

FACIES AND PALAEOECOLOGY OF THE UPPER MEMBER OF THE AISEMONT FORMATION (LATE FRASNIAN, S. BELGIUM): AN UNUSUAL EPISODE WITHIN THE LATE FRASNIAN CRISIS

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(12 figures)

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ABSTRACT The upper member of the Aisemont Formation – also known as the “second biostrome” – is the last significant Upper Frasnian carbonate unit in the northern part of the Namur-Dinant Basin (Southern Belgium). It consists of bioclastic limestone, often dolomitized, with numerous oncoids and corals. Despite its local name, the member is not a biostrome because only one thin bed is constructed by corals. It is mainly composed of limestone with numerous oncoids and a rich fauna of opportunistic organisms (bryozoans, brachiopods, gastropods, sponges, etc.) where *Phillipsastrea* and *Frechastraea* are the dominant coral taxa, associated with *Alveolites*. Ragged colonies of corals, as well as multi-encrusted bodies, show that the sea floor was soft and the rate of sedimentation was seasonal. These factors were unfavourable to common reef builders (stromatoporoids), thus the occurrence of one bed constructed by corals is a remarkable event that corresponds to the colonization of a hard ground defining the base of a falling stage systems tract. This confirms the model of the Aisemont sequence (third-order transgression-regression cycle). The abundant development of microbial structures in the member (oncoids) and in its lateral equivalent in stromatolites and thrombolites of the Petit-Mont Member (Les Valisettes Formation) in the Philippeville Anticlinorium is interpreted as an evidence of the environmental deterioration corresponding to the Late Frasnian Crisis.

KEYWORDS : Late Frasnian Crisis, Namur-Dinant Basin, Aisemont Formation, *Phillipsastreidae*, multi-encrusted bodies, microbialites.

RESUME Facies et paléocéologie du membre supérieur de la Formation d'Aisemont (Frasnien supérieur, S. Belgique): un épisode inhabituel dans la crise du Frasnien supérieur. Le membre supérieur de la Formation d'Aisemont – aussi appelé “second biostrome” – correspond au dernier niveau carbonaté significatif du Frasnien supérieur au bord nord du Synclinorium de Dinant et dans le Synclinorium de Namur, en Belgique. Il est constitué de calcaire bioclastique à oncoïdes et coraux, souvent dolomitisé et n'est donc pas à proprement parler un biostrome puisque seul un niveau très peu épais est construit par des coraux. L'essentiel du membre est formé de calcaire relativement riche en oncoïdes et organismes dont la plupart sont des opportunistes (bryozoaires, brachiopodes, gastéropodes, spongiaires, etc.). Les coraux identifiés appartiennent aux genres *Phillipsastrea* et *Frechastraea*, qui dominent aux côtés du tabulé *Alveolites*. L'observation d'objets multi-encroûtés, ainsi que des colonies effilochées de coraux, laisse penser que le milieu de dépôt était un environnement difficile pour les principaux organismes constructeurs: fond meuble, eaux turbides, sédimentation fine intermittente. Le développement d'un niveau construit par les coraux est donc un événement important, qui correspond à la colonisation d'un fond durci. Ce dernier marque la base d'un cortège régressif et confirme le modèle de la « séquence d'Aisemont » (cycle transgression-régression de troisième ordre). Enfin, la prolifération de structures microbiennes tant dans le membre, sous forme d'oncoïdes, que dans son équivalent latéral, sous forme de thrombolithes et stromatolithes, dans le Membre de Petit-Mont (Formation des Valisettes dans l'Anticlinorium de Philippeville) est interprétée comme le résultat des détériorations environnementales menant aux crises du Frasnien supérieur.

MOTS-CLES : Crise du Frasnien supérieur, Bassin de Namur-Dinant, Formation d'Aisemont, *Phillipsastreidae*, objets multi-encroûtés, microbialites.

1. Introduction

The Late Frasnian time is characterized by a major biotic crisis near the Frasnian-Famennian boundary (Late Devonian). About 70 % of the species, 50% of the genera and 21 % of the families (McGhee, 1996, House, 2002) get extinct, making this crisis one of the “Big Five” crisis of the Phanerozoic (Hallam & Wignall, 1997, discussed by House, 2002). The most striking consequence of the

Late Frasnian Crisis is the demise of the corals-stromatoporoids reefs (Cooper, 2002). The crisis is not punctual but extends along the Late Frasnian and Early Famennian period and is marked by the Kellwasser Events (Schindler, 1993). The Lower Kellwasser Event is situated in the upper *Palmatolepis rhenana* conodont Biozone, the Upper Kellwasser Event belongs to the *P. linguiformis* Biozone.

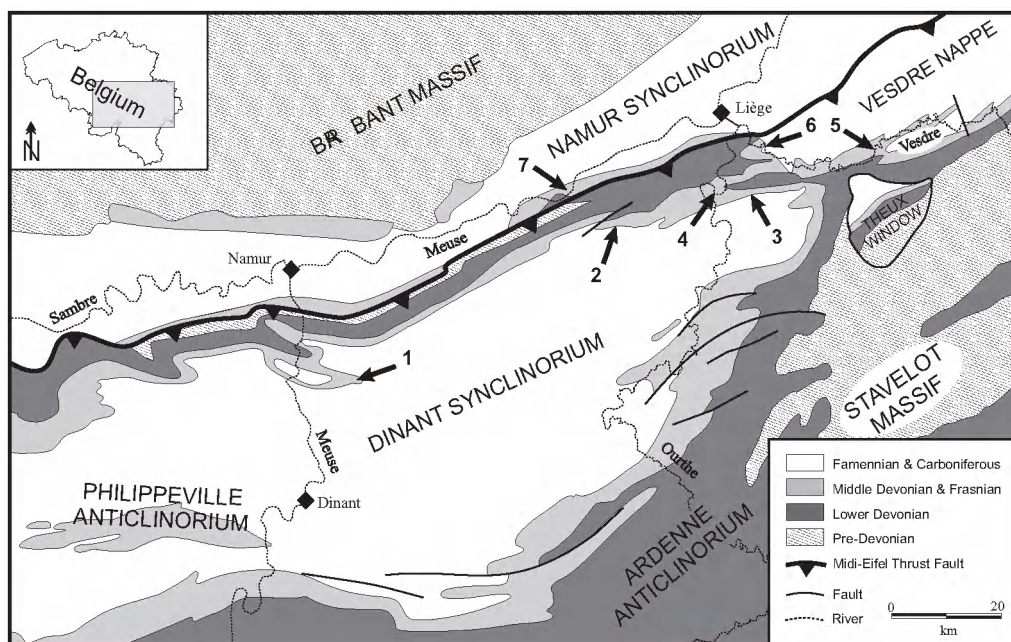


Figure 1 : Structural map of Belgium and neighbouring countries, with location of studied sections. Post-Carboniferous strata have been omitted of the map. 1: Bauche, 2: Bagnée, 3: Dolembreux, 4: Hony, 5: Lambermont, 6: Fond-des-Cris, 7: La Mallieue.

In the Namur-Dinant Basin (Southern Belgium, Fig. 1), these events are clearly separated and their intensity depends on their position along the ramp (Mottequin, 2008a). The Lower Kellwasser Event has been recognized (Gouwy & Bultynck, 2000) in the lower part of the Matagne Formation (southern part of Dinant Synclinorium, Fig. 2), at the base of the Les Valisettes Formation (Philippeville Anticlinorium) and in the middle member of the Aisemont Formation (northern part of the Namur-Dinant Basin). The Upper Kellwasser Event corresponds to the upper part of the Matagne Formation, and is located at the top of the Les Valisettes and Lambermont formations (Fig. 2).

