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TOWARDS A PALAEOGEOGRAPHICAL AND SEQUENTIAL FRAMEWORK FOR THE GIVETIAN OF BELGIUM

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(23 figures)

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ABSTRACT. This paper starts with a review of facies and reef morphologies from the Givet Group in the Ardenne area. Platform initiation and evolution are analyzed and related to external factors at a global scale (sea level changes, climate changes), at a regional scale (local subsidence, change in detrital supply) and to internal factors like organic communities composition. More specifically, the location of reef barriers are related to sea level changes and a sequence stratigraphic canvas is proposed.

KEYWORDS. Givetian, Ardenne, reef, carbonate platform, sequence stratigraphy.

1. Introduction and global context

This paper is dedicated to the Givetian reefal development in the Ardenne area, close to the classical stratotype sections. Emphasis will be placed on palaeogeography, sequence stratigraphy and long term patterns in reef morphologies and development.

Widespread Devonian reef development indicates that the climate was mild and warm, sea levels were high worldwide, and much of the land laid submerged under vast shallow epicontinental seas. A large ocean covered the rest of the planet (Fig. 1). In fact, the Devonian has been globally referred to a greenhouse age, and global high temperatures allowed reefs to develop at unusually high latitudes, reaching 65°N-55°S during the Middle Devonian (Copper 2002a).

When considered in more detail, the Devonian Period shows long-term patterns of reef development. During the Lower and Early Middle Devonian, when sea level was still relatively low, reefs were characterized by poor diversity and provinciality. Their growth was reduced, probably related to low accommodation. Detrital supply, originating from the erosion of the Caledonian mountain belt hindered reef development in a number of coastal areas (Burchette 1981). In Europe, for example, the earliest Devonian reefs occur in regions where marine sedimentation was continuous from the Lower Palaeozoic through to at least the Middle Devonian: Carnic Alps, Bohemia, Armorican Massif and the Cantabrian and Pyreneean mountains. On the periphery of the Caledonian orogen and where the Devonian overlies the Lower Palaeozoic unconformably, reef growth did not begin until Middle Devonian: Ardennes, Rhenish Schiefergebirge, Harz, Poland and Moravia (Boulvain & Wood, 2007). Lower to Early Middle Devonian reefs were of limited extent and thickness and show relatively low biodiversity. Mounds and banks were the dominant morphologies. In the Emsian-Givetian, a 'super greenhouse' time span, there were six major reef belts with lengths exceeding 2500 km (Copper, 2002b): Western Laurentia, NW Europe, S Europe-N Africa, Urals-Eastern side of Baltica, Siberia, Mongolia and S China (Kiessling et al. 1999).

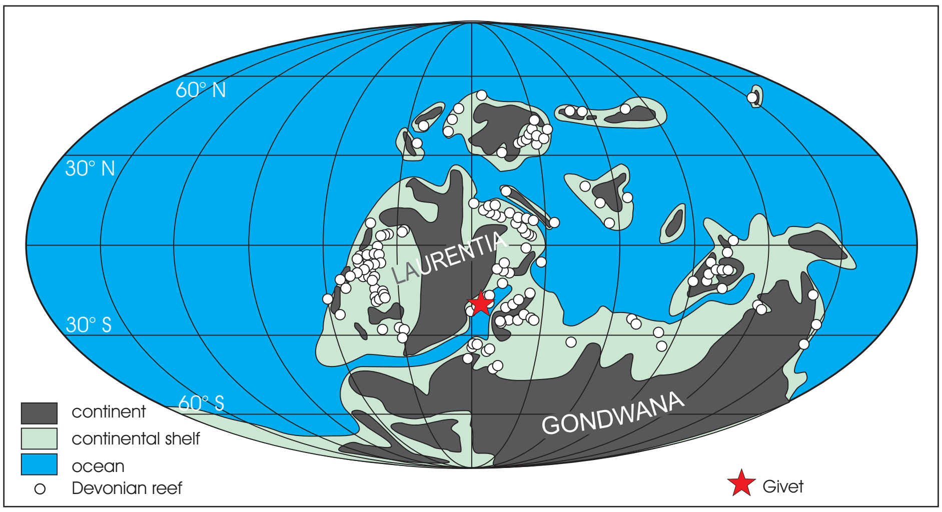

Figure 1: The Devonian world (After Boulvain & Wood, 2007).

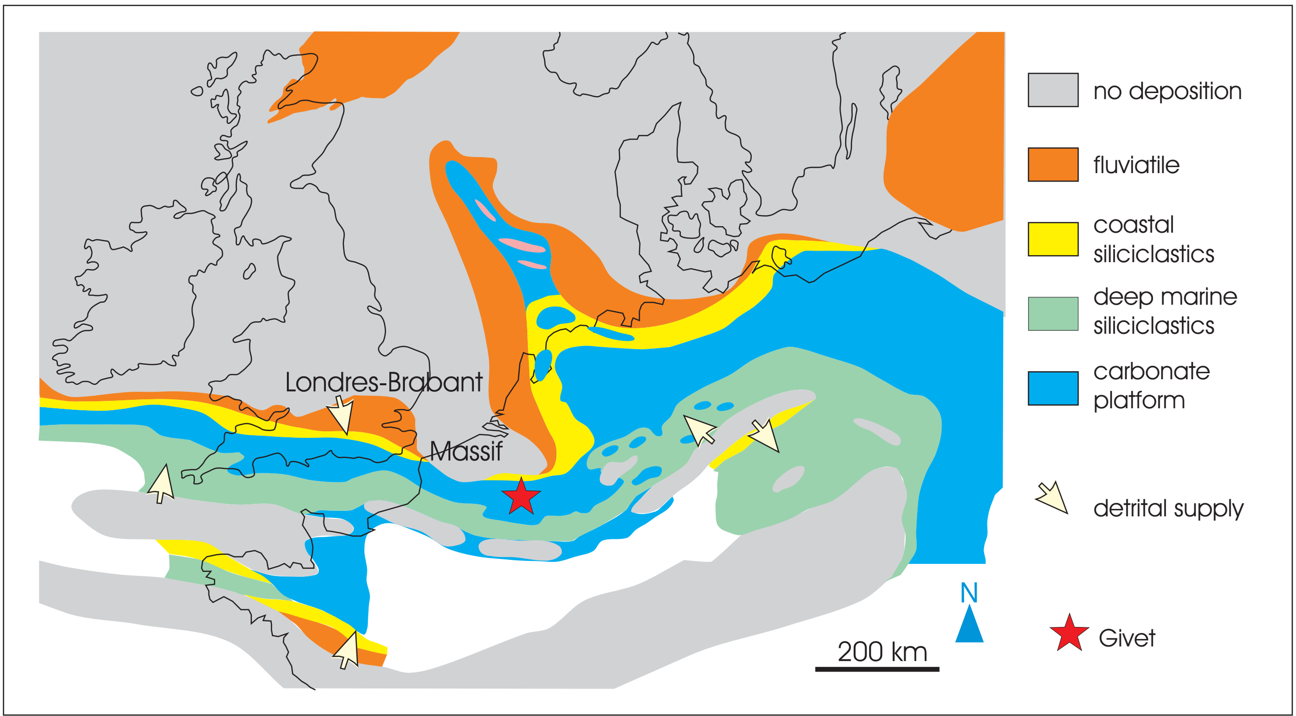

Figure 2: Simplified palaeogeographical map of the Middle Devonian in Western Europe. Modified after Ziegler (1982).

Reef morphologies included barriers, platform reefs, fringing reefs, atolls and mounds. During the Frasnian, the Canning Basin complexes added another reef belt over 2000 km in length. However, Frasnian reefs were characterized by loss of diversity, cosmopolitanism and collapse of the carbonate factory at the end of the stage (Copper, 2002a, b). Frasnian eustatic fluctuations were severe (Johnson et al. 1985) and sea-level variations controlled the reef development. The early Frasnian experienced reduced episodes of reef building, while the Middle Frasnian represented an acme in reef development when nearly all reef morphologies were represented: platform reefs, barriers, atolls, and mounds. Late Frasnian reefs were smaller and more restricted and were progressively replaced by mounds. After the Frasnian extinction, representing the end of the great Silurian-Devonian reef ecosystem, the Famennian was characterized by post extinction reefs, in a context of sea level lowstand and major loss of reef habitats.

2. Givetian geological context

The Givetian belongs to the second Devonian transgression starting during the Eifelian. In Belgium, the sea reached the Northern border of the Namur Syncline. Reduced terrigenous supply, coming from the North, indicates that

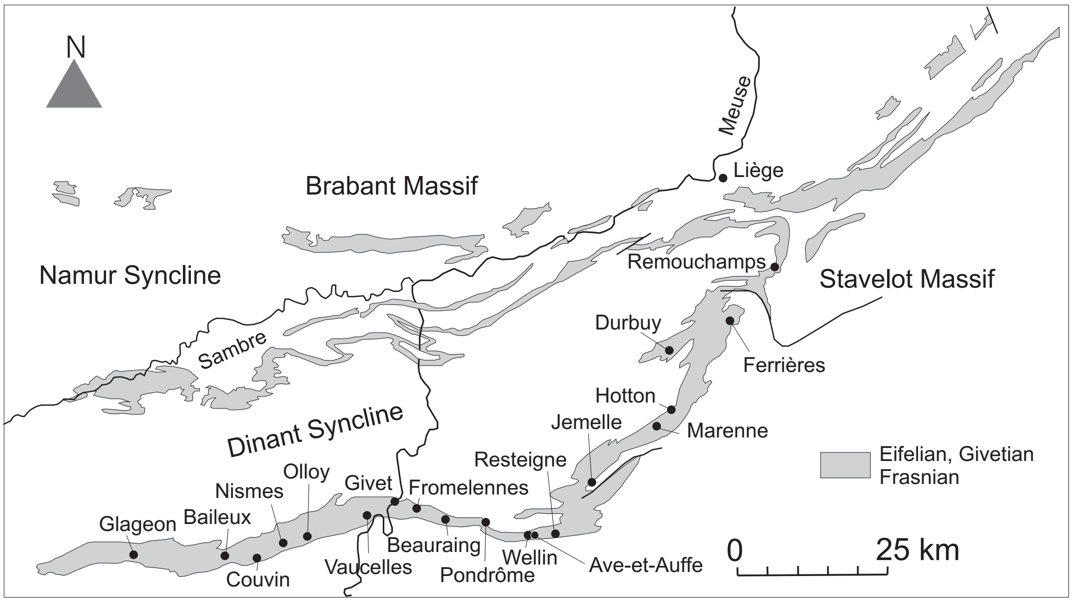

Figure 3: Location of the main sections in the Givetian of the southern border of the Dinant Syncline.

