 20 m above the base of the unit. It is marked by a change in strike and dip of stratification from N092E – 53N to N112E – 20N. This fault repeats more or less five metres of strata (Bultynck, 1970; Marion & Barchy, 1999). This first unit corresponds to units *i* to *k* from Bultynck (1970).

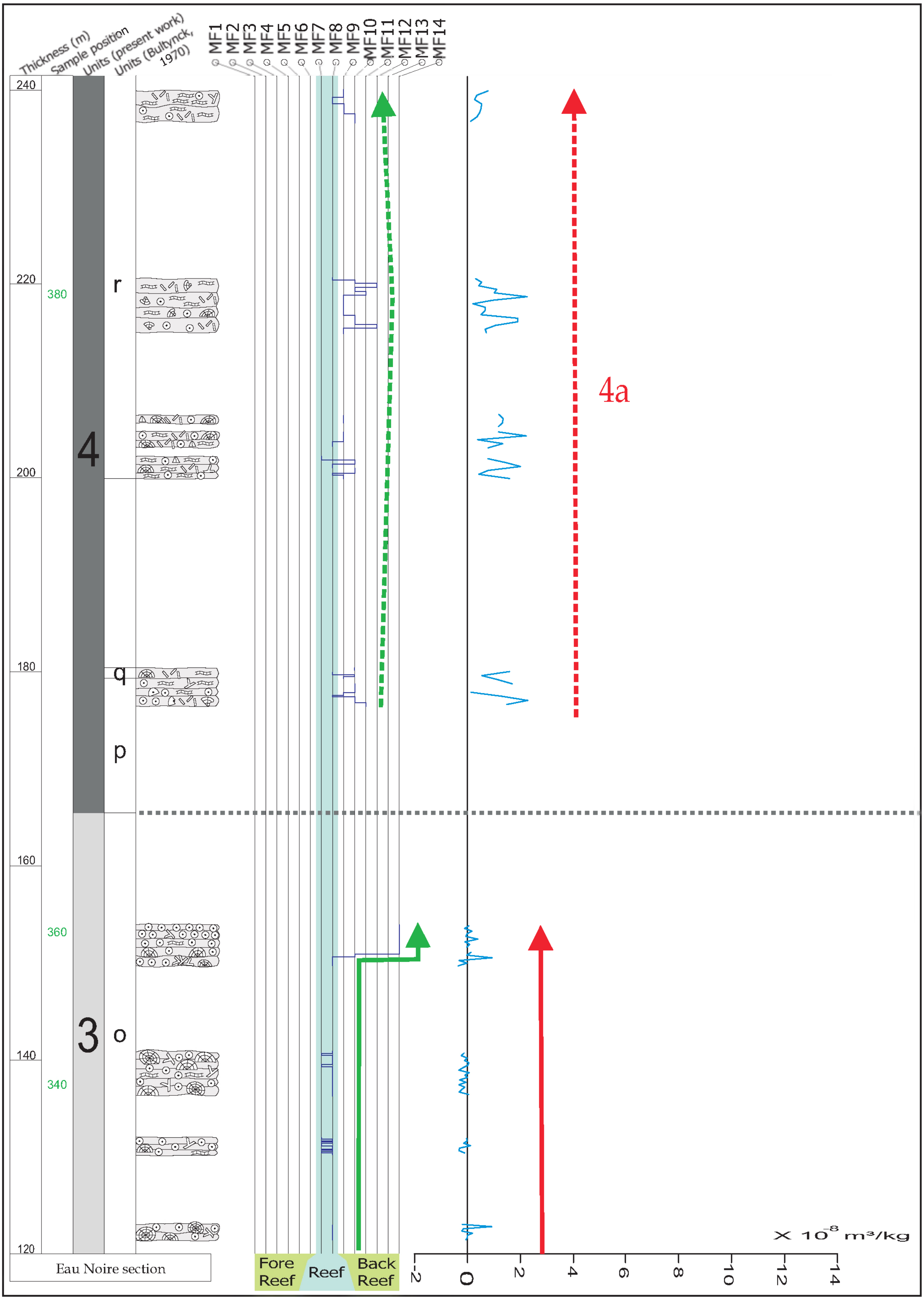
(2) The second unit (from 41 m to 80 m) corresponds to fine-grained argillaceous crinoidal limestones. Beds are locally nodular. The fauna mainly consists of crinoids and brachiopods. However, some laminar, bulbous and domical stromatoporoids, rugose corals, gastropods, bryozoans and branching tabulate corals are also observed. In the first part of the unit, some centimetre-thick argillaceous interbeds are present. This unit corresponds to unit *l* from Bultynck (1970).

(3) The following third unit (from 80 to 162? m) is characterised by the development and abundance of decimetre to metre-sized domical and bulbous stromatoporoids. Branching tabulate corals are also abundant and some colonies are found in living position. Some laminar stromatoporoids are also present. The matrix between these organisms is rich in crinoids and some beds are composed of crinoidal rudstones. This unit includes units *m*, *n*, and *o* after Bultynck (1970).

(4) The fourth unit (from 162? to 254 m) is thick-bedded and characterised by a more diversified fauna. Laminar stromatoporoids and branching tabulate corals dominate laminar and massive tabulate corals, solitary and fasciculate rugose corals, domical stromatoporoids, brachiopods and crinoids. Branching stromatoporoids are also present in the uppermost strata of this unit which corresponds to units *p* to *r* after Bultynck (1970) and is the last unit of the Foulerie Member.

(5) The fifth and last unit corresponds to the Abîme Member and encompasses the last part of the Eau Noire section and the whole Falaise de l'Abîme section, totalising an approximate thickness of 150 m. Very different facies alternate. On one hand, micritic limestone


Thickness (m)
Sample position
Units (present work)
Units (Bultynck, 1970)
MF1
MF2
MF3
MF4
MF5
MF6
MF7
MF8
MF9
MF10
MF11
MF12
MF13
MF14
120
100
80
60
40
20
0
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
3
2
1
o
n
m
l
k
j
i
Fault
Eau Noire section
Fore Reef
Reef
Back Reef
2c
2b
2a
1d
1c
1b
1a
x 10⁻⁸ m³/kg
-2
0
2
4
6
8
10
12
14


Thickness (m)
Sample position
Units (present work)
Units (Bultynck, 1970)
MF1
MF2
MF3
MF4
MF5
MF6
MF7
MF8
MF9
MF10
MF11
MF12
MF13
MF14
240
220
200
180
160
140
120
380
360
340
4
3
r
q
p
o
4a
Fore Reef
Reef
Back Reef
Eau Noire section
X 10-8 m³/kg
-2
0
2
4
6
8
10
12
14