The onset of the Late Frasnian Crisis (named Kellwasser Crisis by Schindler, 1993) starts before the Lower Kellwasser Event, within the Early *rhénana* conodont Biozone with the disappearance of the styliolinids (planktonic cricoconarids, Schindler, 1990). Contrarily to the following upper one, the Lower Kellwasser Event has no significant effect on the diversity of corals (Poty & Chevalier, 2007) and few on brachiopods (Mottequin, 2005) but is an evidence of the degradation of the global environment during the Late Frasnian, as several changes of facies witness it in the Namur-Dinant Basin (Poty & Chevalier, 2007). Thus the upper member of the Aisemont Formation is a key level for the

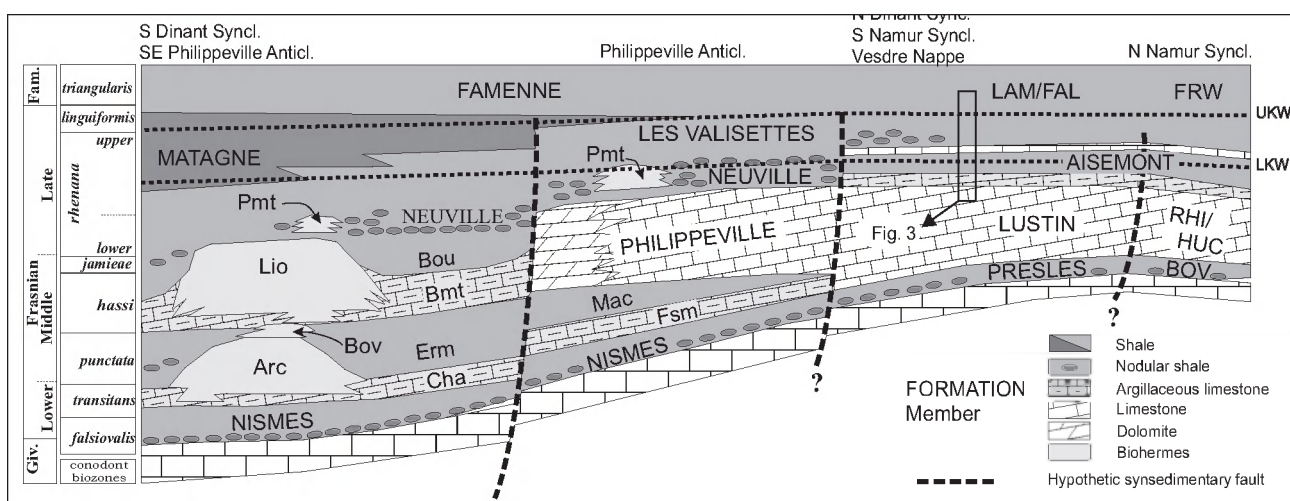


Figure 2: Synthetic sketch of Frasnian formations and members in the Namur-Dinant Basin. The Aisemont Formation and its three members are represented in the northern part of the basin. Legend: Syncl.: Synclinorium, Anticl.: Anticlinorium. Giv.: Givetian, Fam.: Famennian. LKW: Lower Kellwasser, UKW: Upper Kellwasser. LAM: Lambermont Formation, FAL/ Falisole Formation, FRW: Franc-Waret Formation. Cha : Chalon member, Arc : Arche Member, Erm : Ermitage Member, Bov : La Boverie Member (all four form the Moulin Liénaux Formation). Bmt: Bieumont Member, Lio: Lion Member, Bou: Boussu-en-Fagne Member (all three form the Grands Breux Formation). Pmt: Petit-Mont Member (Neuville Formation). Fsm : Fontaine-Samart Member, Mac : Machénées Member (both form the Pont de la Folle Formation). Modified from Boulvain *et al.* (2007), conodont biozones after Bultynck *et al.* (1998).

understanding of the environmental changes as one of the last coral and stromatoporoid bearing limestone of the Late Frasnian. Moreover this study offers a view from the shelf, what is often missing in the worldwide understanding of the Late Frasnian Crisis, mainly based on condensed basal sections. The aims of this paper are (1) to explain the palaeoecological context of the member, (2) to replace it into the global eustatic scheme, and (3) to describe the unusual biotic association, rich in opportunistic organisms and microbial structures.

2. Geological settings

In southern Belgium, Upper Frasnian formations crop out in the Dinant Synclinorium, the Namur Synclinorium and the Vesdre Nappe (structural units that formed the Namur-Dinant Basin, Fig. 1). There are several limestone units among various argillaceous lithologies. In the northern part of the Namur-Dinant Basin, the Upper Frasnian is mainly represented by the Aisemont Formation that consist of three members. The lower member, known in the Belgian literature as the “premier biostrome” (Coen et al., 1976), varies from argillaceous limestone with coquina beds to a biostrome with *Alveolites* and phillipstastreids

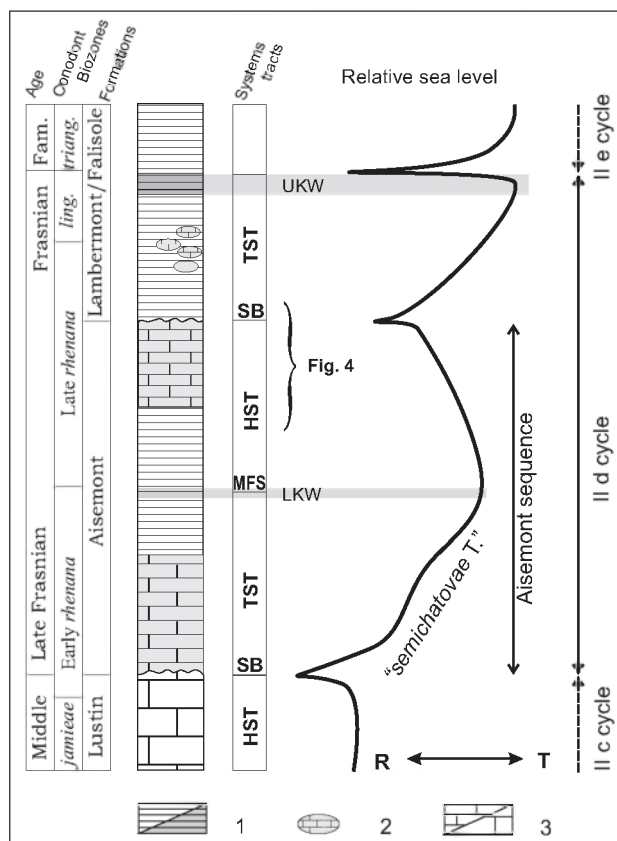


Figure 3: Stratigraphic succession of Upper Frasnian formations in the northern part of the Dinant Synclinorium, in the southern part of the Namur Synclinorium and in the Vesdre Area. Systems tracts are from Poty & Chevalier (2007) model. HST: highstand systems tract. SB: sequence boundary. TST: Transgressive systems tract. MFS: maximum flooding surface FSST: falling stage systems tract. ling.: *linguiformis*, triang.: *triangularis*. R: regression, T: transgression. 1: shale/black shale. 2: nodular limestone. 3: thin/thick bedded limestone.

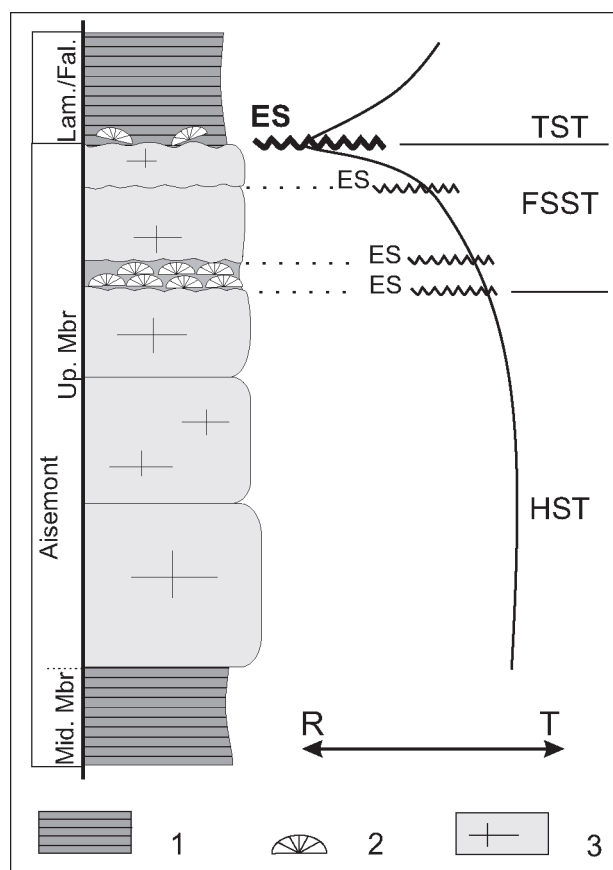


Figure 4: Sketch of the eustatic context of the “second biostrome” showing erosion surfaces (ES) that define a falling stage systems tract (FSST) at the top of the member (Fig. 6). The last erosion surface corresponds to the Aisemont sequence boundary (see Fig. 3). Lam. : Lambermont Formation, Fal. : Falsole Formation. R: regression, T: transgression. 1: shale. 2: phillipstastreids. 3: limestone.

or stromatoporoids. The middle member (“schistes inférieurs” of Coen et al., 1976) is a fossiliferous shaly unit in which a dysoxic level containing numerous pterinopectinids, lingulid brachiopods and bryozoans has been recognized (Mottequin, 2005, 2008a). The upper member is a stylonodular, bioclastic limestone, with corals and numerous oncooids. It has been named “second biostrome” by Coen et al. (1976).