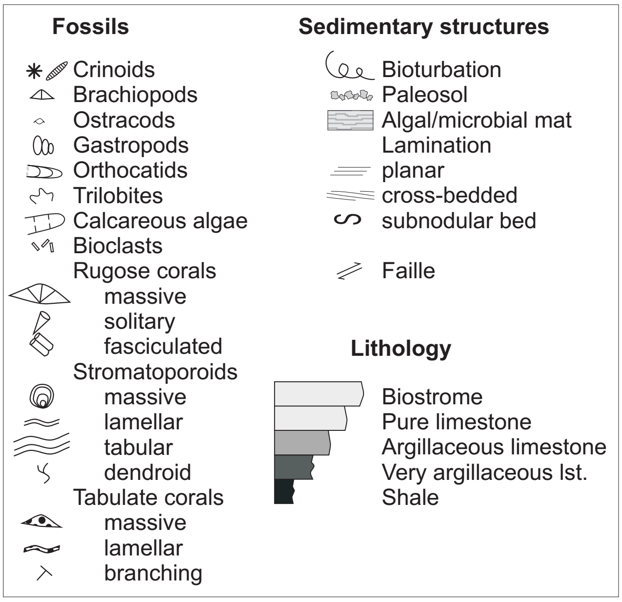

Figure 4: Symbols used on logs and sedimentological models.

the Old Red Continent (and more specifically, the Brabant peninsula) was already deeply eroded or that the climate was relatively dry (Fig. 2).

In the Ardenne area, the Givetian crops out along the southern and south-eastern borders of the Dinant Syncline, forming a continuous calcareous belt, from Glageon in the West (French Avesnois) to Liège in the East. The classical Givet sections are located in the middle (Fig. 3). Several sedimentological studies demonstrated the high lateral continuity of the different sedimentary units (reefs, lagoonal complexes…) all along this calcareous belt (Pel, 1975; Préat & Mamet, 1989). This of course indicates that the Variscan folding direction was nearly perpendicular to the major Givetian palaeogeographical patterns like the Old Red Continent coastline or the Givetian reef barriers.

Lithostratigraphically, the Givetian from the southern border of the Dinant Syncline covers five formations: the upper part of the Hanonet Formation, and the Trois-Fontaines, Terres d'Haurs, Mont d'Haurs and Fromelennes formations (Fig. 5). These five formations pass laterally

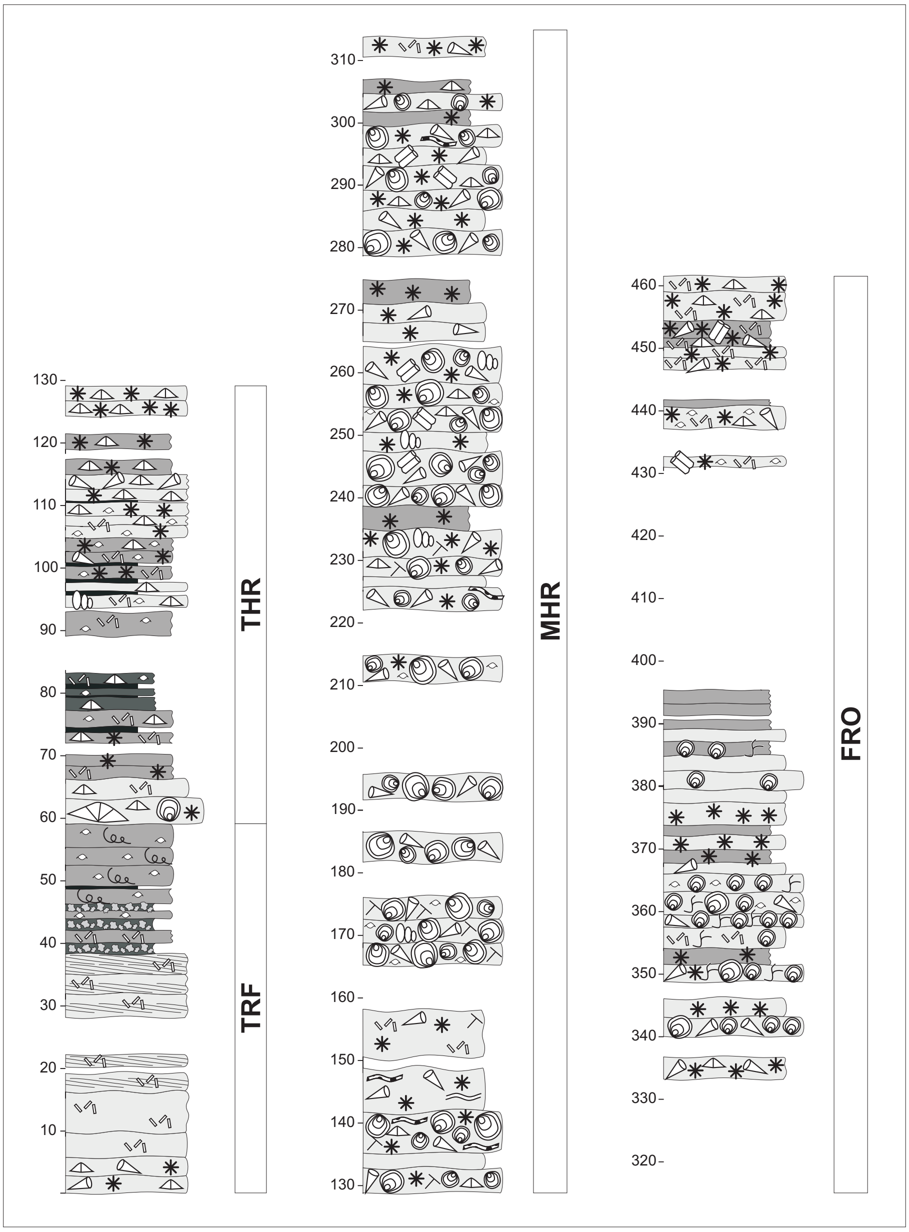

Figure 5: Logs from the Givetian in Givet (Fromelennes-Flohimont road section). TRF= Trois-Fontaines Formation; THR= Terres d'Haurs Formation; MHR= Mont d'Haurs Formation; FRO= Fromelennes Formation. Explanation of symbols, see Fig. 4.

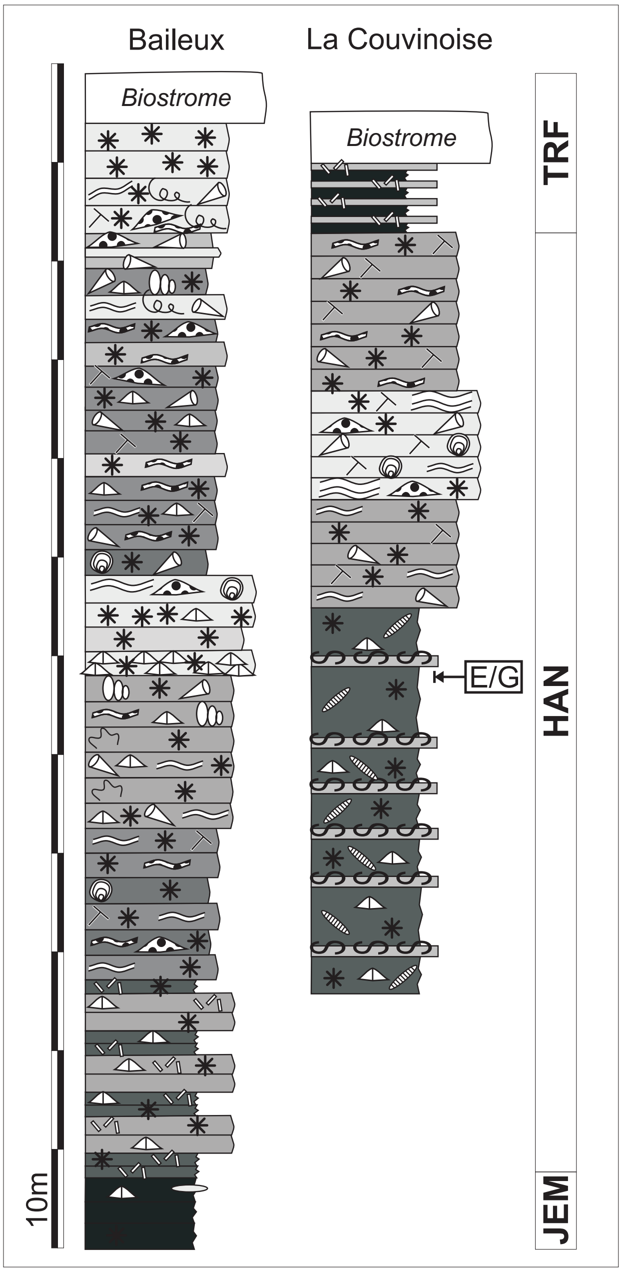

Figure 6: Examples of logs from the Hanonet Formation. JEM= top of the Jemelle Formation; HAN= Hanonet Formation; TRF=base of the Trois-Fontaines Formation. E/G= Eifelian-Givetian boundary. Explanation of symbols, see Fig. 4.

into two units, the Nèvremont and Le Roux formations in more proximal settings (northern border of the Dinant Syncline and southern border of the Namur Syncline) and to one single unit, the Bois de Bordeaux Formation in the vicinity of the Brabant Massif. This last unit is characterized by fluvial conglomerates, bioclastic limestones and detrital sediments with paleosols. This work will be focused on the formations from the southern border of the Dinant Syncline, corresponding to the Givetian stratotype.

3. The Eifelian-Givetian transition and the starting of the carbonate factory

The sedimentary facies from the Eifelian-Givetion transition beds represent an outstanding laboratory for understanding the workings of the carbonate factory. Actually, the Ardenne Eifelian sedimentation corresponds to a mixed regime, with both detrital supply and carbonate production. More specifically, the last unit below the base of the Givet Limestone, the Hanonet Formation, makes the transition between the shales and siltstones from the Jemelle Formation and the first Givetian reef complex.

