S T R A T A

Série 1 : communications

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IGCP 596 - SDS SYMPOSIUM
Climate change and Biodiversity patterns in the Mid-Palaeozoic

FIELD GUIDEBOOKS

ISSN 0761-2443
ISBN 978-2-9548452-6-5

STRATA

Secrétaire de rédaction : Philippe Fauré

Editeur : Association STRATA,
http://strata.fr

Dépôt légal : 4ème trimestre 2015
ISSN : ISSN 0761-2443

IGCP 596 – SDS Symposium

Climate change and Biodiversity patterns in the Mid-Palaeozoic

FIELD GUIDEBOOK

September 20–22, 2015
Brussels, Belgium

Edited by
Julien DENAYER, Bernard MOTTEQUIN & Cyrille PRESTIANNI

***STRATA*, série 1: communications, volume 17, 2015, 81 p.**

Contents

Preface

IGCP 596 – SDS SYMPOSIUM
Climate change and Biodiversity patterns in the Mid-Palaeozoic
Field guidebooks: The Devonian and Lower Carboniferous successions in southern Belgium

Thanks to the abundance and completeness of the Devonian and Carboniferous succession in Belgium, our country has always played a vital role in sedimentary geology and stratigraphy. As early as the beginning of the nineteenth century, in the course of the Industrial Revolution, the pioneer works of geologists such as J. J. d'Omalius d'Halloy (first geological map in the world), A. Dumont (first stratigraphic scale) and G. Dewalque (first geological synopsis) succeeded in a fine comprehension of the geological constitution of Belgium. They inspired researchers worldwide as witnessed by their legacy to the stratigraphic nomenclature including several stages named after Belgian localities.

Alongside, geological surveys were completed by palaeontological studies which resulted in some kind of encyclopedical knowledge of fossil organisms. L.-G.de Koninck, D. Sauveur, J. Gosselet, J. Fraipont and many others are the emblematic fathers of Belgian palaeontology. The need of organizing the strata for mining and mapping purposes led them to the identification of fossil markers, naturally resulting in the establishment of biostratigraphic tools with an unprecedented resolution; part of the global wave of progress marking the end of the nineteenth century. Refinement of these tools never ended. Generations of geologists and palaeontologists achieved the modernization of the tools to become genuine biostratigraphic scales, each based on a peculiar fossil group.

The 1950's acted as a milestone in biostratigraphy with the investigation of microfossils and their identification as powerful biostratigraphic markers. The tremendous abundance of references – both in Belgium and abroad –prevents us to be exhaustive here. We feel obliged to recall here a creative Belgian initiative that mostly remained confidential despite its potential and robustness: the Micropalaeontological Guide Marks (mgm) compiled by Bouckaert and Streel (1974). These guide marks are a combination of spores, conodonts, foraminifers and ostracods distribution data that allowed the division of the Emsian to Viséan interval into 77 zones. The cross combination of the four biozonations are liberated from facies biases and allowed wide-scale correlations.

Today, the limits of individual biostratigraphies based on single groups only are reached. Endless discussions on sharp details, the difficulties to identify the absolute marker as well as the impossible worldwide and facieswide correlations of boundaries and events inevitably drive us to a change of paradigm. It appears more than necessary to think a tool derived from the combination of different guides both basinal and neritic as well as the reconciliation with geological markers.

Let us be inspired by the holistic pioneers and finally break off the break!

This volume combines four thematic field trip guides dedicated to the Emsian-Viséan interval in Southern Belgium with a special focus on bioevents and stage boundaries. It aims to provide a state-of-the art overview of the sedimentary succession in the frame of the IGCP-596 – SDS joined symposium held in Brussels in September 2015.

J. Denayer, B. Mottequin & C. Prestianni

The Middle Devonian succession in the Dinant Synclinorium

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Abstract
Several localities of the Dinant Synclinorium (southern Belgium) are here presented to illustrate the Middle Devonian succession. The Treignes section exposes the transition from Emsian siliciclastics to Eifelian mixed siliciclastic-carbonate deposits. The Petigny section exposes the Lower Eifelian biostromal limestone of the Couvin Formation that recorded the onset of the Devonian 'carbonate factory' in the Namur-Dinant Basin. The Goulette (Olloy-sur-Viroin) section shows the eastwards disappearance of the Eifelian limestone facies, replaced by the shaly Vieux Moulin Member of the Jemelle Formation. The latter is well exposed in its type section in the eponymous locality where the shaly facies of the Lower and Upper Eifelian are particularly fossiliferous. The Eifelian-Givetian transition can be observed in the Resteigne quarry in the Wellin vicinity where the Givetian reefal complex is particularly well developed. The Préalle quarry in Aisne near Barvaux shows the Upper Givetian Fromellennes Formation and the collapse of the carbonate platform at the end of the stage, followed by the shaly facies of the Lower Frasnian Nismes Formation. The Givetian-Frasnian boundary is also exposed in the classical Sourd d'Ave section near Ave-et-Auffe. Finally, a short description of the proximal facies of the Eifelian-Givetian of the northern limb of the Dinant Synclinorium is given for the Marchin locality.

1. Introduction

The Eifelian-Givetian succession is well exposed in the Dinant Synclinorium. Several localities, especially in its southern limb are classical sites (e.g. Couvin, Givet, Wellin) for stratigraphical and palaeontological purposes. The aim of this excursion is to give a brief overview of the main sedimentary and palaeoenvironmental settings of the Belgian Middle Devonian and to give some insight of its global scientific potential.

The sections presented here are mostly not the classical ones usually shown. The choice was made to introduce several less famous localities as the 'grand classics' are renowned and have already been thoroughly discussed. Futhermore, some of them are nowadays poorly exposed (Couvin) or protected (Givet) hampering good observations. Many more good sections are available, even if some are not fully studied from a biostratigraphical or sedimentological viewpoint, they expose quite different facies, are more fossiliferous and better examplify the lithostratigraphic succession.

2. Historical background

Introduced by Dupont & Purves (1885), the term Couvinian was applied to various units defined, notably by d'Omalius d'Halloy (1862) and Dewalque (1868, 1874) as '*Schistes à calcéoles*', '*Schistes et calcaires à calcéoles*' or '*Système du calcaire de Couvin'*. The Couvinian groups the mixed and carbonate formations between the Lower Devonian siliciclastics of the Ardenne and the '*Calcaire de Givet*' (Lecompte, 1955). It was mainly a lithostratigraphic term before being biostratigraphically defined through the works of Godefroid (1968), Tsien (1969) and Bultynck (1970). However, the Couvinian stage was abandoned after a decision of the SDS in 1980 that chose the base of the *partitus* conodont Zone as the base of the Eifelian – and thus the base of the lower stage of the Middle Devonian – rather than the base of the *patulus* Zone that defined the base of the Couvinian (Bultynck, 2006). The global stratotype section and point (GSSP) of the Emsian-Eifelian is subsequently marked by the first occurrence of the conodont *Polygnathus costatus partitus* in the Wetteldorf Richtschnitt section in Germany (Ziegler & Klapper, 1985).

The Givetian corresponds to Gosselet (1879)'s '*Calcaire de Givet'* and was subsequently used in various ways (including or not the Fromelennes Formation at its top) until Sartenaer & Errera (1972) proposed that the Givetian should cover the time period corresponding to the deposition of the Givet Limestone. However, the shallow water facies of the Givetian in the Namur-Dinant Basin yielded a relatively poor conodont fauna precluding the establishment of the stratotype section in the type locality. The base of the Givetian is defined by the entry of the conodont *Polygnathus hemiansatus* at Jebel Mech Irdane (GSSP) in Morocco (Walliser *et* *al*., 1995) but in the Ardenne, Bultynck & Hollevoet (1999) used the entry of *Icriodus obliquimarginatus* as a marker of the Eifelian-Givetian boundary.

Beside its historical interest, southern Belgium comprises a lot of excellent outcrops among which, many are exceptionally rich in fossils. The study of the Devonian macrofossils has begun with the works of G. Dewalque and E. Maillieux, who were involved in the geological mapping of Belgium at the end of the 19th century and collected a huge amount of specimens. During the 20th century, under the impulsion of M. Lecompte among others, research on Devonian stratigraphy and palaeontology progressed spectacularly thanks to a generation of hard worker field and lab geologists including P. Bultynck (conodonts), J.-G. Casier (ostracods), M. Coen (conodonts and ostracods), M. Coen-Aubert (rugose corals), M. Fairon-Demanet (plants), J. Godefroid (brachiopods), P. Sartenaer (brachiopods), M. Streel (palynology), H.H. Tsien (corals), etc.

3. Geological settings

The Middle Devonian Period is characterised, in southern Belgium by the onset of the 'carbonate factory' following the deposition of the Lower Devonian siliciclastics in the Namur-Dinant Basin, and by the onset of reef development. The Middle Devonian is regarded as a greenhouse period with the extensive development of all kind of reefs at the global scale (Kiessling *et al*., 1999).

During this time slice, the Namur-Dinant Basin was situated along the southeastern margin of Laurussia on the Rheno-Hercynian Ocean at an estimated latitude of 25°S (Stampfli *et al*., 2013). This basin underwent the Variscan orogeny during the Late Carboniferous and now belongs to the northern part of the Rhenohercynian fold and thrust belt. The Middle Devonian succession is exposed along the borders of the Dinant Synclinorium, in the Haine-Sambre-Meuse overturned trust sheets (former 'southern limb of the Namur Synclinorium), in the Brabant Parautochton (former 'northern limb of the Namur Synclinorium'), in the Philippeville-Durbuy Anticlinorium and in the Vesdre area (Fig. 1). The facies show a strong proximo-distal distribution along a NE-SW axis.

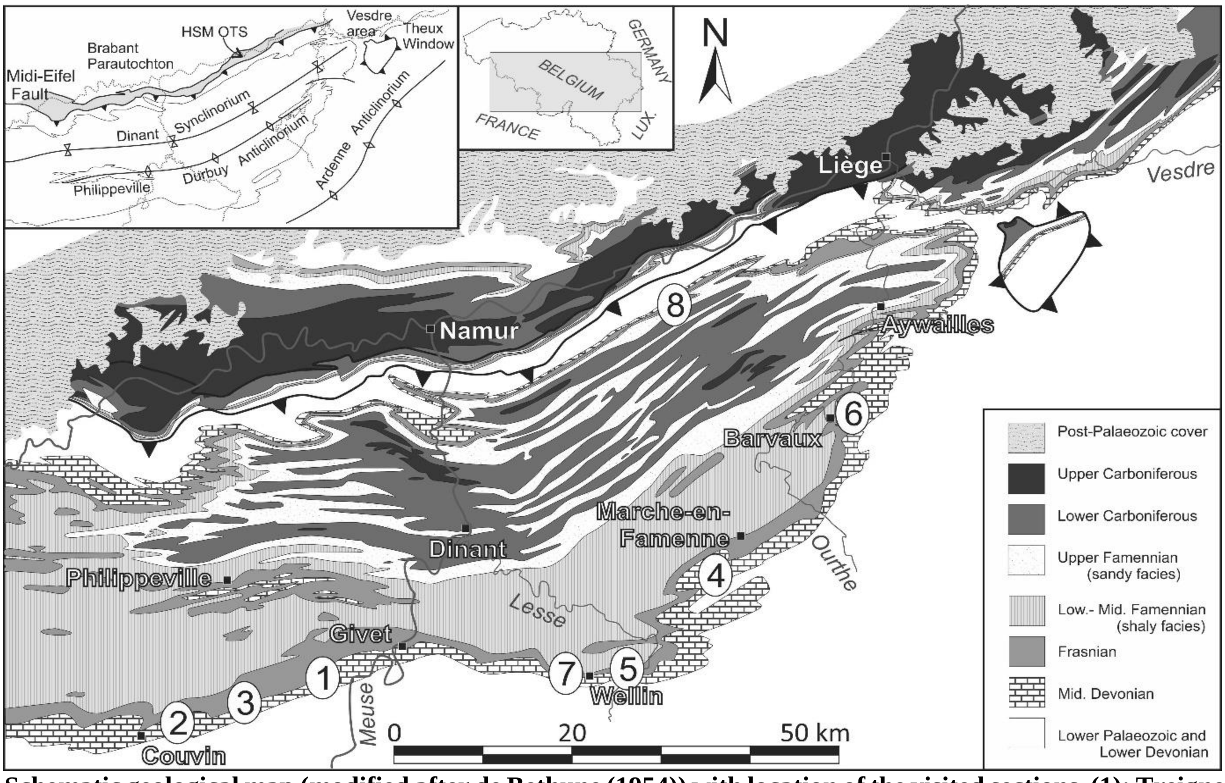

Fig. 1: **Schematic geological map (modified after de Bethune (1954)) with location of the visited sections. (1): Treignes section, (2): Petigny 'Cul d'Enfer' section, (3): Olloy-sur-Viroin 'La Goulette' section, (4): Jemelle section, (5): Resteigne quarry, (6): La Préalle quarry, (7): Sourd d'Ave section, (8): Régissa Rocks.**

4. Lithostratigraphy and Depositional evolution

4.1. Eifelian

The Eifelian depositional history effectively started in the Upper Emsian ('lower Couvinian') in the distal part of the Namur-Dinant Basin. A second-order transgression led to a switch from siliciclastic deposits (Hierges Formation (Fm) and underlying formations) to mixed (Saint-Joseph and Eau Noire formations) then purely carbonate deposits (Couvin Fm). Strong variations in lithological composition occurs along the southern limb of the Dinant Synclinorium (see Bultynck *et al*. 1991 and Dumoulin & Blockmans, 2008 for detailed summary) (Fig. 2). From Nismes to the French border eastwards, the Saint-Joseph and Eau Noire formations correspond to calcareous siltstone and shale with abundant fauna and limestone beds respectively. The increase in carbonate is clear and continuous up to the 'biostromal' complex forming the Couvin Fm. The latter includes a lower member (Foulerie Member (Mbr), 220 m-thick in the type section) typically made of biostromal-non biostromal cycles, very rich in fauna, and an upper member (Abîme Mbr, 160 m) dominated by rather fine-grained limestone and dolostone with some biostromal beds, but less developed and generally poorer in macrofauna. The Couvin Fm is capped by the Jemelle Fm (c. 300 m) composed of shale, calcareous shale and siltstone with some biohermal lenses in its upper part (Bultynck, 1970). The uppermost part of the formation is sitlty or sandy. The Hanonet Fm is dominated by argillaceous limestone alternating with calcareous shale, relatively fossiliferous.

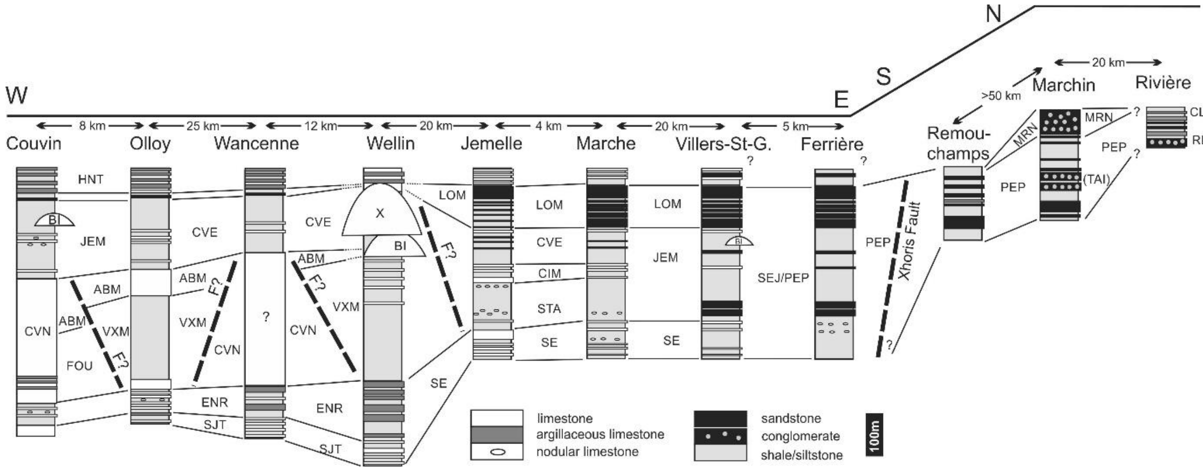

Fig. 2: **Lateral variation of lithostratigraphic units between the Couvin area (West), Villers-Sainte-Gertrude (East) and Rivière area (North). Modified from Dumoulin & Blockmans with data from Barchy & Marion (2014 and in press, a), Marion & Barchy (in press) and Bultynck *et al*. (1991, 2000). Abbreviations: ABM: Abîme Mbr, BI: bioherms, CIM: Cimetière Mbr, CLA: Claminforge Mbr, CVE: Chavées Mbr, CVN: Couvin Fm, ENR: Eau Noire Fm, HNT: Hanonet Fm, JEM: Jemelle Fm, LOM: Lomme Fm, MRN: Marchin Mbr, RLN: Rouillon Mbr, PEP: Pepinster Fm, STJ: Saint-Joseph Fm, SE: Saint-Joseph–Eau Noire Gp, SEJ: Saint-Joseph–Eau Noire–Jemelle Gp, STA: Station Mbr, VXM: Vieux Moulin Mbr, X: unnamed formation, F: fault.**

East of Nismes towards Givet, the Foulerie Mbr and the lower part of the Abîme Mbr are not recorded and passe laterally to the Vieux Moulin Mbr of the Jemelle Fm, represented by calcareous siltstone and shale (Fig. 2). Only the uppermost 70 m of the Couvin Fm can be traced eastwards (Dumoulin & Blockmans, 2008). The Chavées Mbr (upper member of Jemelle Fm) also covers the Couvin limestone. Between Givet and the Wellin area (Figs 1, 2), the Saint-Joseph and Eau Noire formations get thicker and more carbonate. The Couvin Fm is interstratified within the Jemelle Fm and its thickness diminishes. It is however not the case in the Wancennes area where the whole Foulerie Mbr seems to be recorded (Dumoulin & Blockmans, 2008). In Wellin, the very reduced Couvin limestone acts as the sole for a biohermal complex (Formation 'X') which takes place across Jemelle and Hanonet formations (Coen-Aubert *et al*., 1991), (Fig. 2). In the Jemelle area and eastwards, the Saint-Joseph and Eau Noire formations present the same facies and are not distinguished anymore (Barchy & Marion, 2014). The Jemelle Fm is divided in three members (Bultynck *et al*., 1991): the Station Mbr (c. 40 m-thick, sandy shale), the Cimetière Mbr (c. 110 m, shale with some calcareous nodules and limestone beds) and Chavées Mbr (c. 40 m) alternation of shale and limestone, commonly fossiliferous). This last member is overlain by the 110 m-thick sandy Lomme Fm which is not developed westwards. The Hanonet Fm, still represented by calcareous shale and argillaceous limestone finishes the Eifelian succession in this part of the basin. Northeastwards, the Saint-Joseph, Eau Noire and Jemelle formations progressively passes to the Pepinster Fm trough the inclusion of sandy and silty beds and the progressive reddening of the sediments (Barchy & Marion, in press, a; Marion & Barchy, in press). Along the eastern margin of the Dinant Synclinorium and the Vesdre area, the Eifelian is entirely represented by the red siliciclastics of the Pepinster Fm. On the northeastern limb of the Dinant Synclinorium, the Pepinster Fm includes at its top a conglomerate unit (Marchin Mbr) and passes westwards to the Rivière Fm composed of the Rouillon (shale, sandy shale, sandstone, conglomerate, including the Tailfer beds) and Claminforge (calcareous shale and sandstone) members. These last deposits are the proximalmost recorded in the Namur-Dinant Basin.

In conclusion, the Eifelian succession should be regarded as a transgressive deposit showing proximal siliciclastic facies in the northern part of the basin and purely marine argillaceous, mixed and carbonate facies in the southern part, with the development of biostromal facies in the Couvin area, possibly linked to synsedimentary block tectonics and/or the distribution of siliciclastic sediments (rivers?).

4.2. Givetian

The composition of the Givetian is very regular along the southern limb of the Dinant Synclinorium, with a high lateral continuity of the sedimentary units (Tsien 1971, 1976, Préat & Mamet, 1989), indicating a smoothering of the topographies that dictated the deposition of the Eifelian formations (Fig. 3). The Givet Limestone starts with the deposition of the Trois Fontaines Fm which is dominated by bioclastic limestone with locally biostromal units at the base and the middle part (stromatoporoids, rugose and tabulate colonial corals). The upper part of the formation recorded more restricted environment, notably with the deposition of stromatolitic units (Bultynck *et al.*, 1991). The Terres d'Haurs Fm differs from the previous formation by its argillaceous content and the occurrence of bioclastic levels. Its base is marked by a coral bed with *Argutastrea quadrigemina*, *Pachyfavosites* ssp. and *Thamnopora* ssp. that can be traced over tens of kilometres (Coen-Aubert, 2001). The Mont d'Haurs Fm is characterized by thickly-bedded limestone showing an alternation of biostromal and 'lagoonal' facies (Boulvain *et al.*, 2009), i.e. coarsely bioclastic with stromatoporoids and poorly fossiliferous beds. The Fromelennes Fm is divided in three members (Bultynck *et al*., 1991): the Flohimont Mbr is typically composed of argillaceous limestone or calcareous shale with bioclastic beds, the Moulin Boreux Mbr starts with bioclastic rudstone with stromatoporoids, corals and brachiopods then passes upsection to sequential limestone (bioclastic-stromatolitic) poor in macrofauna. The upper member (Fort Hulobiet) is composed of argillaceous limestone with an abundant macrofauna (stromatoporoids, corals, brachiopods). Eastwards, those four formations acquire a sandy part possibly due to the proximity of a source of siliciclastic sediments (see Burnotte & Coen, 1981 for details). Northwards (Marchin), they pass to the Nèvremont and Le Roux formations that corresponds respectively to limestone of various facies (bioclastic, oolitic, biostromal) often sandy, and to a mixed unit of shale, argillaceous limestone, dolostone and sandstone with some bioclastic levels (Bultynck & Dejonghe, 2001). In the Tilff area, the Givetian succession is much reduce and displays very proximal siliciclastic facies (Mottequin & Marion, in press).

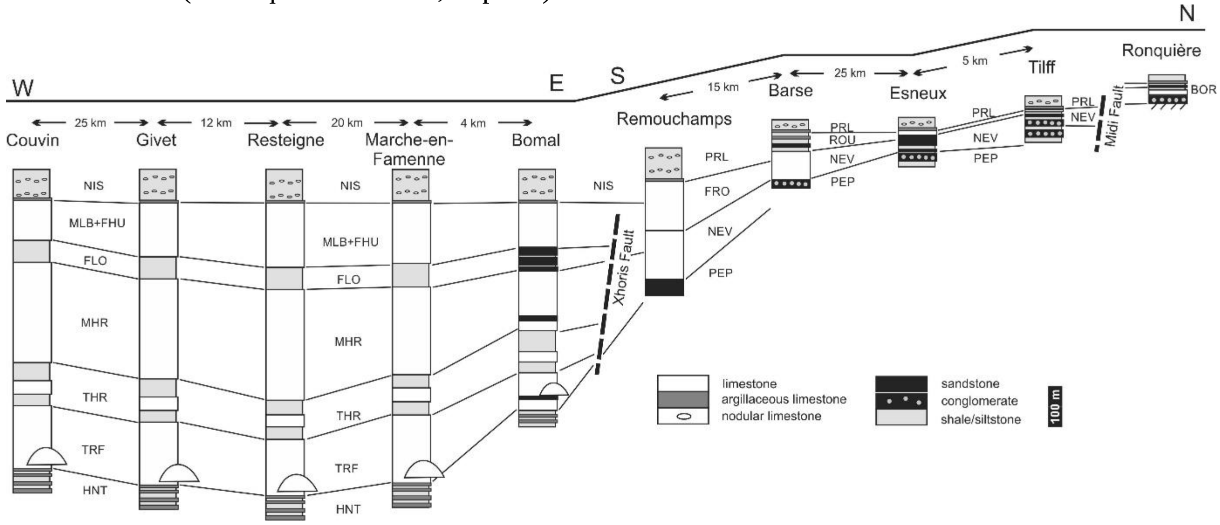

Fig. 3: **Lateral variation of lithostratigraphic units between the Couvin area (West), Bomal (East) and Ronquière area (North). Modified from Bultynck & Hollevoet (1999), Bultynck *et al.* (2000), Bultynck & Dejonghe (2001), Mottequin *et al.* (2014), Mottequin & Marion (in press). Abbreviations: BOR: Bois-de-Bordeaux Fm, FLO: Flohimont Mbr, FHU: Fort Hulobiet Mbr, FRO: Fromelennes Fm, HNT: Hanonet Fm, MHR: Mont d'Haurs Fm, MLB: Moulin Boreux Mbr, NEV: Nèvremont Fm, NIS: Nismes Fm, PEP: Pepinster Fm, PRL: Presles Fm, ROU: Le Roux Fm, THR: Terres d'Haurs Fm, TRF: Trois-Fontaines Fm.**

In the Brabant Parautochton (e.g. Ronquière area), only the Middle-Upper Givetian is recorded by the Bois de Bordeaux Fm which rest unconformably upon the Lower Palaeozoic basement (Bultynck *et al.*, 1991). It contains three members: the Mautiennes Mbr (conglomerate, sandstone, shale), the Alvaux Mbr (mixed carbonate-siliciclastic sediments) and Mazy Mbr (reddish siliciclastics with plant remains). This last member yielded the oldest seed plant (Gerrienne *et al*., 2004).

In conclusion, the Givetian can be seen as in continuity of the transgression started in the Eifelian, with the establishment of carbonate platform facies in the context of a high relative sea-level. The two shaly interruptions

(Terres d'Haurs Fm and Flohimont Mbr) correspond to lower order transgressive pulses. The brutal shift of sedimentation at the Givetian-Frasnian boundary is interpreted as the drowning of the platform with a major increase in sediment input and most probably with a rise in sea-level (Bultynck *et al*., 2001, Casier *et al*., 2013).

5. Biostratigraphy and events

5.1. Eifelian

The base of the Eifelian stage is defined by the entry of the conodont *Polygnathus costatus partitus*, which has been documented in Belgium in a single outcrop (Grupont section, see Godefroid, 1968 and Bultynck *et al*., 2000). In southern Belgium, icriodid conodonts are very abundant and the first appearance datum (FAD) of *I. retrodepressus* is commonly used for an approximate positioning of the Emsian-Eifelian boundary which falls within the Eau Noire Fm (55 m above the base of the formation in the stratotype, Bultynck & Godefroid, 1974) in the southern limb or the Dinant Synclinorium and within the Rouillon Mbr (Rivière Fm) and Pepinster Fm in the northern and northeastern limb of the Synclinorium (Bultynck *et al.*, 2000). Precisions about the distribution of conodonts can be found in the works of Bultynck (1970), Bultynck & Godefroid (1974), Bultynck *et al.* (1991) and Bultynck & Hollevoet (1999). The distribution of *Euryspirifer* and *Arduspirifer* species (brachiopods) are also useful for precise correlation of the boundary according to Godefroid (1977). Traditionally, the rugose coral *Calceola sandalina* was considered as the guide species for the Belgian Couvinian but its first appearance in the Eau Noire Fm, below the base of the Eifelian (Tsien, 1969), and its local occurrence in the lower Givetian Trois Fontaines Fm (Bultynck & Hollevoet, 1999) make it useless in term of boundary definition. Other corals are not sufficiently known and too facies-related for any convenient use in biostratigraphy. The stratigraphy of the Belgian Middle Devonian is summarized in Fig. 4.

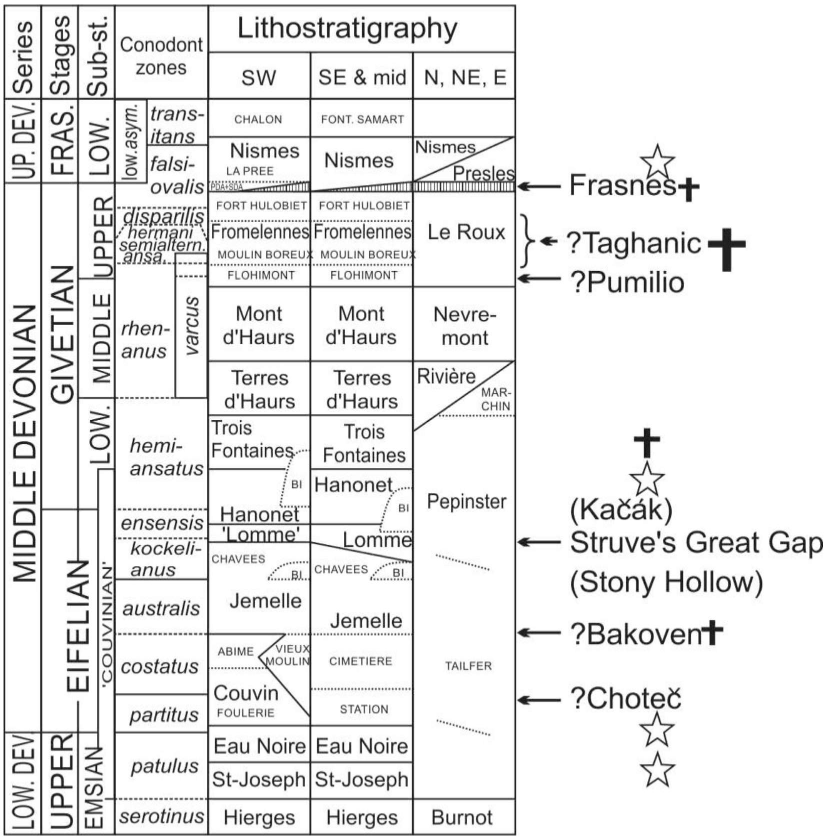

Fig. 4: **Synthetic simplified stratigraphic scale of the Middle Devonian of southern Belgium with position of the bioevents. Names between brackets indicate the theoretical position of events not recognized in Belgium, names preceded by a question marks indicate events hypothetically situated. Crosses indicate extinctions in macrofauna, stars indicate diversification or colonisation events. From Denayer & Mottequin (2015), strongly modified from Bultynck *et al*. (2000). Abbreviations: BI, bioherm.**

The Choteč Event, situated in the upper part of the Eifelian *partitus* zone falls within the lower part of the Foulerie Mbr of the Couvin Fm and theoretically within the Station Mbr of the Jemelle Fm (Fig. 4). Gouwy & Bultynck (2003) postulated that the event could be recorded as a transgressive pulse ending the development of the first biostromes occurring within the Foulerie Mbr in the type area. No significant extinction corresponding to this event has been highlighted so far. The Bakoven Event within the *australis* Zone should fall within the Chavées Mbr of the Jemelle Fm but no black shale is known in the Chavées Mbr. However, the sudden dismiss of the limestones of the Couvin Fm, covered by the shaly Chavées Mbr is not incompatible with the Bakoven Event as a transgressive pulse. Moreover, the transgression led to small-scale extinctions in the coral fauna

(Tsien, 1969). The Stony Hollow Event, in the *kockelianus* Zone is marked by the expansion of tropical faunas into subtropical areas that may correspond to a rise in sea-level and temperature (De Santis & Brett, 2011). In Belgium, it could correspond to the onset of bioherms in the upper part of the Jemelle Fm but neither extinction nor dysoxic facies are known to date at this level (Bultynck *et al*., 2000). At the end of the Eifelian, in the *ensensis* Zone, siliciclastic deposits reappeared in the basin (Lomme Fm and lateral equivalents), witnessing a regression, has been interpreted by Bultynck & Hollevoet (1999) as the expression of 'Struve's Great Gap'. This gap corresponds to a period with many hiatuses in the sedimentary record in shallow environments (Figs 2, 4). The following transgression that led to the deposition of the carbonate Hanonet Fm (*ensensis* Zone) took place within the Kačák events succession but the Lower Kačák Event (*otomari* Event) left no trace in Belgium after Gouwy & Bultynck (2003). Similarly, the Upper Kačák Event (*ostiolatus* Event) should be located in the basal Hanonet Fm but Bultynck & Hollevoet (1999) highlighted the lack of typical facies and significant extinction.

5.2. Givetian

Because the shallow-water facies are not suitable for the polygnathid guide taxa across the Eifelian-Givetian boundary, Bultynck *et al.* (2000) recommended the use of *Icriodus obliquimarginatus* as a marker for the boundary in southern Belgium. The FAD of *I. obliquimarginatus* falls within the Hanonet Fm, c. 42 m above the base of the formation in the Couvin area (Bultynck *et al*., 2000) in a darkish argillaceous limestone unit (Bultynck & Hollevoet, 1999). In proximal areas, the boundary is approximately located near the top of the Claminforge Mbr of the Rivière Fm (Bultynck & Boonen, 1977). The brachiopods do not allow any precise positioning of the boundary as *Invertrypa kelusiana* crosses the presumed boundary whereas the typical Givetian taxa *Gerolsteinites givefex* and *Stringocephalus burtini* both appear in the lower part of the Trois Fontaines Fm (Godefroid, 1995; Bultynck *et al.*, 2000). Similarly the distribution of rugose and tabulate corals (Coen-Aubert, 1990, 1996, 1997, 1998) has little interest for boundary definition as typical Eifelian taxa (*Acanthophyllum heterophyllum, A. vermiculare, Sociophyllum torosum, Keriophyllum maillieuxi*) are still present in the Trois Fontaines Fm. However, the rugose corals and brachiopods offer very precise correlations with the Givetian strata of the Eifel Hills (Bultynck *et al.*, 2000).

Within the lower part of the Trois-Fontaines Fm (Lower Givetian *hemiansatus* Zone) coral genera suffered a minor extinction (Coen-Aubert, 2008) which does not seem to be related to any yet recognized global extinction event (Fig. 4). The Pumilio events (middle and upper *varcus* zones) are possibly correlated to two shelly beds rich in brachiopods in the Flohimont Mbr of the Fromelennes Fm (Maillet *et al.,* 2013). As noted by Gouwy & Bultynck (2003), the Taghanic Event (and the Geneseo Transgression) does not appear as a punctual event but covers the *ansatus* to *semialternans* zones and is consequently spread along the whole Fromelennes Fm with decoupled extinctions within ostracods (Maillet *et al*., 2013), corals (Coen-Aubert, 2004) and brachiopods (Brice *et al*., 2008). The last occurrence of stringocephalid brachiopods in the Moulin Boreux Mbr of the Fromelennes Fm is regarded by Bultynck *et al.* (2000) and Coen-Aubert (2004) as a marker of the Taghanic Event but detailed study are required.

6. Key sections

6.1 Treignes section

Reference

Dumoulin & Coen (2013)

Location and access

Rock along the right bank of the Viroin River, 200 m west of the bridge crossing the railroad, south of the Treignes village. Southern limb of the Dinant Synclinoirum (Fig. 1). GPS: 50°05'16.01"N4°40'06.96"E

Lithostratigraphy and biostratigraphy

The section exposes the top of Hierges Fm, c. 35 m of the Saint-Joseph Fm and the very base of the Eau Noire Fm. In the type sections (Saint-Joseph section, c. 8 km westwards, and Couvin, 13 km westwards) Bultynck *et al*. (1991) indicated the upper Emsian *Polygnatus costatus patulus* conodont Zone for the whole Saint-Joseph and Eau Noire formations, except the upper 5 m of the latter in which *Icriodus retrodepressus* FAD and the last occurrence of representatives of the genus *Paraspirifer cultrijugatus* (Bultynck & Godefroid, 1974, Godefroid, 1977) indicate the base of the Eifelian stage. The Hierges–Saint-Joseph formations boundary constituted the the base of the former Couvinian ('Co1').

Description

The top of the Hierges Fm is mainly composed of siltstone with numerous sandstone beds containing fragmented brachiopod shells (Barrage Mbr). The thin oolithic ironstone capping the formation, known in the nearby Olloy-sur-Viroin section (4 km westwards) has not been observed. The bioclastic bed marking the base of the Saint-Joseph Fm in the stratotype does not appear here (Dumoulin & Coen, 2013) but the base of the formation is located at the first blueish fossiliferous shale bed in the southernmost part of the section. North of a small fault, the bedding dips at 80° to the south but the slate cleavage is almost vertical. Fossiliferous siltstones, locally sandy, alternating with bioclastic limestone bed and rare sandstone horizons dominate the formation. Two centimetric argillaceous beds interpreted as weathered bentonites by Bultynck *et al*. (1991) have been recognized in the section (Fig. 5). A bed rich in *Paraspirifer cultrijugatus*, bryozoans and bivalves yields large plant fragments indicating the continental influence of the mixed sedimentation. A 2 m-thick unit of argillaceous bioclastic limestone marks the boundary with the overlying Eau Noire Fm. This bed yields numerous brachiopods, rugose and tabulate corals (including the first *Heliolites* ssp.). The Eau Noire Fm which is dominantly shaly with numerous, sometimes nodular limestone beds with an abundant fauna but poorly crops out in this section.

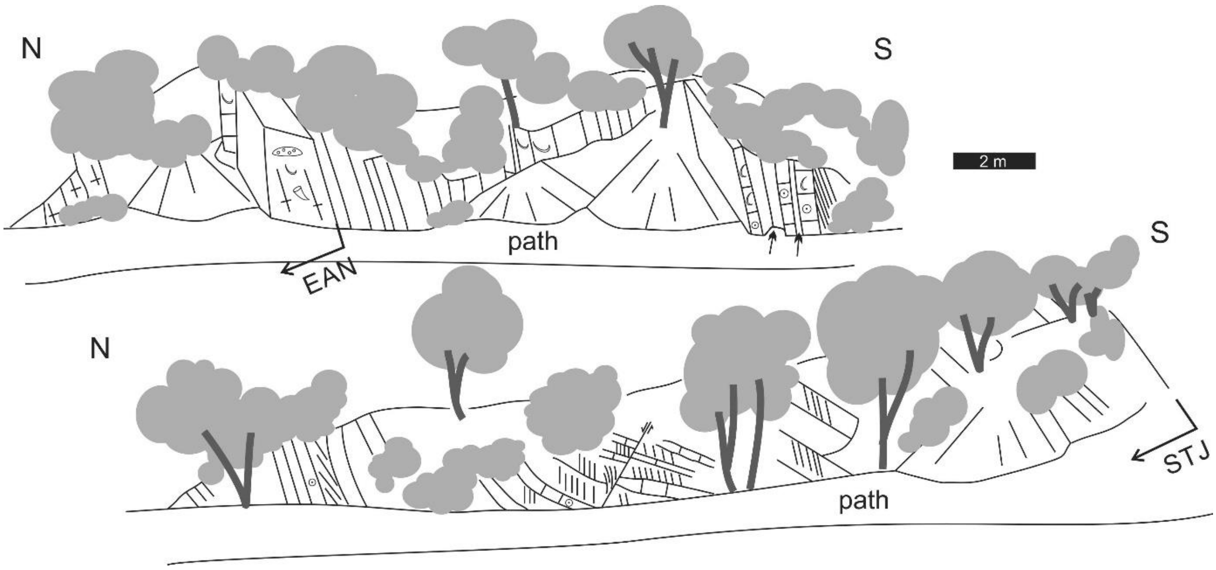

Fig. 5: **Sketch of Treignes Fm with the Hierges, Saint-Joseph and Eau Noire formations. Legend: EAN: base of the Eau Noire Fm, STJ: base of the Saint-Joseph Fm, arrows: weathered bentonites.**

Main faunal components

Crinoids are abundant and are at the origin of the carbonate content in most facies. The following spiriferid brachiopods are characteriristic of this formation accroding to Godefroid (1977) and Bultynck *et al.* (1991): *Paraspirifer sanbergeri*, *P. praecursor*, *P. bucculentus*, *P. curvatissimus*, *Euryspirifer paradoxus*, and *Arduspirifer mosellanus* (see also Godefroid, 1994, 2001). The brachiopods *Paraspirifer cultrijugatus* and *Euryspirifer* ssp. are relatively abundant in some levels. Bivalves, trilobites and fragments of orthoconic cephalopods are occasional. The basal bed of the Eau Noire Fm also yield the corals *Heliolites* ssp. *Cystiphyllum* ssp. and *Kunthia crateriformis.*

6. 2 Petigny 'Cul d'Enfer' section

References

Barchy & Marion (1999)

Location and access

Disused ironstone and sand quarry developed in a palaeokarst in the Eifelian limestone, top the hill dominating the west of Petigny village, east of Couvin. Southern limb of the Dinant Synclinorium (Fig. 1). GPS: 50°03'21.77"N4°31'51.05"E.

