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Stratigraphy of the Lower Palaeozoic of the Brabant Massif, Belgium. Part I: The Cambro-Ordovician from the Halle and Ottignies groups.

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ABSTRACT. Multidisciplinary research in the last 25 years and recent geological mapping in the Brabant Massif, have completely changed our knowledge about one of the poorly known part of Belgian geology. The sedimentary succession is surprisingly complete by comparison with the literature before the 1970s, from the lower Cambrian to the top of the Silurian, and very thick (>13 km), thus highlighting the need to produce an up-to-date stratigraphic nomenclature. In this first paper about the Cambrian and the lowest Ordovician, we describe in detail the formations, which are classified into two new groups, how the description of the units evolved through time, their lithology, sedimentology, boundaries and contacts, thickness, fossil content and type sections or most typical outcrop areas. The lower Halle Group comprises the Blanmont, Tubize and Oisquercq formations that consist of sandstone, siltstone and pale coloured slate. The overlying Ottignies Group comprises the Jodoigne, Mousty and Chevlipont formations formed of a more argillaceous and notably darker lithology. The two groups constitute a very thick (> 9 km) lower Cambrian to lowermost Ordovician siliciclastic succession, mostly pelagic and turbiditic. The cumulative thickness curve is concave-upwards which shows an extensional rift basin. A comparison with the Condroz Inlier shows that only the uppermost part of the sedimentary pile was observed in boreholes (Chevlipont Formation).

KEYWORDS: Brabant Massif, stratigraphy, Cambrian, Avalonia, Condroz Inlier , rift.

1. Introduction

Multidisciplinary studies in the last 20 years show that the Brabant Massif contains a very thick siliciclastic, often turbiditic and quite complete Lower Palaeozoic sequence, from the upper lower Cambrian to the uppermost Silurian and very probably to the lowermost Devonian (lowest Lochkovian; Verniers & Van Grootel, 1991; Steemans, 1994). Its prolongation below the Devonian cover can be traced by boreholes and geophysical data to the NE under the Campine Basin as far as the Roermond Graben, to the S at least under the northern half of the Brabant Parautochthon and to the NW under the North Sea into the concealed Caledonides of East Anglia. The entire fold belt is now called the Anglo-Brabant fold belt (Pharaoh et al*.*, 1993) or Anglo-Brabant Deformation Belt (Verniers et al., 2002).

Fig. 1 gives an overview of the stratigraphic evolution of the Brabant Massif from the pioneering work of Malaise (last version 1911) to the modern synthesis of Verniers et al*.* (2001). It should also be noted that before the 1970s the stratigraphic nomenclature was different in each river basin and the thickness of the sedimentary succession has been much underestimated. A complete history of the geological discovery of the Brabant Massif is given in Debacker (2001).

A detailed 1/10.000-scale bedrock mapping project ran between 1993 and 2007 (13 maps published at a scale of 1/25.000: Doremus & Hennebert, 1995; Herbosch & Lemonne, 2000; Delcambre et al., 2002; Hennebert & Eggermont, 2002; Pingot & Delcambre; 2006; Delcambre & Pingot, 2008; Herbosch & Blockmans, 2012; Herbosch et al., accepted a, b; Blockmans et al., accepted; Hennebert & Delaby, submitted a, b). This mapping combined with stratigraphic, palaeontological, tectonic, geophysical, geochemical and geochronological work (e.g. Ph.D.: Verniers, 1976; André, 1983; Servais, 1993; Everaerts, 2000; Debacker, 2001; Larangé, 2002; Dewaele, 2004; Vanmeirhaeghe, 2006) has highlighted the need to produce a detailed and up-to-date new stratigraphic scheme for the Brabant Massif. All these studies allow the identification of mappable lithostratigraphic units for the Cambrian, Ordovician and Silurian of the whole SE outcropping zone of the Brabant Massif (Fig. 3).

The purpose of this paper is to present the new stratigraphic terminology and to describe of the new groups, formations and members, to explain how the description of the units evolved through time, their lithology, sedimentology, boundaries and contacts, thickness, fossil contents and, where possible, type sections or most typical outcrop areas. This new stratigraphic scheme has been recently accepted by the National Commission

MALAISE C. (1911) Geolgical map n°120 (1910)	**ANTOINE A. et R. (1943)** Sm et Rv inverted succession	**LEGRAND R. (1968)**	**MICHOT P. (1978)**	**VERNIERS *et al.* (2001)**	
ORDOVICIAN (Lower Silurian) Sl 1b - Assise de Gembloux Sl 1a - Assise de Rigenée	Assise de Gembloux	ORDOVICIAN Ashgillien: schistes fossilifères et volcanites Carodoc: schistes noirs	Assise de Rigenée	Madot Formation Huet Formation Bornival Formation Ittre Formation Rigenée Formation	**ORDOVICIAN**
SALMIAN Sm1 - Assise de Villers-la-Ville	Assise de Villers-la Ville: Grès et psammites de Strichon Psammites du Tribotte Quartzophyllades siliceux de Villers	Undifferentiated Lower and Middle Ordovician	Fm. de Villers-la Ville: Assise du Tribotte	Tribotte Formation Abbaye de Villers Formation	
REVINIAN	Assise de Mousty: Quartzophyllades de Chevlipont Grès et schistes Mn	CAMBRIAN Sm1a - quartzozophyllades zonaires micacé Sm1a - quartzites et phyllades	Assise de Laroche: Couches de l'Abbaye Couches de Chevlipont	Chevlipont Formation	
Rv - Assise de Mousty	Schistes noirs de Faux Schistes noirs zonés de Glory	REVINIAN Rvc - Assise de Mousty Rvb - Assise de Jodoigne	Assise de Mousty	Mousty Formation	**CAMBRIAN**
	Assise d'Oisquercq	Rva - Assise d'Oisquercq		Oisquercq Formation	
DEVILLIAN Dv2 - Assise de Tubize Dv1 - Assise de Blanmont (et Dongelberg) Dvo - Assise de Jodoigne	Assise de Tubize	DEVILLIAN Dvb - Assise de Tubize Dva - Assise de Dongelberg (= Blanmont)		Tubize Formation Blanmont Formation Jodoigne Formation	

Figure 1: Historic evolution of the Cambro-Ordovician stratigraphy of the Brabant Massif from Malaise (1911) to Verniers *et al.* (2001).

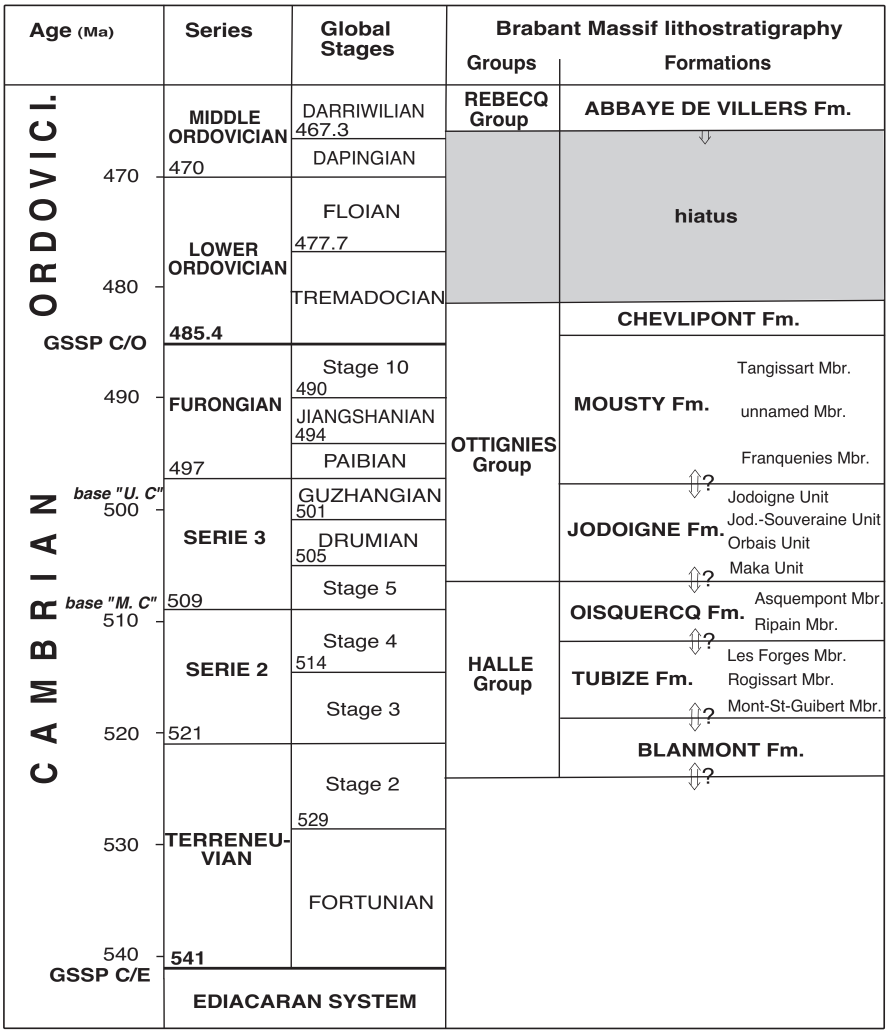

Figure 2: Chronostratigraphic position of the Cambrian and Lower Ordovician lithostratigraphic units in the Brabant Massif (chronostratigraphy after Gradstein *et al.*, 2012). Base "M. C." at 509 Ma and base "U. C." at about 499 Ma are base of the traditional "Middle Cambrian" and "Upper Cambrian" respectively (Peng *et al.*, 2012 p. 477).

of Stratigraphy (sub-commission Lower Palaeozoic; NCS, 2009, 2012). In this first part, we begin with the description of the six formations that cover a large part of the Cambrian and the lowest part of the Ordovician. This time interval corresponds to Megasequence 1 (Vanguestaine, 1992; Verniers et al., 2002; Linnemann et al., 2012) and is interrupted by a large stratigraphic hiatus (Fig. 2). The chronostratigraphy and time scale of Gradstein et al. (2012) are followed throughout the paper.

2. Regional geology: a short introduction

The Brabant Massif (Fig. 3) consists of a largely concealed WNW-ESE directed fold belt developed during Early Palaeozoic times, documented in the sub-surface of central and north Belgium (Fourmarier, 1920; Legrand, 1968; De Vos et al., 1993; Piessens et al., 2005). At first sight, it appears as a gently ESE plunging broad anticlinal structure, with a Cambrian core flanked on both sides by Ordovician to Silurian strata. To the S, SW and SE it is unconformably overlain by the Devonian to Carboniferous deposits of the Brabant Parautochthon (Mancy et al., 1999). To the S, the Brabant Parautochthon is tectonically overlain by the Ardenne Allochthon along the Midi Fault System (Variscan overthrust). To the NW, the massif continues beneath the North Sea and links up with the East-Anglia Basin (Lee et al., 1993). Both areas form part of the Anglo-Brabant deformation belt (Pharaoh et al., 1993, 1995), the eastern branch of a predominantly concealed slate belt moulded around the

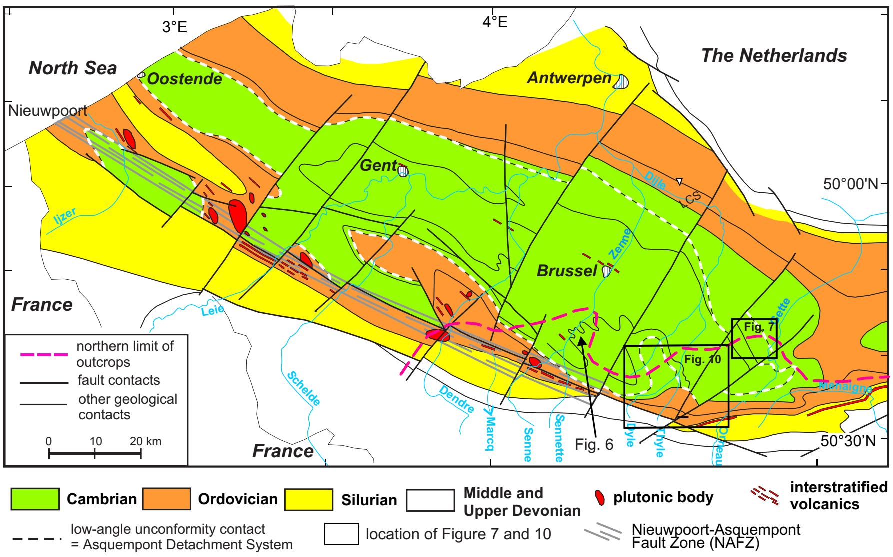

Figure 3: Geological subcrop map of the Brabant Massif (after De Vos *et al.*, 1993; Debacker *et al.*, 2004a) with the location of the Figs. 6, 7 and 10.