The thickness of the Hanonet Formation is variable and may locally reach one hundred metres. Its facies also change laterally (Fig. 6). In Glageon, an argillaceous limestone with crinoids and lamellar stromatoporoids and tabulate corals is observed (Fig. 7) (Boulvain et al., 1995). In Baileux, facies are dominated by storm-reworked bioclastic limestones, rich in peloidal supply, coming from a close reef complex (Mabille & Boulvain, 2007). In Couvin (lithostratotype of the Hanonet Formation), facies are quite similar to Glageon, with stromatoporoid-rich argillaceous limestones. In Pondrôme, the Hanonet Formation, with a reduced thickness, is characterized by shale and coral-rich argillaceous limestones (Coen-Aubert, 1997) and in Resteigne, there are alternations of argillaceous and crinoidal limestone (Casier & Préat, 1990). These environments, interpreted as fore-reef

Figure 7: Limestone with lamellar stromatoporoids and tabulate corals, Hanonet Formation, Glageon quarry.

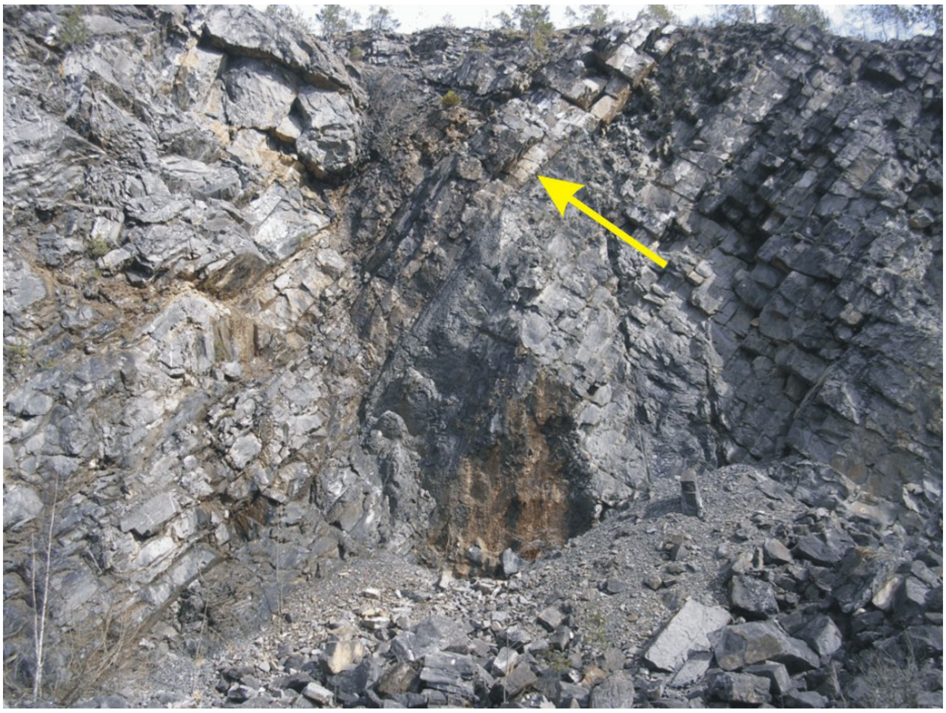

Figure 8: The base of the Trois-Fontaines Formation (arrowed) in the Resteigne quarry.

(Baileux) or middle ramp under the fair-weather wave action zone (the other sections; Casier et al., 1995; Mabille & Boulvain, 2008) show local development of isolated reef lenses. These reefs are observed in Wellin (Pel, 1975; Mamet & Préat, 2005) and in Nismes (Coen-Aubert, 1992; Préat et al., 2007; Dumoulin & Coen, 2008). Getting into details, the Wellin reef (200 m in diametre and 45 m thick) shows, over a crinoid-rich base, a core rich in corals and stromatoporoids, strengthened by early marine cement and flanks colonized by brachiopods and udoteacean calcareous algae (Mamet & Préat, 2005). In Nismes, the succession looks similar, but field observations suggest that several reef lenses are superimposed (Préat et al., 2007). The isolated reefs from Wellin and Nismes may correspond to an initiation stage of the barrier reef that characterizes the base of the Trois-Fontaines Formation (see below).

4. The Givetian carbonate platform

4.1. The Trois-Fontaines Formation

In most sections, except when there is a reef lens like in Nismes or Wellin, the boundary between the Hanonet and Trois-Fontaines formations is sharp. The argillaceous limestone from the Hanonet Formation passes upwards

Figure 9: Tempestites with crinoids at the base of the Trois-Fontaines Formation in Resteigne.

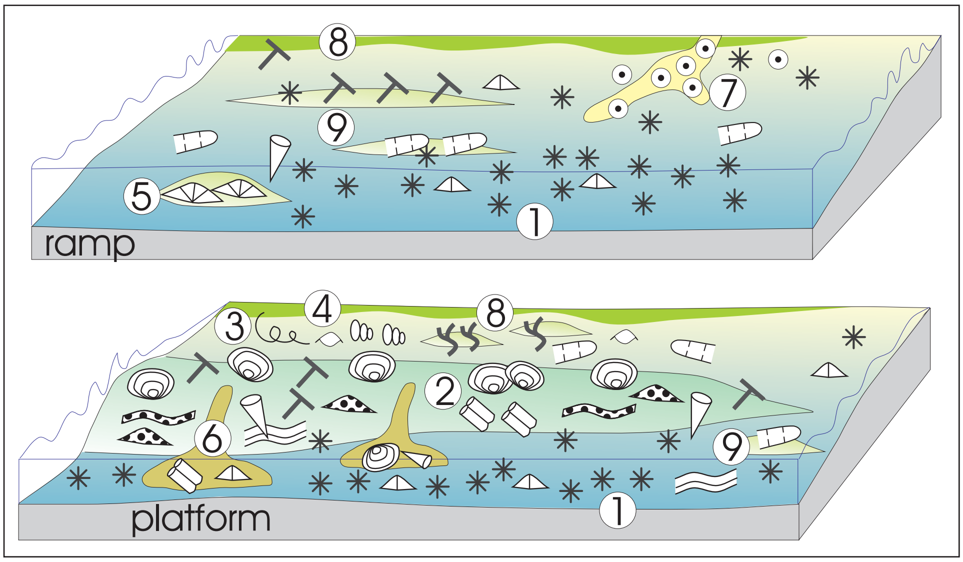

Figure 10: Platform and ramp models. Numbers refer to main facies. 1 : open sea crinoidal facies ; 2 : reef barrier with stromatoporoids, corals and algae ; 3 : lagoon with gastropods and algae; 4 : tidal flats with algal-microbial mats ; 5 : open sea reef lenses ; 6 : debris flows from the reef barrier ; 7 : tidal channels with ooids ; 8 : lagoonal patch reefs ; 9 : algal or coral shoals. Explanation of symbols, see Fig. 4.

into purer limestones, forming the base of the Trois-Fontaines Formation (Fig. 8). This sharp boundary represents the base of the Givetian carbonate platform.

The thickness of the Trois-Fontaines Formation varies slightly: 70 m in Glageon, 80 m in Givet, 90 m in Baileux and Resteigne.

In most sections exposing the base of the Trois-Fontaines Formation, the first metres correspond to relatively coarse grained dm-thick beds (grainstones and packstones) with crinoids and lithoclasts, separated by argillaceous seams. Frequent hummocky cross stratification and erosion seams lead to an interpretation of this facies as proximal tempestites (Fig. 9). This facies is particularly well-developed and rich in crinoids in Resteigne (Préat et al., 1984), Pondrôme (Coen-Aubert, 1998) and Baileux (Mabille & Boulvain, 2008). In Givet (Flohimont), crinoids are replaced by lithoclasts, in Glageon, this unit is reduced and in Couvin, it corresponds to crinoidal argillaceous limestone. In Marenne, (Mabille et al., 2008) and Ave-et-Auffe (Pel, 1975), environmental conditions were different and sandy or silty limestone with crinoids, tentaculitids and brachiopods are present. Storm structures are also observed.

The crinoidal accumulations acted as a sole for reef initiation, and the second characteristic unit of the Trois-Fontaines Formation is a reef ("premier biostrome" auctores). This reef runs from Glageon in the West to Ferrières in the East, over nearly 150 km. Although very constant, its thickness and sedimentological characteristics vary locally and are of great interest for the understanding of the working of the Givetian reef system.

4.1.1. The Trois-Fontaines basal reef: facies and palaeoecology

This reef (Figs 10 (2) & 11) is nearly 10 to 20 metres thick (15 m in Glageon, 12 m in Baileux, 20 m in Resteigne). Its total width is unknown but certainly higher than several hundreds of metres according to its high lateral continuity. The reef started to grow over a crinoidal sole or over reefal lenses from the Upper Hanonet Formation (Fig. 15). In this case, the whole reef complex may reach a global thickness of 60 m. In some places, the reef failed to

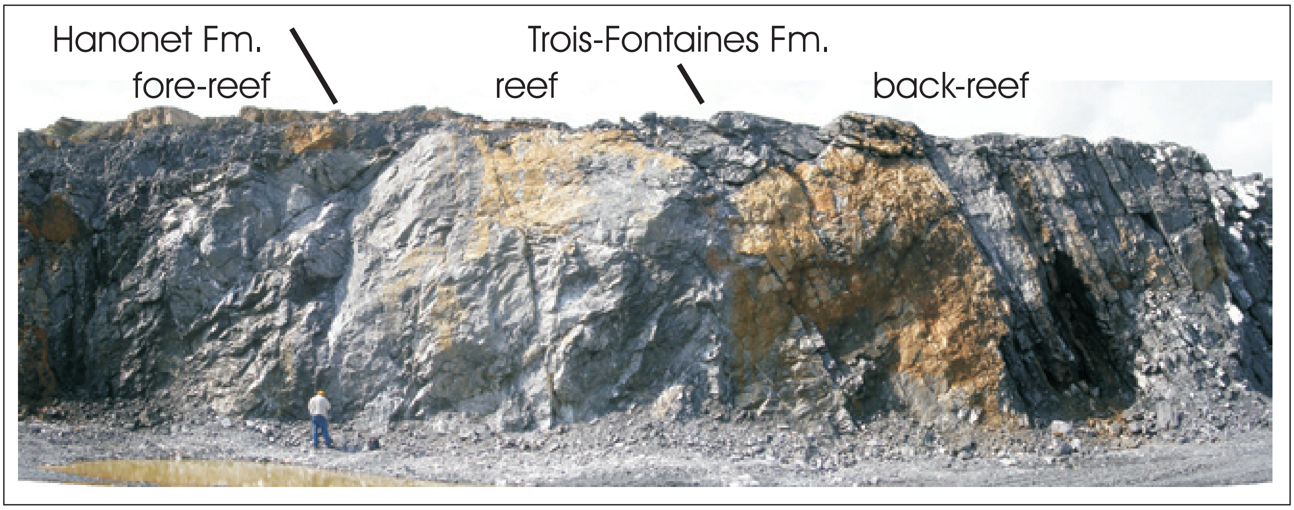

Figure 11: the basal reef of the Trois-Fontaines Formation in the Glageon quarry.