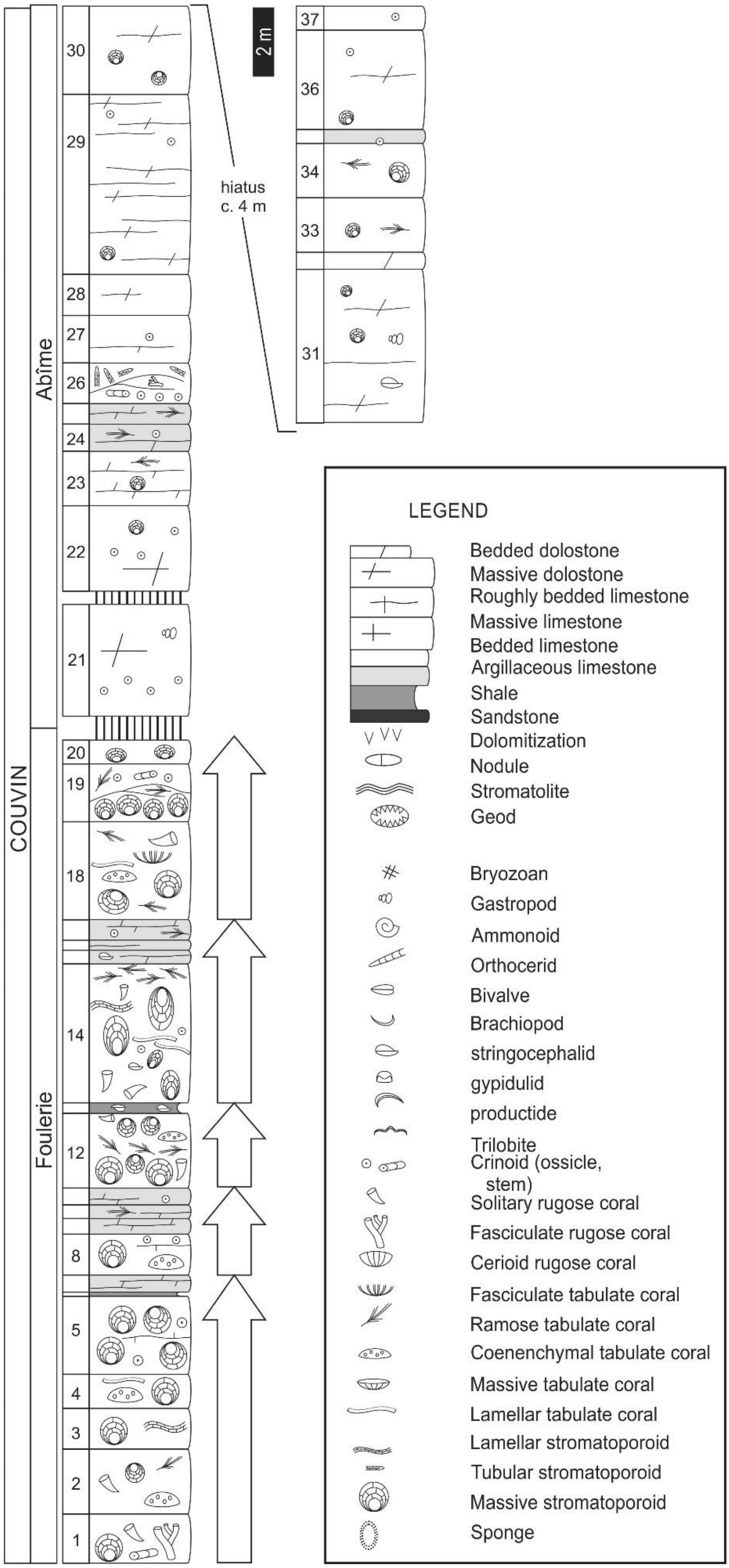

Fig. 6: **Schematic log of the Foulerie and Abîme members (Couvin Fm) in the Petigny section. Formations are in uppercase, members in lower case. Arrows indicate cyclic biostromal deposits.**

Lithostratigraphy and biostratigraphy

This section expose almost continuously the upper part of the Couvin Fm, from the upper half of the Foulerie Mbr to the Abîme Mbr. The top of the formation and the contact with the underlying Jemelle Fm is faulted but according to Barchy & Marion (1999), the part removed by the fault is not thick. The Abîme Mbr, in the type section located c. 2.5 km westwards, belongs to the *costatus* conodont Zone (Bultynck & Godefroid, 1974).

Description

The lower 25 m of the section belongs to the Foulerie Mbr of the Couvin Fm and is dominantly composed of sedimentary cycles (Fig. 6). A cycle typically starts with coarsely bioclastic rudstone with crinoids, stromatoporoids and corals. Macrofossils size increases upwards in the cycle, reaching up to 50 cm in diameter for the largest stromatoporoids and up to 40 cm long for the largest solitary rugose corals. This accumulation forms parabiostromes where elements show no preferential direction. It could represent storm event but further investigation is required. The matrix is commonly a bioclastic packstone-grainstone. The parabiostrome is capped either by calcareous shale or by argillaceous dolostone, usually dark and yielding small brachiopods, tabulate corals and rare trilobites. The cycles vary in thickness from 2 m up to 9 m but the composition is relatively constant and varies only in granulometry and proportion of matrix. Five cycles are exposed along the section (Fig. 6). Together they form a biostromal complex that was called '*second biostrome'* by Bultynck (1970) (units m-q of this author) in the type section of Couvin. These alternations possibly correspond to relative sea level oscillations (parasequences?).

The upper 37 m of the section expose the Abîme Mbr, dominated by fine-grained bioclastic limestone, often dolomitized. Stromatoporoids and corals (mainly tabulate) are still present but in fewer proportion and do not form biostromal accumulations (except bed 24, Figs 6). Thin tubular and branched stromatoporoids (*Amphipora*, *Stachyodes*) form local accumulation in wackestone-packestone matrix.

Based on microfacies analyses, Bertrand *et al*. (1993) concluded that the Couvin Fm deposited on a ramp system but Mabille & Boulvain (2007) interpreted it as a platform. Despite the fact that they worked on the same sections (Couvin and Villers-la-Tour), their results diverge, witnessing the need of detailed field studies.

Main faunal components

Stromatoporoids are largely dominant, large bulbous and spherical reach impressive size. Tubular and branched forms occur as accumulations in the Abîme Mbr. The tabulate corals are represented by massive heliolitids and favositids, laminar alveolitids, ramose thamnoporids (including *Hillaepora*), rare syringoporids and auloporids. Chaetetid sponges are not uncommon. The rugose corals are mainly large solitary *Acanthophyllum* and *Mesophyllum*, along with *Cystiphyllum*, the fasciculate *Stringophyllum* and *Thamnophyllum* are less common (Tsien, 1969; Bertrand *et al.*, 1993). The brachiopods (atrypids, athyridids, productidinids) are uncommon. The conodonts have been listed by Bultynck (1970) from the nearby Couvin section.

6.3 Olloy-sur-Viroin 'La Goulette' section

References

Dumoulin & Blockmans (2008), Dumoulin & Coen (2013).

Location and access

Rock along the road Couvin–Doische, 200 m north-west of the bridge crossing the Viroin at Olloy-sur-Viroin. Southern limb of the Dinant Synclinorium (Fig. 1). This outcrop is protected. GPS: 50°04'30.19"N4°36'05.38"E.

Lithostratigraphy and biostratigraphy

The carbonate Couvin Fm is here much reduced in thickness and interfingered within the pelitic Jemelle Fm. The observed succession is 25 m of the Vieux Moulin Mbr (Jemelle Fm), 75 m of the Abîme Mbr (Couvin Fm) and 30 m of the Chavées Mbr (Jemelle Fm). The age of the transition is not known with certainty (in the upper part of the *costatus* conodont Zone).

Description

The upper part of the Vieux Moulin Mbr is dominated by thickly-bedded greyish to brown siltstone, more or less calcareous with bioclastic accumulation at the base of some beds. The macrofauna (brachiopods, bryozoans) is not abundant. The Couvin Fm is here reduced to its uppermost part (Abîme Mbr) composed of meter-thick biostromal beds (stromatoporoid parabiostromes) alternating with fine-grained limestone beds with few or not macrofauna, corresponding roughly to the units x-z of Bultynck (1970) and Bultynck & Godefroid (1974). The thickness reduction is very rapid as the Couvin Fm loses its lower two thirds in less than 2 km (between Petigny and Nismes, Dumoulin & Coen, 2012), suggesting a synsedimentary block tectonic control (Fig. 3). The Chavées Mbr marks the return to a pelitic sedimentation with deposition of calcareous shale and thinly-bedded limestone and nodular limestone. These facies are particularly rich in marcofauna (brachiopods, orthocerids, trilobites, bryozoans, solitary rugose corals, crinoids, etc.).

6.4 Jemelle section

References

Godefroid (1968), Bultynck & Godefroid (1974), Bultynck *et al.* (1991).

Location and access

Embankments of the disused railroad Jemelle-Rochefort, c. 800 m SW of Jemelle (stratotype). Southern limb of the Dinant Synclinorium (Fig. 1). GPS: 50°09’21.30”N5°15’24.60”E.

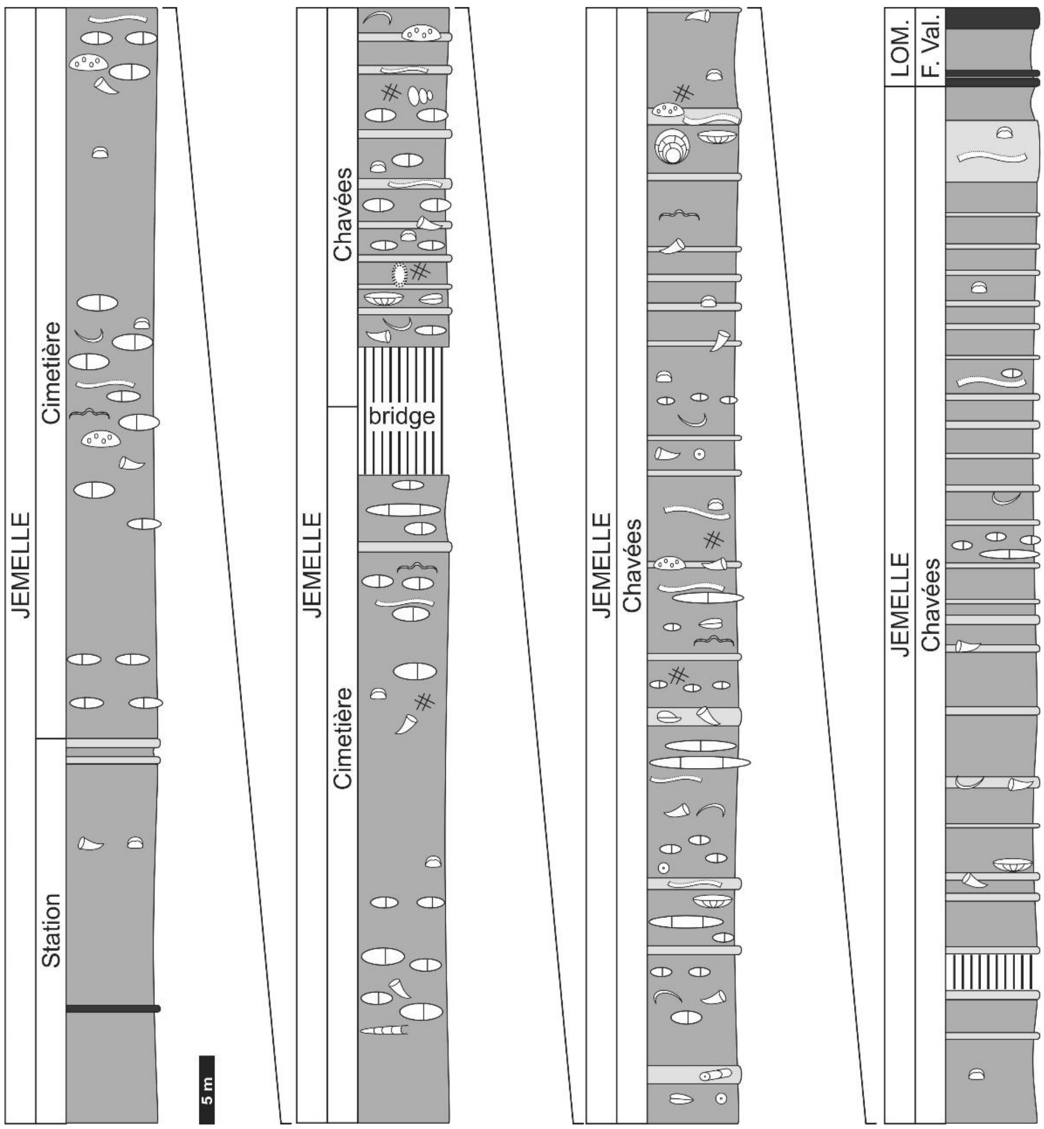

Fig. 7: **Schematic log of the Upper Eifelian Jemelle Fm in its stratotype (modified from Bultynck *et al.*, 1991). Formations are in uppercase, members in lower case. Abbreviations: LOM: Lomme Fm, F. Val.: Fond des Valennes Mbr. See Fig. 6 for legend.**

Lithostratigraphy and biostratigraphy

This section exposes the three members of the Jemelle Fm: the Station Mbr (its lower 10 m are not exposed), the Cimetière Mbr and Chavées Mbr (Fig. 7). The overlying sandy Lomme Fm also crops out but will not be visited during the excursion. Based on occurrences of the conodont *Polygnatus costatus costatus* and *Tortodus* *kockelianus kockelianus* respectively in the lower and upper part of the Chavées Mbr, Bultynck & Godefroid (1974) identified the *costatus* and *kockelianus* zone.

Description
The Station Mbr (c. 40 m-thick after Bultynck *et al.,* 1991) is made of sandy shale in centimetre-thick beds locally micaceous and containing a rare macrofauna (mainly brachiopods). The Cimetière Mbr (c. 110 m) is marked by the appearance of calcareous nodules in the shale, becoming bigger upsection. The shale is usually dark, as are the thin interstratified beds of argillaceous limestone. The macrofauna is dominated by the brachiopods and crinoids with solitary rugose corals (*Cystiphyllum*) and tabulate corals (*Favosites*), whereas trilobites are occasional. The boundary between the Cimetière and Chavées members is hidden by the wall of the bridge. The Chavées Mbr differs from the previous members by its carbonate content. It appears as alternations of argillaceous or nodular limestone and shale (sandy in the upper part). The limestone beds are centimetre- to decimetre-thick and are commonly rich in macrofauna (brachiopods, stromatoporoids, corals, chaetetid sponges; Godefroid, 1968). In the median part of the member, one level is composed of very large domal stromatoporoids associated with favositid and helioitid corals. It may be a lateral equivalent of the bioherm described in the Wellin and Couvin area or a local accumulation of fauna. **Main faunal component**
The brachiopods are particularly abundant (see Godefroid (1968)'s exhaustive list, although it needs to be revised): *Euryspirifer* ssp., *Cyrtinopsis undosa, Spinocyrtia ostiolata, Leptaena rhomboidalis, Devonotrya globa, Gypidula montana* and *Uncinulus* ssp. The tabulate corals genus *Alveolites, Pachytheca, Favosites, Thamnopora* and *Heliolites* are common (Bultynck *et al*., 1991). The rugose corals, abundant but less diverse are mainly *Acantophyllum* ssp., *Cystiphyllum vesiculosum* and *Calceola sandalina*. Stromatoporoids, chaetetids, crinoids, trilobites and bivalves are not rare.

6.5 Resteigne Quarry
References
Préat *et al*. (1984), Coen-Aubert (1988, 2003), Casier & Préat (1990, 1991), Boulvain *et al*. (2009, 2011).

Location and access
Disused quarry of Resteigne in the Lesse valley, north of Wellin. Southern limb of the Dinant Synclinorium (Fig. 1). GPS: 50°05'22.89"N5°10'47.46"E.

Lithostratigraphy and biostratigraphy
The locality presents several sections exposing the upper part of the Eifelian and the Lower Givetian. The upper Eifelian Lomme Fm is discontinuously exposed along the path leading to the quarry, the Hanonet Fm, Trois-Fontaines Fm and the lower part of the Terre d'Haurs Fm are exposed in the quarry. The Mont d'Haurs Fm is also exposed in the northern part of the quarry but will not be observed during the excursion. Biostratigraphical survey has not been done to date on this quarry but Coen-Aubert *et al*. (1991) indicated that the upper part of the Hanonet Fm should be correlated with the base of the Givetian (Fig. 8).

Description
The Hanonet Fm is here represented by c. 75 m of argillaceous limestone with abundant fauna. From the base to the top, 5 lithological units can be distinguished in the quarry. The lower 17 m (unit 1 on Fig. 8) are dominated by greyish argillaceous limestone with some shaly beds. It is followed by unit 2 (c. 35 m) composed of dark argillaceous limestone in 20-30 cm-thick beds interrupted by decimeter-thick beds of calcareous shale. These first two units are extremely rich in fauna: gypidulids brachiopods, solitary rugose corals including *Calceola sandalina,* bryozoan, trilobites, etc. Unit 3 is a 4 m-thick level of dark grey poorly fossiliferous calcareous shale occurs at the top of the limestone that possibly corresponds to the Kačak Event. Unit 4 is composed of bedded argillaceous limestone (c. 15 m) in which the carbonate content increases upsection. The fifth unit is dominated by thickly-bedded dark limestone with an abundant fauna (laminar stromatoporoids and tabulate corals, rugose corals, brachiopods, crinoids, gastropods). The upper metres of this last unit shows the reappearance of shale beds interstratified with coarse crinoidal limestone. The first 2.5 m-thick unit of the Trois-Fontaines Fm is a crinoidal rudstone with fragments of corals, brachipods and numerous stromatoporoids that acted as a frim substrate for the reef initiation (Fig. 8). The reef itself starts with tubular stromatoporoids, fasciculate rugose corals, ramose and massive tabulate corals bound by lamellar stromatoporoids. Upsection, the stromatoporoids became more abundant and the calcareous algae more diverse (Mamet & Préat, 1986). The successive stages of reef formation are described in detail in Preat *et al*. (1984).

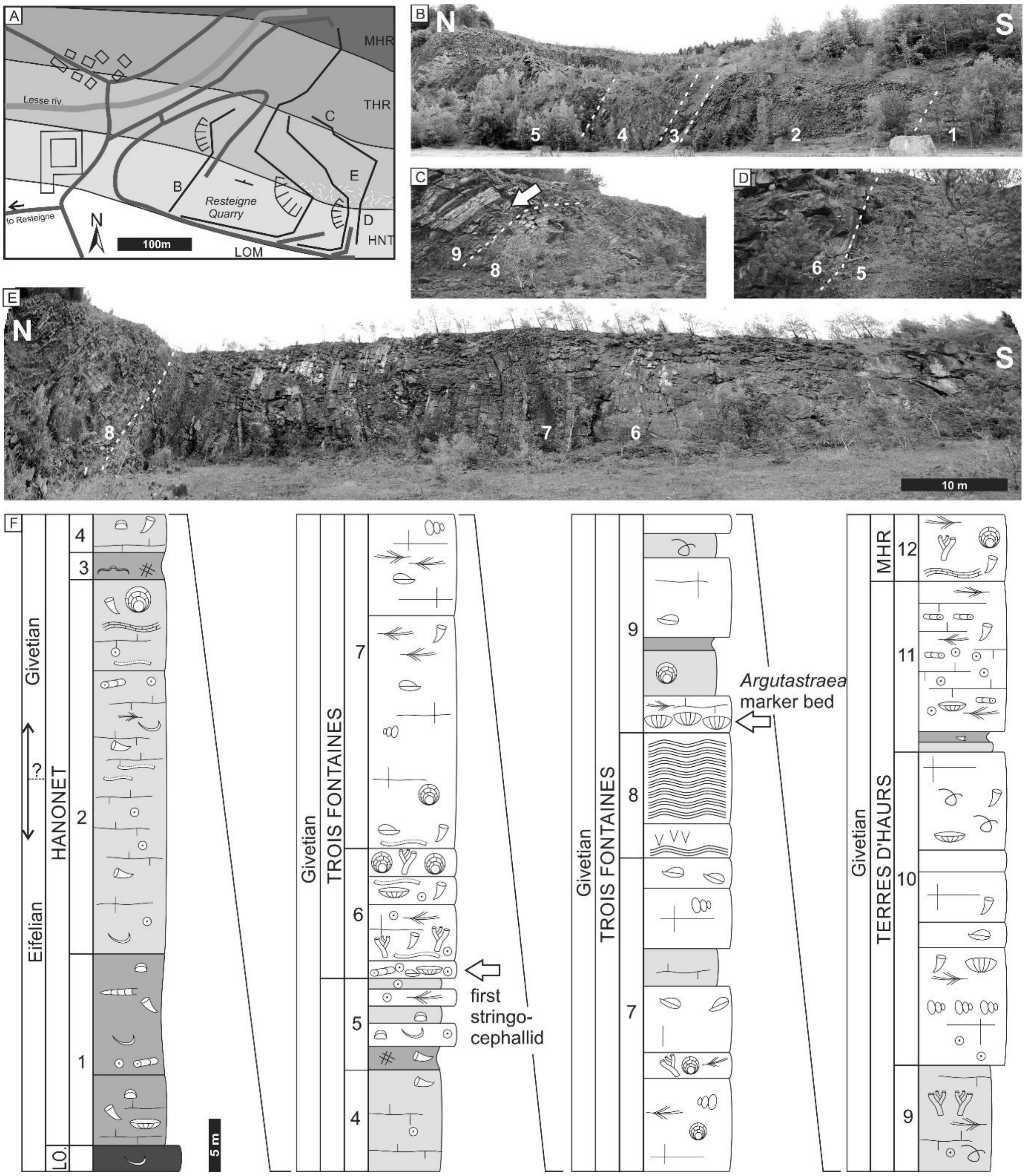

Fig. 8: **A. Schematic geological map of the the Resteigne quarry (modified after Dumoulin & Blockmans, 2013). B. view of the lower quarry wall exposing the Hanonet Fm lines indicate the lithological units. C. view of the *Argutastrea quadrigemina* bed marking the boundary between the Trois Fontaines and Terres d'Haurs formations. D. base of the Trois Fontaines Fm marked by crinoidal rudstone. E. view of the upper quarry wall exposing the Trois Fontaines Fm, the line indicates the top of the reef. F. shematic log of the upper Eifelian and Llower Givetian formations exposed in the Resteigne quarry (modified from Coen-Aubert, 1998, 2001, 2003). Abbreviation: Lo.: Lomme Fm, MHR: Mont d'Haurs Fm**.

Brachiopod (stringocephalids) and gastropod coquina beds overlying the biostrome are interpreted as storm deposits. This first transgressive phase is followed by more restricted facies (unit 7 in Fig. 8) that Preat & Boulvain (1982) interpreted as a lagoon created by the southwards progradation of the reef barrier but that could also be interpreted in terms of sea-level change and/or accommodation. The 'lagoonal complex' is composed of fine grained sediments with a relatively low diversified fauna: leperditid ostracods, murchisonid gastropods, calcispherids and palaeosiphonocladales (Préat & Boulvain, 1982). The 'lagoonal complex' is followed by a 10 m-thick unit (unit 8) of stromatolites witnessing a tidal flat environment (dessication cracks, palaeosols and horizons rich in organic matters). Open marine facies are recorded at the base of the Terres d'Haurs Fm, witnessing a new transgressive pulse. The base of the formation is marked by a horizon of domal *Argutastrea quadrigemina* that can be traced on several tens of kilometres in of the Dinant Synclinorium (unit 9, Fig. 8, Coen-Aubert, 2001). Tabulate corals (thamnoporids and favositids), brachiopods and crinoids reappear quickly in the lower part of the formation in a bioturbated argillaceous limestone (unit 10). Biostromal lenses (patch reefs?) rich in trachyporids locally develop in the lower half of the formation (Coen-Aubert, 1988, 2003). The top of the formation is made of crinoidal limestone with tabulate corals (unit 11). The base of the Mont d'Haurs is badly exposed but shows stromatoporoid and crinoidal limestone with tabulate corals (unit 12).

Main faunal components

Hanonet Fm**:** *Cystiphyllum* ssp., *Breviphrentis martinae*, *Rhytidolasma dahlemense*, *Acanthophyllum heterophyllum*, *A. vermiculare*, *A. tortum*, *Aristophyllum luetti*, *Stringophyllum acanthicum*, *Mesophyllum* ssp. and *Calceola sandalina*, *Favosites goldfussi*, *Thamnopora*, auloporids (*Remesia crispa*), indetermined alveolitids and coenitids (Coen-Aubert, 1988). Abundant brachiopods (pentamerids, atrypids), *Scuttelum* s.l. and phacopid trilobites, orthoconid cephalopods. The conodont fauna was listed by Godefroid (1968) from a nearby outcrop.

Trois Fontaines Fm: The corals were examined in detailed by Coen-Aubert (1988, 1990, 2003, 2004): *Columnaria intermedia*, *Beugniesastraea kunthi*, *B. parvistella*, *Sociophyllum elongatum*, *S. torosum* and *Thamnophyllum occlusum* occur at the base of the formation with a few small corallites of *Coenophyllum groessensi*. The overlying biostrome with massive stromatoporoids below the stringocephalid coquina beds contains *Sociophyllum birenheidi*, *S. torosum*, *Beugniesastraea kunthi*, *Keriophyllum maillieuxi*, *Lyrielasma* sp. *Thamnopora reticulate, T. germanica, Hillaepora spicata* and *Pachyfavosites polymorphus*. *Disphyllum oekentorpi* and *Argutastrea quadrigemina* occur sporadically in the upper part of the formation.

Terres d'Haurs Fm: *A. quadrigemina*, *Temnophyllum wellinense*, many specimens of *Pachyfavosites polymorphus*, *Thamnopora cervicornis* and *H. spicata* occur at the base. *Disphyllum mcleani* and *Spinophyllum spongiosum* and *Acanthophyllum simplex* are known respectively in the middle and upper part of the formation.

6.6 La Préalle Quarry, Aisne

References

Coen & Coen-Aubert (1971), Maillet (2012, 2013), Barchy & Marion (in press).

Location and access

Quarry located west of the Aisne village, near Barvaux. The section extends along the northern and western walls of the quarry. Eastern part of the Dinant Synclinorium (Fig. 1). GPS: 50°21'29.80"N5°32'56.22"E.

Description

The lower member of the Fromelennes Fm, the Flohimont Mbr is dominantly composed of 28 m of argillaceous limestone interstratified with brownish shale, with brachiopods and occasional corals and stromatoporoids. Five metres below the top of the member, Maillet (2013) reported two beds formed almost exclusively of brachiopod shells that he questionably correlated with the Pumilio Event. The base of the Moulin Boreux Mbr is still argillaceous but quickly passes up-section to finely bioclastic limestone, often dolomitized, alternating with purer limestone with coarser bioclastic accumulations. Brachiopods, gastropods, corals and stromatoporoids are common in the lower part. The middle part of the member is composed of bioclastic and pelloidic limestones with stromatoporoid and tabulate corals. Sixty-three metres above the base of the member, Maillet (2012) noted a bed very rich in *Stringocephalus burtini* that represents the last occurrence of this guide species but to date, the stringocephalid brachiopods from southern Belgium remain poorly known (see Godefroid & Mottequin, 2005 and Brice *et al*., 2008). After this author, the ostracod diversity drops just below this bed and the temnophyllid rugose corals disappear approximately at the same level in other sections Coen-Aubert (2004). Maillet *et al.* (2013) thus considered this bed to express the Taghanic Event. However the disappearance of fauna can also been explained by a change from open marine to more restricted facies.

Above this bed, the macrofauna is rather rare, except some stromatoporoid and tabulate coral debris. The upper part of the member shows the development of fining-upwards sequences with a bioclastic base and a micritic top, sometimes capped by stromatolites or by palaeosols (often dolomitized and yellowish in the outcrop). The Moulin Boreux Mbr is topped by a last palaeosol.

The overlying Fort Hulobiet Mbr (c. 25 m-thick) is formed of slightly argillaceous limestone and shows the reappearance of an abundant macrofauna, including large spherical stromatoporoids (up to 50 cm in diameter, 'balls bed' of the quarrymen), *Disphyllum virgatum* beds and horizons crowded with small smooth brachiopods.

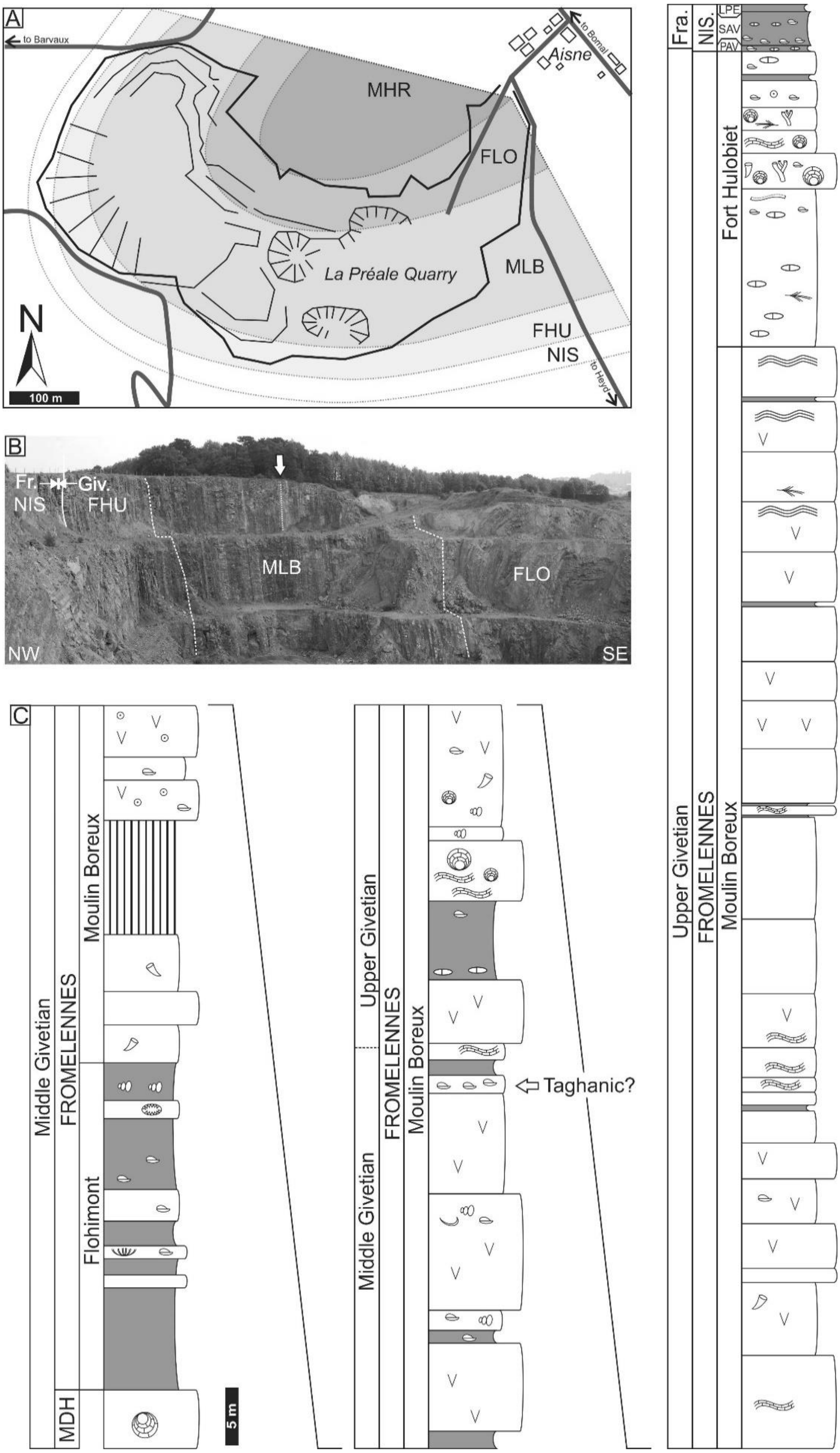

Fig. 9: **A. Schematic map and pictures of the upper Givetian Fromelennes Fm and lower Frasnian Nismes Fm at La Préalle quarry (Barchy & Marion, in press). B. View northwards with position of the lithostratigraphic units. C. Shematic log of the units exposed in the quarry. Abbreviations: FHU: Fort Hulobiet Mbr; FLO: Flohimont Mbr; MLB: Moulin Boreux Mbr; MHR : Mont d'Haurs Fm; NIS: Nismes Fm ; PAV : Pont d'Avignon Mbr ; SAV : Sourd d'Ave Mbr, LPE: La Prée Mbr. See Fig. 6 for legend. The white arrow indicates the position of the last occurrence of stringocephalid brachiopods, questionably corresponding to the Taghanic Event.**

The boundary between the Fromelennes and Nismes formation is sharp (Fig. 9). The first bed of the Nismes Fm is a very typical 70 cm-thick bed of blueish nodular argillaceous and silty limestone containing numerous very large spiriferids and atrypids and known in the Belgian literature as the 'zone des monstres' (e.g. Gosselet, 1871; Sartenaer, 1974). With the overlying 30 cm of nodular shale with brachiopod, it forms the Pont-d'Avignon Mbr. The Sourd d'Ave Mbr is composed of c. 10 m of shale with limestone nodules and still contains brachiopods but smaller in size and less numerous. The nodules correspond mainly to bioturbation and the alternation of 40 cm-thick shale/calcareous shale couplet is likely cyclic. La Prée Mbr is dominated by brownish or greyish shale with rare nodules and brachiopods. Only the base of the member is exposed here then interrupted by a fault.

Main faunal component

Flohimont Mbr: *Stringocephalus* sp. and *Desquamatia* (*Independatrypa*) sp. Corals and stromatoporoids are very uncommon in the shaly facies but occasional in the uppermost part of the member.

Moulin Boreux Mbr: *Stringocephalus* sp., abundant stromatoporoids and corals (*Themnophyllum*, *Sunophyllum*) unidentified solitaries a thamnoporids and alveolitids at the base.

Fort Hulobiet Mbr: *Disphyllum* and ?*Sociophyllum* reappear near the top of the member, together with numerous small smooth brachiopods and large bulbous stromatoporoids. The ostracods are listed in Maillet (2012).

Nismes Fm: essentially spiriferids (e.g. *Eodmitria oblivialis*) and atrypids (e.g. *Desquamatia* (*Neatrypa*) ssp).

6.7. Sourd d'Ave section

References

Bultynck (1974, 1982), Godefroid & Jacobs (1986), Bultynck *et al*. (2001), Birenheide *et al*. (1991), Narkiewicz & Bultynck (2010), Casier *et al*. (2013).

Location and access

Outcrop located at the intersection of the Dinant–Neufchateau road (N48) and Han-sur-Lesse–Wellin road, near Ave-et-Auffe, southern limb of the Dinant Synclinorium (Fig. 1). GPS: 50°06'00.92"N5°07'54.26"E.

Lithostratigraphy and biostratigraphy

The upper Givetian Fromelennes Fm is represented by the upper part of the Moulin Boreux Mbr (8 m) and the Fort Hulobiet Mbr (28 m). The Lower Frasnian Nismes Fm is represented by the Pont d'Avignon Mbr (a 45 cm-thick bed of nodular limestone), the Sourd d'Ave Mbr (9.3 m) and the base of the La Prée Mbr. (Fig. 10). The Givetian/Frasnian boundary lays immediately above the Fromelenne Fm/Nismes Fm boundary at the base of the bed where the first *Ancyrodella* have been recorded by Bultynck (1974), after a 15 m-thick episode without any conodonts. Conodonts from the Sourd d'Ave section have been studied by Bultynck (1974, 1982) and Narkiewicz & Bultynck (2010).

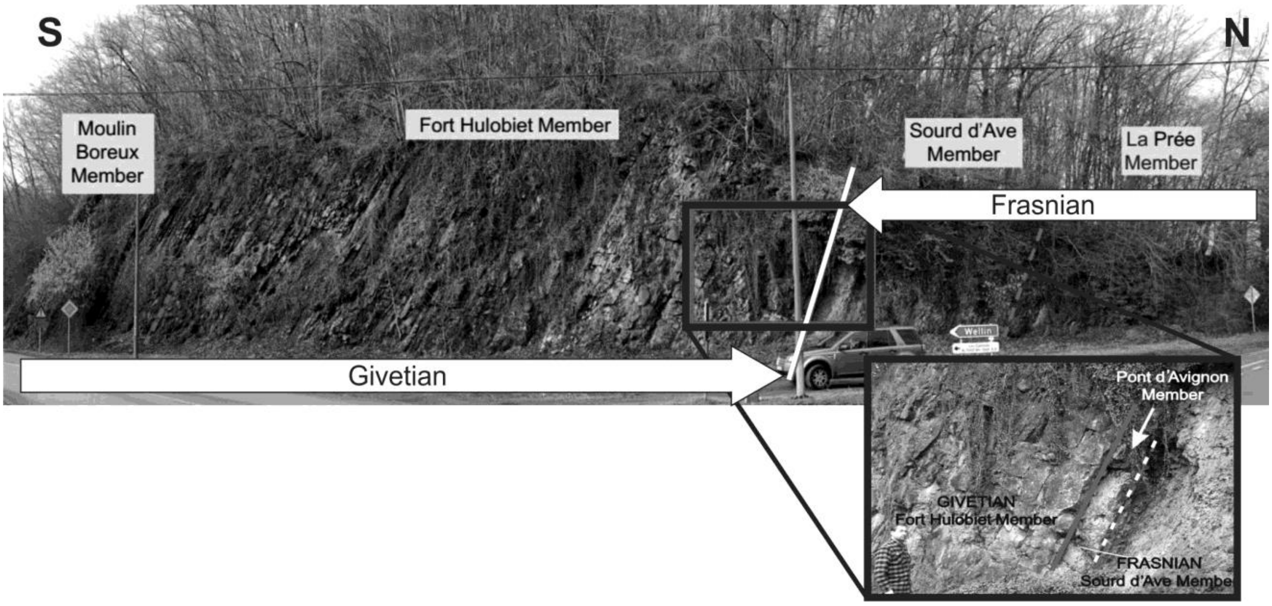

Fig. 10: **Picture of the Sourd d'Ave section with position of the discussed lithostratigraphic units.**

Description

The upper 8 m of the Moulin Boreux Mbr exposed at the base of the section, are composed of fine-grained limestone with massive and branched stromatoporoids. The upper part of the Fort Hulobiet Mbr consists of semi-restricted stromatoporoid boundstones capped by *Amphipora* floatstones, then of fossil-poor units and restricted supratidal laminites with well-developed fenestral fabrics. The boundary between the Fromelennes and Nismes formations is characterized by a dramatic deepening from restricted evaporative lagoonal facies (microfacies 6–13) to open marine interbedded calcareous shale and nodular limestone (microfacies 1–3) (Fig. 11).