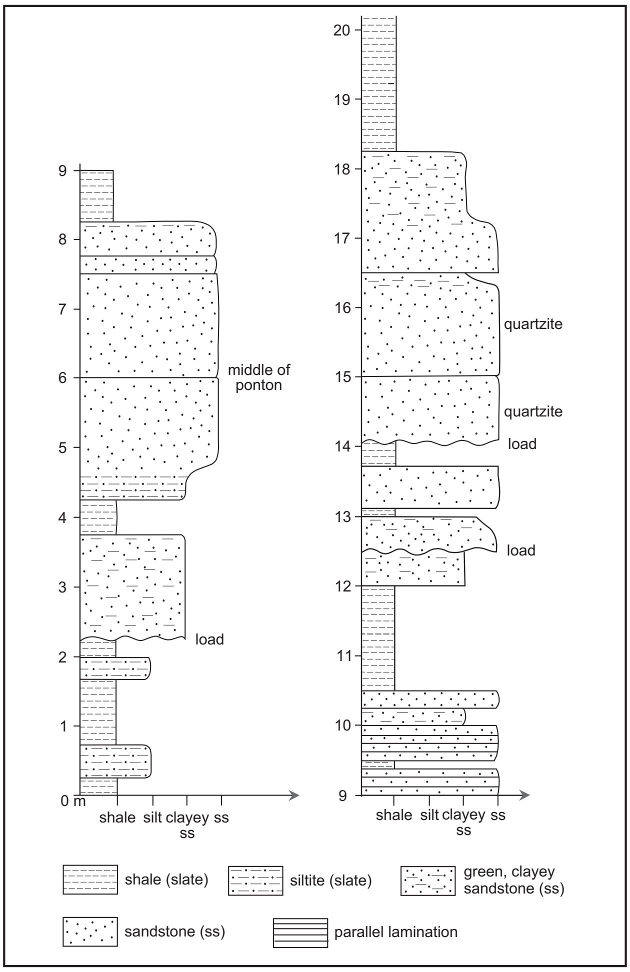

Figure 4: Lithological log of a small part of the Blanmont Formation at Opprebais (Grande Gette valley), eastern end of the Les Fosses quarry (outcrop 22 *in* Herbosch *et al.,* 2008a). Location reported in Fig. 7.

Neoproterozoic Midlands Microcraton. The Anglo-Brabant deformation belt belongs to the Avalonia microplate (Verniers & Van Grootel*,* 1991; Cocks et al., 1997).

The Brabant Massif is poorly exposed and is almost completely covered by Mesozoic-Cenozoic deposits (Fourmarier, 1920; Legrand, 1968). Along its southeastern rim, incising rivers (Figs 3, 10) provide narrow outcrop areas that have recently been mapped in detail and investigated by several researchers (see above). A substantial part of our knowledge is based on boreholes (Legrand, 1968; Herbosch et al., 1991, 2008b) and on the interpretation of gravimetric and aeromagnetic surveys (BGS, 1994; Sintubin, 1999; Mancy et al., 1999; Sintubin & Everaerts, 2002; Everaerts & De Vos, 2012).

The Brabant Massif shows a very thick siliciclastic pile, with an abundant turbiditic and pelagic sequences, ranging from the upper part of the lower Cambrian (Terreneuvian) in the antiformal core to the upper Silurian and even to the lowermost Devonian along the rims (Figs. 2, 3). Twenty years of stratigraphic research (Vanguestaine, 1991, 1992; André et al., 1991; Maletz & Servais, 1996; Herbosch & Verniers, 2002; Verniers et al., 2001, 2002; Vanmeirhaeghe et al., 2005; Herbosch et al., 2008a, b; Owen & Servais, 2007; Vanguestaine & Wauthoz, 2011; Debacker & Herbosch, 2011) and mapping data suggest that the sedimentary record is continuous, with the exception of an important hiatus in the Lower Ordovician (Fig. 2). The total thickness of this sedimentary pile exceeds 13 km, of which over 9 km is Cambrian (Herbosch et al., 2008a; NCS, 2012).

The rocks in the Brabant Massif show a low-grade metamorphic overprint, ranging from epizone in the core to anchizone and diagenesis in the rim (Van Grootel et al., 1997; Larangé, 2002). The origin of this metamorphism is mainly of burial origin (pre-kinematic) but an additional syn-kinematic origin is needed in order to account for the higher metamorphic grade observed in the Silurian rims (Debacker et al., 2005). A more complete and modern interpretation of the Brabant Massif geodynamic history can be found in recent publications (Sintubin & Everaerts, 2002; Debacker et al., 2004a, 2005; Sintubin et al*.*, 2009; Linnemann et al., 2012; Debacker, 2012).

3. Halle Group

We introduce here formally a new group with a new name. Unlike the Ardennes Inliers, the Brabant Massif succession has not been subdivided into groups or only for simplification (as in De Vos et al*.*, 1993, Oisquercq and Tubize groups). That terminology was little used and later abandonned by Verniers et al. (2001).

The Halle Group comprises the three lowest formations in the Brabant Massif: the Blanmont, Tubize and Oisquercq formations. They all consist of siliciclastic sediments (metasandstone, metasiltstone and slate) with pale colours: grey, whitish, greenish, grey blue to purple. They strongly contrast with the dark colour of the next group. This new name comes from the town of Halle situated on the Tubize Formation, near the Blanmont Formation (Buizingen and Dworp outcrops) and near the type-section of the Oisquercq Formation (at Oisquercq) in the Senne valley (Figs. 3, 5).

3.1. Blanmont Formation

The Blanmont Formation was defined very early by Malaise (1873): "*Assise de Blanmont ou des quartzites inférieurs*". The original definition was only slightly improved by Verniers et al. (2002); Herbosch et al*.*, Jodoigne-Jauche map, accepted b; Debacker & Herbosch (2011).

The formation mostly comprises pale whitish, bluish or greenish, massive, medium to coarse-grained quartzite. Granulometry and sorting are very variable and the content of feldspars low (Nijs & Logier, 1990). Stratification is generally

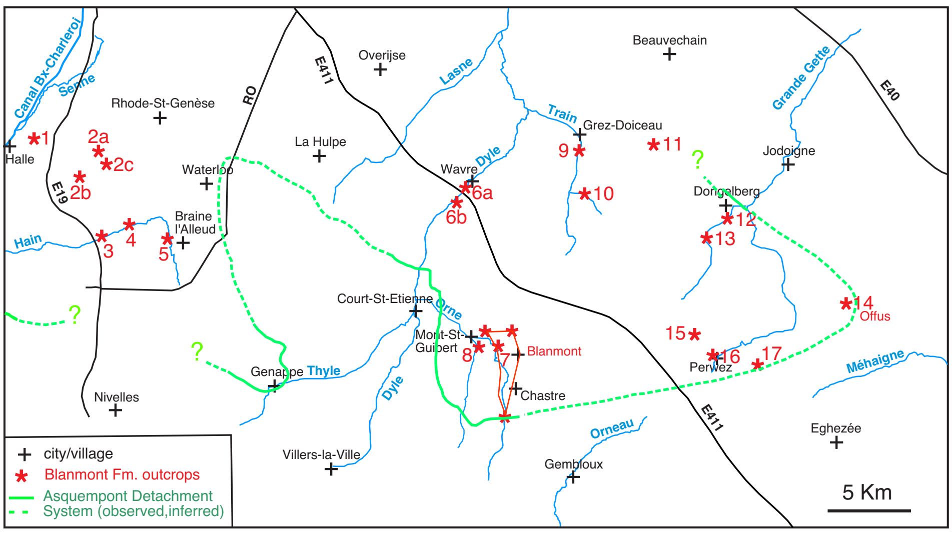

Figure 5: Geographic situation of all observed outcrops of the Blanmont Formation in the Brabant Massif. Trace of the Asquempont Detachment System that corresponds to a low-angle unconformity (reported in Fig. 3) and that marks the limit between the lower Cambrian core and the Ordovician-Silurian rim of the Brabant Massif (see text for references). Table 1 gives the location, description and lithology of the numbered outcrops.

n°	Location	Description	Lithology	Illustration
1	Buizingen, Kluisbos	embanked quarries	quartzite and slate	
2a	Dworp, Meerbeek	outcrop along the brook and drowned quarry	massive quartzite	
2b	SW Dworp, Rulroheidebeek	outcrop, drowned quarry	massive quartzite	
2c	SE Dworp, Meerbeek	small outcrop	massive quartzite	
3	Wauthier-Braine, Hain valley	temporary outcrop	massive quartzite	
4	Sart-Moulin, Hain valley	temporary outcrop and embanked quarries	massive quartzite	
5	Braine l'Alleud, Hain valley	temporary outcrop	massive quartzite	
6a	Wavre, Dyle valley	disapeared outcrop		
6b	Wavre, Dyle valley	embanked quarries		
7	Mont-St-Guibert - Blanmont-Chastre area	numerous and large outcrops and quarries	masive quartzite and argillaceous quartzite	
8	Mont-St-Guibert, Houssière valley	outcrop and embanked quarry	massive quartzite	
9	Biez, Train valley	drowned quarry	massive quartzite	
10	Bonlez, Glabais brook	small outcrop	massive quartzite	Photo 4
11	Pietrebais, Pietrebais brook	large outcrop	massive quartzite	
12	Dongelberg, Orbais valley	two large drowned quarries and outcrop	massive quartzite and stratified quartzite	Photo 1
13	Opprebais, Orbais valley	large drowned quarry and outcrops	stratified qtz and argillaceous sandstone slate intercalations	Fig. 4 Photos 2, 3
14	Offus, Petite Gette valley	drowned quarry	massive quartzite	Photo 5
15	Thorembais-St-Trond	embanked quarry		
16	Perwez, Grande Gette valley	embanked quarry	massive quartzite	
17	Perwez, Jaucelette valley	small outcrops and embanked quarry	massive quartzite	

Table 1: Blanmont Formation outcrop location, description and lithology. Complement to figure 5.

not visible, difficult to observe (Dongelberg quarry photo 1; Alvaux section) or exceptionally well marked (Opprebais quarry photo 2). At the old and very large quarry of Opprebais, well stratified quartzite, greenish sandstone and decimetric to metric intercalations of grey siltstone and slate (Fig. 4; photo 2) with biotite are exposed (de Magnée, 1977; Andre et al., 1991; Debacker & Herbosch, 2011; Herbosch et al*.*, Jodoigne-Jauche map, accepted b). Plane-parallel laminations are also observable in some sandstone beds from Opprebais (Fig. 4). Decimetre-scale pseudo-nodules within the basal parts of some thick beds (photo 3) were observed at the NW extremity of the Dongelberg northern quarry and more rarely plane-parallel and oblique laminations in a small quarry SW of the Dongelberg S quarry (see Debacker & Herbosch, 2011; Herbosch et al., accepted b).

