GEOLOGICA BELGICA (2008) 11/3-4: 133-150

THE STRATIGRAPHIC POSITION OF THE CAMBRIAN JODOIGNE FORMATION REDEFINED (BRABANT MASSIF, BELGIUM)

Alain HERBOSCH[1], Timothy N. DEBACKER[2] & Kris PIESSENS[3]

(11 figures)

1. Département des Sciences de la Terre et de l'Environnement, Université Libre de Bruxelles, Avenue F. Roosevelt 50 CP 160/02, B-1050 Brussel, E-mail : herbosch@ulb.ac.be
2. Research Unit Palaeontology, Geology & Pedology, Universiteit Gent, Krijgslaan 281, S8, B-9000 Gent, E-mail : Timothy.Debacker@UGent.be
3. Geological Survey of Belgium, Jennerstraat 13, B-1000 Brussel, E-mail: Kris.Piessens@naturalsciences.be

Abstract. Until now, the stratigraphic position of the Cambrian Jodoigne Formation was very poorly constrained. On the basis of detailed mapping, lithological and sedimentological observations, structural field work and magnetic studies in the type area of the Jodoigne Formation, combined with an evaluation of existing biostratigraphic data, a much better constrained stratigraphic position is proposed.
In the Cambrian stratigraphy presented herein, the Jodoigne Formation is moved from below the basal Cambrian Blanmont Formation up to a position in between the Lower Cambrian to lower Middle Cambrian Oisquercq Formation and the Upper Cambrian Mousty Formation. Hence, a Middle to Upper Cambrian age is suggested. A time-equivalence between the upper parts of the Jodoigne Formation and the lower parts of the Mousty Formation cannot be excluded.
In the type area of the Jodoigne Formation, the proximity with the Blanmont Formation can be explained by means of the Asquempont Detachment System, this being fully compatible with the nature and orientation of this detachment system. In turn, the new stratigraphic position of the Jodoigne Formation results in a better understanding of the orientation and extent of the Asquempont Detachment System, and fully supports the continuation of this detachment system along the N-side of the Brabant Massif.

Keywords: Anglo-Brabant Deformation Belt, Asquempont Detachment System, Blanmont Formation, Mousty Formation

1. Introduction

Currently, the Cambrian Jodoigne Formation is considered to be the oldest formation of the Brabant Massif (Fig. 1; Verniers *et al.*, 2001). However, the stratigraphic position of this formation, of which the outcrops are restricted to the Jodoigne area in the Grande Gette river valley (Fig. 2), has always been debated. The outcrop area never yielded any biostratigraphic ages, and the stratigraphic position of the formation is based entirely on its relative position with respect to the other lithostratigraphic units within the Brabant Massif. Going from the south towards the more internal parts of the Cambrian core, the following formations are encountered: 1) the Upper Cambrian Mousty Formation, 2) the Lower Cambrian to basal Middle Cambrian Oisquercq Formation, 3) the Lower Cambrian Tubize Formation, 4) the probably lowermost Cambrian Blanmont Formation and 5) the Jodoigne Formation. Because of this seemingly more central position, many authors placed the Jodoigne Formation below the Blanmont Formation (e.g. Verniers *et al.*, 2001 and references therein). Other authors, however, considered this formation as Upper or Middle Cambrian (e.g. Legrand, 1968; De Vos *et al.*, 1993; Vanguestaine, 1992; and references in Verniers *et al.*, 2001).

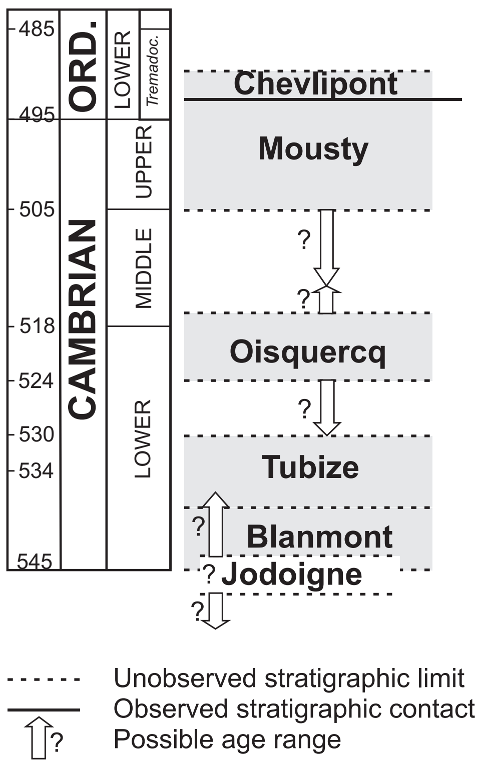

Figure 1: Most recently published stratigraphy of the Cambrian and lowermost Ordovician of the Brabant Massif, taken from Verniers et al. (2001).

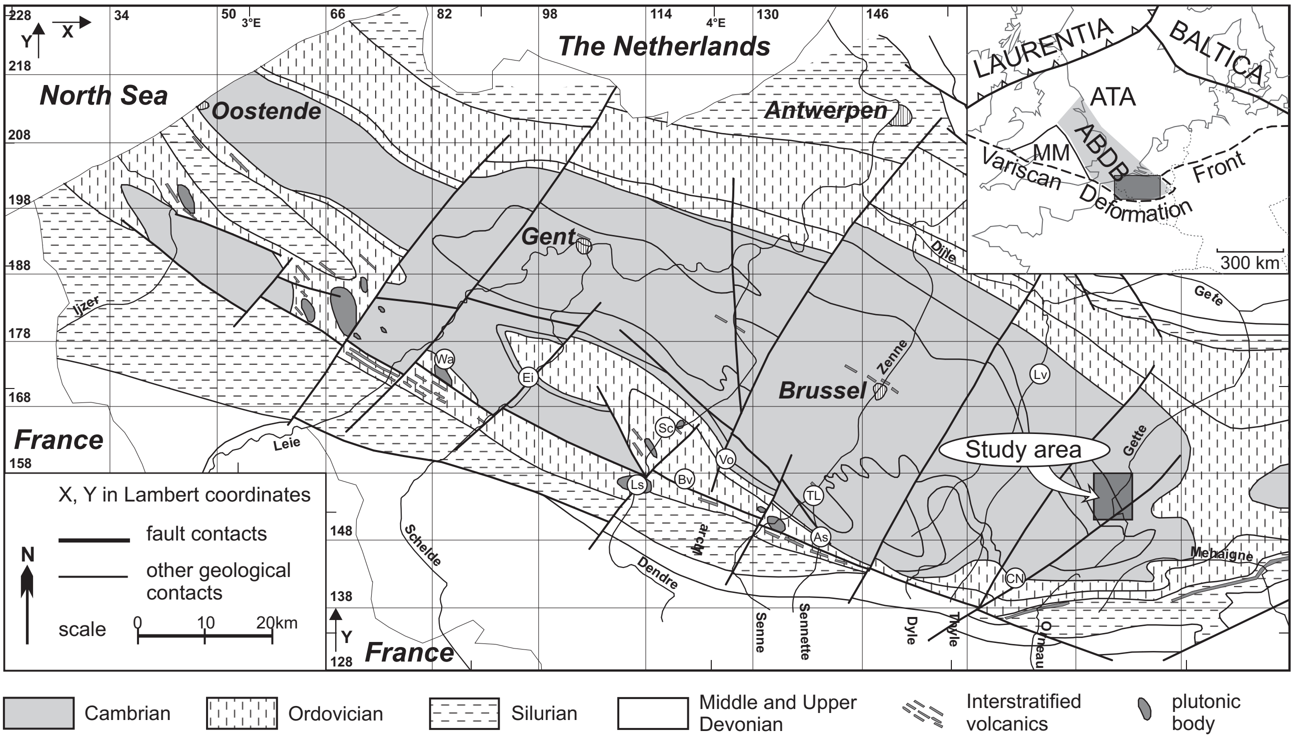

Figure 2: Geological subcrop map of the Brabant Massif (after De Vos et al., 1993 and Van Grootel et al., 1997) showing the position of the studied Gette outcrop area (see also Figs. 3 & 5). The upper right inset shows the position of the Brabant Massif within the Anglo-Brabant Deformation Belt (ABDB) along the NE-side of the Midlands Microcraton (MM) in the context of Avalonia (ATA), Baltica and Laurentia. Localities referred to in the text are indicated: Waregem (Wa), Eine (Ei), Lessines (Ls), Schendelbeke (Sc), Bever (Bv), Vollezele (Vo), Asquempont (As), Tubize and Lembeek (TL), Cortil-Noirmont (CN), Leuven (Lv).

