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DETAILED SEDIMENTOLOGICAL STUDY OF A NON-CLASSICAL SUCCESSION FOR TROIS-FONTAINES AND TERRES D'HAURS FORMATIONS (LOWER GIVETIAN, MARENNE, BELGIUM) – INTRODUCTION OF THE MARENNE MEMBER

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(6 figures, 1 table and 2 plates)

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ABSTRACT. This work details for the first time the sedimentology of the Marenne quarry. It exposes a remarkable succession of strata from the Trois-Fontaines Formation and the base of the Terres d'Haurs Formation. Two sections (Marenne East and Marenne Centre) are investigated within the quarry. The first one (115 metres) covers both formations and is characterized by a mixed carbonate-siliciclastic succession replacing the classical base of the Trois-Fontaines Formation. We propose here to include these particular facies into a new member of the Trois-Fontaines Formation, the Marenne Member. The second one (48 metres) exposes a reefal lens also attributed to this new Marenne Member. Magnetic susceptibility was used to confirm geometric correlations previously obtained between these two sections. Petrographic study leads to the definition of 14 microfacies which are integrated into three palaeoenvironmental models. The first model (six microfacies) is proposed for the Marenne Member. In this ramp model, terrigenous inputs are particularly important. The mid-ramp is composed of four microfacies more or less influenced by storm events. The inner ramp (limited to the FWWB vicinity) is characterized by the development of the reefal lens and by peloidal microfacies. The upper part of Trois-Fontaines Formation is depicted by a back-reef model (three microfacies) which is mainly dominated by lagoons. However, intermittent agitation and non-restricted settings allow the local development and the reworking of branching organisms. The last model proposed (five microfacies) concerns the Terres d'Haurs Formation and corresponds to a ramp profile with the development of shoals. Those shoals locally protect semi-restricted lagoons. Algal mats are also observed. The last part of the work concerns the sedimentary dynamics and proposes sea level variations as the key parameter probably responsible for the succession of these three depositional settings.

KEYWORDS: Lower Givetian, sedimentology, platform, ramp, Marenne Member

1. Introduction

During the Lower Givetian, a large carbonate platform developed throughout northern Europe (Fig. 1A) and overlies the mixed siliciclastic-carbonate ramp characterizing most of the Eifelian. The classical succession illustrating this situation in Belgium (see, e.g., Casier & Préat, 1991) corresponds to mixed facies (Hanonet Formation), overlain by a crinoidal shoal, a biostromal unit and finally a lagoon (Trois-Fontaines Formation).

The studied sections are located along the southern flank of the Dinant Synclinorium (Fig. 1B), and more precisely in an active quarry located north of the Marenne locality (Fig. 2B), between Hotton and Marche-en-Famenne cities. Two sections have been sampled within the quarry (Fig. 2C). The first one, called Marenne East (ME – Pl. 1B), corresponds to the north-eastern flank of the quarry. The second one, Marenne Centre (MC – Pl. 1A), is located under the crushing installations and exposes a reefal lens.

Marenne sections provide a succession of strata encompassing the upper part of the Trois-Fontaines Formation and the base of the Terres d'Haurs Formation (Fig. 3). This stratigraphic interval allows a better understanding of the installation of a carbonate rimmed shelf-related sedimentation characterizing the transition between Eifelian and Givetian. Points of interest of Marenne quarry are multiple. (1) It provides an outstanding opportunity to investigate Lower Givetian of Belgium in this area located east of the classical outcrops. (2) The Trois-Fontaines Formation corresponds here to uncommon lithologies, leading to the introduction of the Marenne Member. (3) The Terres d'Haurs Formation is generally not well exposed due to its more argillaceous character than the surrounding formations (Bultynck & Dejonghe, 2001) and continuous sections are particularly uncommon. (4) This section has never been the subject of detailed sedimentological study.

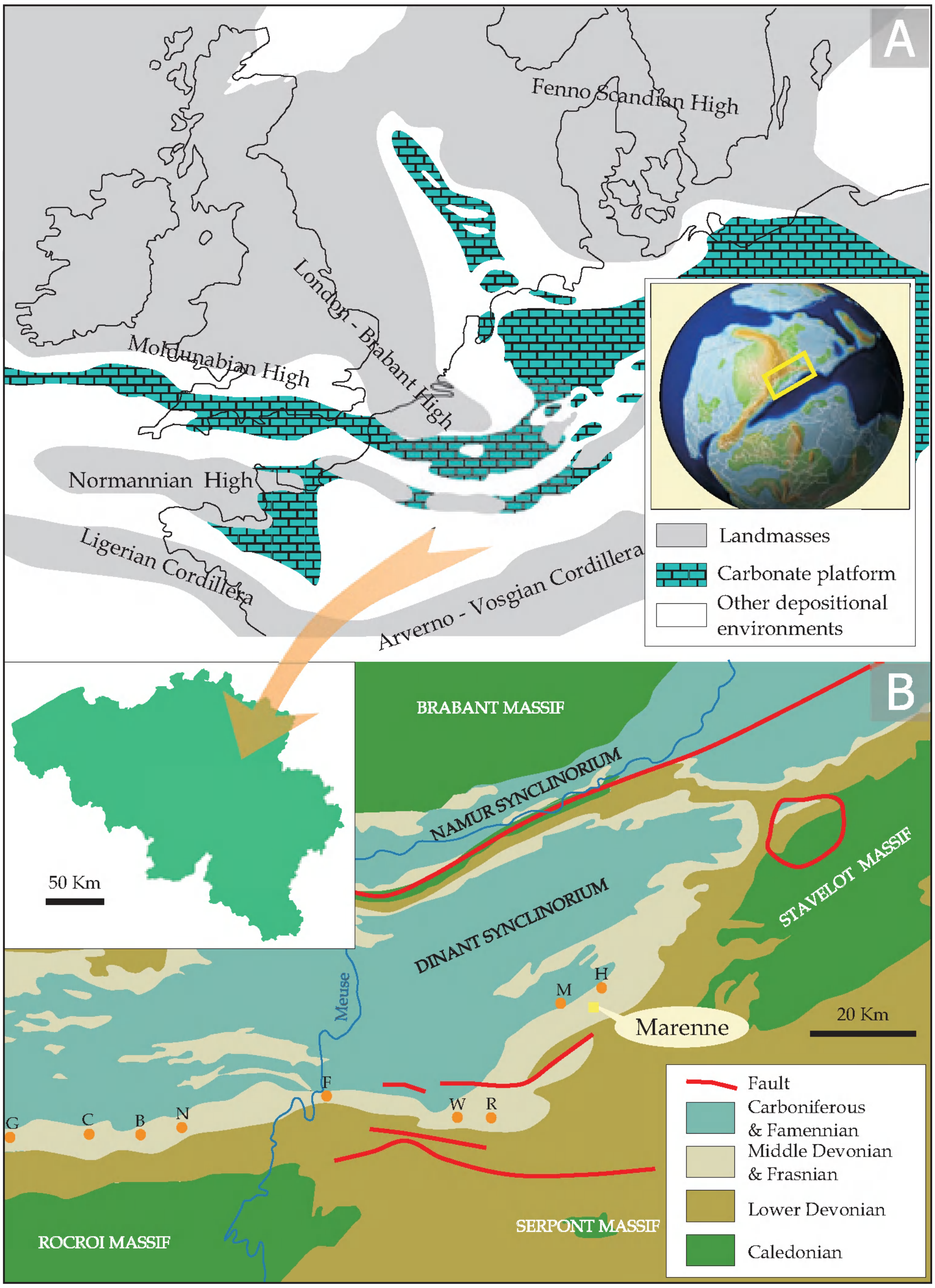

Figure 1 :
A: Palaeogeographical setting during the Eifelian (390 Ma), after Ziegler (1982) and McKerrow & Scotese (1990) showing the large carbonate platform which develops throughout northern Europe and overlies the mixed siliciclastic-carbonate facies.
B: Geological setting and location of Marenne quarry at the southern flank of the Dinant Synclinorium. G: Glageon, C: Chimay, B: Baileux, N: Nismes, F: Fromelennes (Givet), W: Wellin, R: Resteigne, M: Marche-en-Famenne, H: Hotton.

2. Previous work

Sedimentological studies were performed on several Lower Givetian sections located at the southern border of the Dinant Syncline (see Fig. 1B for location and Fig. 3 for stratigraphic interval). The most studied is the Resteigne quarry (description and sedimentological study in Casier & Préat, 1991) which covers a stratigraphic interval between the top of the Jemelle Formation and the base of the Mont d'Haurs Formation. The Glageon section was also the subject of a detailed sedimentological and palaeontological (corals) study (Boulvain et al., 1995). It exposes 63 metres of the Hanonet Formation, the entire Trois-Fontaines, Terres d'Haurs and Mont d'Haurs formations and the first 25 metres of the Fromelennes Formation. The Baileux section, covering a stratigraphic interval between the top of the Jemelle Formation and the base of the Mont d'Haurs Formation, was recently the subject of a detailed sedimentological study (Mabille & Boulvain, 2008). At last, the Fromelennes section, close to Givet, begins near the base of the Trois-Fontaines Formation and ends in the Nismes Formation (Coen-Aubert, 1991). No detailed sedimentological study was ever performed on this last section.

Besides these outcrops covering important stratigraphic interval, some shorter but particular sections (located at the boundary between Hanonet and Trois-Fontaines formations) have been recently studied. This is the case of the Wellin and Fondry des Chiens (Nismes) sections (Mamet & Préat, 2005; Préat et al., 2007). They were studied in order to investigate biohermal lenses and to integrate them in the global framework of the Eifelian-Givetian boundary.

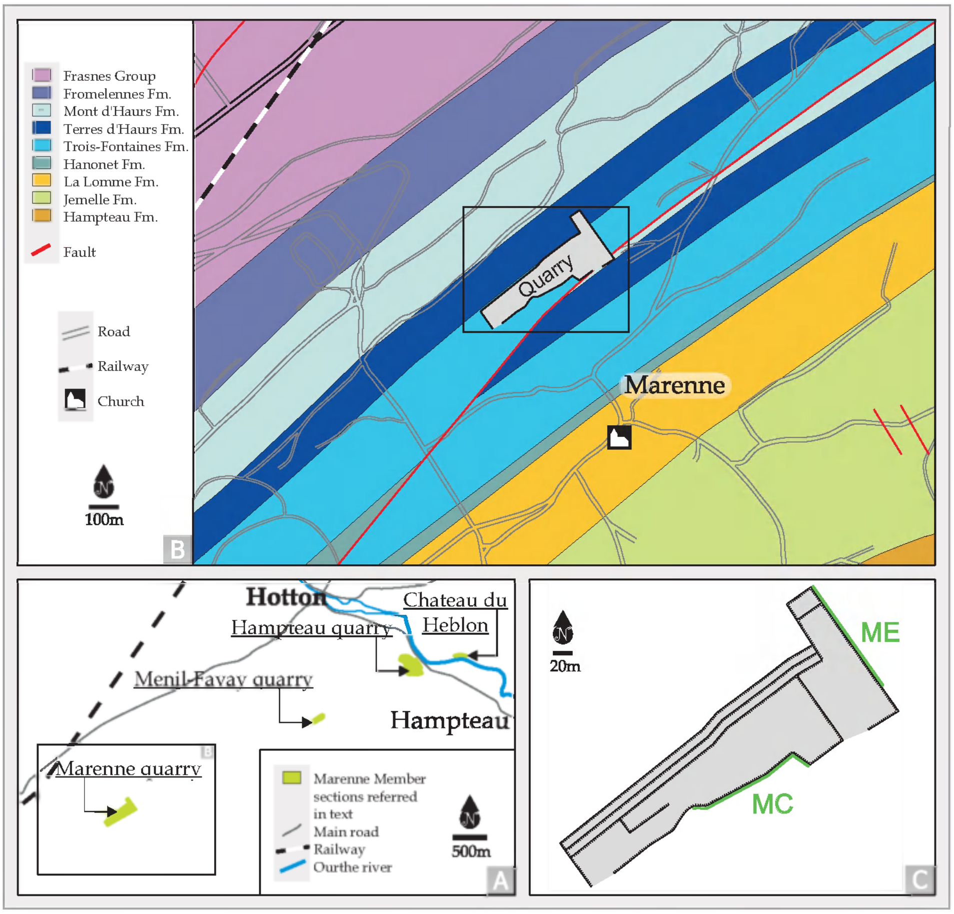

Figure 2 : Location of the studied sections.
A. Location of Marenne Member sections between Marenne and Hampteau. Area enlarged on Fig. 2B is located by black box.
B. Geological map of the Marenne area (Barchy et al., 2004). Marenne quarry is located by black box.
C. Schematic drawing of the quarry, showing the two studied sections. ME: Marenne East section, MC: Marenne Centre section.