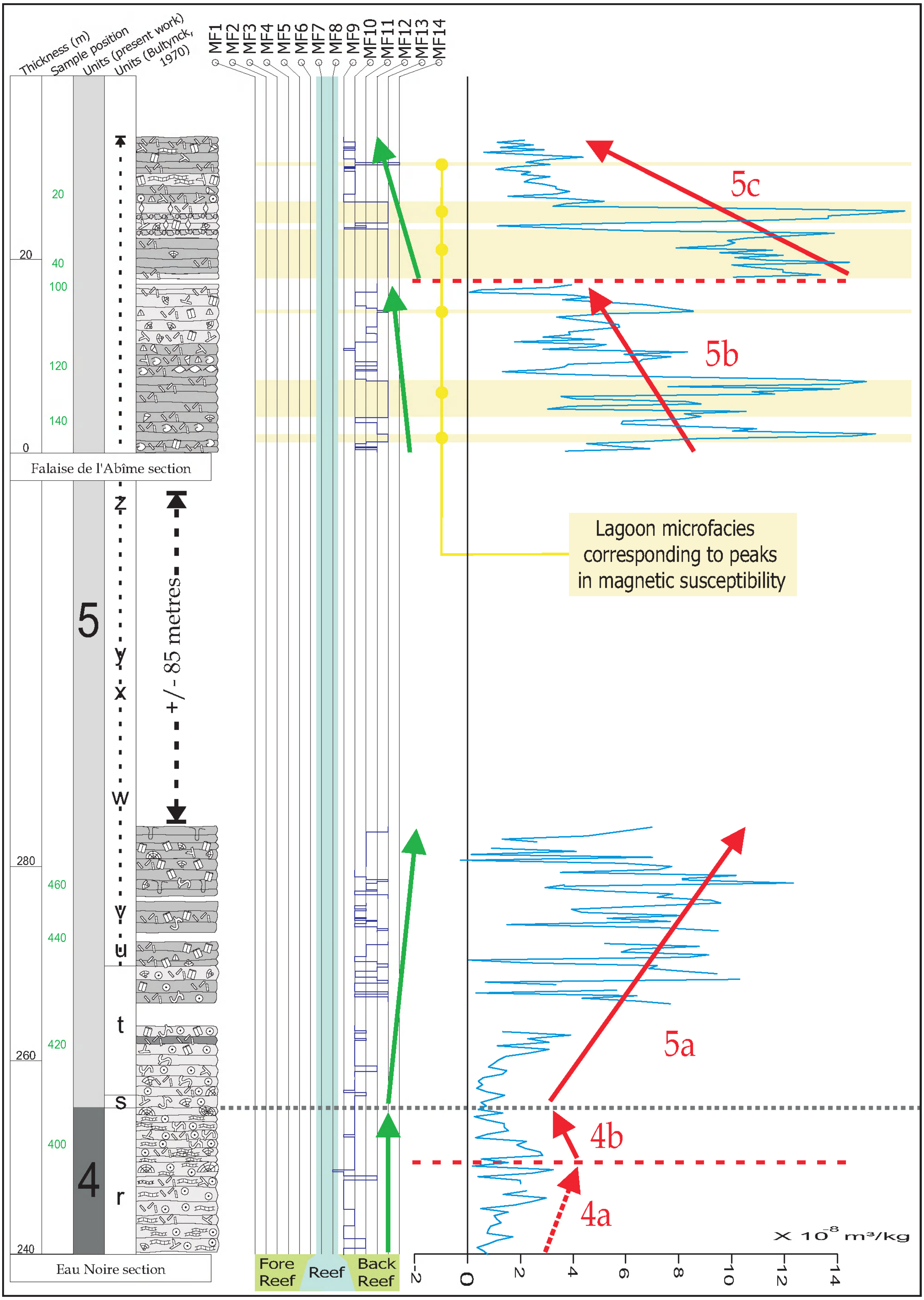


Figure 4: Schematic sedimentological log (see Fig. 5 for legend), lithological units, microfacies curves, and magnetic susceptibility curves of the stratotype. Arrows represent trends in curves and dashed lines events in magnetic susceptibility evolution. Units 1 to 4 correspond to the Foulerie Member and Unit 5 to the Abîme Member. A: units 1 to 3; B: units 3 and 4; C: units 4 and 5.

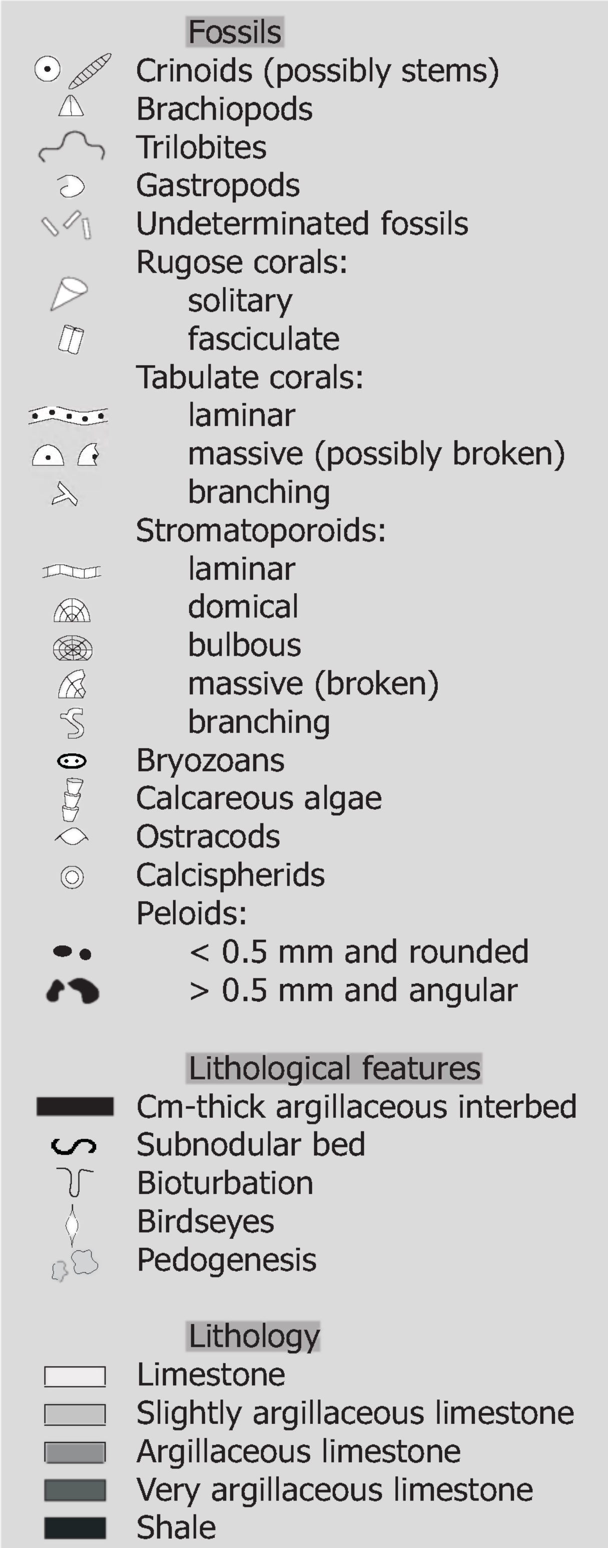


Figure 5: Legend for symbols used in figures.

with gastropods, ostracods or fine-grained bioclasts are observed. These bioclasts include: brachiopods, branching tabulate corals, branching stromatoporoids, fasciculate rugose corals or undetermined skeletal fragments. These beds locally show mm-thick birdseyes, vertical bioturbation or pedogenesis. On the other hand, coarser facies such as floatstones and rudstones are present, and they contain larger clasts of fasciculate rugose corals, branching tabulate corals, and broken parts of massive stromatoporoids. An one-metre thick bioconstructed lens with laminar stromatoporoids was documented in these beds.

2.2. Villers-la-Tour section

The description of Villers-la-Tour section is adapted from the work of Marc Bertrand (Bertrand, 1990; Bertrand *et al.*, 1993). Two lithological units are detailed (A and B on Fig. 6, see Fig. 5 for legend).

(A) The lowest lithological unit is 18 m thick and dominated by poorly stratified thin-bedded argillaceous to slightly argillaceous limestone. However, some massive beds of crinoidal grainstone are also observed. Thick argillaceous interbeds (up to 10 cm) are present. The fauna is poorly diversified and dominated by crinoids. Preserved stems are often observed, and few brachiopods, gastropods, lamellar and broken massive stromatoporoids, and also ostracods are present. The uppermost part of the unit is enriched with broken massive stromatoporoids, and branching tabulate corals.

(B) The second and last unit (from 18 to 55 m) is characterised by less argillaceous and well stratified thick-bedded limestone. However, some poorly stratified thin-bedded argillaceous limestone are also observed. The fauna is more diversified with bulbous, massive and laminar stromatoporoids, solitary and fasciculate rugose corals, massive and branching tabulate corals, brachiopods, and gastropods but still dominated by broken-up crinoids and stems.

3. Description of microfacies

The microfacies are described following a distal-proximal gradient. Each microfacies is illustrated on Plate 2. The description of each microfacies is completed by short remarks concerning the differences existing between the Eau Noire and Falaise de l'Abîme sections on one hand and the Villers-la-Tour section on the other hand.

3.1. MF1: Wackestone and packstone with abundant detrital fraction

Fauna is mainly represented by crinoids, brachiopods, bryozoans, ostracods and trilobites. However, isolated fragments of stromatoporoids and tabulate corals (massive and branching), foraminifers, gastropods and orthocons nautiloids are present in some thin sections. Algae are uncommon and mainly represented by *Girvanella*. The degree of preservation is variable, ranging from well preserved to unidentifiable bioclasts. Detrital quartz can reach concentrations up to 15%. Micas (up to 2.5%) and framboidal pyrite are also observed. The matrix is an argillaceous to silty micrite. Horizontal bioturbation with a non argillaceous and dark mudstone filling is often present.