The Aisemont Formation recorded a transgressive-regressive cycle corresponding to a single third order sequence (Poty & Chevalier, 2007) that coincides with the first part of the IId cycle of Johnson et al. (1985, see Fig. 3) but also with the “*semichatovae* transgression” (Aleksiev et al. 1996). An erosion surface (disconformity) caps the Middle Frasnian Lustin Formation, above a couple of palaeosoils (Boulvain, 2007). Poty & Chevalier (2007) interpreted it as an erosion transgressive surface reflecting an emersion of the shelf. According to these authors, the lower member and part of the middle member of the Aisemont Formation set up the transgressive systems tract of the “Aisemont sequence” (Fig. 3). The maximum flooding surface is reached in the dysoxic shale of the middle member. The highstand systems tract corresponds

to the upper part of the middle member and the lower part of the upper one. A falling stage systems tract is recognized by the presence of erosion surfaces in the upper part of the upper member of the Aisemont Formation (Fig. 4). This member is topped by the shale of the Lambermont, Falisole and Franc-Waret formations (lateral equivalents) which deposited on a last erosion transgressive surface corresponding to the sequence boundary capping the Aisemont Formation limestone. The correlative conformity has also been found in the upper part of the Petit-Mont Member mudmound where an undulating surface caps shallowing-upward grey algal Unit And is overlaid by stromatolite red facies of deeper water (Boulvain, 2007). The same surface is interpreted by Muchez et al. (1996) as the sequence boundary between a transgressive systems tract and a lowstand systems tract. Moreover, it is correlated with debris flow deposits within the surrounding shaly facies of the mudmound (south-eastern part of the Philippeville Anticlinorium). In the northern part of the Philippeville Anticlinorium, (e. g. Beauchâteau quarry), the same sequence boundary surface has been described as a karstic surface by Sandberg et al. (1992). The next sequence witnesses a definitive switch in the sedimentation type toward the predominant argillaceous deposits of the latest Frasnian and earliest Famennian times.

3. Studied sections

Seven sections have been studied in the northern and north-eastern part of the Namur-Dinant Basin (Fig. 1, Fig. 5). Four of them are situated in the northern and north-eastern part of the Dinant Synclinorium (Bauche, Baugnée,

Dolembreux and Hony), one in the southern part of the Namur Synclinorium (La Mallieue) and two in the Vesdre Nappe (Lambermont and Fond-des-Cris). Their description is given from North to South in the supposed palinspastic position in the Upper Frasnian ramp. The correlation to the time-equivalent levels in the southern part of the basin is based on the abundant literature (Boulvain, 1993, 2007, Boulvain et al., 2004, Mottequin, 2005, 2008a, 2008b).

3.1. Bauche section

The Bauche section is situated along the road from Yvoir to Crupet, near the Bauche hamlet, in the Bocq valley (Coen & Coen-Aubert, 1974a). It belongs to the northern side of the Dinant Synclinorium (Fig. 1). The upper member of the Aisemont Formation crops out in a road embankment, and is 11 m thick. The first lithological unit of the member is a 3 m-thick bioclastic mudstones to wackestones rich in gastropods and brachiopods (Unit A). The other 8 m of the section are almost totally constituted of the Unit B: stylonodular metre-thick beds of bioclastic wackestones and packstones with asymmetric oncoids and scattered corals. Within the dominant Unit B, two levels are remarkable. (1) a level of laminated packstones and grainstones, found 5.5 m above the base of the member and (2), 6.5 m above the base, one bed, 40 cm-thick forming the Unit C: a framestone with numerous phillipsastreids (10 to 60 cm in size) and *Alveolites*, often overturned. The top of the upper member of the Aisemont Formation does not crop out in this section but the shale of the Falisole Formation are visible a few decimetres further in the embankment of the road.

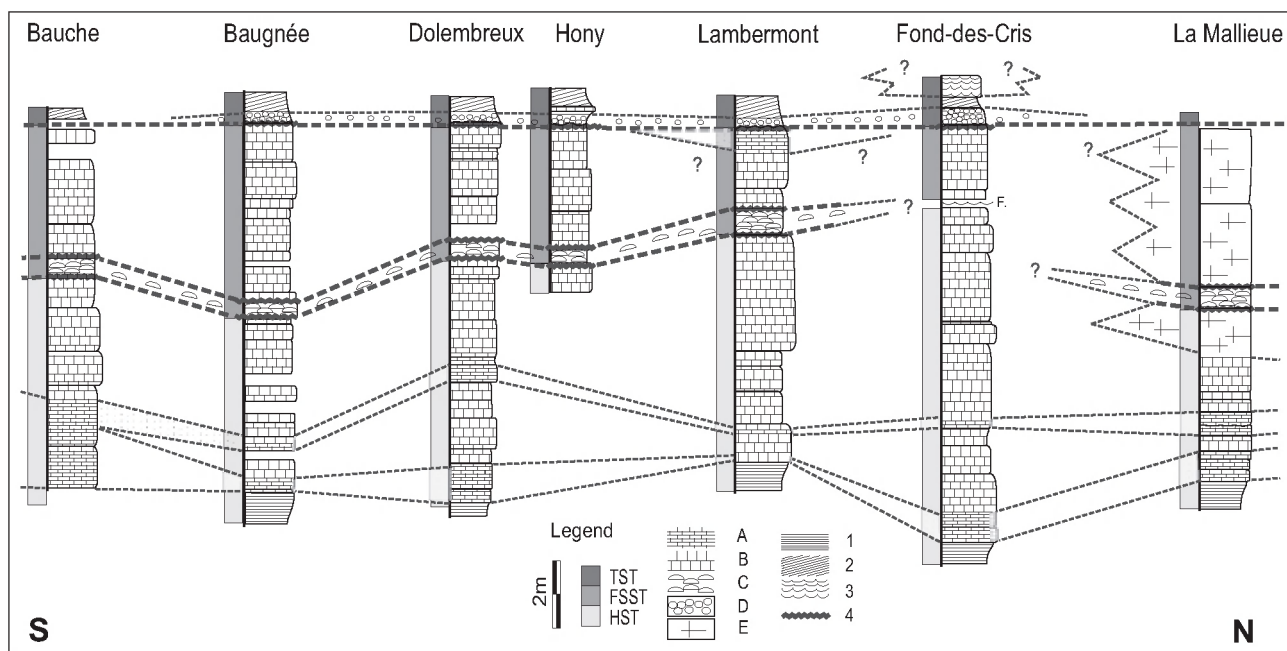


Figure 5: Vertical and lateral assemblage of the main facies constituting the upper member of the Aisemont Formation through the seven studied sections. TST: transgressive systems tract, HST: highstand systems tract, FSST: falling stage systems tract, F.: fault. 1: shale of the middle member of the Aisemont Formation. 2: shale and nodular shale of the Lambermont and Falisole formations. 3: nodular shale with corals of the “troisième biostrome” (Lambermont Formation). 4: erosion surface. Unit A: bioclastic mudstones and wackestones. Unit B: bioclastic and peloidic wackestones and packstones with oncoids. Unit C: framestone with phillipsastreids, *Alveolites* and stromatoporoids. Unit D: bioclastic lenses with corals, crinoids and bryozoans. Unit E: algal grainstone with oncoids.

3.2. Baugnée section

This section (Fig. 1), located along the road from Nandrin to Esneux, belongs to the northern part of the Dinant Synclinorium. It exposes the top of the Lustin Formation, the three members of the Aisemont Formation and the base of the Lambermont Formation (Mottequin, 2005, Poty & Chevalier, 2007). The upper member starts with 50 cm of the Unit A (bioclastic mudstones to wackestones with gastropods and brachiopods, slightly argillaceous). The dominant lithology of the section, the Unit B, appears in a 80 cm-thick level, above the previous beds but is interrupted by a recurrent 40 cm-thick bed of Unit A (Fig. 5). The Unit B reappears immediately above this bed. It is bioclastic wackestones and packstones with numerous oncoids (some are pluricentimetric in size) and microbial coating. 5.2 m above the base of the member, a half-metre-thick bed is a framestone with phillipsastreids and *Alveolites* (Fig. 7a), forming the Unit C. It is followed by a 10 cm-thick laminated packstones to grainstones level. The rest of the member is constituted of the same Unit B. An undulating surface caps the top of the member and above it, the Lambermont Formation starts with 30-40 cm of shale with highly bioclastic lenses (Unit D). The latter contains numerous corals (phillipsastreids, *Macgeea* and *Tabulophyllum*), bryozoans (among these, massive forms of the genus *Cyclotrypa*) and brachiopods. This level is correlated with the lense bed of the Fond-des-Cris section and the “conglomerate” of the Hony section (see below and Fig. 5).

3.3. Dolembreux section

This outcrop belongs to the north-eastern part of the Dinant Synclinorium (Fig. 1). It is located near the Ourthe valley, in Esneux, along the road from Dolembreux to Hayen hamlet. It exposes about 12 m of stylonodular decimetre-thick beds of the upper member of the Aisemont Formation. It starts with 1 m of the bioclastic mudstones and wackestones, more or less rich in brachiopods, gastropods and bryozoans as observed in every other sections (Unit A). Oncoidal and bioclastic wackestones and packstones (Unit B) are dominant in the rest of the member but a 60 cm-thick argillaceous and bioclastic packstone level appears 3.6 m above the base of the member. Another remarkable 60 cm-thick level is visible 5 m above the base of the member. It forms the Unit C, a framestone with numerous phillipsastreids and *Alveolites* in living position. The upper 3.4 m of the member are constituted of the Unit B, capped by an undulating surface. The Lambermont Formation starts above this last surface, with 20 to 40 cm of bioclastic shale (Unit D).

