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FRASNIAN CARBONATE BUILDUPS OF SOUTHERN BELGIUM: THE ARCHE AND LION MEMBERS INTERPRETED AS ATOLLS

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(13 figures and 1 plate)

ABSTRACT. The facies architecture, sedimentary dynamics and paleogeographic evolution were reconstructed for a number of Frasnian buildups developed on a carbonate platform on the south side of the Dinant Synclinorium (Belgium). Bed-by-bed sampling and detailed petrography were complemented by magnetic susceptibility analysis, allowing for high-precision lateral correlation.

Six facies were recognised in the buildups, each characterized by a specific range of textures and assemblage of organisms: grey, pinkish or greenish limestone, with stromatactis, corals and stromatoporoids (facies A3-L3); grey limestone with corals, peloids and dasycladales (facies A4-L4); grey, microbial limestone (facies A5-L5); grey limestone with dendroid stromatoporoids (facies A6-L6); grey, laminar fenestral limestone, (facies A7-L7); grey, bioturbated limestone (facies A8-L8). The time-equivalent off-buildup sediments include a large amount of transported material that originally came from the buildups. Sedimentological evidence suggests that facies A3-L3 developed between the storm wavebase and the fairweather wavebase, in a oligophotic environment. This facies contains lenses of facies A5-L5, with stromatolitic coatings and *Renalcis*-rich thrombolitic bushes. These lenses were developed in greatest abundance closest to the fairweather wavebase, and they became anastomosing. Facies A6-L6 was developed in an environment with slightly restricted water circulation; there is a steady transition between this facies and the fenestral limestone A7-L7, which were deposited in a moderately protected subtidal to intertidal area. Facies A8-L8 developed at subtidal depths in a quiet, lagoonal environment.

The buildups started with the development of facies A3-L3, with microbial lenses and algal facies becoming progressively more abundant upwards. Above about 20m in each buildup, more protected facies are found in the buildup's central part. This atoll-like geometry suggests the development of restricted sedimentation in this central area, sheltered by bindstone or floatstone facies. The initial development of the lower part of a buildup during a transgression and subsequent highstand would have been followed by reefal growth along the edge of the buildup during the succeeding lowstand; an atoll crown would then have started to develop during the following transgressive stage. The presence of restricted facies can be seen as the consequence of the balance between sea level rise and reef growth.

Keywords: Upper Devonian, limestone, Frasnian, Belgium, carbonate buildups, reefs, atolls.

1. Introduction and aim of the work

The Lion and Arche members of the Frasnian of southern Belgium are formed largely of carbonate buildups (Fig. 1; Boulvain *et al.,* 1999). The best known of these crop out in a belt along the southern border of the Dinant Synclinorium, from near Trélon in the west to Marche-en-Famenne in the east (Fig. 2). There has been little sedimentological work on these buildups, and only three outcrops -all in the immediate neighbourhood of Frasnes-have been studied in any detail. These outcrops are the Nord quarry (Lecompte, 1954; Boulvain & Coen-Aubert, 1997), the Lion quarry (Cornet, 1975), and the Arche quarry (Lecompte, 1954; Cornet, 1975); the first two are in the Lion Member, the third is in the Arche Member. The one sedimentological model that has been proposed so far for the Lion and Arche members (Boulvain & Coen-Aubert, 1997) is based on a study of the buildup in the Nord quarry.

The aim of this present work is to develop further the sedimentological model of Boulvain and Coen-Aubert, specifically by incorporating into it information recently obtained from sets of outcrops located some distance from Frasnes. One set of outcrops is at La Boverie, close to Rochefort, whereas the other set is at Moulin Bayot, close to Vodelée. At both locations it is possible to study sections cutting a series of buildups, starting from the Arche Member and ending with the Lion Member; between the buildups are relatively thin units of shale. At both locations there appears to be an additional carbonate buildup unit between the Lion and Arche members. This makes the successions at La Boverie and Moulin Bayot

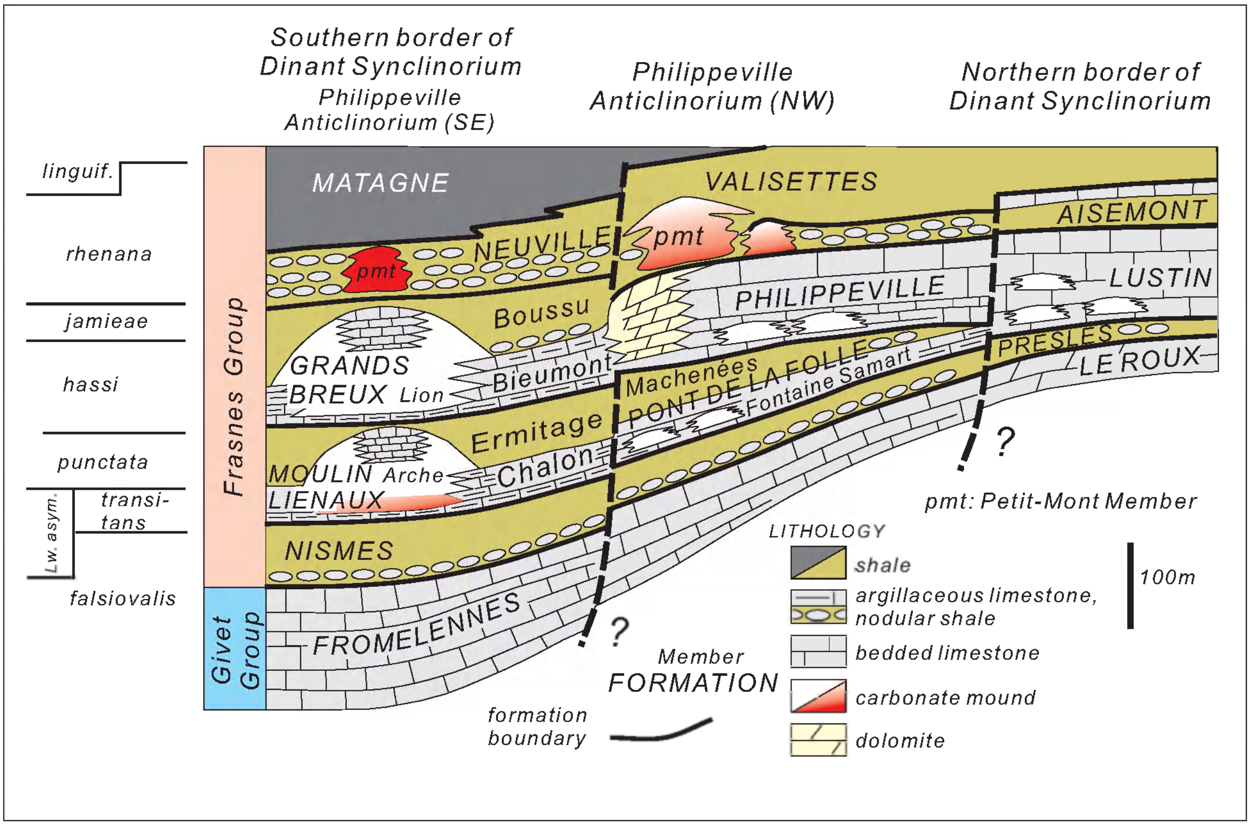


Figure 1. N-S schematic cross-section and lithostratigraphic subdivisions of the Frasnian of the Dinant Synclinorium. Conodont biozones are from Bultynck *et al.* (1998).

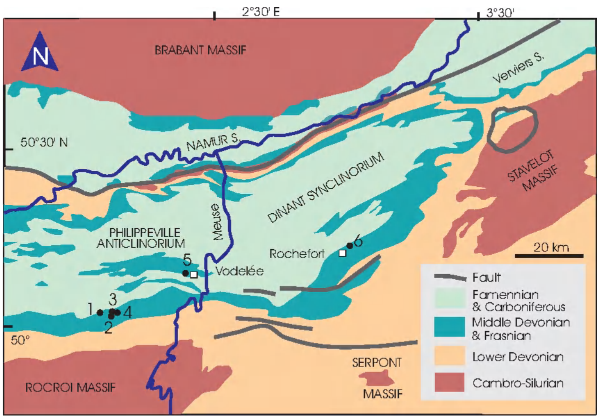


Figure 2 . Schematic geological map of southern Belgium with location of main Frasnian buildups. 1: Lompret quarry; 2: Arche quarry (Frasnes); 3: Nord quarry (Frasnes); 4: Lion quarry (Frasnes); 5: Moulin Bayot sections (Vodelée); 6: La Boverie quarry (Jemelle).

somewhat different from the traditional one (cf. Mailleux & Demanet, 1929). Besides reconstruction of sedimentary architecture of the buildups, sequential aspects are investigated and discussed.

2. Location and geological setting

La Boverie is a quarry located at the south-eastern edge of the Dinant Synclinorium, 3 km north of Rochefort, on the Gerni plateau (IGN map 59/2 X: 212.000; Y: 97.600). The series of buildups exposed in the quarry is nearly 220 m thick (Fig. 3). The buildups extend at least 3.5 km laterally, as outcrops of limestone related to them are found close to Humain, approximately 2 km east of the quarry. Nine sections were studied at La Boverie: eight were in the quarry itself, and one was in Humain, along the Humain-Hargimont road, across the bridge over the Entre Deux Falleux river (map 54/7 X: 213.500;Y: 99.100).

The Moulin Bayot sections are located in the south-eastern part of the Philippeville Anticlinorium, 1 km west of Vodelée, close to the Hermeton valley (IGN map 58/2 X: 175.000;Y: 95.700). The buildup unit extends laterally for approximately 3,5 km, and is more than 150 m thick (Fig. 4). Five sections were studied, on both sides of the river. Some additional samples were also taken close to the village of Vodelée, 145 m east of the last sample of section E.

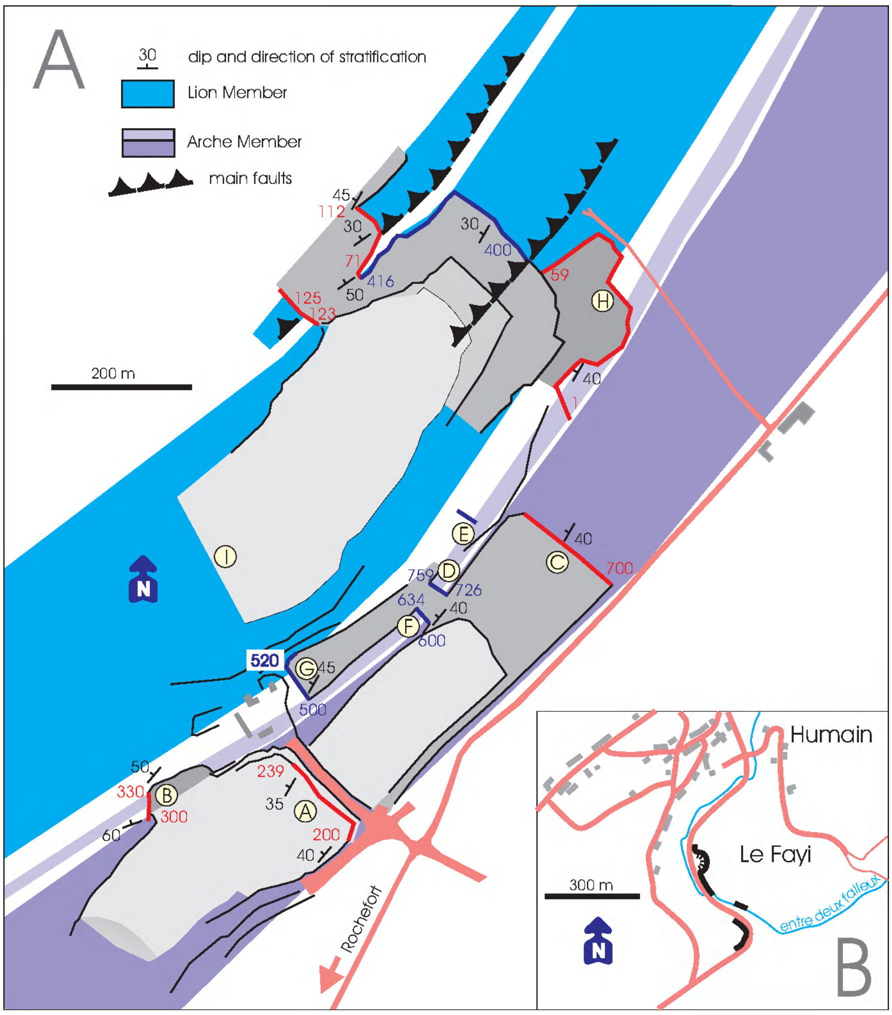


Figure 3 . A: location and geological setting of La Boverie sections. Shaded area correspond to quarry floors; A-H: section number (see Fig. 6); I: section studied by Cornet (1975); red and blue numbers correspond to selected samples. B: location of Humain section.