3.2. MF2: Algal wackestone and packstone

The main feature of this microfacies is the abundance of udoteacean algae, representing up to 90 % of the whole

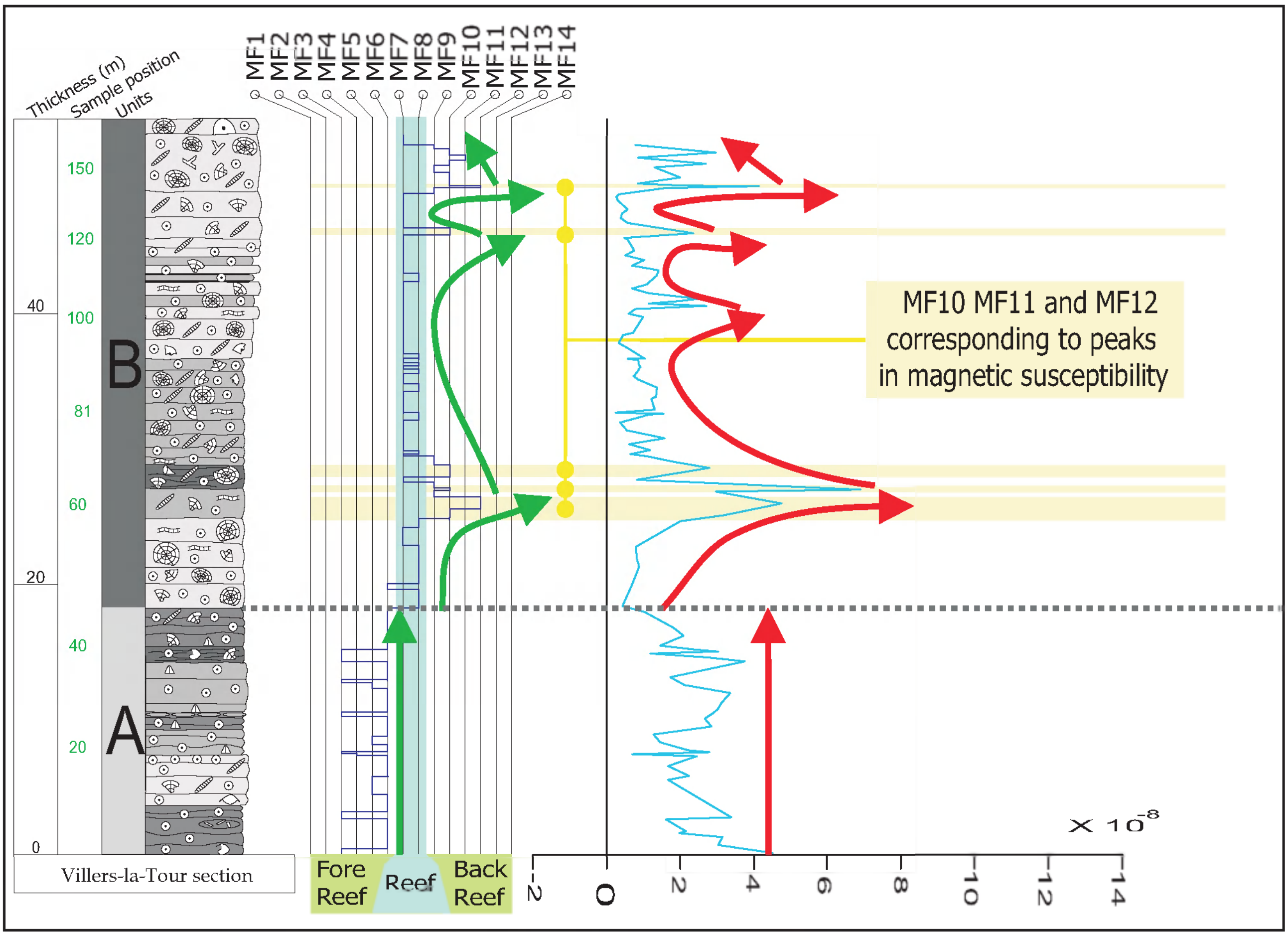


Figure 6: Schematic sedimentological log (see Fig. 5 for legend), lithological units, microfacies curves, and magnetic susceptibility curves of the Villers-la-Tour section. Arrows represent trends in curves.

bioclastic assemblage. Fauna is represented by crinoids, ostracods, gastropods, bryozoans and brachiopods. Sponge spicules are often observed as well as palaeosiphonocladalean. All these elements, and particularly algae, are well preserved. Detrital quartz (up to 2.5%) and micas are present. The matrix ranges from micritic to microsparitic and horizontal bioturbation with a darker micritic filling is locally observed.

3.3. MF3: Crinoidal packstone in a microsparitic matrix

Fauna is well diversified with dominant crinoids, brachiopods, ostracods, bryozoans and trilobites, but also gastropods, massive tabulate corals and stromatoporoids. *Girvanella* and *Sphaerocodium* are present as well as other calcareous algae (dasycladacean, palaeosiphonocladalean and udoteacean). Some peloids (< 0.5 mm and irregular in shape) and lithoclasts (close to 0.5 mm, rounded and with micritised rims) are also present. Entire skeletons are uncommon. Moreover, micritisation and re-crystallisation generate very variable degree of preservation. Detrital quartz is still present and can reach up to 10 % whereas micas are relatively uncommon. Pyrite and hematite are usually framboidal, and cube-shaped crystals are uncommon. The matrix is microsparitic, and the horizontal burrows are regularly and deeply filled with micritic sediment. Wackestone texture is common in Villers-la-Tour section. Quartz is less abundant, and its concentration is usually less than 1%.

3.4. MF4: Coverstone with in situ stromatoporoids in a microsparitic matrix

Beside the laminar organisms, fauna is represented by crinoids, brachiopods, ostracods, trilobites, bryozoans and gastropods. Peloids (0.3 mm and irregular in shape) are observed in few thin sections. Algae, e.g., some palaeosiphonocladalean and *Girvanella*, are present. The shells, skeletons and other allochems in the limestone are slightly recrystallized but stromatoporoids and disarticulated crinoid ossicles are better preserved. Detrital quartz and micas are uncommon. The matrix is microsparitic and textures range from wackestone to packstone. This matrix, by its relative cohesiveness, is favourable to the preservation of shelter porosity under stromatoporoids (Boulvain, 2001).

3.5. MF5: Crinoidal grainstone and packstone

Crinoids dominate the fauna, whereas peloids and bioclasts, such as brachiopods, bryozoans, tentaculites, trilobites, ostracods, gastropods, dasycladacean, udoteacean and *Girvanella* are uncommon. Isolated debris of laminar stromatoporoids and massive tabulate corals are locally observed. Detrital quartz is present in low amounts whereas micas are locally observed. In packstones, the matrix is microsparitic. In grainstones, the cement in an equigranular calcite with some crinoids surrounded by syntaxial cement.

In the Villers-la-Tour section, quartz is uncommon and the microfacies may be coarser, with e.g. parts of crinoids stems reaching up 1 cm in diameter.

3.6. MF6: Poorly-sorted peloidal microsparitic packstone and grainstone

Peloids represent from 20 to 30% of the thin sections and consist of two types: 0.2 to 0.4 mm peloids with blurred rims and 0.5 to 1 mm angular peloids with sharper rims. The latter features can be related to the micritisation of bioclasts or lithoclasts as suggested by sporadic ghosts of original allochem. Some rounded lithoclasts (0.5 to 1 mm) are also present with intensively micritised rims. This microfacies is particularly rich in bioclasts: crinoids (locally abundant), bryozoans, ostracods, brachiopods, branching tabulate corals, massive stromatoporoids and trilobites. Algae are well represented in some thin sections: *Girvanella* (aggregates and symmetrical encrusting), dasycladacean, udoteacean and palaeosiphonocladalean. The degree of preservation of these organisms is variable, from intact to unidentifiable related to variable degree of micritisation, and recrystallization.