In the framework of the construction of the new geological map of the Jodoigne-Jauche sheet (40/3-4; Herbosch *et al.*, submitted), the outcrop area of the Jodoigne Formation was mapped in detail. This resulted in the recognition of four different lithostratigraphic units in the Jodoigne Formation, and gave valuable information on the structural geometry and younging sense of the beds. In combination with data from other sources, these mapping results allow us to reject the idea of the Jodoigne Formation being the oldest formation of the Brabant Massif. In addition, an adequate explanation is provided for the proximity of the Jodoigne Formation to the Blanmont Formation in the Gette outcrop area.

2. Facts about the Cambrian stratigraphy of the Brabant Massif

Up to present, five Cambrian formations have been recognised within the Brabant Massif, many of which are subdivided into different members (Verniers *et al.*, 2001). However, only two stratigraphic contacts have truly been observed (Fig. 1). These are the upper, transitional limit between the Upper Cambrian Mousty Formation and the lower Tremadocian Chevlipont Formation and the limit between the Ripain Member and the overlying Asquempont Member of the Lower to lower Middle Cambrian Oisquercq Formation (Hennebert & Eggermont, 2002; Debacker *et al.*, 2004a; Herbosch *et al.*, in press). All other contacts have never been observed (Fig. 1).

The stratigraphic position of the Mousty Formation is well constrained. Its upper part (Tangissart Member) was dated by means of dendroid graptolites (*Rhabdinopora sp.*; Lecompte, 1948, 1949) and acritarchs (Martin, 1968, 1976; Vanguestaine *et al.*, 1989; Vanguestaine, 1992) and shows a gradational contact with the overlying, well-dated lower Tremadocian Chevlipont Formation (e.g. Lecompte, 1948, 1949; Martin, 1968, 1976). The older parts of the Mousty Formation were dated by means of acritarchs as belonging to the lower, middle and upper parts of the Upper Cambrian (Vanguestaine, 1992; see chap. 7 for more details).

Of the Oisquercq Formation, only the upper member, the Asquempont Member, has been dated (acritarchs in Lessines and other boreholes; Vanguestaine, 1991, 1992). Although no body fossils or trace fossils have been found in the Ripain Member of the Oisquercq Formation, the exposed stratigraphic contact between the Asquempont Member and the Ripain Member in the Sennette outcrop area, in combination with the overall bedding geometry and cleavage/bedding relationships, clearly indicates that the stratigraphic position of the Ripain Member is below that of the Asquempont Member (Hennebert & Eggermont, 2002; Debacker *et al.*, 2004a; Herbosch *et al.*, in press).

The age of the Tubize Formation is constrained only by the presence of the trace fossil *Oldhamia* (Malaise, 1883; Asselberghs, 1918), suggesting a Lower Cambrian stratigraphic position (Tommotian, Nemakitian-Daldynian; Seilacher, pers. comm. 1998 in Verniers *et al.*,

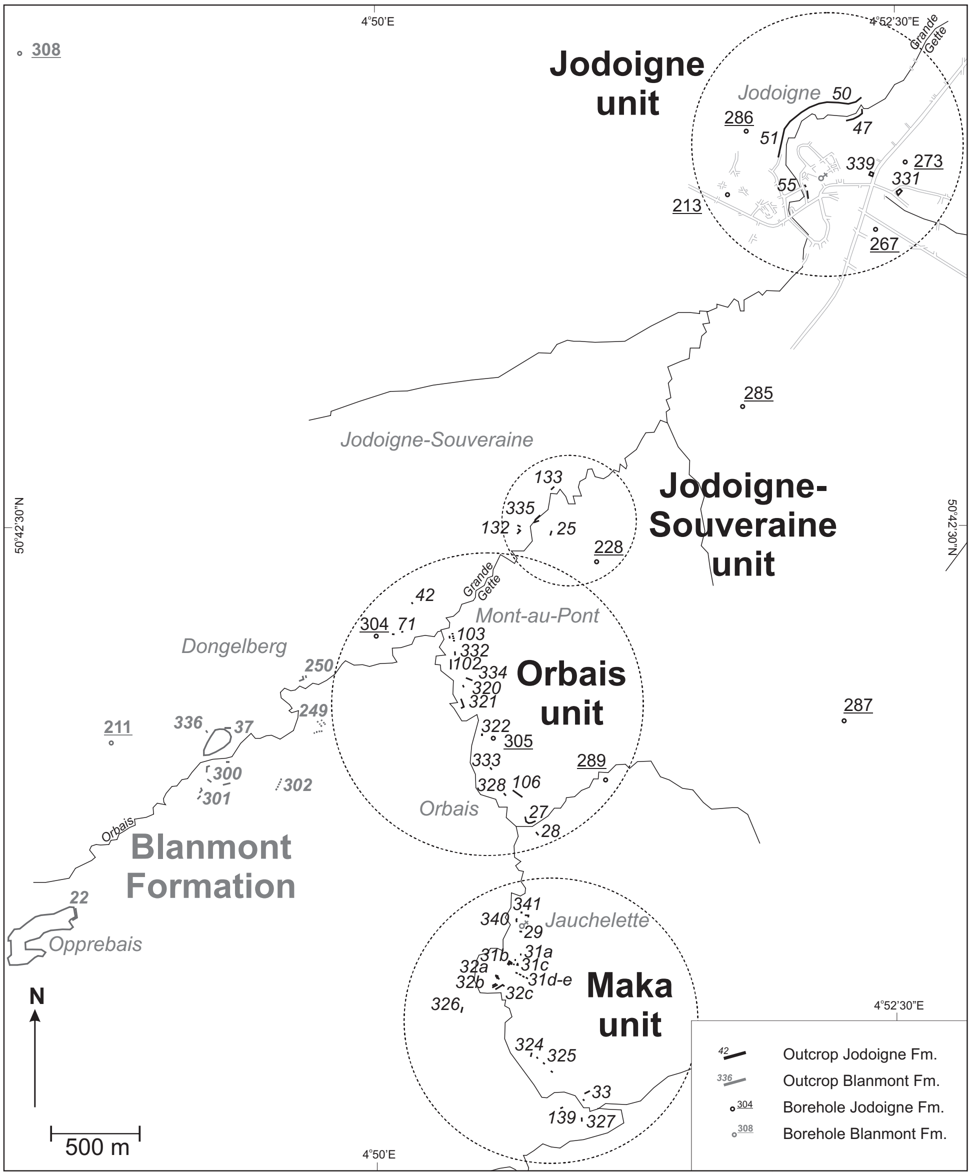

Figure 3 : Simplified topographic map of the Gette outcrop area, showing the outcrop distribution of the Blanmont Formation and of the four units of the Jodoigne Formation (after Herbosch et al., submitted). See Fig. 2 for position within the Brabant Massif. The outcrop numbers are those of the archives of the Belgian Geological Survey and refer to observation points on the geological map 118W.