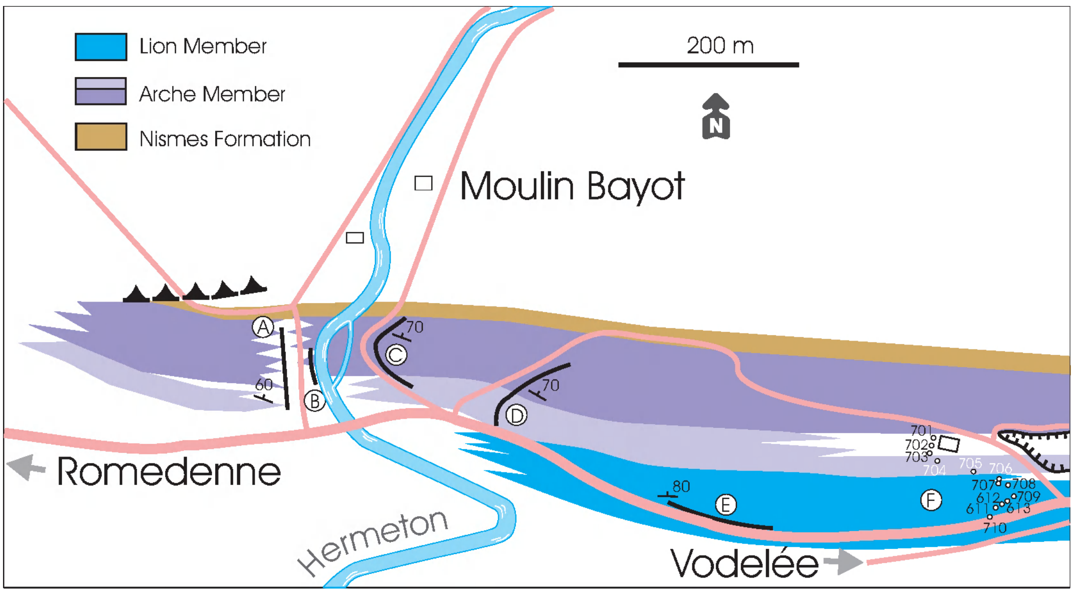


Figure 4 . Location and geological setting of Moulin Bayot sections. A-F: section number (see Fig. 9); other numbers correspond to selected samples.

3. Methods

The bed-by-bed description and sampling used in this work was carried out between 1996 and 2002. The petrographic results for La Boverie and Humain are based on 290 thin sections; those for Moulin Bayot are based on 360 thin sections. Magnetic susceptibility analyses were carried out on each sample, using a Kappabridge KLY-3 device. The purpose of these analyses was to allow high precision lateral correlations, following the method adopted by Crick *et al.* (1994).

4. Previous work

The biohermal complex at La Boverie was first described by Lecompte (1956), who published a planimetric survey based on three trenches. Later the quarry was studied in detail by Cornet (1975). Cornet's work was carried out when only the Lion Member was mined; the Arche Member was known to be present south of the then-active quarry, but only from an exploration trench. The quarry at the time of Cornet's work corresponded to the north-western part of the present-day excavations complex (section I in Fig. 3); this part is currently partially filled with earth. More recent work is by Vanguestaine *et al.* (1999), who studied organic remains and palynomorphs collected in the Boussu-en-Fagne Member and the Neuville Formation, from La Boverie and Lion quarries.
The sections A, C and E (our numbering) at Moulin Bayot were first described by Dumoulin *et al.* (1998) who ascribed them to the Arche and Lion members.

5. Buildup facies and flanking facies

Six buildup facies can be defined in the Arche Member (facies A3 to A8) and the Lion Member (facies L3 to L8), each facies being characterized by a specific range of textures and organic assemblages. Three other facies ('flanking facies') can also be defined; these are thin-bedded bioclastic and lithoclastic facies, and are the lateral time-equivalents of the buildup facies. The components in the buildup facies are essentially autochthonous and directly reflect the influence of oceanic parameters such as water agitation and light intensity. By contrast, the flanking facies contain large amounts of transported material, much of it derived from nearby buildups (Humblet & Boulvain, 2001). The organic assemblages found in the flanking facies therefore do not necessarily reflect the environments in which those facies were deposited.

5.1. Buildup facies

The logic behind the coding scheme used here for designating the buildup facies is the same as that used by Boulvain *et al.* (2001): identical facies are given identical facies numbers, even when they are in buildups at different stratigraphic levels (e.g. A3, L3). This scheme facilitates comparison with the mud mounds of the Petit-Mont Member (facies PM1 to PM5), which have also been described in this way (Boulvain, 2001). The following descriptions of the buildup facies are organised bathymetrically, from deep to shallow, according to textures and fossil assemblage.

5.1.1. Grey, pinkish or greenish limestone, with stromatactis, corals and stromatoporoids (facies A3 and L3)

This facies is composed of wackestones and floatstones showing decimetre-scale stromatactis and centimetre-scale stromatactoid fenestrae (cf. Neuweiler *et al.*, 2001), with abundant branching tabulate corals, brachiopods and crinoids (Pl. 1E). Locally there are massive or tabular (rarely dendroid) stromatoporoids, bryozoans, peloids, and fasciculate rugose corals (Pl. 1C). Some subordinate cricoconarids, palaeosiphonocladalean algae and calcispheres are present. Coatings (*Sphaerocodium*) are rarely developed. Many of the fenestrae correspond to cavities situated below a lamellar organism (umbrella effect) or to growth cavities (Pl. 1C). Local reworking and concentration of bioclasts by storm action might result in this facies evolving into a bioclastic rudstone.

5.1.2. Grey limestone with corals, peloids and Udotaeacea (facies A4 and L4)

This facies is composed of rudstones, grainstones and floatstones, with peloids, lithoclasts (fragments of coating), branching tabulate corals coated by *Sphaerocodium*, brachiopods, some crinoids, dendroid stromatoporoids, radiospheres and calcispheres. Udotaeacea are occasionally found. Stromatactoid fenestrae and stromatactis are present. This facies is similar to facies PM4 in the Petit-Mont Member, which corresponds to the first occurrence of Udotaeacea together with the development of very thick and symmetrical coatings.

5.1.3. Grey microbial limestone (facies A5 and L5)

This facies is composed of thrombolitic and stromatolitic bindstones and bafflestones, with *Renalcis*, stromatoporoids, tabulate corals, some Udotaeacea, brachiopods, bryozoans and rugose corals (Pl. 1F). Thick coatings of *Sphaerocodium* alternate with encrusting microbial laminae rich in peloids. All thrombolites and stromatolites appear as a canvas made up of irregular peloids set in a yellowish pseudosparitic cement (the "structure grumeleuse" of Cayeux, 1935). This facies is commonly found associated with facies A3-L3 or A4-L4, as isolated or coalescent metre-scale lenses. It could possibly also be developed in some large synsedimentary fractures, as parietal incrustation, interlayered with fibrous cement.

5.1.4. Grey limestone with dendroid stromatoporoids (facies codes A6 and L6)

This facies is composed of rudstones, floatstones or grainstones that are rich in peloids, lithoclasts and dendroid stromatoporoids (mainly *Amphipora*) (Pl. 1G). These latter components are thickly coated by *Sphaerocodium* or microbial laminae; the coatings are symmetrical. Calcispheres, palaeosiphonocladales (*Issinella, Proninella*) and Udotaeacea (*Trelonella*?) are found. Branching tabulate corals, gastropods and crinoids are present in places. Irregular fenestrae are found in matrix-rich zones.

5.1.5. Grey laminar fenestral limestone (facies A7 and L7)

This facies is composed of grainstones and wackestones, with peloids, lithoclasts, calcispheres and palaeosiphonocladales (Pl. 1H). There are abundant millimetre-length fenestrae scattered throughout the sediment, bedding-parallel (Pl. 1A). Locally, there are dendroid stromatoporoids which are often thickly coated.

5.1.6. Bioturbated grey limestone (facies A8 and L8)

This facies is composed of wackestones and mudstones with palaeosiphonocladales, calcispheres and peloids. There is commonly evidence of bioturbation: open, vertical burrows filled by pseudosparitic to sparitic cement. Branching tabulate corals, stromatoporoids, ostracods and gastropods are present.

5.2. Flanking facies

The following descriptions of the flanking facies are organised according to content and to grain size.

5.2.1. Microbioclastic packstones (b)

This facies is composed of thin-bedded, dark, often argillaceous, fine-grained (~100 μm) bioclastic packstones, containing brachiopods, crinoids, rugose corals, tabulate corals, fenestellids, ostracods, trilobites, peloids, and cricoconarids. Locally there are laminar stromatoporoids and some palaeosiphonocladales. Deformative bioturbation is commonly intense. The development of microsparite in the matrix is typically more intense than in all other facies, and seems to be related to a higher clay content.

5.2.2. Bioclastic packstones and grainstones (B)

This facies is composed of dark, centimetre- to decimetre-thick beds of rudstones, packstones and grainstones. It forms isolated lenses within facies *b* or within shales. The bioclasts are the same as in facies *b*, but are coarser-grained (~500 μm). Some lithoclasts, radiospheres, calcispheres are present. Hummocky cross lamination is developed in places.

5.2.3. Packstones and grainstones with peloids and lithoclasts (L)

This facies is composed of packstones and grainstones. It differs from facies *B* in containing abundant and commonly sorted peloids and lithoclasts, with some subordinate crinoids, fragments of corals and stromatoporoids, brachiopods and bryozoans. The grain size is approximately 300 μm.

6. Description of sections (Fig. 5)

From the ~3,5 km large Arche and Lion mounds, the La Boverie quarry intersects about 1.1 km sediment, mainly corresponding to the central part of the buildups (see below Fig. 13). The more remote Humain section is located 2 km far from the La Boverie quarry, but still intersects central facies. The Moulin Bayot sections cover a lateral extension of 800 m, but are located in a more peripheral situation, corresponding to a transect ranging from flank (sections A and B) to mound sediments (sections D to F). In the La Boverie quarry, correlations between sections are geometrical (Fig. 6). In Moulin Bayot, the lower quality of the outcrops made geometrical correlations more difficult and use of magnetic susceptibility correlations through comparison of magnetic peaks was necessary (see below Fig. 9).