Detrital quartz is present (up to 1%) in some thin sections and pyrite is uncommon and always in cubes. The matrix of packstones is microsparitic and the cement of grainstones is an equigranular sparite. Grainstones are interbedded with packstones in lenses (mm-thick to a whole bed)

In Villers-la-Tour, sorting is very poor with the occurrence of crinoid stems, and branches of tabulate corals reaching 1 cm in diameter. Isolated and encrusting *Girvanella* are also more abundant.

3.7. MF7: Crinoidal rudstone

Crinoids represent 90 to 95% of the fauna. They are well preserved and range from 2 mm to 1 cm. The other bioclasts are brachiopods, tabulate corals and stromatoporoids. Pyrite (in cubes and often hematitised) is very uncommon. The cement consists of sparite (large crystals) and is often dolomitised.

In Villers-la-Tour, crinoids can reach up 3 cm and dolomitisation of the cement is more important.

3.8. MF8: Rudstone with stromatoporoids and tabulate corals

Debris of laminar and massive stromatoporoids and branching tabulate corals dominate this microfacies. Massive and laminar tabulate corals, crinoids, ostracods, bryozoans, brachiopods and trilobites are also observed. Peloids (0.2 to 1 mm, irregular to regular in shape and with sharp rims) are frequently observed. Rounded lithoclasts (0.5 mm) with micritised rims are also present. The cement is made of sparite (large crystals) and is often dolomitised. Synsedimentary cavities are preserved beneath some laminar or massive organisms.

In Villers-la-Tour section, MF8 is coarser (with crinoids stems of 3 cm in diameter). Moreover, the distinction between MF7 and MF8 is there less well marked because of a lower content in stromatoporoids and tabulate corals. Lithoclasts are absent.

3.9 MF9: Poorly-sorted peloidal and crinoidal grainstone or poorly washed biosparite

Peloids (0.2 to 1 mm with sharp and irregular rims but rounded) are abundant (Eau Noire and Falaise de l'Abîme sections) or uncommon (Villers-la-Tour section). Mud coated grains ranging from 0.5 to 3 mm are present in few thin sections. Crinoids and isolated laminar tabulate corals dominate the fauna. Gastropods, ostracods, brachiopods, isolated laminar and massive stromatoporoids, isolated branching tabulate corals, bryozoans and dasycladacean are also observed. Some lithoclasts (0.5 to 5 mm, micritised rims) are present. All these organisms are poorly preserved, crinoids and tabulate corals often possess micritised rims.

In the Eau Noire and Falaise de l'Abîme sections, the cement, an equigranular sparite, is locally dolomitised. This is quite different in Villers-la-Tour with the local presence of dark micrite, the texture corresponding therefore to a poorly washed biosparite (Folk, 1959).

3.10. MF10: Bioclastic wackestone (floatstone) and packstone with branching and fasciculate organisms

The main characteristic of this microfacies is the presence of poorly preserved debris of branching stromatoporoids and tabulate corals and fasciculate rugose corals. These organisms locally show micritised rims. Other bioclasts are present and poorly preserved: crinoids, ostracods, brachiopods, gastropods, bryozoans, trilobites, laminar stromatoporoids, and tabulate corals, massive tabulate corals and dasycladacean. Detrital quartz is present (1 to 5%) and micas are observed in some thin sections. The matrix is microsparitic and locally dolomitised or dark and enriched in organic matter.

MF10 is more bioclastic in Villers-la-Tour (e.g. crinoids) and quartz is very uncommon.

3.11. MF11: Floatstone with branching and fasciculate organisms

Branching and fasciculate organisms (stromatoporoids, tabulate corals and rugose corals) represent 90% of the fauna. They can be encrusted by laminar stromatoporoids or tabulate corals but are generally well preserved even if some are broken or show thin micritised rims. Crinoids, brachiopods, ostracods and gastropods are uncommon and less well preserved. Detrital quartz is present in some thin sections and can reach up to 5%. The matrix is a mudstone. Locally, growing cavities filled by equigranular sparite are observed.

3.12. MF12: Wackestone and packstone with gastropods

Gastropods dominate the fauna but foraminifers, bryozoans, brachiopods, ostracods, branching tabulate corals and stromatoporoids, fasciculate rugose corals, laminar stromatoporoids, and crinoids are also present. Calcispherids are regularly present. The degree of preservation is generally poor (micritisation and recrystallization), hindering the identification of some bioclasts. Detrital quartz is present (up to 1%) as well as micas in some thin sections. The matrix is microsparitic and locally enriched in organic matter or dolomitised.

As for MF10, MF12 is more bioclastic in Villers-la-Tour (e.g. crinoids) and quartz is very uncommon.

3.13. MF13: Wackestone and mudstone with fenestrae

Two types of fenestrae are observed: birdseyes and spar-filled burrows. Birdseyes are present in every thin sections. They are ranging from 0.5 and 1.5 mm and are filled by equigranular sparite. Vertical burrows are present in some thin sections and are filled by equigranular sparite or well-sorted peloidal grainstone (see MF14). The microfossil assemblage is poor and dominated by calcispherids and/or ostracods which are well preserved. Gastropods, crinoids, branching stromatoporoids and tabulate corals, fasciculate rugose corals, palaeosiphonocladalean and lithoclasts (0.5 mm, rounded, with micritised rims) are uncommon and poorly preserved. Detrital quartz (1 to 10%) and lots of pyrite are present. Micas are observed in nearly all thin sections. The matrix is a fine and dark micrite.

3.14. MF14: Well-sorted peloidal grainstone

Peloids (from 0.2 to 0.5 mm) are ovoidal or spherical and have sharp rims. They represent up to 95% of the assemblage. Crinoids, brachiopods, ostracods, and branching tabulate corals are uncommon. Some rounded lithoclasts (0.2 to 1 mm) are present. Lithoclasts, crinoids and branching tabulate corals often possess micritised rims. Pyrite (framboidal or in cubes) is uncommon and can be hematitised. The cement is an equigranular sparite.

4. Microfacies interpretation

Various criteria are available to interpret the palaeoenvironmental setting of each microfacies. Faunal associations and depositional textures directly reflect water agitation. 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 literature for Eifelian rocks is made when possible. Every microfacies described here above may be interpreted in terms of degree of distality from littoral area and relative bathymetry.

MF1 is characterised by an argillaceous to silty matrix. This is the result of slow accumulation of suspended mud. However, more energetic events such as storms, are needed to explain the local wackestone-packstone texture. As the packstone lenses are relatively thin and fine-grained these lenses can be regarded as distal to intermediate storm deposits. Anyway, the absence of hummocky cross-stratification or grainstone texture rules out a more proximal interpretation (Wright & Burchette, 1996). Moreover, the faunal assemblage implies an open-marine setting. This suggests that this microfacies was located just above storm wave base (SWB).

Algae in MF2 are particularly well preserved and correspond to in situ accumulation (wackestone texture) or reworking under storm action (packstone). The assemblage, notably sponge spicules, suggests an open-marine setting. So, MF2 corresponds to small algal patches developed above the SWB.

The packstone texture of MF3 implies a more energetic setting (Wright & Burchette, 1996), with still open-marine conditions as proven by the assemblage. MF3 represents storm deposits just below fair weather wave base (FWWB). The same interpretation was proposed for similar microfacies of the Eifelian-Givetian boundary interval in the Dinant Synclinorium (MFC3; Mabille & Boulvain, *in press* / *MF3*; Préat & Kasimi, 1995).

The development of laminar stromatoporoids characterizing MF4 corresponds to favourable conditions in terms of bathymetry, substrate and sufficiently low detrital input (see, e.g. Kershaw, 1998). Together with the presence of microsparitic matrix, this suggests a location just below the FWWB. MF4 is similar to MFC5b (Mabille & Boulvain, *in press*).

MF5 is mainly characterised by crinoidal grainstone and packstone. Such an accumulation of crinoids corresponds to storm deposits around the FWWB, close to crinoidal meadows. The environment was largely influenced by open sea water circulation. The same interpretation was proposed for similar microfacies: MFB4 by Mabille & Boulvain (*in press*), and *MF4* by Préat & Kasimi (1995).