2001). Rare body fossils have been found, but these are too poorly preserved to be useful for stratigraphic purposes (unknown body fossil found by de Heinzelin in canal section in Tubize area (unpub. data); undeterminable small shelly fossils found by Debacker (unpub. data 2000) and Debacker & Van Roy (unpub. data 2002) at Tubize, Senne-Sennette outcrop area). The older age of the Tubize Formation with respect to the Oisquercq Formation seems corroborated by the overall bedding geometry, the stratigraphic (sedimentological criteria) and structural (cleavage/bedding relationships) younging sense and the relative occurrence of both formations in the Senne-Sennette outcrop area (see Debacker, 2001; Debacker *et al.*, 2004a; Herbosch *et al.*, in press). Also the lithological similarities between the upper member of the Tubize Formation and the lower member of the Oisquercq Formation are compatible with the relative stratigraphic position of both formations (Herbosch *et al.*, in press).

Also the age of the Blanmont Formation is constrained by the presence of the trace fossil *Oldhamia* (Malaise, 1883; Malaise, 1900 p. 190), suggestive of a Lower Cambrian position (Tommotian, Nemakitian-Daldynian; Seilacher, pers. comm. 1998 in Verniers *et al.*, 2001). In addition, detrital zircons suggest a post-545 Ma age for the Blanmont Formation (Von Hoegen *et al.*, 1990). The stratigraphic position of the Blanmont Formation below the Tubize Formation is suggested by the stratigraphical and structural younging sense, the overall bedding geometry and the relative occurrence of both formations in the Senne-Sennette outcrop area (Piessens *et al.*, 2004) and the Dyle-Thyle outcrop area (Herbosch & Lemonne, 2000; Delcambre *et al.*, 2002; Debacker *et al.*, 2005a).

Thus far, the Jodoigne Formation in the Jodoigne area has not yielded any age constraints. The only arguments for placing the Jodoigne Formation below the Blanmont Formation, and hence making it the oldest formation of the Brabant Massif, are the close proximity to the Blanmont Formation in the Gette outcrop area and the apparently more central position within the Brabant Massif. As outlined above, going towards the NE across the Cambrian (and other) outcrop areas, generally progressively older formations are encountered. As the outcrops of the Jodoigne Formation in the Gette outcrop area are situated to the NE of those of the Blanmont Formation, the Jodoigne Formation might seem older (Fig. 2, cf. Fig. 3). However, without information on the overall bedding geometry and younging sense, such reasoning is quite dangerous.

3. Opinions on the stratigraphic position of the Jodoigne Formation

Basically, two main opinions exist. One group of researchers considers the Jodoigne Formation as being older than the Blanmont Formation, whereas a second group of researchers suggests a Middle to Upper Cambrian stratigraphic position for the Jodoigne Formation.

The first opinion is favoured by Dumont (1848), Malaise (1900; cf. Malaise, 1883), Kaisin (1919), de la Vallée Poussin (1931), Raynaud (1952), Mortelmans (1955, 1977), Lecompte (1957), and Verniers *et al.* (2001). The main argument for this hypothesis is the relative outcrop position within the Brabant Massif with respect to the other Cambrian formations. However, as pointed out by Michot (1980), the outcrops of the Jodoigne Formation are situated "on the northern limb of the Brabant Anticlinorium" (on the map of Legrand, 1968) and therefore should be younger than the Blanmont Formation (Fig. 2). The second opinion, in which the Jodoigne Formation is considered as Middle to Upper Cambrian, is favoured by Malaise (1911), Fourmarier (1921), Legrand (1968), Michot (1980), Vanguestaine (1992) and De Vos *et al.* (1993). However, as pointed out by Raynaud (1952), if this were the case, then the magnetite-bearing Tubize Formation should be present between the Blanmont Formation and the Jodoigne Formation in the Gette outcrop area. A magnetic field survey of Raynaud (1952) did not show magnetic anomalies between both formations, leading him to favour the first opinion.

As becomes clear, although the most recent stratigraphic table of the Brabant Massif (Fig. 1; Verniers *et al.*, 2001) favours the first hypothesis, neither of both hypotheses is convincing, and, depending on the arguments used, both can be criticised.

4. Lithology and sedimentology of the Jodoigne Formation

Although the existence of "*les roches noires de Jodoigne*" has been known since the time of Dumont (1848; Malaise, 1873, 1883, 1911; Fourmarier, 1921), the deposits of the Jodoigne Formation have never been properly described. The term "*Assise de Jodoigne*" was introduced by de la Vallée Poussin (1931 p. 320), who described these rocks as "*quartzite noir, phyllade noir, pyriteux, ressemblant étonnamment au Revinien de l'Ardenne comme André Dumont l'avait déjà noté*" ("pyrite-bearing black quartzite and black slate, that, as was already remarked by André Dumont, closely resemble the Revinian of the Ardennes"). Despite this poor description, these deposits have not been studied anymore after 1931, and the rare occasions where these rocks are mentioned generally only refer to black shales and sandstones.

Recent, detailed mapping in the Jodoigne area shows that, despite the poor degree of exposure, four different lithostratigraphic units can be distinguished within the Jodoigne Formation (see also Herbosch *et al.*, submitted). These are, from south to north: the Maka unit, the Orbais unit, the Jodoigne-Souveraine unit and the Jodoigne unit (Figs 3 and 4).

4.1. The Maka unit

The Maka unit consists of an alternation of massive pale-grey to grey quartzite and pyritic black slate, the latter with intercalated pale-grey centimetric sandstone beds. The quartzitic zones, in which bedding is usually difficult to observe, have a thickness of several tens of metres, and are well exposed (they control the topography and even have outcrops on hill tops), whereas the intercalated black slate and sandstone are rarely observed in outcrop (e.g. outcrops 32c and 341 on Fig. 3). Probably because of the presence of the massive quartzites, numerous outcrops of the Maka unit exist. These outcrops occur between the old mill (outcrops 32a to 32c) and the camping of La Ramée in the south (outcrop 327) and the church of Jauchelette in the north (outcrop 29) on both sides of the Grande Gette (Fig. 3). The best outcrops are found along both sides of the Rue du Maka at Jauchelette (outcrops 31a to 31e, and 32a and 32b).

4.2. The Orbais unit

The Orbais unit consists of well-stratified, decimetric beds of grey to blue-grey quartzitic sandstone to quartzite. Like in the Maka unit, in between these quartzites an alternation occurs of pyritic black slate and thin pale-grey sandstone (e.g. outcrops 28 and 103 on Fig. 3). The quartzitic zones are never more than ~10 metres thick. Frequently the quartzites show a clear bedding-parallel lamination, and occasionally oblique lamination (e.g. outcrop 321). One of the most characteristic features is the common occurrence of quartzite/quartzitic sandstone containing black shale fragments (e.g. outcrops 106 and 321). The amount of shale fragments is very variable, ranging from <1 to ~30%. The Orbais unit occurs from Orbais in the south up to Mont-au-Pont in the north and is only found along the E-side of the Grande Gette river. The deposits of this unit are best observed in a 50m-long outcrop at Orbais, directly south of the road Perwez-Jodoigne, along the N-side of an unnamed SW-running brook (outcrop 27).