6.1. La Boverie, sections A & B

At the base of section A (Figs. 3 & 7) is a greenish shale belonging to the Chalon Member. It includes lenses of well-sorted bioclastic limestone containing an open-marine fauna (crinoids, brachiopods, fenestellids, peloids). Thick, symmetrical coatings of *Sphaerocodium* are found in places, and partial silicification by calcedonite affects

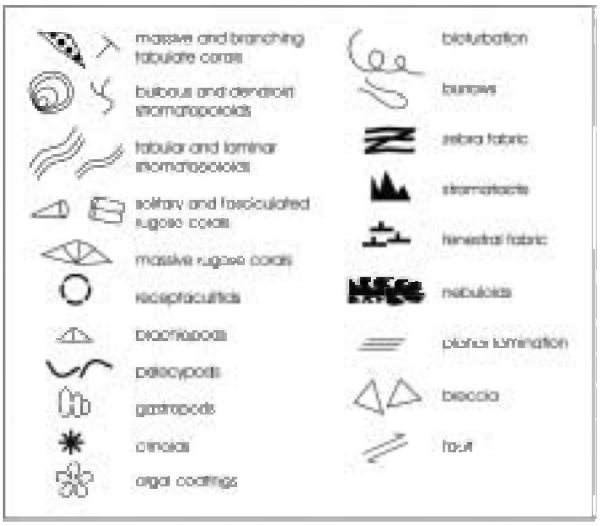


Figure 5 . Legend for symbols used in the lithologic logs.

PLATE 1

A. lithoclastic limestone with fenestrae; facies L7; La Boverie quarry, Jemelle, Lion Member.

B. bioconstructed limestone from the Lion Member, Les Roches outcrop, Moulin Bayot, section E, Vodelée. Stratification is nearly vertical.

C. bioconstructed limestone with fasciculated rugose corals and large growth-framework fenestrae; facies A3, La Boverie quarry, Jemelle, Arche Member.

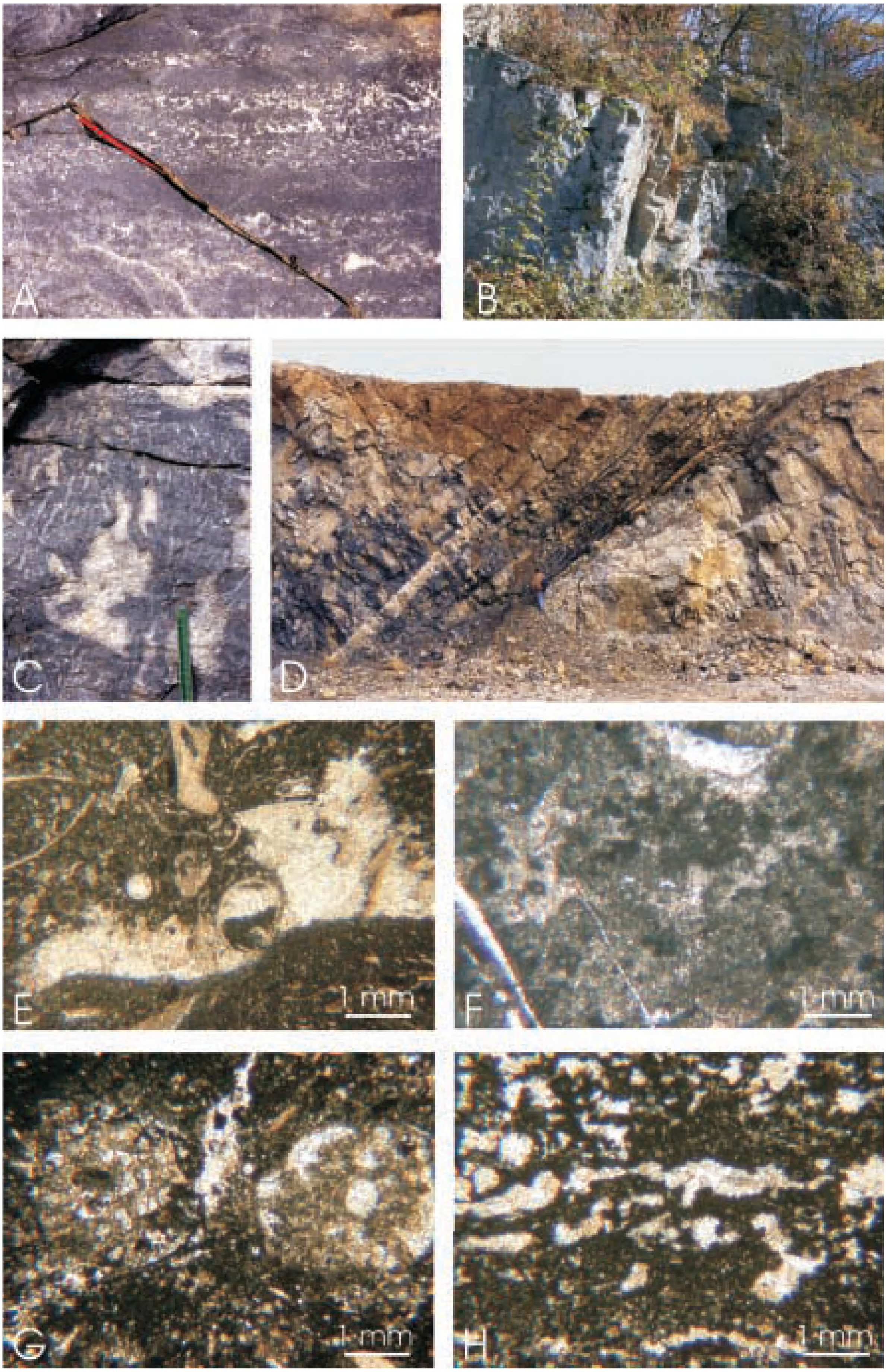
D. transition between the upper part of the Arche Member (to the right) and the Ermitage Member (to the left) in La Boverie quarry, section D.

E. wackestone with stromatactoid fenestra, crinoids and brachiopods; facies A3, thin section B209, normal light; La Boverie quarry, Jemelle, Arche Member.

F. bafflestone with thrombolites and *Renalcis*; facies L5, thin section H31, normal light; Humain section, Lion Member.

G. floatstone with dendroid stromatoporoids (*Amphipora*); facies L6, thin section B407b, normal light; La Boverie quarry, Jemelle, Lion Member.

H. lithoclastic packstone with fenestrae; facies L7, thin section B46, normal light; La Boverie quarry, Jemelle, Lion Member.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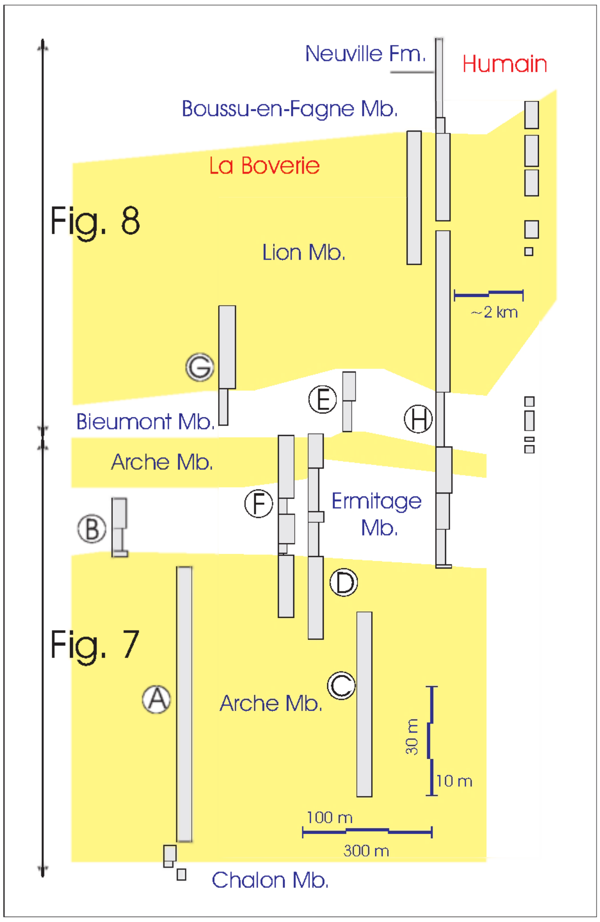

Figure 6 . Correlation of La Boverie and Humain sections; buildup facies are in yellow; flanking facies are in white.

some beds. The uppermost part of the Chalon Member is an argillaceous limestone containing *Alveolites*, *Disphyllum*, *Thamnopora* and solitary rugose corals. The basal unit of the Arche Member is a grey limestone that in its lower part (9-29 m) contains corals (*Alveolites*, *Disphyllum*, *Thamnopora*), some stromatoporoids, stromatactis and zebra structure; further upwards (29-44 m), this unit becomes richer in fasciculate rugose corals, tabulate corals and tabular stromatoporoids. In thin section, floatstones with brachiopods and tabular stromatoporoids (A3) characterized by a fine-grained bioclastic matrix rich in peloids, some calcispheres and palaeosiphonocladales, are followed by an alternation of thrombolitic bindstones with stromatoporoids, tabulate corals, *Renalcis*, some Udotaeacea (facies A5) and wackestones with small fenestrae, peloids, bioclasts (facies A3). Between 44-52 m, there is a significant facies change. This is marked first by the occurrence of stromatactis, then (52- 63 m), by the development of dendroid stromatoporoids. In thin section, this facies change is seen to be marked by an increase in the abundance of peloids and lithoclasts. The dendroid stromatoporoids are heavily encrusted, and are representative of facies A6. From 63 m to 66 m is a unit of fenestral limestone with peloids, lithoclasts and calcispheres (facies A7). This unit passes upwards into dendroid stromatoporoids rudstones and floatstones (facies A6), which, from 70 m, become finer-grained and richer in bioclasts. At about 90 m there is a marked change in the section. Above this level there is interbedded fine-grained facies (wackestones) and highly bioclastic facies (grainstones, rudstones); the fine-grained beds have palaeosiphonocladales (facies A8), and the bioclastic facies contain reworked corals and stromatoporoids, lithoclasts and crinoids. The buildup ends, after an observation gap, with fine-grained facies containing some tabulate corals, fenestellids and palaeosiphonocladales.

In section B are exposed the nodular shale and argillaceous limestone overlying the buildup. These are microbioclastic packstones, which contain brachiopods, crinoids, bryozoans, trilobites, and fragments of corals and stromatoporoids.

6.2. La Boverie, sections C, D & E

In section C (Fig. 7), the lowest facies in the buildup (as in section A) is a floatstone with tabular stromatoporoids, brachiopods, crinoids, branching tabulate corals and occasional thrombolites (facies A3; Fig. 7). Above this, and up to 14 m, the microbial facies A5 becomes dominant, with bindstones and bafflestones containing thrombolites, stromatoporoids and tabulate corals. From 14 to 36 m, rudstones and bindstones are common; these contain stromatoporoids, branching tabulate corals, peloids and gastropods (facies A6). Peloidal limestone with birdseyes (facies A7) is dominant from 36 m to 67 m. The uppermost part of the buildup exposed in section D is composed of packstones and wackestones; these contain peloids, palaeosiphonocladales, calcispheres and vertical burrows (facies A8).