3.4. Hony section

Recent works on the railway Liège-Jemelle near the Hony station (Fig. 1), have enlarged the classical Hony section (Streel et al., 2000) to the last 5 metres of the upper member of the Aisemont Formation. The latter consists of bioclastic wackestone and packstones with oncoids (Unit B) interrupted by a 30 cm-thick biostrome with domal

phillipsastreids and *Alveolites* (Unit C, Fig. 6b). The base and the top of this bed are marked by an undulating surface cutting bioclasts and fossils, and stained with brown clayed sediment (I and II on Fig. 6a). The upper bed of the member also shows an undulating erosion surface, separating the limestone and the shale of the Lambermont Formation. Above this irregular surface, a 20-50 cm level of reworked phillipsastreids colonies is present, forming a kind of “conglomerate” (Unit D). It results probably of the breaking up of a coral boundstone, as the lenses bed seen in the upper part of the Fond-des-Cris section (see below). The section also exposes the Lambermont Formation characterized by several half-metre-thick shale-argillaceous limestone alternations (Paquay, 2002).

3.5. Lambermont section

The section is situated in the Vesdre valley, in the eastern part of the Vesdre Nappe (Fig. 1). It is located below the motorway Liège-Prüm in the town of Verviers. About 10 m of the upper member of the Aisemont Formation, as

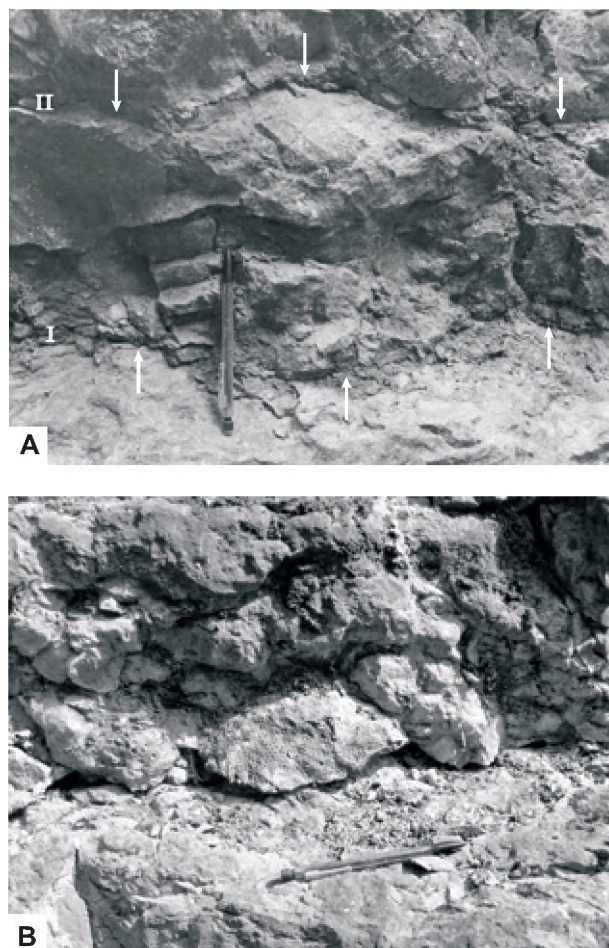


Figure 6: Biostrome from the Hony section. A: The lower surface (I, arrows) stained by brownish argillaceous material is the first erosion surface linked to an emersion. The second surface (II, arrows), cutting the colony and other bioclasts, also results of the emersion of the substrate. B: Phillipsastreids and *Alveolites* have been put in relief by erosion of the matrix. Hony section. Scale given by the pencil (15 cm).

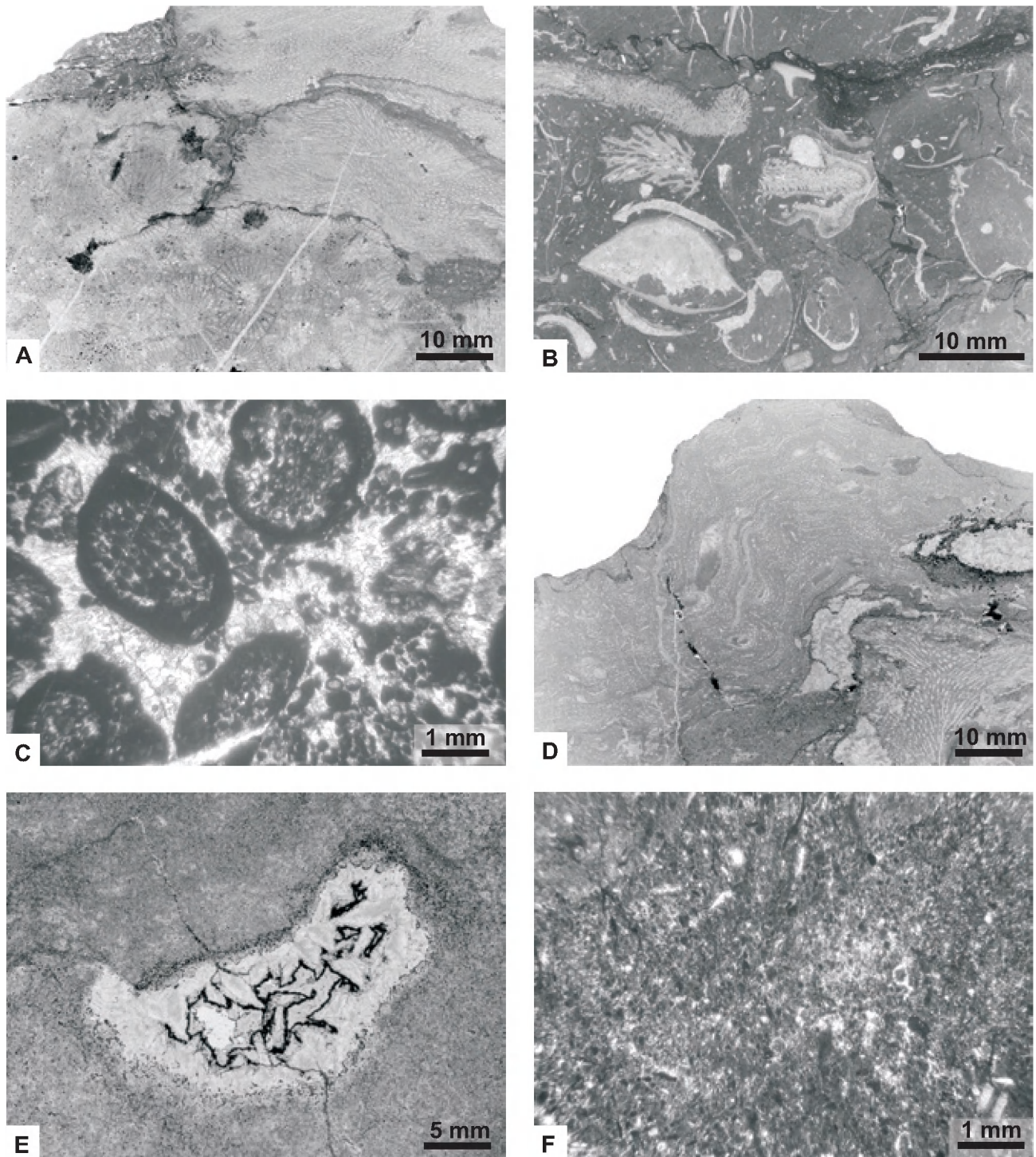


Figure 7: Facies and microfacies of the upper member of the Aisemont Formation. A: Framestone with phillipsastreids and *Alveolites*. Stromatoporoids lamina and solitary rugosa are sometimes present. The matrix varies from an argillaceous mudstone to bioclastic wackestones to packstone. Baugnée section, top of the biostromal bed Unit C (16/360). B: Bioclastic floatstone with wackestone-packstone matrix and brachiopod shells, tabulate corals and bryozoans. Note the central body: it is a branched *Scoliopora* with *Metriophyllum bouchardi* (little rugose coral) encrusted by stromatoporoids and the bryozoan *Cyclotrypa*. Lambermont section, Unit C (bed 7/110). C: Bioclastic and algal grainstone with oncoids and the udoteacea *Paralitanaia*. Udoteacean thallium is consistently the nuclei of irregular oncoids. Each grain shows microbial coating and sometimes dolomite crystals (early diagenetic dolomite). La Mallieue section, Unit E (bed 64/53). D: Framestone with *Alveolites* and stromatoporoids. This facies constitutes the biostromal bed (Unit C) of the La Mallieue section. The matrix is a dolomitic bioclastic and algal grainstone with peloids, oncoids and numerous dasycladacean thallium *Radiosphaeroporella*. La Mallieue section, base of the biostromal bed (63/0). E: Geode with epigenetic dolomite crystals, zoned and take place in a cavity left by dissolution of late diagenetic dolomite. The thin level of light crystals around the geode is calcite edge in the border of dedolomitized dolomite crystals. The matrix is late diagenetic dolomite forming a “mozaïc” (Dejonghe, 1987). Top of the La Mallieue section (bed 65/45). F: Bioclastic and peloidic wackestones to packstones with oncoids. Bauché section, base of the Unit B (bed 14/405).