The earlier descriptions (Malaise, 1873, Stainier, 1889; Fourmarier, 1920; Leriche, 1921; de la Vallée Poussin, 1931; Raynaud, 1952) stressed the massive appearance of these quartzites, but also the presence of interstratified slate levels. As an example, Stainier (1889 p. 35) describes, 300 m to the SE of Chastre (Orne valley), two plurimetric interstratified levels of green slate in the quartzite of an active quarry no more exposed today. These levels seem to have been more widespread than is visible nowadays. Finally, these authors described also facies that were coarser, more arkosic and conglomeratic, with oblique stratification in the area of Jodoigne (Grande Gette valley) and Mont-St-Guibert (Orne valley). These coarser facies have not been observed any more during the recent mapping.

This formation is poorly known, even if it is observed in numerous small outcrops appearing very locally in the bottom parts of river valleys (e.g. Glabais brook photo 4) and/or in old flooded quarries (e.g. Offus photo 5) in the south central part of the Brabant Massif (Fig. 5, Table 1). The formation contains a lithology which is the most resistant to erosion of the entire Caledonian basement and hence, the old palaeorelief frequently shows topographic peaks or ridges below the Mesozoic-Cenozoic cover (Camerman, 1950). This is clearly visible on the isohypse map of the top of the Palaeozoic basement prepared by Delcambre et al. (2002) for the Chastre-Gembloux map (see under the map). Also in the outcrop area this has frequently been noticed. The best example is the outcrop of Pietrebaix (Fig. 5 n° 11) where, along and near a 100 m long small brook, quartzite towers 2 to 3 metres high can be observed. The Blanmont Formation covers a large area in north central Brabant and figure 5 shows the distribution of all the very scattered outcrops of this zone. The figure clearly shows that they are all situated to the north, i.e. under the footwall, of the Asquempont Detachment System (Fig. 5; Debacker, 2001; Debacker et al., 2004b). The distribution shows that this detachment system is also present and visible along the northern flank of the Brabant anticlinal axis from about Offus to Dongelberg (Piessens et al., 2005; Herbosch et al., 2008a; Debacker, 2012). The Fôdia quarry (Offus, photo 5) is the easternmost outcrop of the Blanmont Formation and it seems to mark the periclinal end of the central Cambrian part of the Brabant Massif.

The thickness of the Blanmont Formation is estimated certainly to exceed 1.5 km in the Jodoigne area where two large quarries occur (Herbosch et al*.*, 2008a, accepted b; Debacker & Herbosch, 2011). The overall stratigraphic thickness in the two Dongelberg quarries and their immediate surroundings is certainly 200 m (N-S subvertical stratification) and the stratigraphic thickness in the "Les Fosses" quarry at Opprebais is about 300 m (E-W bedding and dips steeply south). The upper contact of the Blanmont Formation with the base of the Tubize Formation has nowhere been observed. **It is at present considered to be the oldest formation in the outcropping or subcrop area of the Brabant Massif** (Herbosch et al., 2008a).

Malaise (1900, p. 190; 1901, p. 4) is the only author who mentioned the presence of fossils in interstratified slates in between quartzites of the Blanmont Formation from the Orne valley: the ichnofossil *Oldhamia radiata*. No other fossils (macro- or micro-) have been reported. An age could however be attributed by correlation with the upper part of the Deville Group in the Ardennes Inliers. Indeed, the occurrence of *Oldhamia* in the lower part of the 4 Fils Aymon Formation (Rocroi Inlier) and in the middle part of the Bellevaux Formation (Stavelot Inlier) was dated by acritarchs from an interval between the middle part of the lower Cambrian and the lower part of the middle Cambrian (Vanguestaine, 1992 Figs 2 and 4, Zone 0). It corresponds in the Baltica trilobite biozonation with the range of the *Holmia* Zone to the *Paradoxides oelandicus* Zone (see also Herbosch & Verniers, 2011 Fig. 1). In the new global Cambrian stratigraphy (Peng et al. *in* Gradstein et al., 2012) this interval is situated between the middle of the Stage 3 (Series 2) and about three quarters of the way up Stage 5 (Series 3; base of the *P. gibbus* Zone). As the Tubize and Oisquercq formations belong to the same biozone (see below), the Blanmont Formation should fall in the lower part and probably also be within the interval **from the uppermost Terreneuvian to the middle part of Stage 3** (Fig. 2).

No type-section has been defined yet. The historical type area is situated in the numerous outcrops and old quarries arround Blanmont in the Orne valley (number 7 in Fig. 5; see also Delcambre and Pingot, 2002 Figs. 3, 4). In this region, the long outcrop of the Alvaux section, at 150 m S of the Tour des Sarrasins (x 168.76 y 146.65) displays very interesting lithology and tectonics. However the best sections are now found in the Jodoigne area: in the flooded quarries of Dongelberg (x 181,80 y 154,01) and of Opprebais (x 181.00 y 153.15) (Figs. 4, 7, 8, 9; photos 1, 2, 3). The Opprebais quarry is the only place where at present it is possible to observe slate intercalations and where the stratification is well marked in the quartzite (Fig. 4; Debacker & Herbosch, 2011; Herbosch et al., Jodoigne-Jauche map, accepted b).

3.2. Tubize Formation

The Tubize Formation was also defined by Malaise in 1873: as the "*Assise de Tubize ou des quartzites et phyllades aimantifères*". The definition was upgraded and members added by Vander Auwera & Andre (1985); De Vos et al. (1993); NCS (2009) and Herbosch et al. (Ittre-Rebecq map, accepted a).

The Tubize Formation mainly consists of slate (mudstone and siltstone), but also contains metasandstone, meta-arkose and metagreywacke. It is easily recognizable by the dominant greyish green colour and the frequent presence of magnetite porphyroblasts (important for the magnetic survey interpretation). In some places, millimetric euhedral pyrite crystals are also seen. A rhythmic repetition of sandstone units passing upwards into siltstone and slate is also frequently seen especially in the lower and middle members of the formation. The best outcrops are in the Senne Basin area, where Vander Auwera & André (1985) described three new informal lithostratigraphic units from bottom to top: the Rogissart Unit, the Fabelta Unit and the Les Forges Unit. Later detailed geological mapping of the entire map sheet (Herbosch et al., Ittre-Rebecq map, accepted a) showed that the Rogissart Unit is sufficiently characteristic and mappable to be defined as the Rogissart Member. In contrast, the facies of the two other informal units actually correspond to the facies of the lower part of the "Assise de Oisquercq (Rv1a)" as described by Legrand (1968, p. 15). Magnetite and *Oldhamia* (Asselberghs, 1918) were observed in this lower part and in consequence it seems more logical to include these two units in the upper member of the Tubize Formation under the new name "Les Forges Member". The name "Fabelta Unit" was hence dropped as a separate mappable unit (Verniers et al., 2001).

The detailed geological mapping allowed confirmation of the presence of another unit below the Rogissart Member that was described by Legrand (1968). This lower dominantly pelitic member is poorly exposed in the Senne area (only in and around Halle; see Piessens et al., 2004 Fig. 33). It was recognized in the Dyle Basin and formally named the **Mont-St-Guibert Member** (NCS, 2009). In the latter region, from Genappe towards Mont-St-Guibert and Ottignies, the same general characteristics such as green colour and the occurrence of magnetite, are always present, albeit with an overall more fine-grained and argillaceous lithology. Nevertheless, some decimetric Bouma sequences containing sandstone-siltstone-slate can be observed locally (e.g. at Mont-St-Guibert photo 6, Sintubin et al., 2002; or at Blanc Ri near Ottignies, Herbosch and Blockmans, Wavre - Chaumont-Gistoux map, 2012). The outcrop zone Beaurieu - Mont-St-Guibert (Orne valley) belongs also to the lower Mont-St-Guibert Member. Decametric slumps have been described by Debacker (2001 p. 117 and Fig. 3.16) at Beaurieu.

As mentioned above, the middle member of the formation is the **Rogissart Member** approximately 800 m thick**.** It contains fine to coarse-grained pale quartzitic sandstone, feldspathic

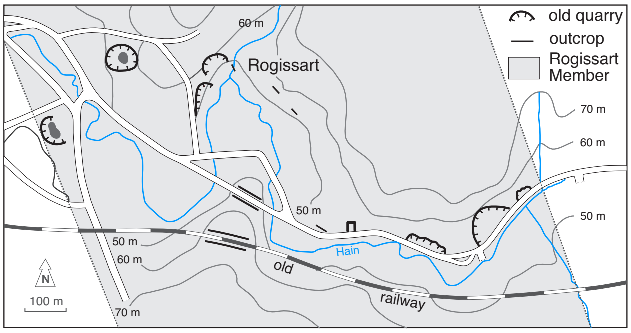

Figure 6: Geological map and outcrops of the Rogissart Member of the Tubize Formation in the Hain valley, SE of the town of Tubize. The stratification shows a mean direction of N334°E and a dip of 76°NE and the cleavage direction N308°E, dip 71°NE, these values imply a very steep fold. Location in the Brabant Massif reported in Fig. 3 by an arrow.

sandstone, arkose and greywacke in decimetric to metric beds (Hameau du 45 photo 7), alternating with more or less clayey siltstone and green slate (claystone), together forming fining upward sequences (Vander Auwera and André, 1985). Numerous millimetric porphyroblasts of magnetite ar often present, mostly in the metasiltstone. The sandstone beds are massive, planar, oblique and sometimes show convolute laminations. The rhythmic sedimentation is interpreted as high-density turbidites of the Bouma type. This member is well exposed in the Senne valley from Halle to Clabecq (Herbosch et al., Ittre-Rebecq map, accepted a) and in the Hain valley (Fig. 6) where it was intensively mined during the 19th century (Dehem, 1908). In the Hain valley numerous old quarries and good outcrops (Fig. 6 and photo 7) enabled Debacker (2001 p. 85-86) to show that this zone belongs to the limb of a large subvertical fold. The Rogissart Member was temporarily well exposed along the high-speed train cutting south of and under the city of Halle (Sintubin et al., 1998; Piessens et al., 2004). The member seems to be absent and cut out by faulting in the Orne valley. Interestingly a dioritic intrusion (?) of unknown age was mined at Lembeek during the 19th century (Champ-St-Véron quarry; de la Vallée Poussin and Renard, 1879; Corin, 1965; Van Grootel et al., 1997).

The upper unit, the **Les Forges Member,** mainly consists of grey-green to dark grey-blue homogeneous to zoned slate (mudstone to siltstone), sometimes containing metamorphic magnetite. The dark grey-blue colour is a distinctive characteristic of this member (Asselberghs, 1918; Legrand, 1968; NCS, 2009; Herbosch et al., Ittre-Rebecq map, accepted a). Mostly complete decimetric Bouma sequences in metric sets or isolated within the slate continue to be visible. One can observe green and characteristically millimetric to centrimetric beds with abundant chlorite (Vander Auwera & André, 1985). The size and the structure of these beds, and particularly the succession of fining upward wavy chlorite laminae (photo 8), are very similar to the fine-grained turbidite model of Stow (Stow & Piper, 1984; Piper & Stow, 1991). These observations suggest an origin as low-density turbidity currents modified by subsequent metamorphism (Herbosch et al., Ittre-Rebecq map, accepted a). Outcrops of this member are scarce in the Sennette valley and absent in the Dyle Basin.

The contacts with the underlying Blanmont Formation or with the overlying Oisquercq Formation have nowhere been observed. The total thickness of the formation is estimated at more than 2 km, with the Rogissart Member alone about 800 m thick (NCS, 2009; Herbosch et al., Ittre-Rebecq map, accepted a).