The Marenne quarry was previously the subject of micropalaeontological approaches (Coen et al., 1974; Lessuise et al., 1979) and palaeontological investigations on brachiopods (Godefroid & Mottequin, 2005). The quarry has also been studied in order to estimate the geometry of the Marenne Fault (Barchy et al., 2004) defined during the revision of the geological map Aye – Marche-en-Famenne.

At regional scale, detailed study of the Eifelian-Givetian transition along the southern border of the Dinant Synclinorium led to the definition of 10 major microfacies and several sub-microfacies deposited on a mixed siliciclastic-carbonate detrital ramp (Préat & Kasimi, 1995; Kasimi & Préat, 1996).

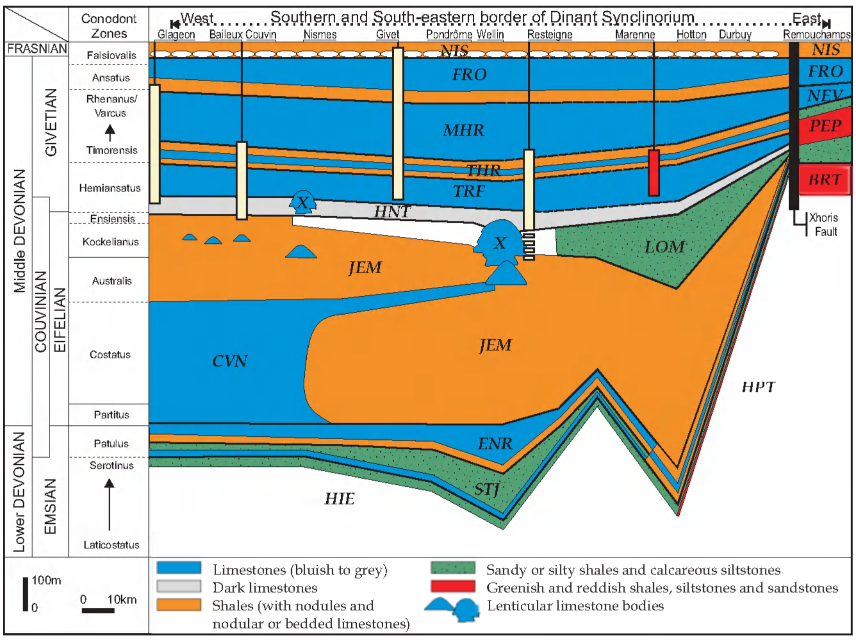

Figure 3: Generalized lithostratigraphic cross-section of Middle Devonian formations across the southern and south-eastern border of the Dinant Synclinorium, adapted from Bultynck & Dejonghe (2001), Dumoulin & Blockmans (2008) and Préat & Bultynck (2006). The studied interval is located just above the boundary between the Eifelian (ramp-related sedimentation) and the Givetian (carbonate platform-related sedimentation). The lithostratigraphic interval covered by the Glageon, Baileux, Fromelennes (Givet), Resteigne and Marenne sections are represented by boxes. Formations represented are: Hierges (HIE), Saint Joseph (STJ), Hampteau (HPT), Eau Noire (ENR), Jemelle (JEM), Couvin (CVN), X Formation (X), La Lomme (LOM), Hanonet (HNT), Burnot (BRT), Pépinster (PEP), Névremont (NEV), Trois-Fontaines (TRF), Terres d'Haurs (THR), Mont d'Haurs (MHR), Fromelennes (FRO), and Nismes (NIS).

3. Methods

Bed-by-bed description and sampling were carried out between 2004 and 2005. From the samples, 343 thin sections were prepared. The textural classification used to characterize the microfacies follows Dunham (1962) and Embry & Klovan (1972). The description of stromatoporoids is based on the morphological classification of Kershaw (1998). The terms used are branching, laminar and encrusting. The term massive (Tucker & Wright, 1990) is used for both domical and bulbous forms when the difference cannot be made (fragments or thin sections). This led to the definition of 14 microfacies: six for the Marenne Member, three for the upper part of Trois-Fontaines Formation and five microfacies for the Terres d'Haurs Formation. These microfacies are compared to those defined in Resteigne (Casier & Préat, 1990; Casier & Préat, 1991), in Glageon (Boulvain et al., 1995), in Baileux (Mabille & Boulvain, 2008), in Couvin (Mabille & Boulvain, 2007a), in Wellin (Mamet & Préat, 2005), in Nismes (Préat et al., 2007) and in Aisemont (Casier & Préat, 2006), and also with the microfacies defined for the Eifelian-Givetian boundary interval (Préat & Kasimi, 1995) and for the Eifelian Couvin Formation (Mabille & Boulvain, 2007b). References are also made to the standard ramp microfacies of Flügel (2004) and to the ramp facies of Burchette & Wright (1992). Samples were then submitted to magnetic susceptibility (MS) measurements with a KLY-3 (Kappabridge) device. Each sample was measured three times and weighed with a precision of 0.01g. These operations allow the definition of the mass-calibrated magnetic susceptibility of each sample and the drawing of magnetic susceptibility curves.

4. Description of sections

4.1. Marenne East section

The base of the section is characterized by the faulted zone of Marenne defined by Barchy et al. (2004). In this study, the base of sampling and investigations corresponds to the first succession of beds which is not affected by this faulted zone (base of part A in Barchy et al., 2004). The studied section is 115 metre thick and is divided into the Trois-Fontaines and Terres d'Haurs formations (Fig. 4 – Pl. 1B).

4.1.1. Trois-Fontaines Formation

The Trois-Fontaines Formation is divided into two parts: a lower part corresponding to the Marenne Member and an upper part comparable to classical successions (see details below).

4.1.1.1. Marenne Member

The lower part of this member is not observed and only the 24 upper metres are present (Pl. 1C). It corresponds to locally sandy limestone with the presence of siltstone beds, particularly near the base of the studied interval. Beds are 10 cm to 1 metre thick. Macrofauna is dominated by brachiopods and crinoids, with reworked branching tabulate corals. An important feature is the abundance of sedimentary structures corresponding to planar and hummocky cross stratification.

Comparison with previous works: From a sedimentological point of view, the unit is characterized by an open-marine fauna (dominated by crinoids and brachiopods), the presence of hummocky cross stratification and by the regular occurrence of sands and silts. These features lead to consider a mixed siliciclastic-carbonate ramp related sedimentation (see microfacies interpretation for details). As the Trois-Fontaines Formation classically corresponds to the succession of a crinoidal shoal, a biostromal unit and finally a lagoon (Bultynck & Dejonghe, 2001); the sedimentary dynamics recorded here are deeply different and seem to exclude the generally admitted attribution to the Trois-Fontaines Formation.

The attribution to the Hanonet Formation could be preferred because the mixed siliciclastic-carbonate ramp related sedimentation is closer to what is generally described as the Hanonet Formation (Casier & Préat, 1991; Mabille & Boulvain, 2007a). However, lithologies also clearly differ, the top of the Hanonet Formation being more carbonate-rich in classical sections.

We propose here the introduction of the Marenne Member to name particular lithologies recorded in Marenne. This Marenne Member is attributed to the Trois-Fontaines Formation. This is based on palaeontological considerations (rugose corals; Barchy et al., 2004 and also conodonts; Coen et al., 1974). The top of this part of the section is considered as laterally equivalent to the reefal lens outcropping in MC section. Two species of rugose corals found in the reefal lens, *Columnaria intermedia* (COEN-AUBERT, 1990) and *Sociophyllum elongatum* (SCHLÜTER, 1881) are considered as characterizing the base of the Trois-Fontaines Formation (Coen-Aubert, 1989; 1990). The part of ME section attributed in the present work to the Marenne Member is then regarded as part of the Trois-Fontaines Formation. This is notably the point of view adopted in the geological map Aye – Marche-en-Famenne (see Fig. 2B).

The Marenne Member crops out from Marenne to Hampteau (Fig. 2A), even if thickness seems to decreases from Menil-Favay to Hampteau. In Hampteau quarry, only a few metres are observed beneath the crinoidal shoal of the biostrome of the Trois-Fontaines Formation. The East side of Ourthe valley ("Château du Héblon") corresponds to the last record of the Marenne Member to the East (Barchy, pers. comm.).

4.1.1.2. Upper part

This unit is 58 metres thick and consists of an interbedding of several metre-thick sets of beds of pure limestone and of locally more argillaceous limestone. Pure limestone dominates the base of the unit. Beds are thick and the fauna is composed of crinoids, brachiopods, massive (and rare branching or lamellar) stromatoporoids, branching