The main characteristic of MF6 is the abundance of peloids. They probably have a shallow water, low-energy origin like a lagoon or a back-reef area (see, e.g., 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 supplies also calcareous algal debris and possibly micrite, but, according to the fauna, an open-marine influence was still present. 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 wave agitation. The grainstone texture and the absence of sedimentary structure suggest a location within the FWWB (Wright & Burchette, 1996). It is quite interesting to remember that, in Villers-la-Tour, peloids are less abundant whereas *Girvanella* is common. So, at least a part of the peloids observed in the stratotype could be poorly-preserved unidentifiable *Girvanella*. MF6 is similar to MFC6a and MFC6b described by Mabille & Boulvain (*in press*)

The very good preservation of crinoids in MF7 suggests an in situ sedimentation. Moreover, the rudstone texture implies a location within the FWWB. This microfacies could correspond to fore-reef settings but it is found in close association with MF8 and better corresponds to a crinoidal matrix between corals and stromatoporoids. MF7 is considered as a reefal microfacies.

Several criteria show that MF8 corresponds to a reefal environment: the abundance of stromatoporoids, tabulate corals and crinoids, their good preservation, the presence of synsedimentary cavities and the rudstone texture.

MF9 is characterised by an important peloidal supply. These peloids have the same characteristics as those found in MF6 and therefore probably the same origin(s). The poor sorting and the grainstone texture lead us to consider an intermittent agitation. MF9 corresponds to a back-reef environment with a possibility of in situ laminar organisms.

MF10 corresponds to a return to less agitated conditions as shown by the presence of matrix. Branching organisms are poorly preserved (breaking and recrystallization) as well as massive and laminar ones. The environment corresponding to MF11 can be the source of the branching organisms. Moreover, environment corresponding to MF8 (and MF9?) can provide massive and lamellar ones. So MF10 is located in a back-reef area, in a quiet environment and largely influenced by inputs coming from surrounding environments.

The main characteristic of MF11 is the presence of branching and fasciculate organisms in living position or showing a very limited transport, indicating a very quiet environment. This corresponds to little coral-patches with a fine grained sedimentation trapped between the different branching and fasciculate organisms. The presence of growing cavities indicates the cohesiveness of the matrix.

MF12 differs from MF10 by a lower abundance of massive stromatoporoids and tabulate corals and the presence of gastropods. The environment was still quiet but different, being more influenced by a lagoonal environment as shown by the presence of calcispherids.

MF13 is characterised both by the presence of fenestrae (and notably birdseyes) and an assemblage consisting essentially of calcispherids and ostracods. This indicates an intertidal and restricted lagoon. This is also the interpretation made for similar microfacies of the Eifelian-Givetian boundary interval in the Dinant Synclinorium (*MF9*; Préat & Kasimi, 1995).

MF14 is often observed in close association with MF13 (filling of bioturbation, lenses). This observation combined to the fact that Wilson (1975) groups two microfacies similar to MF13 and MF14 in his *SMF19* leads to consider an intertidal and restricted lagoon for MF14.

Summary – Palaeoenvironmental model

To summarize and illustrate the interpretation made for each microfacies, a palaeoenvironmental model is proposed (Fig. 7). It corresponds to a platform model where the reef is mainly composed of an accumulation of crinoids, stromatoporoids and tabulate corals (MF7 and MF8). The fore-reef environment is characterised by a high influence of storm events (MF1, MF3 and MF5) and local development of laminar stromatoporoids (MF4) or calcareous algae (MF2). Then, the influence of back-reefal and reefal environments is marked by a large input in peloids, reworked reef-building organisms, and possibly micrite (MF6). The back-reef environments include agitated ones (MF9) and lagoons (MF13 and MF14) or corresponding to MF11 where branching and fasciculate organisms are able to grow. MF10 and MF12 are transition microfacies between MF11 and respectively the reefal environment and the lagoon.

The Villers-la-Tour section is similar but slight differences have to be noted: (1) Detrital quartz is uncommon and reaches hardly up to 1%. (2) Crinoid stems are observed in all microfacies (up to 3 centimetre in diameter). (3) Back-reefal microfacies show more open-marine faunal assemblage: crinoids, trilobites, brachiopods, bryozoans, … but also good development of massive stromatoporoids (4) MF9 is a poorly washed biosparite. And (5), MF6 is richer in *Girvanella*.

The model described here corresponds to a platform model. However, the Couvin Formation has been previously described following a ramp model (Bertrand, 1990; Bertrand *et al.*, 1993). This difference can be easily explained by some observations. First of all, the work of these authors concerns only the first 50 metres of the Couvin Formation in the Eau Noire section. This implies that their work does not take into account the accumulation of crinoids, stromatoporoids, and tabulate corals corresponding to Unit 3 (Fig. 4). This is important because this unit is interpreted here as a reefal unit. Moreover, both of proposed models differ significantly from the initial definition of «ramp» and «platform». In fact, a ramp *sensu stricto* corresponds to an uniform slope from shoreline to basin (Arh, 1973). At the opposite, platforms are characterised by an important break of slope (Read, 1985). In fact, both proposed models are intermediate between these two definitions. The “ramp model” (Bertrand, 1990; Bertrand *et al.*,, 1993) is closer to a ramp *sensu stricto,* even if it possesses a slight break of slope. On the other side, the “platform model” (present work) is characterised by a more important break of slope when considering Unit 3, and is consequently closer to a platform. In the actual state of the art, it is difficult to make an accurate estimation of the break of slope corresponding to the Couvin Formation within the Jemelle Formation. So, further sedimentological investigations on the architecture of the Couvin Formation, sequence stratigraphy, and lateral variations are needed to definitively choose the most appropriate term to describe the geometry of the model. In the following part of the text, the term “platform” is preferred.

In all cases, the proposed model has to be coherent with its geological context. The lateral transition from the Couvin Formation to the Jemelle Formation is represented in Fig. 8. This figure is based on data from the geological map of Belgium and from the work of various authors (see legend for details). However, further sedimentological investigations are needed to complete this first approach. Anyway, remembering that the Couvin Formation has a limited extension and is surrounded by detrital facies, two