The Frasnian Pont d'Avignon Mbr shows a rich faunal assemblage (bryozoans brachiopods, molluscs, nautiloids, tentaculitids, ostracods) suggesting an abrupt drowning from the marginal Givetian carbonate platform into a Frasnian distal ramp setting or basinal environment below or near the storm wave base. This transgressive event at the Givetian-Frasnian boundary is highlighted by argillaceous shale, calcareous shale and tempestites with open-marine interbedded nodular limestones, and the development of a rich fauna succeeding the depauperate communities that prevailed during Late Givetian time.

Ongoing research are now focusing on geophysical (magnetic susceptibility – MS – and magnetic mineralogy, gamma-ray spectrometry) and geochemical analyses (inorganic and organic carbon and inorganic oxygen isotopes) across the Givetian-Frasnian boundary and throughout the section. A total of 339 samples were collected for the study of low-field magnetic susceptibility (X_{LF}) in the Sourd d'Ave section.

The MS values were measured with a Kappabridge MFK1-A with a CS-3 furnace and CS-L cryogenic apparatus. The MS values range between 6.0 x 10^{-10} m³/kg and 4.52 x 10^{-7} m³/kg. The highest X_{LF} values are present in the Fort Hulobiet Mbr and observed at the top of magnetic susceptibility evolutions. A clear decreasing trend of the X_{LF} is discernable at the end of the Fort Hulobiet Mbr and the X_{LF} values remain weaker in the sediments at the base of the Frasnian. Nevertheless, the X_{LF} are quite high and remain around 1 x 10^{-7} m³/kg throughout the Frasnian (Fig. 11).

Gamma-ray spectrometry (GRS) measurements (n =188) were measured on the field with a Gamma Surveyor handheld spectrometric probe with a 6.3 in³ BGO detector. Counts per seconds in selected energy windows were directly converted to concentrations of K (%), U (ppm) and Th (ppm). One measurement with a 120^{-s} count time was performed at each logging point, placed on the outcropping rock section and at full contact with the rock. The section was logged at a 0.25-m interval both in the Fromelennes and Nismes formations. K and Th concentrations fluctuate cyclically during the Givetian but remain generally below 1% and 5 ppm respectively. The concentrations start to increase for both elements before the Givetian-Frasnian boundary and continue into the Nismes Fm at the base of the Frasnian. The K values increase up to 5-6 % at the top of the section. The Th concentrations follow a similar trend revealing an increase up to 18.6 ppm. GRS data show a strong correlation between K and Th values (R^2=0.97) which indicates a strong positive correlation between these elements. Th and K concentrations usually related to the presence of aluminosilicates (illite and other clay minerals, potassium feldspars, micas) in carbonates while a good correlation between K and Th is considered to reflect a fine-grained siliciclastic admixture in carbonate rocks (Koptikova *et al*., 2010). U/Th ratios remain generally below 0.8 with few peaks up to 1.0 during the Givetian. The U/Th ratios decrease at the base of the Frasnian in the Nismes Fm down to an average value around 0.25. The U/Th ratio is generally interpreted as an index to derive information on the paleo-redox conditions of the depositional environments. The U/Th ratios indicate relatively well-oxygenated paleo-conditions in the marine waters throughout the section and even more in the Nismes Fm (Fig. 11).

Main faunal component

Conodont content of these formations is provided by Narkiewicz & Bultynck (2010). Ostracods has been studied by Casier (1987) and Milhau (1983). Atrypid brachiopods were investigated by Godefroid & Jacobs (1986).

6.8 Regissa Rocks, Marchin

References

Godefroid et al. (1994), Mottequin *et al*. (2014), Mottequin & Marion (in press).

Location and access

Rocks along the road Huy–Modave in the Hoyoux valley, south of Regissa hamlet. Northern part of the Dinant Synclinorium (Fig. 1). GPS: 50°29'19.07"N5°15'30.80"E.

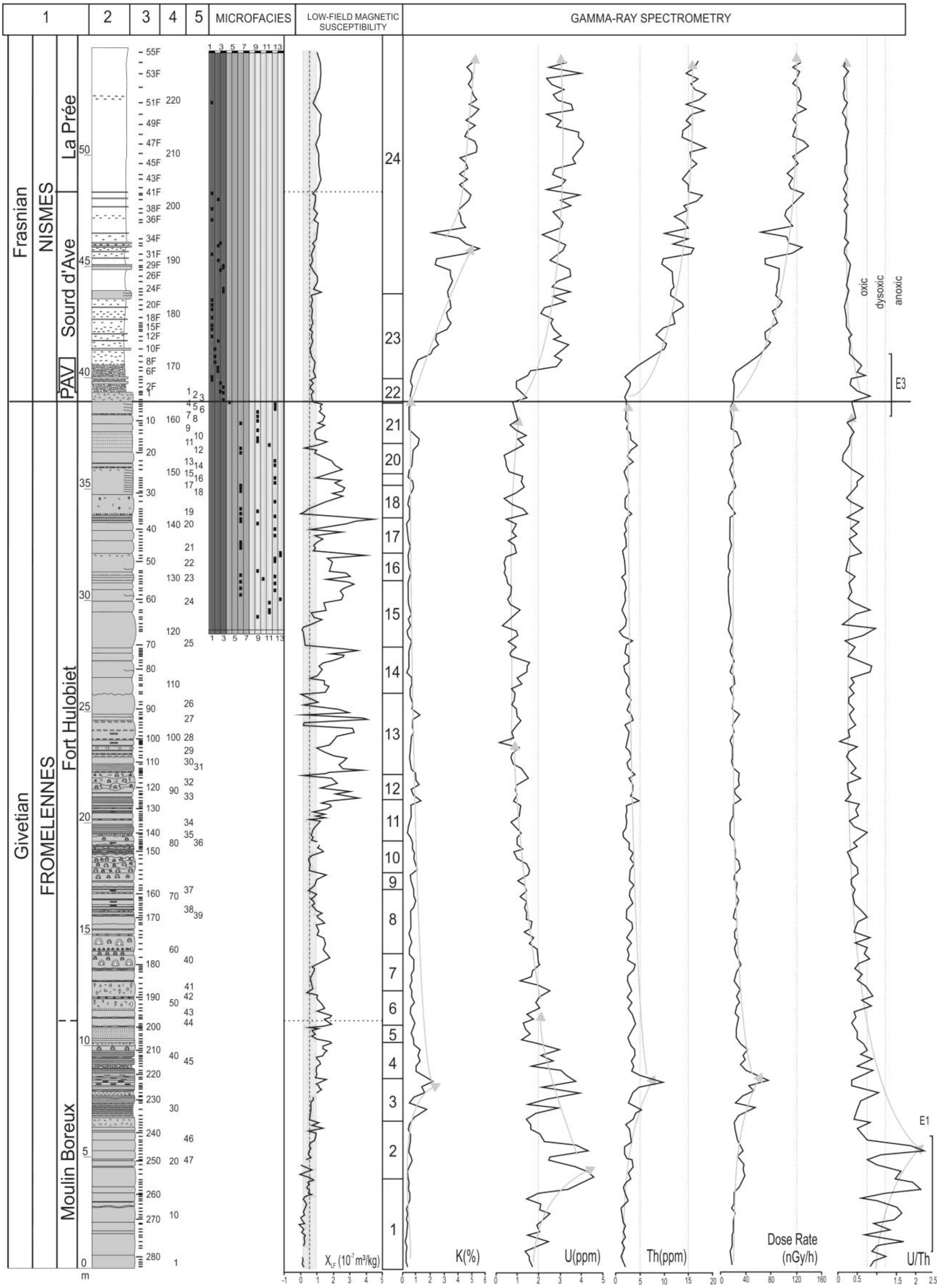

Fig. 11: **Chrono- and litho-stratigraphy (1), lithology (2), XLF sample distribution (3), GRS measurement (4), ostracod samples (5), microfacies, magnetic susceptibility, gamma-ray spectrometry across the Givetian-Frasnian boundary in the Sourd d'Ave section. Abbreviations: PAV: Pont d'Avignon Mbr, SAV: Sourd d'Ave Mbr**

Lithostratigraphy and biostratigraphy

The Emsian-Givetian succession of the northern part of the Dinant Synclinorium is dominated by siliciclastics with a strong proximal character. The Burnot Fm is considered to be Emsian to basal Eifelian in age (Bultynck & Dejonghe, 2001). The Pepinster Fm belongs to the AD palynological biozone (Hance *et al.*, 1992) which crosses the Eifelian-Givetian boundary. The overlying Nevremont Fm yielded *Stringocephalus* sp. and *Argutastrea* ssp. indicating a Givetian age. The Marchin Mbr is consequently a proximal equivalent of the Middle Givetian Terres d'Haurs Fm.

Description

The Emsian Burnot Fm is composed of thick unit of reddish sandstones and conglomerate and followed by the Pepinster Fm which develops in the Hoyoux valley two conglomerate members: an unnamed equivalent of the Tailfer Mbr and the Marchin Mbr. The first is a 25-30m-thick unit of polygenic conglomerate of quartz and quartzite pebbles in a greenish siliceous cement. The second that develops in the upper part of the formation is a 20 m-thick unit of withish conglomerate of mainly quartz pebbles (Mottequin & Marion, in press). This member probably deposited in a fluvial environment.

7. References

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Middle to Upper Frasnian succession, Kellwasser events and the Frasnian–Famennian Boundary in the Namur–Dinant Basin

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Abstract

Seven sections distributed in the Namur–Dinant Basin (southern Belgium) are presented in order to illustrate the Frasnian succession and its variations through time and space. The Neuville railway section exposes the contact between the carbonate Philippeville Formation and the Upper Frasnian mixed argillaceous–carbonate succession (Neuville, Les Valisettes and Matagne formations) as well as the base of the Lower Famennian. Both Kellwasser horizons can be observed in this important section. The former Beauchâteau quarry (Senzeille) shows a red carbonate mound of the Petit-Mont Member (Upper Frasnian) in subhorizontal position. Middle Frasnian succession characteristic of the distal part of the Namur–Dinant Basin and including 'reefs' can be extensively observed in the Nortd and Lion quarries at Frasnes, which is the historical area of the Frasnian stage. In the Engis area (Tchafornis park and La Mallieue sections), the Upper Frasnian Aisemont Formation is well exposed. It is characterized by two carbonate members, of which the older includes biostromal horizons (rugose and tabulate corals), and is separated by an argillaceous one (Lower Kellwasser horizon). The Prayon section (Vesdre area) displays the Middle Frasnian carbonate Lustin Formation reflecting shallow-water environments that overlays the Middle Devonian siliciclastic Pepinster Formation.

1. Introduction

The Frasnian succession is particularly well exposed around the village of Frasnes (or Frasnes-lez-Couvin) (Fig. 1), which corresponds to the historical type area of the Frasnian stage (Coen-Aubert & Boulvain, 2006), but also in numerous regions of southern Belgium. The purpose of this excursion is to present a transect across the Namur–Dinant Basin (see below) to show the environmental variations through time and space during the Frasnian.

As for the excursion devoted to the Eifelian-Givetian succession (Denayer *et al.*, this volume), we have chosen to present some sections off the beaten tracks due to their significance for illustrating some particular facies.

2. Historical background

Both stages of the Upper Devonian, the Frasnian and Famennian, were originally defined in the Namur–Dinant Basin. The term Frasnian, clearly related to the '*Système du Calcaire de Frasnes'* introduced by d'Omalius d'Halloy (1862), first appeared in Gosselet (1879a) in his description of the Maubeuge canton in northern France (see also Coen-Aubert & Boulvain, 2006). The term Famennian was introduced by Dumont (1855) as the '*Système Famennien'* and included the lower part of the '*Système Condrusien'* that he introduced anteriorly (Dumont, 1848) (see Thorez *et al.* (2006) for more details).

In a footnote, Gosselet (1879b) subdivided the Upper Devonian in two parts: the Frasnian including the 'Zone à *Rhynchonella cuboides* et la Zone à *Cardium palmatum*' and the Famennian in which he put together '*les schistes de Famenne*, *les Psammites du Condros* (sic), *les calcaires d'Etrœungt'*. Concerning the southern flank of the Dinant Synclinorium, the 'Zone à *Rhynchonella cuboides*' *sensu* Gosselet (1879b) corresponds, in terms of current lithostratigraphic units (see below), to the Nismes, Moulin Liénaux, Grands Breux and Neuville formations whereas his 'Zone à *Cardium palmatum*' (= *schistes de Matagne à Cardium palmatum* (Gosselet, 1880)) corresponds to the Matagne Formation. Gosselet (1880) restricted the Famennian to the '*schistes de Famenne*' and to the '*Psammites du Condroz'*. According to this author, the '*schistes de la Famenne'* include, from base to top, the '*Schistes de Senzeilles* à *Rhynchonella Omaliusi*' and the '*Schistes de Mariembourg* à *Rhynchonella Dumonti*'.

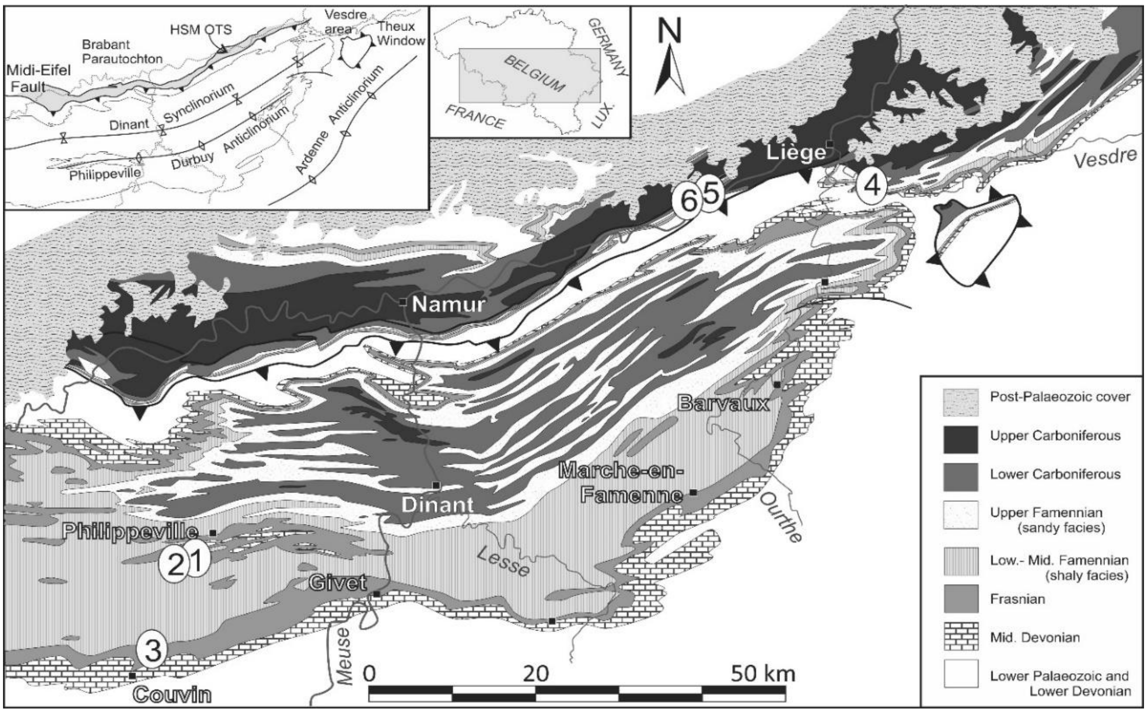

Fig. 1: **Schematic geological map of southern Belgium (modified from de Béthune, 1954) with location of the visited sections: (1) Neuville railway trench, (2) Beauchâteau quarry (Senzeille), (3) Nord Quarry (Frasnes), (4) Lion Quarry (Frasnes), (5) Tchafornis park (Engis), (6) La Maillieue (Engis), (7), Prayon. Abbreviation: HSM OTS, Haine–Sambre–Meuse overturned trust sheets.**

In 1986, the International Union of Geological Sciences ratified the proposal of the Subcommission on Devonian Stratigraphy aiming to place the base of the Frasnian at the first occurrence of the conodont *Ancyrodella rotundiloba*, that is at the base of the Lower *asymmetricus* Zone of Ziegler (1971) or within the Lower *falsiovalis* Zone of Ziegler & Sandberg (1990). The Global Stratotype Section and Point (GSSP) is located at the Pech de la Suque pass near Saint-Nazaire-de-Ladarez, southwest of the Montagne Noire (France, Hérault) (Klapper *et al*., 1987). The base of the Famennian coincides with that of the lower *triangularis* Zone; the GSSP is located at Coumiac, near Cessenon in Montagne Noire (Klapper *et al.*, 1993, House *et al*., 2000).

Originally, the Frasnian–Famennian (F–F) boundary *sensu* Gosselet was placed at the contact between the '*schistes de Matagne à Cardium palmatum*' and the '*schistes de Famenne à Cyrthia Murchisoniana*' in the Charleroi-Vireux railway trench, south of the village of Senzeille (Gosselet, 1879b) (Fig. 2). A sketch of this section was published by Gosselet (1888) and complemented by Sartenaer (1960). Unfortunately, this famous section has disappeared in 1976 and, despite the two trenches dug by the Royal Belgian Institute of Natural Sciences in the late 1980's, the F–F boundary is no longer exposed (Bultynck & Martin, 1995; Casier & Bultynck, 2000).

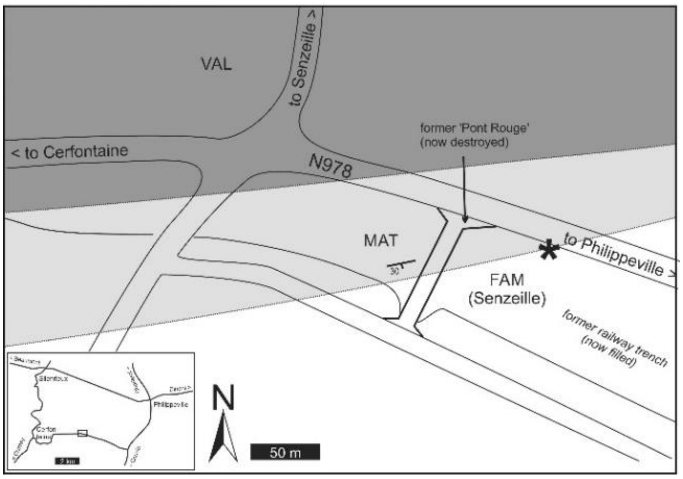

Fig. 2: **The original Frasnian–Famennian boundary at Senzeille (Namur Province): location of the former stratotype section (Gosselet, 1877, 1880, 1888) and the reference section partly filled in nowadays (Bultynck & Casier, 2000).**

Frasnian faunas from southern Belgium have been intensively studied since the 19th century, notably with the pioneering works of J. Gosselet, E. Maillieux and M. Lecompte. The latter, who was a famous coral and stromatoporoid specialist (Sorauf *et al.*, 2012), has promoted both palaeontological and sedimentological research from the years 1960.

3. Geological setting

Frasnian strata extensively crop out in several Variscan structural units, such as the Dinant Synclinorium (Fig. 1), the Haine–Sambre–Meuse overturned trust sheets (former 'southern limb of the Namur Synclinorium), the Brabant Parautochton (former 'northern limb of the Namur Synclinorium') (see Belanger *et al.*, 2012), the Philippeville-Durbuy Anticlinorium (Barchy & Marion, in press) and the Vesdre area (Fig. 1). They constituted the Namur–Dinant Basin during the Devonian that developed along the southeastern margin of Laurussia (Golonka, 2000). The Frasnian succession of facies reflects a ramp setting with several breaks of slope (Boulvain *et al.*, 2004). The distal part of the Namur–Dinant Basin, which corresponds to the southern flank of the Dinant Synclinorium, recorded the development of several carbonate mound levels (Arche, La Boverie, Lion and Petit-Mont members) separated by argillaceous episodes (Maillieux, 1908, 1913; Boulvain & Coen-Aubert, 2006).

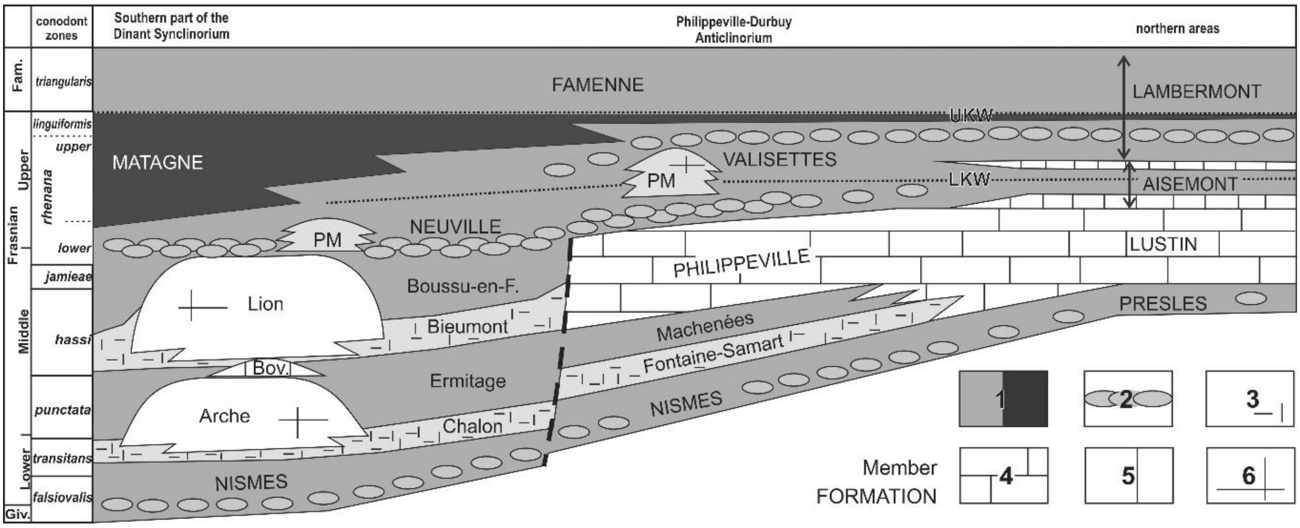

Fig. 3: **Schematic proxio-distal cross section and main lithostratigraphic units of the Namur – Dinant Basin before the Variscan Orogeny (modified from Boulvain *et al*., 2004). 1: shale; 2: nodular shale; 3: (argillaceous) limestone and shale; 4: thin-bedded limestone; 5: thick-bedded limestone; 6: carbonate buildup. Abbreviation: PM: Petit-Mont Mbr.**

4. Lithostratigraphy

The lithostratigraphy of the Frasnian of southern Belgium has been summarized in Boulvain *et al.* (1993, 1999b) and Bultynck & Dejonghe (2001) (Figs 3–4). We here describe only briefly the Frasnian succession of the zones of the Namur–Dinant Basin that will be visited during the field trip.

4.1. Southern margin of the Dinant Synclinorium/Southeastern part of the Philippeville–Durbuy Anticlinorium

The Frasnian starts with the essentially shaly Nismes Fm (c. 40 m) with some carbonate beds in its lowermost part; it includes three members, from base to top: Pont d'Avignon, Sourd d'Ave and La Prée (Bultynck *et al.*, 1988a; Bultynck & Coen, 1999). The Givetian–Frasnian boundary is located in the lowermost part of the Sourd d'Ave Mbr. The overlying Moulin Liénaux Fm (*transitans* to *punctata* zones) is subdivided classically into three members, from base to top: the Chalon (shale and argillaceous nodular limestone), Arche (bioherms rich in stromatoporoids, corals and stromatactis) and Ermitage (shale with some beds of nodular limestone) (Bultynck & Mouravieff, 1999). Locally, in reefal area, a fourth member (La Boverie Mbr) is developed and consists of well-bedded and massive limestone (c. 30-45 m) (Boulvain & Coen-Aubert, 2006). The Grand Breux Fm (*hassi* to lower *rhenana* zones) is composed of the Bieumont, Lion and Boussu-en-Fagne members. In the Frasnes area where the reference sections are located, the Bieumont Member begins with 16 m of micritic to bioclastic, argillaceous to nodular limestone and ends with 21 m of micritic to argillaceous limestone (Coen-Aubert 1994). The Lion Mbr includes greyish massive carbonate buildup, up to 250 m thick (Monty *et al.* 1988).

The Boussu-en-Fagne Member attains up to 81 m in thickness (Coen-Aubert & Boulvain, 1999) and is mainly composed of shale with some nodular levels and limestone beds. The Neuville Fm (lower *rhenana* Zone) consists of nodular limestone with intercalations of shale in the Philippeville Anticlinorium where its thickness is always small (about 10 m). On the southern flank of the Dinant Synclinorium, shale with limestone nodules predominate and the formation attains up to 110 m in thickness (Coen, 1977) but it thins eastwards. The reddish carbonate buildups (30 to 80 m thick), developed within the formation, are assigned to the Petit-Mont Member (Boulvain *et al.*, 1999b).

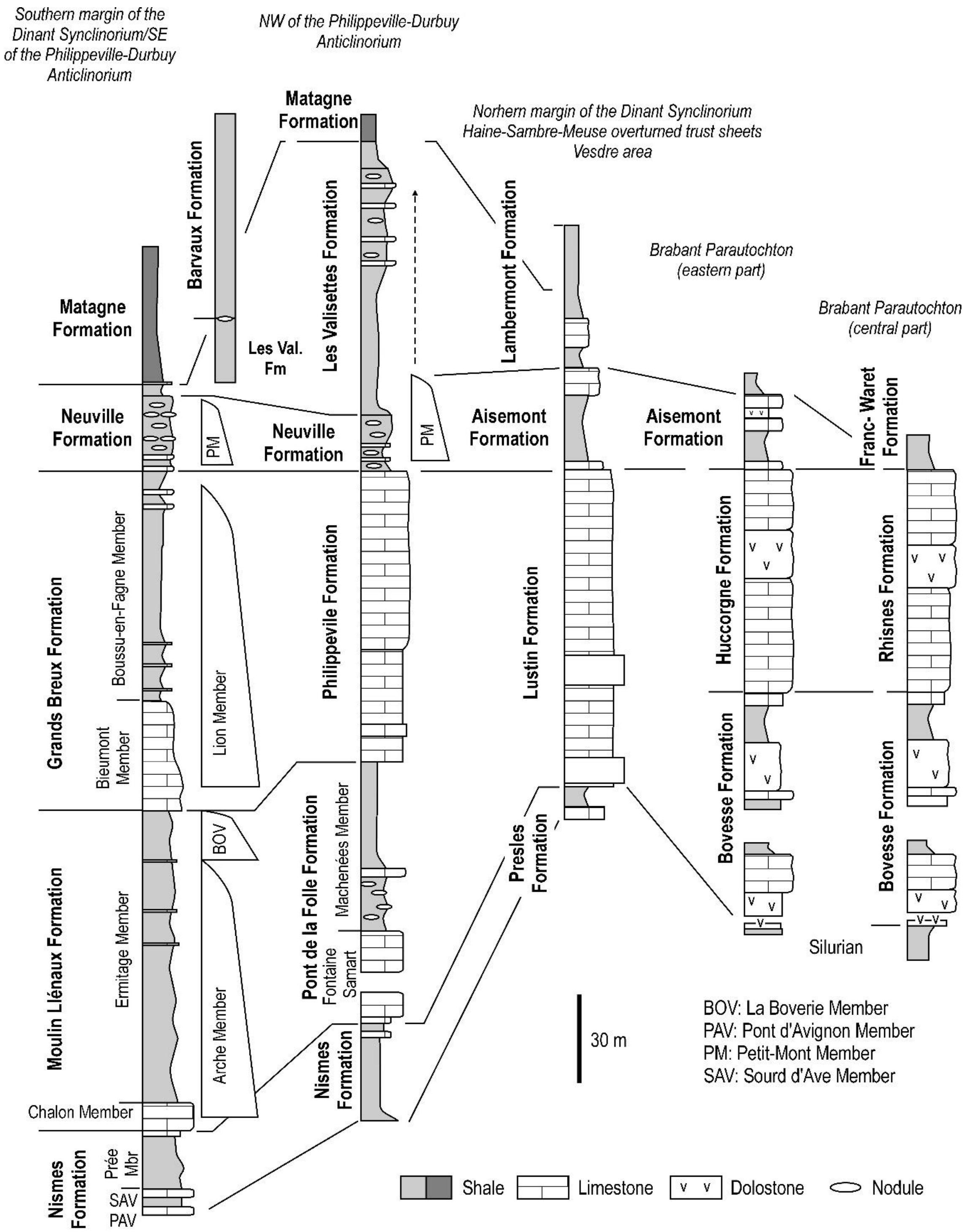

Fig. 4: **Lithostratigraphical correlations of the Frasnian formations across the Namur–Dinant Basin (southern Belgium) (modified from Boulvain *et al.*, 1999a).**

The Matagne Formation starts with one or several beds of limestone with goniatites and bivalves followed by fine greenish-brown to black shale. Its thickness attains more than 50 m on the southern flank of the Dinant Synclinorium but is reduced to about 10 m in the Philippeville Anticlinorium (Coen *et al.*, 1999). It is highly diachronous because it begins in the basal part of the upper *rhenana* Zone on the southern flank of the Dinant Synclinorium whereas it is only developed in the *linguiformis* Zone in the Philippeville Anticlinorium (Bultynck *et al.*, 1998). On the southeastern border of the Dinant Synclinorium, the Matagne Fm is replaced by the Barvaux Fm (about 90 m thick; upper *rhenana* to lower *triangularis* zones), characterized by purplish to green shale with some sandy layers and nodules (Coen, 1999).

4.2. Southwestern part of the Philippeville–Durbuy Anticlinorium

In this part of the anticlinorium, the Moulin Liénaux passes laterally to the Pont de la Folle Fm (c. 90 m; upper part of the *transitans* to the lower part of *hassi* s.l. zones) that includes two members, from base to top: the Fontaine Samart (30 m of limestone) and the Machenées (60 m of more or less nodular shale) members (Boulvain *et al.*, 1999c). It is overlain by the thin- to thick-bedded, frequently dolomitized limestone of the Philippeville Fm (c. 100 m; lower part of the *hassi* s.l. to the lower part of the lower *rhenana* zones) (Boulvain *et al.*, 1999d). The Neuville Fm rests abruptly on the Philippeville Fm and is overlaid by the Les Valisettes Fm (upper *rhenana* Zone), about 90 m thick in the Philippeville Anticlinorium, is essentially shaly. Greenish to reddish nodular limestone and shale develop in the vicinity of the buildups of the Petit-Mont Member (Boulvain *et al.*, 1999e). It occurs also on the south-eastern border of the Dinant Synclinorium, between the Neuville and Barvaux formations, where its thickness is considerably reduced.

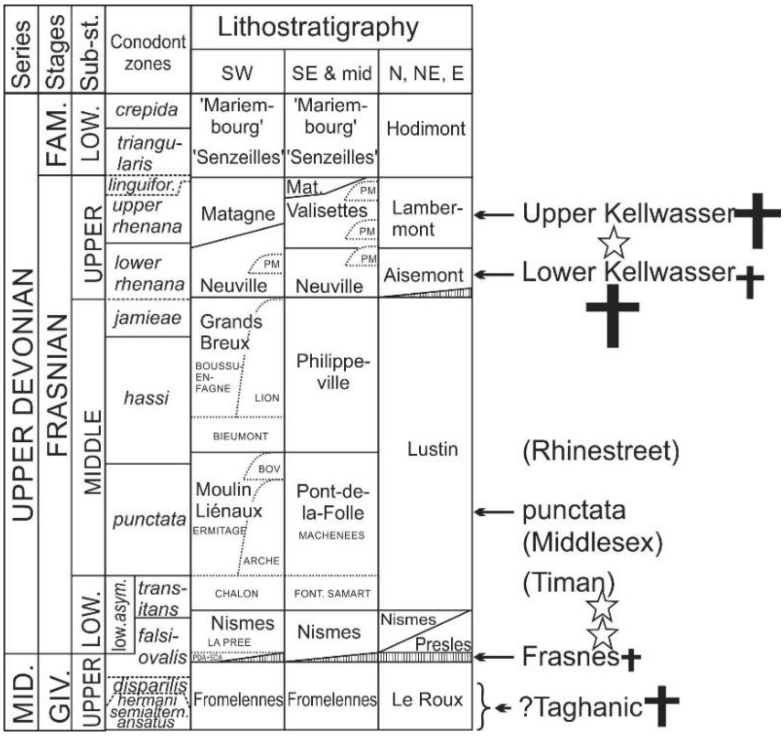

Fig. 5: **Synthetic simplified stratigraphic scale of the Givetian (*partim*) and the Frasnian succession of southern Belgium with position of the bioevents. Names between brackets indicates the theoretical position of events not (yet) recognized in Belgium, named preceded by a question marks indicates events hypothetically situated. Crosses indicate extinctions in macro-fauna, stars indicate diversification or colonization events. Strongly modified from Bultynck *et al.* (2000) and Boulvain *et al.* (1991). Abbreviations: BI, bioherm; BOV, La Boverie Mbr; Font. Samart, Fontaine Samart Fm; PDA + SDA, Pont d'Avignon and Sourd d'Ave members; PM, Petit-Mont Mbr; *linguifor.* : *linguiformis* (modified from Denayer & Mottequin, 2015).**

4.3. Northern border of the Dinant Synclinorium, Haine–Sambre–Meuse overturned trust sheets and Vesdre area

In these areas, the Frasnian starts with the shaly Presles Fm (c. 1–16 m; top of the upper *falsiovalis* Zone to lower part of *transitans* Zone) that includes some thin limestone beds in its basal part as well as horizon with haematitic oolites (Coen-Aubert *et al.*, 1985; Coen-Aubert, 1999a). It is overlaid by the Lustin Fm (ca. 100 m) that mainly consists of thick-bedded limestone frequently rich in corals and stromatoporoids (Coen-Aubert & Coen, 1975; Coen-Aubert, 1999b). The Aisemont Fm (c. 20 m; lower *rhenana* to basal part of the upper *rhenana* Zone) comprises limestone and argillaceous limestone in its lower and upper parts; the middle part consists of shale and nodular shale (Lacroix, 1999). Both limestone horizons are known in the Belgian literature as the first and second '*biostromes with Phillipsastrea'* of Coen-Aubert & Lacroix (1979) but the '*second biostrome'* is devoid of biostromal units (Poty & Chevalier 2007; Denayer & Poty, 2010). The Lambermont Fm (50 to 100 m thick; upper *rhenana* to. *triangularis* zones) mainly consists of shale and nodular shale with intercalations of limestone beds (Laloux & Ghysel, 1999). Its middle part is characterized by the '*third biostrome with Phillipsastrea*' (Coen-Aubert & Lacroix, 1979), especially developed in the Vesdre area and consisting of argillaceous, nodular limestone and calcareous shale with a biostromal bed rich in massive rugose corals (*Frechastraea* and *Iowaphyllum*).

5. Biostratigraphy and events

The base of the Frasnian stage is marked by the first occurrence of the conodont *Ancyrodella rotundiloba* within the lower part of the Nismes Fm (base of the Sourd d'Ave Mbr) and almost coincides with the Givetian–Frasnian boundary as originally defined by Gosselet (1874). This is well-documented in the Nismes section, on the southern flank of the Dinant Synclinorium, which has been selected as an auxiliary type section of the Givetian-Frasnian boundary in neritic facies (Bultynck *et al.*, 1988a).

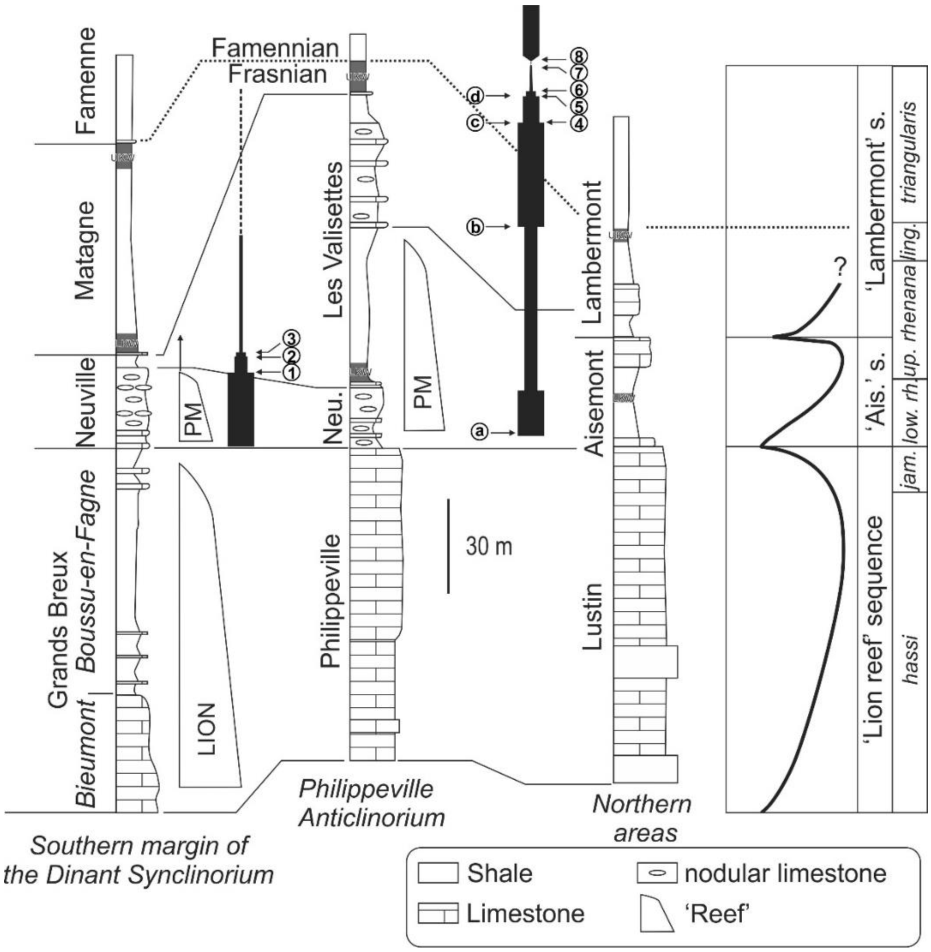

Fig. 6: **Mid- to Upper Frasnian lithostratigraphy of southern Belgium with sequence stratigraphy and comparison between the different extinction and recovery phases observed among the brachiopods and rugose corals from the southern margin of the Dinant Synclinorium and the Philippeville Anticlinorium (Neuville railway section) (modified from Boulvain *et al*., 1999a and Mottequin & Poty, 2015). Conodont data are from Bultynck *et al.* (1998), modified from Mottequin (2005). LKW, Lower Kellwasser; UKW, Upper Kellwasser. Brachiopods: (1) local disappearance of pentamerids; (2) local disappearance of atrypids; (3) first occurrence of *Ryocharhynchus tumidus* (rhynchonellid); (4) last occurrence of pentamerids; (5) last occurrence of atrypids; (6) first occurrence of *R. tumidus* and decimation of the last Frasnian representatives of the strophomenoids (strophomenids), productids, spiriferids, athyridids and orthids, etc.; (7) disappearance of *R. tumidus*; (8) appearance of new spiriferid, athyridid and rhynchonellid species. Corals: (a) extinction of thamnoporoids and disphyllids, and replacement by phillipsastreids ('fauna 1' of Coen *et al.*, 1977); (b) appearance of *Iowaphyllum* ('fauna 3' of Coen *et al*., 1977); (c) extinction of all the colonial and dissepimented solitary rugose corals; and (d) extinction of the last non dissepimented solitary rugose corals. Abbreviations: Ais., Aisemont; s., sequence, LKW, Lower Kellwasser; PM: Petit Mont Member; UKW, Upper Kellwasser.**

Frasnian events are rather well-situated stratigraphically (Fig. 4). The Frasnes Event corresponds to the development of shaly facies at the base of the Frasnian (La Prée Mbr of the Nismes Fm; Becker, 1993) and possibly with the deposition of the chamositic and haematitic ironstone horizons of the Nismes and Presles formations. The *punctata* Event, close to the Lower–Middle Frasnian boundary has been located in the Ermitage Mbr of the Moulin Liénaux Fm but no significant extinction has been observed (Casier & Olempska, 2008). The Timan, Middlesex and Rhinestreet events (*punctata* to *hassi* zones) are theoretically situated within the Moulin Liénaux and Grands Breux formations and their lateral equivalents (Pont de la Folle, Philippeville and Lustin formations) but have not been highlighted so far in Belgium. The Late Frasnian Crises are the best known as they are responsible for both extinctions within benthic and pelagic faunas. Extinctions of macrofauna started near the Middle–Upper Frasnian boundary (close to the base of the lower *rhenana* Zone), at the top of the Grands Breux, Philippeville and Lustin formations (Poty & Chevalier, 2007). The Lower Kellwasser Event has been proven to be related to a third order transgression (*semichatovae* Transgression) bringing anoxic water onto the platform but extinctions are diachronic and clearly linked to the progression of the anoxia (Mottequin & Poty, 2015). The Lower Kellwasser Event is recognized at the base of the Matagne and the Les Valisettes formations and within the middle member of the Aisemont Fm (Bultynck *et al.*, 1998; Poty & Chevalier, 2007). The Upper Kellwasser Event covers the upper part of the Matagne and Barvaux formations and the middle part of the Lambermont Fm within the *linguiformis* Zone (Bultynck *et al.*, 2000) (Figs 5, 6).