4.3. The Jodoigne-Souveraine unit

The Jodoigne-Souveraine unit contains black massive quartzite to sandstone, in which bedding is difficult to observe. Exposures of this unit are very scarce. The Jodoigne-Souveraine unit occurs between the old railway station of Jodoigne-Souveraine (now private property;

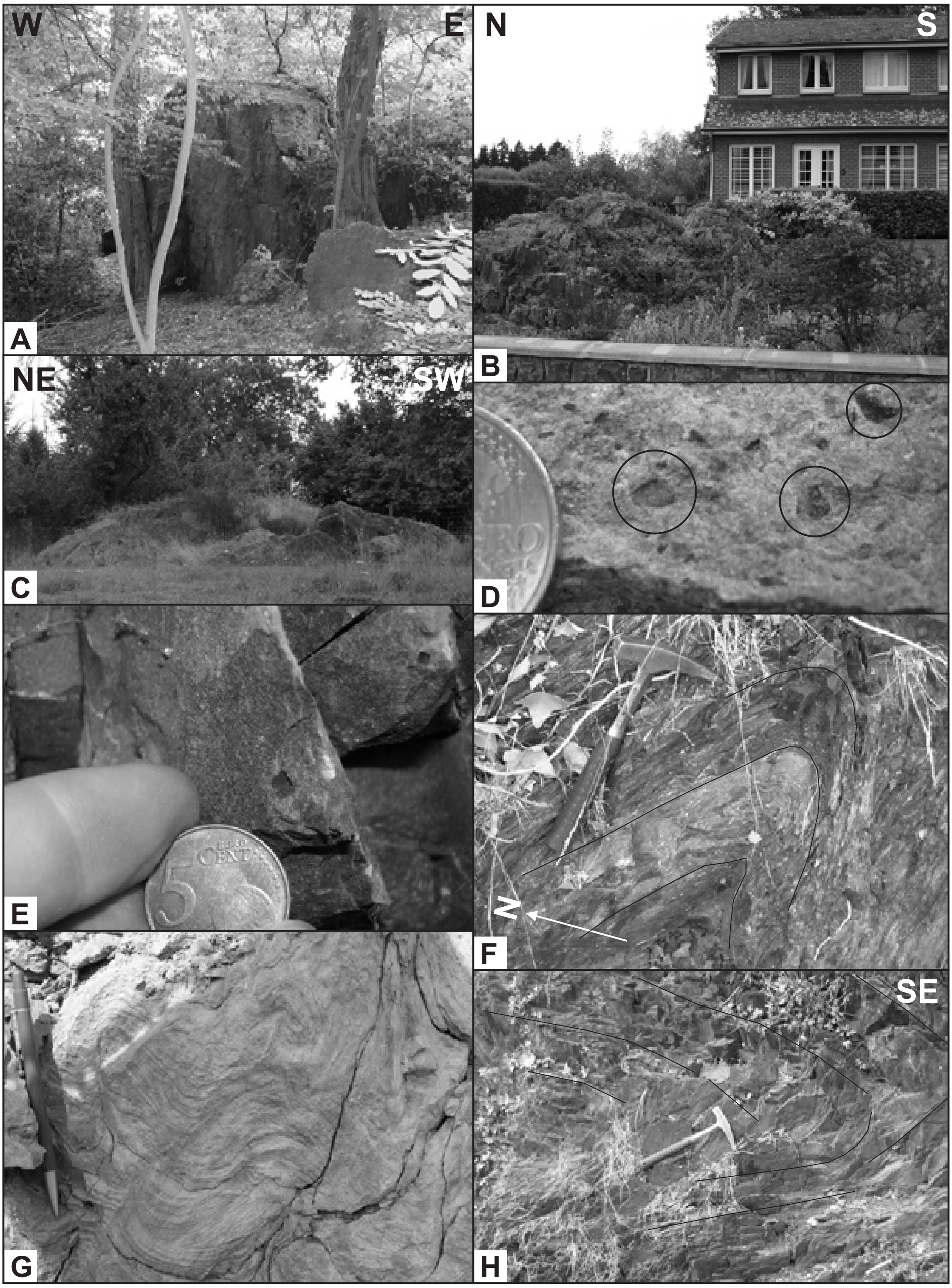

Figure 4: Photographs showing typical lithologies and outcrop appearance of the four units distinguished in the Jodoigne Formation in the Gette outcrop area. a) Large exposure of quartzite of the Maka unit, SW-side of Rue du Maka; the wall is ~3.5 m high. b) Outcrop of quartzite of the Maka unit in a garden at the E-side of Rue du Maka; note the high topographic position of the outcrop. c) Outcrop of quartzite of the Maka unit in a meadow at the E-side of Rue du Maka; note the high topographic position of the outcrop. d) Typical facies of the Orbais unit, consisting of pale quartzitic sandstone with shale clasts; largest shale clasts are encircled. e) Typical black quartzitic sandstone of the Jodoigne-Souveraine unit. f) Typical facies of the Jodoigne unit below the town hall of Jodoigne, consisting of an alternation of black shale and parallel-bedded and cross-bedded siltstone and sandstone, interpreted as being of turbiditic origin (Herbosch et al., submitted). Note the asymmetric, steeply plunging fold style (type B fold; bedding is marked in black). g) Coarse-grained facies of the Jodoigne unit, consisting of an alternation of thick, pale-coloured, often convoluted sandstone, and thin, interbedded black shale. Photograph taken in large temporary excavation (disappeared) in the Rue du Pietrain. h) Fine-grained facies of the Jodoigne unit below the town hall of Jodoigne, similar to facies shown in f, but with much less sandstone beds. Note the gently E-plunging fold, with curved hinge line, interpreted as having a slump-origin (bedding is marked in black; cf. Debacker et al., 2006).

outcrop 132 on Fig. 3) and the surroundings of the Chapel of "*Notre-Dame du Perpétuel Secours*", and probably up to a farm 300 m further north (based on old descriptions during construction of the railway line). The deposits are best observed along the Grande Gette river in the old railway floor, downstream of the bridge close to the Chapel of "*Notre-Dame du Perpétuel Secours*" (outcrop 335) and to the east in the castle park (outcrop 25).

4.4. The Jodoigne unit

The Jodoigne unit contains metre- to decametre-thick zones of black slate, often with intercalated millimetric to centimetric siltstone beds, alternating with zones consisting of rhythmic, mostly decimetric sequences of sandstone, siltstone and black slate. The slates and thin siltstone beds are black and pyrite-bearing. The sandstone may be pale-grey, grey or black. The pale-grey sandstone variety was best observed in two large temporary excavations in the eastern part of the town of Jodoigne (outcrops 339 and 331 on Fig. 3). Sedimentological observations in these two outcrops by Herbosch indicate that these sequences were deposited as high-density turbidites (Bouma, 1962), as testified by the rythmic graded sequences, convolute bedding, oblique lamination... Structural observations in several outcrops of the Jodoigne unit point to the abundance of slump folds (Debacker *et al.*, 2006). The depositional environment of the Jodoigne unit is interpreted as a fairly deep, anoxic basin with pelagic, hemipelagic and distal to less distal turbidite deposits. The Jodoigne unit crops out on both sides of the Grande Gette, from the southern suburbs of the old town, to the surroundings of the Bordia castle in the north of the town (outcrop 47). The Jodoigne unit is best exposed below the Pastur castle (town hall of Jodoigne: outcrop 55) and in an abandoned small quarry at the W-side of the Grande Gette river, facing the "Grand Moulin" (outcrop 51). In both outcrops, the sandstone beds are grey to black, and rarely more than 30 cm thick. The more sandy, more energetic sequences with decimetre- to even metre-thick pale-grey sandstone are only observed in the two aforementioned, disappeared excavations and, with a slightly darker colour, in the private property of Bordia castle (Herbosch *et al.*, submitted).