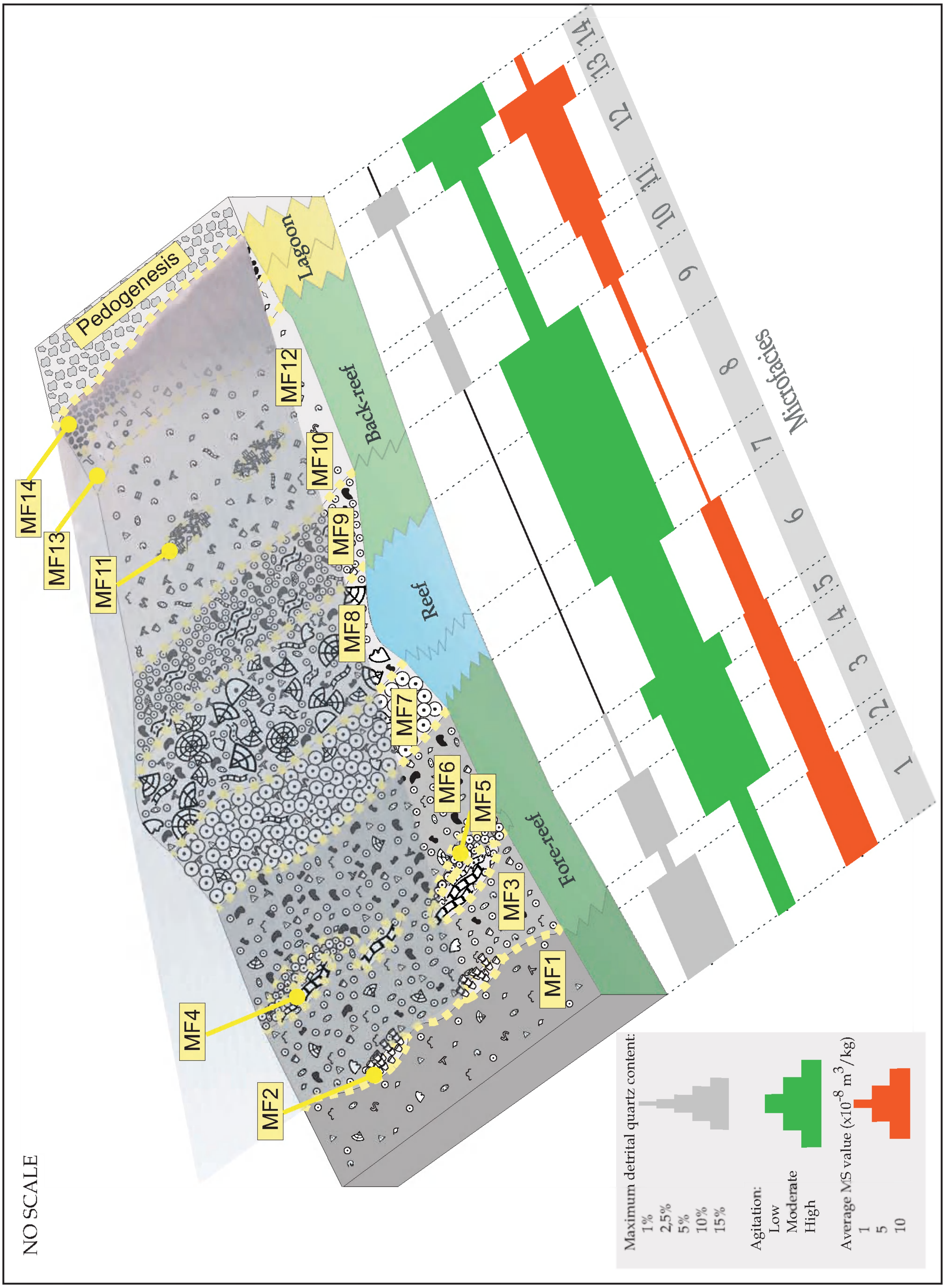


Figure 7: Proposed palaeoenvironmental model for the Couvin Formation (see Fig. 5 for legend). It corresponds to a platform model where the reef is mainly composed of an accumulation of crinoids, stromatoporoids and tabulate corals. The fore-reef environment is characterised by a great influence of storm events and local development of laminar stromatoporoids and calcareous algae. The back-reef includes agitated environments and lagoons. For each microfacies, maximal abundance of detrital quartz, agitation, and average magnetic susceptibility values are given.

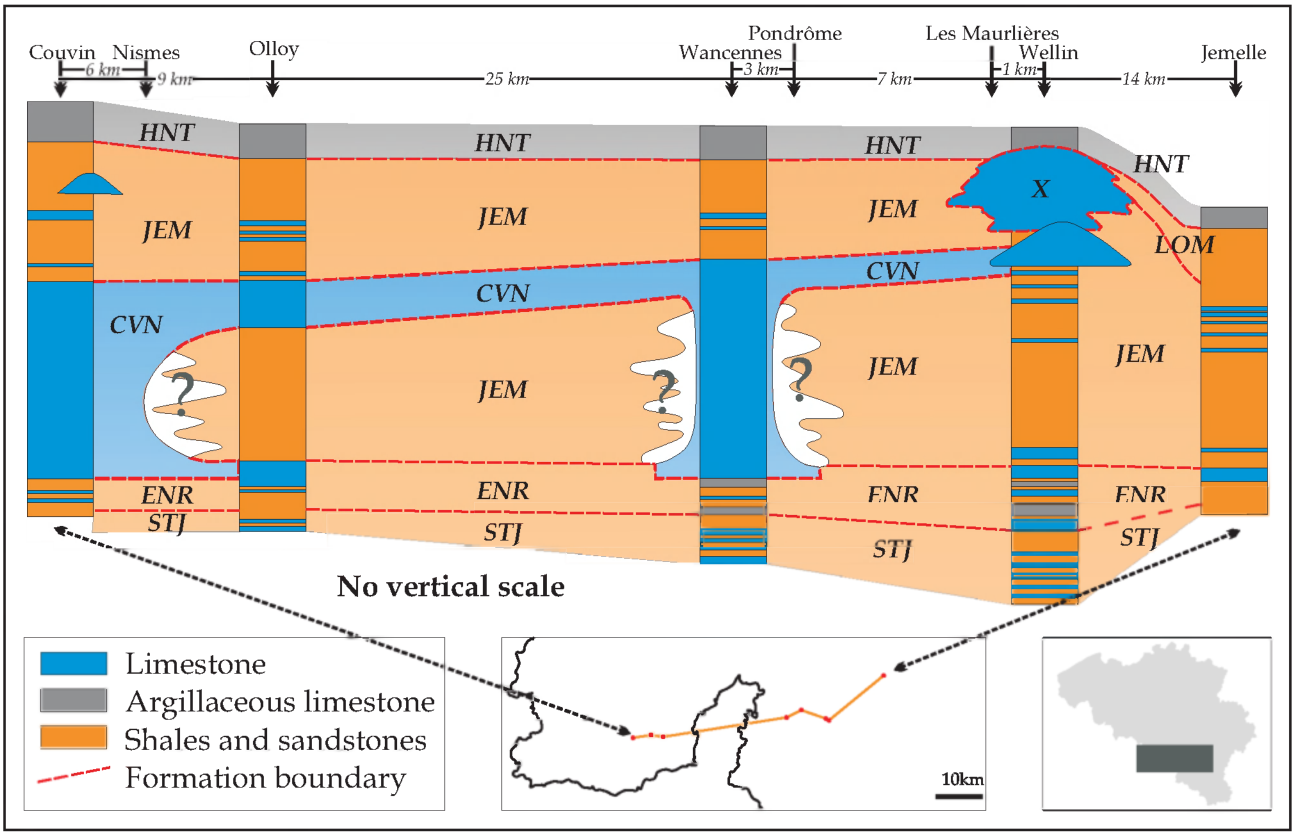


Figure 8: Lateral varation of the Couvin Formation along the southern flank of the Dinant Synclinorium (between Couvin and Jemelle localities), modified from Dumoulin *et al.*, 2006 corresponding to the compilation of data from Blockmans & Dumoulin (*in press a*), Blockmans & Dumoulin (*in press b*), Bultynck (1970), Dumoulin & Coen (*in press*), and Godefroid (1968). The formations represented are: Saint Joseph Formation (STJ), Eau Noire Formation (ENR), Jemelle Formation (JEM), Couvin Formation (CVN), X Formation (X), La Lomme Formation (LOM), and Hanonet Formation (HNT).

interpretations of this carbonate episode are possible. The first one is to consider that the Couvin Formation corresponds to an isolated platform (Read, 1985). The second one, already evoked by Tsien (1974), is based on the observation that the outcrop area of the Couvin Formation corresponds to the northern side of the Rocroi Massif. In this case, this would imply a fringing reef setting evolving into a barrier reef close to an island. Note that the presence of detrital quartz in the back-reef microfacies (e.g. 1 to 10% in MF13) fits better with the barrier reef in providing a plausible source for the detrital material. Moreover, some palynological analyses were performed on samples from the base of the Eau Noire section to test this interpretation. Spores, structured debris (maybe corresponding to tracheids), and few acritarchs, scolecodonts, and Chitinozoa (Steemans & Breuer, *personal communication*) are present. The low ratio acritarch/spores and the presence of structured debris imply the proximity of emerged areas (Wicander & Wood, 1997) also fitting with the barrier reef hypothesis.

5. Microfacies evolution

5.1. Eau Noire and Falaise de l'Abîme sections (stratotype)

The microfacies evolution shows a general shallowing-upward trend. It is interesting to consider this evolution unit by unit to allow a better understanding of the sedimentary dynamics and of the palaeoenvironmental evolution (Fig. 4).

(1) The first unit shows frequent oscillations of the curve between two poles. The first corresponds to the fore-reef background sedimentation. It includes mainly MF1 and MF3 but also MF2, MF4 and MF5. This environment is regularly flooded by proximal carbonate input consisting in algae, peloids and possibly micrite (corresponding to MF6). Moreover, the influence of this less argillaceous microfacies is marked at the outcrop level: the second third of the unit, where MF6 is more abundant, is much more massive than the two others.

(2) The sedimentary dynamics of the second unit is similar. The main difference is that MF6 dominates the other microfacies, indicating a more marked influence of proximal areas. This is particularly the case for the top of the unit. At this level, MF7 and MF8 appear, announcing the reef installation.

(3) The third unit corresponds to the reef development (MF7 and MF8). At the top, a sharp fall in the sea level puts an end to its development by providing intertidal lagoonal conditions (MF14) without transitional facies.

(4) The following fourth unit corresponds to back-reef and non-lagoonal sedimentation (MF9 to MF12). The occurrence of MF8 confirms the fact that laminar organisms develop in back-reef settings and can also be

found in-situ in MF9.