The trace fossil *Oldhamia* (photo 9) was found in all three members (Malaise, 1883a, b, 1900, 1901; Stainier, 1889; Asselberghs, 1918; Corin, 1938; Legrand, 1968; Van Tassel, 1986). A tentative age may be assigned by comparison with the upper part of the Deville Group in the Ardennes Inliers. Indeed, the occurrences of *Oldhamia* in the lower part of the 4 Fils Aymon Formation (Rocroi Inlier) and in the middle part of the Bellevaux Formation (Stavelot Inlier) were dated by acritarchs (Vanguestaine, 1992, Fig. 2 and 4, zone 0) from the interval between the middle part of the lower Cambrian and the lower part of the middle Cambrian. In age, this corresponds to the Baltica trilobite biozones ranging from the *Holmia* Zone to the *Paradoxides oelandicus* Zone (see also Herbosch & Verniers, 2011 Fig. 1). In the new global Cambrian stratigraphy (Peng et al., 2012) this interval is situated between the middle of Stage 3 (Series 2) to about 3/4 of the way up Stage 5 (Series 3; base of the P. gibbus Zone). As the Tubize Formation is geometrically younger than the Blanmont Formation we can estimate that its age covers roughly **the interval from the middle of Stage 3 to the middle of Stage 4** (unnamed Serie 2) (Fig. 2).

No type-section has been defined. The outcrops with the most typical lithology of the Rogissart Member are situated in the Hain valley (Senne Basin) around Hameau du 45 where many outcrops and old quarries can be observed (e.g. Rogissart x 140.5 y 152.12; photo 7 and Fig. 6). Good observations of the Mont-St-Guibert Member can be made in the Orne valley between Mont-St-Guibert and Beaurieu (Mont-St Guibert x 168.27 y 147.00; Beaurieu x 166.07 y 148.05 and x 165.32 y 147.70; see also Delcambre & Pingot, 2002 Figs 6, 7). Outcrops of the Les Forges Member are small and very scarce.

3.3. Oisquercq Formation

The Oisquercq Formation was also defined by Malaise (1873*): « Assise d'Oisquercq, ou des phyllades bigarrés et graphiteux »*. The name was later retained but only for the "phyllades bigarrés*"* which now comprise the lower Ripain Member (Beugnies, 1973; NCS, 2009) and the upper Asquempont Member (Verniers et al., 2001; NCS, 2009). The "phyllades graphiteux" corresponds now to the Mousty Formation.

The lower **Ripain Member** consists of grey-blue to purple extremely homogeneous fine-grained slate (claystone; canal section Asquempont, photo 10). Stratification is not visible or very difficult to observe even in thin section. Green patches or pluricentimetric green bands are frequently present but are unrelated to the bedding. The colour is very sensitive to weathering and changes easily from purple to claret red. The **Asquempont Member** (Verniers et al., 2001) forms the upper part of the formation and is interrupted by the Asquempont Fault. It contains greenish grey to green very fine slate also without stratification. The transition between the two members is gradual over a short distance (2 to 5 metres) and only marked by the change in colour. However, towards the top of the member the grain-size increases and a rough stratification appears. These slates are interpreted as pelagic sediments. The contact with the underlying Tubize Formation has nowhere been observed and the upper contact is always faulted (Asquempont Fault).

The discovery of acritarchs in the Asquempont Member from the Lessines and Oudenaarde boreholes was used for correlation with the trilobite biozonation: from the *Holmia* Zone up to the *Paradoxides oelandicus* Zone (Vanguestaine, 1991 Fig. 6), corresponding chronostratiphically with the mid early to early middle Cambrian. After the revision of the dating of the acritarch Biozone 0 in the Ardennes (Fig. 4 and p. 2 to 4), Vanguestaine (1992, p. 8) emphasized that this age bracket is exactly the same as for the upper part of the Deville Group. In the new global chronostratigraphy of the Cambrian (Peng et al., 2012), this interval can be considered to range from the middle part of Stage 3 (Series 2) to about the ¾ of the way up Stage 5 (base of the *P. gibbus* Zone, Series 3). Vanguestaine (1991, 1992) mentioned several times that the age is close to the lower-middle Cambrian boundary and hence the Oisquercq Formation should be situated in this interval near the boundary of Stages 4 - 5. As the Oisquercq Formation it situated stratigraphically above the Blanmont and Tubize formations it cover roughly an interval from the **middle of Stage 4 to the lower part of Stage 5.**

A type-section for the upper part of the Ripain Member (photo 10) and for the Asquempont Member has been designated along the E bank of the Brussels-Charleroi canal cutting between km 41.10 (x 140.66 y 148.74) and km 40.12 (x 140.85 y 147.68).

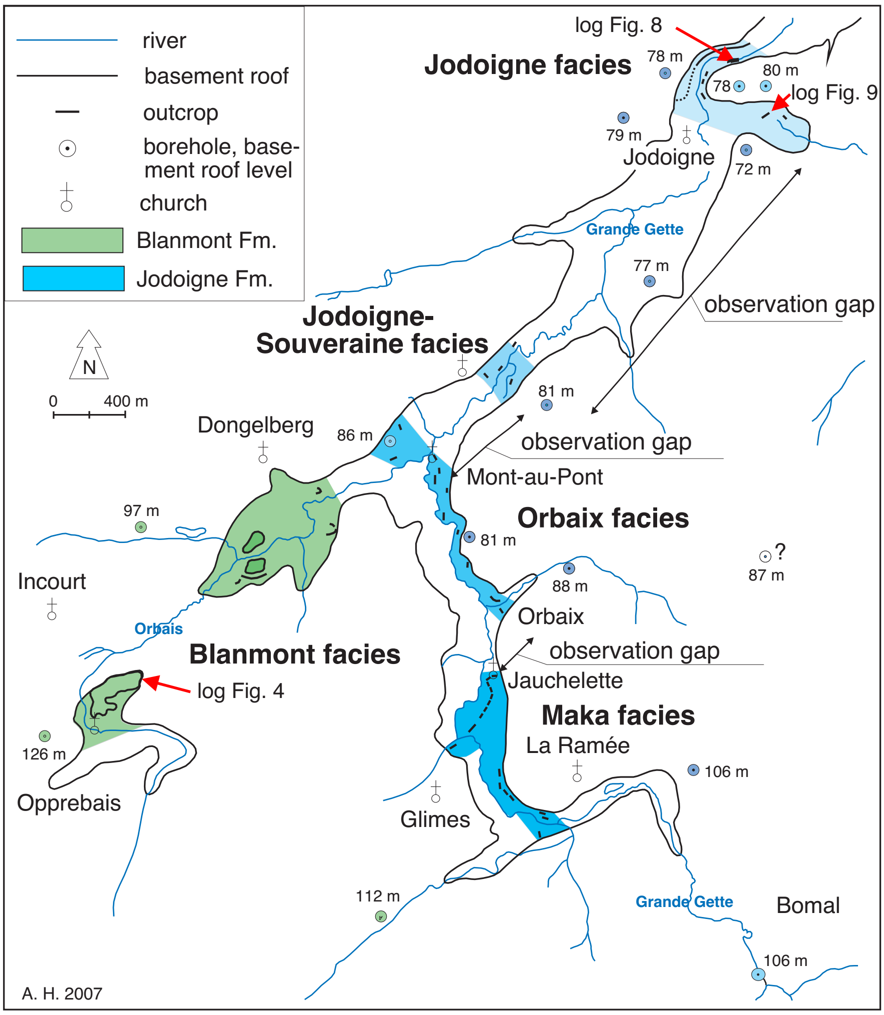

Figure 7: Geographic location of outcrops, different units, observation gaps and boreholes in the Jodoigne Formation and the Blanmont Formation in the Grande Gette Basin (after Herbosch *et al.*, 2008a). Position in the Brabant Massif reported in Fig. 5.

This section is fully described by Debacker et al. (2004a, pp. 12-15, Figs. 6, 12, 24). Outcrops typical of the Ripain Member are visible along the eastern bank of the old canal from km 43.0 to km 43.4 (in the km counting of the present-day active canal) (La Bruyère, approximately x 139.72 y 150.00).

4. Ottignies Group

The three following formations Jodoigne, Mousty and Chevlipont are grouped into a new larger unit: the Ottignies Group. They are all made up of siliciclastic sediments: metasandstone, metasiltstone, slate and black slate, with dark colours: grey, dark grey and black. These dark colours contrast with the lighter colouration of the covering group (see below). The new name comes from the town of Ottignies, situated near the type-sections of the Mousty and Chevlipont formations in the Dyle valley (Fig. 10).

4.1. Jodoigne Formation

The Jodoigne Formation was described very early on in the literature under the name "roches noires de Jodoigne" (Dumont, 1848; Malaise, 1873, 1883 a, 1911; Fourmarier, 1920). It was only formally defined in 1931 by de la Vallée Poussin (p. 320) as: "*Assise de Jodoigne: quartzite noir, phyllade noir, pyriteux, ressemblant étonnament au Revinien de l'Ardenne comme André Dumont l'avait déjà noté"*. During the new geological mapping campaign of the Jodoigne-Jauche map (Herbosch et al., 2008a; NCS, 2009; Herbosch et al., accepted b) it became clear that this definition could still be used, although slightly upgraded.

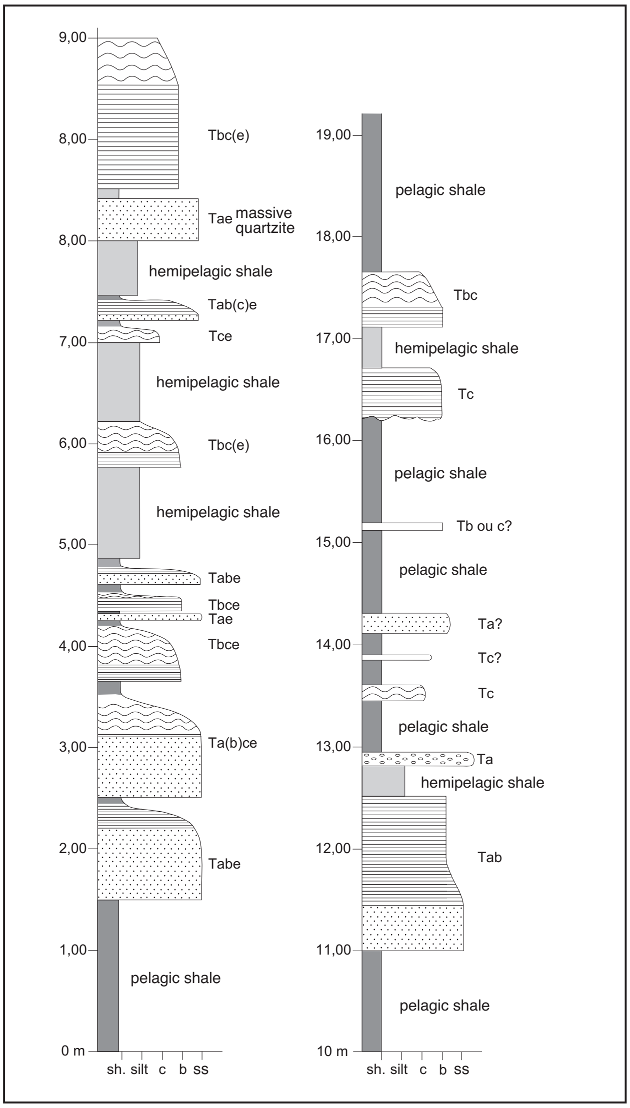

Figure 8: Log of a part of the Jodoigne unit of the Jodoigne Formation at Bordia castle, E side of the Grande Gette, NW of Jodoigne (after Herbosch *et al.,* Jodoigne-Jauche map, accepted b). Location reported in Fig. 7.