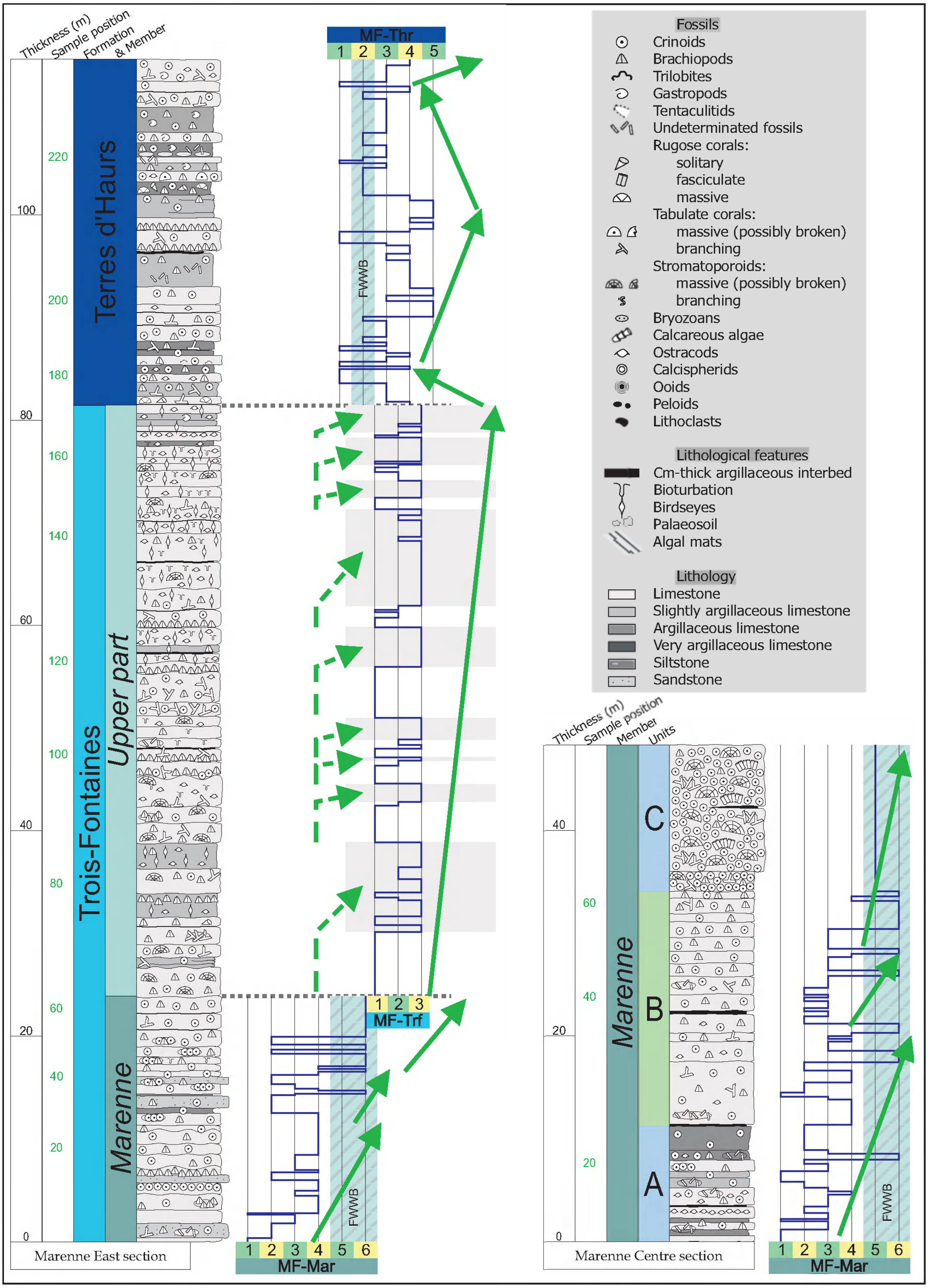

Figure 4: Schematic sedimentological log, lithostratigraphic units, lithological units and microfacies curves (FWWB = Fair Weather Wave Base) of the Marenne East and Marenne Centre sections. Dashed arrows represent shallowing-upward sequences and green arrows trends in curves.

tabulate corals (Pl. 1G), and solitary rugose corals. More argillaceous sets of beds are thin-bedded and dominate the top of the unit. Fauna is therein represented by ostracods and gastropods. Birdseyes and burrows are common.

Comparison with previous works: The Trois-Fontaines Formation is traditionally divided into 3 parts: (1) a crinoidal shoal, (2) a biostromal unit and (3) a lagoonal unit (Bultynck & Dejonghe, 2001). (1) The crinoidal shoal, missing in our section, is described as crinoidal limestone locally enriched in corals in the stratotype (Préat & Tourneur, 1991a). Some exceptions are noted, as in La Couvinoise, where it corresponds to more argillaceous crinoidal limestone (Bultynck & Dejonghe, 2001; Mabille & Boulvain, 2007a). (2) The biostromal unit, also missing in our section, was studied in detail in Resteigne (see, e.g., Préat et al., 1984). This study pointed out the lateral variations (thickness and facies) within this unit. (3) The last unit is generally composed of micritic and locally laminated limestone (Bultynck & Dejonghe, 2001). In Resteigne, this third part is mainly characterized by fenestral and burrowed mudstone or wackestone and ends with a thick succession (≈ 10 meters) of laminites (Préat & Boulvain, 1987). Facies observed in Marenne differs by the regular occurrence of sets of beds with more diversified fauna and the nearly absence of laminites even if lagoonal facies are well represented.

4.1.2. Terres d'Haurs Formation

The first bed of the Terres d'Haurs Formation corresponds to the first coral-rich layer (*Argutastrea quadrigemina*, after Barchy et al., 2004). The 33 first meters of the Terres d'Haurs Formation are visible (Pl. 1D). They correspond to diversely argillaceous limestone. The fauna is generally represented by crinoids, brachiopods (locally forming coquina beds – Pl. 1H), undeterminable broken shells, gastropods, ostracods and trilobites. Some beds are also characterized by the abundance of branching and massive tabulate corals and of massive and solitary rugose corals. Several cm-thick argillaceous interbeds are present.

Comparison with previous works: This formation is described as alternating argillaceous limestone and calcareous shales (Bultynck & Dejonghe, 2001). Terres d'Haurs Formation appears to be here less argillaceous and more carbonated than generally observed. As recorded here in Marenne (Barchy et al., 2004), the base is generally underlined by the development of a biostrome with massive rugose corals (Bultynck & Dejonghe, 2001), notably in the stratotype (Préat & Tourneur, 1991b), in Glageon (Boulvain et al., 1995) and in Resteigne (Casier & Préat, 1991).

4.2. Marenne Centre section

This section is 48 metres thick and is laterally equivalent of the first lithological unit of Marenne East section (attributed to Marenne Member). Three lithological units are here defined for the Marenne Member (Fig. 4 – Pl. 1A).

A unit corresponds to the first 11 metres of the section. It consists of an interbedding of slightly argillaceous limestone and of argillaceous limestone. Several cm-thick clayey interbeds are present. The fauna is poorly-diversified with crinoids, brachiopods and ostracods. Bioclasts are locally concentrated into lenses (cm- to dm-thick). Sedimentary structures such as planar and hummocky cross stratification are particularly abundant (Pl. 1E).

Passage to B unit (22 m-thick) is characterized by the presence of thick-bedded limestone and a more diversified fauna with the occurrence of reworked branching tabulate corals. Sedimentary structures are still abundant.

The two first metres of C unit (14 m-thick) correspond to thick-bedded crinoidal limestone with few brachiopods, branching tabulate corals and massive stromatoporoids. Following 12 metres are massive and correspond to a reefal lens. Crinoids and brachiopods are still present, but reworked (and in-situ) reef-building organisms are more abundant (Pl. 1F): massive and branching tabulate corals, massive stromatoporoids and solitary and fasciculate rugose corals.

Comparison with previous works: This section is considered as a lateral equivalent of the base of Marenne East section, and then corresponding to the Trois-Fontaines Formation (see, e.g., Barchy et al., 2004). As discussed in point 4.1.1.1, we propose to integrate the Marenne Centre section into the Marenne Member. The regular presence of detrital quartz recorded in thin section (up to 20%, see 5.1.5) clearly indicates that the reef developed under the important terrigenous influence characterizing the Marenne Member. The reefal lens described in this section slightly differs from biostromal lenses described in Wellin and Nismes (Mamet & Préat, 2005; Préat et al., 2007). In particular, reworking seems to be more important in Marenne and few organisms are found in living position. These differences are also marked in thin-section (see 5.1.5.). It is important to note that correlations between our reefal lens and biostromal lenses of Nismes and Wellin are not precise enough to assess their time-equivalence.

5. Microfacies

Microfacies are divided into three series. The first one (MF-Mar) is dedicated to the Marenne Member, the second one (MT-Trf) to the upper part of the Trois-Fontaines Formation, and the last one (MF-Thr) to the Terres d'Haurs Formation. Microfacies are illustrated on Plate 2 and a summary of microfacies with their assemblage, setting features and comparison with previously defined microfacies is provided in Table 1.

5.1. Microfacies of the Marenne Member

5.1.1. MF-Mar1: Siltstone and fine-grained sandstone with a poor fauna

Detrital quartz (from 10 to 50%) corresponds to the granulometry of silt and fine sand. Micas flakes locally reach 5%. Hematite and pyrite are often abundant.

The matrix is micritic and particularly argillaceous. Lamination consists of light layers enriched in quartz alternating with more argillaceous and dark layers. Bioturbation is mainly horizontal and is marked by a more sandy and coarse infilling (Pl. 2A). Occurrence of fauna is sporadic, consisting of rare crinoids and brachiopods bioclasts. Locally, the fauna includes broken ostracods and trilobites. Debris, ranging between 0.3 and 1.5 mm, are locally highly altered. Small ovoidal peloids (< 0.1 mm) are rare to abundant.

Interpretation: MF-Mar1 is mainly characterized by siltstone interbedded with sandstone. The primary sedimentation process is slow accumulation of suspended mud and minute debris (micrite, silt and bioclasts), but sandstone lenses likely represent distal storm deposits (Johnson & Baldwin, 1996). This suggests that this microfacies was located just above the storm wave base (SWB) as proposed by Préat & Kasimi, 1995. Anyway, the absence of hummocky cross-stratification or grainstone texture rules out a more proximal interpretation (Wright & Burchette, 1996).

This particularly detrital-rich microfacies is similar to MF1 observed in Aisemont (Casier & Préat, 2006) and can be regarded as equivalent of more bioclastic ones interpreted as deposited just above the SWB: MFa1 in Baileux (Mabille & Boulvain, 2008), MFi in Resteigne (Casier & Préat, 1990), MF1 in Glageon (Boulvain et al., 1995) and MF1 in Wellin (Mamet & Préat, 2005).

5.1.2. MF-Mar2: Laminated and bioclastic carbonated sandstone

Detrital quartz is dominating with concentrations up to 60% (Pl. 2B). Granulometry corresponds to fine sands but coarse silts are also observed. Micas flakes (up to 5%) and disseminated pyrite or hematite are locally observed.

Matrix is carbonate and corresponds to microspar. In most cases, a slight lamination (1 to 2 mm thick) is preserved: levels rich in quartz alternate with levels rich in matrix. These laminations are underlined by the occurrence of more bioclastic layers corresponding to wackestone and packstone. Vertical or horizontal burrows (2-3 mm in diameter) with a darker and more micritic infilling are locally present.

The fauna is mainly represented by crinoid ossicles, brachiopods and tentaculitids but also by rare ostracods, trilobites, bryozoans and gastropods. Small ovoidal to sphericalpeloids(0.1to0.3mm)andpaleosiphonocladaceae are locally present. All these fossils are generally broken (0.2 to 3 mm) but poorly altered.

Interpretation: This microfacies corresponds to the amalgamation of storm deposits with erosion of the major part of a classical storm sequence (compare, e.g., Nelson, 1982). This led to the preservation and repetition of truncated sequences, mainly corresponding to the coarser material deposited at the base of the complete sequence. The presence of these amalgamed storm deposits coupled with the presence of lamination indicates a location within the transition zone (sensu Aigner & Reineck, 1982). The environment is both influenced by open-marine conditions with crinoids, brachiopods and tentaculitids, and by an important terrigenous input (quartz and mica sheets). This implies a location below fair weather wave base (FWWB) but above SWB with an important terrigenous influence.

No similar microfacies have been described at the southern border of the Dinant Synclinorium, highlighting the particular detrital influence recorded in Marenne. Equivalent microfacies, MFO3, is described in the Eifelian of Eifel at the Ohlesberg quarry (Mabille et al., work in progress).