From 75.5 m to 82 m (section D) is exposed an argillaceous bioclastic limestone (facies b) that includes fragments of corals, crinoids, brachiopods and fenestellids (Pl. 1D); locally within it there are trilobites. From 82 to 88 m, the facies remains rather similar with some grainstone beds and an increase upwards in peloids and palaeosiphonocladales (facies L). From 88 m to 103 m, there is again the argillaceous bioclastic facies, which locally is relatively rich in peloids. There is a sharp change in the section at 103 m, with the unit that is developed above this level (from 103 to 113 m) being composed of rudstones and grainstones containing stromatoporoids, encrusted rugose and tabulate corals, crinoids, peloids, lithoclasts and palaeosiphonocladales (facies L6). The uppermost part of this unit is a bioturbated fine-grained limestone, at the top of which is a hardground with a ferruginous coating. Synsedimentary lithification is demonstrated by the presence of early scalenoedric calcite cement that has been overlain by a detrital micrite. Bed 759 (at 111 m) consists of a mudstone with birdseyes. 113 to 130 m (section E, Fig. 8) consists of an argillaceous

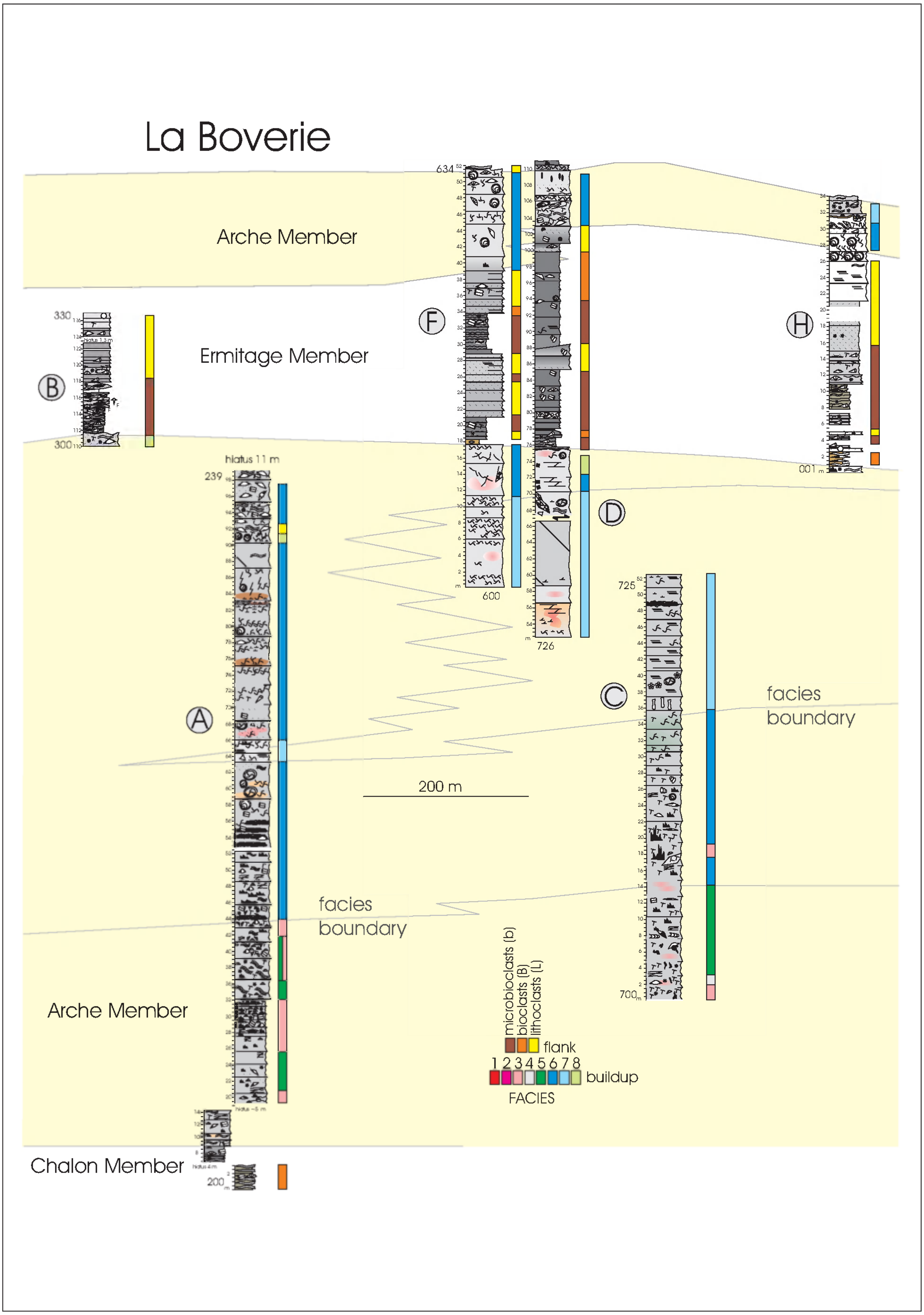

Figure 7 . Lithologic logs of La Boverie sections with facies interpretation (Arche and Ermitage members).

bioclastic limestone containing fragments of corals, crinoids, stromatoporoids, brachiopods and fenestellids. This limestone appears to correspond to a succession of tempestites, with one short biostromal interval indicated by laminar stromatoporoids.

6.3. La Boverie, section F

The uppermost part of the Arche buildup in section F (Fig. 7) is made up of peloidal and lithoclastic grainstones rich in dendroid stromatoporoids (facies A6). It is covered, from 18 m to 21 m, by an argillaceous limestone, initially bioclastic, with crinoids, peloids and brachiopods, and then microbioclastic. From 21 to 29 m is a massive limestone. Its lower part is composed of peloidal-lithoclastic grainstones with some reworked dendroid stromatoporoids; its upper part is composed of microbioclastic-peloidal packstones. From 29 m to 33 m there is a microbioclastic argillaceous limestone, followed from 33 m to 40 m, by grainstones rich in peloids and palaeosiphonocladales. From 40 m to 51 m, sediment colour becomes lighter and grainstones to rudstones with peloids, dendroid stromatoporoids and corals (facies A6) are observed again, passing upwards into rudstones with stromatoporoids and rugose corals.

6.4. La Boverie, section G

Above some beds of argillaceous limestone and up to 63 m, there is calcareous shale (Fig. 8). These rocks are composed of argillaceous, often bioturbated bioclastic packstones with brachiopods, fenestellids, laminar stromatoporoids, crinoids and cricoconarids. Further upwards, this unit becomes richer in branching tabulate corals and crinoids and common centimetric lenses of micrite within bioclastic packstones, probably announcing the starting of an indigenous carbonate production. The Lion mound starts sharply with greenish-pinkish massive limestone that includes tabulate corals, crinoids, brachiopods and some fasciculate rugose corals or laminar stromatoporoids (L3). In thin section, these facies are characterized by a very fine-grained primary micrite and a considerable proportion of internal sediment in growth or shelter cavities later filled by fibrous cement.

6.5. La Boverie, section H

The section begins with a grey limestone bed corresponding to the top of the Arche mound (Fig. 7). Above this, and up to 6 m, is an argillaceous limestone with lenses of bioclastic grainstone (with brachiopods, crinoids, fenestellids and peloids). These beds are tempestites. From 6 m to 16 m there is exposed a nodular shale that passes upwards into an argillaceous well-sorted bioclastic packstone, progressively enriched in peloids. The interval from 16 m to 26 m consists of a grey bioclastic limestone passing upwards into a light grey, locally laminar, indistinctly bedded limestone including peloids, lithoclasts, dendroid stromatoporoids, calcispheres, palaeosiphonocladales and crinoids. From 26 to 31,5 m, there are rudstones with bulbous and dendroid stromatoporoids, lithoclasts, peloids and calcispheres, followed by floatstones with solitary and massive rugose corals, tabular stromatoporoids, crinoids, and bioclasts. This unit passes upwards (31,5 m to 32 m) into fenestral limestone with peloids, birdseyes, calcispheres and palaeosiphonocladales. From 32 to 34 m, there is a well-sorted, darker bioclastic and argillaceous limestone including crinoids, tabular stromatoporoids and solitary rugose corals with some fenestellids. From 34 to 38 m (Fig. 8), shales with bioclastic lenses are observed. Above this and up to 49,5 m (base of the Lion Member), the nodular shale becomes gradually richer in laminar stromatoporoids, tabulate corals as well as fasciculate and massive rugose corals. Locally, centimetric lenses of micrite are observed.

The bottom unit of the Lion mound is a light grey floatstone with stromatactis, branching tabulate corals, crinoids, brachiopods and stromatoporoids (facies L3). This facies is developed until 60,5 m where thrombolites and *Renalcis* (facies L5) become abundant. From 61 m to 66 m, the sediment becomes more bioclastic (rudstones and grainstones with crinoids, peloids, tabulate corals and stromatoporoids, facies L3). Further upwards, from 66 to 68,5 m, algal coatings are well developed and grainstones with peloids, tabulate corals, stromatoporoids, gastropods and *Radiosphaeroporella* (dasycladales, cf. Mamet & Boulvain, 1992) are observed (facies L4). At 68,5 m there is a marked change in the section, corresponding to a darker limestone rich in birdseyes and dendroid stromatoporoids (facies L6 and L7): this facies is developed until the top of the mound, at 121,5 m. The topmost of the buildup is characterized by a rudstone with stromatoporoids, tabulate corals and brachiopods.

From 121,5 m to 126 m, there are grey shales rich in branching tabulate corals, crinoids, brachiopods and limestone beds (tempestites). Further upwards, from 126 m to 139 m, brownish shales with some nodular levels are observed. These units belong to the Boussu-en-Fagne Member. Finally, from 139 m to 149 m, an obvious increase in limestone nodules, together with an increasing bioturbation and the occurence of sponges, mark the base of the Neuville Formation. From 149 m to 186 m, the upper part of the Lion Member is observed again, due to tectonic repetition.

6.6. Humain

The Humain section is situated nearly 2 km east from La Boverie quarry and it exposes mound facies that are quite similar to those observed in La Boverie (Fig. 3). At the base of the section is 16 m of a black, locally dolomitized, microbioclastic limestone (b) that includes crinoids, brachiopods and sparse tabulate corals (Fig. 8). The last bed is rich in massive rugose corals. A 40 m thick cov-

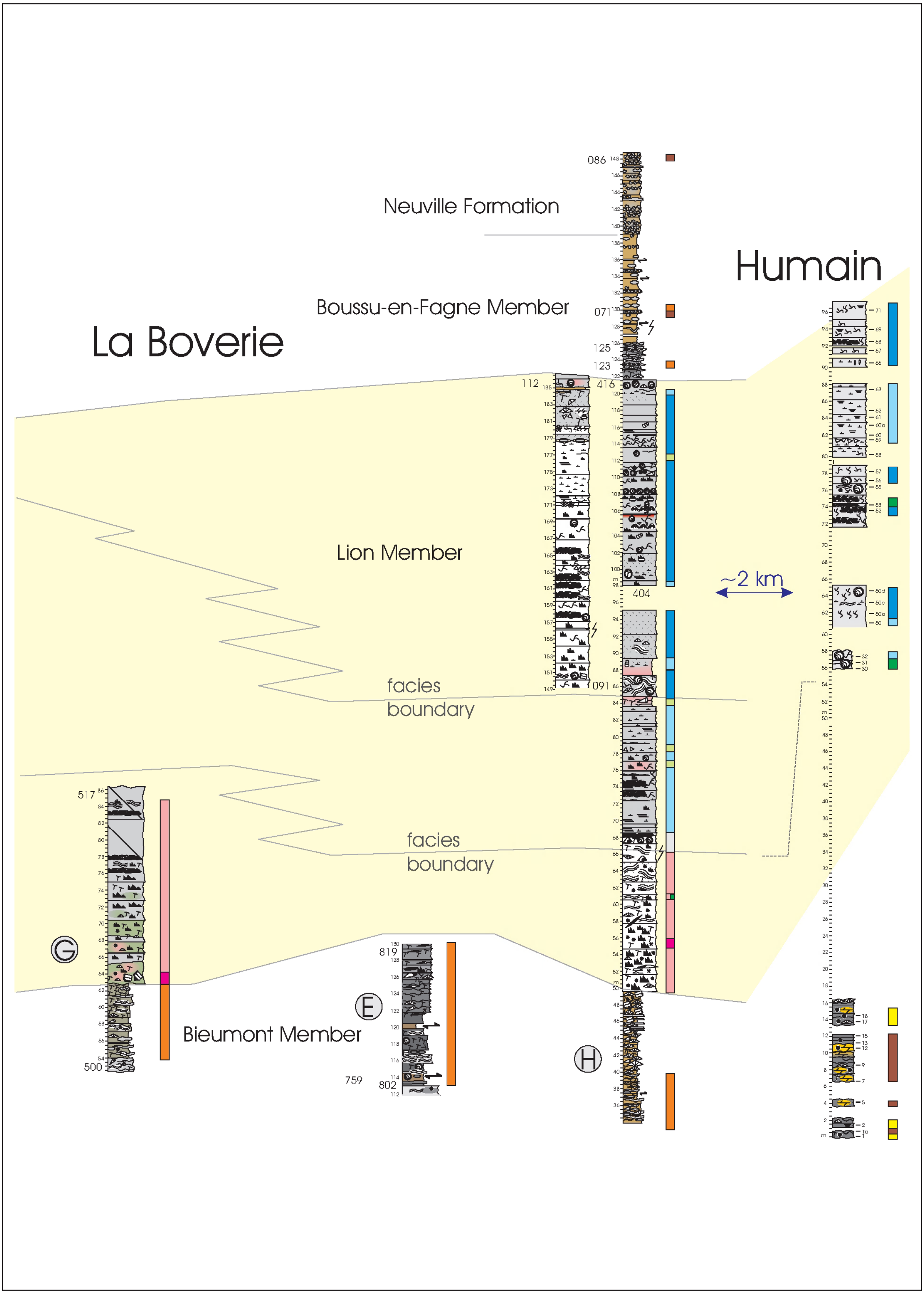

Figure 8 . Lithologic logs of La Boverie and Humain sections with facies interpretation (Bieumont, Lion and Boussu-en-Fagne members, Neuville Formation)