6. Key sections

6.1. Neuville railway section

References

Bouckaert *et al.* (1970), Coen & Coen-Aubert (1974), Boulvain *et al.* (1993, 1999), Bultynck *et al.* (1998), Godefroid & Helsen (1998), Azmy *et al.* (2012), Mottequin & Poty (2015).

Location and access

Embankment of the Couvin–Charleroi railway, located south-west of the village of Neuville, Philippeville Anticlinorium (Fig. 1). GPS: 50°09'56.33'N4°29'49.43'E.

Lithostratigraphy and biostratigraphy

It exposes an almost continuous section ranging from the top of the Philippeville Fm (*hassi* s.l. to lower part of the lower *rhenana* Zone) to the base of the Famenne Fm (*triangularis* Zone) (Fig. 6). The conodonts from this section were described by Coen & Coen-Aubert (1974) and Bultynck *et al.* (1998).

Fig. 7. **A. Contact between the thick-bedded limestone of the Philippeville Fm and the nodular shale of the Neuville Fm in the Neuville railway section. B. Close-up of the sharp contact between the thick-bedded limestone of the Philippeville Fm and the nodular shale of the Neuville Fm (Neuville railway section).**

Description

The top of the Philippeville Fm consists of an alternation of thick beds of grey to black limestone rich in stromatoporoids that form the core of a low anticline (Fig. 7A). Massive rugose corals are frequent. The Neuville Fm is mostly composed by nodular limestone with some beds of shale with or devoid of carbonate nodules. Its first 5 m shows the same rugose coral fauna dominated by the cerioid disphyllid *Hexagonaria* than observed in the Boussu-en-Fagne Member (Grands Breux Fm). The base of the Les Valisettes Fm includes about 50 m of poorly fossiliferous shale in which four beds of limestone occur at the bottom of the formation. They are followed by red to green nodular limestone and shale and shale with carbonate nodules rich in macrofauna (brachiopods, corals, receptaculitides, sponges, etc.). The top of the Les Valisettes Fm consists of 9 m of green shale rich in brachiopods which are topped by limestone beds (Fig. 8). The Matagne Fm (thickness c. 9 m) is composed of thin black shale with rare brachiopods and pelecypods. The contact with the overlying Famenne Formation is faulted.

The Neuville Fm is correlated biostratigraphically and from a sequence stratigraphy viewpoint with the Aisemont Fm (lower and middle member, Poty & Chevalier, 2007) as TST and HST of the 'Aisemont sequence' whereas the Les Valisettes Fm shaly member corresponds to the upper member of the Aisemont Fm and Lambermont Fm as (Poty & Chevalier, 2007; Denayer & Poty, 2010) (Fig. 6)

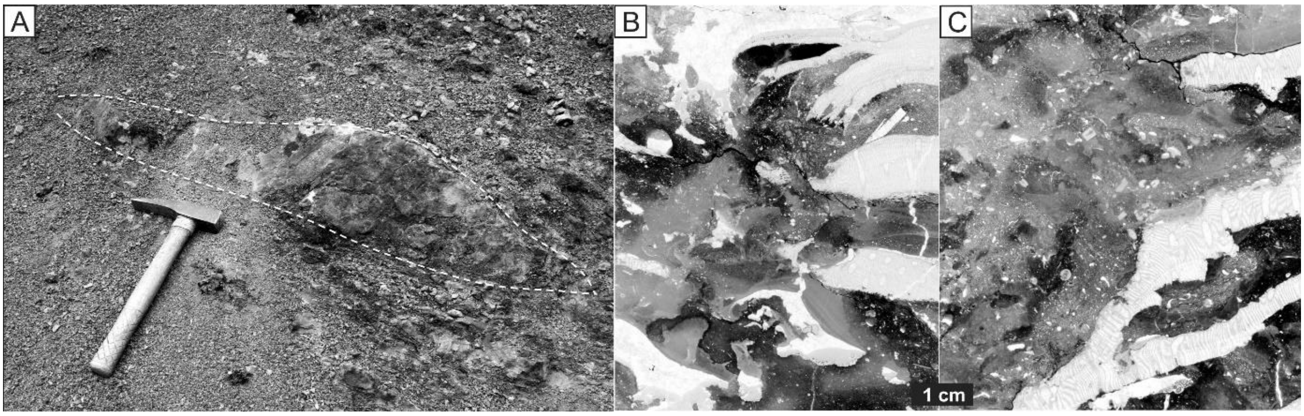

Fig. 8. **A. Micro-mudmound in the upper part of the Les Valisettes Formation (Neuville railway section): mudstone with numerous rugose corals (*Frechastraea*). B-C. Pictures of thin sections in this micro-mudmound.**

6.2. Beauchâteau quarry, Senzeille

References

Tsien (1971, 1976a, 1976b, 1976c, 1977a, 1978, 1979, 1980, 1984), Tourneur (1982), Birenheide *et al.* (1991), Boulvain & Coen-Aubert (1992), Boulvain (1993, 2001), Boulvain *et al.* (2011).

Location and access

Disused quarry 2.5 km SE of Senzeille, Philippeville Anticlinorium (Fig. 1). GPS: 50°09'36.12'N4°29'03.60'E.

Lithostratigraphy and biostratigraphy

Neuville Fm, Petit-Mont Mbr, Upper Frasnian. Lower? to upper *Palmatolepis rhenana* Zone (Tourneur, 1982; Sandberg *et al. in* Bultynck *et al.*, 1988) (Fig. 9).

Description

The mound exposed in this disused quarry is in sub-horizontal position and all the 'marble' facies corresponding to different growth stages of the mound are nicely exposed on large sawn faces whereas flank facies can be observed laterally. Post-reef strata are poorly exposed.

On the lower central panel of the quarry, slumped structure affecting bioclastic-argillaceous alternations can be seen (Figs 9, 10). The abundance of large bioclastic fragments and almost intact coral colonies indicate that organisms colonized the central part of the mound. The SE side of the mound is dominantly colonized by solitary rugose corals in living position whereas the NW side shows lamellar tabulate corals stabilizing bioclastic accumulation (Figs 6, 9). This asymmetry provides some clues about the palaeorelief and palaeocurrents of the reef. Upwards, the red to pink facies passes to greyish facies (grey algal facies of Boulvain, 2007) which also includes laminar stromatoporoids. The top of the mound shows the reappearance of stromatactoid-bearing red facies rest on an erosive surface. Indeed the mound recorded the third order Aisemont sequence of Poty & Chevalier (2007) (Fig. 6): the main red and pink facies corresponds to the TST show a deepening followed by shallowing trend. The grey facies corresponds to the HST, capped by the sequence boundary (described as a karstic surface by Sandberg *et al.*, 1992, Figs 9, 10) and correlated to the bioclastic debris flow deposits surrounding the mounds. Hence, the uppermost red facies corresponds to the TST of the following Lambermont sequence (Denayer & Poty, 2010; Mottequin & Poty, 2015) (Figs 6, 9). This succession is biostratigraphically verified because Birenheide *et al.* (1991) indicates the second coral assemblage ('faune 2' of Coen *et al.*, 1977) dominated by *Frechastraea micrastraea*, *Phillipsastrea ananas*, *Thamnophyllum hollardi*, *Macgeea pauciseptata* and *Tabulophyllum implicatum*, is identified below the erosive surface whereas the third coral assemblage ('faune 3') characterized the uppermost red facies, with *Frechastraea pentagona*, *F. minima*, *Phillipsastrea falsa*, *Iowaphyllum rhenanum* and *I. mutabile*.

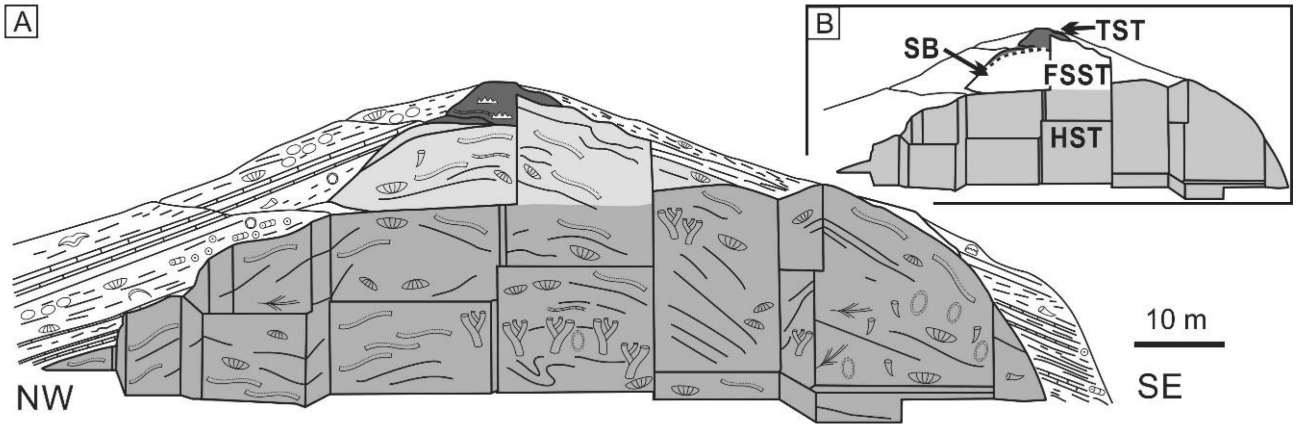

Fig. 9: **A. Sketch of the Beauchâteau quarry at Senzeille (Petit-Mont Mbr) with the distribution of the main facies and macrofossils (modified from Tourneur, 1982) and Birenheide (1991). B. Sequential interpretation of the facies after Denayer & Poty (2010) and Mottequin & Poty (2015). Legend: see Fig. 15**

Main faunal components

The Beauchâteau quarry is the type locality for the rugose corals *Tabulophyllum implicatum*, *Iowaphyllum mutabile*, *Phillipsastrea falsa* and the tabulate corals *Thecostegites dumoni*, *Senceliaepora tenuiramosa* (Boulvain *et al*., 2011). The most common corals are small platy colonies of by *Frechastraea micrastraea*, and *Phillipsastraea ananas* the solitary *Macgeea pauciseptata* and *Tabulophyllum implicatum* (Birenheide *et al.* 1991). The tabulate corals are dominated by alveolitids and *Thamnopora micropora* (Lecompte, 1939), cladoporids *Egosiella* sp. and *Senceliaepora tenuiramosa*. The lateral shaly facies yields a diverse brachiopod fauna mainly including mainly atrypids and athyridids. The crinoids are rather common and calices of *Melocrinites* ssp. are not rare in the bioclastic lenses. Conodonts have been investigated in detail by Tourneur (1982) and Sandberg *et al. in* Bultynck *et al.* (1988).

Fig. 10: **A. View of the Beauchâteau quarry at Senzeille (Petit-Mont Member). B. Top of Beauchâteau mudmound: emersion–transgression surface capping the grey restricted lime mudstone with fenestrae.**

6.3. Nord Quarry, Frasnes

References
Maillieux (1913), Lecompte (1954), Boulvain & Coen-Aubert (1997), Mottequin & Poty (2015).

Location and access
Large active quarry, northwest of the village of Frasnes near Couvin, southern limb of the Dinant Synclinorium (Fig. 1). GPS: 50°04'46.67'4°29'46.46'E.

Stratigraphical units and age
Grands Breux Fm (Lion and Boussu-en-Fagne members); Middle Frasnian (*hassi s.l.* Zone).

Description
This very large (900 m x 300 m) active quarry (Carmeuse S.A.) intensively extracts the limestones of the Lion Mbr for the production of lime. It allows the observation of the top of the Boverie Mbr and all the third-order sequence ('Lion sequence') corresponding to the onset and the vertical and lateral evolution of a Lion build-up (Figs 6, 11).

During the Middle Frasnian, the onset and vertical growth of the three levels of build-ups (Arche, Boverie and Lion, Figs 6, 11) correspond to the transgressive system tract (TST) of the sequences. During the high-stand (HST) and the falling-stage system tracts (FSST), their vertical growth decreased, and they evolved to progradant carbonate platforms, 1–3 km wide and up to 140 m high (including the biohermal core), in which boundstone is replaced by packstone–grainstone, then by shallow-water and intertidal mudstone (FSST). There is no evidence for the development of atolls rimmed by stromatoporoid-coral barriers, as it has been suggested.

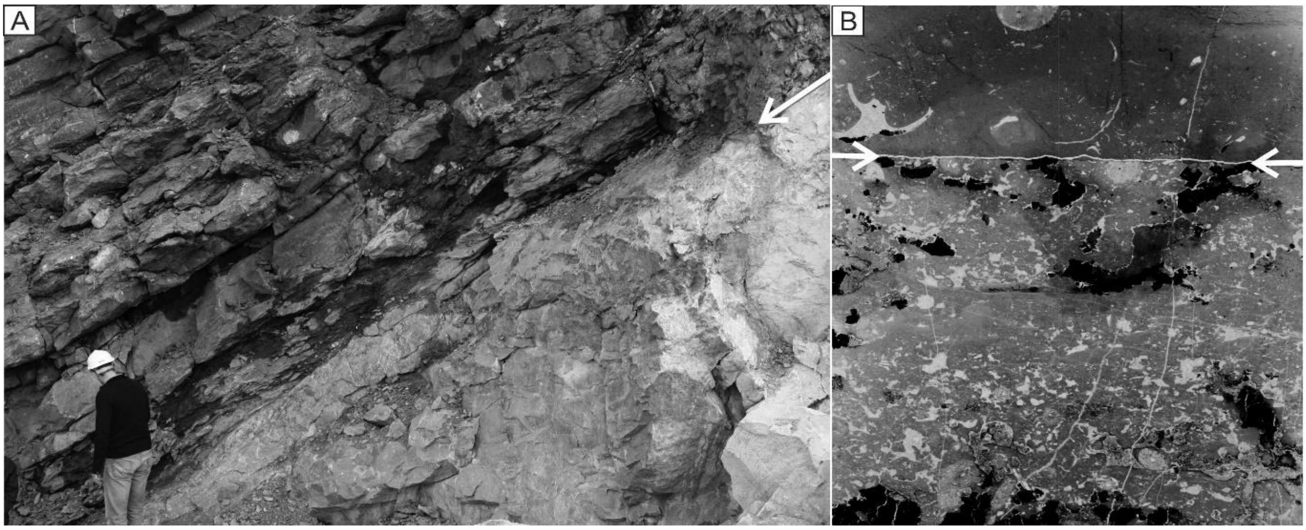

Fig. 11: **A.: Emersion–transgression surface on the top of La Boverie Mbr (arrow) and the base of the 'Lion reef sequence' in the La Boverie quarry at Jemelle. B. Thin section of the emersion-transgression surface at the top of the La Boverie Mbr (restricted shallow water mudstone with *Amphipora* and fenestrae) and the base of the 'Lion reef sequence' (open marine mudstone with shells).**

The final emersion of these reef-platforms in the distal areas of the basin, and of the carbonate platform in the proximal areas, stopped the carbonate production until the following transgression–regression sequence (Fig. 11). The last (third) Middle Frasnian regression caused the end of the Lion buildup and of the middle Frasnian type reefs in proximal facies (see the description of the Prayon section, Fig. 6).
The sequence starts with shale, calcareous shale and thin-bedded limestone rich in crinoids, tabulate and rugose corals developing from an emersion-transgression surface on the top of the Boverie Mbr (Figs 11, 12). These deposits can be considered as the LST of the sequence. The development of crinoidal rudstones stabilized the substrate and triggered the dominant vertical growth of a build-up (massive bounstone) made of stromatoporoids, stromatactis and corals (TST of the sequence).

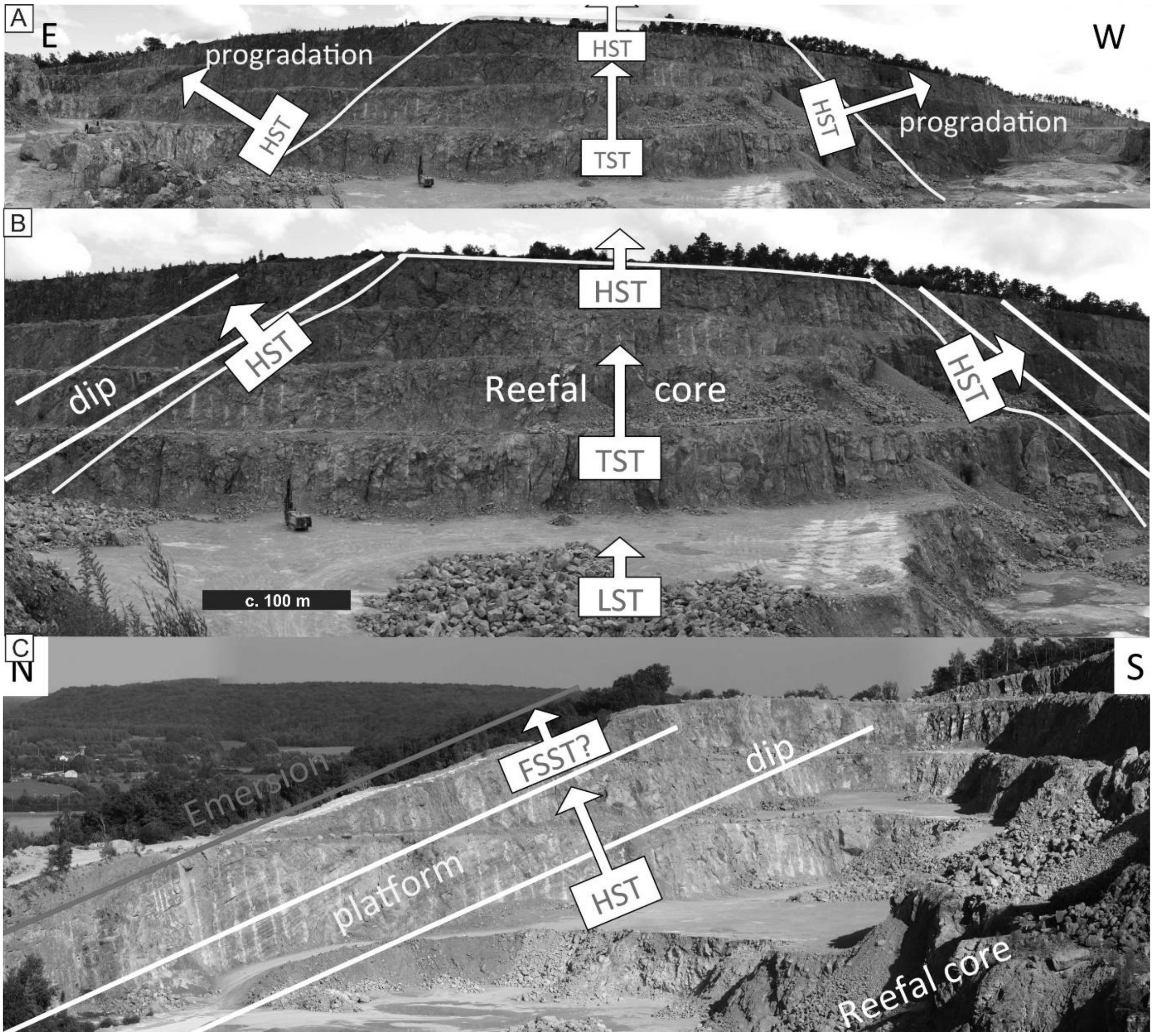

Fig. 12: **A. General view of the Nord quarry at Frasnes showing the wide progradation of limestone deposits compared to the reefal core of the Lion Mbr. B. Eastern central part of quarry showing the reefal core and the lateral prograding carbonates. C. View of the south-eastern part of the Nord quarry showing the aggrading carbonate platform and its final emersion. The limestone beds are moderately dipping northwards.**

The decrease in the sea-level rise (HST) caused a decrease in the aggradation of the carbonates and the end of the building phase (Fig. 12B). It gave way to a progradation from the 20–30° slopes of the bioconstruction and the development of a carbonate platform (Figs 12C, 13).The prograding limestones are mainly irregular beds of packstone and grainstone, with some corals and stromatoporoids, sometimes including blocks from the edge of the platform; slumps can be present. The platform is made of bioclastic limestone, then of wackestone to mudstone with *Amphipora* and fenestrae. The latter are typical of restricted shallow water to intertidal environment and mark the end of the HST and possibly the beginning of the FSST. They are topped by an emersion surface (Figs 12C, 14). There is no trace of bioconstruction at the edge of the platform which seems to be not an atoll as usually suggested.

Fig. 13: **South-eastern face of Nord quarry at Frasnes showing irregular beds of the HST prograding limestone on the slope of the reefal core. The dips correspond more or less to the original dip of the deposits**.

6.4. Lion Quarry, Frasnes

References

Lecompte (1954, 1960, 1963), Mouravieff (1970, 1974), Tsien (1974, 1975, 1977, 1980), Bultynck *et al.* (1988b), Boulvain & Coen-Aubert (1991), Sandberg *et al.* (1992), Coen-Aubert (1994), Bultynck *et al.* (1998), Vanguestaine *et al.* (1999), Guillot *et al*. (2006), Boulvain *et al.* (2011).

Location and access

Southernmost access trench to the disused Le Lion quarry south-east of Frasnes, southern limb of the Dinant Synclinorium (Fig. 1). GPS: 50°04'18.97'N4°30'38.89'E.

Stratigraphical units and age

Grands Breux (Lion and Boussu-en-Fagne members) and Neuville formations. Middle to Upper Frasnian. Upper *hassi* to lower *rhenana* zones (Sandberg *et al*., 1992). Very detailed conodont analysis of the Lion section was published by Sandberg *et al.* (1992). According to these authors, the Boussu-en-Fagne Mbr belongs to the upper part of the upper *hassi* conodont Zone. The Neuville Fm is placed entirely within the lower *rhenana* conodont Zone (Bultynck *et al*., 1998). CAI values ranging between 3 and 4, which corresponds to burial temperature of 120-190°C (Helsen, 1992).

Description

The Grand Breux Fm contains the Lion Member buildup overlain by the shaly Boussu-en-Fagne Mbr. The base of the Neuville Fm is observed in the upper part of the section. The massive light grey limestone of the Le Lion Member were formerly intensely quarried for lime production; the thickness of the buildup probably attains 150 m. The contact between the massive limestone of the Lion Mbr and the essentially shaly Boussu-en-Fagne Mbr is clear-cut (Fig. 14B). The latter includes some levels rich in carbonate nodules and some decimetre- to pluridecimetre-thick beds of nodular limestone in its uppermost part. Macrofauna is sometimes abundant in the lower part of the Boussu-en-Fagne Mbr and includes brachiopods, corals, gastropods and trilobites. The overlying Neuville Fm starts with nodular to massive limestone alternating with thin beds of nodular shale and continues with nodular shale with rare brachiopods and solitary rugose corals with some intercalations of nodular limestone (Fig. 15). The stratification is dipping 45° to the North and a minor fault is present on the northern flank of the main trench in the Boussu-en-Fagne Mbr implying that some beds are not any more visible there. Nevertheless, the southern flank of the trench contains the missing beds allowing a complete sampling along that section without any gap.

The base of the section is represented by 11 m of grey, bioclastic limestone of the Lion mud mound. At the very base of the Boussu-en-Fagne Mbr, a rapid rise in sea-level effectively drowned the Lion build-up. The Boussu-en-Fagne Mbr is more than 43-m thick and begins with 4 m of grey nodular bioclastic (brachiopods, crinoids, corals such as *Alveolites*, *Thamnopora*, *Hexagonaria*, etc.) shale. It passes abruptly upwards into green shale containing discrete calcareous nodules interbedded with carbonate layers. Temporary increase in energy is attested by the presence bioclastic beds possibly corresponding to storm deposits. Five thicker bioclastic limestone beds alternating with shale are observed overlaid by 3.5 m of green shale with carbonate nodules corresponding to the end of the Boussu-en-Fagne Mbr.

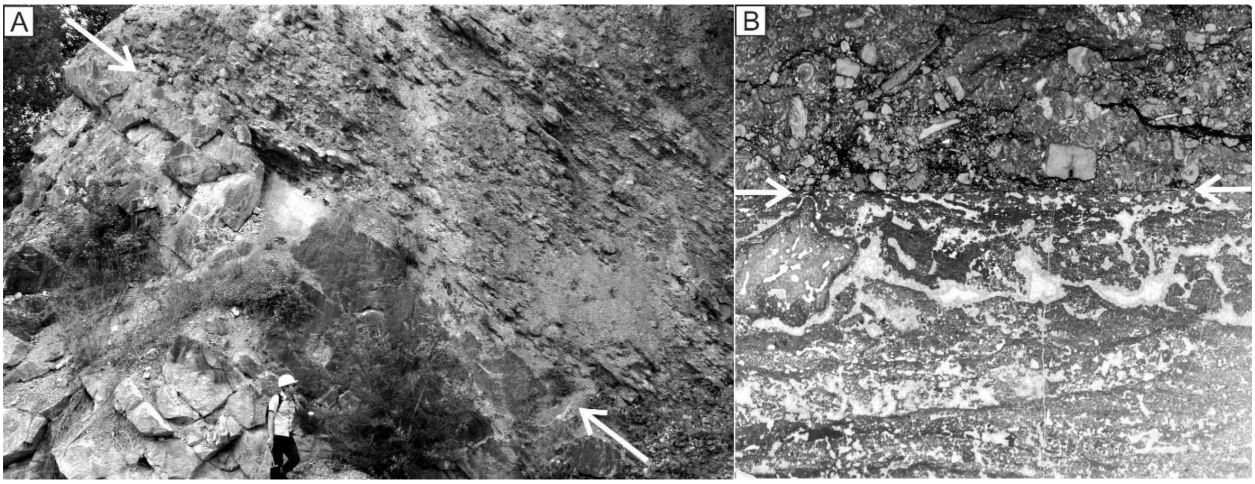

Fig. 14: **A. Clear-cut contact between restricted limestone of the Lion Mbr and the open marine shale with limestone beds and numerous corals of the Boussu-en-Fagne Mbr (Nord Quarry, Frasnes), corresponding to an emersion-transgression surface (arrows), Bernard Mottequin for scale B. North quarry (Frasnes), view in thin section of the emersion-transgression surface (arrows) on the top of restricted mudstone with fenestrae (top of the Lion carbonate platform) and the base of open marine crinoidal packstone (base of the Boussu-en-Fagne Mbr).**

The Neuville Fm starts with 4.5 m of shale containing abundant carbonates nodules and reddish mudstones containing brachiopods. The following 8.5 m are characterized by alternating nodular limestones and green shale.

Following the sequential analysis of Boulvain & Herbosch (1996), the upper part of the Lion Mbr was traditionally interpreted as a highstand system tract (HST) overlaid by a transgressive surface and the transgressive system tract (TST) corresponded to the Boussu-en-Fagne Member. The Neuville Fm is thus indicative of the next HST The alternative explanation developed here is that the Lion Mbr is the HST and FSST, the Boussu-en-Fagne Mbr is the LST of the following sequence, and the Neuville Fm is the TST of the 'Aisemont sequence' (see Figs 6, 12).

This section was recently (2014, Devleeschouwer and colleagues) sampled at very high resolution (5 cm) for magnetic susceptibility measurements and more than 250 measurements of gamma-ray spectrometry were also done every 25 cm throughout the whole section. Moreover, the section contains five bentonite layers distributed in the upper part of the Boussu-en-Fagne Mbr and the Neuville Fm. These ash-fall deposits have a yellow-brown clay texture from a few mm to 2 cm thick. Two bentonite were studied in details and zircons extracted for datations. They all occur in the same (Lower *rhenana*) conodont Zone. At the base of the lower *rhenana* conodont Zone, zircons yield an age of 377.2 ± 0.5 Ma based on 10 concordant fractions including several CA-TIMS fractions but heritage is suspected. Higher upwards in the section but in the *jamieae* conodont Zone, a more reliable age of 370.4 ± 0.6 Ma is obtained and based on 4 fractions by CA-TIMS (Guillot *et al*., 2006). These datations are not concordant with the age obtained on the bentonite of the Steinbruch Schmidt quarry by Kaufmann *et al*. (2004).

Main faunal components

The main Lion trench is the locality where ten species belonging to the rugose corals genera *Hexagonaria*, *Aristophyllum*, *Phillipsastrea*, *Frechastraea*, *Scruttonia*, *Peneckiella* and *Trapezophyllum* have been recognized in the Boussu-en-Fagne Member and Neuville Fm (Coen-Aubert, 1994).

The conodonts have been described by Sandberg *et al.* (1992) whereas the organic debris and palynomorphs have been investigated by Vanguestaine *et al.* (1999).

Mottequin (2005) listed the brachiopod fauna. The Boussu-en-Fagne Mbr yields *Costatrypa variabilis*, *Exatrypa marmoris, Adolfia* sp. *Emanuella* sp., *Cyrtina* sp., *C. douvellei, Athyris* cf. *murchisoni*, *A. oehlerti*, *Douvillinia dutertrei*, *Nervostrophia* sp., *Productella subaculeata*, *Schizophoria* gr. *striatula*, *Coeleterorhynchus* sp., *Hypothyridina cuboides* and indetermined Pugnacidae and Pentamerida.

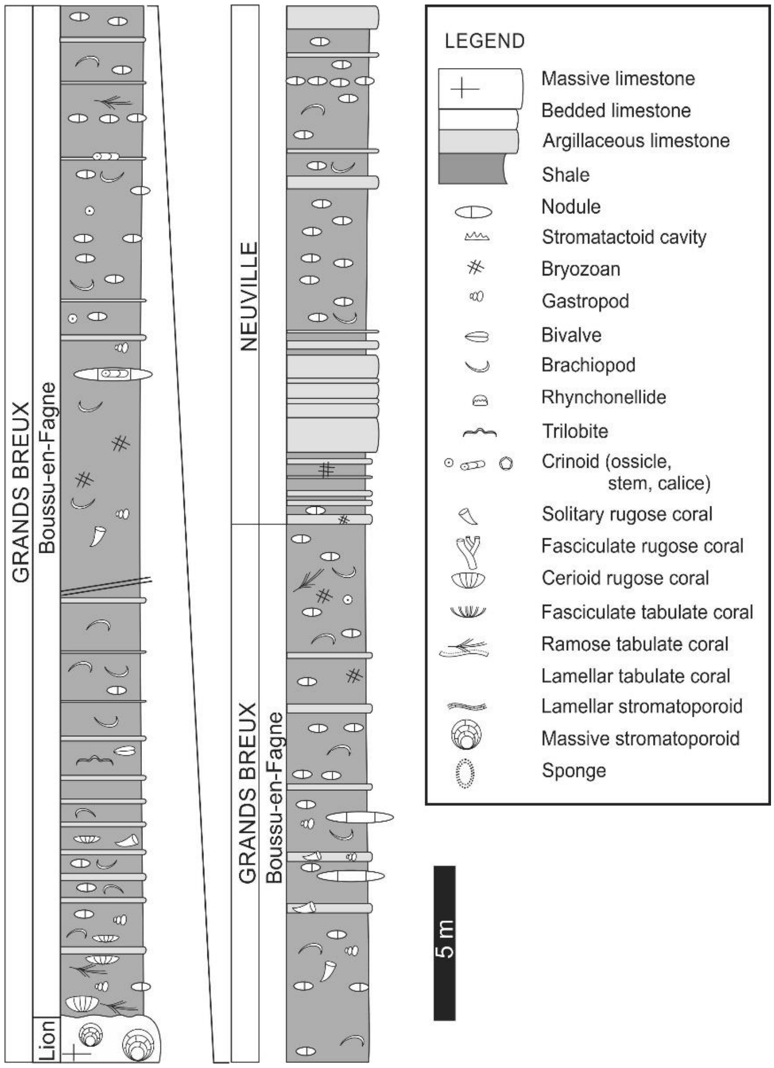

Fig. 15: **Lithological column of the Lion trench with the bioclastic content observed in thin sections (modified from Mottequin (2005) and Boulvain & Coen-Aubert (1991)).**

6.5. Tchafornis park (Engis)

References

Poty & Chevalier (2007), Boulvain *et al.* (2011), Mottequin *et al.* (2013), Mottequin & Poty (2015).

Location and access

Disused quarry near the center of Engis, redeveloped as a public park (Tchafornis park). Southeastern part of the Brabant Parautochton (Fig. 1). GPS: 50°35’03.26’N5°24’19.88’E.

Lithostratigraphy and biostratigraphy

Lustin Fm and lower part of Aisemont Fm (Middle Frasnian and lower part of the Upper Frasnian). Both the upper part of the Lustin Fm and the lower member of the Aisemont Fm are situated in the lower *rhenana* conodont Zone (Bultynck *et al.* 2000: Gouwy & Bultynck 2000). The lower member corresponds to the first coral assemblage of Coen *et al.* (1977; ‘first biostrome with *Phillipsastrea*’).

Description

The upper part of Lustin Fm (16.5 m thick, Fig. 16) is composed of plurimetre-thick shallowing-upwards sequences comprising typically from the base to top: (1) bioclastic limestone (wackestone, packstone) rich in stromatoporoids, tabulate and rugose corals, and (2) mudstone and stromatolitic boundstone. The latter dominates the upper part of the section. Nodular argillaceous beds correspond to palaeosols developed from cineritic levels. One of them, 75 cm thick, is possibly the same than the one observed in the Prayon section.

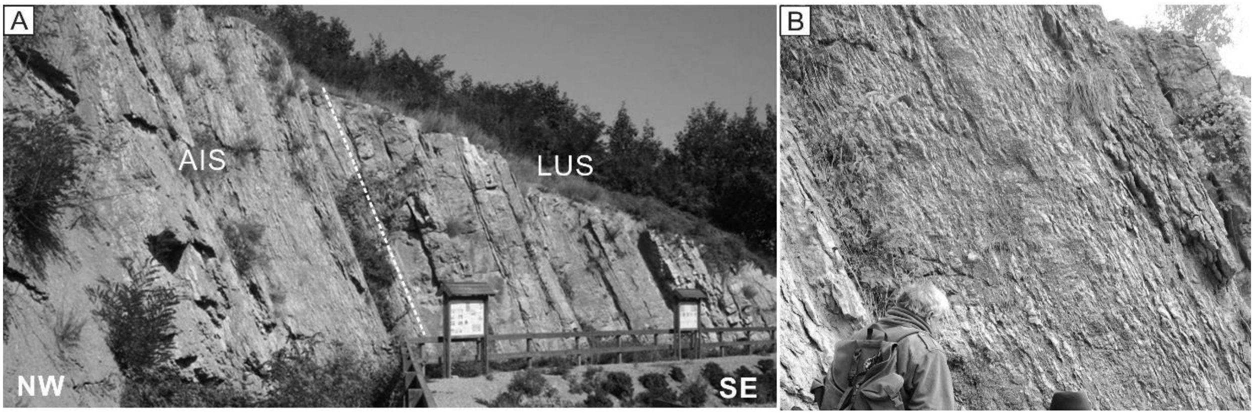

Fig. 16: **A. View of the former Tchafornis quarry at Engis. The section is reversed: the Lustin Fm is at the right of the left panel, the Aisemont Fm at left. B. Close-up view of the *Frechastraea* biostrome (unit B on Fig. 17). Abbreviations: AIS: Aisemont Fm (lower member); LUS: Lustin Fm.**

The lower member of Aisemont rests disconformably on an erosional transgressive surface capping the Lustin Fm. It can be divided into four units, from base to top (Fig. 17):

1) A 40 cm-thick unit of more or less argillaceous wackestone to grainstone, strongly bioturbated, rich in siliceous sponge spicules and crinoids, including some layers of calcareous shale. It contains numerous colonies of *Frechastraea* and *Alveolites*, mostly in living position (Fig. 16).

2) A 3.7 m-thick coral autobiostrome composed mainly of *Frechastraea* and *Alveolites*. *Frechastraea* colonies are laminar and discoid, from a few centimetres up to 80 cm in diameter, and from a few millimetres to 7 cm thick. It is remarkable that there were not firmly attached to the substrate (a dead colony), but they hug tightly it and rest intimately on it to resist to the turbulence. *Alveolites* are laminar to conical, encrusting the substrate. *Phillipsastrea* colonies and laminar stromatoporoids are also present, taking the same shape and strategy than *Frechastraea*. Colonies of rugose corals are often overturned, being used as substrate for other ones. The density of the frame builder can reach 90% of the rock (Poty & Chevalier, 2007; Fig. 16). The matrix is a shale or a slightly argillaceous packstone.

3) A 1.5 m-thick, more or less dolomitized, argillaceous limestone passing to calcareous shale, with numerous *Frechastraea*, *Alveolites* and *Hankaxis*, and some *Phillipsastrea*, often tipped or overturned. The shape of the colonies varies from tabular to domal, with margins more or less ragged. Some of the ragged domal colonies show a deflected growth indicating a response to an unidirectional current. *Alveolites* are domal to columnar, from some cm up to 15 cm in height.

4) A 35 cm-thick argillaceous diagenetic dolomite with some rugose and tabulate corals. This unit is overlain by the shale of the middle member of the formation.

The first unit is considered as being deposited within the fair-weather wave zone, with episodes of clay deposition, as the base of the transgressive phase (Fig. 17). The second, biostromal unit developed in an argillaceous environment with uncommon limestone inputs, in the fair-weather wave zone and commonly disturbed by storm waves. That environment usually does not allow the growth of stromatoporoids. The third unit deposited in an environment probably below the fair-weather wave zone, but subjected to bottom currents and affected by storm waves. The relatively high rate of carbonated argillaceous sedimentation affected the coral growth and prevented the growth of stromatoporoids and bryozoans. The last unit corresponds to a similar, but slightly deeper than the previous one.

Main faunal components

The Lustin Fm includes corals that are not precisely identified such as *Disphyllum* sp., *Arguastrea* sp. and *Alveolites suborbicularis*. Stromatoporoids include massive forms and *Amphipora*.

The lower member of Aisemont Formation yields *Frechastraea limitata* (the most common), *F. pentagona*, *Phillipsastrea ananas*, *Hankaxis insignis*, uncommon *Tabulophyllum* sp. and *Peneckiella* sp., *Alveolites tenuissimus*, *A. suborbicularis*, *Aulopora serpens*, *A. repens*, uncommon fragments of *Thamnopora* sp., *Scoliopora* sp., and laminar stromatoporoids. Brachiopods are rare (e.g. atrypids).