5.1.3. MF-Mar3: Laminated and locally silty to sandy wackestone and packstone

The fauna becomes more abundant in comparison with MF-Mar2 but is still dominated by crinoids, brachiopods and ostracods. Tentaculitids, trilobites and bryozoans are well represented. Small (0.1 to 0.3 mm) ovoidal to spherical peloids and gastropods are locally present. Paleosiphonocladaceae, gastropods and debris of stromatoporoids and tabulate corals are scarcely observed in the sediment. Fossils are variously broken and generally range between 0.3 and 2 mm with some centimetric exceptions. Sorting is moderate.

Detrital quartz abundance (fine sand and coarse silt) locally reaches 30% but is generally comprised between 5 and 15%. Micas flakes are locally present. Disseminated pyrite and rare hematite are observed.

Matrix is microsparitic and often affected by dolomitization (euhedral dolomite crystals). Lamination corresponds to levels rich in quartz alternating with levels rich in matrix. These laminations are underlined by the occurrence of more bioclastic layers (1 to 2 mm thick) corresponding to coarser packstone (Pl. 2C).

Interpretation: The faunal assemblage suggests an open-marine setting. The presence of packstone lenses within wackestone can be interpreted as storms deposits (Dott & Bourgeois, 1982). Thus, this microfacies corresponds to an open-marine environment located below FWWB but above SWB and can be regarded as a lateral equivalent for MF-Mar2 with a less well printed terrigenous influence and a more effective carbonate production.

The same interpretation was made for similar microfacies: MF2 of the Eifelian-Givetian boundary interval in the Dinant Synclinorium (Préat & Kasimi, 1995), MFC2 and MFC3 in Couvin (Mabille & Boulvain, 2007a) and MF3 in Glageon (Boulvain et al., 1995).

5.1.4. MF-Mar4: Locally silty coarse grainstone with crinoids and tentaculitids

Crinoids, tentaculitids, brachiopods and trilobites dominate the faunal assemblage of the grainstone (Pl. 2D) but ostracods, bryozoans, tabulate corals, stromatoporoids and gastropods are also abundant. Small ovoidal to spherical peloids (0.1 to 0.2 mm) are locally well represented as well as algae (*Girvanella*, paleosiphonocladaceae, dasycladaceae and *Sphaeroccodium*). Fossils are intact or broken and mainly ranging between 1 and 2 mm with exceptions comprised between 0.5 mm and 2 cm. They are generally not altered but symmetrical algal encrustations are present. Sorting is good to moderate.

Detrital quartz (coarse silt) is present (1 to 15%) or not. Disseminated pyrite is observed whereas hematite and micas flakes are scarce in the sediment.

Cement is an equigranular sparite with local occurrence of syntaxial cement and dolomitization by euhedral dolomite crystals. Lamination is underlined by preferential orientation of brachiopods shells and crinoids ossicles in thin section. At the outcrop level, this lamination corresponds to planar and to hummocky cross stratification.

Interpretation: This grainstone is particularly coarse with slightly broken bioclasts characterizing open-marine settings. A rapid burial, preventing for important breakage by wave agitation, could explain the relatively good preservation of bioclasts. The absence of matrix and the presence of hummocky cross stratification indicate amalgamation of storm deposits occurring just below FWWB (Wright & Burchette, 1996). The variable presence of quartz indicates an episodic terrigenous influence.

This microfacies has no equivalent along the southern border of the Dinant Synclinorium and is related to RF6 (Burchette & Wright, 1992).

5.1.5. MF-Mar5: Rudstone and floatstone with crinoids and/or branching tabulate corals

Although the fauna is dominated by crinoids and branching tabulate corals, fasciculate rugose corals, brachiopods, massive stromatoporoids and bryozoans are also well represented. These organisms are well preserved and range between 2 mm and 2 cm.

The matrix between these fossils corresponds to packstone (microsparitic with high terrigenous content) or to grainstone (equigranular sparite with local occurrence of syntaxial cement). In both cases, the assemblage is similar and composed of crinoids (locally abundant) (Pl. 2E), brachiopods, bryozoans, ostracods, trilobites and paleosiphonocladaceae. They are well preserved and range between 0.5 and 2 mm. Sorting is moderate to poor.

Authigenic quartz locally reaches 2.5% whereas detrital one is generally comprised between 0 and 5% but reaches concentrations up to 20% in some floatstones (Pl. 2F). Micas flakes and disseminated pyrite or hematite are locally observed. Dolomitization by euhedral dolomite crystals is locally intense.

Interpretation: This microfacies is associated to the bioconstructed lens described in MC section (see 4.2.). Criteria showing that MF-Mar5 corresponds to a reefal environment are: the abundance of tabulate corals and crinoids, their good preservation and the rudstone texture (thin section) and the presence of massive stromatoporoids and solitary and fasciculate rugose corals (field observation, see 4.2.). The grainstone texture is indicative of a location above FWWB. However, the floatstone texture with high terrigenous content leads us to interpret that the reefal development occurred around the FWWB, allowing the local and episodic deposition of matrix. Moreover, this detrital-rich matrix indicates that the reef developed under an important terrigenous influence.

This microfacies includes similar microfacies described in Nismes (MF3, MF5 and MF6 in Préat et al., 2007) and in Wellin (MF4, MF5a and MF6 in Mamet & Préat, 2005). These facies are in both cases respectively interpreted as the sole, the flank and reworked facies of the biostromal lens. Even if these microfacies are grouped into one in our study, it is important to note that the microfacies corresponding to the cemented barrier (MF7 in Nismes and Wellin) is not observed in Marenne. Marenne also differs by the presence of matrix and detrital material within the reefal lens, suggesting a location around FWWB whereas biostromal units in Nismes and Wellin are considered as located above FWWB.

5.1.6. MF-Mar6: Fine-grained peloidal packstone (and grainstone) interbedded with bioclastic layers

Except for bioclastic layers (described here under), ovoidal to spherical peloids (0.1 to 0.3 mm) represent more than 50% of thin-section surfaces. Some poorly-preserved skeletal fossil remains (0.4 to 0.8 mm) are present: crinoids, brachiopods, tentaculitids, ostracods, trilobites, bryozoans, paleosiphonocladaceae and *Girvanella* (Pl. 2G). Symmetrical algal encrustations are regularly observed (mainly around crinoids). Sorting is good.

Detrital quartz abundance (coarse silt) ranges between 0 and 20%. Micas flakes and disseminated pyrite or hematite are locally observed.

The matrix of packstone is microsparitic. The grainstone cement is an equigranular sparite. A mm-thick lamination is regularly observed and corresponds to darker levels enriched in peloids. This lamination is underlined by more bioclastic and coarser occurrences (wackestone to grainstone almost free of peloids). Within these layers, the fauna is mainly represented by branching tabulate corals (possibly accompanied by branching stromatoporoids and fasciculate rugose corals), tentaculitids, brachiopods and crinoids. Some trilobites, ostracods and massive stromatoporoids are also present. These skeletons of organisms are variously broken and range between 0.5 and 3 cm. Branching organisms are regularly affected by symmetrical algal encrustation.

Interpretation: MF-Mar6 is characterized by two main features: the abundance of peloids and the occurrence of bioclastic layers. Peloids probably have shallow-water, low-energy origin like a lagoon or a back-reef area (see, e.g., Tucker & Wright, 1990). An important point to note is that in other Lower Givetian sections studied in Belgium, the presence of peloids is generally 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. The occurrence of bioclastic layers indicates temporary increasing of wave energy by storm events.

These storms rework open-marine bioclasts but also reef-building organisms which could be either local in origin or correspond to the dismantling of MF-Mar5. The mixing between grainstone and packstone textures coupled to the preservation of sedimentary structures and bioclastic layers suggest a location around the FWWB (Wright & Burchette, 1996).

MF-Mar6 is equivalent of MFC6a and MFC6b defined in Couvin (Mabille & Boulvain, 2007a) and MF6 in Glageon (Boulvain et al., 1995).

5.1.7. Summary – Palaeoenvironmental model for the Marenne Member

To summarize and illustrate the interpretation made for each microfacies, a palaeoenvironmental model is proposed (Fig. 5A). The ramp profile was selected because of (1) the abundance of storm related deposits, (2) the facies observed at field scale is mainly characterized by planar and hummocky cross stratification, (3) the abundance of detrital material is high, and (4) the absence of proof indicating the influence or the presence of a continuous reefal barrier.

In detail, the model corresponds to a ramp where terrigenous inputs are particularly important. This is marked in two ways. The first one is the presence of two detrital-dominated microfacies (MF-Mar1 and MF-Mar2) and the second is the local possibility for detrital quartz to reach 20% in other microfacies. This ramp model can be divided into a mid-ramp and an inner ramp following definitions introduced by Burchette & Wright (1992). The mid-ramp includes four microfacies. The most distal one, MF-Mar1, is located just above the SWB. Its detrital content is notably high, indicating an important terrigenous influence and/or low carbonate productivity. MF-Mar2 and MF-Mar3 are lateral equivalent located below FWWB but above SWB. The first microfacies corresponds to an important terrigenous input and a low carbonate productivity (sandstone) whereas the second corresponds to the opposite (wackestone and packstone). Then MF-Mar4 consists of amalgamation of storm deposits occurring just below FWWB. The inner ramp is characterized by the development of the reefal lens (MF-Mar5) and by peloidal microfacies interbedded with storm-related bioclastic layers (MF-Mar6). Both