ered interval, with some grey limestone beds containing stromatoporoids (facies L5 and L6), separates this first unit from the second one, consisting of light grey massive limestone. After some fenestral limestone (facies L7), 4 m of a stromatoporoid-rich limestone (L6) passes upwards into 7 m of limestone with dendroid stromatoporoids (facies L6) and lenses of fibrous cement (nebuloids). The next unit, from 76,5 m to 85 m, exposes fenestral limestone (facies L7) with a 10 cm-thick level of breccia at 78,5 m. The last unit, from 87 to 94 m, is again a limestone with dendroid stromatoporoids (facies L6).

6.7. Moulin Bayot, section A

From west to east, the Moulin Bayot sections cut flank sediments (sections A and B), an intermediate zone (section C) and the central part of the mounds (sections D and E).
Section A develops NS along the road to Moulin Bayot, west of the Hermeton river (Figs 4 & 9). The layers are overturned, with a strike of N110°E and a dip of 60°N. Above the shale of the Nismes Formation, exposed closer to the river, the first 4 m of the section are cm-thick beds of dark bioclastic limestone. Some dendroid and laminar stromatoporoids, crinoids, brachiopods and cricoconarids are observed. Further upwards, up to 42 m, there is a brown black bioclastic limestone with smaller dendroid stromatoporoids, brachiopods and crinoids. Locally, some beds look more massive (36-40 m). This first unit is separated from the next one by 5 m of shale. In the second unit, there is again 3 m of black bioclastic limestones passing into 6 m of grey brown limestones. Further upwards, the section ends with a lighter-coloured and more massive limestone. The entire section is characterized by an alternation of bioclastic grainstones with peloids and lithoclasts and argillaceous microbioclastic packstones with some peloids.

6.8. Moulin Bayot, section B

This section is close to section A, along the river (Figs 4 & 9). At the base, there is 7 m of dm-thick beds of black bioclastic limestones with crinoids, brachiopods, branching tabulate corals and stromatoporoids. Further upwards, after a gap, a lighter and more massive limestone develops. The section ends with dark bioclastic limestones. Petrographically, an alternation of bioclastic argillaceous micropackstones and lithoclastic grainstones is observed again, the latter dominating clearly. A bioconstructed facies appears at 7 and 11 m; this facies is rich in dendroid stromatoporoids (facies A6).

6.9. Moulin Bayot, section C

This section is exposed along a footpath on the eastern side of Hermeton river (Figs 4 & 9). The general aspect is more massive than in sections A and B. Beds have a strike of N110°E and a dip of 70°N. Above the shale of the Nismes Formation, the section exposes 21 m of medium grey limestone including crinoids, brachiopods, tabulate corals and some dendroid stromatoporoids. There are peloidal wackestones, packstones and grainstones (facies A3 and A4), grading upwards into thrombolitic microbial bindstones and bafflestones (facies A5). The next unit consists of 4 m of darker peloidal-bioclastic limestone. Further upwards, there are 24 m of medium grey limestone, similar to the first unit, with alternations of facies A3 and A4. The section exposes then 3 m of dark bioclastic and lithoclastic limestone (facies L) and ends with 10 m of light grey limestone with branching tabulate corals, peloids and crinoids (facies A4). This interval is characterized by a significant lithoclastic supply. Section C reflects the transition between the reworked bioclastic facies of sections A & B and the bioconstructed facies of the central parts of the buildup.

6.10. Moulin Bayot, section D

Section D is located in the Bonne Fontaine wood, between the Hermeton river and “Les Roches” (Figs 4 & 9). The strike of the beds is N120°E with a dip of 75°N. The first limestone beds are exposed some 30 m above the shale of the Nismes Formation. These dark floatstones include brachiopods, solitary rugose corals, tabulate corals, crinoids and stromatoporoids with some fenestrae and stromatactis (facies A3). Further upwards, from 14 up to 53 m, the macrofauna becomes sparse and the rock change to grey massive limestones with some fenestrae and zebra (facies A7) locally rich in dendroid stromatoporoids (facies A6). From 53 m to the end of the section, there is again facies A3 with corals, fenestrae, brachiopods, crinoids, bryozoans and peloids. The top of the section is characterized by bioclastic sediments rich in peloids (facies L) overlying the bioconstructed facies. Near 63 m are decimetric stromatactis connected to neptunian dykes and filled with red microsparitic internal sediments.

6.11. Moulin Bayot, section E

This section is located along the road from Romedenne to Vodelée, near “Les Roches” (Figs 4 & 9). The strike of the layers is N90°E with a dip of 80°N. Metric to plurimetric beds of light-grey massive limestone are observed all along the section (Pl. 1B). From the base of the section up to 18,5 m, massive and tabular tabulate corals and stromatoporoids associated with some centimetric stromatactis predominate (facies L3). Further upwards, from 18,5 m to the end of the section, the macrofauna becomes sparse with some dendroid stromatoporoids. The facies is rich in mm-length fenestrae. It corresponds to an alternation of a peloidal facies with dendroid stromatoporoids (facies L6) and a fine-grained facies with peloids and palaeosiphonocladales (facies L8).

6.12. Moulin Bayot, section F

It is not strictly a section, but a succession of discontinuous outcrops located close to the village of Vodelée (Fig. 4). The oldest samples (701-703) show flanking, first microbioclastic, then lithoclastic facies, followed by (704-709) bioconstructed L3 and L4 facies with one lithoclastic lens. Finally, the section ends (612-611) with limestone containing dendroid stromatoporoids (facies L6).

7. Rugose coral faunas

7.1. Distribution and biostratigraphy

Rugose coral faunas are listed stratigraphically, first for the La Boverie and Humain sections, then for the Moulin Bayot outcrops. A synthesis is given at Fig. 10.

At the base of the Moulin Liénaux Formation at La Boverie, there are, in the Chalon Member that crops out in section A (Fig. 7), many colonies and corallites of *Disphyllum* accompanied by a few solitary coralla of *Macgeea rozkowskae* Coen-Aubert, 1982. This species is also present at the base of the Arche Member and locally in the lower part of this buildup exposed in section C (Fig. 7).

The base of the overlying Ermitage Member, the thickness of which varies between 31.5 m and 34 m, is characterized by argillaceous limestones. These are rather rich in diverse corals and are interbedded with a few thin layers of shale. Solitary coralla of *Macgeea* sp. A, *M.* sp. B and *Sinodisphyllum* sp. have been found in sections B and D (Fig. 7) and occur also up to 10 m above the Arche Member, in section H (Fig. 7) where these argillaceous deposits are more developed. One colony of *Hexagonaria mirabilis* Moenke, 1954 has been sampled in section B, 6 m above the base of the Ermitage Member. After several levels containing fasciculate colonies of *Disphyllum*, the Ermitage Member ends with a small buildup which is 6 m to 10 m thick. *H. mirabilis* has been collected in section D, at about 10 m and 8 m below the top of the Moulin Liénaux Formation.

The Bieumont Member, at the base of the Grands Breux Formation, consists of 10 m to 17 m of argillaceous limestones and shales that are very rich in laminar stromatoporoids and various corals. The rugose coral fauna of this lithostratigraphic unit has been investigated in detail in sections G and H (Fig. 8). These are massive colonies, mostly of *H. mirabilis*, but also of *Scruttonia balconi* Coen-Aubert, 1980. Fasciculate rugose corals are represented by *Peneckiella fascicularis* (Soshkina, 1939) associated with *P. isylica* (Bulvanker, 1958); they have only been observed in the upper part of the Bieumont Member exposed in section H. Among the solitary coralla, *Tabulophyllum conspectum* Tsien, 1977 is present in all the sections. *Sinodisphyllum kielcense* (Rozkowska, 1979) is abundant at the base of the Bieumont Member, in section G, whereas *Aristophyllum irenae* Rozkowska, 1979 and *Tabulophyllum sylvaticum* Rohart, 1988 have been found in its middle part, in section H. Rare and small specimens of *Macgeea* sp. A occur also in the Bieumont Member.

The Lion Member has been measured completely in section H (Fig. 8) and there it is only 72 m thick. However, it is interrupted in its middle part by a complicated zone of folding and faulting. *Hexagonaria mirabilis* occurs in the lower 19 m of the Lion Member, characterized by a massive and coarsely crinoidal limestone in which stromatactis, massive and tabular stromatoporoids are often common. A fragment of *Argutastrea konincki* (Roemer, 1855) has been found about 35 m above the top of the Bieumont Member. Another similar fragment has been observed close to the top of the section of the Lion Member repeated by an inverse fault (bed 112, Figs. 3 & 8), to the north of the Neuville Formation. According to Cornet (1975), the Lion Member reaches a thickness of 150 m in section I (Fig. 3) where *Hexagonaria mirabilis* and occasionally *Scruttonia balconi* are present in its lower 27 m.

In La Boverie quarries, the highest levels, which are rich in rugose corals are the lowest 4.5 m of the Boussu-en-Fagne Member; this lithostratigraphic unit is represented in section H by about 16 m of shales with some nodules. Unfortunately, this succession and the boundary with the underlying Lion Member are locally faulted. At the base of the Boussu-en-Fagne Member, numerous colonies of *Hexagonaria mirabilis* are accompanied by *H. mae* Tsien, 1978, *Trapezophyllum roharti* Coen-Aubert, 1994, *Macgeea gallica gallica* Lang & Smith, 1935 and *Tabulophyllum conspectum*. A single specimen of *Hexagonaria davidsoni* (Milne-Edwards & Haime, 1851) has been collected higher in the Boussu-en-Fagne Member.

The Bieumont Member exposed in the lower part of the outcrops at Humain (Fig. 8) has a thickness of 16 m and has a more typical facies with rather rare corals than at La Boverie quarries. *Hexagonaria mirabilis* is present at the base of the Humain section and becomes abundant at the top of the Bieumont Member where it is associated with *Argutastrea konincki*. After a gap of about 24 m, a discontinuous succession in the Lion Member is 47 m thick.