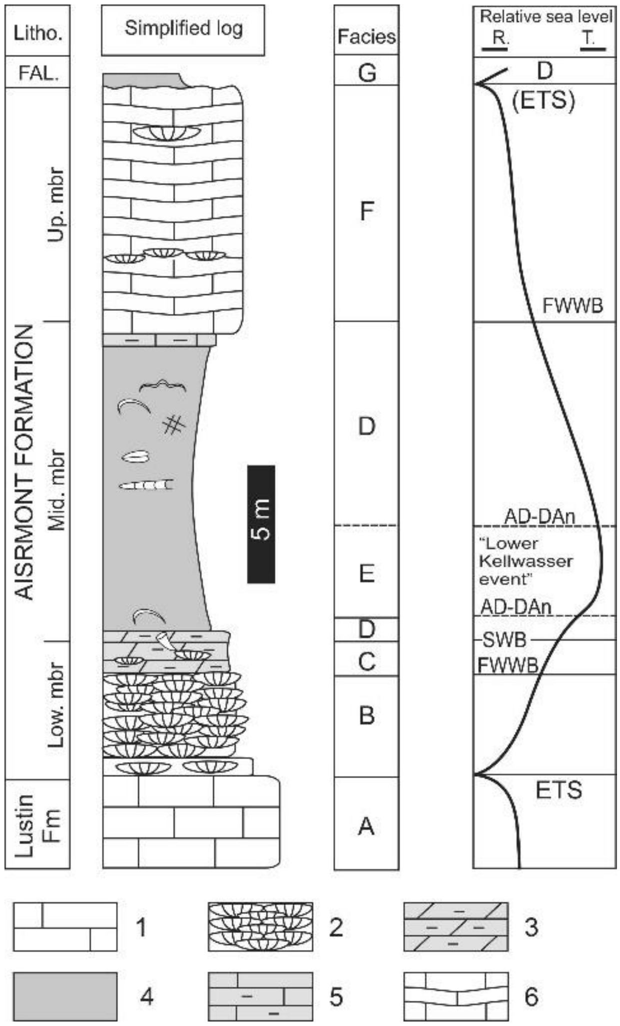

Fig. 17: **Log of the Aisemont Fm in Engis and La Mallieue sections. A, limestone with corals and stromatoporoids (including *Amphipora*) or with stromatolites, of open marine to restricted environment; B, *Frechastraea-Alveolites* biostrome in the fair-weather wave zone with argillaceous input; C, coral meadow on soft carbonate-argillaceous substrate in the storm wave zone; D, brachiopod association in an aerobic-dysaerobic argillaceous environment under the storm wave base; E, dysaerobic-anaerobic argillaceous facies; F, coral-oncolites open-marine limestone facies; G, carbonated argillaceous environment; R and T, regressive and transgressive relative sea level; ETS, disconformity (erosion transgressive surface); FWWB, fair-weather wave base; AD-DAn, aerobic to dysaerobic-anoxic transition; SWB, storm wave base; 1, limestone; 2, biostrome; 3, dolomitic shale; 4, shale; 5, calcareous shale; 6, argillaceous limestone; 7, colonial coral; 8, oncolite; Litho, lithostratigraphy; FAL., Falisole Fm. (modified from Poty & Chevalier, 2007).**

6.6. La Mallieue section (Engis)

References

Coen-Aubert & Lacroix (1979), Poty & Chevalier (2007), Denayer & Poty (2010), Mottequin & Poty (2015).

Location and access

Small cliff along the road Flemalle-Huy on the northern bank of the Meuse rive, c. 2km west of Engis. Southeastern part of the Brabant Parautochton (Fig. 1). GPS: 50°24’23.06’N5°22’54.18’E.

Lithostratigraphy and biostratigraphy

The three members of the Aisemont Fm are exposed (Fig. 17). They belong to the Late Frasnian lower to upper *rhenana* conodont zones (Bultynck *et al.*, 2000: Gouwy & Bultynck, 2000). The lower member corresponds to the first coral assemblage of Coen *et al.* (1977; ‘first biostrome with *Phillipsastrea*’), the upper member corresponds to the second coral assemblage (‘second biostrome’).

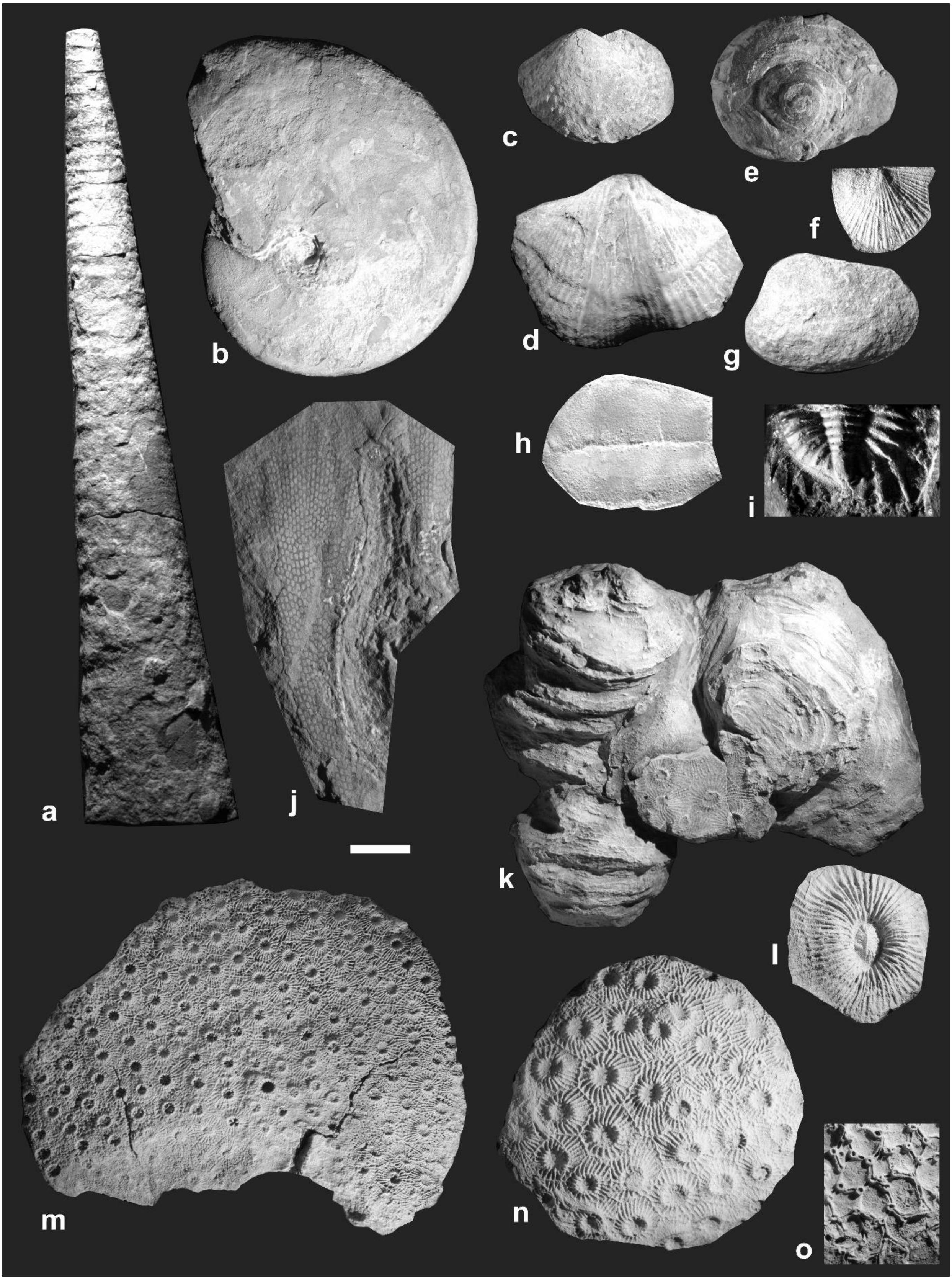

Fig. 18: **Selected late Frasnian macrofauna from La Mallieue section; a: indet. orthocerid; b: *Manticoceras* sp.; c: *Productella* sp.; d: *Cyrtospirifer verneuili*; e: indet. straparollid gastropod; f: indet. Pectinid pelecypod; g: indet. pelecypod; h: *?Euletherocaris* sp.; i: *Bradocryphaeus* sp.; j: *Fenestella* sp.; k: *Hankaxis insignis* (left) and *Frechastraea pentagona* (a large overturned colony overgrown by a smaller one); l: *Hankaxis insignis*, calicinal view; m: *Frechastraea pentagona*; n: *Phillipsastrea ananas*; o: *Aulopora reptens* incrusting a *Frechastraea* colony. A-J are from the middle shaly member of the Aisemont Fm, k-o are from the lower member of the formation. Scale bar equals 10 mm except for f, h, i and o (5 mm).**

Description

The lower member of the Aisemont Fm presents the same characteristics than in the previous section. The middle shaly member, known in the Belgian literature as 'intermediate shales', presents four facies: (1) the lowest 70 cm are made of dolomitized calcareous shale with spiriferid brachiopods; (2) the following 4 m of greyish shale are almost devoid of fauna; (3) 7.3 m of brownish shale, sometimes slightly calcareous containing brachiopods (spiriferids, small productids), lingulids, 'paper pectens', abundant fenestellid bryozoans, gastropods, phyllocarid remains, trilobites, orthocerids and rare goniatites (Fig. 19); and (4) the last meter of shale is calcareous and bioturbate passing to an argillaceous limestone with abundant brachiopods and gastropods.This middle member deposited below the fair-weather wave zone and recorded a deepening-upward trend (TST) culminating in the second facies which is interpreted as the maximum flooding surface of the sequence and correlated with the Lower Kellwasser Event (Figs 6, 17). The following facies recorded the shallowing-upward trend of the HST which continues in the third member of the Aisemont Fm.

The upper member starts with a 2 m-thick unit of thinly-bedded bioturbated bioclastic mudstone and wackestone, often dolomitized. It passes upwards to bioclastic packstone then grainstone with numerous oncoids and uncountable *Paralitanaia* (udoteacean green algae), *Radiosphaeroporella*, *Sphaerocodium*, *Girvanella* and umbellids. A 60 cm-thick bed, situated 5.2 m above the base of the member, is a framestone with *Alveolites* and domal stromatoporoids. An emersion surface caps the member but is poorly exposed. This member was deposited in a shallow-water proximal ramp but under marine influence as shown by the presence of open-see organisms such as trilobites and fistuliporid bryozoans (Ernst *et al.*, 2014). The member is interpreted as the HST and FSST of the third order Aisemont sequence (Denayer & Poty, 2010) (Figs 6, 17).

Main faunal components

The lower member of Aisemont Formation yields the same fauna recorded at the Tchafornis park section (see above). Its middle member includes notably orthocerids, *Manticoceras*, numerous brachiopods (*Costatrypas* sp., *Cyrtospirifer verneuilli*, *C. condrusorum*, *Adolfia* sp., indet. Productidina, *Retrorstrophia retrorsa, Gamphalosia* sp., *Ripidorhynchus* sp., *Schizophoria* gr. *striatula;* Mottequin, 2005) and lingulids, bryozoan, bivalves (including pectenids), straparollid grastopods, trilobites and phyllocarid remains (Fig. 18). The upper contains *Phillipsastrea ananas, Frechastraea pentagona, Alveolites suborbicularis* and a diverse microflora (dasycladacean: *Paralithanaia*).

6.7. Prayon section (Vesdre Area)

References

Rensonnet (2005), Poty & Chevalier (2007), Boulvain *et al.* (2011).

Location and access

Disused quarry and outcrops on the corner of the northern flank of the Magne river valley at Prayon (Trooz) in the western part of the Vesdre tectonic unit (Fig. 1). GPS: 50°34'49.29'N 5°40'14.27'E.

Lithostratigraphy and biostratigraphy

The section exposes the Pepinster Fm (Middle Devonian), Lustin Fm (Middle Frasnian) and lower part of Aisemont Fm (lowermost Upper Frasnian). The uppermost part of the Lustin Fm is, by correlation, situated in the lower *rhenana* conodont Zone, as the lower member of the Aisemont Fm (Bultynck *et al*,. 2000: Gouwy & Bultynck, 2000). The lower member corresponds to the first coral assemblage of Coen *et al*. (1976; 'faune 1').

Description

In the Prayon area, the Lustin Formation is about 45 m thick; it overlies directly the red silstone of the Pepinster Fm. The 15 m exposed in the section are composed of limestone showing metre- to plurimetre-thick succession of shallowing-upward sequences. A typical cycle starts with a transgressive rudstone with dense accumulation of reef-builders (bulbous stromatoporoids, fasciculate, massive, and solitary rugose and tabulate corals forming parabiostromes) passing upwards to more proximal mudstone/wackestone with lagoonal fauna and flora to supratidal facies. In the upper part of the Lustin Fm the top of the cycles are characterized by a succession of floatstone/rudstone with *Amphipora* passing to bioturbated mudstone and thin-bedded stromatolitic limestone with bird-eyes. The subtidal facies were developed under the fair-weather wave base within a shallow carbonate platform occasionally affected by tropical storms. The overall succession evidences a clear shallowing-upward trend.

The section contains two autobiostromes. The first one crops out spectacularly along the hillside (35 m² plan view), depicting a seafloor dominated by *Disphyllum* sp. and *Alveolites*. The overturning rate is low with 85% of these colonies being in living position. The exceptional level of conservation is due to a draping 40 cm-thick argillaceous deposit. This layer is interpreted as a cinerite subsequently transformed in a calcrete-type palaeosoil. Large lobate carbonate nodules found in troughs of the autobiostrome top surface result from the presence of an arborescent palaeoforest. The second autobiostrome terminates the section and consists of a bindstone made of laminar and tabular stromatoporoids. This latter bed may represent the transition to the 'lagoonal unit' referenced by Coen-Aubert & Lacroix (1978) (A in Fig. 19).

The upper part of the Lustin Fm with its typical lagoon-type limestone and the Aisemont Fm crop out 250 m northwards along a footpath. The section exposes 3 m of bioclastic limestone rich in corals and stromatoporoids of the top of the Lustin Fm, and the lower limestone member of the Aisemont Fm (11 m thick) resting disconformably on an erosional transgressive surface capping the Lustin Fm. The lower member can be divided into three lithological units which are more or less dolomitized (Poty & Chevalier, 2007):

(B in Fig. 19) The lower unit comprises 2.7 m of decimetre to pluridecimetre-thick bedded packstone, bioturbed and slightly argillaceous, with numerous laminar stromatoporoids and common laminar to tabular *Alveolites* and *Frechastraea*. The latter may be reworked and overturned, but the stromatoporoids and *Alveolites* are in living position, encrusting and stabilizing the substrate. The base of the unit is slightly sandy. This first unit was deposited in a shallow-water environment, under a moderate influence of the fair-weather wave zone, but subjected to storm waves, as indicated by the reworked fossils. The argillaceous input was low, allowing the growth of stromatoporoids, *Alveolites* and sponges, which stabilized the substrate.

(C) The middle unit is composed of 1.5 m of massive bioturbated packstone with numerous laminar to tabular *Frechastraea* and common laminar *Alveolites* acting as sediment binders in a coral meadow. Laminar stromatoporoids are uncommon and only present at the base of this unit, their growth has likely been prevented by the high sedimentation rate. Corals are partly reworked and overturned. A slightly deeper environment is suggested by the general evolution of the section, still subjected to storm waves.

(D) The upper unit is a 6.7 m-thick autobiostrome composed of laminar *Alveolites*-stromatoporoid bindstone with some *Frechastraea*. The matrix varies from packstone to mudstone-wackestone, sometimes slightly argillaceous. It formed under or near the storm-wave base and was subjected to input of limestone sediments, maybe triggered by storms.

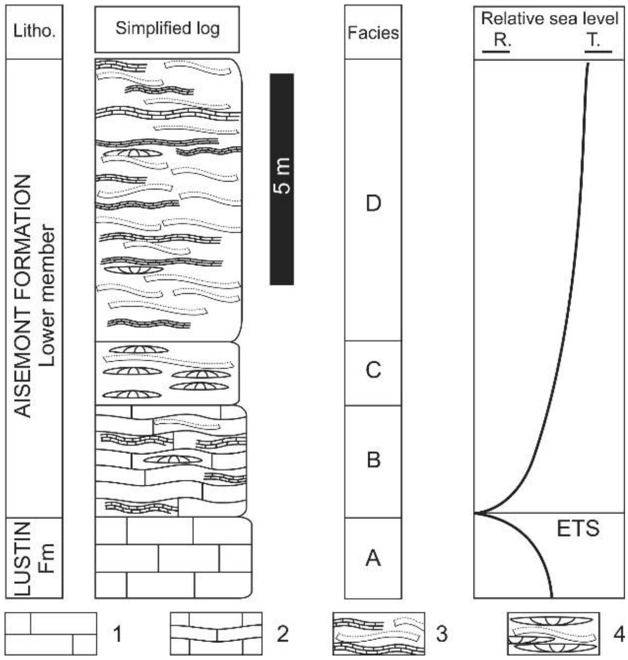

Fig. 19: **Log and facies evolution of the lower member of the Aisemont Fm at Prayon. A, open-marine coral-stromatoporoid limestone; B, laminar stromatoporoid-coral biostrome; C, *Frechastraea-Alveolites* biostrome; D, laminar *Alveolites*-stromatoporoid biostrome. R and T, regressive and transgressive relative sea level; D (ETS), disconformity (transgressive erosion surface); Litho, lithostratigraphy; Fm, Formation; 1, limestone; 2, slightly nodular limestone with stromatoporoids and corals; 3, *Alveolites*-stromatoporoid biostrome; 4, limestone with corals; 5, laminar stromatoporoid; 6, laminar *Alveolites*; 7, phillipsastreid (from Poty & Chevalier, 2007).**

Main faunal components

See Tchafornis section.

7. References

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The Famennian succession: marine, continental and reefal facies in the Dinant Synclinorium and Vesdre area

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Abstract
Southern Belgium is a classical area for the study of the Famennian sedimentary succession. Here are presented three localities providing an insight of the whole regressive Famennian with a particular view on the proximal-distal duality. The Rochefort section is one of the rare outcrop showing the Lower Famennian Famenne Formation which is particularly fossiliferous. The Limbourg quarry exposes the unique Middle Famennian Baelen reef from its microbialitic core to the crinoidal lateral facies. The quarry being partly undergroungit provides a unique three-dimensional view of the reef facies. The Tienne des Marteaux Quarry is a good example of proximal facies of the Belgian Famennian, with alluvial and fluvial deposits commonly rich in plant and vertebrate remains.

1. Introduction

The international stage Famennian was defined in Belgium. Its type localities are located in the Dinant Synclinorium and Vesdre area. Several hundred outcrops have been recorded ranging from small rocks to hundred meters wide quarries and railway sections. They expose a variety of depositional conditions ranging from immediately near the continental margin up to distal sediments. This excursion aims to provide an overview of main sedimentary and palaeoenvironmental settings of the Belgian Famennian to prove its value as an international stage.

2. Historical background

The term 'Famennian' was first used by Dumont (1855) in its legend of the '*Carte géologique de l'Europe*' as referring to the siliciclastic '*Psammites du Condroz'* of d'Omalius d'Halloy (1868) (which included the Upper Frasnian shales). Mourlon (1875-1886) was the first to divide the Famennian succession in lithostratigraphical units ('*assises*' in the old literature) among which many have since been redefined as Formations. Gosselet (1878, 1879, 1880) recognized major facies changes in the Namur-Dinant Basin and correlated the Condroz Psammites with the more distal units in the southeastern part of the Basin and Avesnois area (N France). The Belgian Famennian biostratigraphical scheme is the result of works by Sartenaer (1957, rhynchonellids), Bouckaert *et al*. (1965, 1968, 1969), Dusar & Dreesen (1984, conodonts), Thorez *et al*. (1977) (spores) and Conil *et al*. (1986).

The sedimentological and palaeoecological studies are mainly due to Thorez *et al.* (1977, 1988), Thorez & Dreesen (1986) and Paproth *et al.* (1986). The synopsis by Thorez *et al.* (2006) summarizes the mot recent knowledge of the Belgian Famennian.

The base of the Famennian Stage is defined as the base of the Lower *Palmatolepis triangularis* Zone. The Global Stratotype Section and the Point for the Frasnian/Famennian boundary was defined in Coumiac (Montagne Noire, S France, Klapper *et al*., 1993). The upper boundary of the Stage coincides with the Devonian-Carboniferous Boundary defined by the entry of the conodont *Siphonodella sulcata* (currently controversial, see Aretz (2013)). The Famennian historical type sections are situated in the Ourthe area between the towns of Esneux and Comblain-la-Tour and in the Famenne area (around Mariembourg and Senzeilles) but most of them are nowadays badly exposed (Thorez *et al*., 2006). Fortunately, numerous good-quality sections will be visited during the excursion.

3. Geological settings

The Famennian succession witnesses of a large-scale regression. It immediately follows a period of very high relative sea level that corresponds to the Givetian-Frasnian interval. In the sediments, these changes are marked by a transition from a mainly carbonate sedimentation in the Givetian – mid-Frasnian to thick argillaceous deposition during the Late Frasnian and Early Famennian. During the rest of the Famennian, siliciclastics dominate with the notable exceptions of the carbonate Souverain-Pré Formation and its reefal Baelen Member.

During this time slice, the Namur-Dinant Basin was situated along the southeastern margin of Laurussia on the Rheno-hercynian Ocean at an estimated latitude of 20°S (Stampfli *et al*., 2013). It underwent the variscan orogeny during the Late Carboniferous and now belongs to the northern part of the Rhenohercynian fold and thrust belt. The Famennian succession is exposed along the borders of the Dinant Synclinorium, Haine-Sambre-Meuse overturned trust sheets (former 'southern limb of the Namur Synclinorium), the Brabant Parautochton (former 'northern limb of the Namur Synclinorium'), the Theux Tectonic Window and the Vesdre area (Fig. 1). The most proximal facies are found along the Brabant Parautochton and Vesdre area, the deepest and most marine facies are found in the SW part of the Dinant Synclinorium and Avesnois area.

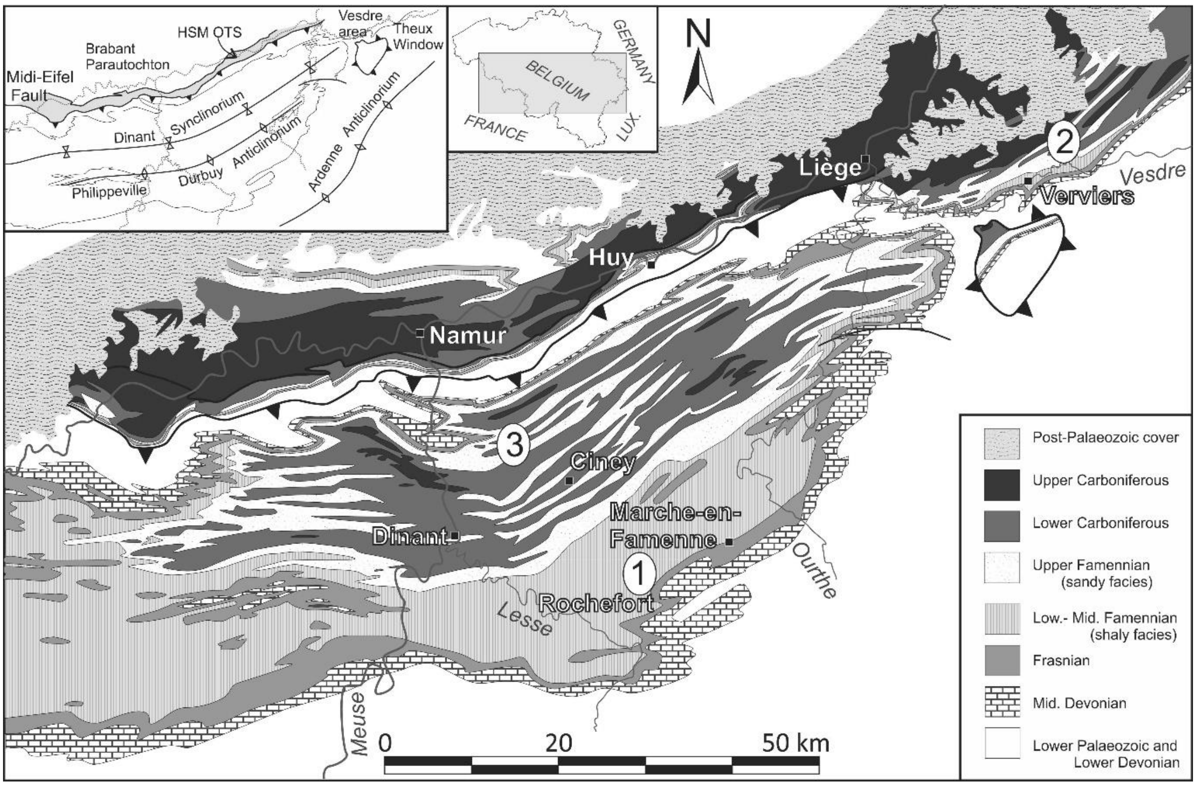

Fig. 1: **Schematic geological map (modified after de Bethune (1954)) with location of the visited sections: (1): Rochefort section, (2): Limbourg underground quarry; (3): Spontin Tienne des Marteaux Quarry.**

4. Lithostratigraphy and Depositional evolution

The lithostratigraphy and depositional settings have been described and discussed by Thorez & Dreesen (1986), Thorez *et al.* (1977), Paproth *et al.* (1986) Thorez *et al.* (1988) and Thorez *et al*. (2006). The present description is largely inspired from this last paper.

The argillaceous deposition established in the Upper Frasnian continued through a large part of the Lower Famennian with no major change of facies across the Frasnian–Famennian boundary. The Famenne Formation (Fm) is a rather thick and monotonous greyish to greensish shaly unit in which are included the two former *'assise de Mariembourg'* and *'assise de Senzeille*'. Both display a similar lithology and are separated on the basis of their fossil content (mainly rhynchonellid brachiopods). In proximal areas, the basal Famennian is marked by oolitic haematitic ironstone horizon in the Falisole and Franc-Waret (pars.) formations (levels I and II of Dreesen, 1986) that is interpreted as material reworked by storm events and mark transgressive pulses (Dreesen, 1982). Moreover, it is traced all over the basin and passes eastwards to volcanoclastics sediments (Dreesen, 1987). In the Vesdre area, this oolitic ironstone occurs within a marly unit (base of Hodimont Fm) that yielded small solitary rugose corals and smooth rhynchonellid brachiopods (Denayer *et al*., 2012). Another oolitic horizon (level III of Dreesen, 1986) occurs at the top of the Famenne Fm and equivalent and has been correlated eastwards to the *Cheiloceras* limestone of western Germany (Dreesen, 1982). Coarser siliciclastics deposition started with the Esneux Fm. It consists of thinly-bedded micaceous siltstone and passes laterally to the Aye shaly Fm and Watrissart sandy Mbr respectively southwards and westwards (Thorez *et al*., 2006).

Starting with a fourth ironstone horizon, the Souverain-Pré Fm is a transgressive carbonate unit. It consists of nodular silty limestone, commonly sandy in proximal areas and argillaceous in distal parts. The limestone is a wackestone-packstone with abundant crinoid and brachiopods debris. The formation has been dated of the upper *marginifera* Zone in the southern part of the Namur-Dinant Basin and to the uppermost *marginifera* and lower *trachytera* zones in the northern part (Bultynck & Dejonghe, 2001). The diachronism of the formation is thus well marked. In the Vesdre area, the formation passes to the Baelen Mbr that constitutes one of the rare examples of Famennian reef known worldwide. The reef includes a microbialitic core with stromatactoid cavities and reddish facies. The flanks facies are mainly croinoid accumulation ('peastone') in a reddish, locally highly argillaceous matrix (see description of the Limbourg quarry for details).

After this carbonate episode, the siliciclastic sedimentation returned. The Poulseur Mbr (Comblain-la-Tour Fm) is a bioturbed marine sandstone with shell accumulations (storm deposits) that passes upwards to the Monfort Fm. This formation is dominated by thickly-bedded arkosic sandstone deposited as a sand barrier (Thorez & Dreesen, 1986). In the proximal zones, it is replaced by the massive red sandstone of the Citadelle de Huy Fm. The Monfort Fm is topped by a shaly interval (Bon Mariage Mbr).

The overlying Evieux Fm is composed of several members all corresponding to a peculiar environment. The Royseux Mbr corresponds to rhythmic alternations of sandstone, mudstone and palaeosols (including dolcretes). Locally, restricted ostracodal limestone develops at the top of the rhytms (Fontin Mbr). The Crupet Mbr corresponds to alluvial red siliciclastics includings dolcretes and channels with bone beds and plant accumulations. The latter yielded an abundant vertebrates (including tetrapods), arthropods and a diverse fauna (see Denayer *et al*., in press for a recent review). Distally, the Evieux Fm passes to the rhytmic Beverire Fm, then basinwards, to the Ciney Fm, a thick sequence of siliciclastic and carbonate alternations corresponding to a barrier system (Thorez *et al*., 1988). All these formations grade to the purely marine shaly units of the Sains Fm in the southwestern part of the basin (Avesnois area).

The Evieux Fm and lateral equivalent witness the maximum of regression of the Famennian sequence. It is followed by a major transgression marking the return of marine settings and fauna in the Comblain-au-Pont Fm and its lateral equivalent: Etroeungt Fm southwards and Dolhain Fm eastwards. The latter two show the development of stromatoporoid biostromes. This transgression corresponds to the Epinette Transgression of Paproth *et al.* (1991) and to the sequence 1 of Hance *et al*. (2001). It also coincides with the Strunian biodiversification event of macrofauna (Poty, 1999). All these formations show a cyclic pattern interpreted by Poty *et al.* (2013, 2015) as excentricity-driven climatic oscillations. The Hangenberg event and the Devonian–Carboniferous boundary, recorded at the top of these units, are not in sequence with the cycles, witnessing their complete independency of the sedimentation record. See Denayer *et al.* (this volume) for more details.

4. Biostratigraphy and events

Long-term biostratigraphical research led to the definition of a very fine stratigraphical scheme for the Famennian. The conodonts zonation was successfully applied (Bouckaert *et al*., 1965; 1968; Dreesen *et al*., 1986; Conil *et al.,* 1986; Dusar & Dreesen, 1984) and latter complemented by the study of foraminifers (Bouckaert *et al*., 1966), ostracods (Becker *et al*., 1974) and, for the lower(most) Famennian, brachiopods (i.e. Sartenaer, 1957; Dusar, 1976) and acritarchs (Vanguestaine *et al*., 1983). The establishment of a palynological zonation in Belgium has essentially been a step by step process that started in 1960 and is still ongoing today. The first Devonian spore assemblage ever reported in the country was published by Leclercq (1960). This discovery opened a new field of investigation in her laboratory and led to the hiring of Maurice Streel that initiated a program of systematic investigation for palynological remains of nearly all known Devonian sections in Belgium leading to more than one hundred publications dealing with spore taxonomy and stratigraphy (see Steemans and Loboziak (1994) for partial bibliography). This work at the University of Liège culminated in 1987 by the publication of an unified scheme for the spore zonation of the whole Devonian of the Ardenne-Rhenish region as well as correlations with faunal zonations (Steemans, 1987; Streel et al., 1987). Very importantly these publications establish a considerable number of biostratigraphic subdivisions in the Devonian in both Oppel and interval zones. Oppel zones are defined by an association of selected taxa of restricted range while Interval zones are defined as the interval between two distinctive biostratigraphic horizons. This dual system is a very useful tool still used today and allowing long distance correlations. Since 1987, the general appearance of the palynological zonation and its general philosophy has not changed much. Ongoing research by notably P. Steemans and M. Streel himself have however led to small modification and/or precision of the original zonation (e.g. Higgs *et al*., 2013).

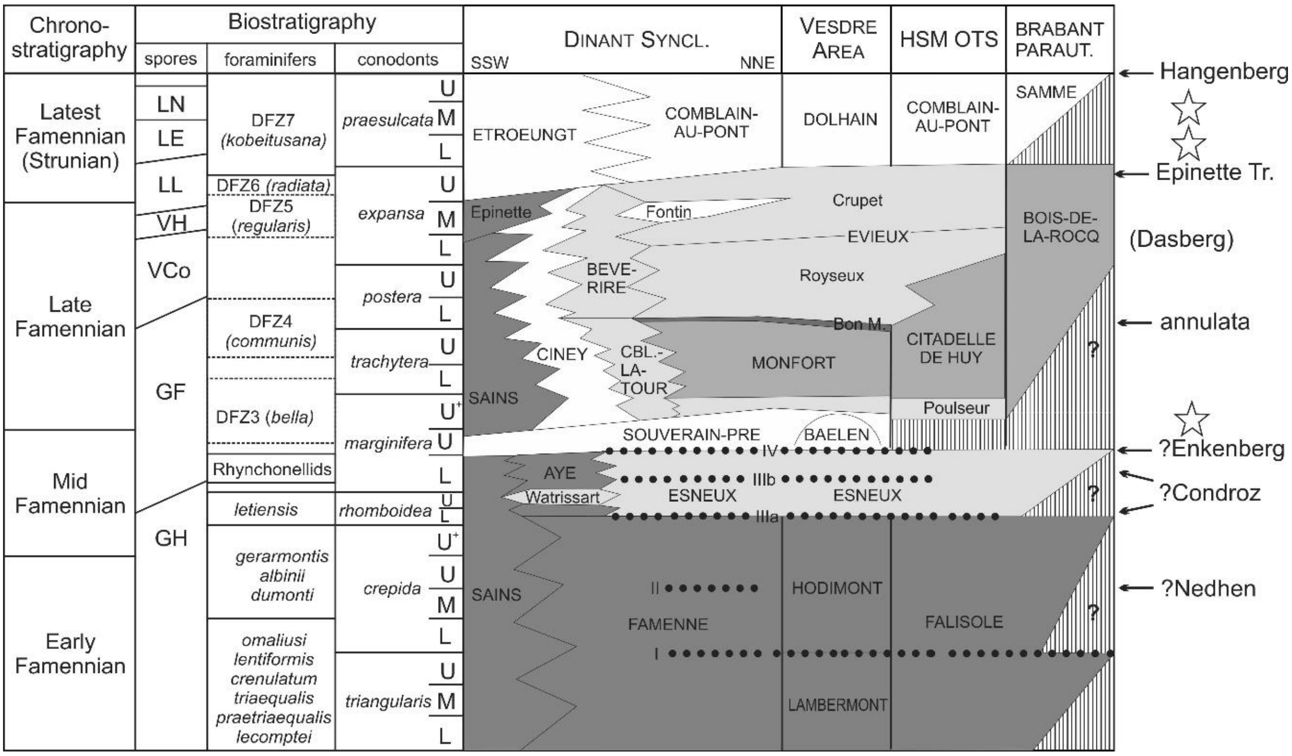

Fig. 2: **Simplified lithostratigraphical scheme of the Famennian in different tectonic units of southern Belgium, incorporating the Avesnois (northern France) (modifid from Thorez *et al*. (2006) and Denayer *et al.* (2012, 2015)). Black dotted lines and roman numerals correspond to oolitic ironstone levels (Dreesen, 1982). Names between brackets indicate the theoretical position of events not (yet) recognized in Belgium, names preceded by a question marks indicates events hypothetically situated. Crosses indicate extinctions in macrofauna, stars indicate diversification or colonisation events. L, M, U, U +: lower, middle, upper and uppermost conodont zones (after Sandbeg & Ziegler, 1990), spore zonation of Streel *et al*. (1987). foraminifers zonation of Conil *et al.* (1986) and Poty *et al.* (2006), rhynchonellid zonation after Sarteanaer (1972). Names in upper case are formations, names in lower case are members. Syncl.: Synclinorium, Paraut.: Parautochton, HSM OST : Haine-Sambre-Meuse Overturned Thrust Sheets (former 'southern limb of the Namur Synclinorium), Bon M.: Bon Mariage Mbr, CBL-la-Tour: Comblain-la-Tour Fm, Tr.: Transgression. Colours: white: carbonate-dominated units, light grey: sandstone-dominated units, middle grey: mixed facies units, dark grey: shaly units. Modified from Denayer & Mottequin (2015).**

The Belgian Famennian being dominated by proximal siliciclastic deposits, the events defined on the basis of ammonoid extinctions are far from obvious. Three oolithic ironstone horizons described by Dreesen (1982) have been correlated by Becker (1993) respectively to the Nedhen Event (horizon II within the Famenne Fm, upper *triangularis* zone) and the Condroz Event (horizons IIIa and IIIb in the Esneux Fm, lower *marginifera* Zone) that questionably recorded a drop in sea level and the development of coarser siliciclastic sediments after the monotonous deposition of the lower Famennian shales. The Enkenberg pulse is questionably correlated with the transgressive limestone of the Souverain-Pré Fm starting by the IV horizon of oolithic ironstone and associated to carbonate mounds of the Baelen Mbr. The *annulata* Event is recorded by the shaly Bon Mariage Mbr of the Evieux Fm (Thorez *et al*., 2006). The Dasberg Event remains unrecognized in Belgium. The 'Strunian' diversification can be correlated with the Epinette Transgression (sequence 1 of Hance *et al.* (2001)) allowing the reestablishment of marine conditions and the re-colonization of the shelves by shallow-water ecosystems. Finally, the Hangenberg Event (*praesulcata* Zone) has been recognized in the uppermost Famennian Comblain-au-Pont and Etrœungt formations with the record of several decimetre-thick dysoxic shaly units whereas the very base of the Hastière Fm is correlated with the Hangenberg Sandstone (Poty *et al*., 2015).

5. Key sections

5.1 Rochefort section

Location and access
Outcrop around the industrial building of the 'Betons de la Lomme' company in the Rochefort vicinity. Southern limb of the Dinant Synclinoirum (Fig. 1). GPS: 50°10'43.16'N5°12'16.48'E

Lithostratigraphy and biostratigraphy
The lower Famennian Famenne Formation is well exposed, but its base and top do not crop out. Although conodont data are lacking for this outcrop, the range of the Famenne Formation (in terms of conodont zones) spans the interval of the lower *triangularis* to the upper *crepida* zones. In terms of brachiopod biostratigraphy (see e.g. Sartenaer, 1968, 1972), on the basis of the available data, the outcrop starts within the *Ptychomaletoechia omaliusi* Zone and ends within the *Basilicorhynchus basilicus gerardimontis* Zone.

Description
The marine Famenne Formation is essentially shaly, with some levels rich in pluricentimetre-thick nodules and rare intercalation of thin beds of sandstone and limestone. These argillaceous sediments reflect relatively open marine conditions and were deposited essentially offshore on a shallow epicontinental platform (Dreesen & Thorez, 1980; Thorez *et al*., 2006). The abundant and well preserved macrofauna indicate that they are in situ. However some shell beds with disarticulated brachiopod valves are interpreted as strom deposits. Thinly laminated sandstone beds with oblique stratifications are possibly distal turbidites.

Main faunal component
The macrofauna is largely dominated by brachiopods: several rhynchonellid species (*Ptychomaletoechia omaliusi*, *P. dumonti*, *Cavatisinurostrum faniae*, *Basilicorhynchus basilicus gerardimontis*) as well athyridids (Cleiothyridininae), spiriferids (Cyrtiopsinae, notably *Cyrtiopsis graciosa sensu* Sartenaer (not Grabau)), and productidines. Bivalves are common in some levels. Cephalopods (orthocerids and rare goniatite) and fish remains occur sporadically.

5.2 Limbourg disused quarry and cliffs

References
Marion (1985); Dreesen *et al*. (2013, 2015)

Location and access
Disused underground quarry and nearby cliff in a private property between the Limbourg and Dolhain villages. Vesdre area (Fig. 1). GPS: 50°36'32.10'N5°56'27.83'E.