(5) In the fifth and last unit, there is a great difference between the base, corresponding to the end of the Eau Noire section, and the top, exposed at the Abîme Cliff. The base of the unit shows short lagoonal episodes (MF13) often occurring in a dominant back-reef sedimentation, mainly represented by MF10, MF11 and MF12. As these occurrences are absent in the first part, a slight shallowing upward-trend can be envisaged. However, the top of the unit is marked by thicker lagoonal episodes suggesting higher stability of the environment.

5.2. Villers-la-Tour section

(A) Unit A (Fig. 6) is characterised by the same oscillations as those observed in the first and second units in the Eau Noire section. The sedimentary dynamics is the same, with a background sedimentation (represented by MF3, MF4, and MF5) regularly flooded by proximal carbonate influx (MF6). No regressive or transgressive trend is observed in this unit.

(B) Unit B is dominated by a reefal sedimentation (MF7 and MF8). There are two kinds of exceptions. The first one occurs at the base at the unit and corresponds to a poorly-developed turn-back to fore-reef settings (MF6). The second one, much more significant, represents back-reefal occurrences (MF9, MF10, MF11, and MF12).

6. Magnetic susceptibility

6.1. Principles

Magnetic susceptibility (MS) is a measure of the sample response to an external magnetic field. It was first used in the study of Palaeozoic rocks during the 1990s (Crick *et al.*, 1994; Crick *et al.*, 1997; Crick *et al.*, 2000; Ellwood *et al.*, 1999). For sedimentary rocks, the major influence on MS is the terrestrial fraction. This can generally 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 contrary, 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; Hladil, 2002; da Silva & Boulvain, *in press*). 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.

6.2. MS evolution and interpretation

The interpretation of the MS records is focused particularly on evolution of mean magnitudes of this variable, where the trends relate to proportions of non-carbonate (terrigeneous) and carbonate components in this mixed sedimentary system. This has a direct facies context and great importance for understanding the facies architecture of the Couvin Formation.

6.2.1. Eau Noire and Falaise de l'Abîme sections (stratotype)

The discontinuous character of the outcrops limits the interpretation of MS evolution. However, it provides further information about the environment evolution (Fig. 4).

(1) The first lithological unit is divided into four main trends. 1b does not show any significative evolution in the MS signal. 1a and 1c correspond to an increase of MS values, whereas 1d to a decreasing. The first trend could correspond to a regressive event whereas the second to a transgression after the theory of Crick and Ellwood. These trends are just at the opposite of those observed in the microfacies curve (see 6.2.3. for discussion).

(2) The second unit is separated into two main opposite trends, 2a corresponding to increasing MS values, and 2c to the opposite. Trend 2b is more hypothetical, but seems to give decreasing trend. Here again for 2a and 2c, trends in MS curves are opposed to trends observed in the microfacies curve. The lowering in MS values in trend 2c can be explained by a rise in the carbonate input, as proven by the dominance of MF6. This carbonate input can dilute carrying minerals of the MS and explain this opposition.

(3) The MS values are low and stable in the third unit. This is explained by the reef development which corresponds to purer limestone. Note that the jump observed in the microfacies curve at the top of the unit is absent in MS values.

(4) The fourth unit is separated into two light trends fitting with the absence of significant evolution observed from the microfacies curve. However, note that the first MS trend is hypothetical and that the second is maybe too slight to be significant.

(5) An increasing trend followed by two deacreasing trends characterises the fifth and last unit. These general evolutions fit with the evolution deduced from the microfacies curve. Moreover, the oscillation between non-lagoonal and lagoonal environments is particularly well-printed in MS signal which oscillates between a large range of values. At the top of the unit, each time lagoonal environment (MF13) did install, it corresponds to a peak in MS values.

6.2.2. Villers-la-Tour section

For this section, there is a parallelism between the microfacies curve and the MS evolution (Fig. 6).

(A) In the A Unit , the MS signal oscillates but do not display any significant evolution.

(B) The B Unit is much more interesting because of a similar behaviour of this described here above for the fifth unit. Each peak observed in the MS curve can be related to the occurrence of particular microfacies. For the Falaise de l'Abîme section, it is MF13 which occurs in back-reefal but non-lagoonal microfacies that causes peaks in MS values. For this section, each time MF10, MF11 or MF12 occurs, it is related to a peak in MS values.

6.2.3. Discussion on the magnetic susceptibility variations

As said here above (see 6.2.1) many parameters are thought to have a possible influence on the MS signal. Here, the average MS value for each microfacies in the stratotype is compared to two main but non exhaustive parameters (Fig. 7). The first one is a semi-quantitative estimation of detrital quartz for each microfacies. While the detrital quartz does not carry the MS signal, it can be considered as a good indicator of the detrital input (Mabille & Boulvain, *in press*). The second parameter is wave agitation, because higher the agitation is, lower is the sedimentation of thin particles carrying the MS signal. These parameters are considered in four microfacies belts: fore-reef, reef, back-reef, and lagoon.

For the fore-reef environment, the MS values are decreasing from distal to proximal settings. The values are ranging from 4.825×10^{-8} m^3/kg (MF1) to 2.830×10^{-8} m^3/kg (MF6). This decreasing evolution is also observed in the detrital quartz abundance. This can be related to a global increasing in wave agitation from MF1 to MF6.

The reef is characterised by the absence of detrital quartz and very low MS values: 0.216×10^{-8} m^3/kg (MF7) and 0.309×10^{-8} m^3/kg (MF8). This nearly absence of MS carrying minerals is due to the permanent agitation of the environment.

The back-reef shows increasing values from distal to proximal microfacies. The low values observed in MF9 (0.931×10^{-8} m^3/kg) can be explained as above by the permanent agitation. However, there are no great differences in the wave agitation observed in MF10, MF11, and MF12 to explain the increasing values from 2.930×10^{-8} m^3/kg (MF10) to 5.604×10^{-8} m^3/kg (MF12). The dominant parameter is therefore the increasing proximity of the emerged areas, considered as source of detrital input.

For the lagoon, the MS values are very different for MF13 (10.49×10^{-8} m^3/kg) and MF14 (0.925×10^{-8} m^3/kg). This is the combination of a high terrigeneous influence present in MF13 but ineffective in MF14 because of a permanent agitation. The fact that MF14 is literally washed by the wave agitation explains why no peak is observed in the MS signal in the uppermost part of Unit 3.

This interpretation of MS variations can easily explain the differences observed in the MS curve when compared to the microfacies curve. In the back-reef area, the "Crick & Ellwood" model is working. As the average MS value increases from MF9 to MF13, each regressive trend corresponds to an increasing in MS values. The parallelism between MS and microfacies curves is preserved (Fig. 4). However, the situation is just at the opposite in the fore-reef area with a decreasing of MS values from MF1 to MF6. The "Crick & Ellwood" model do not works anymore because a regressive trend implies a decreasing trend in the MS signal. This gives an opposition between the MS and microfacies curves (Fig. 4).

7. Comparison between the stratotype and Villers-la-Tour sections

This comparison suffers from (1) a lack in precise correlation based on biostratigraphy and (2) the discontinuity of the stratotype. This last point makes almost impossible any correlation based on sequence stratigraphy or magnetic susceptibility. To be convinced of it, one just has to consider that the gap between the Eau Noire and the Falaise de l'Abîme sections (85m) in the stratotype is 30 metres thicker than the entire Villers-la-Tour section.

However, it is possible to make a good approximation of the lateral relations between the stratotype and the Villers-la-Tour section. In fact, conodonts analyses (Bertrand *et al.*, 1993) and comparison with the geological map (Marion & Barchy, 1999) both indicate that the Villers section is part of the Abîme Member (corresponding to the fifth unit). So comparing this member in the stratotype and the Villers-la-Tour section is interesting to approach the lateral variability of the Couvin Formation.

It is easy to notice the more open-marine settings in Villers-la-Tour. It is particularly the case for the A Unit with fore-reef microfacies. The B Unit is less different with the same kind of sedimentary dynamics as observed in the Falaise de l'Abîme section. Both correspond to a background sedimentation corresponding respectively to reefal and back-reefal but non-lagoonal settings. These sedimentations are perturbed by occurrences of a back-reefal but non-lagoonal sedimentation in the B Unit and lagoonal sedimentation in the Falaise de l'Abîme section.