The Moulin Bayot sections at Vodelée are much poorer in rugose corals (Figs 4 & 9). Some corallites of *Disphyllum* are present at 10 m above the base of section A. Debris of *Macgeea* have been observed in section C, at 37 m and 53 m. A small fragment of *Thecostegites* was recovered at 61 m, in section D. This is a curious tabulate coral which occurs locally in the Frasnian of Belgium. As the colony of Moulin Bayot has rather small corallites, it can probably be assigned to *T.* cf. *lepas* Sokolov, 1952 (Coen-Aubert, 1980, p. 106). This species has been found in the middle part of the reefal facies from the Lustin Formation, on the north side of the Dinant Synclinorium and on the south side of the Namur Synclinorium as well as at the top of

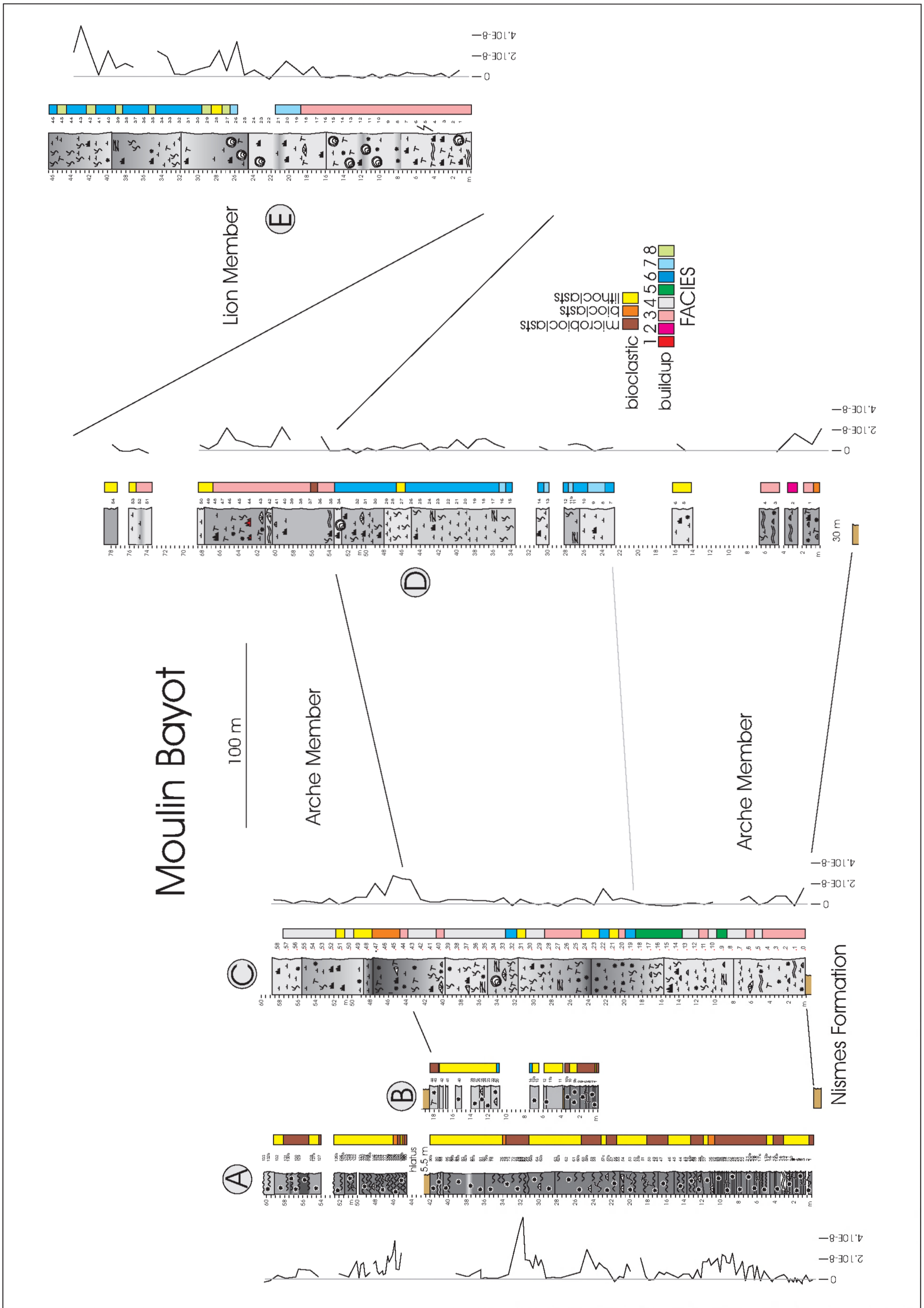

Figure 9 . Logs of Moulin Bayot sections with facies interpretation and magnetic susceptibility in m³/kg.

the Fontaine Samart Member from the Pont de la Folle Formation, in the Western Entre-Sambre-et-Meuse. The first occurrence has also been mentioned by Boulvain *et al.* (1999, p. 89) and the second one by Dumoulin (2001, p. 19). As noted previously by Dumoulin *et al.* (1998, p. 82), *Hexagonaria mirabilis* has been collected at 14 m and 31 m, in section E of Moulin Bayot which belongs to the Lion Member.

7.2. Taxonomic note

According to Schröder (2002, p. 522), *Tabulophyllum sylvaticum* should be placed in synonymy with *T. lineatum* (Quenstedt, 1881) from the Frasnian of the Sudetes in Poland. This may be correct although the Polish collection figured by Schröder (2002) is partly heterogeneous.
The name *Sinodisphyllum kielcense* is retained herein for the Belgian material assigned by Boulvain & Coen-Aubert (1997, p. 33) to *Mansuyphyllum elongatum* (Rozkowska, 1979). The precise dimensions of the holotype of *Sinodisphyllum kielcense* from the Frasnian of the Holy Cross Mountains in Poland have been redescribed by Rohart (2002, p. 115) who reported this species from the middle part of the Frasnian of the Boulonnais in France. Moreover, a few smaller coralla of *S. kielcense*, which are similar to those described by Rozkowska (1979) and Rohart (2002), have been collected at La Boverie quarries. As the variability of *S. kielcense* is now well understood, it is better to use this species instead of *S. elongatum* which is represented only by its holotype. Following Rohart (2002), *Sinodisphyllum* Sun, 1958 from the Frasnian of the Hunan Province in China is herein preferred provisionally over *Mansuyphyllum* Fontaine, 1961 from the Middle Devonian of Vietnam. These two taxa are sometimes regarded as synonyms and undoubtedly need revision.

8. Stratigraphical interpretation

The good lateral continuity of the beds in La Boverie quarries allows the sections there to be easily correlated geometrically (Figs 6, 7 & 8). Above the nodular shales of the Chalon Member, there is a 100 m thick buildup that belongs to the Arche Member. This is capped by more argillaceous and bioclastic facies which are assigned to the Ermitage Member. These facies pass rapidly upwards into a relatively thin buildup unit corresponding to the final development of the Arche Member. The more argillaceous facies, which follow, are ascribed to the Bieumont Member. The 70 m thick Lion Member overlies these argillaceous-bioclastic facies. Above this mound, there are about 18 m of more or less nodular calcareous shale belonging to the Boussu-en-Fagne Member, which is succeeded by the Neuville Formation. In Humain, the black limestones from the base of the section are characteristic of the Bieumont Member. These limestones are followed by grey massive limestones from the Lion Member.

The correctness of these lithostratigraphic correlations is confirmed by the investigation of the numerous rugose corals in La Boverie quarries. Thus, Macgeea rozkowskae occurs also in the coralliferous beds at the top of the Chalon Member exposed in the Arche quarry at Frasnes, which is the stratotype of the Arche Member. The fauna of the overlying Ermitage Member, normally represented by shales, is unusual at La Boverie quarries, in that *Hexagonaria mirabilis* has been found rather low in this lithostratigraphic unit and characterizes also the small buildup developed at its top. This species is also present in the Bieumont Member and at the base of the Lion and the Boussu-en-Fagne members. However, the long stratigraphic range of *H. mirabilis* in La Boverie quarries is similar to that noted by Boulvain & Coen-Aubert (1997) in the Lion and Nord quarries at Frasnes (Fig. 10).
In addition to *H. mirabilis*, the rugose corals fauna of the Bieumont Member is highly diversified at La Boverie. According to Boulvain & Coen-Aubert (1997) and Boulvain et al. (1999), *H. mirabilis*, *Peneckiella fascicularis* and *Tabulophyllum conspectum* are already known from this lithostratigraphic unit, on the south side of the Dinant Synclinorium whereas a few specimens of *Scruttonia balconi* and *Sinodisphyllum kielcense* have been recovered from the "red marble" (facies L3), close to the base of the Lion Member from the Nord quarry at Frasnes. In that same exposure, *Tabulophyllum sylvaticum* and *Aristophyllum irenae* are associated with Hexagonaria mirabilis in the black argillaceous limestones of the neptunian sill intersecting this red marble.
Several of the species occurring in the Bieumont Member at La Boverie have also been observed in the Philippeville Anticlinorium and in the Entre-Sambre-et-Meuse. At Barbençon, *Hexagonaria mirabilis* appears at the top of the Fontaine Samart Member of the Pont de la Folle Formation (Dumoulin, 2001, p. 16). In various localities of these two structural units, *H. mirabilis* is associated with *Scruttonia balconi*, *Sinodisphyllum kielcense* and *Tabulophyllum conspectum* in the shales of the overlying Machenées Member, whereas it is accompanied in addition by *Peneckiella fascicularis* and *P. isylica* in the bedded limestones from the lower part of the succeeding Philippeville Formation.
The same fauna occurs in the lower part of the Lion Member from the Nord quarry at Frasnes, but there it is more diverse than at La Boverie quarries. According to Boulvain & Coen-Aubert (1997), no colony of *Argutastrea konincki* was collected at Frasnes whereas this species is already present at the top of the Bieumont Member at Humain and is abundant in the upper part of the Philippeville Formation. The rugose corals from the base of the Boussu-en-Fagne Member are similar to those identified at Frasnes and Boussu-en-Fagne by Boulvain & Coen-Aubert (1997) and Boulvain et al. (1999).
The complex of La Boverie quarries is unusual in that it is characterized by a nearly continuous succession of reefal limestones without any significant intercalation

of shales. Therefore, it is not possible to recognize the Ermitage Member at La Boverie, especially because there is a small buildup at its top, just below the Bieumont Member. A more or less similar situation occurs with a much reduced thickness in the lower and reefal part of the Lustin Formation from the north side of the Dinant Synclinorium and the south side of the Namur Synclinorium which was described by Boulvain et al. (1999). Indeed, the Lustin Formation starts with a first level of massive limestone belonging to the Saint-Anne marble (auctores) and overlain by argillaceous limestones containing widespread thickets of *Disphyllum*. Then, a second level of massive limestone is capped by bedded limestones with laminar stromatoporoids which have more or less the same facies as the Bieumont Member of La Boverie quarries. It is interesting to mention that *Thecostegites cf. lepas* and *Hexagonaria mirabilis* are present locally below the second level of massive limestone. Additionally, the latter species occurs up to the top of these reefal limestones in which *Tabulophyllum conspectum* has also been collected. The upper part of the Lustin Formation is represented by lagoonal limestones containing *Argutastrea konincki* and *A. lecomptei* (Tsien, 1978), a similar situation to that in the upper part of the Philippeville Formation.

The sections at Moulin Bayot, which are overturned, are more difficult to correlate lithostratigraphically with each other; this is due to the discontinuity of the outcrops and to structural complications. Moreover, only sections A and B show an interval of shale (Fig. 9). Below this shale bed, the lower part of section A yielded the conodonts *Polygnathus asymmetricus* Bischoff & Ziegler, 1957 and *Ancyrodella gigas* Youngquist 1947 which indicate an age similar to that of the Moulin Liénaux Formation (Dumoulin et al., 1998). It is clear that sections B and C belong to the same lithostratigraphic unit and this is probably also the true for section D which contains in its upper part a small fragment of *Thecostegites cf. lepas*. By contrast, section E is located in the Lion Member (Dumoulin et al., 1998). These lithostratigraphic correlations are confirmed by the curves of magnetic susceptibility (Fig. 9). These curves are particularly valuable in that they allow a correlation of sections C and D, on the basis of characteristic patterns of high values appearing in the upper part of the two sections and succeeding to low values recognized in their lower part. It should also be noted that the dissimilarity between the susceptibility curves of the upper part of section D (53-78 m) and the lower part of section E (0-19 m) is an additional argument for their non-contemporaneity.