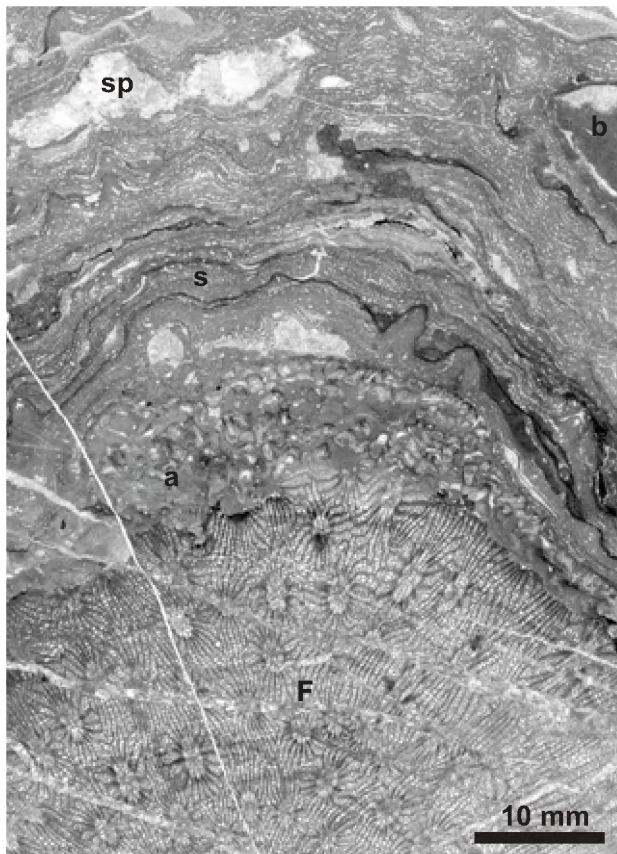


Figure 8: Domal stromatoporoid-*Frechastraea* association. *Frechastraea pentagona* colony (F) has first been thickly encrusted by aulopores (a). This latter have been covered by irregular laminar stromatoporoids (s) where sparitic cavities correspond to (small?) decayed sponges (sp). Stromatoporoids have also wrapped brachiopod shell (b) and other bioclasts. This is an uncommon case of growth because usually, stromatoporoids form only thin lamina like in bodies shown in pictures 11. Lambermont section, Unit B (bed 13/80).

well as the Lambermont Formation and parts of Hodimont Formation are exposed in an intensively tectonized area (Van Brabant et al., 2003, Mottequin, 2005). The upper member is composed of metre to plurimetre-thick beds of argillaceous and stylonodular limestone covered with brownish spots due to local dolomitization-dedolomitization process (Dejonghe, 1987). These limestones are oncoidal and bioclastic wackestones and packstones to floatstones (Unit B, Fig. 7b). Two thin intercalation of mudstones and wackestones of Unit A constitute 10 cm-thick levels at the base and the top of the first bed of the member. Corals (*Alveolites*, phillipsastreids and solitary rugose corals), brachiopods, and gastropods are very common in the unit but stromatoporoids are rare (Fig. 8). 6.8 m above the base of the member, a 80 cm-thick bed is a framestone with numerous phillipsastreids and *Alveolites* colonies in living position (Unit C). The matrix is a bioclastic and dolomitic shale rich in bryozoans. The upper 80 cm-thick bed of the member is intensively bioturbated bioclastic mudstones and wackestones corresponding to the Unit A (Fig. 5). This reappearance of

the Unit A in the upper part of the member is known only in the Lambermont section. An undulating surface caps the member and the nodular shale of the Lambermont Formation is visible above it (Unit D).

3.6. Fond-des-Cris section

This outcrop is located in the Fond-des-Cris disused quarries, west of Chaudfontaine near the Vesdre valley. It belongs to the Vesdre Nappe (Fig. 1). The top of the Lustin Formation and the lower member of the Aisemont Formation crop out in the southern quarry (Poty & Chevalier, 2007). The upper member and the Lambermont Formation are visible in the northern one in a highly tectonized zone. The middle shale member crops out badly between the two quarries (Da Silva, 2004). The upper member reaches 12.5 m in thickness. The lower 80 cm of the member are composed of mudstones and wackestones rich in bioclasts (mainly brachiopods and gastropods, Unit A). The rest of the member is constituted of bioclastic and oncoidal wackestones and packstones (Unit B) with brachiopods, gastropods, corals, stromatoporoids and centimetre-sized oncoids. Algae are very common (*Udoteacea*, *Sphaerocodium*, *Girvanella*) in oncoids and scattered in the matrix. 3.4 m above the base of the member, a thin level (25 cm) of mudstone of Unit A is present. A half-metre-thick level of laminated grainstone containing very irregular cauliflower-shaped oncoids (Fig. 9) is interbedded in the packstones of Unit

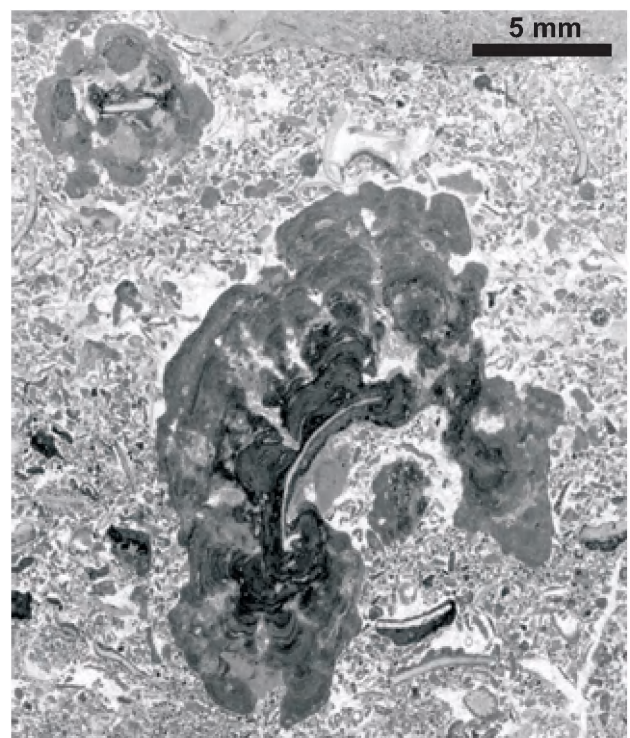


Figure 9: Very irregular oncoid with cauliflower shape. Microbial coating occurs on one side of the shell. Perforations are mainly borings. This asymmetric shape witnesses a very quiet environment. The grainstone matrix results of storm action. Fond-des-Cris section, laminated level, Unit B (bed 8/0).

B, 6 m above the base of the member. No biostromal bed (Unit C) has been observed, probably because of fault action. An undulating surface marks the top of the upper member of the Aisemont Formation. A framestone with domal phillipsastreids and *Alveolites* tops this last surface. The framestone is rich in centimetre-thick lenses highly bioclastic rudstone with abundant brachiopods, bryozoans and crinoids. This bed forms the lateral equivalent of Unit D seen in the “conglomerate” of the Hony section and bioclastic lenses of Baugnée, Dolembreux and Lambermont sections. The shale of the Lambermont Formation are, here, reduced to 30 cm of unfossiliferous shale (Fig. 5) immediately followed by a thick unit of nodular limestone and shale with phillipsastreids, crinoids, and numerous brachiopods (“troisième biostrome” of Coen et al., 1976). Note that, in the Chaudfontaine-termes borehole (about 1 km eastward), the “troisième biostrome” directly overlays the upper member without any shale intercalation. Moreover, in this borehole, an evaporitic barite deposit have been observed in the top of the upper member of the Aisemont Formation. Dejonghe & Boulvain (1993) supposed it is a barite pseudomorph after gypsum deposit accumulated in small shallow water basins within the sediment.

3.7. La Mallieue section

This section, belonging to the southern border of the Namur Synclinorium, crops out along the road from Liège to Huy, on the left bank of the Meuse valley (Fig. 1). The lower and middle members of the Aisemont Formation are observable in the slope of the road (Coen-Aubert & Lacroix, 1978, Chevalier, 1994, Poty & Chevalier, 2007). The upper member is exposed in a small disused quarry. Its thickness reaches 10.5 m but its top crops out very badly. The first two metres are decimetre-thick stylonodular beds of bioturbated and bioclastic mudstones and wackestones (Unit A) often dolomitic. A 45 cm-thick bed of bioclastic packstone with oncoids (Unit B) is intercalated in the mudstone. A 20 cm-thick laminated grainstone layer, 3.6 m above the base of the member, makes the transition between the wackestone-packstone and a grainstone poor in corals but rich in oncoids and with a huge amount of the Udoteacea *Paralitanaia* (Mamet & Boulvain, 1992), *Radiosphaeroporella*, *Sphaerocodium* and “*Umbella*” that forms the Unit E (Fig. 5). Oncoids, centimetric-sized, are regular and the nuclei are often an udoteacean thallium (Fig. 7c). This last facies, more and more dolomitized to the top constitutes the rest of the section. One bed, 60 cm in thickness, situated within the Unit E 5.2 m above the base of the member, is a framestone with *Alveolites* and domal stromatoporoid (Fig. 7d).