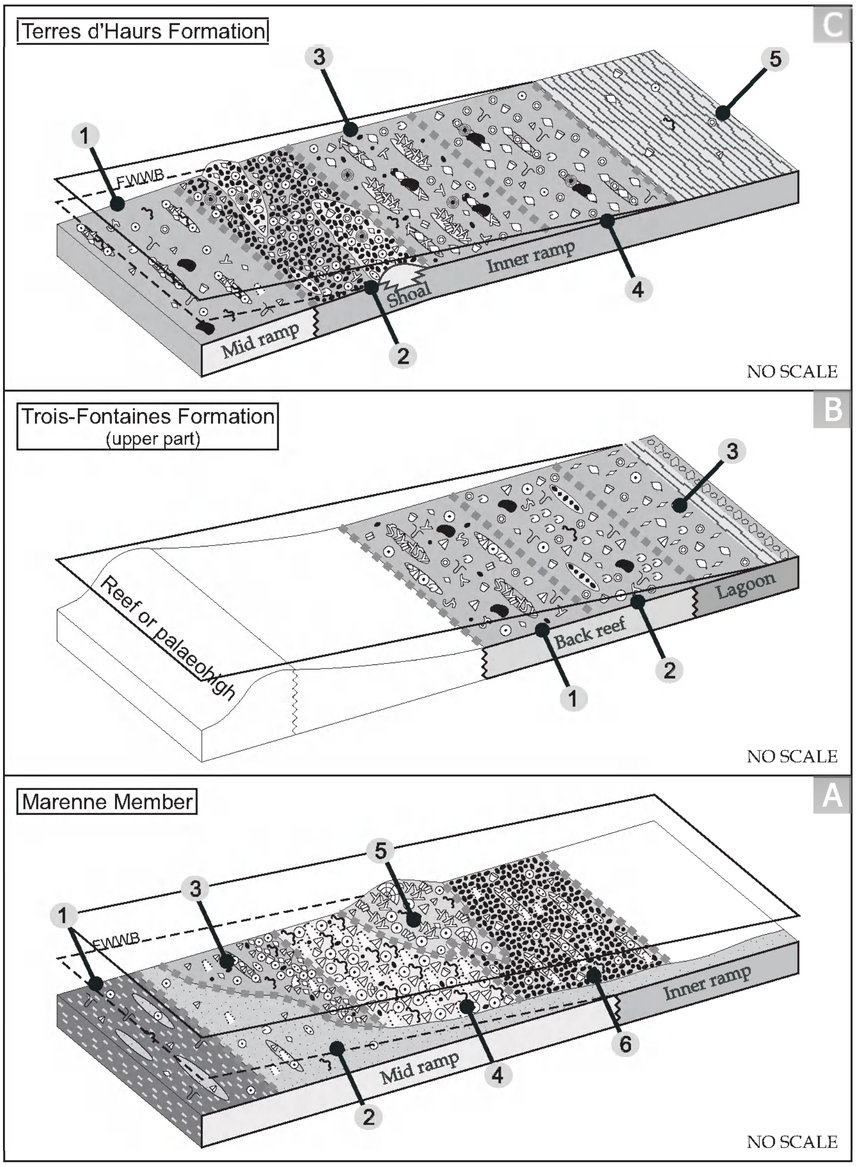

Figure 5: Proposed palaeoenvironmental model for (A) Marenne Member, (B) Upper part of the Trois-Fontaines Formation and (C) Terres d'Haurs Formation (see Figure 4 for legend). FWWB = Fair Weather Wave Base.
A: Model proposed for the Marenne Member corresponds to a ramp model where terrigenous inputs are particularly important. The mid-ramp is composed of four microfacies more or less influenced by storm events. The inner ramp (limited to the FWWB vicinity) is characterized by the development of the reefal lens and by peloidal microfacies.
B: The Trois-Fontaines Formation (upper part) is depicted by a back-reef model which is mainly dominated by lagoons. Intermittent agitation and non-restricted settings allow the local development and the reworking of branching organisms.
C: The Terres d'Haurs Formation model corresponds to a ramp profile with the development of shoals. Those shoals locally protect semi-restricted lagoons. Algal mats are also observed.

microfacies are deposited around the FWWB.

This mixed ramp related sedimentation clearly differs from what is classically observed at the base of the Trois-Fontaines Formation, i.e. the installation of a biostromal unit (see, e.g., Casier & Préat, 1991). Altough it is closer to the classical sedimentary dynamics of the Hanonet Formation, and notably of the stratotype (Mabille & Boulvain, 2007a), the detrital influence is here particularly notable. This leads to particular lithologies, differing from classical lithologies observed for Hanonet and Trois-Fontaines formations. This explains why the Marenne Centre section and the base of the Marenne East section are here considered as part of the newly defined Marenne Member.

5.2. Microfacies of the Trois-Fontaines Formation (Upper part)

5.2.1. MF-Trf1: Bioclastic wackestone (floatstone) and packstone with branching organisms

The main characteristic of this microfacies is the presence of poorly preserved debris of branching tabulate corals and stromatoporoids. These organisms regularly show micritised rims. Other fossil remains are present and diversely preserved: brachiopods, crinoids, ostracods, gastropods, fasciculate rugose corals, massive or encrusting stromatoporoids and tabulate corals and trilobites. Algae are locally well represented with calcispheres, *Girvanella* (symmetrical encrustations) and paleosiphonocladaceae. Fossils are broken and range between 0.5 and 1 mm, with some exceptions reaching up to 3 cm like brachiopods, gastropods, tabulate corals, stromatoporoids and rugose corals. Ovoidal to irregular peloids (between 0.1 and 0.5 mm) are locally present as well as lithoclasts (between 0.5 and 2 mm) (Pl. 2H). These lithoclasts correspond to mudstone and wackestone related to MF-Trf3. Sorting is moderate to poor.

Detrital quartz abundance generally ranges between 0 and 2.5% but locally reaches 15%. Authigenic quartz, micas flakes and disseminated hematite and pyrite are observed in some thin-sections.

The matrix of wackestone, floatstone and packstone is micritic to microsparitic and is locally dolomitised by euhedral dolomite crystals or argillaceous. Vertical mm-sized burrows are locally observed and are infilled by a peloidal and microsparitic packstone. Some samples with similar assemblage are related to this microfacies and are composed of well-sorted grainstone with equigranular cement (Pl. 2H).

Interpretation: MF-Trf1 corresponds to relatively quiet conditions as shown by the presence of matrix. Branching organisms are well represented but poorly preserved (breakage and micritised rims). This could correspond to the dismantling of little coral-patches allowed to grow in this quiet environment located in a back-reef area (Mabille & Boulvain, 2007b). The presence of calcispheres reinforces this assessment. Occurrences of well-sorted grainstone probably correspond to storm events disrupting the quiet back-reef setting.

Similar microfacies was described in Couvin Formation (MF10 in Mabille & Boulvain, 2007b).

5.2.2. MF-Trf2: Bioclastic wackestone and packstone interbedded with peloidal grainstone

Crinoids, gastropods (locally abundant), ostracods, brachiopods and trilobites dominate this microfacies (Pl. 2I). Algae are regularly present (calcispheres, paleosiphonocladaceae, *Girvanella* encrustations and dasycladaceae). The local occurrence of branching tabulate corals and stromatoporoids and of lithoclasts (between 0.5 and 3 mm, similar to those described for MF-Trf1) is noted. These organisms are broken and poorly-preserved. They are mainly smaller than 2 mm, except for tabulate corals and stromatoporoids (up to 1 cm).

Detrital quartz (< 2.5%) and pyrite (regularly associated with hematite) are present.

Matrix is micritic. Peloidal grainstone occurrences correspond to mm to cm-thick lenses or to burrows infilling. These peloids are ovoidal to spherical (0.1 to 0.2 mm).

Interpretation: MF-Trf2 differs from MF-Trf1 by a lower abundance of branching stromatoporoids and tabulate corals and by the abundance of gastropods and algae. The environment was still quiet but different, being more influenced by lagoonal environment as shown by the abundance of calcispheres. MF-Trf2 is then interpreted as a back-reef microfacies submitted to a relatively limited wave agitation but regularly affected by more energetic events as shown by the occurrence of peloidal grainstone.

MF-Trf2 is similar to MFa10 defined in Baileux (Mabille & Boulvain, 2008) and MF12 in the Couvin Formation (Mabille & Boulvain, 2007b).

5.2.3. MF-Trf3: Fenestral wackestone and mudstone with ostracods and calcispheres

The microfossil assemblage is dominated by ostracods and calcispheres (Pl. 2J). Ostracods are particularly well preserved and reach up to 5 mm. Accessory bioclasts (< 1 mm) are paleosiphonocladaceae, crinoids, brachiopods, *Girvanella* (aggregates and encrustations), gastropods, branching tabulate corals and stromatoporoids, dasycladaceae and trilobites.

Detrital quartz is present (generally < 2.5%) and locally associated with micas flakes. Lots of pyrite and hematite are disseminated into the sediment or concentrated within fenestrae.

The matrix is a fine-grained and dark micrite. It is locally affected by dolomitization. Birdseyes are present in every thin-section. They are ranging from 0.5 and 3 mm and are filled by equigranular sparite. Vertical burrows are present in some thin sections and are filled by microsparitic mudstone, equigranular sparite or well-sorted peloidal grainstone.

Some thin-sections show lamination underlined by well-sorted peloidal grainstone layers. They are associated with elongated fenestrae ranging between 1 and 5 mm in length but never exceeding 0.5 mm in height. Moreover, some data indicate slight pedogenesis: nodulization, breccia, mineralizations (Pl. 2K).

Interpretation: MF-Trf3 is characterized by the presence of fenestrae (and notably birdseyes) and by an assemblage consisting essentially of calcispheres and ostracods. Moreover, the presence of peloidal grainstone with elongated fenestrae suggests the presence of algal mats (Flügel, 2004). This indicates an intertidal and restricted lagoon.

This is also the interpretation made for similar microfacies described in the Eifelian and Givetian in the Dinant Synclinorium (MF13 in Mabille & Boulvain, 2007b; MF10a in Préat & Kasimi, 1995). MF-Trf3 is similar to MF9 defined in Resteigne (Casier & Préat, 1991) and can be compared to MF14 and MF15 defined in Glageon (Boulvain et al., 1995) and to MFa11 and MFa12 in Baileux (Mabille & Boulvain, 2008).

5.2.4. Summary – Palaeoenvironmental model for the upper part of the Trois-Fontaines Formation

To summarize and illustrate the interpretation made for each microfacies, a palaeoenvironmental model is proposed (Fig. 5B). The platform profile was preferred because of the presence of a well-developed protected lagoon associated with calcispheres and algal mats. This assessment is confirmed by comparison with similar microfacies association found in the Eifelian (Mabille & Boulvain, 2007b) and the Givetian (Casier & Préat, 1991; Mabille & Boulvain, 2008). However, it is impossible to determine whether a reefal barrier was effectively protecting this back-reef sedimentation or if we have to consider a palaeo-high.

In detail, the model corresponds to a platform part, only representing back-reefal area and lagoon. The back-reef environment is mainly dominated by quiet settings where branching organisms were probably able to grow (MF-Trf1). Local occurrences of grainstone show that this environment was affected by more energetic events, like the MF-Trf2 setting. This microfacies is transitional to a restricted and protected lagoon (represented by MF-Trf3).

5.3. Microfacies of the Terres d'Haurs Formation

5.3.1. MF-Thr1: Laminated wackestone with crinoids and brachiopods interbedded with packstone and grainstone

Although bioclasts are mainly represented by crinoids and brachiopods, ostracods, trilobites, and few branching tabulate corals and stromatoporoids, gastropods, bryozoans, paleosiphonocladaceae, dasycladaceae, foraminifers, tentaculitids, *Girvanella* and calcispheres are also present (Pl. 2L). These fossils are generally smaller than 1mm in wackestones and packstones and smaller than 4mm in grainstones, with few centimetric exceptions. They are generally not altered. Some irregular peloids (from 0.1 to 0.4 mm) and micritic lithoclasts (related to MF-Thr4) are locally observed. Sorting is moderate.

Detrital quartz occurrence is sporadic, with local concentrations up to 1%. Micas flakes, pyrite and hematite are regularly observed.

Planar lamination results from two features: the first one is a preferential shell orientation parallel to the bedding; the second one are regularly spaced mm- to cm-thick packstone and grainstone layers. The matrix is a brownish micrite and is locally argillaceous or dolomitised. Horizontal burrows are present and underlined by a lighter and microsparitic infilling.

Interpretation: The assemblage is dominated by crinoids and brachiopods, pointing to an open-marine setting. The combined presence of mud and more bioclastic lenses and layers corresponds to slow accumulation of suspended mud and minute debris interbedded with distal storm deposits. This suggests that this microfacies was located above the SWB (Préat & Kasimi, 1995).

MF-Thr1 is similar to MFb1 of Baileux (Mabille & Boulvain, 2008) and can be compared to RMF13 (Flügel, 2004).

5.3.2. MF-Thr2: Peloidal packstone and grainstone with crinoids and ostracods

Irregular to spherical peloids (0.1 to 0.3 mm) dominate the assemblage. Skeletal fossil remains are mainly crinoids, ostracods and brachiopods (Pl. 2M) but some gastropods, trilobites, bryozoans, paleosiphonocladaceae, calcispheres, *Girvanella* (aggregates and encrustations), and branching tabulate corals and stromatoporoids are regularly observed. These fossils are generally poorly-preserved and intensively broken. They range between 1 and 2 mm with some centimetric exceptions (few brachiopods, branching tabulate corals and stromatoporoids). Moreover, branching organisms regularly show symmetrical algal encrustations. Spherical to ovoidal ooids ranging between 0.2 and 0.5 mm are locally present. Sorting is moderate.