4.5. Summary and comparison with other formations

Although the four units can fairly easily be distinguished, each unit is essentially made up of an alternation of pyrite-bearing black slate and quartzite/sandstone. It is the relative amount and thickness of the black slate and quartzite/sandstone, together with more specific features such as the quartzitic nature, the presence of rhythmic, graded sequences, the presence of shale clasts and the colour of the sandstone, that allow distinguishing one unit from another (Fig. 4).

None of the contacts between the four different units has been observed. 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. 3). Likely, these 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 about 2 km occurs. Also this gap likely coincides with the presence of a black-slate-dominated sequence, especially considering the largely pelitic nature of the adjacent units and the particularly flat topography in this part of the Grande Gette valley. It was in this gap that several authors, who considered the Jodoigne Formation as being much younger than the Blanmont Formation (e.g. Fourmarier, 1921), placed the Tubize Formation, in an attempt to explain the apparent proximity of the Jodoigne Formation and the Blanmont Formation. However, this hypothesis was rejected by Raynaud (1952) after a magnetic study. In addition, a bore core from within this zone (118W285) contains a centimetric to decimetric, rhythmic alternation of grey sandstone, siltstone and black slate of turbiditic nature, very similar to the Jodoigne unit.

Considering the lithological and sedimentological characteristics of the Jodoigne Formation described above, only two of the Cambrian formations known from the Brabant Massif bear some resemblance to (parts of) this formation. The quartzites and quartzitic sandstones of the Orbais unit, and especially the quartzites of the Maka unit, are very difficult to distinguish from the quartzites of the Blanmont Formation (cf. Verniers *et al.*, 2001). This resemblance may explain why Rutot & Malaise (1893), Fourmarier (1921) and de la Vallée-Poussin (1931) placed the limit of the Jodoigne Formation to the east of the Maka unit (see Fig. 3). However, an important difference between the Jodoigne Formation and the Blanmont Formation can be found in the intercalated fine-grained parts. As pointed out above, the fine-grained parts of the Jodoigne Formation consist of black, pyrite-bearing slate, whereas the fine-grained parts of the Blanmont Formation consist of grey or green compact slate (mudstone and siltstone) without organic matter (Verniers *et al.*, 2001; Herbosch *et al.*, submitted). Hence, provided the intercalated, fine-grained beds are observed, it is possible to distinguish the quartzites of the Jodoigne Formation (e.g. Maka unit) from those of the Blanmont Formation. Whereas the coarse-grained parts of the Jodoigne Formation resemble the Blanmont Formation, the fine-grained parts resemble the Mousty Formation. The latter formation is described in Verniers *et al.* (2001) as: "*Shale or slate, sometimes mudstone, of grey-blue to grey-black colour, graphitic and pyritic. Massive bedded or finely laminated…; stratification can also be marked by light or greenish coloured, more silty beds or laminae, or by banded, layer-parallel colour variations. Sometimes grey more or less clayey siltstone with pyrite occurs, and occasional centimetric to decimetric fining upward sandstone or siltstone bands, interpreted as distal turbidites. The high concentration of the element Mn ... the presence of garnet and Mn-ilmenite. The middle part of the formation is clearly more silty with grey-black pyritic shale gradually passing downwards into a grey pyritic siltstone and sometimes a sandstone*". Except for

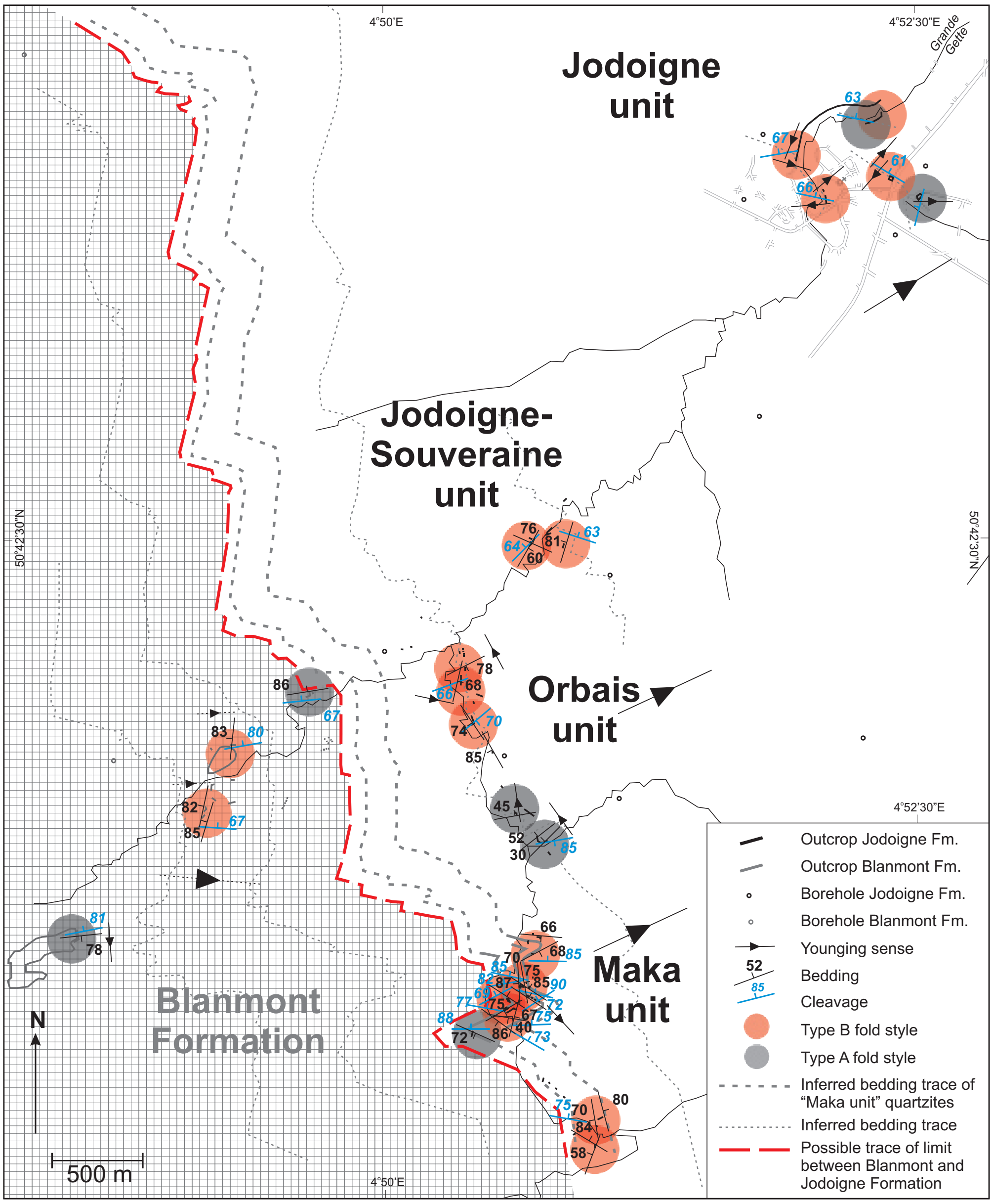

Figure 5 : Simplified topographic map of the Gette outcrop area, showing the outcrop distribution of the Blanmont Formation and the Jodoigne Formation (see also Fig. 3), together with the mean bedding and cleavage orientation per outcrop and the stratigraphic younging sense (where observed; small arrows represent local observations, large arrows correspond to the overall younging sense) (cf. Herbosch et al., submitted). Also added are fold type (type A or type B), as deduced from the cleavage/bedding relationship, as well as the probable bedding traces, as inferred from structural outcrop data (see text and Figs 6 and 7).

the presence of Mn, such a description also applies to the fine-grained parts of the different units of the Jodoigne Formation. In addition, also the sedimentological interpretation of at least some parts of the Mousty Formation (distal turbidites) matches that proposed for the most fine-grained parts of the Jodoigne Formation. Starting from the deposits of the Mousty Formation, one can imagine that, if sediment supply were to increase, and the deposition area would shift towards a more proximal position, the resulting Mousty Formation would become very difficult to distinguish from the deposits of the Jodoigne Formation described above. Hence, if one were to place the Jodoigne Formation somewhere between the other Cambrian formations, purely on the basis of lithology and sedimentology, a logical choice would be to place it directly below, or at the same level of, the Mousty Formation.