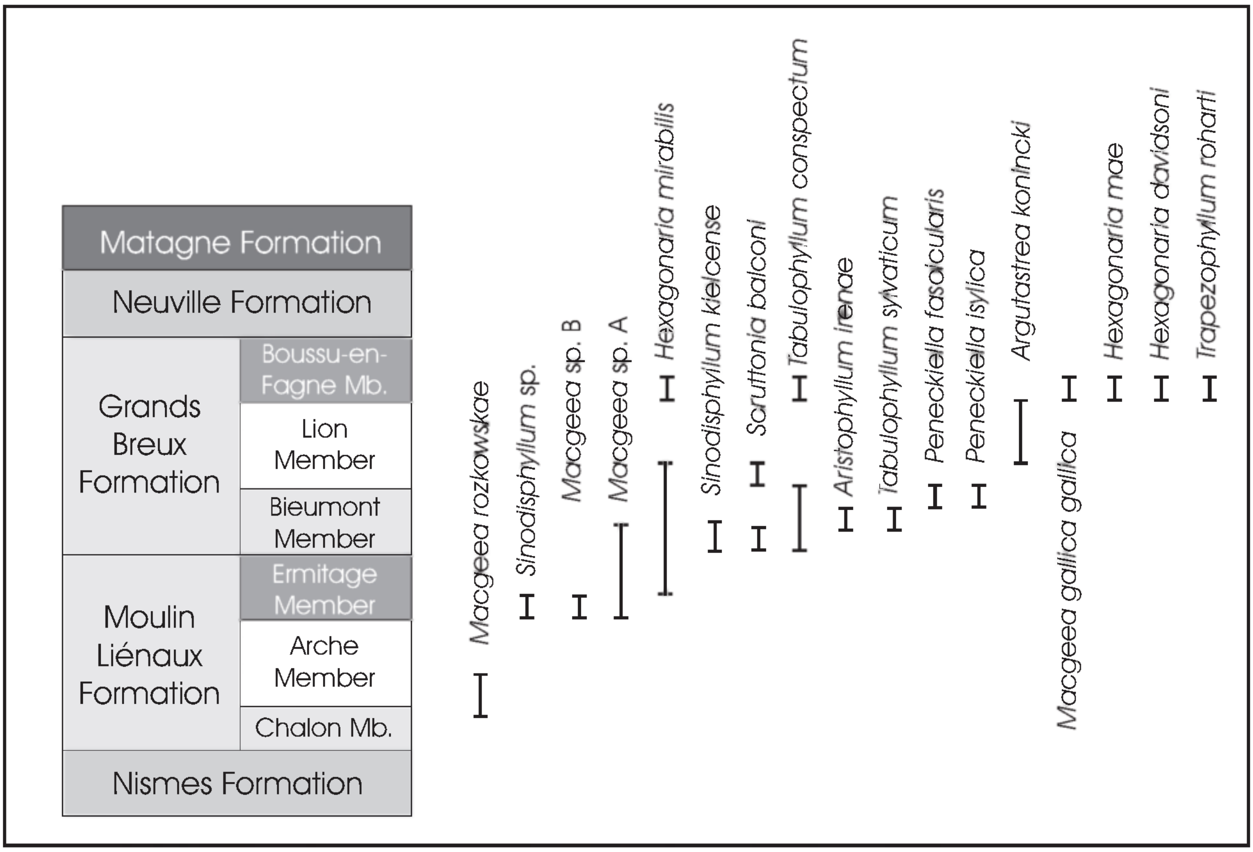

Figure 10. Stratigraphic distribution of the rugose corals in the Frasnian of La Boverie quarries.

9. Facies interpretation

Sedimentological interpretation of the six buildup facies allows them to be positioned on a relative bathymetric scale based on simple reference marks such as the base of the photic zone, the storm wave base (SWB) and the fairweather wave base (FWB). The nature of the assemblages also allows the buildup facies to be interpreted in terms of the degree of restriction of the environment.
The A3-L3 facies with stromatactis, corals and stromatoporoids includes few cyanobacteria and shows episodic reworking by storm waves. It developed close to SWB, in a oligophotic environment. This facies includes some lenses of facies A5-L5, with stromatolitic coatings and thrombolitic bushes rich in *Renalcis*. These lenses become abundant and anastomosing when the water depth decreases; additional evidence of this shallowing is the progressive occurrence of green algae, as in facies A4-L4. These two facies (A4-L4 and A5-L5) developed close to the FWWB, in a photic environment. There is no progressive transition between any of these first three facies (A3-L3, A4-L4, A5-L5) and the other three buildup facies (A6-L6, A7-L7, A8-L8). Facies A6-L6 facies is characterized by its peloidal character, by the abundance of dendroid stromatoporoids, and by the dominant grainstone texture, with possible graded bedding. This facies corresponds to an environment located above the FWWB, with the onset of restricted water circulation being marked by a relatively low faunal diversity. Facies A6-L6 shows a progressive transition to fenestral limestone rich in peloids, calcispheres and palaeosiphonocladales (facies A7-L7); this latter facies developed in a moderately protected, subtidal to lower intertidal area. The last facies (A8-L8) is fine-grained and develops in a quiet lagoonal, subtidal environment.
The flanking facies are composed of material eroded from the buildups and of already deposited material that is reworked and sorted by storm waves (Humblet & Boulvain, 2001). Bioclastic packstones and micropackstones are characterized by an open facies with brachiopods, bryozoans, crinoids whereas lithoclastic packstones and grainstones show a clearer influence of the buildups by massive input of lithoclastic material.

10. Geometry of buildups

10.1. Flanking facies

Microbioclastic packstones (facies b) and, to a lesser extent, bioclastic packstones (facies B) are off-mound facies; by this it means that the influence of any nearby buildups on the sediment budget of these facies is relatively low. In contrast, the lithoclastic packstones and grainstones (facies L) are ones in which the supply of substantial amounts of material originating from the buildups is significant. Flanking facies are present in section A at Moulin Bayot (Fig. 9), and open facies alternate there with reworked sediment from the buildups. Section B at Moulin Bayot is rather similar, but closer to the buildup; this relative closeness is shown by the fact that the flanking facies are now interfingering with bioconstructed facies. Flanking facies are also present in La Boverie, where they overlie the first part of the Arche Member (Fig. 7). These facies indicate the presence of a retrograding buildup, as they are mainly made up of reworked lithoclastic material (facies L).
Although outcrops are uncommon in flanking sediments, a probable polarity could be inferred from the comparison of section A from Moulin Bayot (Fig. 9), or the Lompret section (Humblet & Boulvain, 2001) with the Leus quarry (Boulvain & Coen-Aubert, 1997). The first two sections are characterized by a high proportion of open marine facies, while the later shows only very well-sorted lithoclastic material. This probably reflects a fore-reef – back-reef differentiation, as represented in Fig. 13.

10.2. The base of the buildups

Two different geometries are found at the bases of the buildups. The first is found where the pre-buildup facies show a gradual development of carbonate production; in effect, the substrate is colonised progressively, first by corals and crinoids, then by sponges. The second geometry is found where buildup facies directly overlie shale, without any transition. This resulted where an existing buildup prograde over detrital sediments.
Only the second geometry is found at Moulin Bayot, in section C (Fig. 9). Both geometries are found at La Boverie: the first geometry is illustrated in section G by the initiation of the Lion Member, and the second geometry is illustrated by the extension of the Lion Member in section H (Fig. 11). The initiation of the Lion Member begins with the development of large coral colonies (massive and fasciculate rugose corals in section H, and tabulate corals in section G) in an argillaceous sediment. The density of these colonies increases progressively upwards (sometimes with the development of crinoidal lenses), and eventually carbonate production started and resulted in the formation of centimetre-scale to decimetre-scale lenses of micrite. The process of lateral extension of a buildup operated by the simple building out of reefal facies over flanking facies, without the substrate having first been colonized by corals. The fact that two colonization sequences can be found at the base of the Lion Member (sections G and H; Fig. 11), which are separated laterally by shale, suggests that the initiation of buildup development could have taken place in several places simultaneously, with the whole buildup ultimately resulting from the coalescence of individual lenses.

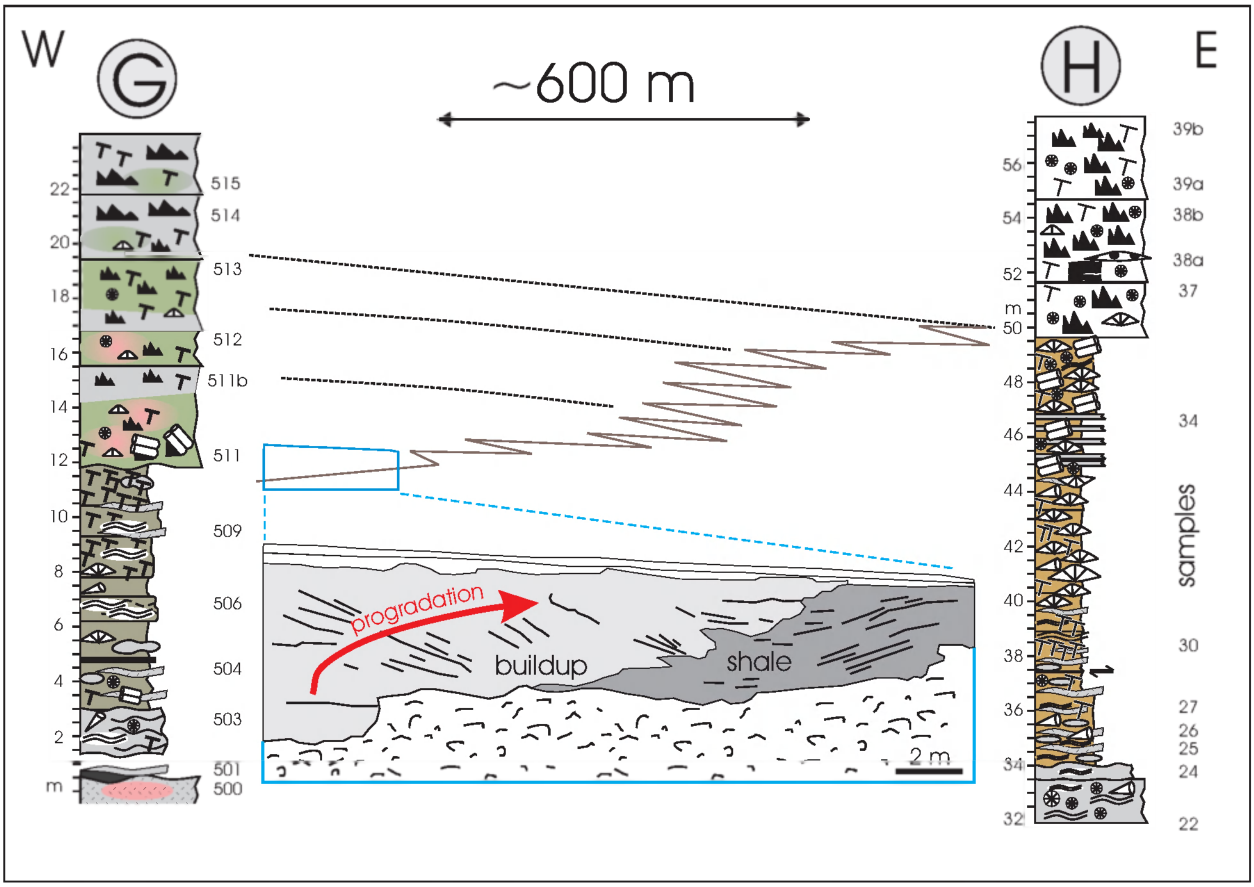

Figure 11. Development of the Lion Member over the argillaceous facies of the Bieumont Member in La Boverie quarry. In section G, substrate stabilization and colonization were the consequence of branching tabulate corals, whereas in section H it was done by fasciculate and massive rugose corals. Laterally to section G, the progradation took place over argillaceous facies without colonization by corals. Legend as in Fig. 5.