Lithostratigraphy and biostratigraphy
The Middle Famennian Baelen Mbr is exquisitely exposed. Rich conodont faunas occurring within the bioclastic limestone beds from the extreme base of the Baelen Member belong to the lower to upper *P. marginifera* zones. Samples taken from bioclastic and crinoidal limestones at different stratigraphical levels within the mudmound complex, contained rather poor conodont faunas characteristic of the Late *P. marginifera* Zone (Dreesen, 1978; Dreesen *et al*., 1985, 2013).

Description
This section offers the opportunity to observe the 'Red Crinoidal Marble of Baelen', which is only recognized in this part of the Vesdre area. Dreesen & Flajs (1984), Marion (1984, 1985) and Dreesen *et al*. (1985) were first to identify its (microbial) mudmound origin, to stress its particular synsedimentary tectonic setting and to highlight its unusual biota. Aretz & Chevalier (2007) confirmed the microbial origin but considered the Baelen limestone rather to represent microbial reefs. Webb (2002) interpreted the Baelen carbonate buildups as deeper water mudmounds. However, the abundance of biota such as crinoids and algae point to shallower depositional environments.

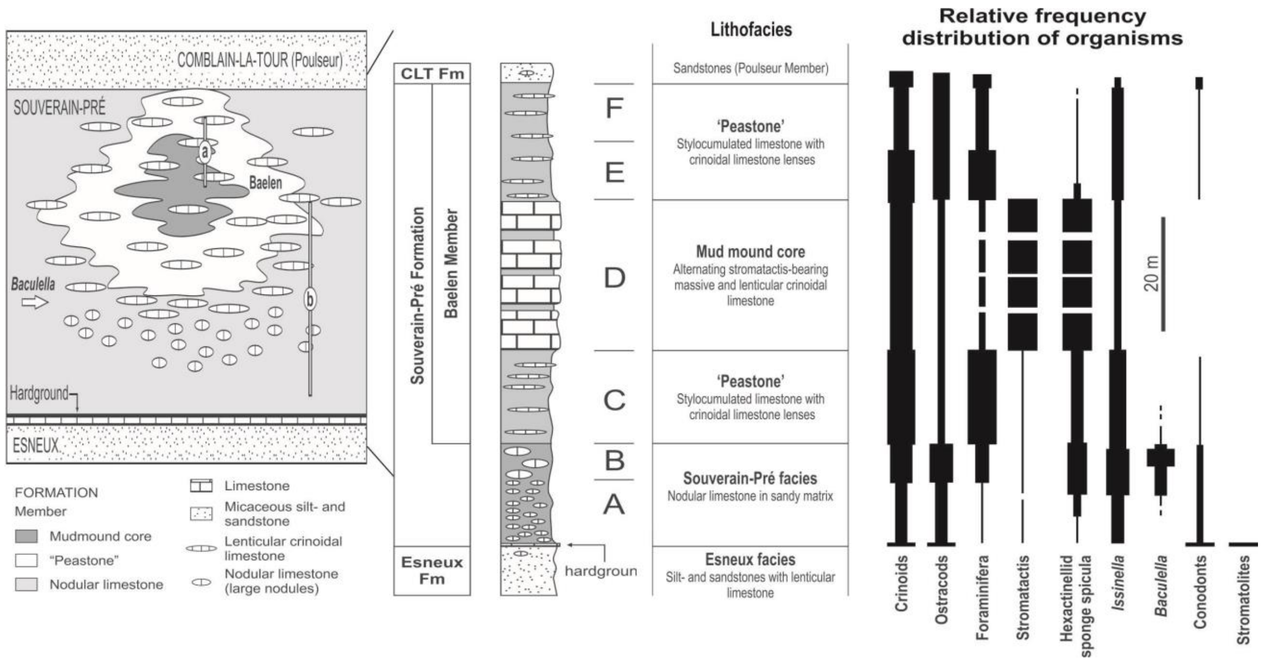

Fig. 3: **Dreesen *et al.* (2013)'s model (not to scale) for the Baelen Member showing the temporal-spatial relationships (lithofacies framework) of the different lithologies observed in the field. Note the position of the different facies observed within the individual sections within the model. Composite litholog showing the distribution of the main lithofacies types within the Baelen Member and the relative frequency distribution of the observed micro-organisms (Dreesen et al., 2013, modified from Dreesen *et al.*, 1985 and Dreesen *et al.*, 1993). Abbreviations: Abbreviations: a, Limbourg underground quarry; b, Limbourg, Hors-Les-Portes section; CLT, Comblain-la-Tour; Fm, Formation. A-F: lithological units (see text).**

This quarry ranks among the best sections for observing the core of a mudmound and its flanks but its base and top are not visible. The typical facies of the Souverain-Pré Formation (Fig. 3) is exposed within the Limbourg Hors-les-Portes section (a former medieval town moat), located close to the Limbourg quarry.

In the areas of the mounding sites, 12-15 m of silty nodular limestone embedded in calcareous micaceous silt/sandstone (Souverain-Pré facies) represent the 'basement' of the mudmound *sensu stricto* (corresponding to the former sequences A-B of Dreesen *et al*., 1985) (Fig. 3). The size of the nodular limestone beds seems to increase towards the top. Microscopically the latter limestone correspond to silty algal mudstone, bioclastic wackestone and algospongal bindstons (locally floatstons), often affected by bioturbation. Very conspicuous is the abundance of Algospongia, in particular that of issinellids (*Issinella* and *Baculella*) over a few meters in the upper part of the nodular limestone sequence (Fig. 3B). This particular occurrence represents a true lithostratigraphical reference horizon in the field due to the abundancy of silicified tests of *Baculella gemina* (Fig. 4e). Indeed, the subspherical or ovoid tests of *Baculella* strongly resemble large hollow ooids that can easily be seen with the naked eye or with the hand lens.

Other biota include palaeoeberesellids, hexactinellid sponge spicules, few plurilocular foraminifera, bryozoans, thin-shelled ostracods, crinoids and rare athyridid, spiriferid and productid (Productidina) brachiopods. The latter microfacies characteristics clearly differ from those of the 'regular' nodular limestone of the Souverain-Pré Formation, containing more open marine-influenced bioclastic wacke/grainstone with crinoids, plurilocular foraminifera, girvanellids, palaeoberesellids, thick-shelled ostracods, bryozoans, brachiopods and conodonts.

The overlying sequence (C) is composed of alternating lithologies with a total thickness of at most 30 m: it consists of silty nodular and lenticular limestone that are strongly affected by pressure solution and produce so-called stylocumulated 'argillaceous' limestone, randomly enclosing thick and coarse lenticular crinoidal limestone beds (Fig. 4d). Microscopically, the former correspond to algospongal wackestones/packstone and spiculitic/cryptalgal mudstones, the latter to densely packed crinoidal grainstone. Due to strong pressure solution, the actual grainstone/mudstone ratio is exaggerated with respect to the original mudmound composition. In the stylocumulated limestone (Fig. 4h), abundant crinoid ossicles occur, forming so-called '*pierre poitée'* or 'peastone' (because of the presence of numerous white circular sections of the crinoid ossicles, resembling peas).

The mudmound core (sequence D) is composed of a sequence up to a maximum of 30 m of rather massive, greyish to red-stained (pinkish to reddish) stromatactis- or zebra-bearing limestone (Fig. 4c) (the Red Marble of Baelen) that frequently but randomly incorporate pale-grey lenticular coarse-grained crinoidal limestone. The stromatactoid limestone consist of spiculitic/microbialitic mudstones enclosing palaeoberesellids, algosponges, ostracods, fenestellid bryozoans and crinoids (Fig. 4f). Besides the presence of characteristic stromatactis and zebra structures (dark mud/wackestone alternating with centimetre-sized parallel layers of white calcite), both filled in with radiaxial fibrous calcite cements, microbial textures and small stromatactoid laminoid-fenestral fabrics can be observed.

The pale-grey crinoidal limestone lenses otherwise consist of crinoidal-foraminiferal packtone/grainstone and rudstone, that are often partially dolomitized and silicified (Fig. 4gB). Successive plurimetric beds of massive stromatactoid limestone are separated by decimetric to metric interbeds of red-stained crinoid-rich stylocumulated limestone (Fig. 4b), conspicuous by the numerous white sections of crinoid ossicles (locally undissociated crinoid stems of over 25 cm in length have been observed). The red staining of the above limestone results from finely disseminated hematite, probably related to the activity of chemo-autotrophic iron bacteria (Boulvain, 1989; Mamet & Préat, 2005). Both (red-stained) lithofacies have been extracted and used as ornamental stone.

In the top layers of the stromatactoid limestone, milky-white sparite-filled neptunian dykes locally occur (e.g. in the historical underground quarry at Limbourg Hors-les-Portes). The mound core facies is overlain by a sequence of stylocumulated crinoid-rich limestone (‘peastone’) (sequences E–F), mimicking the carbonate facies just below the mound core (sequence C). Thick lenticular and coarse crinoidal limestone are randomly interlayered, the number of which seems to decrease towards the top. The red staining is totally gone and the carbonates are becoming silty again. This ‘argillaceous’ carbonate sequence rather ends abruptly and changes into thin-bedded micaceous sandstones with rare and scattered limestone nodules.

Large slumps have been described from the upper mound flank facies (Dreesen *et al*., 1985) (Fig. 4a): they are related to conditions of instability or reduced rigidity of the mound, with flank dips up to 15°–35° as suggested by Aretz & Chevalier (2007).

Based on old data (Marion, 1984; Dreesen *et al*., 1985) and recent field observations, Dreesen *et al.* (2013) proposed a new model for the Baelen Member (Fig. 3), showing the spatial relationships of the described different lithologies. This model confirms also earlier observations made by Aretz & Chevalier (2007): a red-stained siliciclastics-free mudmound core is surrounded by mixed siliciclastic-carbonate facies. The latter, in turn, is enveloped by silty nodular limestone that are embedded in fine-grained siliciclastic sediments (the ‘regular’ Souverain-Pré facies). Coarse-grained crinoidal limestone occur as lenticular interbeds in all if not most of the above lithofacies. They have also be encountered in the coeval micaceous siltstone and sandstone outside the mounding site, e.g. as debris or storm deposits (pluricentimetric to decimetric lenses mostly).

The end of the mound growth is probably related to reduced accommodation space as a consequence of a regression (Aretz & Chevalier, 2007) or as a result of synsedimentary block faulting activity, combined with a renewed influx of siliciclastics.

Main faunal component

Stemmed echinoderms are excessively abundant but usually dissociated and no research has been conducted so far on them. Locally, productid brachiopods are abundant. Microfossils (algae and ‘algosponges’, microproblematica (Fig. 4e) and foraminifers (Fig. 4g) have been inverstigated by Dreesen & Flajs (1984) and Dreesen *et al.* (1985).

5.3 Spontin Tienne des Marteaux Quarry

References

Goemaere (1984), Di Clemente (1985), Fagnant (1999), Thorez *et al*. (2006).

Location and access

Disused quarry near the western end of the Spontin village in the Bocq valley. Condroz area, central part of the Dinant Synclinorium (Fig. 1). GPS: 50°19’40.82’N5°00’01.78’E.

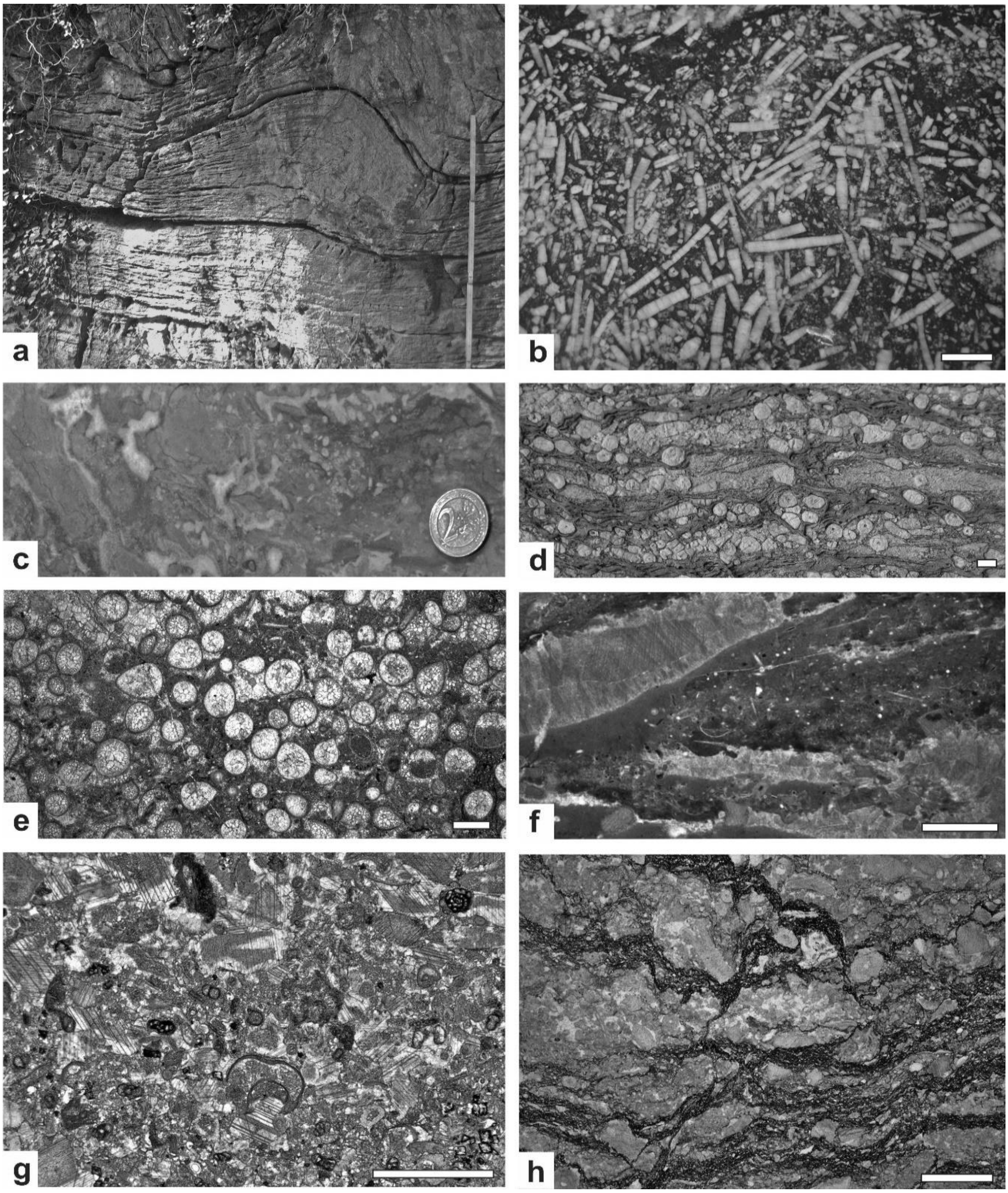

Fig. 4: **Lithofacies and microfacies from the Baelen Mbr, modified from Dreesen *et al.* (2013). a. Large slumps affecting limestone beds of unit E (crinoidal limestone) in the upper part of the Baelen Mbr, Limbourg quarry. b. Polished slab of the second variety of Red Marble of Baelen: the red-stained 'peastone' or argillaceous limestone with numerous sections of crinoid ossicles. Baelen, Les Forges quarry (ccale bar: 20 mm). c. Polished slabs of Baelen mud moundcore facies showing stromatactoid structures and crinoid ossicles. The total absence of stromatoporoids and corals is striking. Verviers train station, ticket-window ledge. d. Lenticular crinoidal encrinites (crinoidal grain- and rudstone) interrupting the stylocumulated 'argillaceous' limestone. The coarse crinoidal limestone are affected by incipient karst, preferentially along diaclases (scale bar: 2.5 mm). e. Algospongal wackestone/packstone with numerous sections of *Baculella gemina* (micrograph of a thin section, transmitted light), Goé-North section (scale bar: 2.5 mm). f. Stromatactis-bearing spiculitic mudstone characteristic of the mud moundcore facies. Micrograph of thin section, transmitted light. Note red staining, presence of small stromatactoid structures (fenestral fabric) and sections of hexactinellid sponge spiculae. Baelen, Les Forges quarry (scale bar: 2.5 mm). g. Crinoidal grainstone frequently enclosing plurilocular endothyrid-tournayellid foraminifera in thin section, Les Forges section, Baelen (scale bar: 2 mm). h. Micrograph of a thin section in a stylocumulated argillaceous or silty limestone with corroded crinoidal grainstone and crinoid ossicles ('*pierre poitée*') (scale bar: 2.5 mm).**

Lithostratigraphy and biostratigraphy

This quarry is opened in the heterolithic facies of the Evieux Fm. The nearby Spontin-Source section has been studied in detail. The palynological analyses has been done in the framework of a master thesis but was never published (Di Clemente, 1985). The general arenaceous nature of the sediments prevented a high resolution sampling; only height samples were fossiliferous. The first part of the section has been attributed to the VCo (*Diducites versabilis–Grandispora cornuta*) Oppel zone (*sensu* Streel *et al*., 1987) (Fig. 5). The top of the section (12 m) has been attributed to the LL (*Retispora lepidophyta–Knoxisporites literatus*) Oppel zone. Maziane *et al.* (1999) revised the Famennian palynozonation and subdivided the VCo Oppel zone, establishing the VH (*Apiculiretusispora verrucosa–Vallatisporites hystricosus*) Oppel zone. The latter is impossible to locate in the Spontin-sources section due to the poor resolution of the sampling. The characteristic spores of this zone very likely first occur within the barren interval marked by a question mark on Fig 5. Di Clemente (1985) also processed several samples for conodont extraction. Only one sample (see Fig. 5 for localization) was fossiliferous and identified *Bispathodus ultimus* indicative of an upper *expansa* to lower-middle *praesulcata* interval. A lithologic correlation between the two sections is proposed on Fig. 5.

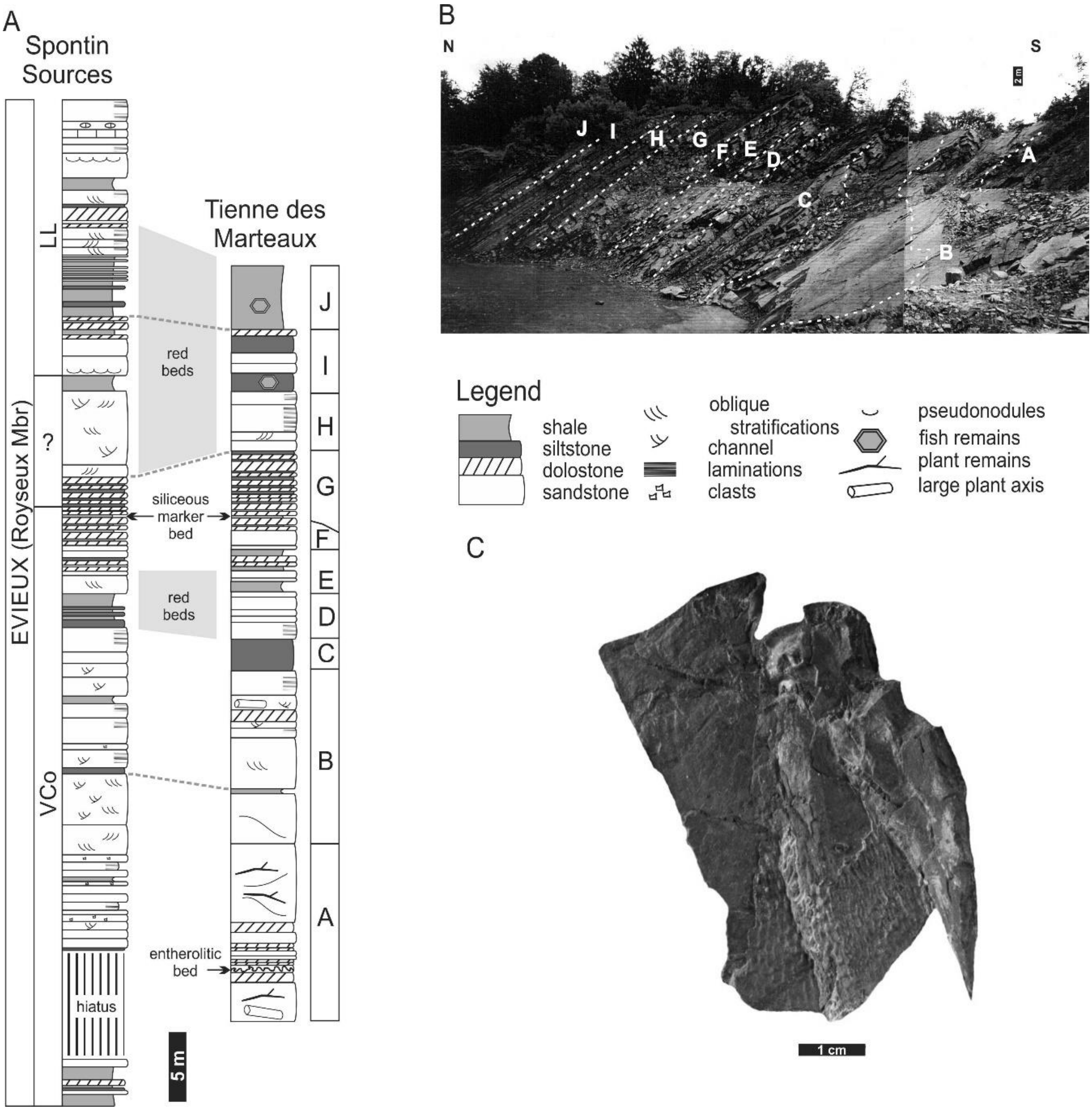

Fig. 5: **A. Schematic logs of the Spontin-source section and Tienne des Marteaux quarry with some correlation horizons (modified from Goemaere, 1984 and Fagnant, 1999). Palynological zones are from Di Clemente (1985), updated. B. Picture of the quarry (in 1985!) with indication of the main facies. C. Pectoral fin and anterior ventrolateral plate of *Remigolepis durnalensis* (from Olive, 2015).**

Description

This stop aims to exemplify the most common facies of the Belgian Upper Famennian, known as the old generic name '*Psammites du Condroz'*. The Evieux Fm exposes continental and proximal siliciclastic facies dominated by micaceous sandstone and siltstone ('psammite') with frequent red beds. The Royseux Member is dominated by sandstone and arkosic sandstone alternating with massive or layered evaporitic dolomite, often yellowish and pulverulent where weathered. Red beds, dessication cracks and dolcretes are not rare. The Crupet Member contains sandstone and siltstone, usually arkosic, assembled in finning-upward sequences with common sedimentary structures as planar and undulating stratification, megaripple and submarine dunes, sand bars, cross stratifications, asymmetric ripples and channels. Fossil flora are common in all the facies while fish remains occurs as bones beds in channel lags. The Fontin Member, interstratified within the two other members, present a marine-dominated sedimentation composed of brachiopod shells accumulated by storm (Thorez *et al*., 2006).

The Evieux Formation has long been interpreted as a witness of proximal environments. Sedimentary structures indicate a deposition as a distal alluvial fan with estuarine influence (northwards), marshes and shabka-type lagoon with occasional marine influence (southwards) preserved as storm deposits. Detailed environmental reconstructions have been proposed by Dreesen & Thorez (1994), Paproth *et al.* (1986), Thorez & Dreesen (1986). From an eustatic point of view, the Evieux Formation corresponds to a regressive depositional system (Thorez & Dreesen, 1986), most probably a lowstand system tract, overlain by the transgressive system tract of the Comblain-au-Pont/Etroeung Fm (Strunian transgression).

Main floral and faunal component

A relatively diversified plant assemblage has been collected from this quarry and from the very near Bocq river valley quarries (Fairon-Demaret, 1996; Prestianni, 2004; Prestianni & Gerrienne, 2006; 2010). Its composition conforms to the other Famennian floras found elsewhere in Southern Belgium and commonly known as the Evieux flora (Stockmans, 1948). The two main components of this fauna are the progymnosperm *Archaeopteris halliana* and the (pre)fern *Rhacophyton condrusorum.* The latter species is particularly common in the Tienne des Marteaux quarry. This flora is remarquable by the diversity of spermatophytes that it comprises (Prestianni and Gerrienne, 2010). Indeed, if seed plants very likely evolved in the Givetian (Gerrienne *et al*., 2004), their first radiation is only recorded in the Famennian. In the Bocq river valley they are *Condrusia rumex*, *Moresnetia zalesskyi*, *Pseudosporogonites hallei* and *Dorinnotheca streelii*. Finally other components of the Evieux Fauna present in the Bocq river valley are the enigmatic *Barinophyton cirtulliforme* together with several pinnule species and diversed undetermined sporangia. Interestingly, the low diversity of encountered Lycophytes and Progymnosperms as opposed to the relative high diversity in spermatophytes is a characteristic of south-eastern Laurussian floras (Prestianni & Gerrienne, 2014; Streel & Marshall, 2006). This was proposed to be linked to the dry conditions prevailing in this region by the end of the Famennian as witnessed by the amount of evaporites that suggest a sabkha type of environment (Paproth *et al*., 1986; Streel & Marshall, 2006; Thorez & Dreesen, 1986).

The fish assemblage is mainly dominated by large remains of the antiarch placoderm *Remigolepis durnalensis* (Olive, 2015). They are essentially found disarticulated with some exceptions, i.e. a pectoral fin in connection with the anterior ventrolateral plate (Fig. 5). Except for the doubtful occurrence of a *Remigolepis* species in Scotland, this is the first record of this genus in Western Europe. The minor component of the fish assemblage is represented by sarcopterygian fishes, i.e. holoptychiid fishes. Such a distribution (high placoderm rate versus weak sarcopterygian rate) is also observed in the Famennian localities of Trooz and Becco (Olive *et al*., 2015), whereas it is the strict opposite in the Famennian tetrapod-bearing locality of Strud.

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The Devonian–Carboniferous Boundary and the Lower Carboniferous succession in the type area

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Abstract
The Dinant Synclinorium (southern Belgium) is the classical area for the study of the Lower Carboniferous. Five key sections are presented here. They cover the interval between the Uppermost Devonian (Strunian) to the basal Viséan and exposes several well known biological and sedimentary events. The Royseux section exposes the Devonian-Carboniferous boundary with an equivalent of the Hangenberg Sandstone recorded in proximal marine facies quite rich in macro- and micro-fauna. The Gendron-Celles section exposes without discontinuity the Strunian, the Hastarian and the lower part of the Ivorian. The latter substage is characterized by the development of Waulsortian buildups in the Namur–Dinant Basin. The same interval is exposed in the Nutons quarry (Chansin) in the Bocq valley but with shelf facies (no Waulsortian reef). The Dinant vicinity and Bayard Rock are two historical section for the Tournaisian-Viséan boundary. Finally, the Salet section exposes the Tournaisian-Viséan transition with the renowned 'Black Marble' facies of the basal Viséan. The late section will be visited with special focus on climatic and eustatic cycles.

1. Historical background

Southern Belgium is the cradle of Lower Carboniferous (=Dinantian) geology, stratigraphy and palaeontology. Following the pioneer works of Dumont (1832), who subdivided the Carboniferous limestone in two stages that later became "*calcaire de Tournai*" (or Tournaisian) and "*calcaire de Visé*" (or Viséan), Gosselet (1860) added a third stage "*étage houiller*" that correspond to the Upper Carboniferous coal measures. The name 'Dinantian' as synonym of Lower Carboniferous was chosen by de Lapparent (1893) in reference of the Dinant area where these rocks are particularly well exposed and to honour the pioneer works of E. Dupont in the Meuse valley (Groessens, 2006). Based on the palaeontological works of de Koninck (1842-1851) and especially of Demanet (1958), the base of the Dinantian was placed at the first limestone units capping the Upper Devonian (now Uppermost Famennian, 'Strunian' substage) and its top at the first appearance of the goniatite *Eumorphoceras*. The boundaries were subsequently used until the 1970's. In 1971, during the Krefeld International Congress on geology and stratigraphy, the division of the Lower Carboniferous in Tournaisian and Viséan was decided officially. Conil *et al.* (1977) refined the stratigraphic column of the Dinantian by the introduction of five stages (Hastarian, Ivorian, Moliniacian, Livian and Warnantian) based on foraminifer and conodont distributions in conformity with international stratigraphic rules. Conil *et al.* (1977) used the Strunian as the first stage of the Dinantian but the Devonian affinity of the Strunian fauna and flora was long known (Streel, 1969). The substage was therefore reintroduced as the uppermost part of the Famennian when the Devonian-Carboniferous was defined in the 1990's (Paproth *et al.*, 1991). The 'Strunian', often incorrectly used in lithostratigraphic viewpoint (shallow-water carbonate facies) is however stratigraphically defined: its base corresponds to that of the upper *expansa* conodont Zone which is an equivalent of the base of the foraminifer *Quasiendothyra kobeitusana kobeitusana* Zone after (Streel *et al.*, 2004). The Strunian is consequently synonymized with the Uppermost Famennian substage (Streel *et al.* 2004, 2006)

After a decade of discussion, the Devonian-Carboniferous boundary was re-defined. The former base defined by the entry of the goniatite *Gattendorfia* was replaced by the first appearance of the conodont *Siphonodella sulcata* in the evolutionnary lineage *Siphonodella praesulcata–S. sulcata* whose entry immediately preceedes that of *Gattendorfia* (Sandberg, 1972, Sandberg *et al.*, 1978). Research in Belgium failed to find the conodont lineage (Bouckaert & Groessens, 1976), thus the base of the Carboniferous and Tournaisian was not possible any longer on that definition. The global boundary stratotype at La Serre (Montagne Noire, France) was finally chosen (Paproth *et al.*, 1991). Moreover, in 2004, the International Union of Geological Sciences ratified the division of the Carboniferous System in two sub-systems, namely the Mississippian and the Pennsylvanian. This division is not applicable in Western Europe but replaces officially the Dinantian at the global scale.

Nevertheless, this term is still in use to designate the Lower Carboniferous carbonate succession at the regional scale (Groessens, 2006).

The palaeontological studies began with de Koninck (e.g., 1842-1851, 1872) then Delepine (1911) and Demanet (e.g., 1923, 1958) who described the highly diverse fauna from the highly fossiliferous Tournaisian from Tournai and Viséan from Visé. The Lower Carboniferous stratigraphy was investigated from a lithological point of view by Pirlet (1963, 1964, 1968) and from a biosratigraphical point of view by Conil (1964, 1967, 1968), Conil *et al.* (1977, 1986, 1988, 1991) and Conil & Pirlet (1970) for the foraminifers and Groessens (1975) and Groessens *et al.* (1982) for the conodonts. Paproth *et al.* (1983) summarized all these data that were subsequently reviewed by Poty *et al.* (2006, 2014). The revised litho- and biostratigraphy of the Dinantian allowed the definition of a sequence stratigraphic model by Hance *et al.* (2001), Poty *et al.* (2003) and Poty *et al.* (2006). Nine third-order sequences have been recognized in the Belgian Tournaisian and Viséan. System tracts follow the terminology of Plint & Nummedal (2000).

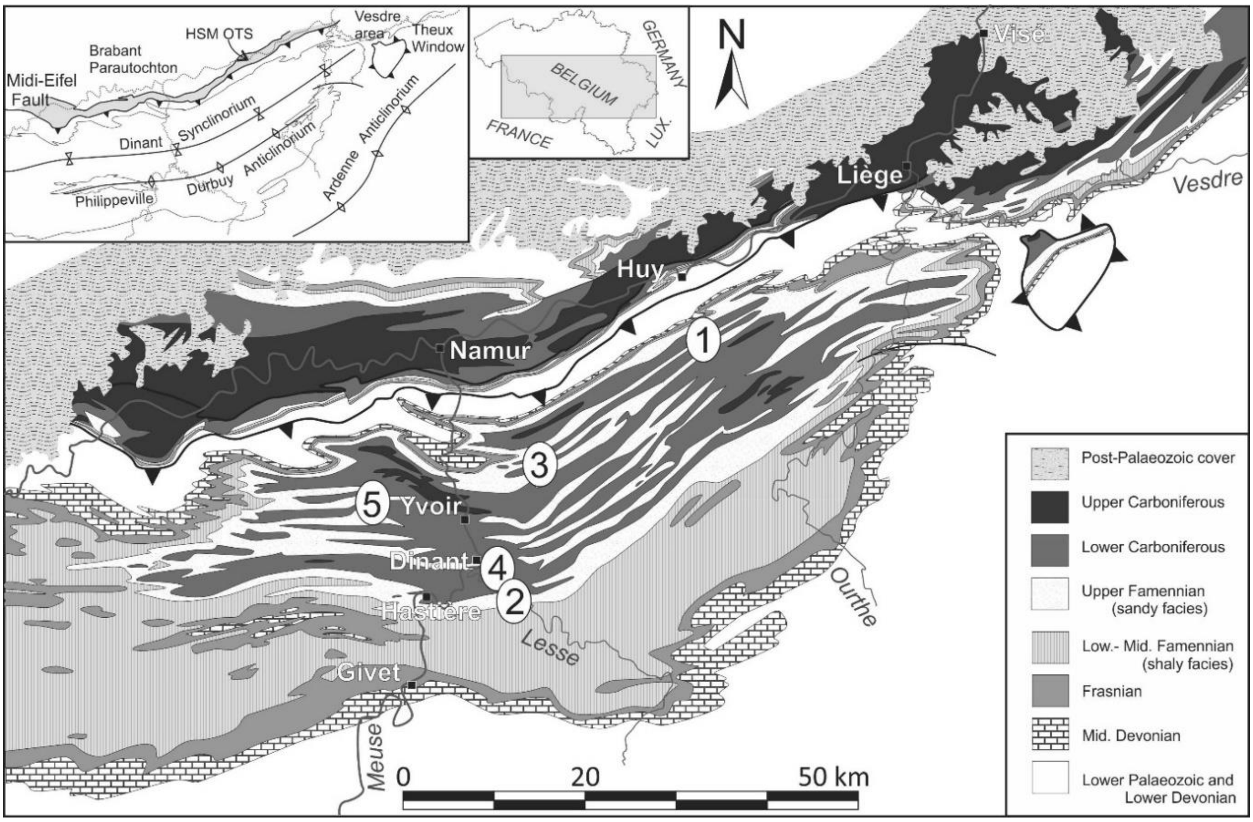

Fig. 1: **Schematic geological map (modified after de Bethune, 1954) with location of the visited sections: (1): Royseux, (2): Gendron-Celles, (3) Chansin 'Les Nutons' quarry, (4): Bayard Rock at Dinant, (5): Salet road section and Tanret quarry**

2. Geological settings

Southern Belgium is part of the Rhenohercynian Fold Belt, which extends across Europe from Southern Portugal through southern England, northern France, Belgium, and Germany, into Poland eastwards and resulting of the Variscan deformation.

During the Late Devonian and Early Carboniferous, the Namur–Dinant Basin (Fig. 1) recorded proximal facies in its northern part whereas its southern part acted as a shallow basin with deeper facies. However, deeper water environment of Kulm facies are not known in Belgium but are suggested to the south of the Namur–Dinant Basin, on the basis of the westward facies prolongation into the British Isles where a southern Kulm-type basins existed during most of the Lower Carboniferous. Conversely, the presence of proximal carbonate facies in the southern Avesnois suggests a local or regional platform area southwards rather than a basin.

The Namur–Dinant Basin was divided in six sedimentation areas by Poty (1997) corresponding to tectono-sedimentary units (Fig. 2). The Namur sedimentation area (NSA) located on the southern margin of the Brabant Massif, displays an incomplete succession of proximal facies. The Condroz sedimentation area (CSA) extends south of the NSA and also exposes proximal facies with several stratigraphic hiatuses that increase eastwards. The Dinant sedimentation area (DSA) is characterized by a deeper-water (but still not deep) sedimentation and was strongly influenced by the development of Waulsortian buildups during the Late Tournaisian–EarlyViséan. The Hainaut sedimentation area (HSA) was strongly subsident and recorded a 2500 m-thick sequence of Dinantian rocks of various facies, including several thick evaporitic intercalations. The southern Avesnois sedimentation area (ASA), in northern France and southwestern Belgium, displays facies similar to those of the CSA. The Visé sedimentation area (VSA) is a small area at the south-eastern end of the Brabant Massif, affected by synsedimentary block-faulting and tilting. It was connected with the NSA during the Upper Devonian and Tournaisian and connected to a graben open eastwards to the Campine Basin during the Viséan (Poty 1997). Poty *et al.* (2011) defined a last sedimentation area, the Vesdre-Aachen Sedimentation Area (VASA) is the eastern continuation of the CSA and NSA, that recorded a similar but incomplete stratigraphic succession of the latter areas.

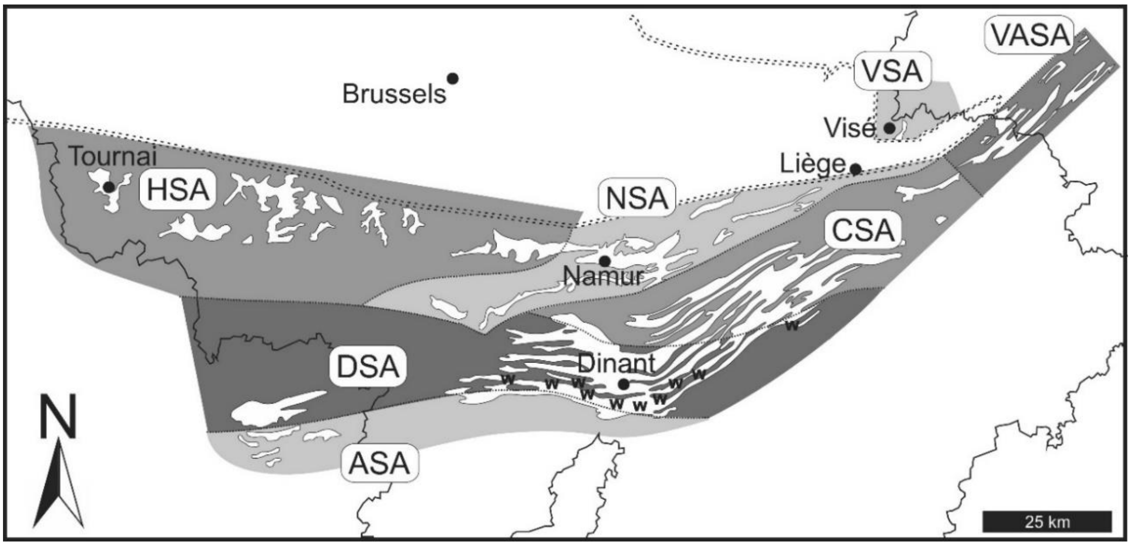

Fig. 2: **Sedimentation areas for the Dinantian strata around the Brabant Massif in Belgium and western Germany. Dinantian strata in white. ASA: Avesnois sedimentation area, CSA: Condroz sedimentation area, DSA: Dinant sedimentation area, HAS: Hainaut sedimentation area, NSA: Namur sedimentation area, VSA: Visé sedimentation area, VASA: Vesdre-Aachen sedimentation area, W: main Waulsortian developments (modified from Poty *et al.*, 2011).**

3. Lithostratigraphy and Depositional evolution

3.1. Latest Famennian ('Strunian')

In Belgium, the mixed carbonate-siliciclastic sedimentation typical of the Strunian follows the dominantly siliciclastic succession of the Famennian (see Denayer *et al.*, this volume). The facies indicate an internal to median ramp environment close to but below the base of the fair-weather wave zone and under the influence of both detrital and marine inputs, with common storm deposits (Thorez & Dreesen, 1986, Paproth *et al.*, 1986, Van Steenwinkle, 1990). The lithostratigraphic unit composed of an alternation of carbonate and shale is named Comblain-au-Pont Formation (Fm) in the northeastern part of the Namur–Dinant Basin (CSA) and Etroeungt Fm in the south and southwestern part (DSA). In the Avesnois area (ASA), the latter shows biostromal facies. A third formation, the Dolhain Fm, known in the eastern part of the basin (VASA) is characterized by stromatoporoid biostromes. These three formations are lateral equivalent of each other and their composition shows a proximal-distal gradient oriented NE-SW (Devyust *et al.*, 2005). To these formation succeeds the purer carbonate of the Hastière Fm, first of the Carboniferous succession in the basin. This unit exposes at its base one bed including Devonian faunas (quasiendothyrid foraminifers, campophyllid corals, phacopid trilobites) and detrital grains. The reworked aspect of these faunas is debated (Van Steenwinkel, 1988, Casier *et al.*, 2004). Hence this basal bed is still clearly Devonian in age. The following beds typically yielded a Tournaisian assemblage.