Figure 12: Accumulation of stringocephalids by storms in upper intertidal area (Trois-Fontaines Formation, La Couvinoise quarry, Couvin).

develop (or developed in a more proximal setting, not visible in the outcrops) (Figs 14 & 15). For instance, the reef is not observed in Ave-et-Auffe (Coen-Aubert, 1998) and Givet (Flohimont) where the coarse grained limestone with storm structures reaches nearly 40 metres. In Marenne, only a 10 m thick isolated reef lens is observed (Fig. 15), surrounded by open sea facies (Mabille et al., 2008). In this last case, it is supposed that high detrital influx inhibited reef development.

Detailed study of the Resteigne, Glageon and Baileux sections allowed reconstruction of the different development stages of the reef (Préat et al., 1984; Boulvain et al., 1995; Mabille & Boulvain, 2008). Over the crinoidal sole grew lenses rich in lamellar and tabular stromatoporoids, solitary and fasciculate rugose corals, branching and massive tabulate corals. Progressively, massive stromatoporoids became more abundant, associated with some rugose and tabulate corals and brachiopods. Multiple coatings associating stromatoporoids, corals, cyanobacteria (*Girvanella*, *Bevocastria, Sphaerocodium*) attest to a strong competition for life space. The community became richer in calcareous algae as palaeosiphonocladales (mainly *Issinella*), phylloids (*Resteignella*) and dasycladales (*Givetianella*)

Figure 13: Paleosol (brownish bed) in the Trois-Fontaines Formation in Givet (Fromelennes-Flohimont road section).

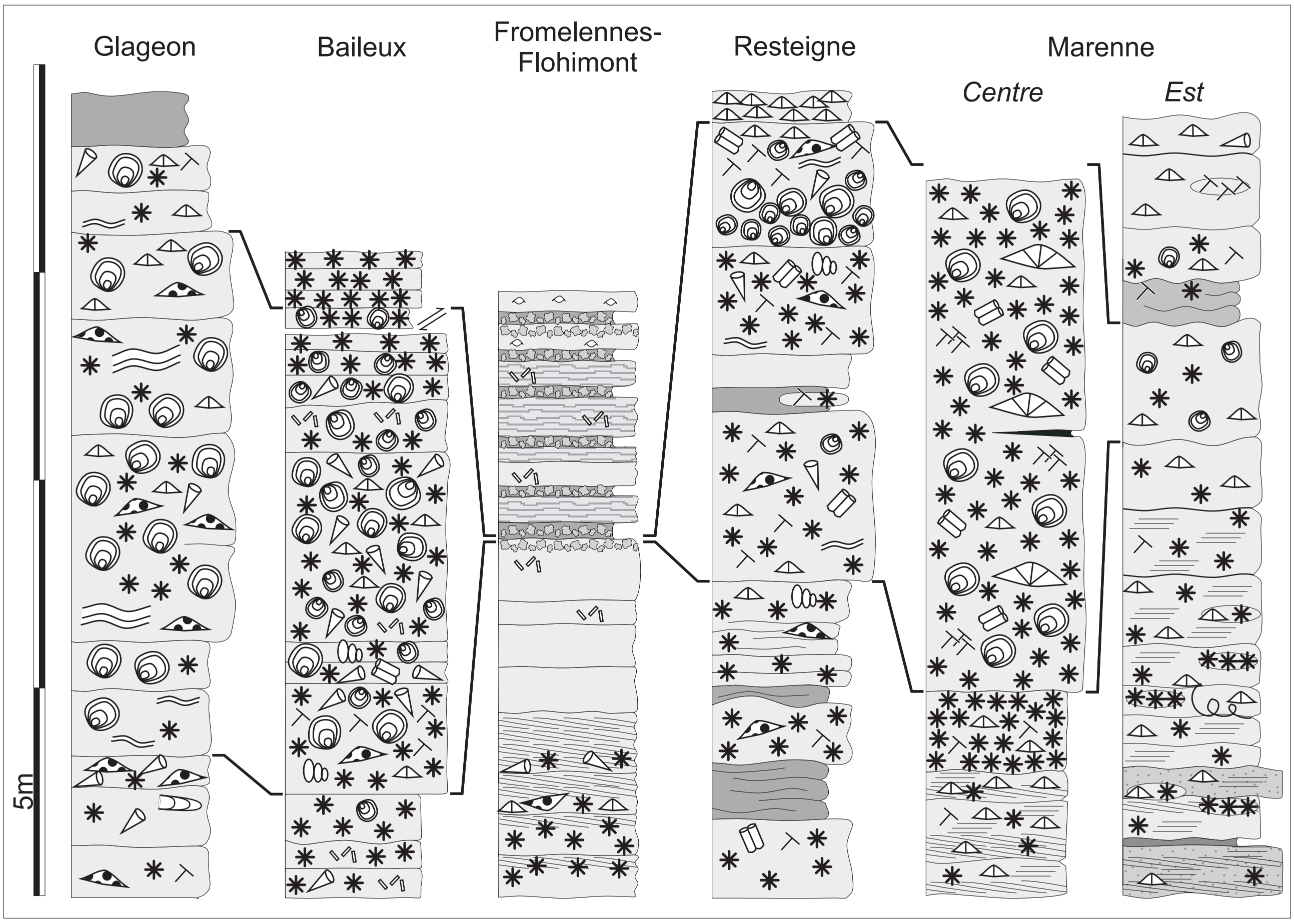

Figure 14: Lateral variations in the base of the Trois-Fontaines Formation. The correlation lines mark the reef base and top. Location of sections, see Fig. 3. Legend of symbols, see Fig. 4.

(Mamet & Préat, 1986). Peloids are abundant. All the organisms, greater than several tens of cm in size, are broken and overturned; this is a common feature in shallow reefs, even in present day barriers (Riegl & Piller, 1997). It corresponds to periods of reef development, alternating with high energy events like tsunamis or major storms, responsible for breaking and reworking of reef building organisms.

In Marenne, in a context of continuous detrital supply, the reef is poorly developed, but the constituents remain the same (Mabille et al., 2008).

Above the reef, dm-thick accumulations of brachiopods or gastropods ("coquina beds") are frequently observed. These beds are storm deposits left on the shore (Couvin, Resteigne, Vaucelles) (Fig. 12).

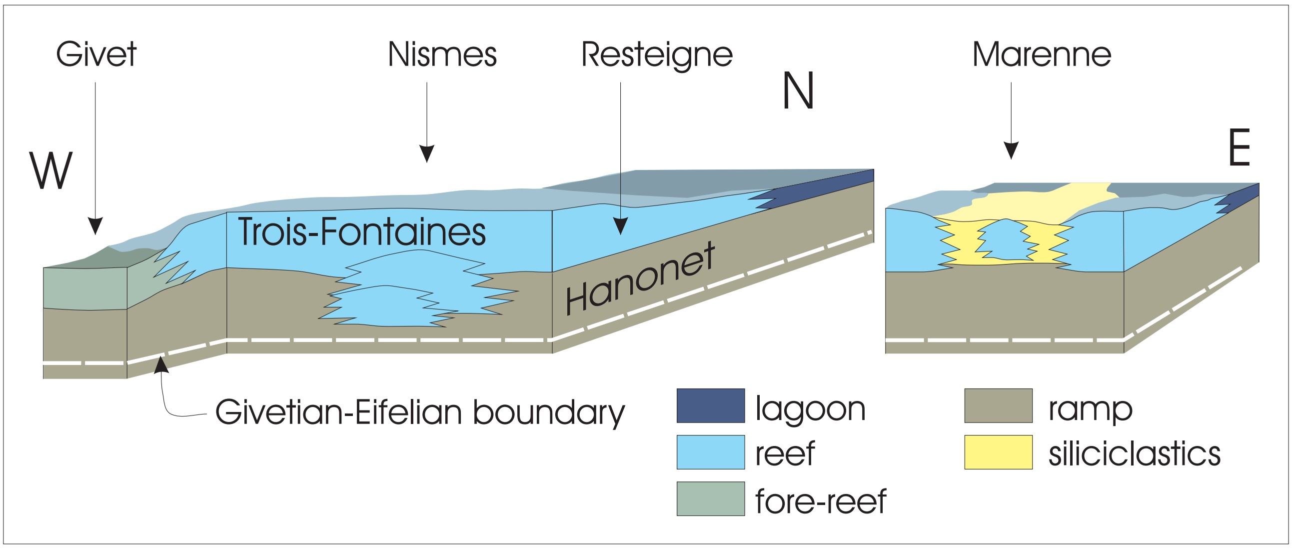

Figure 15: 3-D reconstruction of lateral variations in the first reef barrier, from Givet to Marenne. No scale.

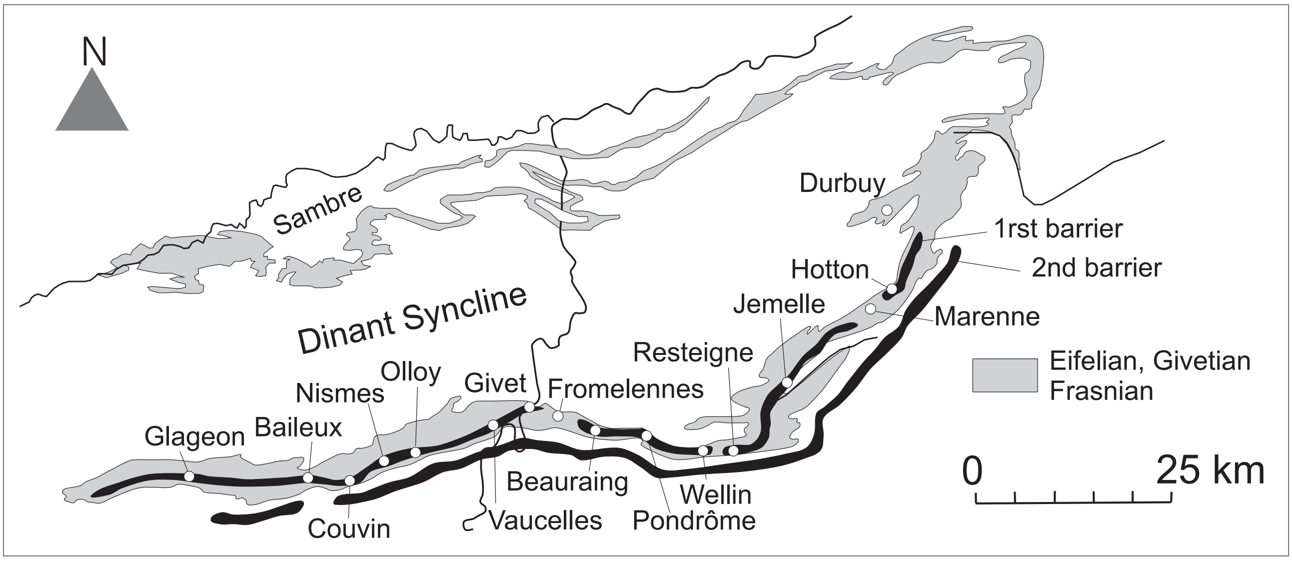

Figure 16: Hypothetical extension of the two Givetian reef barriers from the Trois-Fontaines Formation: the « premier biostrome » from the base of the Trois-Fontaines Formation (first barrier) and the barrier responsible for the development of the lagoonal facies forming the upper half of the formation (second barrier).