The Jodoigne Formation only crops out in the Grande Gette valley and even there the outcrops are very scarce, discontinuous and with long observational gaps (Fig. 7). This is the reason why only four informal lithostratigraphic units could be defined and not true formal members (Herbosch et al., 2008a, Jodoigne-Jauche map, accepted b; Debacker & Herbosch, 2011).

The oldest **Maka Unit** consists of an alternation of massive, pale-grey to grey quartzite and pyritic black shale, the latter with intercalated pale-grey centimetric sandstone beds. The quartzitic zones, in which bedding is extremely difficult to observe, are several tens of metres thick and are well exposed (Jauchelette photo 11), whereas the intercalated black slates are difficult to observe. Outcrops occur on both sides of the Grande Gette valley between the camp site of La Ramée in the S and the church of Jauchelette in the N (Fig. 7).

The **Orbais Unit** consists of well-stratified, decimetric beds of grey to blue-grey quartzitic sandstone to quartzite. In between these quartzites an alternation of pyritic black slate and thin pale-grey sandstone occurs. The quartzite sets are never more than about 10 m thick and show clear bedding-parallel or occasionally oblique lamination. One of the most characteristic features is the common occurrence of sandstone containing shale fragments (already described by Dumont, 1848; Orbais photo 12) in much variable abundance (< 1 to 40%). This unit occurs only along the E-side of the Grande Gette river and N-side of the Orbais river from Orbais in the S to Mont-au-Pont to the N (Fig. 7).

The **Jodoigne-Souveraine Unit** contains black massive quartzite with bedding difficult to observe. Black slate and grey quartzite occur also but exposures are very scarce. The unit occurs between the old railway station of Jodoigne-Souveraine (now a private property) and the surroundings of the chapel of "Notre-Dame du Perpétuel Secours" (along the Grande Gette river) and 150 m to the E in the park of the castle (Fig. 7).

The **Jodoigne Unit** of the Jodoigne Formation contains metre- to decimetre-thick zones of black slate, often with millimetric to centimetric siltstone beds, alternating with zones consisting of rhythmic, mostly decimetric sequences of sandstone, siltstone and black slate (Fig. 8). The slate and thin siltstone beds are black and contain pyrite; the sandstone can be grey or black. Two large temporary excavations in the eastern part of the town of Jodoigne have shown alternation of Bouma turbidite sequences and black slate (Fig. 9, photo 13). Structural observations in several outcrops of this unit point to the abundance of slump folds (Debacker et al., 2006). The depositional environment is interpreted as a fairly deep, anoxic basin with pelagic, hemipelagic and distal to less distal turbidite deposits. This unit crops out on both sides of the Grande Gette valley, from the southern suburbs of Jodoigne to the surroundings of the Bordia castle in the N of the town where the formation disappears under Cenozoic cover.

None of the contacts between the four units has been observed. Moreover, observational gaps of several hundred metres exist between the Maka Unit and the Orbais Unit, and between the latter and the Jodoigne-Souveraine Unit (Fig. 7). Probably these observational gaps coincide with the presence of black slate-dominated sequences. Between the outcrops of the Jodoigne-Souveraine Unit and the Jodoigne Unit, an apparent observational gap of 2 km occurs. Also this gap probably coincides with the presence of a black slate-dominated sequence, considering the particularly flat topography of the Grande Gette valley. A core from a borehole within this zone (Fig. 7 borehole 77 m) contains a centimetric to decimetric rhythmic alternation of grey sandstone, siltstone and black slate of turbiditic nature, very similar to the facies of the Jodoigne Unit.

The thickness of this formation is particularly difficult to estimate because of the tectonic complexity, the outcrop discontinuity and the presence of several large observational gaps. Tentatively more than 3 km of thickness is estimated (Herbosch *et al.*, 2008a; Debacker and Herbosch, 2011; NCS, 2012).

No macro- or microfossils have been observed, in spite of the numerous samples processed by Michel Vanguestaine. Several ages have been suggested, primarily based on lithological similarity with other formations (Mousty Formation, Revin Group in the Ardennes inliers) or on overall geometrical position. Basically, two main hypotheses have been put forward. One group of authors (Dumont, 1848; Malaise, 1900; Kaisin, 1919;

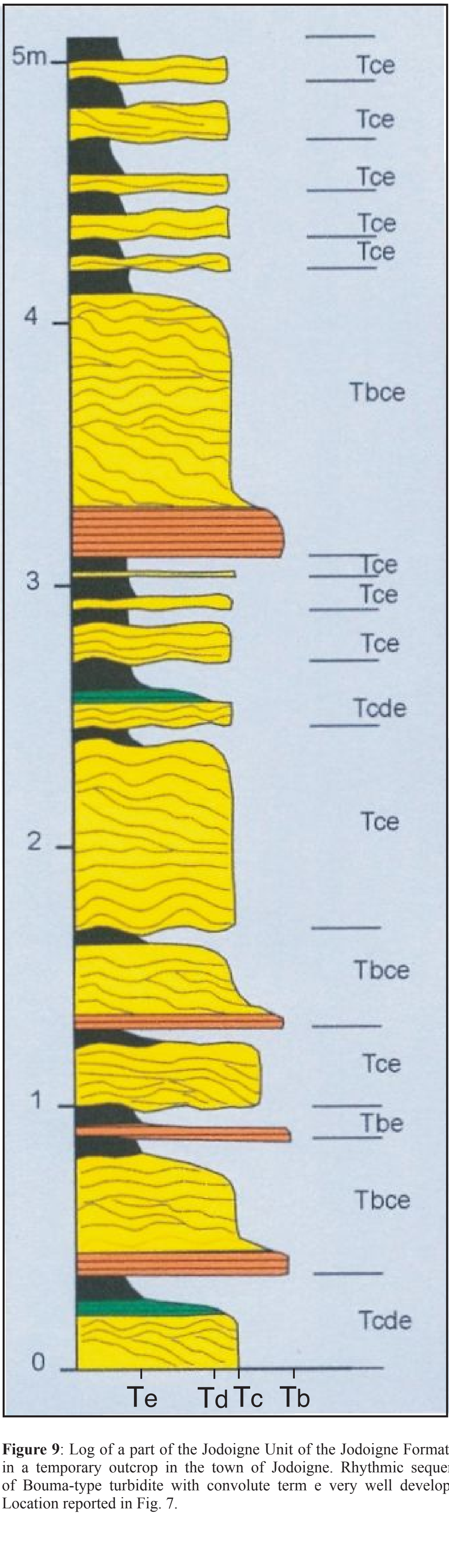

Figure 9: Log of a part of the Jodoigne Unit of the Jodoigne Formation in a temporary outcrop in the town of Jodoigne. Rhythmic sequence of Bouma-type turbidite with convolute term e very well developed. Location reported in Fig. 7.

de la Vallée Poussin, 1931; Raynaud, 1952; Mortelmans, 1955, 1977; Lecompte, 1957 and Verniers et al., 2001) considered the Jodoigne Formation older than the Blanmont Formation (Fig. 1). The main argument for this hypothesis is the relative geometric position with respect to the other formations within the Brabant Massif, apparently below all other units. However, as pointed out by Michot (1980), the outcrops of the Jodoigne Formation are situated "on the northern limb of the Brabant Anticlinorium" and therefore should be younger than the Blanmont Formation (Fig. 5).

In the second hypothesis the Jodoigne Formation is considered as middle to upper Cambrian, as favoured by Malaise (1911), Fourmarier (1920), Legrand (1968), Michot (1980), Vanguestaine (1992) and De Vos et al. (1993). However, as pointed out by Raynaud (1952), if this was so the magnetite-bearing Tubize Formation should have to be present between the Blanmont and Jodoigne formations in the Grande Gette outcrop area. A magnetic field survey by this author did not show magnetic anomalies between both formations, leading him to favour the first hypothesis.

Recently, based on detailed mapping, lithological and sedimentological observations, structural field work, combined with an evaluation of existing biostratigraphic data, Herbosch et al. (2008a and Jodoigne-Jauche map, accepted b) suggested that this formation belongs to the middle Cambrian, possibly extending into the lower upper Cambrian. An important argument is found in the Leuven borehole (89E01), dated by acritarchs and correlated with the lower part of the middle Cambrian (Vanguestaine, 1974; 1992 Fig. 8, Zone 1). This borehole and also the Heverlee borehole (89E363) show a typical turbiditic facies allowing these two boreholes to be assigned to the Jodoigne Formation rather than to the Mousty Formation, to which they were assigned earlier (e.g. De Vos et al., 1993). In the new global Cambrian chronostratigraphy (Peng et al., 2012) this interval corresponds rather well with Series 3.

No type-section has been identified but the type area lies in the Grande Gette valley between Jodoigne in the north and Glimes in the south (Fig. 7). Good outcrops of the Maka Unit can be observed at Jauchelette in front of the church and along the Rue du Maka (x 183.44 y 152.76; photo 11). For the Orbais Unit, the best outcrop is near a small brook at Orbais (x 183,62 y 153,72). For the Jodoigne Unit, a quite continuous 300 m long outcrop is exposed along Rue du Grand Moulin at Jodoigne (W bank of the Grande Gette; x 185.05 y 157.52) (see also Debacker et al., 2006).

4.2. Mousty Formation

The Mousty Formation was recognized by Malaise (1883a p. 200) as "couches noires de Mousty" and formally defined by Malaise (1900): "*Assise des phyllades et schistes noirs ou graphiteux avec phtanites, de Mousty*". Anthoine and Anthoine (1943) added four members to the original definition but these members could not be substantiated during the recent mapping campaign. Three members could be defined (but not mapped): an upper Tangissart Member, a middle unnamed monotonous and very thick member and a lower Franquenies Member (Herbosch and Lemonne, Nivelles-Genappe map, 2000; Verniers et al., 2001; Delcambre et al., Chastre-Gembloux map, 2002; NCS, 2009). The Court-St-Etienne borehole 40/5-540 (unpublished log; see also Fig. 7 from Debacker et al., 2004a) strongly suggests that another member, not observed in outcrop, exists under the Franquenies Member.