10.3. Architecture of buildups

There is a considerable similarity of facies between the Arche and Lion members. The facies successions and their distributions in the two members are also very similar. Each of the two buildups begins with a grey (locally pinkish or greenish) limestone, exhibiting stromatactis, corals and stromatoporoids (facies A3-L3), in which microbial limestone lenses become progressively more abundant upwards. After about 20 m, a more protected facies occurs; comparison of sections C and D from Moulin Bayot (Fig. 9) indicates that this facies seems probably to have developed in a central part of the buildup. This particular geometry suggests an area of protected sedimentation, probably as a kind of inner lagoon sheltered by bindstone or floatstone facies. This same atoll-like geometry is also seen in the Nord quarry (Boulvain & Coen-Aubert, 1997), and the name "atoll" is therefore proposed to describe the Arche and Lion members.

11. Sedimentary dynamics

It is possible to use recent models of atoll development in response to eustatic variations (e.g. Warrlich *et al.*, 2002, see Fig. 12) to propose a dynamic interpretation for the geometry and the sedimentary succession in reefs or mounds. According to this model (Fig. 12), the initial development of the lower part of a buildup during a transgression and subsequent highstand would have been followed by reefal growth along the edge of the buildup during the succeeding lowstand; an atoll crown would then have started to develop during the following transgressive stage. The presence of restricted facies can be seen as the consequence of the balance between sea level rise and reef growth.
In Belgian mounds, the sedimentary effects of bathymetric changes are known from Lecompte studies (1954). Deepening and shallowing events induce respectively large-scale retrograding and prograding geometries. A retrogradation-progradation episode occurred evidently

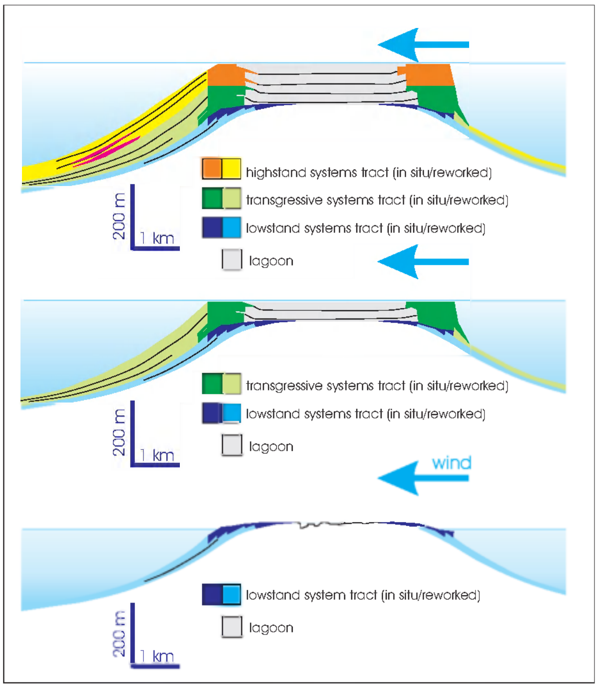

Figure 12 . Model of atoll development as a function of eustatic variations. Modified from Warrlich *et al.* (2002).

near the top of the Arche Member. This episode is particularly visible in sections D, F and H at La Boverie (Fig. 7), where, for a thickness of over 30 m, there is an alternation of bioclastic and lithoclastic facies (facies B, b and L) with reefal facies with stromatoporoids (facies A6). The Moulin Bayot sections in the Philippeville Anticlinorium show the same interval of retrogradation; it is shown in section D (Fig. 9) by the occurrence of the relatively deep stromatactis facies (facies A3) over the shallower protected stromatoporoid facies (facies A6; Fig. 9). This retrogradation was apparently insufficient to cause the demise of buildup facies and the reappearance of detrital facies. However, it is recorded in two buildups over a distance of 40 km, and therefore it was almost surely a basin-wide phenomenon. If the recurrence of deeper water facies in Moulin Bayot is taken into account, the forcing mechanism of the retrogradation can be taken as probably eustatic.

On the basis of the geometry of the buildups and their bathymetric interpretation, it is possible to propose a 3rd order sequential subdivision of buildups and lateral

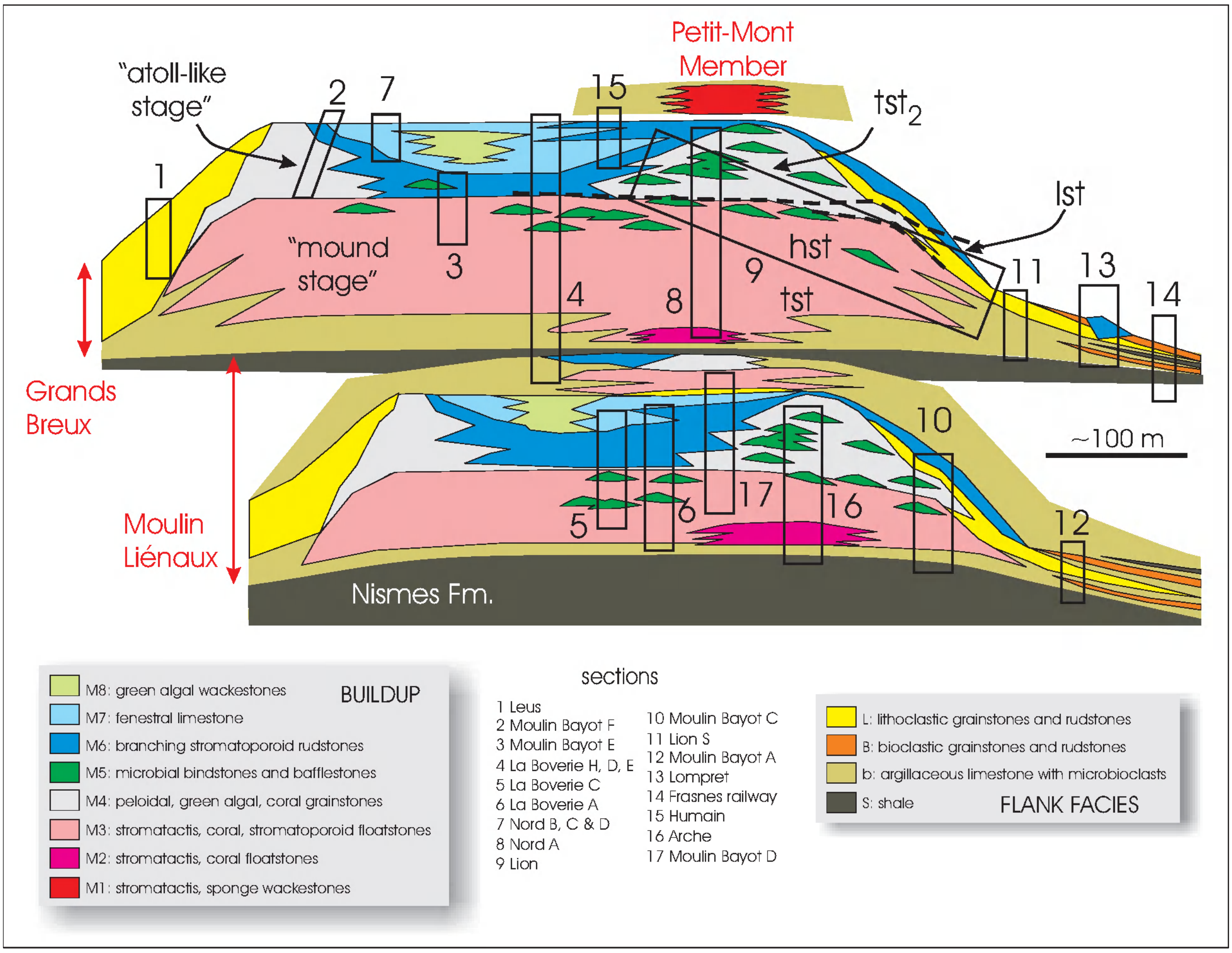

Figure 13 . Sedimentological model of Arche and Lion members with location of the sections (Nord, Lompret, Lion, Leus and Frasnes sections: see Boulvain *et al.*, 2004). Sequence stratigraphic interpretation of the Lion Member.

sediments (Fig. 13). At the present stage, this subdivision only concerns the Lion Member and correlative lateral deposits of the platform (da Silva & Boulvain, 2004). The lower and middle parts of the buildups correspond to a succession of a transgression (TST, Fig. 13) and sea-level stillstand (HST) with progradation associated with reduced accommodation space. Mound development during a succeeding sea-level drop (LST) was restricted to the edge of the buildup, with possible emersion and lithification from meteoric waters. The atoll crown development corresponds to a transgression resulting in marked lateral facies differentiation between fore-mound and interior lagoon (TST2+HST2). The demise of mound development was then the consequence of a final transgression associated with the deposition of the Boussu-en-Fagne Shale. The last regression-transgression cycle, responsible for the atoll-stage evolution of the carbonate mounds, can be correlated with the platform-scale development of lagoonal facies and paleosols belonging to the upper part of the Lustin Formation (da Silva & Boulvain, 2004).
This reconstruction gives rise to the following interpretations: transgressive systems tracts correspond to various types of units according to the development stage of buildups and perhaps to the rate of sea level rise. They may correspond to restricted facies developed in an atoll lagoon with a keep-up type dynamic (Neumann & Macintyre, 1985) or, on the contrary, to a retrograding, give-up type dynamic. The lowstand systems tracts are poorly developed, which would imply a very weak accommodation, and even a brief emersion of the buildups, perhaps marked locally by the presence of early lithification (section D of La Boverie, Fig. 7).
Our sequence-stratigraphic interpretation of Belgian Frasnian buildups is to be considered only as a means to describe transgressive and regressive phases and the presence of complete Exxon-type sea-level fluctuations (Vail *et al.*, 1977) is not yet proven. For smaller scale variations (4th and 5th orders), our observations show that buildup facies do not show sequential organization, suggesting some kind of feedback of organic communities to variations of oceanic parameters (Boulvain, 2001).

12. Conclusions

Facies description and interpretation of Frasnian Arche and Lion carbonate buildups leads to the definition of six buildup facies (facies A3-A8 or L3-L8) and three lateral facies (facies b, B and L). Buildups started with a stromatoporoid-coral-sponge assemblage (facies A3-L3) in a relatively deep, quiet subphotic environment, then reached the fairweather wave base and the euphotic zone with algal-microbial facies (facies A4-L4 and A5-L5). The upper parts of the buildups are characterized by high degree of lateral differentiation, with algal-microbial facies protecting a central restricted sedimentation area that has a dendroid stromatoporoid facies (facies A6-L6) and fenestral limestone (facies A7-L7). The flanking facies reflect different kind of input of mound reworked material in the near mound area, from fine-grained sheet flows to coarse-grained debris flows.
Knowing the geometry of these sedimentary bodies and their bathymetric interpretation, it is possible to propose a dynamic interpretation of the buildups and flanking sediments. The lower and middle parts of the buildups ("mound stage") correspond to the succession of a transgression and a sea-level stillstand. Mound development during the subsequent period of low sea-level was restricted to the edge of the buildup, with possible emersion. The atoll crown development corresponds to a new transgression with lateral facies differentiation between fore-mound and mound lagoon. The demise of mound development was then the consequence of a last transgression associated with the deposition of shale.
This first sequence-stratigraphic interpretation of Belgian Middle Frasnian buildups argues for the presence of transgressive and regressive phases, but the existence of complete Exxon cycles of sea level fluctuations (Vail et al., 1977) is not yet proven. Observations show that buildup facies do not reflect sequential organization into smaller scale cycles (4th and 5th orders), suggesting some kind of biofeedback in relation to variations in oceanic parameters (Boulvain, 2001).

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