When comparing and interpreting the different sections in the Trois-Fontaines basal reef ("premier biostrome"), it is possible to recognize three main development stages, which intergrade and provide a fairly continuous vertical ecological gradient of facies (Fig. 14). This continuous ecological gradient is typical for a reef catching up to the surface of the sea (Riegl & Piller, 2000):

- sea level stabilization at the Eifelian-Givetian transition. Lowering of detrital supply, development of crinoidal meadows and accumulation of crinoidal sand in the storm wave zone; this corresponds to the stabilization stage from Walker & Alberstadt (1975);
- progressive development of pioneer communities of corals and stromatoporoids, building reef lenses close to the fair weather wave base; this corresponds to the colonization stage;
- increasing of carbonate production, organic diversification and edification of the main part of the reef by stromatoporoids, calcareous algae and corals. This rapid vertical development allows the reef to reach shallower water and finally, the sea surface. This third step corresponds to the diversification stage.

Besides own reef development, a sea level drop must be supposed to explain the final emersion of the reef top. This sea level drop is attested in the Flohimont section at Givet by several paleosols (Wright, 1994) developed directly on the top of bioclastic limestones deposited below the fair weather wave base (Fig. 13). Moreover, in Ave-et-Auffe, lagoonal limestones lie directly over the Hanonet Formation (Coen-Aubert, 1998).

How to interpret this important reef complex? Is it a barrier reef? This question is difficult to solve, by lack of time equivalent outcrops located to the north of the outcropping area. It is however very likely that this thick laterally continuous reef, developing in shallow water and catching up to the sea surface was a Givetian equivalent of the great Australian reef barrier, locally interrupted near estuaries where sandy or silty material inhibited reef growth (Marenne, Ave-et-Auffe) (Figs 14, 15 & 16).

Most sections in this Givetian barrier show probably what could be interpreted as proximal back reef deposits, resulting from accumulation in quieter water of material reworked by storms or tsunamis. It is tempting to suppose that the exceptionally thick early cemented reefs of Wellin and Nismes (Mamet & Préat, 2005 ; Préat et al., 2007) represent some parts of the reef front and that other areas where the reef is replaced by open marine facies (Ave-et-Auffe, Flohimont), correspond to the fore reef environment (Fig. 15).

4.1.2. After the reef, the development of lagoons and tidal flats

After reef emersion, mainly related to a sea level fall, the loss of accommodation induced a basinward shift of reef building communities (Handford & Loucks, 1993; Riegl & Piller, 2000). The exact location of the new reef is impossible to determine by lack of outcrops, but it seems logical that the new barrier was situated some kilometres to the south of present day Givetian outcrops.

The development of a new barrier southward from the former is responsible for the deposition of the lagoonal complex constituting the upper half of the Trois-Fontaines Formation. This was observed in Givet, Vaucelles (Préat & Boulvain, 1982), Olloy (Préat et al., 1987), Wellin (Mamet & Préat, 2005) and Resteigne. The lagoonal complex is characterized by fine grained sediments with a relatively low diversified fauna: leperditids ostracods (Casier & Préat, 1991), gastropods, burrowing organisms, and a flora dominated by calcispherids and palaosiphonocladales (Préat & Boulvain, 1982). This facies suggests that the lagoonal complex was restricted. Locally, monospecific coral populations of *Hillaepora* developed in the lagoon (Préat et al., 1984; Tourneur, 1987; Hladil, 1994), or storm events reworked material

Figure 17: Laminated limestone (algal-microbial mats) near the top of the Trois-Fontaines Formation in Resteigne. Stratification is vertical

coming from the barrier, deposited as rudstone beds interrupting the lagoonal deposits.

The constant accumulation of lagoonal deposits over several tens of metres was the consequence of a new sea level rise, allowing a vertical aggradation of the reef barrier. At the end of this period, a sea level stabilisation favoured the filling of the lagoon and development of extensive tidal flats. The tidal flats were dominated by algal-microbial mats, covering the intertidal and supratidal area of the carbonate platform (Préat et Boulvain, 1987). Similar sediment types are observed today, for example in the Bahamas (Purser, 1983). Present day field observations show that the laminated features are due to an alternation of microbial mats and sediment lenses brought by storms (Hardie & Ginsburg, 1977) (Fig. 17).

The lateral continuity of the algal-microbial mat tidal complex, nearly as high as the reef barrier, shows the large extension of the littoral zone during the deposition of the top of the Trois-Fontaines Formation.

Several sections however differ from this model: the Marenne section for example shows open marine beds within the lagoonal complex (Mabille et al., 2008), and Glageon is characterized by poorly developed lagoonal facies, probably related to an interruption in the southern reef barrier (Boulvain et al., 1995) (Fig. 16).

4.1.3. Sequential interpretation

No high frequency cycles or parasequences (4^{th}-5^{th} orders) are observed in the Trois-Fontaines Formation. At the system tracts scale (3th order) however, a clear sequential pattern appears (Fig. 21). The prograding reef corresponds to a highstand system tract (HST), the aggrading lagoonal unit corresponds to a transgressive system tract (TST) and the tidal complex is interpreted as a highstand system tract (HST). Between the HST and TST, the amalgamated emersion-transgression surface ("sequence boundary" sensu Van Wagoner et al., 1988) corresponds to a series of coquina beds ("lumachelles à stringocéphales") (Boulvain et al., 1995), like the transgressive brachiopod accumulations described by Hladil (1994) from the Givetian Moravian Karst.

The relatively proximal character of the sections cropping out along the southern border of the Dinant Synclinorium prevents any access to lowstand systems tracts (LST). Recent recommendations by Catuneanu (2006) suggest a merging of shelf margin system tract (SMST) and LST, because differences are poorly visible on discontinuous sections. However, the lack of extensive erosion in the Trois-Fontaines Formation all over the inner platform suggests that the LST should actually correspond to a SMST sensu Posamentier et al (1988).

4.2. The Terres d'Haurs Formation

After lagoon filling and final development of tidal flat complexes corresponding to the top of the Trois-Fontaines Formation, the sedimentation started again during a new marine transgression. The Terres d'Haurs Formation is 60-75 m thick in Givet, Resteigne and Baileux and is only 45 m thick in Glageon. It is characterized by argillaceous limestone with horizontal burrows (Fig. 18), locally rich in crinoids, brachiopods (often concentrated in coquina beds by storms), gastropods and coral patch reefs. The base of the formation is underlined by a metre-thick uninterrupted (Wellin, Vaucelles) or lenticular (Pondrôme, Beauraing) reef with massive rugose (*Argutastrea*) or tabulate corals (*Thamnopora, Pachyfavosites*,…) (Préat et al., 1984 ; Coen-Aubert, 1977, 2003; Coen-Aubert et al., 1986) (Figs 19 & 10 (5)). In Ave-et-Auffe, a lateral

Figure 18: Argillaceous limestone with horizontal burrows in the Terres d'Haurs Formation at Glageon.

transition between patch-reefs and stratified coral carpets was observed by Coen-Aubert & Tourneur (in Birenheide et al., 1991) and Coen-Aubert (2003). Near the top of the formation, several metres of crinoidal limestone appear in most sections. In the Hotton quarry, the facies from the Terres d'Haurs Formation are more varied (Coen-Aubert, 2003).

All these facies point to an open environment, below the wave base. However, the sporadic occurrence of oolitic beds or of calcareous algae suggests an easy communication with shallower zones, as is the case on a ramp profile (Boulvain et al., 1995; Mabille & Boulvain, 2008) (Fig. 10).

4.2.1 Sequential interpretation

The transition from a shelf with a well-developed barrier reef (Trois-Fontaines Formation) to a ramp (Terre d'Haurs Formation) is the result of a rapid sea-level rise. The deeper facies and strongly aggrading pattern of the Terre d'Haurs Formation point to a transgressive system tract (TST) (Fig. 21) overlying a sequence boundary. No parasequential signal is observed.

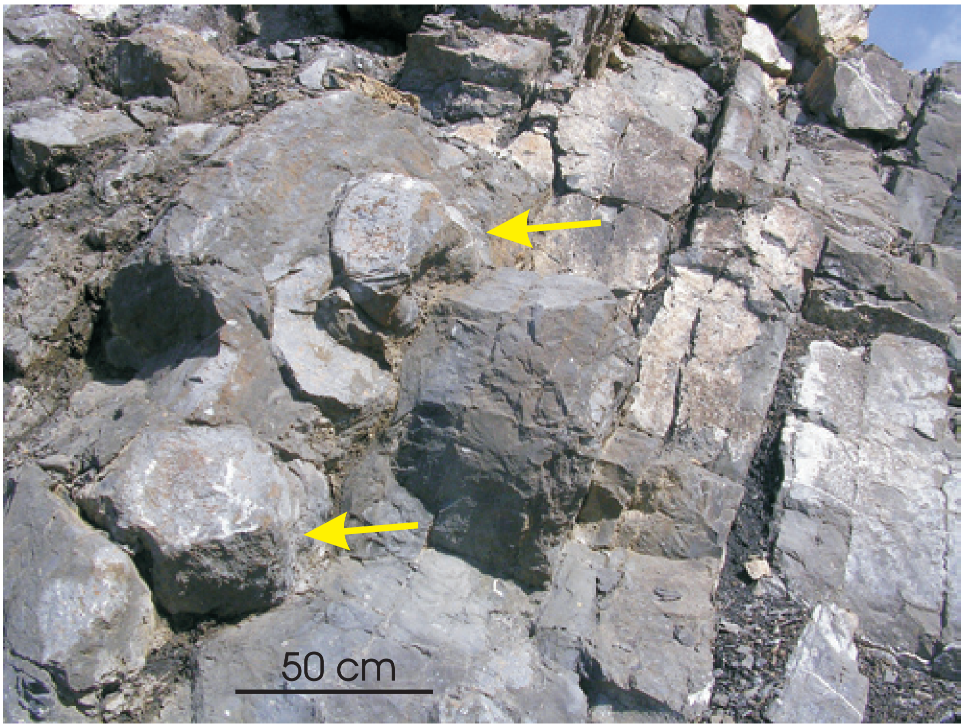

Figure 19: Base of the Terres d'Haurs Formation in Resteigne. Arrows point to isolated colonies of massive rugose corals.