Detrital quartz occurrence is sporadic, with local concentrations up to 1%. Micas flakes, pyrite and hematite are regularly observed.

Matrix is microsparitic and cement corresponds to an equigranular sparite. Planar lamination results from two features: the first one is a preferential shell orientation parallel to the bedding; the second one are regularly spaced mm- to cm-thick grainstone layers interbedded within packstone.

Interpretation: MF-Thr2 is characterized by the abundance of peloids and of crinoids and ostracods. Peloids probably have shallow-water, low-energy origin (see, e.g., Tucker & Wright, 1990). This proximal environment supplies also calcareous algal debris but, according to the fauna, an open-marine influence was also present. The poor bioclast preservation coupled to the presence of ooids indicates intense wave agitation and reworking, typical of shoals settings. This leads us to consider a location above FWWB but the presence of matrix suggests intermittent agitation. MF-Thr2 is considered as being located around the FWWB, close to peloidal and bioclastic shoals.

This microfacies can be related to RMF26 (Flügel, 2004) and to RF9 (Burchette & Wright, 1992). MF-Thr2 is also an equivalent of MF13 defined in Glageon (Boulvain et al., 1995).

5.3.3. MF-Thr3: Wackestone with ostracods and branching tabulate corals debris interbedded with packstone and grainstone layers

The main characteristic of MF-Thr3 is the presence of both branching tabulate corals debris (from 0.5 to 1 cm) (Pl. 2N) and broken *Leperditia*-like ostracods (from 1 to 3 mm). The remaining assemblage consists of crinoid ossicles, brachiopods, trilobites, gastropods, bryozoans, fasciculate rugose corals, paleosiphonocladaceae, *Girvanella* (aggregates and encrustations), dasycladaceae, calcispheres and ovoidal to spherical peloids (0.1 to 0.3 mm). Fossil remains are variously preserved, locally preventing determination, with sizes that range between 0.5 and 3 mm. Symmetrical algal encrustations are common. Sorting is poor to moderate. Detrital quartz rarely exceeds 1%. Micas flakes, pyrite and hematite are abundant.

Matrix is a mixture of dark micrite, microspar and dolomite. Some mm- to cm-thick packstone and grainstone layers regularly occur. The grainstone assemblage is enriched with lithoclasts (from 3mm to 1cm, related to MF-Thr4 and MF-Thr5), ooids and more diversified peloid forms (presence of irregular peloids and mold peloids, < 0.8 mm). The cement is an equigranular sparite.

Interpretation: MF-Thr3 characteristics suggest quiet settings, allowing mud deposition. However, the regular association with grainstone layers demonstrates episodic increase of wave energy. This corresponds to a protected location within the inner ramp with a possible reworking under storm action. The fauna indicates relatively protected settings (dominance of ostracods with the occurrence of calcispheres) together with an open-marine influence (trilobites, brachiopods and crinoids). The abundance of poorly preserved (breakage and micritised rims) branching tabulate corals could indicate the dismantling of little coral-patches growing in this quiet environment.

MF-Thr3 is to compare to RMF18 (Flügel, 2004).

5.3.4. MF-Thr4: Wackestone and mudstone with calcispheres and ostracods interbedded with packstone and grainstone layers

The microfossil assemblage is dominated by calcispheres and ostracods. These ostracods are particularly well preserved and reach up to 5 mm. Other common bioclasts (< 1 mm) are paleosiphonocladaceae, crinoids, brachiopods, *Girvanella* (aggregates and encrustations), gastropods, branching tabulate corals and stromatoporoids, dasycladaceae and trilobites.

Detrital quartz is present (generally < 2.5%) and locally associated with micas flakes. Lots of pyrite and hematite are disseminated into the sediment.

The matrix is a fine and dark micrite. It is locally affected by dolomitization. Burrows up to 5 mm in diameter are present in some thin-sections and are filled by well-sorted peloidal grainstone. Packstone and grainstone layers (mm- to cm-thick) are regularly observed (Pl. 2O). Assemblage of packstone is similar (nature and granulometry) to the surrounding mudstone and wackestone. At the opposite, the assemblage of grainstone is coarser and differs by the presence of ooids and lithoclasts (up to 3mm). Their nature corresponds to the surrounding wackestone and mudstone.

Interpretation: MF-Thr4 possesses numerous common characteristics with MF-Trf3, leading to consider a similar lagoonal environment. However, important differences have to be noted. The first one is that birdseyes are not observed. Then, a lesser dominance of calcispheres and ostracods is recorded, providing a more diversified assemblage. This could indicate less restricted conditions compared to MF-Trf3 environment. This is confirmed by the occurrence of episodic increasing of wave energy as shown by the grainstone layers. These events, probably related to storm, are responsible for the reworking and in-situ deposition of micritic lithoclasts. MF-Thr4 is then related to a semi-restricted environment protected of normal waves but under storm influence.

This MF-Thr4 can be regarded as equivalent to MFb5 defined in Baileux (Mabille & Boulvain, 2008), RMF18 (Flügel, 2004) and RF10 (Burchette & Wright, 1992).

5.3.5. MF-Thr5: Very well-sorted peloidal grainstone with fenestrae

Ovoidal to spherical peloids (< 0.1 mm) dominate (Pl. 2P). Bioclasts like ostracods, brachiopods, crinoids, trilobites, *Girvanella* (aggregates), paleosiphonocladaceae and calcispheres are scarcely present. These bioclasts are intensively broken (< 0.3 mm) and altered. The sorting is particularly good.

Detrital quartz is rarely observed but locally reaches 2.5% and disseminated pyrite is abundant.

Cement is an equigranular sparite. Lamination corresponding to light layers (peloidal grainstone) alternating with dark ones (micritic packstone), is locally observed. These laminations never exceed 2 mm in thickness. Fenestrae filled with large crystals of calcite are regularly observed and consists in two types. The first type corresponds to small angular fenestrae (< 1 mm), whereas the second one underlines the lamination. It corresponds to elongated fenestrae ranging between 1 and 5 mm in length but never exceeding 0.5 mm in height.

Interpretation: The presence of elongated fenestrae within the peloidal grainstone suggests that MF-Thr5 may correspond to algal mats (Flügel, 2004) and leads us to consider an intertidal and restricted lagoonal environment.

MF-Thr5 is equivalent to RMF23 (Flügel, 2004).

5.3.6. Summary – Palaeoenvironmental model for the Terres d'Haurs Formation

A palaeoenvironmental model, corresponding to a ramp profile, is proposed for the Terres d'Haurs Formation (Fig.

5C). The ramp geometry was preferred due to (1) the development of bioclastic and peloidal shoals related to MF-Thr2, (2) the presence of storm-related deposits in proximal settings, (3) the presence of an open marine fauna associated to proximal settings (lagoon and algal mats), and (4) the local presence of ooids.

This model can be divided into a mid-ramp and an inner ramp following definitions introduced by Burchette & Wright (1992). The mid-ramp is characterized by a background sedimentation corresponding to wackestone with open-marine fauna (MF-Thr1) interrupted by storm-related events (packstone and grainstone). The boundary between the mid-ramp and the inner ramp is characterized by the development of shoals (MF-Thr2) protecting the inner ramp area even if storm related deposits are regularly observed. In details, the inner ramp corresponds to relatively quiet settings where branching organisms are able to grow but are regularly dismantled by storms (MF-Thr3). The presence of a semi-restricted lagoon is noted (MF-Thr4) as well as algal mats (MF-Thr5).

6. Magnetic susceptibility study

6.1. Principles

Magnetic susceptibility (MS) values are obtained by means of laboratory measurements of the rock sample response to an external magnetic field. Since the pioneer studies performed fifty years ago, the magnetic susceptibility logging and sample measurements in stratal successions have a long history (e.g. Rees, 1961; Hamilton, 1967; Hrouda & Janak, 1971). First MS logs and sample measurements from the Devonian carbonate beds were published in early 1990's (e.g. Hladil, 1992; see also Fryda et al., 2002). The high-resolution MS stratigraphy in Devonian carbonate sequences was particularly developed by R. E. Crick & B. B. Ellwood (e.g. Crick et al., 1994; 1997; 2000; Ellwood et al., 2000 and many other papers until the present see, e.g., da Silva & Boulvain, 2002; 2006). MS measurements have been used in these rocks also in combination with gamma-ray spectrometry and chemical/mineralogical analyses (e.g. Hladil, 2002; Hladil et al., 2006).

For sedimentary rocks, the major influence on MS is generally the terrestrial fraction (Ellwood et al., 2000). This can generally be linked to eustasy because when sea level falls, erosion of exposed continental masses increases and this leads to higher MS values. On the contrary, when the sea level rises, MS shows lower values. Similarly to delivery of terrigenous material by riverine transport, the role of eolian transport and atmospheric deposits was also considered (Hladil, 2002) in terms of fine-scale, stratigraphic MS variations, particularly in very pure and shallow-water limestones. It is important to note that other influences like climatic changes (precipitation, ice ages and pedogenesis), tectonism, diagenesis, volcanism, impact ejecta and so on may influence MS values (e.g. Crick et al., 1994; Ellwood et al., 1999; Stage, 2001; Hladil et al., 2006). MS was already tested on Eifelian and Givetian sections of Belgium. Two main parameters influencing the MS were underlined by survey of these thick, argillaceous limestone deposits: terrigenous input and wave agitation (Mabille & Boulvain, 2007a; 2007b). Stratigraphic MS variations in limestone rocks provide accurate correlations with higher resolution than that offered by biostratigraphy (Crick et al., 1997; da Silva & Boulvain, 2006; Hladil, 2002). However, the detailed biostratigraphical marks are always a necessary prerequisite of this research (Crick et al., 1994).

6.2. Correlations

MS measurements were performed on Marenne East and Marenne Centre sections and MS curves for the Marenne Member are presented on Fig. 6. Marenne East section shows three decreasing trends in MS values: ME1, ME2 and ME3 (red arrows on Fig. 6). Marenne Centre is also characterized by three decreasing trends: MC1, MC2 and MC3. Microfacies curves and MS curves are in opposition, contradicting the parallelism generally observed (see, e.g., da Silva & Boulvain, 2006). This was also the case for other mixed ramp-related sections of the Eifelian and the Givetian of Belgium (Mabille & Boulvain, 2007a; 2008).