The La Mallieue section exposes intensively dolomitized proximal facies and the vertical distribution of the dolomite type follows a continuum as shown by Dejonghe (1987). Non dolomitized limestone, often affected by diagenetic stylonodular dolomite is present at the base of the member. Early diagenetic dolomite occurring in the lower beds of the member consists of 30–150 µm rhomboedric crystals scattered in the non-

dolomitic matrix. Upper beds contain late diagenetic dolomite in subedral to anedral crystals forming a “mosaic”. Epigenic dolomite forming large zoned crystals takes place into cavities left by dissolution and dedolomitization of the last beds (Fig. 7e).

4. Paleontological material

During the Early *rhenana* conodont Biozone, phillipsastroid corals replaced disphyllid corals (*Disphyllum* and *Hexagonaria*) that were dominant with pachyporid tabulate corals (*Thamnopora*) and stromatoporoids in older strata (Poty, 1999). In the northern part of the Namur-Dinant Basin, the *Disphyllidae* disappeared at the top of Middle Frasnian formations (mainly Lustin Formation, Fig. 2) and have been replaced by *Phillipsastraeidae* at the base of the Upper Frasnian Aisemont Formation. Moreover, in the southern part of the basin, some specimens of disphyllid corals are present in the lateral equivalent Neuville Formation (Fig. 2). Example is given in the Neuville section (Philippeville Anticlinorium) where the last *Hexagonaria* have been found with *Phillipsastrea*, 5 m above the base of the Neuville Formation (Coen & Coen-Aubert, 1974b). Shifted appearances of the *Phillipsastraeidae*, of the conodont *Ancyrognathus triangularis* and of the brachiopod *Tyocyropsis bironensis* at the base of the Neuville and Aisemont formations witness the diachronism of their deposition and the resulting gap with the Middle Frasnian formations (Gouwy & Bultynck, 2000, Poty & Chevalier, 2007).

Note that the genus *Scruttonia* is the only *Phillipsastraeidae* known in the Middle Frasnian in the Namur-Dinant Basin but several other genera of the family are known since the Middle Devonian in Eurasiatic basins (Hill, 1981). The important loss of diversity associated with the collapse of large shelf biostromes and basinal bioherms happened near the Middle-Late Frasnian boundary (lowermost Early *rhenana* conodont Biozone) and could be the first onset of the Late Frasnian Crisis. However, further investigations are needed to estimate precisely the biotic depletion on corals (both Tabulata and Rugosa), stromatoporoids and brachiopods. In the Late Frasnian, the diversity of corals is relatively low and never recovered its previous value. Coen et al. (1976) have described three associations of rugose corals: “Faune 1” typical of the lower member of the Aisemont Formation, “Faune 2” from its upper member and the “Faune 3” characteristic of the Lambermont Formation (Fig. 10). The first assemblage groups various morphotypes of *Frecheastraea pentagona* (initially described as sub-species by Coen-Aubert, 1974), *F. limitata*, *Phillipsastrea ananas*, *Hankaxis insignis*, *Tabulophyllum* sp., *Thamnophyllum* sp. and *Peneckiella* sp. The “Faune 2” shows the lowest diversity: *F. pentagona*, *F. limitata*, *P. ananas*, *Tabulophyllum* sp. (including *T. implicatum*) and the first occurrence of *Mcgeea gallica*. The third assemblage is constituted of *F. pentagona*, *F. limitata*, *P. ananas*, *Tabulophyllum* sp., *M. gallica* and records the appearance of the cerioid *Iowaphyllum*. Tabulate corals are represented

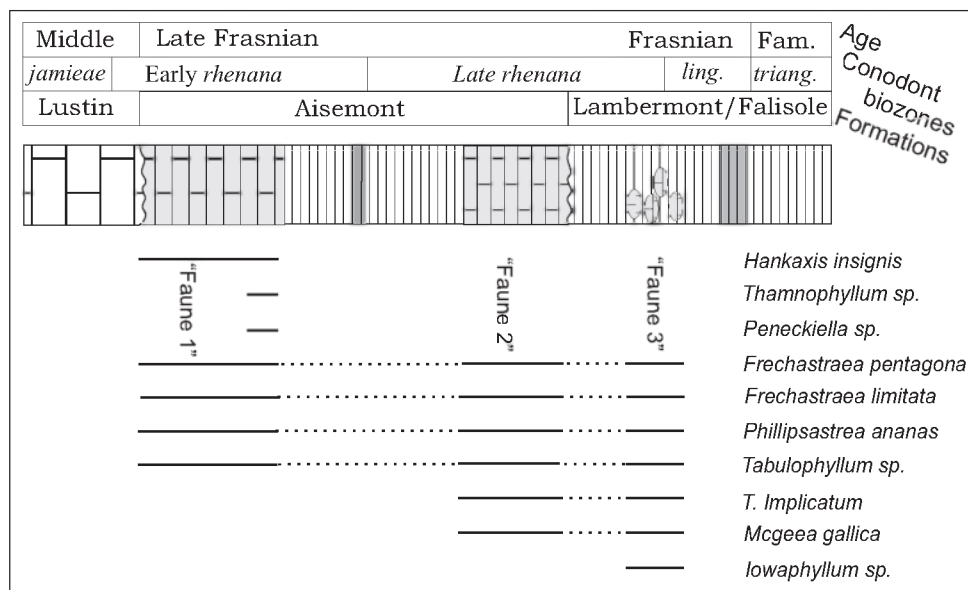


Figure 10: Rugose corals association from the Late Frasnian in the northern part of the Namur-Dinant Basin. “Faune 1”, “Faune 2” and “Faune 3” are the three associations of Coen et al. (1976). Data are from Coen et al. (1976), Coen-Aubert (1974), Coen-Aubert (1982), Chevalier (1994), Paquay (2002), Poty & Chevalier (2007) and personal observations. Legend: see Fig. 3.

by *Alveolites suborbicularis*, *A. tenuissimus* and a few species of *Aulopora*, *Thamnopora* and *Scoliopora*.

In the upper member of the Aisemont Formation, the corals are not diversified but very common, as other organisms. Brachiopods are mainly represented by spire-bearers (atrypids, athyrids, spiriferids) but productids, orthids and terebratulids have also been recognized, as well as “*Hypothiridina*”, a genus usually associated with Upper Frasnian reefs (see Mottequin, 2008a and 2008b). Some species of gastropods with thin discoid shell are largely present. Bryozoans, mainly fenestellids and fistuliporids, are particularly well developed in the member. The massive genus *Cyclotrypa* is especially abundant and plays a significant role as encruster. Stromatoporoids are common in these beds but their diversity is unfortunately badly known. Sponges, echinids, crinoids, spirorbiform tube-worms (*Spirorbis*), and foraminifers (*Nanicella*) are other major components. Flora is also diversified with the udoteacean *Paralithanaia*, *Sphaerocodium* (*Rothpletzella*), the dasycladacean *Radiosphaeroporella*, and “*Girvanella*”.

5. Palaeoenvironmental context and discussions

Previous studies of Upper Frasnian carbonates in Southern Belgium (Tsien, 1971, Boulvain, 1993, 2007, Da Silva, 2004) have interpreted the upper member of the Aisemont Formation as an oncoidal shoal on a south-facing gentle sloped ramp, in a shallow water environment, below the fair weather wave base and thus, inside the storm wave zone. The present work confirms this view.

The dominant facies of the member is a bioclastic wackestone to packstone with oncoids (Unit B, Fig. 7f). It is actually a mix of several sub-microfacies. (1) Bioturbated bioclastic wackestones and packstones with microbial intraclasts, pellets and bioclasts of corals, brachiopods and gastropods shells, bryozoans, foraminifers and oncoids. Inside this microfacies, two poles can be distinguished from the dominant grain: intraclast and pellets on one side, bioclasts on the other side, with a large

variety of intermediate microfacies. (2) A bioclastic packstone, tending to a grainstone with microbial intraclasts, gastropods, brachiopods, corals, algae (*Sphaerocodium* and *Paralithanaia*) and numerous asymmetric oncoids. Grainstone spots correspond mainly to bioturbation. Several centimetre to decimetre-thick laminated levels have been observed in the section, always within the main facies (Unit B or E). They are interpreted as storm deposits (see Fig. 9). The vertical succession of the facies and dolomite types show a shallowing trend and the occurrence of undulating surfaces are difficult to explain in a different way than erosion surfaces linked to emersion and subaerial alteration. Both are defining features of the falling stage systems tract. The reappearance of mudstones and wackestones of Unit A in the wackestones and packstones of Unit B, observed in the seven sections, a few metres above the base of the member, could be the result of two distinct phenomenon: (1) a short lasting deepening in the main regression trend, or (2) a light variation of the sedimentary accommodation. The latter is favoured because it fits with the increasing thickness of the Unit A in the distal sections. Moreover, accommodation could explain the difference in thickness of the member and the reappearance of the mudstones at the top of the member in the Lambermont section. Indeed block-faulting movement has been demonstrated in the Vesdre Nappe since the Middle Devonian (Thorez & Dreesen, 1986).