4.3. The Mont d'Haurs Formation

The base of the Mont d'Haurs Formation corresponds to the first massive bed with stromatoporoids and corals (Bultynck et al., 1991). This formation is divided in two parts (Fig. 5); the lower unit shows relatively monotonous argillaceous limestone with crinoids, brachiopods, issinellids and gastropods, locally interrupted by metre-thick stromatoporoid- and coral-rich beds (Fig. 20). The upper part is characterized by purer limestones with peloids, oolithes, calcispherids and palaeosiphonocladales (Boulvain et al., 1995). Some beds rich in massive and dendroid stromatoporoids, branching tabulate and solitary or massive rugose corals are observed in the upper unit (Coen-Aubert, 1999). The whole formation reaches 160 m in Givet, 180 m in Wellin and only 130 m in Glageon.

The lower unit shows several characteristics of an open environment, located below the wave base, such as the facies observed in the Terre d'Haurs Formation. The sporadic occurrence of beds rich in building organisms is not easily explained, as these beds do not show any crinoidal sole, nor ecological development sequence like that observed in the Trois-Fontaines basal reef (Fig. 20). Moreover, the relatively rich and diversified fauna (Coen-Aubert, 1999, 2002) does not correspond to a coral carpet, generally characterized by poorer assemblages (Riegl & Piller, 2000). This paradox disappears when closely examining these beds: they are in fact debris flow reworking material coming from a reef barrier located northwards from the outcrop zone. These debris flows were deposited during major storms or tsunamis.

The upper part of the Mont d'Haurs Formation, shows more protected, restricted environments, alternatively quiet or more agitated, located behind a reef barrier. Periodic destruction of the barrier provided material for the coarser beds. Small local patch reefs with dendroid stromatoporoids and branching tabulate corals also developed in this lagoon.

Near the top of the Mont d'Haurs Formation, the environment became progressively more open marine, as coral fauna is observed to become richer and more diversified (Coen-Aubert, 1999). This can be correlated with the marine transgression that characterizes the base of the Fromelennes Formation.

4.3.1. Sequential interpretation

No parasequential signal is observed in the Mont d'Haurs Formation. However, two system tracts separated by a sequence boundary can be recognized. The base of the formation corresponds to a highstand system tract (HST), and the upper unit to a transgressive system tract (TST), followed by a highstand system tract (HST). The boundary between the two systems is an amalgamated emersion-transgression surface (Boulvain et al., 1995).

4.4. The Fromelennes Formation

The Fromelennes Formation includes three members which are from base to top (Bultynck et al., 1991): the Flohimont Member, consisting in 30 m of argillaceous limestone beds with brachiopods separated by clay seams; the Moulin Boreux Member characterized by nearly 80 m of fine-grained limestones with dendroid stromatoporoids and finally, the Fort Hulobiet Member which shows some 20 m of argillaceous limestones and shales (Fig. 5). The thickness of the Fromelennes Formation is 135 m in Fromelennes, 100 m in Durbuy and 80 m in Remouchamps, within the eastern part of the Dinant Syncline.

Some lateral variations are observed in the Flohimont Member which becomes sandier towards the East (Coen & Coen-Aubert, 1971). Furthermore, the facies difference

Figure 20: Coral- and stromatoporoid-rich bed in the Mont d'Haurs Formation. It is interpreted as a debris flow coming from a reef barrier located northwards. Fromelennes-Flohimont road section.

between the two upper units also vanishes towards the East, as stromatoporoids appear in the Fort Hulobiet Member.

The Fort Hulobiet Membre is a transgressive unit, deposited during sea level rise. Along the southern part of the Dinant Syncline, sedimentation occurs below wave base while eastwards, the bathymetry decreases and coarser detrital supply suggests a close proximity to a coastline.

The most calcareous part of the Fromelennes Formation, the Moulin Boreux Member, shows typical cyclic facies successions:

- a metre-thick basal unit with dendroid stromatoporoids (*Amphipora*, *Stachyodes*), bulbous stromatoporoids, branching tabulate corals and sporadic rugose corals; all these organisms are often coated by codiaceae (*Bevocastria*);

- a thinner middle unit comprised of bioturbated limestones, with poor macrofauna but abundant ostracods (leperditids), palaeosiphonocladales (*Kamaena* and *Triangulinella*), characeae (*Umbella*), calcispherids, gastropods, peloids and fragments of cyanobacterial coatings;

- an upper unit showing algal-microbial mats, and locally paleosols (Fromelennes-Flohimont section).

These cycles show that some coral-stromatoporoid carpets were periodically growing in a relatively protected environment (delicate forms are often preserved). Coral carpets commonly show a stronger lateral than vertical component. This gives rise to the biostromal nature of the basal unit of the sequences and explains the absence of internal ecological gradients (Riegl & Piller, 2000). The carpets were followed by lagoonal and intertidal algal-microbial sediments following accommodation decrease. These sequences are very similar to the metre-thick shallowing upwards cycles from the back-reef area of the Pillara Limestone (Givetian-Frasnian, Canning Basin, Australia) (Playford, 1981). The presence of characeae and dominance of amphiporids suggest frequent salinity fluctuations (Mamet & Préat, 1986, Pohler, 1998).

In addition to information collected from fossil associations, two other important elements have to be taken into account: the occurrence of evaporite pseudomorphs (Boulvain & Coen-Aubert, 1997) and the relatively high abundance of primary dolomite. These observations, suggest a highly periodical salinity indicating a restricted, partially evaporitic character for the Fromelennes platform. Biological communities were dominated by specialized organisms (dendroid stromatoporoids, cyanobacteria), developing carpets and mats in the subtidal environment (Fig. 10 (8)).

After this long period of stability, the top of the Fromelennes Formation (Fort Hulobiet Member) shows an opening of the platform, attested by a faunal diversification and more specifically, the return of corals and crinoids. This announces the large marine transgression characterizing the base of the Frasnian.

4.4.1 Sequential interpretation

The main part of the Fromelennes Formation is aggradational and probably corresponds to a transgressive system tract (TST). The metre-thick shallowing upwards cycles often observed in the Fromelennes Formation may correspond to a parasequential signal.

5. The collapse of the Givetian carbonate platform and the Frasnian transgression

Excepting a relative opening of the platform during the deposition of the top of the Fromelennes Formation, nothing is indicative of the sharp nature of the Frasnian marine transgression. The beginning of the Frasnian records a decline of the Devonian carbonate factory and the nearly complete collapse of the Givetian platform. The 40 metres of shales and nodular shales of the Nismes Formation have a sharp contact with the top of the Givetian limestone in nearly all the sedimentation area (Fig. 22). This shale, rich in atrypids and spiriferids brachiopods was deposited below the wave base.

Later, during the Middle Frasnian, a carbonate platform develops again (Da Silva & Boulvain, 2004). The resulting facies belts resemble the Givetian ones, but are strongly shifted towards the North (Philippeville Anticline, Northern and Eastern borders of the Dinant Syncline) (Fig. 23). This retrogradation was the result of the Frasnian eustatic rise. The famous Frasnian atolls and mounds develop along the southern border of the Dinant Syncline, in front of the Frasnian platform at this time (Boulvain, 2007).

6. Conclusion

The development of Givetian reefs in the Ardenne area depended on external factors operating (1) on a global scale (sea level or climate changes), (2) on a regional scale (local subsidence, change in detrital supply, change in marine currents) and (3) on internal factors such as the composition of organic communities and adaptability to external changes.

When considering the Trois-Fontaines Formation, the carbonate platform initiation coincided with a sea level stabilisation and a reduction of detrital supply. The vertical facies evolution of the basal reef complex was the result of the ecological organisation of the reef in response to its own vertical development and correlative bathymetric decrease. As the reef grew towards the sea surface, this resulted in modifications to the local environment, a process that fed back into its organic communities. This period of stable sea level (HST) was followed by a sea level lowering (LST) responsible for a possible emersion of the inner platform and a seaward shift of the barrier (Fig. 21). Then, the important development of lagoonal facies in the upper part of the Trois-Fontaines Formation was the consequence of a vertical growth of the southern barrier in response to a sea level rise (TST). The final development of microbial mat-dominated extensive tidal flats corresponded to the end of this transgression (HST).