5. Map, structural observations and younging sense

The map in Fig. 5 shows mean cleavage and bedding data for each outcrop, as well as the stratigraphic younging sense (i.e. younging sense inferred from sedimentological criteria). In most outcrops, bedding and cleavage orientation remains fairly constant. For the outcrops in which the orientation of bedding (and cleavage) does change significantly (e.g. due to complex folding), and hence for which the mean cleavage and bedding orientation is quite meaningless, the values refer to the "regular" bedding orientation only. With "regular" bedding we mean bedding from the larger outcrop parts with relatively uniformly dipping layers.

As can be seen on Fig. 5, in most outcrops bedding is steeply dipping (>60°). However, the strike of the predominantly steep bedding is highly variable between the different outcrops, seemingly suggestive of steeply plunging folds. In contrast to the strongly variable bedding trend, cleavage trend shows much less variation. Cleavage is virtually always steeply N-dipping and has a mean E-W-trend. In those outcrops where the steep bedding is at a high angle to the cleavage, the resulting cleavage/bedding intersection is steeply plunging, again suggestive of steeply plunging folds (Fig. 6). In addition, in some outcrops, due to the low angle between bedding and cleavage trend, and/or due to the low bedding dip, the cleavage/bedding intersection is gently dipping, suggestive of gently plunging folds (Fig. 6).

The local presence of steeply plunging folds within the Cambrian core of the Brabant Massif has been known for quite some time (e.g. Fourmarier, 1921; Vander Auwera, 1983). On the basis of structural observations in a large temporary outcrop of the Lower Cambrian turbidites of the Tubize Formation at Lembeek (Sennette valley), Sintubin *et al.* (1998) provided the first detailed description of the steeply plunging folds, and also demonstrated the tectonic nature of these folds. At Lembeek, the folds plunge steeply to the NW, have straight limbs, a common Z-shaped geometry, steeply N-dipping, E-W-trending axial surfaces, open interlimb angles, sub-angular hinges, wavelengths between 100 and 150 m, and a west-ward fold facing (younging direction). The cleavage shows a pronounced divergent cleavage fanning: in the sub-vertical, NW-SE-trending limbs the cleavage is sub-

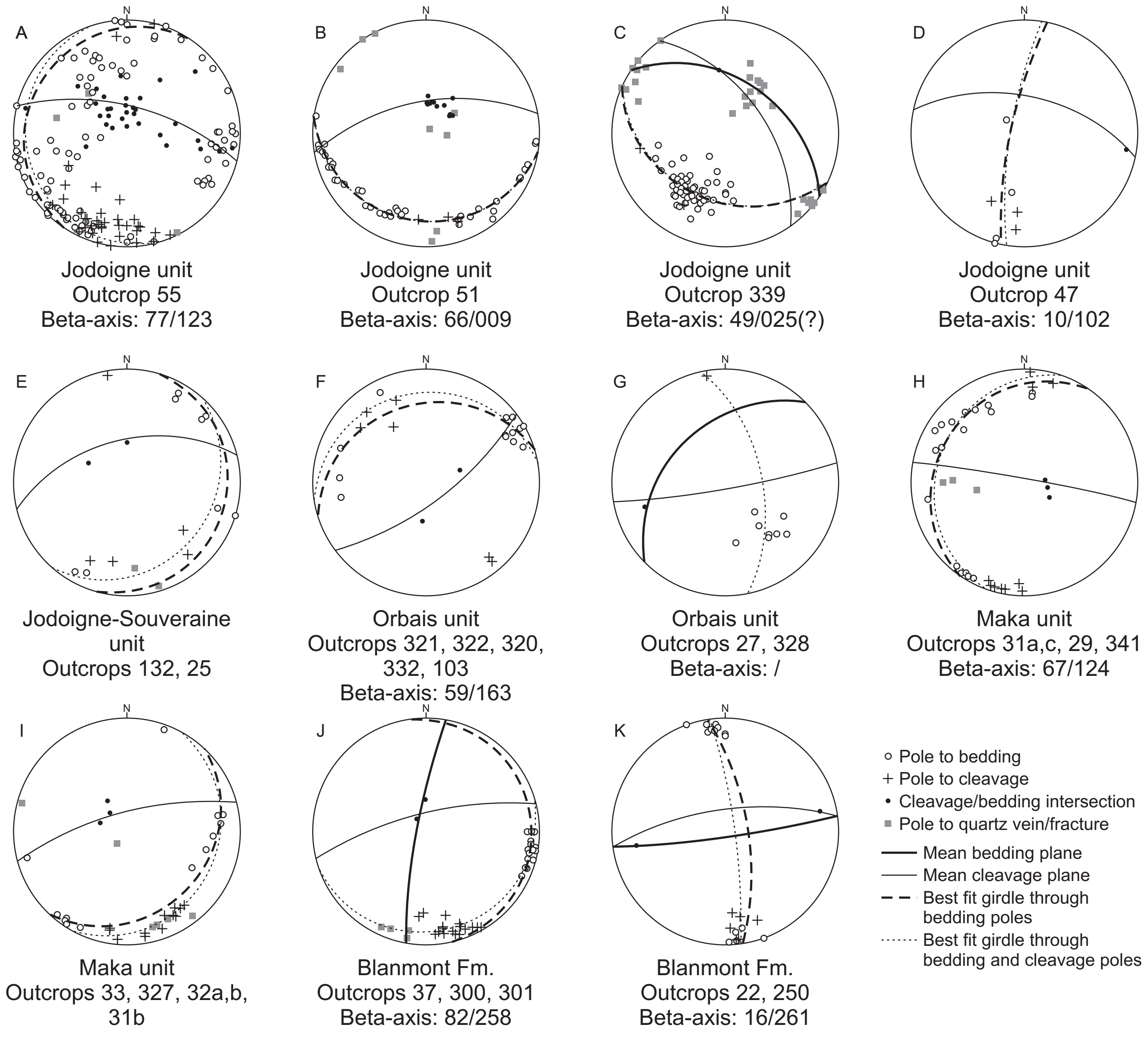

Figure 6: Lower-hemisphere equal-area projections of bedding, cleavage and fracture data across the study area, demonstrating the presence of both type A and type B folds (see also Figs 5 and 7). Where possible, taking into account the proximity and structural compatibility, data from several outcrops, belonging to the same lithostratigraphic unit, have been grouped (plots E, F, G, H, I, J and K). Data of pre-cleavage (slump?) folds and of bedding geometries for which a pre-cleavage origin cannot be ruled out, have been omitted (e.g. outcrops 331, 32c and parts of outcrops 55 and 51; cf. Debacker et al., 2006 and Debacker, Similox-Tohon, van Noorden, Kenis & Sintubin, unpub. data). The reason for the large spread of bedding poles and cleavage/bedding intersection within outcrop 55, seemingly suggestive of non-cylindrical folds, can be found in Debacker et al. (2006).