From a sequence stratigraphy viewpoint, the third-order sequence 1 of Hance *et al.* (2001) straddles the Devonian-Carboniferous boundary. Its transgressive system tract (TST) covers the Etroeungt, Comblain-au-Pont and Dolhain formations as well as the lower member of the Hastière Fm. The highstand system tract (HST) is represented by the middle member of the Hastière Fm. Recently, Kumpan *et al.* (2014) interpreted the Etroeungt Fm as a HST and the Hastière Fm as the following TST, using the Hangenberg Event as the sequence boundary. However these authors failed to locate correctly their sections along the proximal-distal gradient and thus failed to interpret their staking patterns. Consequently, their sequential interpretation is incorrect. Moreover, as note by Hance *et al.* (2001), (1) the facies across the Devonian-Carboniferous boundary being very similar, it is difficult to include them in different system tracts, (2) the very homogenous composition of the middle member of the Hastière Fm, and (3) its wide extension in the basin are typical of a HST.

2.2. Tournaisian

The Hastarian (Lower Tournaisian) succession is rather uniform throughout all the sedimentation areas of the Namur–Dinant Basin. Towards the south the succession becomes thicker and more complete. The inherited Late Devonian palaeotopography showing rather deeper facies in the south indicates a very slowly dipping ramp setting for the Hastarian (Hance & Poty, 2006). The Hastière Fm recorded bioclastic and crinoidal accumulation with some argillaceous interbeds. The Pont d'Arcole Fm is one of the rare argillaceous unit through the Dinantian carbonate succession. It corresponds to the development of dysoxic shale facies on the lower Hastarian carbonate ramp in link with a change of accommodation and perhaps a reduction of carbonate production. The gradual changes from and to the underlying and overlying formations and the abundance of fossils in the Pont d'Arcole Fm may not fully support the idea of a disastrous black shale event as the Alum Shale Event (Poty *et al.,* 2001). The Landelies Fm recorded the return of 'normal' carbonate sedimentation dominated by crinoidal packstone-grainstone and shows a remarkable regularity all over the Namur–Dinant Basin. Sequence 2 starts abruptly in the DSA and CSA with the upper member of the Hastière Fm (LST?-TST) and the Pont d'Arcole Fm (TST). The medium to thick-bedded crinoidal limestones of the Landelies Fm form the HST and FSST.

All these lithostratigraphic units show a striking cyclic development, interpreted as orbitally-forced climatic sequences (greenhouse-icehouse eccentricity cycles, Poty *et al.*, 2013a, 2013b). The sequences varry from alternations of shale and calcareous shale (mainly in the Pont d'Arcole Fm) to alternations of calcshale and limestone (essentially in the Hastière Fm), and to limestone dominated (mainly in the upper part of the Landelies Fm). Their thickness varies from about 0.2 m to 1 m (average c. 0.4 m), and is strongly influenced both by the sediment production and by the compaction in the argillaceous levels and pression dissolution in the limestone levels (Poty *et al.,* 2013a).

Considering the sequences as the result of precession cycles, it is possible to calibrate the duration of the Hastarian substage but also of the third order sequence 2. According to Berger *et al.* (1989), precession cycles for the Lower Tournaisian are about 17 and 20.2 ky, and it is possible to consider 18.6 ky as a rough average for their duration. On the other hand, according to Giles (2009) who calibrated the three last third-order sequences of the Viséan to 2.4 My and considered that they could correspond to eccentricity cycles, we consider that the Tournaisian ones also could last about 2.4 My. Therefore the 93 precession sequences recognized in the third-order sequence 2 may represent 1.73 My, suggesting that the erosion surfaces marking the sequence boundaries between sequence 1 and 2, and 2 and 3, could correspond to gaps as long as about 0.67 My if we consider a similar number of precession sequences in both sequences 1 and 3. So, considering the duration of the 31 precession sequences in the Hastarian part of the third-order sequence 1, i.e. 0.577 My (not including the unknown time corresponding to the 1.75 m-thick unit at the base and the 3.65 m-thick unit at the top), + 0.67 My, + 1.73 My, + 0.67 My, + 31 sequences in the Hastarian part of the third-order sequence 3, i.e. 0.577 My, we obtain 4.224 My as a possible duration for the Hastarian (Poty *et al.*, 2013a, 2015). Note that, according to Menning *et al.* (2001), the Hastarian lasted for about 6 My. A refinement of that method and the extension of the recognition of orbitally-forced sequences to the Ivorian Substage (Upper Tournaisian) could possibly contribute to a better definition of its duration and thus of that of the Tournaisian Stage.

From sequence 2 on, the topography of the ramp changed and a strong proximo-distal pattern develops. It is probably due to synsedimentary faulting and consequent deepening of the Dinant sedimentation area where Waulsortian complex started growing (Bayard, Leffe, Waulsort, Molignée and Salet formations, see description of the Gendron-Celles section). North of the Yvoir-Ciney line, the facies are typically shallower in the CSA (Yvoir, Ourthe, Martinrive and Longpré formations, see Poty *et al.*, 2001 for detailed description). Similarly, south of the Waulsortian development, the ASA shows shelf facies similar to those of the CSA. In the NSA and VASA, the succession is similar but often dolomitized (Namur and Vesdre dolostone). The Maurenne Fm, Bayard Fm and Hun Mbr (Yvoir Fm) corresponds to the LST whereas the Yvoir and Waulsort formations form the TST respectively in the CSA and DSA. The HST are represented by the Ourthe and Waulsortian facies in the CSA and DSA. Sequence 4 is represented in the DSA by the LST-TST deposits of the lower part of the Leffe Fm and in the CSA with the TST deposits of the Martinrive Fm. The crinoidal rudstone of the Flémalle Mbr and the overlying oolithic limestone of the Avins Mbr correspond to the HST and HST-FSST. These two members correspond respectively to the lower and upper parts of the Longpré Fm.

2.3. Viséan

Straddling the Tournaisian-Viséan boundary, the Waulsortian complex still influenced the sedimentation in the DSA (Fig. 3) with the deposition of the restricted turbiditic facies (e.g. Overlau, 1966, Hance, 1988, Mottequin, 2004) of the Molignée Fm ('black marble' facies) developed in a depression at the prograding inner-outer shelf transition (Lees, 1997). This peculiar facies records a switch in the cyclic deposition pattern from short-term climatic cycles in the Tournaisian to a parasequence-based pattern that dominates during the whole Viséan and probably witnesses the onset of the Viséan glaciation. Sequence 5 is preserved only in the DSA (Fig. 3) and in the Visé sedimentation area (VSA). In the transition CSA-DSA, it corresponds to the Sovet Fm and its equivalents to the south, namely, the upper part of the Leffe Fm and the overlying Molignée Fm. Submarine topographic irregularities inherited from different sedimentation rates and Waulsortian buildups were smoothed out in the late Moliniacian. Sequence 6 filled the inherited topographic irregularities in the DSA. Evaporitic facies developed in the CSA and NSA (lower part of the Terwagne Fm) are interpreted as the LST. The latter rest disconformably upon the underlying Avins Mbr (FSST of sequence 4) with local karst development in the NSA and VASA. In these sedimentation areas, the TST corresponds to upper part of the Terwagne Fm. In the DSA, the Salet Fm and, further south, the upper part of the black limestones (Molignée Fm) forms the LST and TST. In the entire Namur–Dinant Basin, the sequence 6 ends with the thick-bedded packstones and grainstones of the Neffe Fm as the HST and FSST (high energy oolithic, pelloidic and bioclastic facies).This formation is capped by the '*Banc d'Or de Bachant*', a bentonite, partly reworked in palaeosol (Delcambre, 1989).

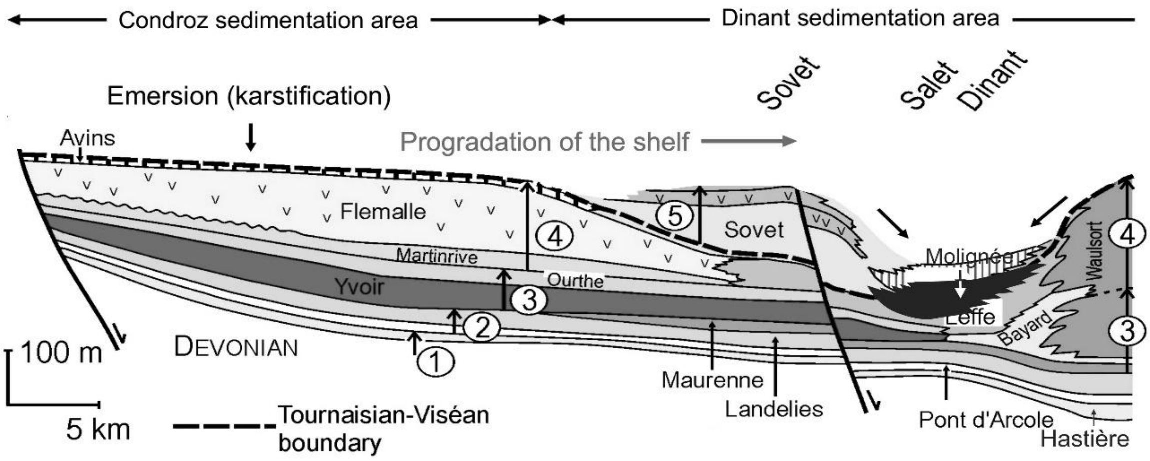

Fig. 3: **North-South transect through the Dinant-Namur Basin showing the spatial relationship of the lithostratigraphic units and their eustatic interpretation. Modified from Devuyst *et al.* (2005) and Poty *et al.* (2006).**

During the Livian (Mid Viséan) and much of the Warnantian (Late Viséan), sedimentation was controlled by an aggrading shelf and glacio-eustatic sea-level fluctuations (Chevalier *et al.* 2006). Resulting parasequences can be correlated along the entire Belgian shelf and from the Aachen area in Germany towards the Bristol area in Britain (Hance *et al.*, 2001).

The Livian is characterized by a change in basin geometry due to the onset of the Variscan movements, open marine facies develop to the north, whereas restricted facies and evaporites (and associated collapse breccia) developed in the south. Sequence 7 includes the LST (Haut-le-Wastia Mbr), TST (Corphalie and Awirs Mbrs) and HST(-FSST?) (Seilles and Maizeret members). Sequence 8 is the thinnest sequence observed in the basin. It corresponds to the Bay-Bonnet Mbr (LST and TST), characterized by stromatolitic limestones, and to the bioclastic limestone of the Thon-Samson Mbr (HST) of the Bonne Fm. This shallow-water sedimentation continues through the Warnantian (Upper Viséan) during the sequence 9 that covers the Poilvache Mbr (LST?-TST) and the Anhée Fm (HST). Except in the VSA where large bioherm developed with an abundant fauna, the Warnantian is very monotonous (Hance & Poty, 2006). Very locally in the DSA, inner platform sedimentation (sequential microbialithic limestone) is interrupted by the deposition of small (plurimetric) coral biostromes (Aretz, 2001). This last sequence is lacking in many parts of the NSA, VASA and ASA, due to non-deposition or subsequent erosion. In the NSA and VSA, the lower 'Namurian' siliciclastics fill palaeokarstic depressions reaching up to the Livian formations. The gap extends up to the Arnsbergian E2 goniatite Zone (westwards) to the the Chokierian H1 Zone (eastwards, Bouckaert, 1967).

4. Biostratigraphy, sequence stratigraphy and events

The litho- and biostratigraphy of the Dinantian has been reviewed recently by Poty *et al.* (2006, 2014). The rugose coral biozonation of Poty *et al.* (2006) is a useful tool in the field. The foraminifer biozonation established and enhanced by Conil during more than 25 years was summarized by Poty *et al.* (2006) with the redefinition of 17 biozones through the Latest Famennian and Early Carboniferous. Coupled with the sequence stratigraphy, these biozonations are powerful tools for global correlation as proven by Hance *et al.* (2011), Poty *et al.* (2002), Denayer (2014), etc. The conodonts are of poor interest in the Viséan but are rather abundant in the Tournaisian (Groessens, 1975). Figure 4 summarizes the Lower Carboniferous biostratigraphy and lithostratigraphy of Belgium with reference to bio- and sedimentological events.

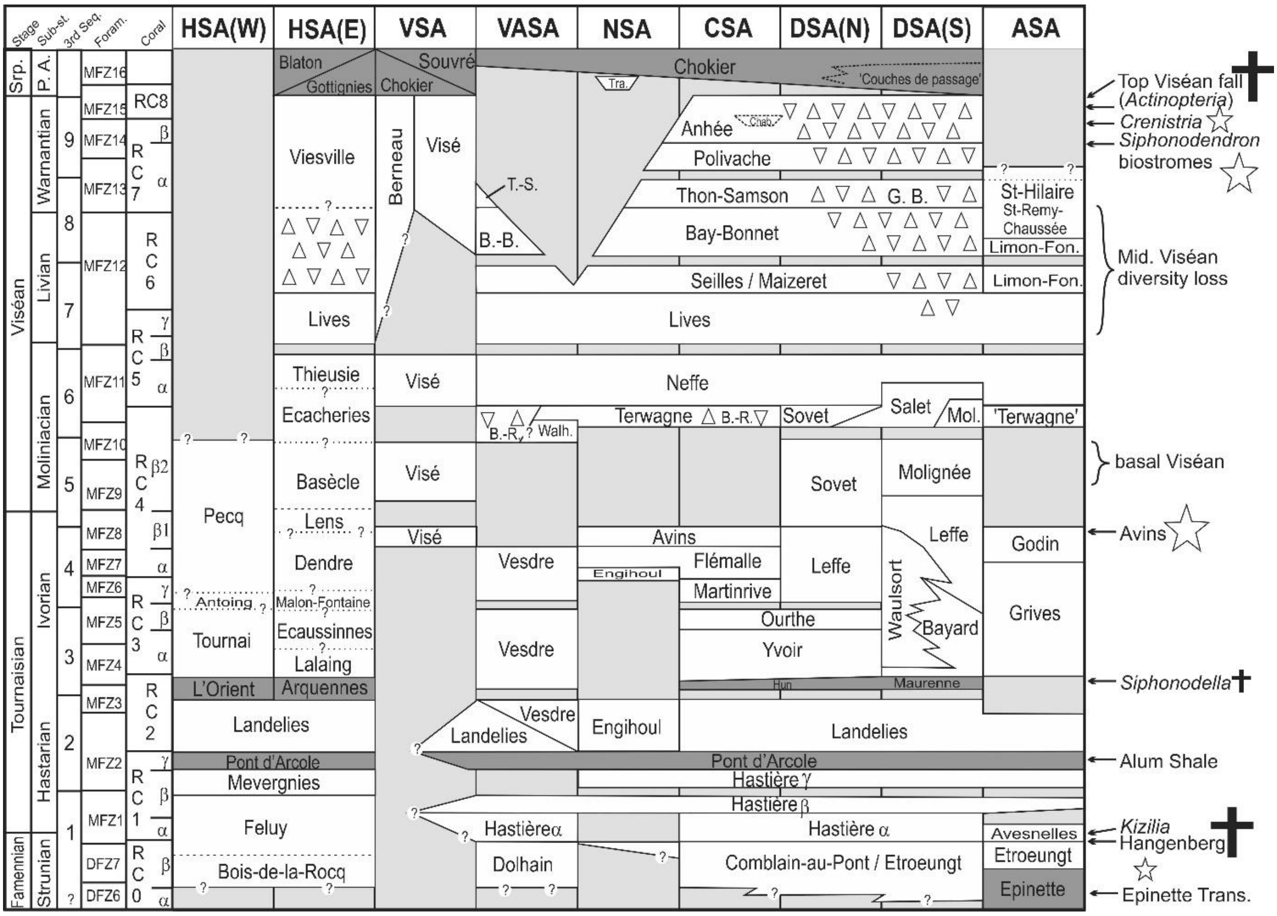

Fig. 4: **Lithostratigraphic, biostratigraphic and sequence stratigraphic framework for the uppermost Devonian, Tournaisian, Viséan and Lower Serpukhovian of Southern Belgium and surrounding areas, with position of some events. Gaps are indicated by light gray zones, units in white are carbonate, units in dark grey are siliciclastic. Third-order sequences according to Hance *et al.* (2001) and Devuyst *et al.* (2005). Biostratigraphy (foraminifers and rugose corals biozones) after Poty *et al.* (2006). Legend: Subst.: substages, Coral: Rugose Corals biozone, Foram.: Foraminifers biozones, 3rd Seq.: third-order sequences, Srp.: Serpukhovian, P. A.: Pendleian and Arnsbergian, Limon-Fon.: Limont-Fontaine Fm, Mol.: Molignée Fm, Walh.: Walhorn Mbr, B.-R.: Belle-Roche Breccia, B.-B.: Bay-Bonnet Mbr, T.-S.: Thon Samson Mbr, G. B.: Grande Brèche, Cha.: Chabôfosse Facies, Tra.: Tramaka Mbr. Modified after Poty *et al.* (2002, 2006, 2011), Poty & Hance (2006a, 2006b), Devuyst *et al.* (2006), Hance & Poty (2006), Hance *et al.* (2006a, 2006b, 2006c).**

Comparatively to the Devonian, very few bioevents were defined in the Lower Carboniferous, possibly because of the typical 'event facies' such as black shale are not developed in the proximal facies of the Dinantian (Fig. 4). The Hangenberg Event occurs at the top of the Devonian but its effects had huge consequences on the Lower Tournaisian environments. As in other neritic sections worldwide, the recognition of the Devonian–Carboniferous boundary on the basis of its current guides (the conodonts of the *Siphonodella praesulcata–S. sulcata* lineage) is not possible in southern Belgium. Nevertheless, the faunal change and extinctions associated with the boundary have been recognized long time ago and very well documented (e.g., Conil & Lys, 1970;

Streel, 1969; Streel *et al.*, 2006; Poty, 1986, 1999; Hance & Poty, 2006; van Steenwinkle, 1990; Nicollin & Brice, 2004; Mottequin *et al*., 2014). Contrarily to most pelagic condensed sections used to study global boundaries, the succession across the Devonian–Carboniferous of southern Belgium consists of a relatively thick series of shallow water siliciclastic evolving to transgressive carbonate deposits ('Epinette Transgression'). This thick succession allows a good understanding of the Famennian and Tournaisian transition and of the crisis affecting the marine ecosystems across the boundary. In the Namur–Dinant Basin, the Hangenberg Black Shale Event is not well marked because its anoxic facies, probably never spreads – or only exceptionally – into the shallow-water environments, and carbonate facies rich in benthic fossils continued to develop during its development in other areas (see Kaiser *et al*., in press). Conversely, the following Hangenberg Sandstone Event, which reflects a strong sea-level drop, is easily recognizable and traceable from the Aachen (Germany) to the Dinant areas. It sharply overlies levels with numerous Strunian brachiopods, rugose corals, stromatoporoids and foraminifera. Only reworked Strunian marine fauna are recorded in the sandstone bed and therefore the extinction event occurred immediately after the deposition of that sandstone unit. Therefore, in the Namur–Dinant Basin, the extinction event perfectly corresponds to the sudden sea-level drop reflected by the deposition of sandstone or sandy limestone, but not to the development of black shale facies. Moreover, the depositional and sedimentological patterns before and after the event are identical and made of carbonate-shale cycles corresponding to precession orbitally-forced sequences (20 Ky, Poty *et al.*, 2015). Hence, the sea-level drop and associated extinctions may be related to a single very short event, probably corresponding to an unusual short-living ice-age event, and not in sequence with the rest of the deposits and absolutely not to a major sequence boundary as suggested by some authors.

In the lower Hastarian, the first member of the Hastière Fm displays a peculiar facies of thinly-bedded nodular limestone (Fig. 5) which can be traced up to NW Turkey (Yılanlı Fm, Denayer, in press) and SE China (Shangyueshan Mbr, Hance *et al.*, 2011). This depositional event is yet not fully understood but may be related to the re-establishment of the carbonate factory immediately after the Hangenberg perturbations. Moreover, it recorded the comeback of the Lazzarus taxon *Kizilia* (a solitary stringophyllid coral that was unknown since the Late Givetian). We name it consequently the *Kizilia* Event as it is also known in SE China in the same beds. The lower Alum Shale Event, well developed in the Rhenish Mts is correlated with the shaly Pont-d'Arcole Fm but it must be noted that no extinction is recorded at this level and that is corresponds only to a sedimentary event. The extinction of numerous species of the genus *Siphonodella* in the uppermost Hastarian is potentially a bio-event associated with a sea-level drop after the high-stand of sequence 2 after Aretz & Herbig (2010). In Belgium it is recorded by sandy limestone and shale of the Maurenne Fm in the DSA and Hun Mbr of the Yvoir Fm in the CSA (see description of the Chansin quarry). This extinction event is followed by a rapid diversification of macrofauna. The latest Ivorian Avins Event (Poty, 2007) is the first significant diversification event following the relatively poorly diversified Tournaisian time slice. It is commonly recorded as oolithic limestone with an abundant fauna that suddenly became cosmopolitan (e.g. *Amygdalophyllum, Palaeosmilia, Merlewoodia*). Poty (2007) interpreted it as linked to a very high sea-level period that allowed communication between basins and momentaneous break-down of palaeobiogeographic barriers. Based on occurrence of carbonate units in deep basinal settings in the basal Viséan (e.g. Faugères Fm in Montagne Noire), Aretz & Herbig (2010) suggested that the sea-level drop of sequence 5 of Hance *et al.* (2001) should be considered as a sedimentological event. It is correlated in platform settings by a karstic surface and associated gap. In Belgium, it is recorded as 'black marble' facies of the Molignée Fm only in the southern DSA. The Middle Viséan (Livian) is characterized, in Belgium, by restricted shallow-water facies relatively poor in fauna. The low diversity – though, without marked extinction – is a common phenomenon at the global scale for this time-slice. In the Upper Viséan platform settings, *Siphonodendron* biostromes developed along the margin of the Rhenohercynian Ocean (Belgium, England, Ireland, N Spain; Aretz *et al.*, 2010) which is not a proliferation of corals but rather a colonization of shallow-water settings due to a relatively high sea-level. Finally, the *Crenistria* Event, which is defined by the sudden proliferation of the ammonoid genus *Crenistria* in the Rhenohercynian Ocean (Aretz & Herbig, 2010), is recorded, among others, in Belgium (Visé and Anhée formations), England, Portugal and Rhenish Mts. Due to unsuitable settings, the *Actinopteria* Black Shale Event (Nyhuis *et al.*, 2015) has not been recognized in Belgium. It has to be noted that the Late Dinantian recorded a significant sea-level fall at the end of the Viséan (glaciation?) that corresponds to an emersion of the carbonate platform associated to extinctions in shallow-water communities (Hance *et al*., 2001)

5. Key sections

5.1 Roysseux section

References
Conil *et al.* (1986), Van Steenwinkel (1988), Sautois (2007), Azmy *et al.* (2009).

Location and access
Section along the disused railroad in the Hoyoux valley between Huy and Modave. Northern limb of the Dinant Synclinorium (Fig. 1). GPS: 50°28’09.98”N5°16’03.13”E.

Lithostratigraphy and biostratigraphy
The upper part of the Comblain-au-Pont Fm and the Hastière Fm are exposed. The Lower Tournaisian also crops out southwards but discontinuously. The description here focuses on the Devonian-Carboniferous boundary (Fig. 5). The Comblain-au-Pont Fm belongs to the DFZ7 foraminifer biozones of Poty *et al.* (2006) which is commonly associated to the upper *praesulcata* conodont Zone but, as discussed above, the latter has never been observed in Belgium. The first bed of the Hastière Fm (bed 104) still contains Devonian fauna. The base of the Carboniferous is consequently placed at the base of the overlying bed (n°105). Upsection, the MFZ1 and MFZ2 foraminifers biozones have been recognized, as well as the RC1 rugose coral zone of Poty *et al.* (2006), indicating the lower Hastarian.

Description
Comblain-au-Pont Fm (Fig. 5):
Beds 78 to 80 (0.9 m): pluridecimetre-thick beds of dark blue crinoidal packstone-grainstone, often sandy.
Beds 81 to 89 (3.8 m): alternation of pluridecimetre-thick beds of brownish calcareous shale, slightly micaceous, with some sandy layers and pluricentimetre-thick to pluridecimetre-thick calcareous crinoidal sandstone, more or less argillaceous, often blueish in colour.
Beds 90 to 92 (1.3 m): blueish crinoidal rudstone with large crinoid stems and brachiopod shells.
Beds 93 to 103 (4.5 m): alternation of pluridecimetre-thick beds of brownish calcareous shale, slightly micaceous and pluricentimetre-thick to decimetric beds of sandy bioclastic limestone with argillaceous layers, bioturbed and crinoidal.
Hastière Fm (Fig. 5):
Bed 104 (0.8 m): blueish sandy crinoidal grainstone-packstone with shelly accumulation (brachiopods, gastropods, crinoids) interrupted by millimetre-thick argillaceous layers. This bed still contains Devonian quasiendothryrid foraminifers, and phacopid trilobites and has been correlated with the Hangenberg Sandstone by Mottequin & Poty (2014).
Beds 105 to 107: (0.6 m): blueish crinoidal grainstone-packstone rich in large crinoidal stems and brachiopod shells, interrupted by millimetre-thick argillaceous layers producing undulating beds.
Bed 108 (0.6 m): nodular bed of argillaceous crinoidal packstone with numerous *Kizilia kremersi* (a Lazzarus rugose coral, see introduction) and *Conilophyllum priscum*. The clay content increases upwards.
Bed 110 (0.4 m): calcareous shale with bioclastic layers (brachiopods, crinoids, corals).
Beds 111 to 117 (2.2 m): crinoidal packstone-grainstone with undulating argillaceous layers (pression-dissolution nodularisation).

The dominant lithofacies from the top of the Comblain-au-Pont Fm to the base of the Hastière Fm is thus a sandy crinoidal limestone. The correspondant microfacies is relatively monotonous: it is a crinoidal and pelloidal packstone-grainstone with a various quartz content. The grainstone texture dominates but packstone areas are common but do not seem to be related neither to stratification nor to bioturbation and both textures passe from one to the other without discontinuity. Syntaxial cement is uncommon. Rudstone texture occurs in coarse bioclastic layers (coquina beds). The dominant allochems are peloids, crinoid fragments and detrital quartz grains. The pelloids are rounded or elliptical in section. Their margins are sharp. The micritic pelloids with no internal structure could be interpreted as faecal pellets whereas the elongated ones, occasionnaly showing an irregular internal structure are most probably micriticized bioclasts. Both types are regularly distributed in the beds. The pelloids represent up to 30% of the allochems. Crinoid fragments are usually mud-coated disarticulated ossicles and are 0.8-1 mm large (rarely larger than 2 mm, except in bioclastic accumulation). They represent in average 15-20% of the allochems. The detrital quartz grains are essentially spherical with rounded margins, witnessing a high maturity. Furthermore, rare irregular grains with angular margins could indicate a secondary origin. The proportion of quartz grain is variable (15-20% in average) but can reach 40% in some beds (n° 104). The other allochems are fragments of brachiopods, gastropods, corals and trilobites. Their size rarely reach 1 mm. Foraminifers (quasiendothyrids, unilocular, tournayellids), ostracods, girvanellids and micas are other common allochems occurring in low proportions. Accumulations of shells (brachiopods, gastropods) and larger crinoidal stems possibly correspond to storm events.

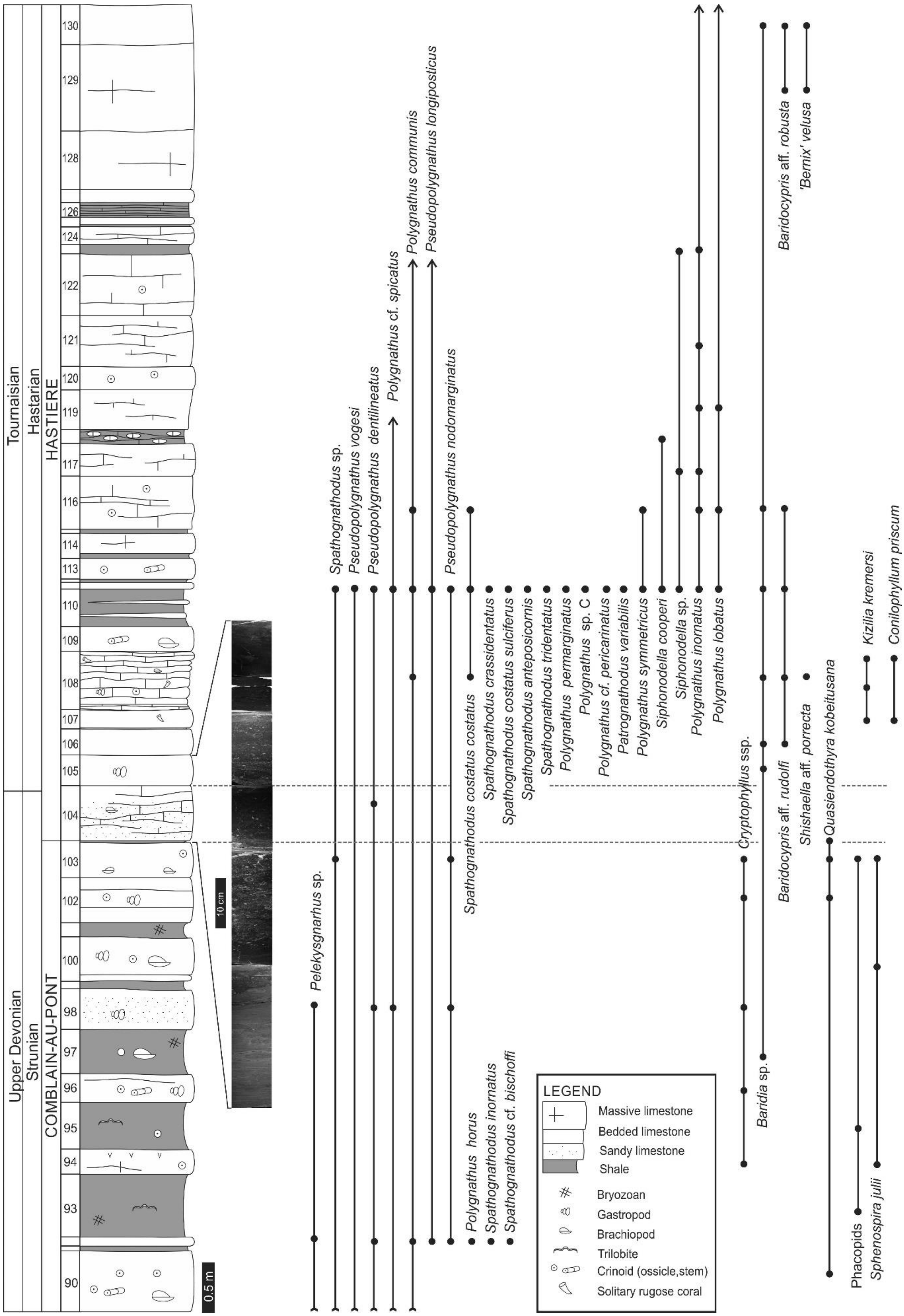

Fig. 5: **Schematic log of the Royseux section with the main facies and stratigraphic distribution of some microfossils and key macrofossils. Modified from Austin *et al*. (1970), Bouckart *et al*. (1974), Sautois (2007) and personal unpublished data.**

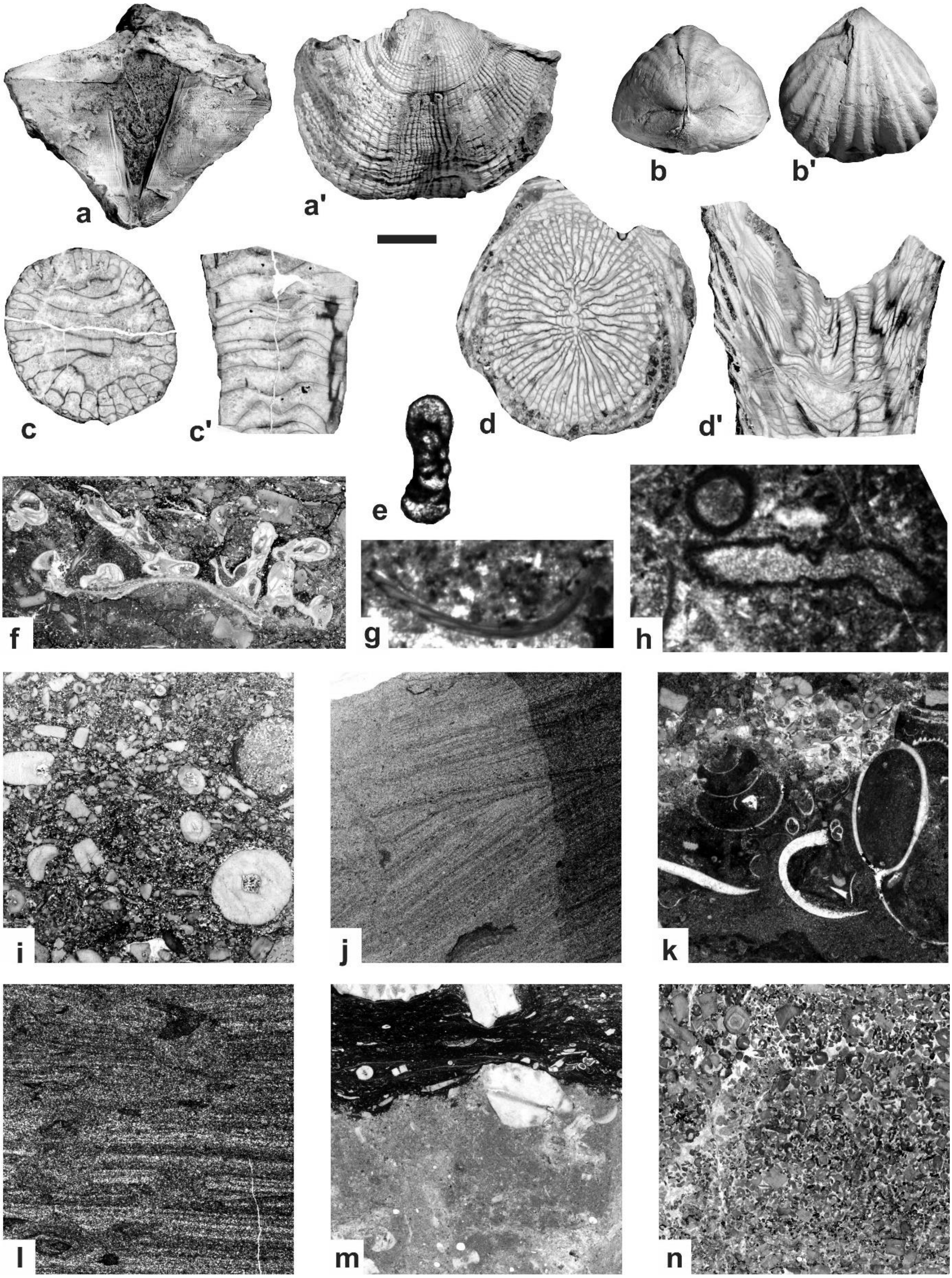
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Fig. 6: **(previous page) Some key fossils from the Royseux section (except if mentioned). a-a': *Sphenospira julii* in ventral and posterior views, Dolhain Fm, Strunian of Trooz; b-b': *Araratella moresnetensis* in ventral and posterior views, Comblain-au-Pont Fm, Strunian from Chanxhe; c-c': *Conilophyllum priscum* in transverse and longitudinal views, Hastière Fm (bed 108), Hastarian; d-d': *Kizilia kremersi* in transverse and longitudinal views, Hastière Fm (bed 108), Hastarian; e: *Quasiendothyra kobeitusana*, Comblain-au-Pont Fm (bed 100), Strunian; f: indetermined auloporid, Comblain-au-Pont Fm (bed 102), Strunian; g: *Cryptophyllus* sp., Comblain-au-Pont Fm (bed 98), Strunian; h: unilocular foraminifers, Hastière Fm (bed 108) , Hastarian; i: sandy bioclastic packstone-grainstone with large crinoid ossicles, Comblain-au-Pont Fm (bed 87), Strunian; j: calcareous sandstone with cross stratifications, Comblain-au-Pont Fm (bed 96), Strunian; k: pelloidal packstone passing to a bioclastic and crinoidal grainstone in the shell accumulation (storm event), Comblain-au-Pont Fm (bed 103), Strunian; l: laminated calcareous sandstone with bioturbations, Hangenberg Sandstone facies, Hastière Fm, base of the basal bed (104), Strunian; m: pelloidal packstone-grainstone with a bioclastic shally layer, Hastière Fm, nodular bed 108 ('*Kizilia* Event'), Hastarian; n: pelloidal and crinoidal grainstone, Hastière Fm (bed 111), Hastarian. Scale bar equals 10 mm for a, equals 5 mm for b-d, f, i-n, and equals 0.1 mm for e, g-h.**

Main faunal component

Comblain-au-Pont Fm: the brachiopods *Sphenospira julii, Prospira struniana* and *Araratella moresnetensis* are present, but not abundant. Auloporid tabulate corals are occasional. Phacopid trilobites and cryptostomid bryozoans are commonly found as fragments. Quasiendothyrid foraminifers and the ostracod *Cryptophyllus* ssp. are common in thin sections (Fig. 6). The conodonts and ostracodes have been investigated respectively by Austin *et al*. (1970) and Becker & Bless (1974). Their distribution is summarized in Figure 5.

Hastière Fm: *Kizilia kremersi* and *Conilophyllum priscum* appear in beds 106-108 (Fig. 6). Brachiopods are rare and poorly preserved.

5.2 Gendron-Celles section

References

Conil (1968), Delcambre & Pingot (1993), Devuyst *et al.* (2005), Groessens (1975), Lees (1997), Lees *et al.* (1985), Sautois (2007), Poty *et al.* (2011), Van Steenwinkel (1990, 1993).

Location and access

Section along the railway Dinant–Bertrix, 200 m north of the Gendron-Celles station, in the Lesse valley (Fig. 1). Dinant Synclinorium, southern part of the Dinant sedimentation area. Southern limb of the Dinant Synclinorium. GPS: 50°12'42.71" N4°57'52.68"E.