Except in the Bauche section, about 80 % of the colonies are in living position and nearly all of them are in contact with each other, therefore, it is a thin autobiostrome (Kershaw, 1994). It is a framestone with phillipsastreids and *Alveolites* and with a bioclastic, argillaceous and often dolomitic wackestone matrix. In La Mallieue, the biostrome is quite different. It is a framestone with branched *Alveolites* and domal stromatoporoids, the characteristic constructors in turbulent shallow water, but with less *Phillipsastre*. The matrix is a dolomitic grainstone with bioclasts and algae. This different facies is probably a consequence of the proximal position of La Mallieue on

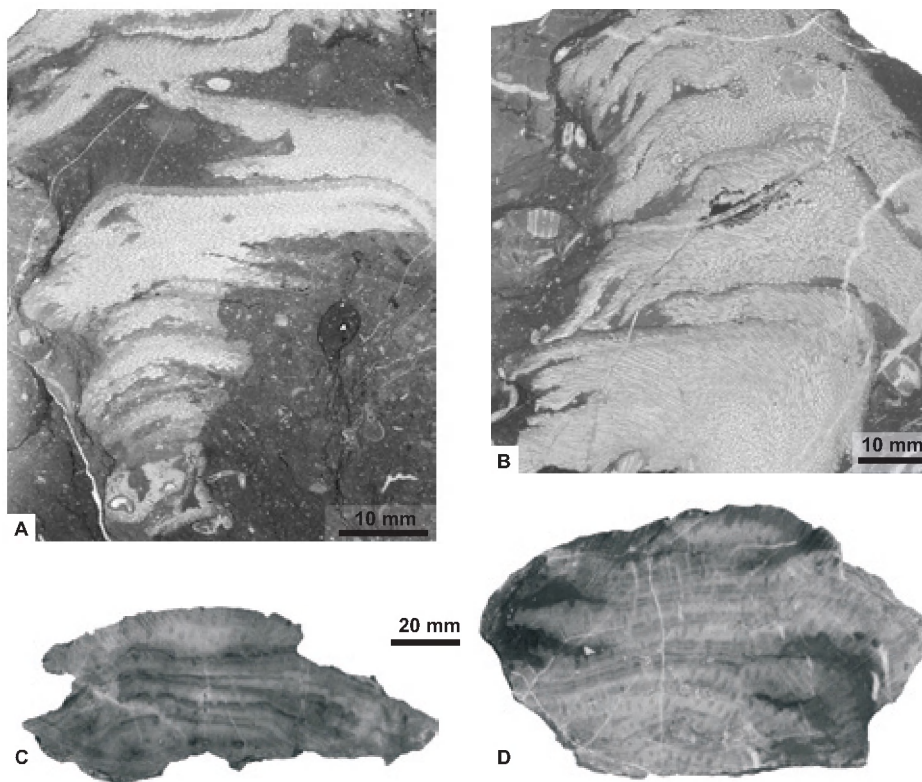


Figure 11: Ragged colonies of corals. Each line is a growing level corresponding to one season: dark line and burial for bad season, light line and rejuvenescence at good season. A: *Alveolites suborbicularis* has grown up on *Cyclotrypa* encrusting spirorbiform-tube worms and is irregular, witnessing a very variable sedimentation rate. Bagnée section, top of Unit B (bed 37/1180). B: Much regular *A. suborbicularis* with growth rate higher than sedimentation permitting a gently domal shape. Bagnée section, top of Unit B (bed 35/1175). C: Polished slabs of *Frechastraea pentagona* colony showing dark lines that correspond to densely packed dissepiments alternating with normally packed dissepiments light lines, Fond-des-Cris section, Unit D (bed 14/39/4). D: *Phillipsastrea ananas* ragged colony, Fond-des-Cris section, Unit D (bed 14/50/9).

the ramp, also shown by the domination of algal grainstone facies (Unit E). Generally, the shape of the phillipsastreid colonies varies from plates to domal or mushroom-shaped. Some of them are ragged and/or striated (Fig. 11) by regular light-dark levels like tree-rings. Each light-dark doublet can be considered as corresponding to one year: corals had developed during the good season, forming a lamina, during the bad season, they were fighting against burial and had decreased (Poty & Chevalier, 2007; Berkowski & Belka, 2008). Each new season corresponds to a new lamina and is also an evidence of cyclic growth linked with seasonal variations in sedimentation rate (Fig. 11). Counting those rings has permitted to estimate the age of the corals: an average of ten years, with a maximum of 19 doublets. Considering the little thickness of the sediment between the colonies, it is possible to calculate the growing time of the biostrome. 4-7 layers of 10-years-old colonies represent less than one century.

As other Rugosa, phillipsastreids had minor role to play in bioconstructions because they were unable to encrust any substrate like stromatoporoids, sponges or algae and were commonly absent of turbulent waters. In some cases, when these constructors are lacking due to unsuitable facies, corals can be the only reef-forming elements. The lower member of the Aisemont Formation is such a case of an unusual biostrome (Poty & Chevalier, 2007). Within the upper member, only one thin bed is a biostrome, furthermore, it is the lower bed of the falling stage systems tract and has presumably developed on the erosion surface marking the base of the tract. Oscillations of the relative sea-level (Figs 4 & 6) could have initiated the coral growth. The emersion of the sediment could have created a hard substrate, more suitable for corals

than soft floor. The organisms have colonized this surface during the sea-level rise following the emersion. The poor extension of the biostrome witnesses that this good conditions have been short-lasting and this ecological niche was stable shortly. It can be reasonably considered that the limited development of corals and the lack of almost all stromatoporoids is due to several factors as sedimentary context, seasonal and muddy sedimentation, turbid water and soft bottom.

The most remarkable feature of the member is its complex oncoids and multi-encrusted bodies. The firsts consist of nuclei (often bioclasts) coated by micritic microbial laminae (on which *Girvanella* are sometimes preserved). Their shapes are various and depend on the nuclei form. Regular oncoids formed in turbulent environment (Fig. 7c). Some of them had sometimes been eroded then re-encrusted again, forming "oncoids around oncoids". Irregular oncoids formed in a calmer water where microbialites had preferentially developed on one side of the nucleus, forming very asymmetric oncoids (cauliflower-shape, Fig. 9). Major encrusting organisms are *Alveolites*, *Sphaerocodium* and stromatoporoids. Minor ones are the bryozoan *Cyclotrypa*, auloporids and serpulids worms. These multi-encrusted bodies (also called "macroids" by Flügel, 2004) are very interesting to analyse for two reasons. Firstly, they represent micro-environments favourable to the development of organisms within unfavourable facies. In fact, each particle may constitute the starting point of growth for the organisms that might result in "micro-patch-reefs" scattered on the soft muddy sea floor. Secondly, these bodies allow to understand the different steps of colonization, encrustation, growth, waxing, waning, overturning and death of the

organisms. Fig. 12 shows clearly the formation of domal and subspheric complex oncoids. On Fig. 12b, the successive stages are visible and geopetal features (micritic-sparitic filling inside serpulid worms cavities) witness several overturnings during growth time.

This kind of intergrown and multi-encrusted bodies are not common through the geological record and witness a specific environment. Chevalier & Aretz (2005) has documented a complex oncoids at the base of metre-thick microbial reef lens within middle Viséan shallow-water limestone in Engihoul (Namur Synclinorium, Southern Belgium). A comparable case has been studied in Silurian reefs of Gotland where stromatoporoids and calcimicrobial framework (framework type 4 of Nose et al., 2006), in association with oncoid facies, characterize early growth stages of patch reefs. Contrary to Silurian reefs, the upper member of the Aisemont Formation has not evolved into larger biostrome because unsuitable environment (climate, sea-level change, sedimentary input, etc.).