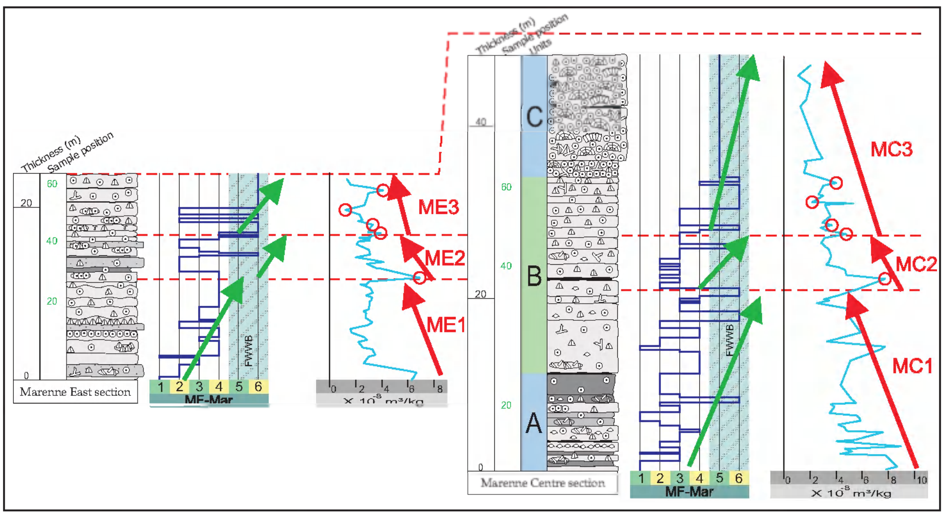

Figure 6: Schematic sedimentological log (see Figure 4 for legend), lithological units, microfacies curves and magnetic susceptibility curves of the Marenne Member. Arrows represent trends in curves and dashed lines proposed correlation lines between Marenne East and Marenne Centre sections. Circles highlight, in both magnetic susceptibility curves, particular succession of peaks.

Correlation lines (red dotted lines on Fig. 6) are here proposed on the base of the particular succession of peaks found in both curves (red circles). It is in agreement with the classical correlation previously suggested (Barchy et al., 2004). The upper one corresponds to the boundary between the Marenne Member and the remaining part of the Trois-Fontaines Formation. As this boundary is not reached in the Marenne Centre section, the correlation line is placed above the top of this section. However, the comparison between curves suggests that MC1, MC2 and MC3 respectively correspond to ME1, ME2 and ME3. It is quite interesting to note the important thickness of MC3 trend compared to ME3. This highlights the role played by the reefal lens on the increasing of carbonate productivity and then on sedimentation rate.

7. Microfacies and environmental evolution

Now that correlations are made between the sections, the drawing of microfacies curve (Fig. 4) allows the description and interpretation of the environmental succession observed in the Marenne quarry. Trends are defined and described following stratigraphical order.

The Marenne Member is characterized by a ramp-related sedimentation and a general shallowing-upward trend, confirming what was previously described for the base of the Givetian (Mabille & Boulvain, 2007a). In details, this general trend corresponds to the vertical stacking of shorter shallowing-upward cycles. This is probably due to the superposition of prograding sedimentary bodies (Casier & Préat, 1990). The main particularity of this part of the Trois-Fontaines Formation in Marenne is the abundance of detrital material (reaching up to 50%) compared to classical sections. It points out the particular position of the Marenne area under an important terrestrial influx.

The boundary between the Marenne Member and the upper part of the Trois-Fontaines Formation corresponds here to an abrupt transition from a location around the FWWB (MF-Mar6) to a relatively proximal back-reef setting (MF-Trf1). An important sea level change as well as a serious hiatus is probably responsible for this situation. This event probably corresponds to a sequence boundary. Studying other sections, and particularly classical sections, is needed to understand this important sequence stratigraphy event.

The sedimentary dynamics of the upper part of the Trois-Fontaines Formation then correspond to a general shallowing-upward cycle consisting of a superposition of similar shallowing-upward sequences (dashed arrows on Fig. 4). Each starts with non-lagoonal settings associated to MF-Trf1 and MF-Trf2 and ends with lagoonal-dominated facies corresponding to MF-Trf3 (grey boxes on Fig. 4). This succession indicates a relative stability of the environment. Moreover, it involves a barrier able to protect such a lagoonal area. The presence of this barrier was already inferred in previously published papers (see, e.g., Préat & Mamet, 1989). Recently, cemented bioconstructed facies were described in two locations: Nismes (Préat et al., 2007) and Wellin (Mamet & Préat, 2005). They were considered as preserved parts of a reefal barrier protecting the lagoonal unit of the Trois-Fontaines Formation. However, they also could correspond to isolated bioconstructed lenses without any link with the inferred barrier. So, in absence of direct piece of evidence, this barrier could even be a reef or a palaeo-high and further investigations are needed in order to choose between these two assessments.

The transition from the Trois-Fontaines Formation to the Terres d'Haurs Formation corresponds to a failure of this barrier allowing a turn-back of open-marine influence. This transition between a back-reef area and a ramp setting was previously described in Baileux (Mabille & Boulvain, 2008). Four trends are defined for the Terres d'Haurs Formation, alternating deepening and shallowing-upward sequences. The second trend, dominated by semi-lagoonal facies (MF-Thr4) and algal mats (MF-Thr5), clearly shows that this ramp is located in more proximal settings than those defined for the Marenne Member.

8. Conclusions

This study is devoted to the Marenne quarry which cuts particular lithologies from the Trois-Fontaines Formation and the base of the Terres d'Haurs Formation. It offers the opportunity of investigating two sections, respectively named Marenne East and Marenne Centre. Because of uncommon lithologies due to sedimentary dynamics dominated by mixed siliciclastic-carbonate deposits occurring on a ramp profile, this work suggests to consider the base of Marenne East section and the Marenne Centre section as part of a new member, the Marenne Member. This newly introduced Marenne Member is characterized by locally sandy and silty limestones with the local development of crinoidal and reefal limestones.

Petrographic analyses led to the definition of 14 microfacies. They correspond to three distinct palaeoenvironmental models. Six microfacies compose the ramp model proposed for the Marenne Member. In this model, terrigenous inputs are particularly important in distal microfacies (MF-Mar1 and MF-Mar2). Both are related to mid-ramp settings, MF-Mar1 being located just above SWB. MF-Mar2 and MF-Mar3 are lateral equivalent located below FWWB but above SWB. The first microfacies corresponds to a carbonated sandstone whereas the second corresponds to wackestone and packstone. Then MF-Mar4 consists of amalgamated storm deposits occurring just below FWWB. The inner ramp is characterized by the development of the reefal lens (MF-Mar5) and by peloidal microfacies (MF-Mar6). Both microfacies are deposited around FWWB.

The model proposed for the upper part of the Trois-Fontaines Formation is composed of three microfacies and corresponds to a back-reef environment which is mainly dominated by lagoonal facies (MF-Trf3). Locally, intermittent agitation and non-restricted settings allow the development and the reworking of branching organisms

(MF-Trf1). MF-Trf2 is also affected by more energetic events and is regarded as transitional with the lagoon.

The last model proposed concerns the Terres d'Haurs Formation. This ramp model is divided into a mid-ramp (MF-Thr1) and an inner ramp (MF-Thr2 to MF-Thr5). The mid-ramp is characterized by an open-marine sedimentation interrupted by storm events. The boundary between the mid-ramp and the inner ramp is characterized by the development of shoals (MF-Thr2) protecting the inner ramp area even if storm related deposits are regularly observed. The inner ramp is associated to relatively quiet settings where branching organisms are able to grow but are regularly dismantled by storms (MF-Thr3). The presence of a semi-restricted lagoon is noted (MF-Thr4) as well as algal mats (MF-Thr5).

Comparison between the two studied sections (correlated by magnetic susceptibility) allows a better understanding of sedimentary dynamics of the Marenne Member as a result of the superposition of prograding sedimentary bodies. The transition to the upper part of the Trois-Fontaines Formation is marked by an important sea-level change and by a break in the sedimentation. This event is interpreted as a sequence boundary. Then, the sedimentary dynamics of the Trois-Fontaines Formation correspond to a general shallowing-upward sequence consisting of stacked shallowing-upward cycles between non-lagoonal and lagoonal-dominated facies. This succession indicates a relative stability of the environment and involves the presence of an important barrier (reef or palaeo-high) able to protect such a back-reefal area. The failure of this barrier is considered as responsible for the transition to the Terres d'Haurs Formation and to the turn-back to a relatively open-marine but proximal ramp setting.

The present work highlights the complex environmental succession occurring during the base of the Givetian. It also shows the probable influence of sea level variations as a key controlling factor on these transitions between ramp and platform profiles. Further studies are needed to clear this and, at last, propose a sequence stratigraphy framework for the top of the Eifelian and the base of the Givetian.

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Plate 1:
A. Marenne Centre (MC) section showing a reefal lens at the top.
B. Marenne East section (ME), base of studied interval is dotted.
C. Base of ME section showing the top of Marenne Member and the boundary with the upper part of the Trois-Fontaines Formation, base of studied interval is dotted.
D. Boundary between Trois-Fontaines and Terres d'Haurs formations (ME section).
E. MC section, A unit from Marenne Member: block showing hummocky cross stratification.
F. MC section, C unit from Marenne Member: reefal lens with massive stromatoporoids (S) and rugose corals (R).
G. ME section, Trois-Fontaines Formation: bioclastic bed with branching tabulate corals (bed n° ME113) interbedded within more argillaceous limestone with ostracods and gastropods.
H. ME section, Terres d'Haurs Formation: coquina with brachiopods (bed n° ME207).