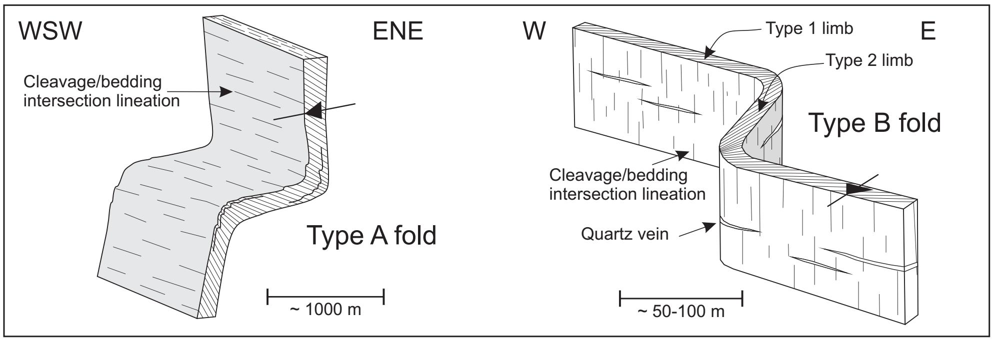

Figure 7: The two main fold types in the Brabant Massif, based on observations in the Sennette outcrop area (type A folds and type B folds; after Debacker et al., 2004a). The sense of younging is given by the arrows. See text and compare with Figs 5 and 6.

vertical to steeply NNE-dipping, whereas in the steeply NW-dipping, NE-SW-trending limbs the cleavage dips steeply towards the NNW. In both limbs the average angle between cleavage and bedding is in the order of 20°. The cleavage/fold relationship points to a cogenetic development of cleavage and folding (Fig. 7). More recent studies demonstrated the large-scale occurrence of these steeply plunging tectonic folds in the Cambrian core of the Brabant Massif. These steeply plunging tectonic folds were labelled type B folds, as opposed to the subhorizontal to gently plunging type A folds, common in the Ordovician and Silurian (Fig. 7; Debacker, 2001; Debacker *et al.*, 2004a). Type B folds, or cleavage/bedding relationships suggestive of steeply plunging folds (type B cleavage/bedding relationships), have been observed in the Sennette outcrop area (Tubize Formation and Oisquercq Formation; Sintubin *et al.*, 1998; Debacker, 2001; Debacker *et al.*, 2004a; Piessens *et al.*, 2004), in the Dyle-Thyle outcrop area (Blanmont Formation, Tubize Formation, Mousty Formation; Sintubin *et al.*, 2002; Debacker, 2001; Debacker *et al.*, 2005a) and recently also in the northern part of the Gette outcrop area, at Jodoigne (outcrops 51 and 55; Debacker *et al.*, 2006; see A and B on Fig. 6). Many of these studies pointed out that the geometry of the type B folds is not always as ideal as that described by Sintubin *et al.* (1998), that type B folds and gently plunging type A folds often co-exist within the same area and that a gradual transition may exist between the type A folds and the type B folds (e.g. Debacker *et al.*, 2004a, 2005a; Piessens *et al.*, 2004). In addition, the recent studies also pointed to a systematic relationship between quartz-filled fractures and the type B folds (Fig. 7; e.g. Debacker *et al.*, 2004a, 2005a, 2006).

On the basis of the bedding orientation, the cleavage/bedding-relation, the orientation of the cleavage/bedding intersection and the relationship between bedding, cleavage/bedding intersection and quartz-filled fractures, it becomes clear that in the Gette outcrop area the steeply plunging cleavage/bedding intersection indeed reflects type B folds, whereas the gently plunging cleavage/bedding intersection usually corresponds to type A folds (Figs 5 and 6; compare with Fig. 7). Exceptions occur in the Jodoigne unit at Jodoigne, where locally a gently plunging cleavage/bedding intersection occurs. As demonstrated by Debacker *et al.* (2006), in at least two outcrops at Jodoigne (outcrops 51 and 55), the gently plunging intersection is due to the local presence of slump folds (data not included in plots on Fig. 6).

As can be seen on the map of Fig. 5 and on Fig. 6, type B cleavage/bedding relationships dominate the area. Especially within the quartzites of the Maka unit, in the southern part of Jauchelette, the presence of decametre- to hectometre-scale type B folds becomes apparent. Type A cleavage/bedding relationships are much less common. Clear examples of type A cleavage/bedding relationships are observed in the abandoned Opprebais quarry (outcrop 22) and in outcrops 250, 27 and 328 (Fig. 6). A complete type A fold occurs in a private property in the vicinity of the Bordia castle, at the northern limit of Jodoigne (outcrop 47).

On the map of Fig. 5, bedding traces were constructed on the basis of an analysis of the bedding orientation, the cleavage/bedding relationship and the inferred fold geometry, in combination with the distribution of the different lithological units.

Where possible, the younging sense of the beds was determined on the basis of sedimentological criteria (stratigraphic polarity: grading, oblique lamination, loadcasts,…) and this was compared with the younging sense suggested by the cleavage/bedding relationship (structural polarity). In three outcrops of the Jodoigne unit at Jodoigne, local mismatches are observed between the structural and stratigraphic polarity. As pointed out by Debacker *et al.* (2006) in two of these outcrops (outcrops 51 and 55), this can be attributed to the local presence of overturned bedding caused by slumping. Also in the third outcrop (outcrop 339), local mismatches might be due to the presence of a slumped zone of overturned bedding (Debacker, Similox-Tohon, van Noorden, Kenis & Sintubin, unpub. data). In the other outcrops, however, a consistent image becomes apparent, both within individual outcrops and between distant outcrops. Across the area, the overall younging sense is towards the eastnortheast, and this younging sense is reflected by observations from the Maka unit, the Orbais unit and the Jodoigne unit of the Jodoigne Formation and from the Blanmont Formation. This indicates that the relative age within the Jodoigne Formation increases from the Jodoigne unit to the Maka unit and suggests that the Jodoigne Formation is younger than the Blanmont Formation.

6. Temperature-dependent variation of magnetic susceptibility

Magnetic susceptibility changes in function of temperature. For paramagnetic carriers, magnetic susceptibility changes inversely with temperature, following the Curie-Weiss-law. In contrast, for minerals with ferromagnetic properties, magnetic susceptibility remains fairly constant over relatively large temperature-intervals, and only changes at specific temperatures, characteristic for the given mineral (e.g. Curie-point, Verwey transition, Morin transition) (e.g. Piper, 1987; Butler, 1992; Hunt *et al.*, 1995; Walz, 2002).