These differences could be interpreted either as a re-opening of the system, not recorded in the stratotype, because located in the gap between the Eau Noire and Falaise de l'Abîme sections or as a lateral variation. In this case, the Villers-la-tour section should be located in a more external position of the platform.

8. Conclusions

For this study of the Couvin Formation, three sections were considered: the Eau Noire, the Falaise de l'Abîme, and the Villers-la-Tour sections. Although the first two correspond to the stratotype, this composite section is particularly discontinuous.

Petrographic analyses led to the definition of fourteen microfacies. All of them were integrated into a carbonate platform model. In this model, the fore-reef environment is characterised by a high influence of storm events and local development of laminar stromatoporoids and calcareous algae. The reef is mainly composed of an accumulation of crinoids, stromatoporoids and tabulate corals. Finally, the back-reef consists in shoals, lagoons, and reef-patches composed of branching and fasciculate corals and stromatoporoids. Moreover, the vertical facies succession corresponds to the platform development from a fore-reef environment located near the storm wave base to an intertidal restricted lagoon.

Magnetic susceptibility (MS) analyses coupled with microfacies analyses allowed to reconstruct the sedimentary dynamics of each lithological unit. Moreover, the MS values were interpreted microfacies by microfacies. This led to the recognition of two main MS controlling parameters. The first one is the detrital fraction related to MS carrying minerals (evaluated by detrital quartz abundance). The second one is the agitation of the environment possibly responsible for the non-deposition of the MS carrying minerals (defined on the base of microfacies interpretation). The fore-reef shows decreasing MS values, related to a global increasing in wave agitation from distal to more proximal areas. Wave agitation was so high in the reef environment that MS carrying minerals were enable to settle, leading to low MS values. The back-reef shows low MS values where wave agitation was permanent and increasing values in less agitated areas or more proximal area.

This complex evolution of the average MS value along a distal-proximal scale is responsible for the parallelism between MS and microfacies curves, according to the generally admitted model of MS, in the back-reef settings. For the fore-reef settings, an opposition between the two types of curves is observed. This implies that the links between MS evolution and microfacies evolution is conditioned by the general sedimentological context. If it is confirmed by further studies, it means that comparison between different time-equivalent sections is possible only if the depositional context is the same.

Finally, the global interpretation pinpointed the lateral variations existing in the Abîme Member. This interpretation suggests that the Villers-la-Tour section was located in a more external position of the platform than the stratotype sections. The relations of the Couvin Formation with its siliciclastic environment are explained by a global setting corresponding to a fringing reef complex.

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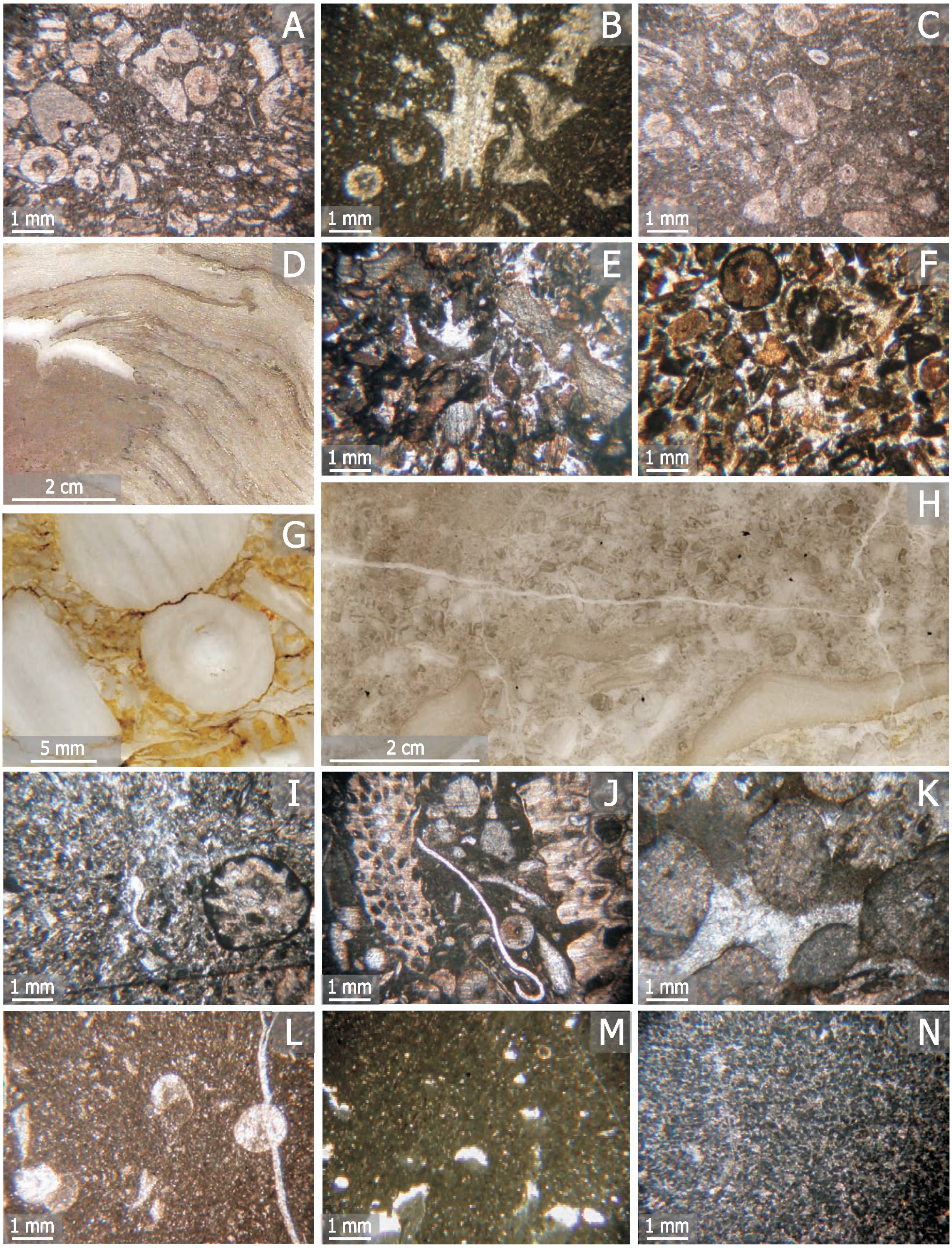
Plate 1:

A. Eau Noire section: base of the Couvin Formation.
B. Eau Noire section: first unit of the Foulerie Member.
C. Eau Noire section: end of field observations, Rochettes Street, Abîme Member.
D. Falaise de l'Abîme section.
E. Villers-la-Tour section (present outcrop).


A
B
C
D
E

Plate 2: Microfacies of the Couvin Formation from Eau Noire (CV), Falaise de l'Abîme (FA) and Villers-la-Tour (VT) sections. Numbers correspond to bed numbers on Figs 4 and 6. See text for more explanations:

A. MF1: Crinoidal packstone in a matrix rich in detrital component (CV4).
B. MF2: Algal (udoteacean) wackestone (CV110).
C. MF3: Crinoidal packstone in a microsparitic matrix (CV29a).
D. MF4: Coverstone with autochthonous stromatoporoids in a microsparitic matrix (CV84b).
E. MF5: Poorly washed crinoidal grainstone (to floatstone) (VT21).
F. MF6: Poorly-sorted microsparitic packstone and grainstone dominated by crinoids and blackened particles corresponding to peloids, *Girvanella*, and lithoclasts (VT20).
G. MF7: Crinoidal rudstone (VT79).
H. MF8: Rudstone with stromatoporoids and tabulate corals (CV301a).
I. MF9: Poorly-sorted peloidal and crinoidal grainstone with a fragment of branching tabulate coral showing micritised rims (FA22).
J. MF10: Bioclastic floatstone with branching tabulate corals; the matrix is highly bioclastic with crinoids and also well preserved trilobites (VT153).
K. MF11: Floatstone with branching stromatoporoids and tabulate corals; note the presence of growing cavities (CV420c).
L. MF12: Wackestone with gastropods (CV447).
M. MF13: Mudstone with *fenestrae* (CV472).
N. MF14: Well-sorted peloidal grainstone with some fine-grained altered skeletal fragments (CV353b).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