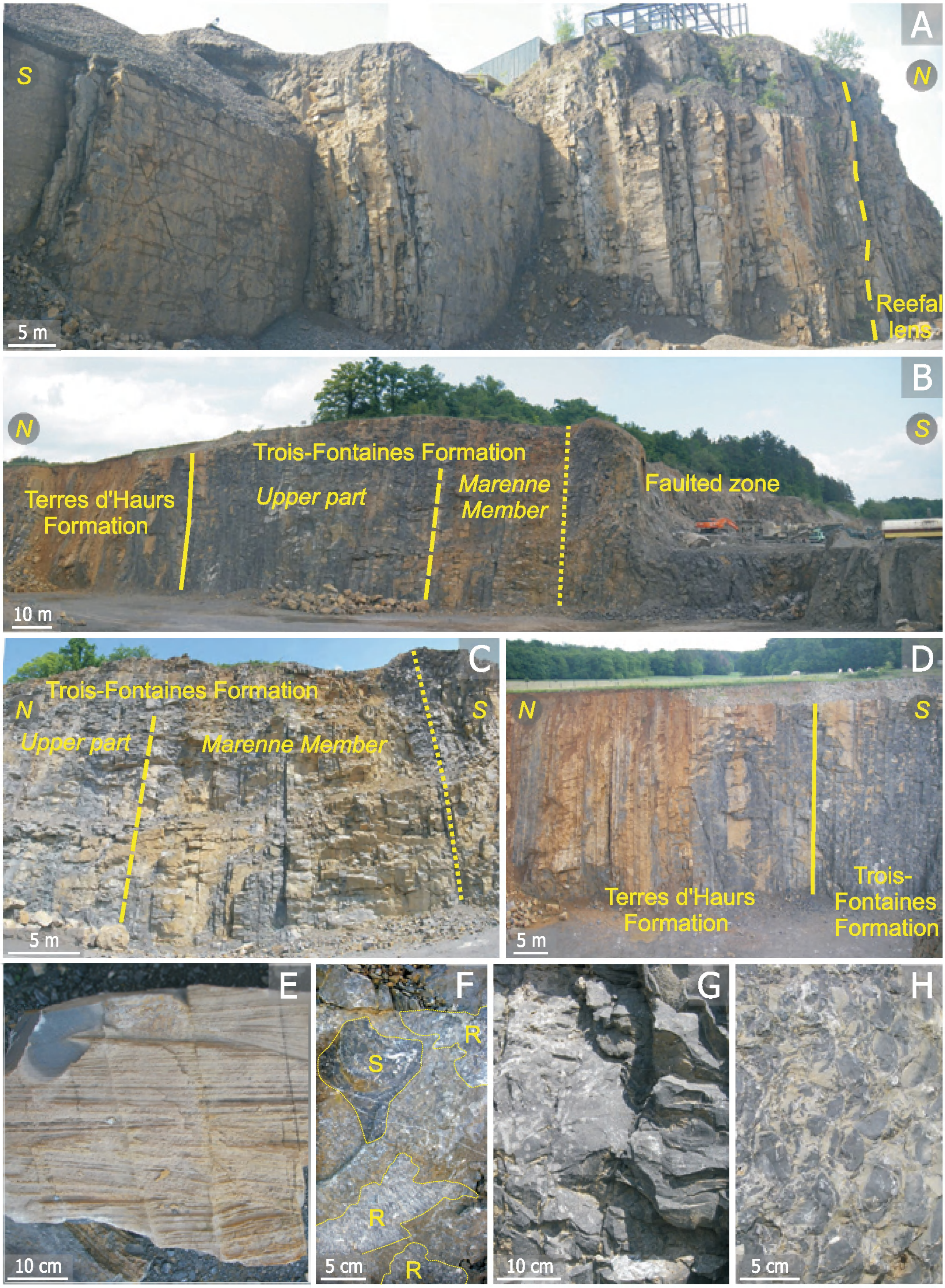
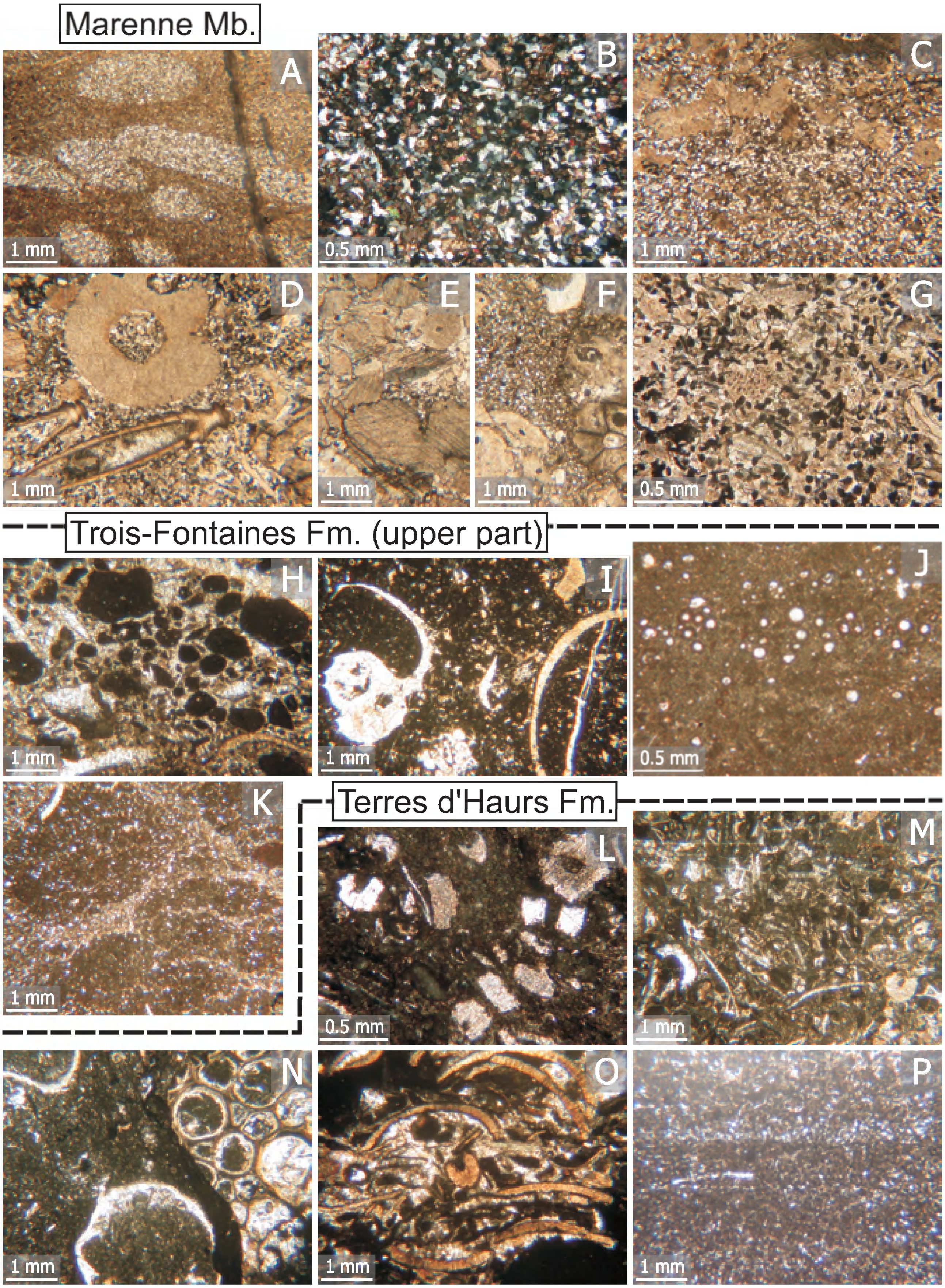

A
S
N
Reefal lens
5 m
B
N
S
Trois-Fontaines Formation
Terres d'Haurs Formation
Upper part
Marenne Member
Faulted zone
10 m
C
Trois-Fontaines Formation
N
S
Upper part
Marenne Member
5 m
D
N
S
Terres d'Haurs Formation
Trois-Fontaines Formation
5 m
E
10 cm
F
S
R
R
R
5 cm
G
10 cm
H
5 cm

Plate 2: Microfacies of Marenne sections. Numbers correspond to bed numbers on Figure 4 and Figure 6 (MC for Marenne Centre and ME for Marenne East section). All photographs are in normal light except B in crossed nicols. See text for more explanations:
A. MF-Mar1: Burrowed siltstone, bioturbation is marked by a more sandy and coarse infilling (MC2).
B. MF-Mar2: Carbonated sandstone (ME32).
C. MF-Mar3: Packstone layer interbedded within a silty wackestone (MC7).
D. MF-Mar4: Silty coarse grainstone with crinoids and tentaculitids (ME27).
E. MF-Mar5: Crinoidal sole of the reefal lens (MC66).
F. MF-Mar5: Floatstone with crinoids and branching tabulate corals, note the detrital quartz abundance (MC73).
G. MF-Mar6: Fine-grained peloidal and bioclastic grainstone (MC63).
H. MF-Trf1: Grainstone layer with lithoclasts interbedded within bioclastic packstone (ME91).
I. MF-Trf2: Bioclastic wackestone with ostracods and gastropods (ME152).
J. MF-Trf3: Wackestone with calcispheres (ME79).
K. MF-Trf3: Mudstone with ostracods and calcispheres showing slight nodulization (ME133).
L. MF-Thr1: Crinoidal wackestone (ME218).
M. MF-Thr2: Peloidal packstone with crinoids and ostracods (ME222).
N. MF-Thr3: Floatstone with branching tabulate corals debris (ME224b).
O. MF-Thr4: Packstone layer interbedded within a mudstone with calcispheres and ostracods (ME185).
P. MF-Thr5: Laminated grainstone related to algal mats (ME211b).


Marenne Mb.
A
1 mm
B
0.5 mm
C
1 mm
D
1 mm
E
1 mm
F
1 mm
G
0.5 mm
Trois-Fontaines Fm. (upper part)
H
1 mm
I
1 mm
J
0.5 mm
K
1 mm
Terres d'Haurs Fm.
L
0.5 mm
M
1 mm
N
1 mm
O
1 mm
P
1 mm

	MF	Name	Assemblage	Setting	Previously defined MF
Marenne Member			Mid ramp		
	MF-Mar1	Siltstone and fine-grained sandstone with a poor fauna	Open-marine	Just above SWB	MFa1[b] / MF1[f] / MF1[g]/ MF1[i] / MFi[m]
	MF-Mar2	Laminated and bioclastic carbonated sandstone	Open-marine >> Proximal influence	Above SWB	MFO3[a]
	MF-Mar3	Laminated and locally silty to sandy wackestone and packstone	Open-marine >> Proximal influence	Above SWB	MFC2 & MFC3[d] / MF3[i] / MF2[j]
	MF-Mar4	Locally silty coarse grainstone with crinoids and tentaculitids	Open-marine > Proximal influence	Close to FWWB	RF6[k]
			Inner ramp		
	MF-Mar5	Rudstone and floatstone with crinoids and/or branching tabulate corals	"reef-building" > Open-marine > Proximal influence	Around FWWB	MF3, MF5 & MF6[e] / MF4, MF5a & MF6[g]
	MF-Mar6	Fine-grained peloidal packstone (and grainstone) interbedded with bioclastic layers	Proximal > Open-marine influence > "reef-building"	Around FWWB	MFC6a & MFC6b[d] / MF6[i]
Trois-Fontaines Formation (upper part)			Back-reef		
	MF-Trf1	Bioclastic wackestone (floatstone) and packstone with branching organisms	"reef-building" > Proximal > Open-marine influence	Protected	MF10[c]
	MF-Trf2	Bioclastic wackestone and packstone interbedded with peloidal grainstone	Proximal > "reef-building" > Open-marine influence	Protected	MFa10[b] / MF12[c]
			Lagoon		
	MF-Trf3	Fenestral wackestone and mudstone with ostracods and calcispheres	Proximal >> Open-marine influence	Restricted	MFa11 & MFa12[b] / MF13[c] / MF14 & MF15[i] / MF10a[j] / MF9[l]
Terres d'Haurs Formation			Mid ramp		
	MF-Thr1	Laminated wackestone with crinoids and brachiopods interbedded with packstone and grainstone	Open-marine >> Proximal influence	Above SWB	MFb1[b] / RMF13[h]
			Inner ramp		
	MF-Thr2	Peloidal packstone and grainstone with crinoids and ostracods	Proximal > Open-marine influence	Close to shoals (peloidal or bioclastic)	RMF26[h] / MF13[i] / RF9[k]
	MF-Thr3	Wackestone with ostracods and branching tabulate corals debris interbedded with packstone and grainstone layers	Proximal & patch reef derived > Open-marine influence	Semi-protected	RMF18[h]
	MF-Thr4	Wackestone and mudstone with calcispheres and ostracods interbedded with packstone and grainstone layers	Proximal >> Open-marine influence	Semi-restricted	MFb5[b] / RMF18[h] / RF10[k]
	MF-Thr5	Very well -sorted peloidal grainstone with *fenestrae*	Algal mats	Intertidal and restricted	RMF23[h]

Table 1 : Microfacies defined for the Marenne Member, Trois-Fontaines (upper part) and Terres d'Haurs formations with their assemblage and setting features (SWB = Storm Wave Base – FWWB = Fair Weather Wave Base). Previously defined microfacies from: Mabille et al., work in progress (a); Mabille & Boulvain, 2008 (b); Mabille & Boulvain, 2007b (c); Mabille & Boulvain, 2007a (d); Préat et al., 2007 (e); Casier & Préat, 2006 (f); Mamet & Préat, 2005 (g); Flügel, 2004 (h); Boulvain et al., 1995 (i); Préat & Kasimi, 1995 (j); Burchette & Wright, 1992 (k); Casier & Préat, 1991 (l); Casier & Préat, 1990 (m).