The formation is mainly formed of grey, grey-blue and dark grey slate (mudstone to siltstone), often with graphite and pyrite (black shale facies; Franquenies photo 14). It is massively bedded or finely laminated with rhythmic variations in clay and organic matter content typical for black shale. Stratification can also be marked by pale or greenish siltier beds or laminae, or by banded, layer-parallel colour variations. Occasional centimetric to decimetric fining upward sandstone or siltstone sequences are visible and they are interpreted as distal high-density turbidites (Bouma type) and fine-grained turbidites (Stow model; Ways photo 18). They are more and more abundant up in the Tangissart Member. A variable enrichment in Mn is frequently observed in outcrops by black and iridescent surface coatings and in thin

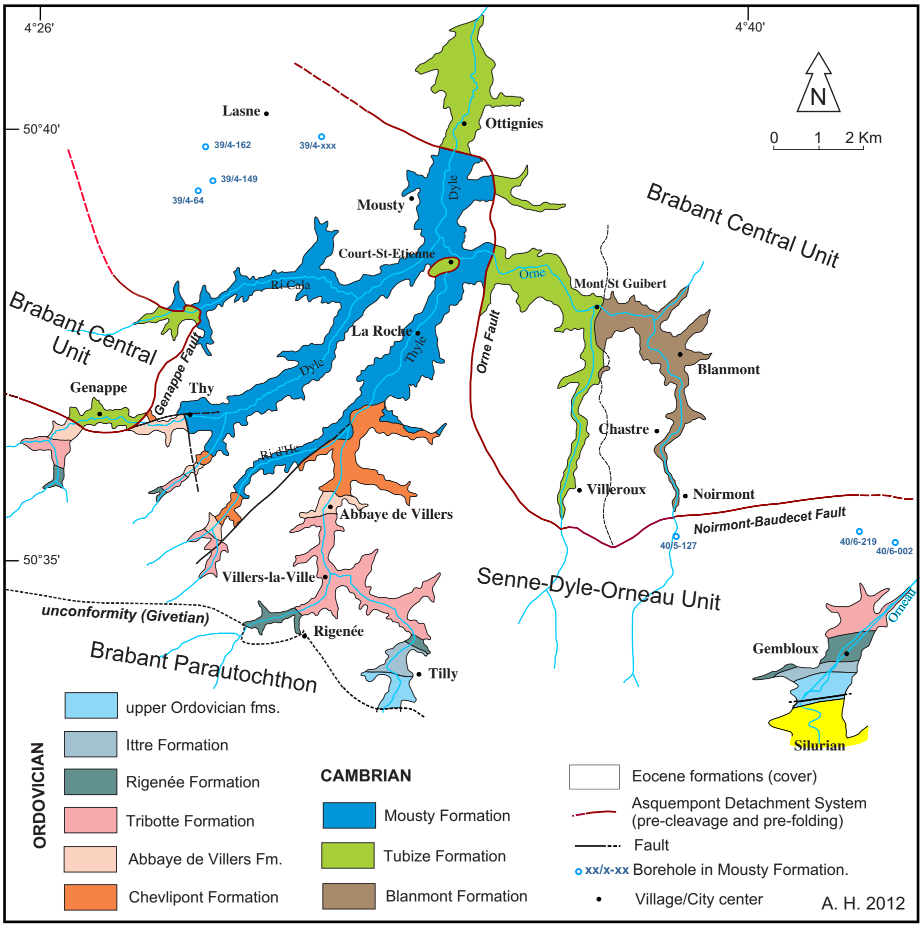

Figure 10: Schematic geological map of the Dyle and Orneau (*pro parte*) basins outcrop area (modified from Herbosch *et al.*, 2002 and Debacker *et al.*, 2005). Location in the Brabant Massif reported in Fig. 5.

sections by the presence of tiny spessartite garnets of varying abundance (spessartite; Laroche photo 15) and Mn-ilmenite and chlorite porphyroblasts (Jodart, 1986; Herbosch *in* André et al., 1991).

In the Dyle Basin, the lower boundary of the Mousty Formation is everywhere marked by a fault (Fig. 10; Asquempont Detachment System, Debacker et al., 2004a) that cuts out an unknown part of the base of the formation. This fault contact could locally be recognized accurately by a magnetic survey, as in Beaurieu in the Orne valley (de Magnée and Raynaud, 1944). In the lower outcropping part of the formation occurs the **Franquenies Member** characterized by decimetric siliceous beds or lenses of chert (phtanite of the older literature) interstratified with typical black shale (old Franquenies quarry photo 16). In thin section, these cherts show numerous transparent objects (100 to 150 microns) formed by cryptocrystalline quartz having the shape and size of radiolarians (photo 17) embedded in a very fine opaque matrix. Radiolarians are known to have existed since the lower Cambrian (Tolmatcheva et al., 2001) and are already well diversified in the Furongian (Pouille, 2012). Their identity cannot yet be confirmed by specialists due to diagenesis and metamorphic overprint (Herbosch et al., 2001 p. 24; Herbosch & Blockmans, Wavre-Chaumont map, 2012). The lithofacies observed in the 161 m cored borehole at Court-St-Etienne begins with a black shale facies (0 to 55 m) but becomes more and more arenaceous and very different from the classical shale facies of Mousty.

The unnamed, monotonous and probably thick middle member of the formation is poorly known due to the lack of marker beds and large outcrops, as numerous but only small and discontinuous pits are present. Some parts are clearly more silty with dark grey pyritic shale gradually passing downwards into grey pyritic siltstone and sandstone (section along the disused railway SW of Court-St-Etienne). The uppermost **Tangissart Member** is characterized by an increasingly recurrent black slate with abundant millimetric pale silty laminae (interpreted as fine-grained turbidite). The top of the highest black slate interval marks the boundary with the overlying Chevlipont Formation. This is the only observable boundary between formations in the lowest two groups of the Brabant Massif.

The lithology and chemistry (particularly the Mn content) of this formation are particularly sensitive to the metamorphism, as shown by the formation of spessartite garnet (Sp 68 Al 26 Gr 6, Jodart, 1986), Mn ilmenite, Mn chlorite, biotite and andalusite (de Magnée and Anciaux, 1945; Herbosch in André et al., 1991). Spessartite with uniform composition has been found as heavy minerals in the sands of the Mesozoic and Cenozoic cover of the Brabant Massif (Van der Sluys, 1991), which indicates the importance of the exposed palaeosurface of the Mousty Formation in the Brabant Massif. Very strong radon anomalies (> 400 Bq/m3) have been observed in the houses of five communes of the upper Dyle Basin (Tondeur et al., 2001). The spatial distribution of these radon anomalies compared to the geological map (Herbosch & Lemonne, 2000; Delcambre et al., 2002) shows that most of the critical cases are associated with the outcrops of the Mousty Formation. This is not astonishing as the black shale are very well known in the geochemical literature for their enrichment in uranium: average shale U = 2-4 ppm; average black shale U = 8 ppm, but the variability is very high up to 189 ppm in the Swedish alum shale (Wedepohl, 1969).

The thickness is again difficult to estimate, but a minimum of 1500 m is tentatively suggested (NCS, 2009). This estimate is corroborated by a graphical section done perpendicular to the strike of the strata (SSE-NNO) between Gembloux (Orneau Basin) and the Noirmon-Baudecet Fault (see Fig. 10; see also section b-b under the map Chastre-Gembloux in Delcambre et al., 2002). In this northern syncline limb the direction and dip are quite constant and the Mousty Formation known in the north by boreholes. The section gives a thickness of 1600 m that confirms our former estimation.

This formation crops out only in the Dyle Basin where it covers quite large area (Fig. 10). It continues under Eocene cover from the outcropping area of La Roche, in the W, to the N of Gembloux, in the E, and also to the NW of Court-St-Etienne towards Lasne (Fig. 10). In these two areas, the Mousty Formation was also observed in several boreholes (Fig. 10) and easy to trace in aeromagnetic surveys due to its low magnetic contrast (Debacker et al., 2005 Fig. 8). The formation is absent from the Grande Gette and Senne basins due to faulting (Asquempont Detachment System; Debacker et al., 2004a). The formation is also penetrated in two boreholes in the Dender Basin (Eine and Vollezele, Vanguestaine, 1992).

The lower and middle members of the formation were dated by acritarchs only in boreholes and never in outcrops (Vanguestaine, 1974, 1992) giving age from the lower and middle part of the upper Cambrian for the Eine (84E1372) and the Vollezele (100E010) boreholes (Vanguestaine et al., 1989b, 1991; Vanguestaine, 1992 p. 8 and Figs. 6, 8). In the Cortil-Noirmont (130W539) borehole, the predominance of the *Prismatomorphitae* (*Timofeevia cristallinium-Ladogella*) over the *Diacromorphitae* (*Acanthodiacrodium-Arbusculidium-Ladogella*) suggests an upper Cambrian age (Vanguestaine *in* Delcambre & Pingot, 2002 p. 17 and pers. comm.). It is important to mention that the Leuven borehole (89E01), dated with acritarchs to the lower part of the middle Cambrian (Vanguestaine, 1974, 1992 Fig. 8, Zone 1), was recently assigned to the Jodoigne Formation because of its turbiditic facies (Herbosch et al., 2008a p. 143). In the new global Cambrian stratigraphy (Babcock & Peng, 2007 chart of correlation Fig. 2; Peng et al., 2012), the upper Cambrian corresponds to the new Series 4 called the Furongian (Peng et al., 2004). In the Tangissart Member the discovery of the trilobite *Rhabdinopora flabelliformis* ssp. *sociale* (between Laroche and Faux, railway trench Km 36) and a few badly conserved acritarchs prove the earliest Tremadocian age of that upper member (Lecompte, 1948, 1949; Martin, 1969a, b, 1976; Vanguestaine et al., 1989a). **The age of the Mousty Formation is Furongian to earliest Tremadocian** (Fig. 2).

No type-section for the formation has been designted, but the type area lies in the Dyle Basin. The Franquenies Member is defined in the old quarry at Franquenies, Céroux-Mousty (x 164,53 y 149,85; photos 16, 17). The disused railway Court-St-Etienne - Genappe (now a bicycle route of the Ravel network) between Km 31 and 32 shows a good section from the middle member. The upper Tangissart Member is defined along the Ottignies-Charleroi railway, S of Laroche, in the section between Km 36,05 and 35,9 (Van Tassel, 1986; Delcambre & Pingot, 2002 pp. 15-17, Figs. 8, 9; NCS, 2012) (between 50°36'46.61" N/4°32'34.32" E and 50°36'51.79" N/4°32'34.32" E).

4.3. Chevlipont Formation

The Chevlipont Formation was named after the old mill of Chevlipont (Thyle valley) by Anthoine and Anthoine (1943): *"quartzophyllade de Chevlipont" Ll 1 de l'Assise de Mousty*». It was used in the same context by Martin (1976); Herbosch *in*: André et al. (1991); Verniers et al. (2001) and NCS (2009).

The most common facies is formed by grey siltstone (called "quartzophyllade" in older literature) with characteristic wavy bedding consisting of millimetric to centimetric alternations of light grey siltstone and dark grey clayey siltstone and mudstone (Chevlipont railway cut photo 19). Silty laminae occur characteristically in small lenses a few centimetres long and a few millimetres thick with oblique laminations forming the base of rhythmic microsequences (T0 of the model of Stow; Stow & Piper, 1984; Piper & Stow, 1991). The dominant facies, interpreted as top-cut sequences of low-density turbidites, can sometimes be replaced by centimetric to decimetric beds with massive, plane-parallel or convolute structures characteristic of Bouma-type turbidites (Herbosch et al., 1991). Small slumps occur abundantly, clearly visible in borehole cores but more difficult to observe in outcrops. The lower boundary with the Mousty Formation is gradual and marked by an upward increase of silt laminae and disappearance of the black shale intervals. The upper limit is nowhere observed in outcrops in the Dyle basin and is faulted in the Senne Basin (Asquempont Detachment System, Fig. 10).

A less abundant facies consisting of decimetric turbidites of the classical Bouma-type is observed in a large slump in the Thyle valley (railway section km 38.1, Beckers, 2004) and in the Marke area (Debacker, 1999, 2001; Longueville, 1997). In the Marke region also interstratified volcanic rocks (metarhyolite) have also been described in outcrops (de la Vallée Poussin & Renard, 1879; Denaeyer & Mortelmans, 1954; Corin, 1965; Hennebert & Delaby, Bever-Enghien map, submitted a) and more recently in boreholes (Longeville, 1997; Debacker, 1999, 2001; Piessens et al., 2002).

This formation is about 150-200 m thick in the Dyle valley and at least 92 m thick in the Lessines borehole (Herbosch et al., 1991; 2008b). It is clearly visible in the Dyle Basin and Marke area. It is absent due to faulting (Asquempont Detachment System) in booth the Grande Gette Basin and the Senne Basin (Herbosch et al., Ittre-Rebecq map, accepted a).