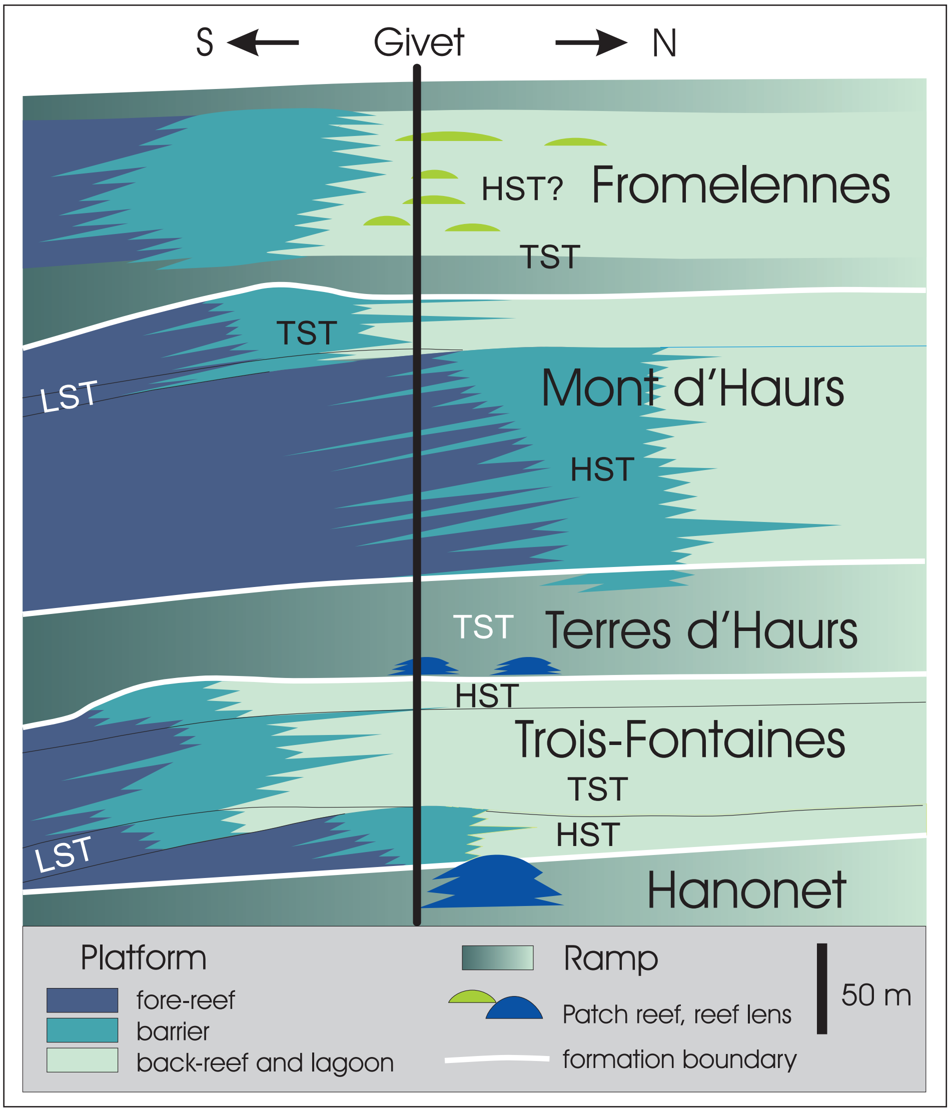

Figure 21 : Palaeogeographical framework of the Givetian in Givet, showing the seaward (progradation) and the landward shifts (retrogradation) of the major facies belts: fore-reef, reef and lagoon. Sequence stratigraphic interpretation: TST: transgressive system tract; HST: highstand system tract; LST: lowstand system tract.

Figure 22. The Frasnian shale from the Nismes Formation (lower right) overlying the Givetian limestone from the Fromelennes Formation. Sourd d'Ave road section, close to Ave-et-Auffe.

The Terres d'Haurs Formation shows relatively deep ramp environments. This transition from a platform to a ramp system was the result of a rapid sea level rise (TST) on a nearly subaerialy exposed platform.

The Mont d'Haurs Formation is characterized by the development of a new reef barrier during a HST, but shifted northwards from the Givetian outcrop belt. The coral- stromatoporoid-rich beds observed in the Givet section are debris flows coming from this barrier. A sea level drop (LST), followed by a transgression (TST) was responsible for the thick lagoonal deposits characterizing the upper part of the formation.

Finally, after a new sea level rise (TST), responsible for the deposition of the base of the Fromelennes Formation, sea level stabilization (HST) allowed the development of a huge protected back-reef area, characterized by bioaccumulations with specialized fauna. These carpets grew mainly laterally in restricted water and interfered much less with their environment. They built a highly structured hard substratum that increased settlement space and had high sediment retention potential. The Fromelennes Formation is also characterized by a more arid climate (Boulvain & Préat, 1986). This climate evolution was responsible for salinity changes in protected environments.

When the relative positions of the Givetian reef barriers are integrated in a general palaeogeographical framework (Fig. 23), the retrogradation-progradation patterns of the Devonian carbonate platforms appear clearly. Different orders of cyclicity were involved. At least four 3th order cycles are recorded within the Givetian.

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References

BIRENHEIDE, R., COEN-AUBERT, M., LÜTTE, B.P. & TOURNEUR, F., 1991. Devonian coral bearing strata of the Eifel Hills and the Ardennes. Excursion B1. *In* LÜTTE, B.P. (Ed.) VI International Symposium on Fossil Cnidaria including Archaeocyatha and Porifera, Excursion guidebook. Forschungsstelle für Korallenpaläzoologie, Münster, 113 pp.

BOULVAIN, F., 2007. Frasnian carbonate mounds from Belgium: sedimentology and palaeoceanography. *In*: ÁLVARO, J. J., ARETZ, M., BOULVAIN, F., MUNNECKE, A., VACHARD, D. & VENNIN, E. (Eds) Palaeozoic Reefs and Bioaccumulations: Climatic and Evolutionary Controls. *Geological Society, London, Special Publications*, 275: 125-142.

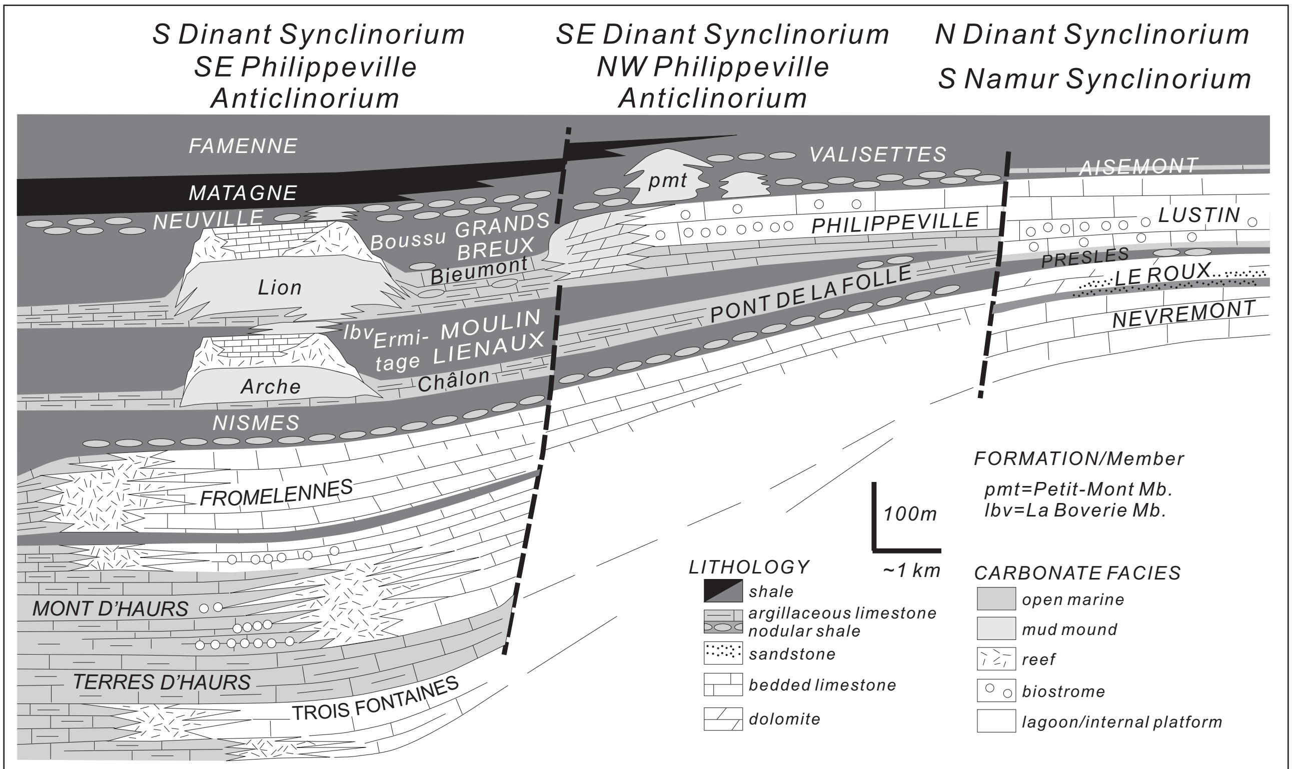

Figure 23. Integrated lithostratigraphical and palaeogeographical framework for the Givetian and Frasnian of Belgium. Relative position of the reefs shows the retrogradation-progradation patterns of the carbonate platforms.

BOULVAIN, F.& COEN-AUBERT, M., 1997. Le sondage de Focant : lithostratigraphie et implications structurales. *Memoirs of the Geological Survey of Belgium*, 43, 74 pp.

BOULVAIN, F., COEN-AUBERT, M., MANSY, J-L., PROUST, J-N. & TOURNEUR, F. 1995. Glageon: une coupe du Givetien en Avesnois (France). Sédimentologie, Coraux, géologie régionale, diagenèse. *Bulletin de la Société belge de Géologie*, 103 : 171-203.

BOULVAIN, F. & PREAT, A., 1986. Les calcaires laminaires du Givétien Supérieur du bord Sud du Bassin de Dinant (Belgique, France. témoins d'une évolution paléoclimatique. *Annales de la Société géologique de Belgique*, 109 : 609-619.

BOULVAIN, F. & WOOD, R., 2007. Devonian. *In*: VENNIN, E., ARETZ, M., BOULVAIN, F. & MUNNECKE, A. (Eds). Facies from Palaeozoic reefs and bioaccumulations. *Mémoires du Museum national d'Histoire naturelle*, Paris, 195: 171-223

BULTYNCK, P., COEN-AUBERT, M., DEJONGHE, L., GODEFROID, J., HANCE, L., LACROIX, D., PREAT, A., STAINIER, P., STEEMANS, P., STREEL, M., TOURNEUR, F., 1991. Les formations du Dévonien moyen de la Belgique. *Mémoires pour l'explication des cartes géologiques & minières de la Belgique*, 30, 106 pp.

BURCHETTE, T., 1981. European Devonian reefs: a review of current concepts and models. *Society of Economic Paleontologists & Mineralogists Special Publication,* 30: 85-142.

CASIER, J-G., KASIMI, R. & PREAT, A., 1995. Les ostracodes au passage Eifelien/Givetien à Glageon (Avesnois, France). *Geobios*, 28 : 487-499.

CASIER, J-G. & PREAT, A., 1990. Sédimentologie et ostracodes de la limite Eifelien-Givétien à Resteigne (bord sud du Bassin de Dinant, Belgique). *Bulletin de l'Institut royal des Sciences naturelles de Belgique*, Sc. de la Terre, 60 : 75-105.

CASIER, J-G. & PREAT, A., 1991. Evolution sédimentaire et ostracodes de la base du Givetien à Resteigne. *Bulletin de l'Institut royal des Sciences naturelles de Belgique*, Sc. de la Terre, 61 : 157-177.

CATUNEANU, O., 2006. Principles of Sequence Stratigraphy. Elsevier: 375 pp.