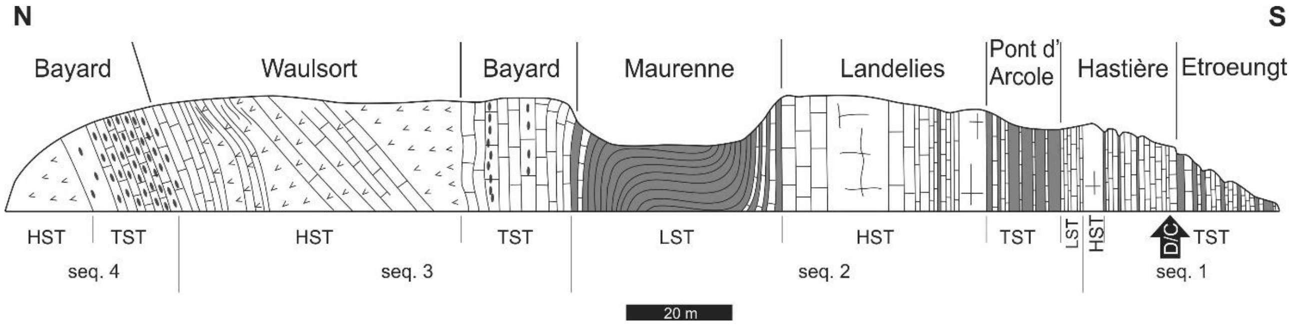

Fig. 7: **Sketch of the Gendron-Celles section, with the position of the lithostratigraphic units and presumed Devonian-Carboniferous boundary (D/C) (modified from Groessens, 1975).**

Lithostratigraphy and biostratigraphy

The uppermost Devonian Etroeungt Fm belongs to the LN miospore biozone (Paproth *et al.*, 1983), to the DFZ7 foraminifer biozone and to the RC0 rugose coral biozone of Poty *et al.* (2006) and classically attributed to the upper *praesulcata* conodont biozone by Conil *et al.* (1991). The Hastière Fm yields a poorly diversified coral fauna typical of the RC1. The Pont d'Arcole Fm corresponds to RC1γ, Landelies and Maurenne Fm, to RC2. The Bayard Fm is devoid of corals, and the Waulsort Fm yields only *Amplexus*. The foraminifers of these formations indicate MFZ1 to MFZ6 after Devuyst *et al.* (2005). Groessens (1975) recognized conodonts belonging to the *duplicata* to *dollymae* biozones.

Description

The upper 15 m of the Etroeungt Fm consist of bioclastic and crinoidal limestones, nodular marly limestone and calcareous shale, usually very fossiliferous. The patterns of deposition made of carbonate-shale alternations corresponding to orbitally-forced precession cycles of 20 ky duration. Up-section, the argillaceous content decreases progressively to the Hastière Fm.

Beds 5 to 16 (3.8 m): cyclic alternations of argillaceous crinoidal limestone in pluridecimetre-thick beds, often nodular (stylonodularization) and decimetric beds of calcareous shale with some limestone nodules.

Beds 17 to 29 (4.1 m): pluridecimetre-thick beds of dark blue argillaceous crinoidal limestone and thin argillaceous layers.

Beds 30 to 38 (3.5 m): alternations of pluridecimetre-thick argillaceous and crinoidal limestone and of brownish nodular calcareous shale with bioclasts.

Beds 39 to 52 (4.5 m): pluridecimetre-thick to metric beds of dark blue argilaceous limestone with thin layers of calcareosu shale.

Hastière Fm:

Bed 52 (2 m): a single massive bed of dark blue crinoidal and bioclastic limestone with layers of coarse crinoidal rudstone. Strunian fauna (corals, foraminifers) seems to be reworked at the base.

The lower member of the Hastière Fm (beds 53 to 94, 15 m) consists of pluridecimetre-thick crinoidal packstone interbedded with centimetre-thick shale beds. A 3 m-thick bed (n° 95-96) of crinoidal packstone/rudstone compose the middle member. The upper member (beds 97 to 113, 4 m) is similar to the lower one but shows more shaly layers.

The Pont d'Arcole Fm starts at the first decimetre-thick shale bed and includes 13 m of calcareous shale and siltstone, usually dark, containing dissolved fossils (brachiopods: Spiriferina peracuta, bryozoans, small solitary rugosan, pelecypods and crinoids). Some argillaceous limestone beds occur in the upper part of the formation.

The overlying Landelies Fm (38 m) starts at the first thick crinoidal packstone/grainstone bed with abundant brachiopods and corals. Thick limestone beds alternate with thin calcareous shale interbeds in the lower part of the formation. The upper third of the formation is made of massive crinoidal limestone with few thin shaly intercalations.

The Maurenne Fm is abruptly resting on the last thick crinoidal limestone bed of the Landelies Fm. It consists of calcshale and argillaceous limestone containing shell accumulations in the upper part. Some cherty argillaceous limestone occur at the top of the unit. Note that a forld occurs within the outcrop doubling the thickness of the formation.

The Bayard Fm begins with 20 m of well-stratified dark or brownish crinoidal limestone with cherts. The upper part of the formation is less stratified and locally dolomitized. It passes upsection and laterally into the Waulsortian ‘mound facies’ of the Waulsort Fm. The latter appear as massive light-grey to beige limestone and diagenetic dolomite devoid of chert, in which three main facies are recognized: (1) Well stratified crinoidal packstone to rudstone, passing laterally to the Bayard Fm. (2) The ‘blue veins facies’, particularly typical in the lower and middle part of the mounds. The ‘veins’ correspond to stromatactoid cavities filled with sparry calcite. Fenestellid bryozoans are abundant in the lower part of this unit (Lees 1997). (3) Massive or poorly stratified bioclastic wackestone particularly developed in the upper part of the mound. The top of the Gendron-Celles section shows the reappearance of 20 m of the Bayard Fm but with much more cherts. This level corresponds to a lateral facies of a Waulsortian mound. A few metres of a second Waulsortian buildup overlie this Bayard facies. Many details can be found in the pioneer work of Dupont (1863) and in the abundant production of Lees (1997, Dehanschutter & Lees, 1996, Lees *et al.*, 1985, Lees & Miller, 1985, 1995).

Main faunal component

Etroeungt Fm: the rugose coral *Campophyllum gosseleti* and the tabulate coral *Yavorskia* sp. are both relatively common in the carbonate and shaly facies. Phacopid trilobites and numerous brachiopods (e.g., *Aulacella interlineata*, chonetidines, etc.), but generally poorly preserved, are also present.

Hastière Fm: the massive limestone yield the corals *Conilophyllum priscum*, *C. streeli*, *Siphonophyllia cylindrical* and abundant syringoporids. The other macrofauna are poorly known.

The Pont d’Arcole Fm yielded brachiopods, small solitary rugose corals and an abundant bryozoan fauna, which remain unstudied.Landelies Fm yields *Siphonophyllia rivagensis* and *Eostrotion konincki* as well as numerous spiriferid brachiopods. Maurenne Fm: this shaly unit only yields brachiopods and undissepimented rugose corals (*Zaphrentites* ssp., *Cyathaxonia cornu*). The Bayard, Leffe and Waulsort Fm are here relatively poor in macrofauna. The conodont fauna of this section was described by Groessens (1974).

5.3 Dinant and the Bayard Rock

References

Conil *et al.* (1988), Delcambre & Pingot (1993), Devuyst *et al.* (2005), Groessens (1975), Groessens & Noël (1975).

Location and access

Rocks situated on the eastern bank of the Meuse river upstream from the town of Dinant, central part of the DSA. South-central part of the Dinant Synclinorium. GPS: 50°14'40.56"N 4°55'16.83"E.

Lithostratigraphy and age

This classical section of the Lower-Upper Tournaisian succession exposes almost continuously the Landelies, Maurenne, Bayard and Leffe formations in peri-Waulsortian setting (Fig. 8). These facies are relatively poor in microfauna but the foraminifers indicate the MFZ4 to MFZ6. The conodonts indicate the upper Tournaisian (see Groessens & Noël, 1975).

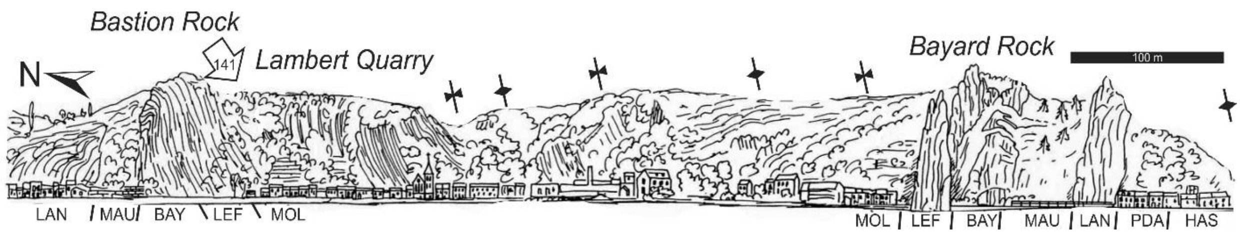

Fig. 8: **Sketch section along the Eastern bank of the Meuse between the Bayard Rock and Bastion Rock in Dinant, with the position of the lithostratigraphic units and historical Tournaisian-Viséan boundary (bed 141) modfifed from Groessens (1975).**

Description

Here are exposed lateral equivalents of the Waulsortian buildups which have a huge development westwards (Moniat section, see Dehanschutter & Lees, 1996). The Bayard Formation is abruptly resting on the Maurenne calcshale (no longer exposed). The formation is a thinly-bedded crinoidal rudstone with some cherty layers. The Leffe Fm consists mainly of finer-grained, grey to purplish blue wackestone to packstone with abundant cherts moulding the bioturbation. The dominant microfacies is a wackestone with coated clasts and and common ostracods, trilobites, bryozoans, sponge spicules, few foraminifers and many problematic microfossils. The Bayard crinoidal limestone is commonly interpreted as the sole of the Waulsortian buildups but also occurs within the mounds and thus represents a lateral equivalent of the lower part of the buildups. The transition to the overlying Leffe Formation is rather progressive and marked by a decrease in crinoidal content and increase of mud-coated clasts proportion. The Leffe Formation is the lateral proximal equivalent for the middle and upper part of the Waulsortian buildups and results most probably from the erosion and resedimentation on the flanks of the buildups. The Maurenne Fm is interpreted as the LST of sequence 3, whereas its TST and HST correspond respectively to the Bayard and Leffe formations. The historical boundary between the Tournaisian and Viséan is located in the nearby 'Lambert Quarry' immediately south of the Bastion Rock, at the base of bed n°141 that correspond to the first intercalation of the black marble' facies in the Leffe Fm. It also coincides with the first occurrence of the calcareous foraminifer genus *Eoparastaffella* (Conil *et al.*, 1969), less than 1 m below the first occurrence datum of the conodont *Gnathodus homopunctatus* (Groessens & Noël, 1977).

5.3 Chansin 'les Nutons' quarry

References

Hibo (1994), Poty *et al.* (2011, 2013a).

Location and access

The quarry is open 800 m south of Durnal village, in the northern bank of the Bocq valley. Central part of the Dinant Synclinorium, transitional zone between Condroz sedimentation area (CSA) and Dinant sedimentation area (DSA). GPS: 50°19'42.36"N 4°59'07.28"E.

Lithostratigraphy and age

The Lower Tournaisian Hastière Fm (top of the middle member and upper member), Pont d'Arcole Fm, Landelies Fm ('*Petit-Granit du Bocq'* ornamental and building stone), Yvoir Fm (Hun Mbr) are exposed.

Rugose coral associations yielded by the middle and upper members of the Hastière Fm are characteristic of the RC1β biozone. Corals from the Landelies and Hun Mbr indicate RC2 biozones. The upper Mbr of the Hastière, Pont d'Arcole Fm and Landelies Fm belongs to the MFZ2, and the Hun Member to the MFZ3 foraminifer biozone of Poty *et al.* (2006). The Hastarian-Ivorian boundary is situated about 15 m above the top of Landelies Fm, close to the first cherty band at the top of the Hun Member which is a marker bed found in the stratotype of the substage in Yvoir (Groessens, 1975).

Description

The uppermost two metres of the middle member (β) of the Hastière Fm consists of thick-bedded bioclastic limestone with large gastropods (*Straparollus*). The contact with the upper member (γ) of the Hastière Fm is sharp, corresponding to an erosion surface (Fig. 9). This last member (8 m) is made of decimetric beds of bioclastic, often argillaceous, grey limestone with many large solitary rugose corals (*Conilophyllum streeli*). Shaly interbeds are frequent and usually full of brachiopod shells. The boundary between the Hastière and Pont d'Arcole formations is gradual, and marked by the increase of shale layers (in thickness and frequency). The Pont d'Arcole Fm consists of brown grey to dark shale, often calcareous and silty, rich in fossils (crinoids, brachiopods – among which small *Spiriferellina peracuta* – small corals, bryozoans, trilobites, etc.). The upper part of the Pont d'Arcole Fm is marked by the increase of carbonate content. The last decimetre-thick shale bed marks the top of the Pont d'Arcole Fm and the boundary with the overlying Landelies Fm.

The lower part of the Landelies Fm is made of a 20 m-thick alternation of 40 cm-thick limestone beds and centimetric argillaceous limestone layers. These alternations are very regular in thickness and facies. The limestone is mainly wackestone-packstone more or less rich in crinoids (10-20 %) and brachiopods. The argillaceous layers are rich in bryozoans. The following 20 m are made of decimetre to metre-thick beds, among which the most massive are quarried as '*Petit Granit du Bocq*', a building and ornemental stone. The facies are still wackestone and packstone but the crinoid content increases to 35-40 % (Hibo, 1994)

Oblique and cross-stratification are common in these crinoidal limestone; however stratigraphic joints and/or stylolites can define 60-100 cm-thick beds. The macrofauna is common and comprises large solitary rugose corals (*Siphonophyllia*), tabulate corals (micheliniids, *Yavorskia*, cladochonids) and brachiopods. The boundary with the overlying formation is sharp and marked by argillaceous and sandy limestone belonging to the Hun Member of the Yvoir Fm (lateral equivalent of the Maurenne Fm). The overlying limestone beds are cherty, with a very rich macrofauna, especially in the upper part: small solitary rugose corals, michelinids, cladochonids, bryozoans, brachiopods, trilobites, crinoids, etc. Splendid silicified fossils can be found in the weathered debris of the rock (Fig. 10). The Yvoir Fm *s.s.* is badly exposed in the uppermost part of the quarry and is not accessible. Its base is defined with the appearance of the first limestone with black chert layer.

The HST of sequence 1 is recognized in the middle member of the Hastière Fm (Fig. 9), whereas the upper member corresponds to the LST of the overlying sequence 2 of Hance *et al.* (2001). The TST of this sequence corresponds to the Pont d'Arcole Fm in which the dark shale corresponds to the maximum flooding surface. The Landelies Fm corresponds to the HST (and questionably the FSST) of sequence 2. The sharp contact with the overlying Hun Mbr of the Yvoir Fm corresponds to the sequence boundary. The latter member is interpretted as the LST of sequence 3 and contains the base of the Ivorian Substage (base of Upper Tournaisian, base of *Polygnathus communis carina* Zone).

All these lithostratigraphic units shows a striking cyclic development, interpreted as orbitally-forced sequences. The sequences varry from alternations of shale and calcareous shale (mainly in the Pont d'Arcole Fm) to alternations of calcshale and limestone (mainly in the Hastière Fm), and to limestone bed dominated (mainly in the upper part of the Landelies Fm). Their thickness varies from about 0.2 m to 1 m, and is strongly influenced both by the sediment production and by the compaction in the argillaceous levels and pression dissolution in the limestone levels. The distribution of their sedimentary nature follows the sedimentary evolution of the third-order sequences 1 to 3 described by Hance *et al.* (2001). Truncations at the top of the sequences indicating emersion can occur during the lowstand and the falling-stage system tracts of the third-order sequences. They are not marked during the transgressive and highstand system tracts, suggesting relatively low eustatic variations at the scale of these sequences. Fifteen sequences form the upper member of the Hastière Fm, corresponding to the LST of the sequence 2, 24 sequences compose the Pont d'Arcole Fm (TST 2), 28 the lower part of the Landelies Fm (HST 2), and 26 the upper part of the formation (FSST 2). Thirty-one sequences compose the lower part of the Yvoir Fm (LST and TST 3) until the Hastarian/Ivorian boundary (Lower/Upper Tournaisian boundary). In complement, the Gendron-Celles section (south of Dinant) exposes the lower members of the Hastière Fm, there composed of 31 sequences (excluding the basal beds where no cycle were recognized). Therefore, the whole Hastarian totalizes 93 sequences (Poty *et al.*, 2013a, see introduction).

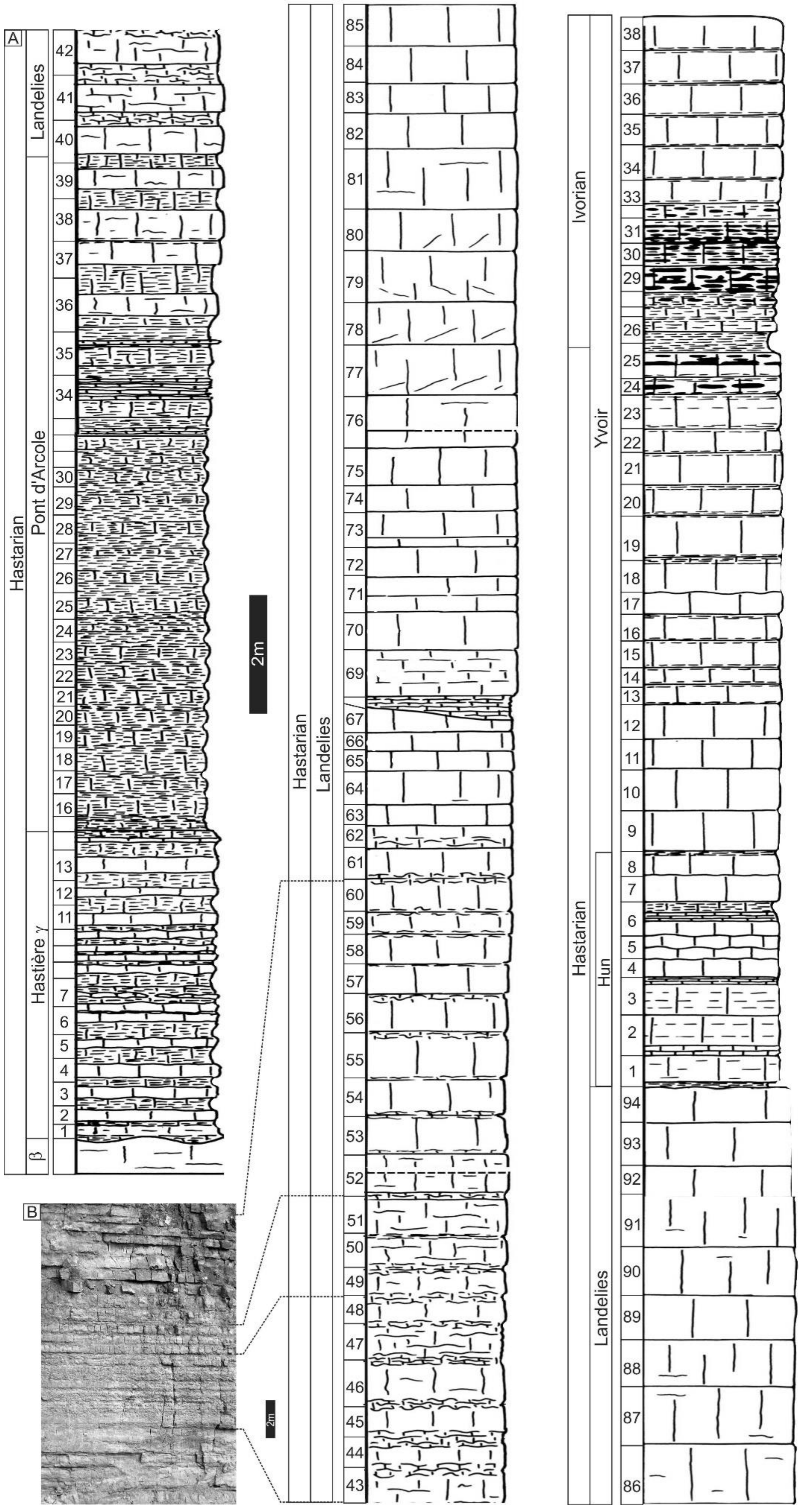

Fig. 9: **A. Schematic log of the Chansin quarry with the main sedimentary cycles. B. Picture of the cycles 43 to 60 in the Landelies Fm.**

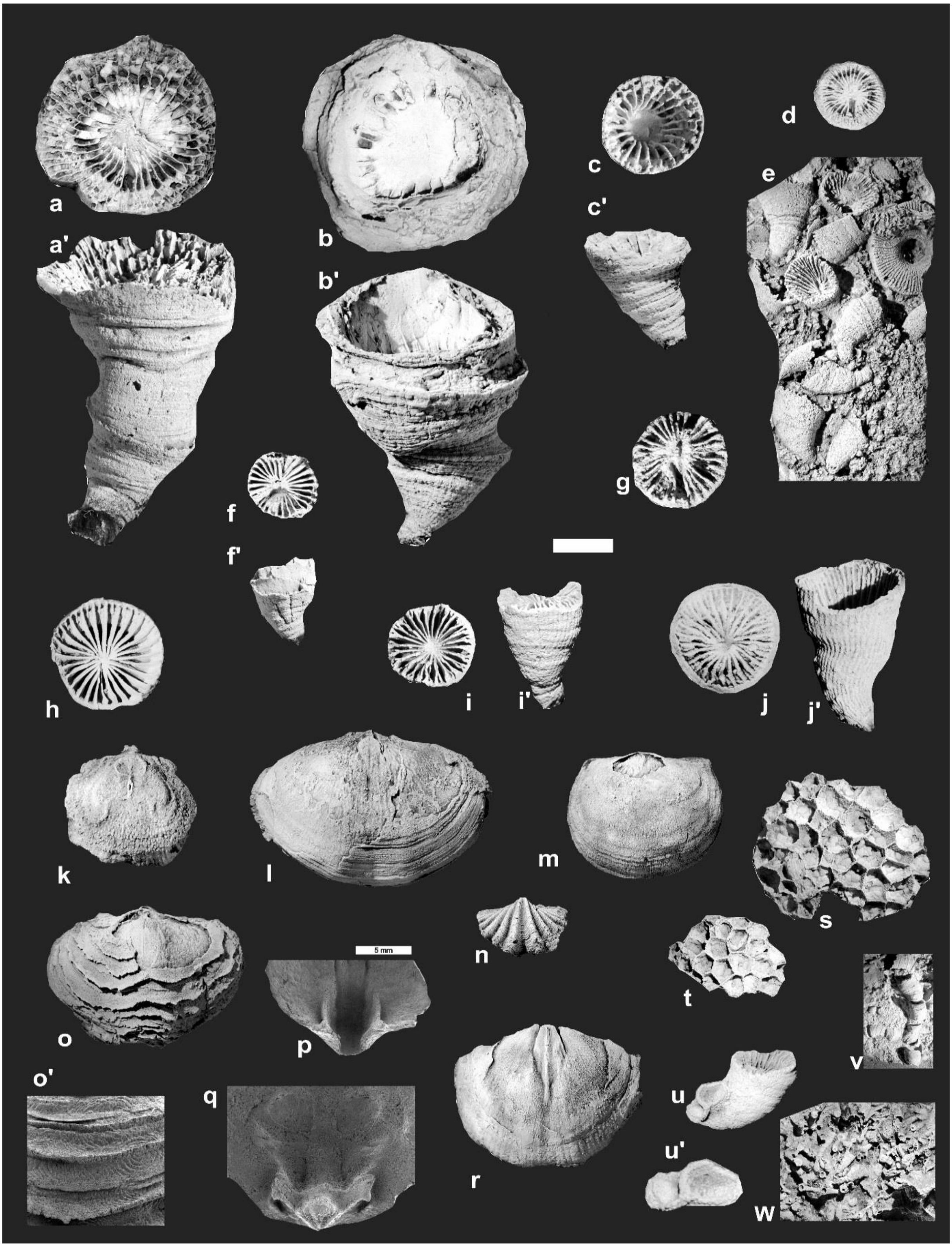

Fig. 10: **Some silicified fossils from the lower Ivorian Yvoir Fm in the Chansin quarry. a-a': *Caninophyllum patulum*; b-b': *Caninia* sp.; c-c': *Caninia cornucopiae*; d: *Sychnoelasma konincki*; e: accumulation of *Sychnoelamsa konincki* and large crinoid ossicles; f-f': *Zaphrentites delanouei*; g: *'Lophophyllum' konincki*; h: *Rotiphyllum* sp.; i-i': *Saleelasma delepinei*; j-j': *Proheterelasma omaliusi*; k: unidentified productid, dorsal interior; l: *Cleiothyridina* sp., ventral view; m: *Schellwienella* sp., dorsal view; n: *Spiriferellina* cf. *peracuta*, ventral valve; o-o': *Lamellosathyris lamellosa*, complete specimen in dorsal view and close-up of a ventral valve showing the beekite rings on a ventral valve; p: *Composita* sp., dorsal interior; q: *Rhipidomella michelini*, dorsal valve; r: *Mesochorispira konincki*, internal mould in ventral view; s-t: indet. michelinid; u-u': *Palaeacis* sp. on the concave side of a *Sychnoelasma konincki* and close-up view; v: indet. beaumontid; w: indet. cladochonid. Scale bar equals 10 mm for all, except for p, q and u' (= 5 mm) and r (= 2.5 mm).**

Main faunal component

The Landelies Fm yields numerous *Siphonophyllia rivagensis*, *Cyathaxonia cornu, Zaphrentites* sp., *Eostrotion* sp., *Saleelasma delepinei, Yavorskia* sp. and *Cladochonus* sp. The brachiopods are diverse but remain poorly known. The uppermost part of the formation is rich in bellerophontids, small gastropods and tube worms. The whole formation is rich in crinoids.

The shaly Hun Mbr yields an abundant fauna. *Septosyringothyris demaneti* and abundant productids are known from the basal beds, together with *Caninia cornucopiae*, *Zaphrentites delanouei* and abundant cryptostomid bryozoans.

The Yvoir Fm yielded a silicified fauna (Denayer *et al.*, 2015, Fig. 10) composed of *Caninia cornucopiae, Caninia* sp., *'Lophophyllum' konincki, Siphonophyllia* sp., *Amplexus coralloides, Caninophyllum* gr. *patulum*, *Sychnoelasma konincki*, *Zaphrentites delanouei*, *Proheterelasma omaliusi*, *Amplexizaphrentis* sp., *Saleelasma delepinei, Michelinia* sp., *Beaumontia* sp., *Palaeacis* sp and numerous indetermined cladochonids. The brachiopods include notably *Mesochorispira konincki*, *Spiriferellina* cf. *peracuta*, *Lamellosathyris lamellosa*, *Schellwienella* sp., *Composita* sp., *Rhipidomella michelini* and productids. Gastropods, bryozoans and crinoids are also common.

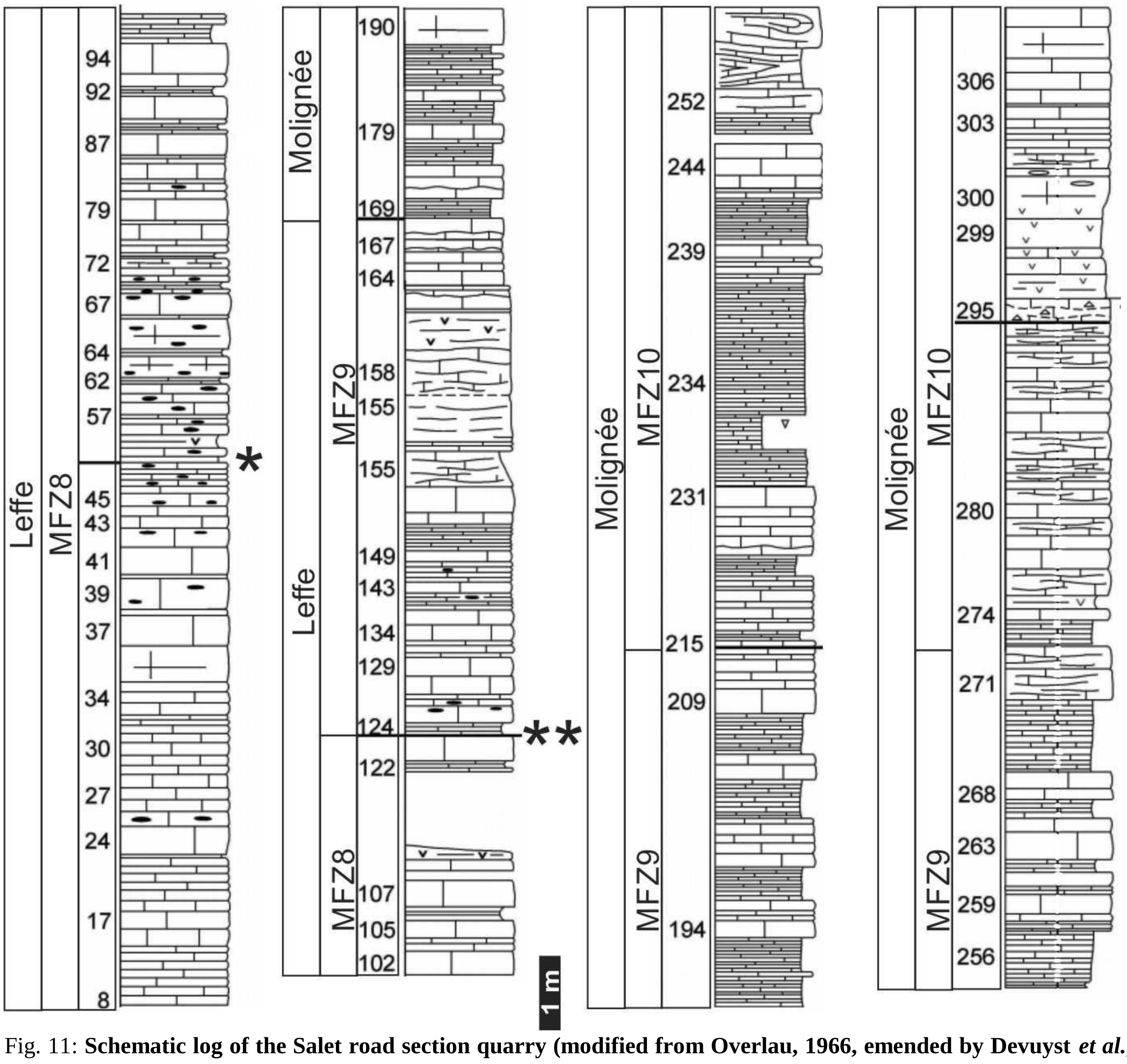

Fig. 11: **Schematic log of the Salet road section quarry (modified from Overlau, 1966, emended by Devuyst *et al.*, 2005). *: original base of the Moliniacian after Conil *et al*. (1977), **: emended base of the Moliniacian after Poty et al. (2006).**

5.4 'Tanret' quarry and Salet road section

References

Overlau (1966), Groessens (1975), Hance, (1988), Lees (1997), Mottequin (2004, 2008), Devuyst *et al*. (2005, 2006).

Location and access

Salet village is located on the northern side of the Molignée river northwest of Dinant. The road section is the embankment of the road leading from the village to the valley. The Tanret quarry is situated along this road. Central part of the Dinant sedimentation area, north of the main Waulsortian development, Dinant Synclinorium (Fig. 1). GPS: 50°18'23.77"N 4°49'40.77"E (quarry), 50°18'38.13" N4°49'48.31"E (road).

Lithostratigraphy and biostratigraphy

The Bayard, Leffe, Molignée, Salet and Neffe formations (Ivorian to Moliniacian) are well exposed along the road section (the Livian formations are poorly exposed) and the 'Black Marble' facies are fossiliferous in the Tanret quarry. They correspond to the MFZ6 to MFZ11 foraminifer biozones of Poty *et al.* (2006). This section is the stratotype of the Moliniacian Substage. Its base was defined at the first thin beds of dark fine-grained limestone known as 'Black Marble' facies appearing in the upper part of the Leffe Formation (bed 52, Conil *et al*., 1977). That level corresponds also to the top of the *S. anchoralis europensis* local range and is about 2 m below the entry of *Mestognathus praebeckmanni* (Conil *et al*.,1988). These authors considered that this level was correlated with the base of the Viséan in the Bastion section (historical stratotype for the base of the Viséan, see Hance *et al*., 2006b) marked by the first appearance datum (FAD) of *Eoparastaffella* and *Gnathodus homopunctatus*, which is 19 m below the base of the Viséan stage marked by the FAD of *Eoparastaffela simplex*. However, the reinvestigation of the boundary transitional beds allowed Devuyst *et al*. (2006) to emend the definition of the Moliniacian and to correlate its base with the base of the Viséan Stage.

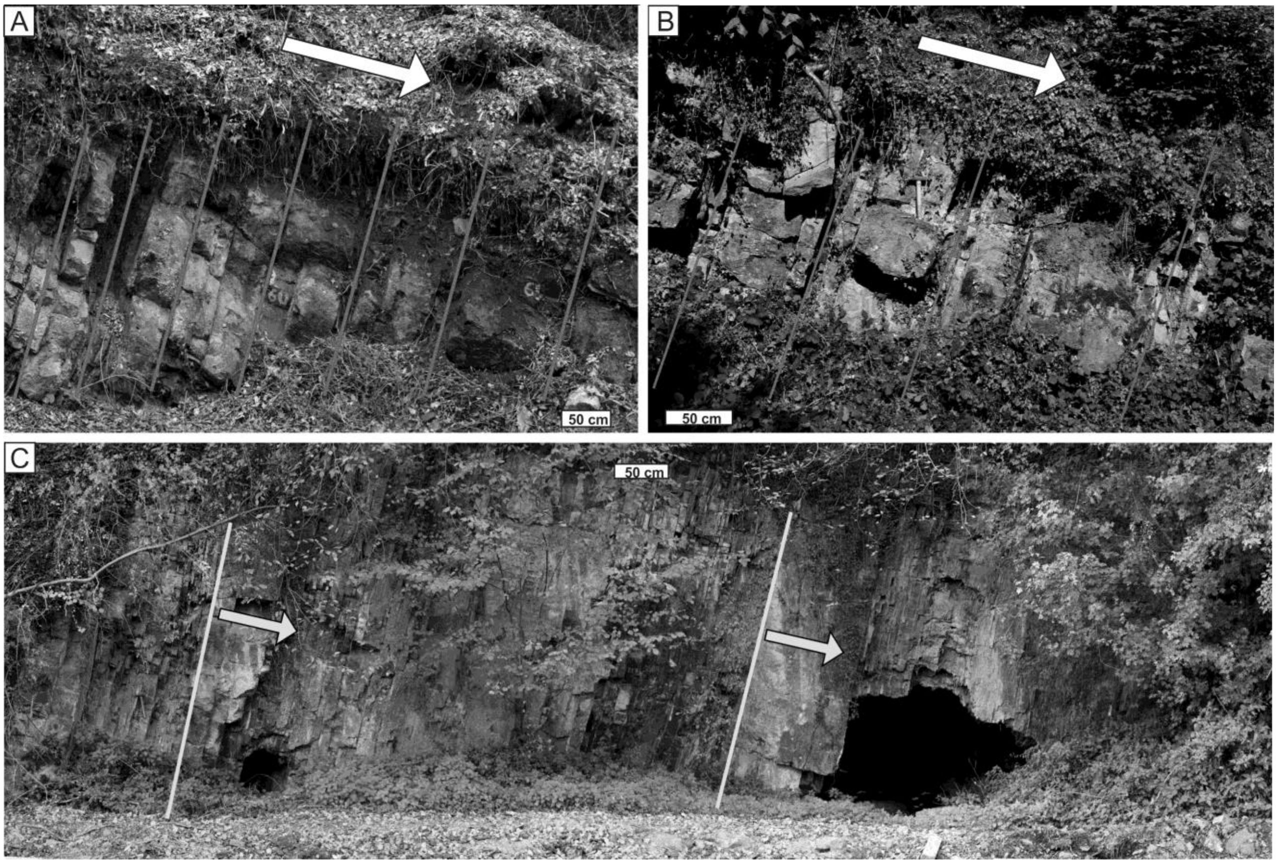

Fig. 12: **A. Precession cycles (c. 18.6 ky) due to monsoon-dry climate alternation in the Leffe Fm (Ivorian). B. Relatively thick and symmetric cycles (precession + obliquity?) in the upper part of the Leffe Fm (top of the Tournaisian), witnessing a transition in the cycle types. C. Shallowing-upwards parasequences in the Molignée Fm (basal Viséan).**

Description

Leffe Fm (beds 1 to 161, Fig. 11): well-bedded violet-grey cherty limestone tending to become darker progressively to the overlying Molignée Fm. The limestone is mainly a mottled wackestone-packstone with an open marine microfauna and abundant the microbially coated intraclasts.The chert usually moulds burrows.

Molignée Fm (beds 162 to 294, 55m): the lower part of the formation is very similar to the previous one but included thinly-bedded, laminated black limestone which become progressively dominant upwards. The black limestone is dominantly composed of mudstone with rare are radiolarians, calcispheres, ostracods, moravamminiids passing upwards to a peloidal packstone and peloidal bioclastic packstone-grainstone with calcispheres and various algae (*Girvanella, Koninckopora* and other dasyclads) and rare lithoclasts (Devusyt *et al*., 2005). The Molignée Fm corresponds mainly to distal turbidites deposited in a deep lagoonal environment setting in the central part of the DSA (Mottequin, 2004) alternating with background suspension sedimentation (calcispheres and radiolarian mudstone). The alternations are interpreted as parasequences (Devuyst et al., 2005) produced by sea-level changes alternatively opening and closing the lagoon with sequential input of oxygenated waters. The 'Black Marble' is a Konservaat-Lagerstatte (Mottequin, 2004, 2008) that preserved exquisitely a rare fauna of echinoid, fishes and soft organisms. This formation is one of the rare to record of the sequence 5 of Hance *et al.* (2001) (Fig. 3).

Salet Formation (beds 295 to 480, 76m): it starts with a breccia bed including dolomitic clasts (debris flow, marking the sequence boundary). It is typically composed of various shallow-water facies (oolithic, pelloidic, bioclastic), partly dolomitized and cherty in the upper part. The Salet Fm corresponds to the TST of sequence 6.

The thick-bedded to massive packestone to grainstone of the Neffe Fm that recorded the HST of sequence 6 was deposited in a high-energy environment. It is capped by a marker bed, the '*Banc d'Or de Bachant'*. This horizon can be traced from Aachen to Northern France. It is interpreted as a bentonite having suffered pedogenesis (Delcambre, 1989) and constitutes the sequence boundary between sequence 6 and 7 as well as the boundary between the Moliniacian (lower Viséan) and Livian (middle Viséan) Substages.

Ongoing research on cyclstratigraphy tends to show that the switch form a climatic-driven cyclicity to a eustatic-driven cyclicity occurred across the Tournaisian-Viséan boundary (Poty *et al.*, 2013). Indeed the Leffe Fm is dominated by limestone-argillaceous limestone alternations probably due to precession-driven climatic cycles ranging from 60 to 120 cm-thick (Fig. 12A). The top of the formation show a transition with 1-3 m-thick cycles possibly driven by precession and obliquity (Fig. 12B). The Molignée Fm recorded the first shallowing-upwards parasequences (4-12 m-thick, Fig. 12C) of eustatic origin. Afterwards, the deposition is only driven by parasequence through the whole Viséan. The switch in cycle is interpreted as the onset of the Viséan ice-house period (Poty *et al.*, 2013).

Main faunal component

In the Denée area (c. 5 km northwest of Salet), the Molignée Fm yielded a diverse macrofauna including fishes, echinoids and dendroid graptolites (see review in Mottequin *et al.*, 2015), but in fact this particular lithostratigraphic unit is very poor (Mottequin, 2004, 2008). In the Dinant area, it yields mainly brachiopods (Delépine, 1928) and pelecypods (Demanet, 1929).

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This field trip brought together geologists, palaeontologists, geochemists and sedimentologists within the frame of the International Geoscience Programme (IGCP) Project 596 (climate change and biodiversity patterns in the mid-Palaeozoic) and the Subcommission on Devonian Stratigraphy (SDS) of the International Union of Geological Sciences.

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Editeur : Association Strata, Muséum d'Histoire naturelle, 81600, Gaillac

ISSN 0761-2443
ISBN 978-2-9548452-6-5