The lower half of the formation contains the dendroid graptolites *Rhabdinopora flabelliformis ssp. socialis* and *typica* (Lecompte, 1948, 1949) and also very well preserved acritarchs (Martin, 1969a, b, 1976; Vanguestaine, 1992) that indicate an early Tremadocian age. In the upper part (Bois de l'Hermitage), Lecompte (1949) described a clearly different subspecies *R. flabelliformis aff. norvegica* which indicate a younger level. If these quite old graptolite determinations are still valid they indicate the global chronozone 2 "Zone of *Rhabdinopora flabelliformis parabola*" of Cooper (1999) that is about 1 Ma after the Cambrian-Ordovician boundary. In the recent graptolite zonation of Britain (Zalasiewicz et al., 2009; Cooper & Sadler, 2012) the *R. flabelliformis* biozone covers the first third (485-482 Ma) of the Tremadocian except for its extreme base. In a synthesis of his acritarchs investigations in the Senne Basin, Vanguestaine (2008 p. 13) place the Chevlipont Formation in the *Acanthodiacrodium angustum* assemblage. *Acanthodiacrodium* spp., *Cymatiogalea* spp., and *Stelliferidium* spp. are commonly found, *Acanthodiacrodium ubuii* is probably also recorded but poorly preserved and *Vulcanisphera flagellum* only observed in the La Tourette section (Sennette valley). For Vanguestaine the assemblage is similar to this observed in Chevlipont Formation from the Thyle river, the Lessines and Wépion boreholes and also in the Solwaster and Spa members of the Jalhay Formation (Stavelot Inlier). An early Tremadocian is most probable, full determination of *A. ubuii* would be interesting as the species is restricted to the lower part of the Tremadoc (Rasul & Downie, 1974). In conclusion **the age of the Chevlipont Formation is clearly lower Tremadocian** but the top of the Mousty Formation was deposited at the extreme base of the stage.

No type section has been assigned. A very large section is present in the Thyle valley, along the railway section between Tangissart and Chevlipont, from Km 37.3 (50°36'17.61" N/ 4°32'13.22" E; photo 19) to km 38.2 (50°35'44.28" N/4°32'00.25" E). The upper part of the formation is visible along the path to the Bois de l'Hermitage, 50 to 100 m east of the railway (50°35'45.29" N/4°32'09.93" E to 50°35'44.37" N/4°32'04.87" E). At Marke (Enghien) a disused quarry (50°41'55.67" N/4°00'53.58" E) shows the Bouma turbidite facies.

4.4. Hiatus that ends the Ottignies Group

The contact between the Chevlipont Formation and the overlying Abbaye de Villers Formation is nowhere visible in the outcropping area of the southern Brabant Massif. But biostratigraphic work has proved a large hiatus between these two formations (Samuelsson and Verniers, 2000; Verniers et al., 2002). Recent micropalaeontological investigations (Vanguestaine & Wauthoz, 2011) show that this stratigraphic hiatus is more important than previously thought: it extends from the lower Tremadocian (see §4.3) to the latest Dapingian or early Darriwilian age (c. 482-467 Ma; Fig. 2). This observation has also been made in the Wépion borehole (Condroz Inlier, see §6), where a thin conglomerate overlies the top of the hiatus (Graulich, 1961) that extends from the lower Tremadocian to the middle Darriwilian (Servais & Maletz, 1992; Vanmeirhaeghe, 2006). In consequence, there is no longer any doubt that there is **an unconformity at the top of the Ottignies Group**.

5. Subsidence history

New estimates of the sedimentary thicknesses, especially for the Halle and the Ottignies groups (Herbosch et al., 2008, in press a, b; NCS 2009, 2011) allow us to construct a new cumulative thickness curve (see Fig. 11). Such a curve has already been constructed by

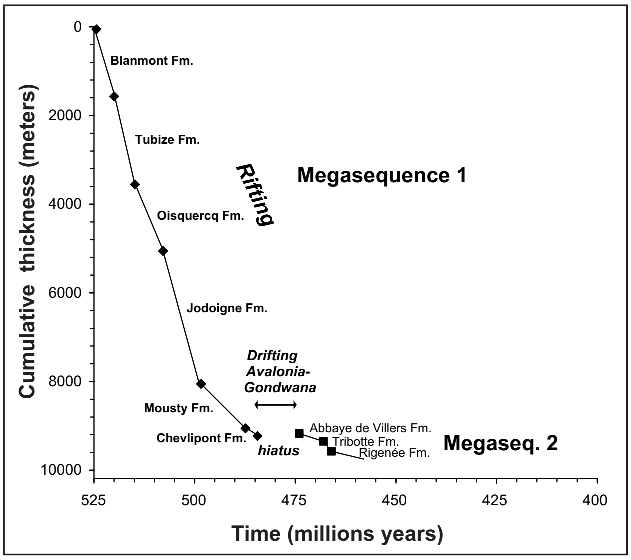

Figure 11: Cumulative sediment (by formation) thickness curve for the Halle and Ottignies groups plotted against the stratigraphic age (time scale Gradstein *et al.,* 2012). Reported thicknesses are estimated minimum thicknesses (Herbosch *et al*., 2008a; NCS, 2009).

Debacker (2001) based on the thicknesses of Verniers et al. (2001) and repeatedly used (Verniers et al., 2002; Debacker et al., 2005; Sintubin et al., 2009) as evidence for an extensional basin for Megasequence 1. Effectively, Megasequence 1 shows a concave-up curve with a very high sedimentation rate, especially from the Blanmont to Jodoigne formations (about 8 km deposited in 27 m.y.). This high rate of sedimentation and the sedimentological observations seem only compatible with a rift environment. The thicknesses of the Mousty and Chevlipont formations show a decreasing sedimentation rate, announcing the rifting of Avalonia from Gondwana (Cocks & Torsvik, 2002, 2005) marked by the lower Tremadocian to mid-Ordovician hiatus and unconformity.

6. Comparison with the Condroz Inlier

The Condroz Inlier (Bande du Condroz or Bande de Sambre-et-Meuse of authors) corresponds to a set of thrust sheets lying between the Brabant Parautochthon to the N and the Ardenne Allochthon to the S (Michot, 1980; Vanmeirhaeghe, 2006; Owens & Servais, 2007; Belanger et al., 2012). The tectonic origin of these trust sheets is controversial but the Lower Palaeozoic part of them belongs to the Brabant Basin (Verniers et al. 2002). In this inlier, the Halle and Ottignies groups are not observed in outcrop, but the upper part of the Ottignies Group was discovered in the Wépion borehole (Graulich, 1961). This borehole shows >140 m of the Chevlipont Formation with its characteristically wavy bedded facies (silt turbidites), numerous small slumps and its lower Tremadocian graptolites (*Rhabdinopora sp*., Graulich, 1961). The same borehole shows a 5 centimetres thick conglomerate at the base of the overlying Huy Formation (Graulich, 1961). This conglomerate is formed by 1 to 3 centimeters clasts of mudstone and sandstone. Vanguestaine (1992 p.10) pointed out numerous altered and reworked Tremadocian acritarchs in the beds that overlie the microconglomerate, an observation that underlines the erosive conditions of these basal deposits.

7. Conclusions

The Halle and Ottignies groups constitute a very thick (>9 km) upper Terreneuvian (lower Cambrian) to lower Tremadocian (lowest Ordovician) succession (525-482 Ma). The sediments are clastic, mostly pelagic and turbiditic, and were probably deposited in an embayement of a large rift developped on the western Gondwana margin just after the Pan-African orogeny (Linnemann et al., 2012). This rift seems to have evolved early in the Cambrian towards a proto-Rheic Ocean (Nance and Linnemann, 2008 Fig. 23; Nance et al., 2012; Van Staal et al., 2012) and led during the Tremadocian to the rifting of Avalonia away from Gondwana (Cocks & Torsvik, 2002, 2005; Linnemann et al., 2011).

These two groups are subdivided into 6 formations and several members that can be traced without important lateral variations across all the southern outcrop area of the Brabant Massif. They show a continuous sedimentological evolution forming Megasequence 1 defined by Vanguestaine (1992). In the Brabant Massif, Megasequence 1 ends with an important sedimentary hiatus that extends from the lower Tremadocian to the latest Dapingian or Early Darriwilian (14-15 Ma). In the Condroz Inlier, at the southern parautochthonous boundary of the Brabant Massif, only the Chevlipont Formation is observed in the Wépion borehole, which here is also is limited by an unconformity ending the Megasequence 1. The unconformity corresponds to the rifting of Avalonia from Gondwana (Cocks & Torsvik, 2002, 2005; Linnemann et al., 2012).

Megasequence 1 begins with the Blanmont Formation which was deposited in a shallow but rapidly subsiding rift environment. Its observed base is most probably not far from the basement of the Brabant sedimentary succession, a Pan-African basement belonging to the Midland Microcraton and/or the Lüneburg-North-Sea Microcraton (Pharaoh et al., 1987; André, 1983; Pharaoh, 1999; Sintubin et al., 2009). The ages and potential sources of the detrital zircons of the Ottignies Group provide decisive arguments to support this hypothesis (Linnemann et al., 2012).

Megasequence 1 is also seen in the Stavelot and Rocroi inliers (Ardennes) where it shows precisely the same sedimentary evolution and depositional environment from the Terreneuvian to the lower Tremadocian. However, the sedimentary succession contrast to the Brabant Massif as it continues at least up to the top of the Tremadocian and/or the lower Floian (Vanguestaine & Servais, 2002; Breuer & Vanguestaine, 2004; Vanguestaine et al., 2004). The stratigraphy in the Rocroi Massif is too discontinuous and insufficiently known (Beugnies, 1963; Meilliez & Vanguestaine, 1983; Vanguestaine, 1992; Ribecai & Vanguestaine, 1993) to extend that observation to all the Ardennes Inliers. Currently it could be that the Tremadocian/Dapingian unconformity is absent in the Ardennes Inliers.

At the scale of the whole Avalonia microplate, Megasequence 1 corresponds to the Dyfed Supergroup observed in the Welsh Basin particularly in the Harlech Dome (Woodcock, 1990, 1991) and to the Goldenville and Halifax groups of the Meguma terrane from Nova Scotia (Waldron et al., 2011; Linnemann et al., 2012). These three regions present the same very thick sedimentary succession, show great stratigraphical, sedimentological and isotopic similitudes that suggest a same basinal deep clastic sea environment of deposition (Linnemann et al., 2012, Fig. 23).

Work in progress involves a Part II concerning the Rebecq Group that ranges from the Ordovician to the lowermost Silurian formations, and later a Part III devoted to the Silurian formations after their revision.

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Plate 1:

Photo 1: The Blanmont Formation in the Dongelberg quarry (n° 12 in Fig. 5 and Table 1): massive, clear grey quartzite; stratification (S0) is subvertical and the bedding is not very well visible.

Photo 2: The Blanmont Formation in the Opprebais quarry (n° 13 in Fig. 5 and Table 1): well stratified quartzite and sandstone alternating with darker slate.

Photo 3: The Blanmont Formation in the Dongelberg quarry (n° 12 in Fig. 5 and Table 1): pseudo-nodules and/or water escape structures in the quartzite. Stratification (S0) is subvertical.

Photo 4: The Blanmont Formation at Bonlez in the Glabais brook (n° 10 in Fig. 5 and Table 1). The quartzite beds outcropping perpendicular (S0) to the direction of the brook cause the appearance of small falls in the river bed. Up- and downstream only Cenozoic outcrops are present, showing the completely isolated position of this outcrop in the brook, far from the other Blanmont Formation outcrops (see Fig. 5).

Photo 5: The Blanmont Formation at the Fôdia (Offus) flooded quarry (n° 14 in Fig. 5 and Table 1). Only some quartzite beds are visible. Like the outcrop in the Glabais brook this outcrop is completely surrounded by the Cenozoic cover and far from other Blanmont outcrops (see Fig. 5). It is the easternmost outcrop of the Blanmont Formation.