COEN, M. & COEN-AUBERT, M., 1971. L'Assise de Fromelennes aux bords sud et est du Bassin de Dinant et dans le Massif de la Vesdre. *Annales de la Société géologique de Belgique*, 94 : 5-20.

COEN-AUBERT, M., 1977. Distribution stratigraphique des rugueux massifs du Givétien et du Frasnien de la Belgique. *Annales de la Société Géologique du Nord*, XCVII : 49-56.

COEN-AUBERT, M., 1992. Rugueux coloniaux mésodévoniens du Fondry des Chiens à Nismes (Ardenne, Belgique). *Bulletin de l'Institut royal des Sciences naturelles de Belgique,* Sc. de la Terre, 62 : 5-21.

COEN-AUBERT, M., 1997. Rugueux solitaires près de la limite Eifelien-Givetien à Pondrôme (Belgique). *Bulletin de l'Institut royal des Sciences naturelles de Belgique*, Sc. de la Terre, 67 : 5-24.

COEN-AUBERT, M., 1998. Thamnophyllides et Acanthophyllides près de la limite Eifelien-Givetien à Wellin et Pondrôme (Belgique). *Bulletin de l'Institut royal des Sciences naturelles de Belgique*, Sc. de la Terre, 68 : 11-27.

COEN-AUBERT, M., 1999. Description de quelques Rugueux coloniaux de la Formation givetienne du Mont d'Haurs en Ardenne. *Bulletin de l'Institut royal des Sciences naturelles de Belgique*, Sc. de la Terre, 69 : 27-46.

COEN-AUBERT, M., 2002. Temnophyllids and Spinophyllids (Rugosa) from the Givetian Mont d'Haurs Formation in Belgium. *Bulletin de l'Institut royal des Sciences naturelles de Belgique*, Sc. de la Terre, 72 : 5-24.

COEN-AUBERT, M., 2003. Description of a few rugose corals from the Givetian Terres d'Haurs Formation in Belgium. *Bulletin de l'Institut royal des Sciences naturelles de Belgique*, Sc. de la Terre, 73 : 5-24.

COEN-AUBERT, M., PREAT, A. & TOURNEUR, F., 1986. Compte-rendu de l'excursion de la Société belge de Géologie du 6 novembre 1985 consacrée à l'étude du sommet du Couvinien et du Givétien au bord sud du Bassin de Dinant, de Resteigne à Beauraing. *Bulletin de la Société belge de Géologie*, 95 : 247-256.

COPPER, P., 2002a. Silurian and Devonian reefs: 80 million years of global greenhouse between two ice ages. *Society of Economic Paleontologists & Mineralogists Special Publication,* 72: 181-238.

COPPER, P., 2002b. Reef development at the Frasnian/Famennian mass extinction boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 181: 27-65.

DA SILVA, A-C. & BOULVAIN, F., 2004. From palaeosols to carbonate mounds: facies and environments of the Middle Frasnian platform in Belgium. *Geological Quarterly*, 48: 253-266.

DUMOULIN, V. & COEN, M., 2008. Notice explicative de la carte Olloy-sur-Viroin – Treignes. Carte Géologique de Wallonie 58/5-6, Ministère de la Région Wallonne, 103 pp.

HANDFORD, C.R. & LOUCKS, R.G., 1993. Carbonate depositional sequence and system tracts-responses of platform to relative sea-level change. *In*: LOUCKS, R.G. & SARG, J.S. (Eds) Carbonate sequence stratigraphy. *Memoirs of the American Association of Petroleum Geologists*, 57: 3-41.

HARDIE, L.A. & GINSBURG, R.N., 1977. Layering: the origin and environmental significance of lamination and thin bedding. *In*: HARDIE, L.A. (Ed.) Sedimentation on the Modern carbonate tidal flatx of Northwest Andros Island, Bahamas. The J. Hopkins University Press: 50-124.

HLADIL, J., 1994. Moravian Middle and Late Devonian build-ups: evolution in time and space with respect to Laurussian shelf. *Courier Forschunginstitut Senckenberg*, 172: 111-125.

JOHNSON, J. G., KLAPPER, G. & SANDBERG, C. A., 1985. Devonian eustatic fluctuations in Euramerica. *Geological Society of America Bulletin* 96: 567-587.

KIESSLING, W., FLÜGEL, E. & GOLONKA, J., 1999. Paleoreef maps: evaluation of a comprehensive database on Phanerozoic reefs. *American Association of Petroleum Geologists Bulletin* 83: 1552-1587.

MABILLE, C. & BOULVAIN, F., 2007. Sedimentology and magnetic susceptibility of the Upper Eifelian - Lower Givetian (Middle Devonian) in southwestern Belgium: insights into carbonate platform initiation. *In*: ÁLVARO, J. J., ARETZ, M., BOULVAIN, F., MUNNECKE, A., VACHARD, D. & VENNIN, E. (Eds) Palaeozoic Reefs and Bioaccumulations: Climatic and Evolutionary Controls. *Geological Society, London, Special Publications*, 275: 109-124.

MABILLE, C. & BOULVAIN, F. 2008. Les Monts de Baileux section: detailed sedimentology and magnetic susceptibility of Hanonet, Trois-Fontaines and Terres d'Haurs formations (Eifelian-Givetian boundary and Lower Givetian, SW Belgium). *Geologica Belgica*, 11: 93-121.

MABILLE, C., DE WILDE, C., HUBERT, B., BOULVAIN, F. & DA SILVA, A-C., 2008. 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. *Geologica Belgica*, 11 : 217-238.

MAMET, B. & PREAT, A., 1986. Algues givetiennes du bord sud du Bassin de Dinant et des régions limitrophes. *Annales de la Société géologique de Belgique*, 109 : 431-454.

MAMET, B. & PREAT, A,. 2005. Microfaciès d'une lentille biohermale à la limite Eifelien/Givetien (Wellin, bord sud du Synclinorium de Dinant). *Geologica Belgica*, 8 : 85-111.

PEL, J., 1975. Etude sédimentologique et stratigraphique du Givétien, Synclinorium de Dinant, de Givet à Liège. *Publications de la Faculté des Sciences appliquées de l'Université de Liège*, 53, 113 pp.

PLAYFORD, P.E., 1981. Devonian reef complexes of the Canning Basin, West Australia. Geological Society of Australia, 5th Australian geological convention field excursion guidebook, 64 pp.

POHLER, S.M.L., 1998. Devonian carbonate buildup facies in an intra-oceanic island arc (Tamworth Belt, New South Wales, Australia). *Facies*, 39: 1-34.

POSAMENTIER, H.W. & VAIL, P.R., 1988. Eustatic controls on clastic deposition II- sequence and systems tract models. *In* WILGUS, C.K., HASTINGS, B.S., KENDALL, C.G.St.C., POSAMENTIER, H.W., ROSS, C.A. & VAN WAGONER, J.C. (Eds) Sea Level Changes- An integrated Approach. *Society of Economic Paleontologists & Mineralogists Special Publication,* 42: 125-154.

PREAT, A., BLOCKMANS, S., CAPETTE, L., DUMOULIN, V. & MAMET, B., 2007. Microfaciès d'une lentille biohermale à la limite Eifelien/Givetien ("Fondry des Chiens", Nismes, Bord sud du Synclinorium de Dinant). *Geologica Belgica*, 10 : 3-25.

PREAT, A. & BOULVAIN, F., 1982. Etude sédimentologique des calcaires givetiens à Vaucelles (bord sud du Synclinorium de Dinant). *Annales de la Société géologique de Belgique*, 105 : 273-282.

PREAT, A. & BOULVAIN, F., 1987. Les calcaires laminaires du Givétien inférieur du Bassin de Dinant : témoins paléogéographiques et paléoclimatiques. *Annales de la Société Géologique du Nord*, CVI : 49-64.

PREAT, A, CEULENEER, G. & BOULVAIN, F., 1987. Etude sédimentologique des calcaires du Givétien Inférieur d'Olloy-sur-Viroin (bord Sud du Bassin de Dinant, Belgique). *Annales de la Société Géologique du Nord*, CVI : 251-265.

PREAT, A., COEN-AUBERT, M., MAMET, B. & TOURNEUR, F., 1984. Sédimentologie et paléoécologie de trois niveaux récifaux du Givetien inférieur de Resteigne (bord sud du Bassin de Dinant, Belgique). *Bulletin de la Société belge de Géologie*, 93 : 227-240.

PREAT, A. & MAMET, B., 1989. Sédimentation de la plate-forme carbonatée givétienne franco-belge. *Bulletin Centres de Recherche Exploration-Production Elf-Aquitaine*, 13 : 47-86.

PURSER, B.H., 1983. Sédimentation et diagenèse des carbonates néritiques récents. Tome 2: Les domaines de sédimentation carbonatée néritiques récents; application à l'interprétation des calcaires anciens. Technip, 389 pp.

RIEGL, B. & PILLER, W. E., 1997. Distribution and environmental control of coral assemblages in northern Safaga Bay (Red Sea, Egypt). *Facies,* 36: 141-162.

RIEGL, B. & PILLER, W. E., 2000. Reefs and coral carpets in the northern Red Sea as models for organism - environment feedback in coral communities and its reflection in growth fabrics. *In*: INSALACO, E., SKELTON, P. W. & PALMER, T. J. (Eds) Carbonate Platform Systems: components and interactions. *Geological Society, London, Special Publications*, 178: 71-88.

TOURNEUR, F., 1987. Mise au point sur le genre Trachypora Milne-Edwards & Haime 1851 (Tabulata, Dévonien). *Annales de la Société géologique de Belgique*, 110 : 297-308.

VAN WAGONER, J.C., POSAMENTIER, H.W., MITCHUM, R.M., VAIL, P.R., SARG, J.F., LOUTIT, T.S. & HARDENBOL, J., 1988. An overview of sequence stratigraphy and key definitions. *In* WILGUS, C.K., HASTINGS, B.S., KENDALL, C.G.St.C., POSAMENTIER, H.W., ROSS, C.A. & VAN WAGONER, J.C. (Eds) Sea Level Changes- An integrated Approach. *Society of Economic Paleontologists & Mineralogists Special Publication,* 42: 39-45.

WRIGHT, V.P., 1994. Paleosols in shallow marine carbonate sequences. *Earth-Science Reviews,* 35: 367-395.

WALKER, K.R. & ALBERSTADT, L., 1975. Ecological succession as an aspect of structure in fossil communities. Paleobiology, 1: 238-257.

ZIEGLER, P.A., 1982. Geological atlas of the Western and Central Europe. Shell Internationale Petroleum Maatschappij B.V., 130 pp.,40 plates.

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