The abundance of oncoids is also remarkable. Shi & Chen (2006) and Shapiro & West (1999) consider that oncoid-rich deposits are constrained by two main

conditions: (1) a drop in sea level (here compatible with the 3rd order regression of the “Aisemont sequence”) that produces shallow water high energy environment, and (2) proliferation of microbialites. Such deposits have been described in the Upper Silurian strata from Gotland (Calner, 2005). The Eke Formation is a 10–14 m-thick unit of oncoid wackestones to packstones and its lateral equivalent is rich in stromatolites of various shape. All these features remind the upper member of the Aisemont. Moreover, the Eke Formation deposited during the Lau Event that caused significant extinctions (e.g. conodonts, brachiopods, Talent et al., 1993). Oncoids deposits linked to major crisis are known from the Early Famennian of Alberta basin in Canada (Whalen et al., 2002), from the Late Ordovician (Sheehan & Harris, 2004) and from the Early Triassic of China (Kershaw et al., 2009, Shapiro & West, 1999, Schubert & Bottjer, 1992). In fact, microbialite and anachronistic structures have been documented for the five main extinction events of the Phanerozoic and for several minor crisis (Calner, 2005). Thus the omnipresence of oncoids could be an evidence of the environmental change within the Kellwasser events. Indeed, in the

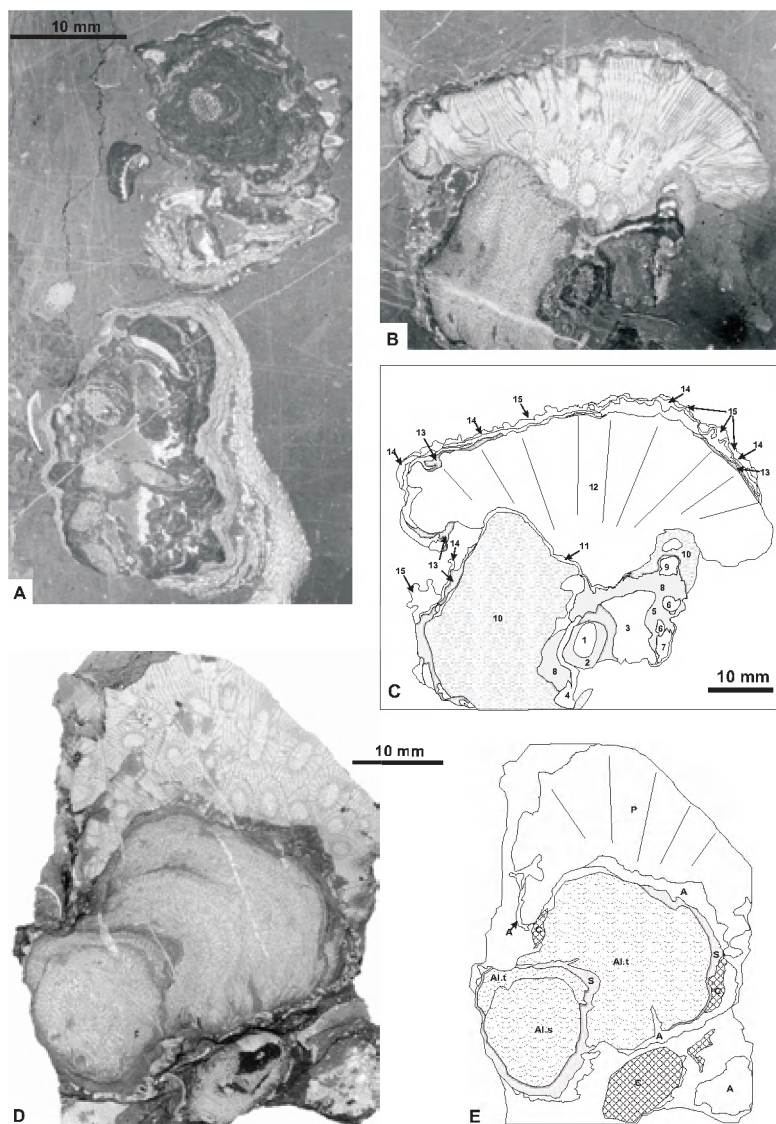


Figure 12: Complex oncoids and multi-encrusted bodies. A: Globular oncoid mainly constituted by microbial (“*Girvanella*”) coating, *Alveolites* and stromatoporoid around *Scoliopora* branches. *Sphaerocodium* and auloporids are other components of the cortex. Bagnée section, base of Unit B (bed 9/215). B: “Micro patch reef” with numerous encrusting organisms. Bagnée section, base of Unit B (bed 9/215). C: Growth steps of (B). The nucleus of the body is a *Scoliopora* fragment (1) with microbial coating forming an oncoid (2). A tabulate coral (3) encrusted one side then a stromatoporoid (4) encrusted the other side. Those has been covered by microbial coating (5) on which spirorbiform-tube worms (*Spirorbis*, 6) have grown up in the same time as a tabulate coral (7) then coated by microbial level (8). This first body has been turned over as shown by the geopetal shape in *Spirorbis*. Another *Spirorbis* (9) has encrusted the body, followed by *Alveolites* (10) with a ragged shape. After a new overturn, stromatoporoids (11) encrusted it and *Phillipsastrea* (12) began to grow on it. The latter has been coated by cryptalgal lamina (13) and stromatoporoids (14). In the same time, auloporids (15) have grown on 11 and 12. Finally, the body was turned again and has been buried in muddy sediment. D and E: Irregular domal multi-encrusted body involving different organisms. Nucleus is, here, a bulbous *Alveolites suborbicularis* (Al.s) encrusted by *A. tenuissimus* (Al.t), then by stromatoporoids (S) and auloporids (A). A second stage of *A. tenuissimus* (Al.t) has grown then covered by auloporids (A), stromatoporoids (S) and *Cyclotrypa* (C). *Phillipsastrea* (P) has grown on this overturned body, in a ragged colony itself encrusted by auloporids (A). Note the stylolitic fabric. Lambermont section, biostromal bed, Unit C (bed 7/110).

southern part of the Namur-Dinant Basin, the Petit-Mont Member mud mounds (Fig. 2) developed into muddy environment of the Les Valisettes Formation show thrombolites and stromatolites facies (grey algal facies of Boulvain, 1993) as lateral equivalent to the upper member of the Aisemont Formation. Both could be the result of eutrophic water, maybe turbid and cool, in link with the degraded environment of the late Frasnian that led to the crisis.

6. Conclusions

In Southern Belgium, the Late Frasnian crisis is thus progressive and recorded extinction events ranging from the Middle-Late Frasnian boundary to the Frasnian-Famennian boundary. In fact, the first event occurred in the earliest *rhenana* conodont Biozone, at the top of the Middle Frasnian formations with the extinction of the disphyllid corals and the collapse of the stromatoporoid reefs (Poty & Chevalier, 2007). This is perhaps quiet earlier than the Kellwasser Crisis of Schindler (1993) and Walliser (1996) starting within the Early *rhenana* Biozone. This onset might be correlated with the “*semichatovae* transgression” (Alekseev et al., 1996). Although, this transgression might presumably correspond to the base of the “Aisemont sequence” because it is the first transgressive pulse in the Early *rhenana* Biozone.

One of the (numerous) invoked causes of the crisis is the Late Frasnian anoxia. Riquier et al. (2006) has documented different mechanisms leading to the Lower and Upper Kellwasser anoxic events and the deposit of the black shale. Following this author, the Lower Kellwasser shale results in the “early Upper *rhenana* anoxic event”, mainly recorded in shallow environments. The Upper Kellwasser Event is the consequence of the “*linguiformis* anoxic event” and recorded both on basinal and platform settings where dysoxic features prevailed. The causes of these oxygen depleted conditions are largely explained by Riquier et al. (2005, 2006), Racki et al. (2002), Racki (2005), Bond et al. (2004), Copper (2002), etc., but not discussed here because the Lower Kellwasser has no significant effect on the shallower part of the Namur-Dinant Basin and the inter-Kellwasser strata studied here have recorded no anoxic evidence. A short lasting climatic cooling is often admitted for the Late Frasnian, in link with volcanic-hydrothermal activity and CO₂ cycle perturbation (see Joachimski et al. (2009) for recent discussion). An “express-glaciation” is evoked by Poty & Chevalier (2002) as the cause of the Upper Frasnian third-order sequences. The demise of such a glaciation in the high latitudes could have resulted in the rapid transgression of the “Aisemont sequence”. Indeed, during this “*semichatovae* transgression”, the carbonate shelves have been worldwide buried under argillaceous sediments that has deeply wounded the shallow-water communities (Bond & Wignall, 2008). More evidences should be found and further works on shelf sections of the Late Frasnian are necessary to get a better understanding of the crisis and the correlation with the events in basin environment.

More than sudden mass extinction, the Late Frasnian Crisis has led to the weakening of ecosystems in a damaged environment. The upper member of the Aisemont Formation is such an environment where opportunistic organisms have constituted a remarkable association of common Devonian fauna (rugose and tabulate corals, spire-bearer brachiopods, pelmatozoans, gastropods, bryozoans, sponges, stromatoporoids) and flora. The unusual feature of the association is the fact that these organisms form multi-encrusted oncoids, implying several encrusters, scattered on the muddy bottom as “micro-patch-reefs”. The occurrence of microbial structures both in the upper member of the Aisemont Formation and in its distal equivalent is another evidence of a deteriorate environment causing the global crisis.

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