Photo 6: The Mont-St-Guibert Member of the Tubize Formation under the church at the centre of Mont-St-Guibert; sandstone, siltstone and slate form Bouma turbiditic sequences. In the centre of the photo a thick complete Tabce sequence can be observed. Both the stratification and the cleavage are subvertical.

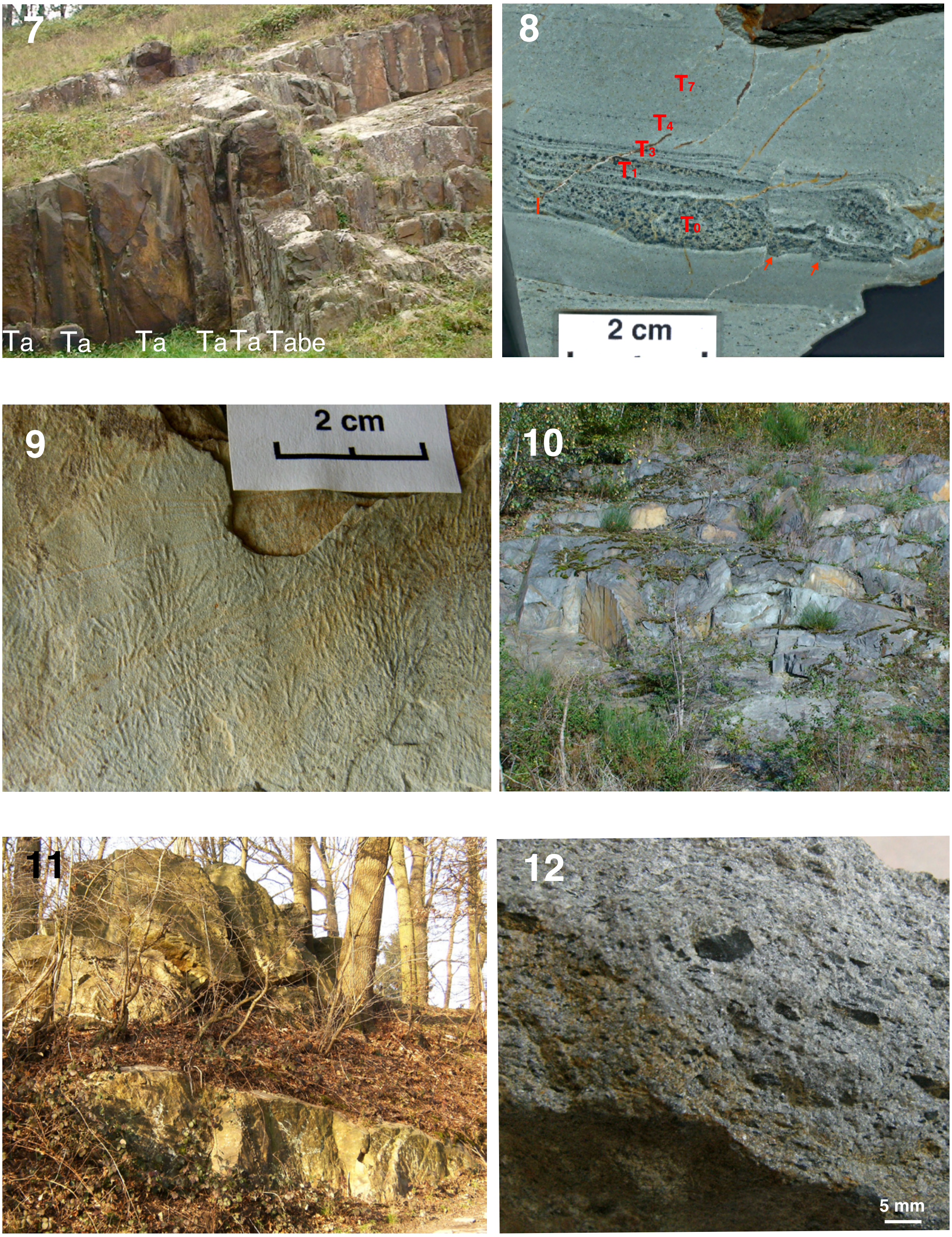

Plate 2:

Photo 7: The Rogissart Member of the Tubize Formation at Clabecq, Hameau du 45 (Hain valley, Fig. 5); sandstone, siltstone and slate form Bouma turbiditic sequences. To the left thick amalgamated sequences (TaTaTa) are present and to the upper right more distal sequences (TabeTaeTabe).
Photo 8: The Les Forges Member of the Tubize Formation near Clabecq (Sennette valley). Macrophoto of a sawn and polished sample, that shows a characteristic sequence of low-density turbidite (Stow model). The general green colour and the neoformation of flakes of chlorite in the silty laminae are due to metamorphism of the greenschist facies. A wavy silty layer (T0) with faint oblique laminations (l) and load structures (red arrows) forms the base of the sequence. A set of thinner and thinner silty layers separated by mudstone can be observed in the lower part of the sequence (T1, T3, T4). The upper part of the sequence is formed by a thick lamina of massive mudstone (T7).
Photo 9: The trace fossil *Oldhamia radiata* at the surface of a siltstone from the Mont-St-Guibert Member of the Tubize Formation in a temporary excavation in Beaurieu (collected by A. Herbosch in 2009).
Photo 10: The Ripain Member of the Oisquercq Formation from the trench along the canal in Asquempont; purple massive slate with clearly developed cleavage and without visible stratification.
Photo 11: The Maka Unit of the Jodoigne Formation near the old mill of Maka, Jauchelette. Huge blocks of quartzite are present along the E side of the Grande Gette valley.
Photo 12: The Orbais Unit of the Jodoigne Formation in Orbais (Grande Gette valley). Macrophoto of a lithic sandstone: the plurimillimetric fragments of shale are black.

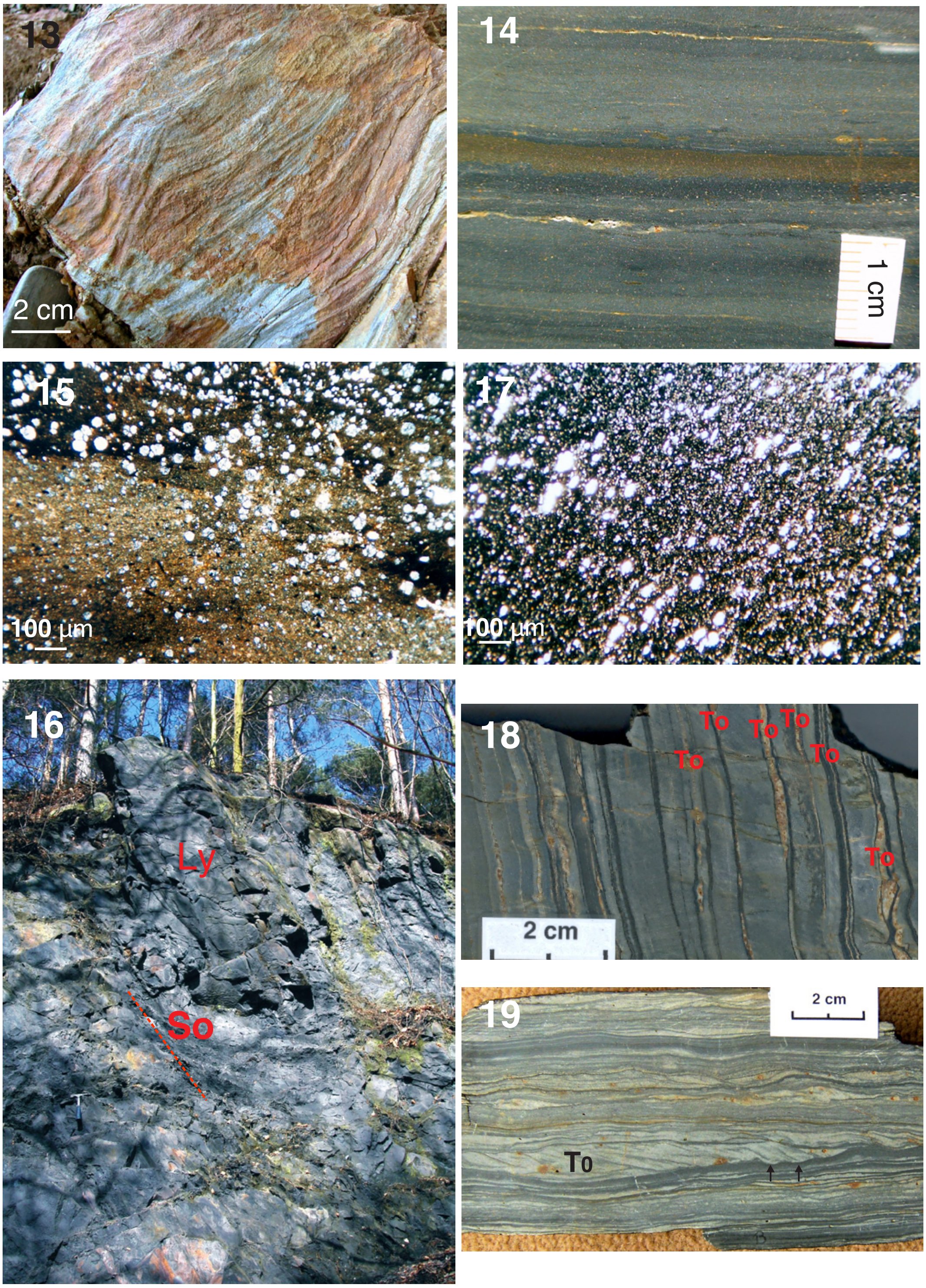

Plate 3:

Photo 13: Temporary outcrop in the centre of Jodoigne with the Jodoigne Unit of the Jodoigne Formation. Macrophoto of a convolute structure (Tc) from a Bouma turbidite sequence (see log in Fig. 9).
Photo 14: The Franquenies Member of the Mousty Formation at the Franquenies quarry, Mousty. Macrophoto of the typical facies of black shale in a sawn and dressed but weathered sample.
Photo 15: The middle unnamed member of the Mousty Formation at the vallon Ste Gertrude in Laroche. Thin section in a dark slate (normal light): the light coloured porphyroblasts are transparent spessartite garnets and the smaller opaque needles are Mn-ilmenite.
Photo 16: The Franquenies Member of the Mousty Formation at the Franquenies quarry, Mousty. The black slates are rich in graphite and pyrite and some beds contain garnets; the stratification (S0) is subvertical and the cleavage parallel to the wall. The upper central part of the wall (Ly) shows a lydite level (phtanite of authors).
Photo 17: The Franquenies Member of the Mousty Formation in “Bois des Rêves”, Mousty. Thin section (normal light) in a lydite sample (phtanite of earlier authors), the black matrix is formed by graphite and the white elongated holes filled with microquartz underlining the stratification, are interpreted as phantoms of radiolarians.
Photo 18: The unnamed middle member of the Mousty Formation in Ways (Dyle valley). Macrophoto of a sawn and polished sample, showing wavy laminated black shale, interpreted as mud turbidites (Stow model). Pyrite weathered to iron oxide with orange colours occur in several of the basal silt laminae (To). Note the centimetric scale of the turbidite sequences.
Photo 19: The Chevlipont Formation in the railway trench at Chevlipont. Macrophoto of a sawn and polished sample, showing an alternation of wavy bedded siltstone and mudstone laminae interpreted as silt turbidites. Near the centre a very characteristic wavy basal sequence lamina (T0) shows load structure (arrows) and internal oblique laminations. By comparison with the sequence-model of Stow the observed sequences are top-cut (mudstone < siltstone). Note the centimetric scale of the turbidite sequences that are frequently amalgamated.