We analysed small temperature-dependent changes of magnetic susceptibility for a large number of lithostratigraphic units of the Brabant Massif. This was done at the lab of M. Sintubin (K.U.Leuven), using a KLY3S Kappabridge (AGICO; Jelinek & Pokorny, 1997). Cooling and heating were done by means of a standard fridge and a digital laboratory oven, respectively, in which the temperature was checked using the same classical mercury thermometer. In order to achieve thermal homogeneity, samples were kept at a given temperature during at least 2 hours. The chosen temperature-interval is, what we call, the "room-temperature-interval", ranging from 0 to 40°C. In this interval, the magnetic susceptibility of most ferromagnetic (*s.l.*) carriers remains virtually constant, whereas the paramagnetic susceptibility changes according to the Curie-Weiss-law. Magnetic susceptibility was measured on particular samples of particular lithostratigraphic units that were cooled or heated to various temperatures between 0 and 40°C. This resulted in different temperature-susceptibility-curves for samples of different lithostratigraphic units. Although the procedure may seem rather crude (except for the kappabridge, standard house-hold appliances were used), the slope of the curves for particular samples is virtually identical between different temperatures in the 0-40°C-interval. In an attempt to quantify this temperature-dependent change in magnetic susceptibility, for each sample we (re-) calculated the percentage of change in magnetic susceptibility for a temperature change of 20°C within the 0-30°C temperature-interval. This value is plotted on Fig. 8, as a function of stratigraphy. As can be seen on Fig. 8, most of the Silurian and Ordovician lithostratigraphic units exhibit a considerable, but relatively constant, temperature-dependent change in magnetic susceptibility. This suggests a predominantly paramagnetic behaviour, with only a minor ferromagnetic (*s.l.*) contribution (see theoretical lines on Fig. 8). In contrast, in the Cambrian, much more variation is observed. Three units show a completely different behaviour from that of the Ordovician and Silurian units (Ripain Member of Oisquercq Formation and Les Forges Member and high-susceptibility levels of Rogissart Member of Tubize Formation), one unit has a susceptibility change identical to that of the Ordovician and Silurian units (Asquempont Member of Oisquercq Formation), and two units show very large spreads, with several samples having very large susceptibility changes (9 to 17%; Mousty Formation and Jodoigne Formation).

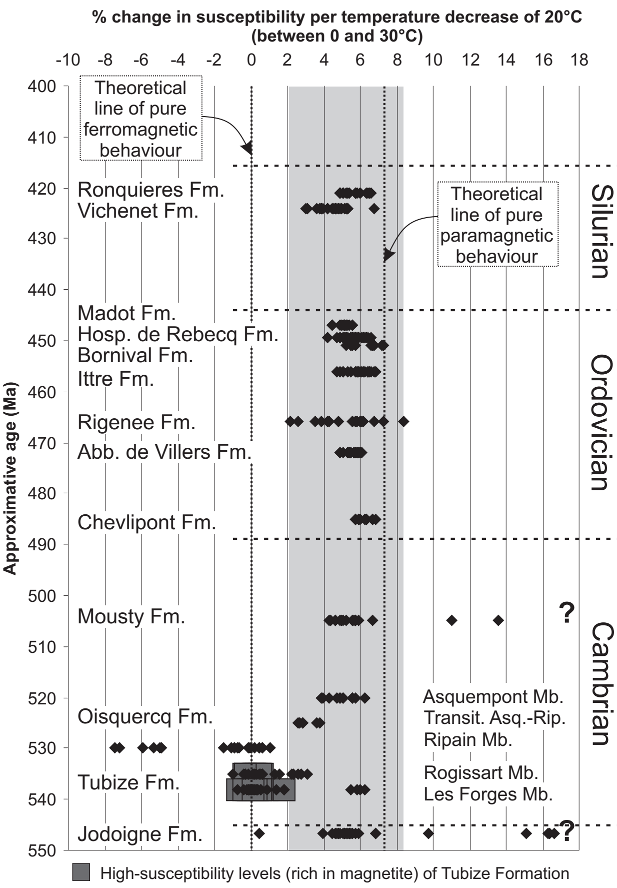

Figure 8: Graph showing the variation of magnetic susceptibility, in terms of percentage, in the interval between 0 and 30°C, for a temperature variation of 20°C, of samples from different Lower Palaeozoic stratigraphic units of the Brabant Massif (stratigraphy of Verniers et al., 2001). The interval in light grey corresponds to the temperature-dependent susceptibility change shown by most lithostratigraphic units, and reflects a predominantly paramagnetic behaviour (in theory ~7.3% for pure paramagnetic behaviour). Deflections to the left of this (in theory 0 for pure ferromagnetic behaviour) characterise units with a significant amount of ferromagnetic (s.l.) carriers, being hematite in the Ripain Member and hematite or magnetite in the low-susceptibility levels of the Les Forges Member and magnetite in the high-susceptibility levels of the Les Forges Member and the Rogissart Member (see Debacker et al., 2004b, 2005b). A deflection to the right is shown only by samples of the Mousty Formation and the Jodoigne Formation (marked by ?).

A comparison with remanence studies and studies on the magnetic mineralogy (Debacker *et al.*, 2004b, 2005b) sheds light on the different values obtained for the Cambrian units. Both the Les Forges Member of the Tubize Formation and the Ripain Member of the Oisquercq Formation contain a significant amount of hematite, which is a high-coercivity ferromagnetic (*s.l.*) mineral, and hence explains the virtually 0% temperature-dependent susceptibility change. The large spread in temperature-dependent change in susceptibility of samples of the Rogissart Member of the Tubize Formation is directly related to the occurrence of high-susceptibility magnetite-rich zones (~0% temperature-dependent susceptibility change) in between magnetite-poor low-susceptibility zones (~6% change: predominantly paramagnetic behaviour). The significant change in susceptibility of the Asquempont Member of the Oisquercq Formation, being identical to that of the Ordovician and Silurian rocks, is due to its predominantly paramagnetic mineralogy. However, several samples of both the Jodoigne and the Mousty Formation show a very large temperature-dependent susceptibility change, which is much more pronounced than that observed within any of the other investigated lithostratigraphic units, and which cannot be attributed to paramagnetic behaviour. Although the cause of this remains unknown (possibly diamagnetic behaviour?), it does suggest a comparable magnetic (*s.l.*) mineralogy for both formations.

7. Biostratigraphic age

As outlined above, the Jodoigne Formation never yielded any biostratigraphic ages (Verniers *et al.*, 2001). Also several dating attempts by means of acritarchs on the newly described lithologic units proved unsuccessful (Vanguestaine, pers. comm.).

The upper parts of the Mousty Formation were dated in outcrop as belonging to the base of the Tremadocian (Lecompte, 1948, 1949; Martin, 1968; Vanguestaine *in* André *et al.*, 1991). The older parts of the Mousty Formation were only dated in boreholes by means of acritarchs (see Fig. 9 for borehole positions). The biostratigraphic ages of the Mousty Formation from Eine (84E1372) and Vollezele (100E010) correspond to the lower and middle parts of the Upper Cambrian (Vanguestaine, 1992 and pers. comm.), whereas the recently obtained age from Cortil-Noirmont (130W539) corresponds to the Upper Cambrian (Vanguestaine *in* Delcambre & Pingot, 2002 p. 17 and pers. comm.). Hence, judging from these borehole and outcrop data, the Mousty Formation extends at least from the base of the Upper Cambrian to the base of the Tremadocian. However, in a borehole at Leuven (89E01) a markedly different biostratigraphic age was obtained. The rocks in this borehole were described as Silurian by Rutot & Van den Broeck (1890; "*schistes noirâtres passant au grès*" (*i.e.* "black slates passing into sandstones") and later as "*Revinien supérieur*" ("Upper Revinian" or the Mousty Formation) by Legrand (1968, p. 85; "*phyllades satinés, noir dense, un peu pyriteux. A la base quelques lits de quartzophyllades*" (*i.e.* "lustrous black, dense slates, containing minor amounts of pyrite. Near the base an alternation of sand and claystone"). By means of acritarchs, these deposits were dated as belonging to the lower part of the Middle Cambrian (Vanguestaine,1973, 1992), which is significantly older than the age obtained from the other boreholes containing the Mousty Formation (see above). However, boreholes in the surroundings of Leuven (Leuven, 89E01; Heverlee 89E363) consist of a facies described as "*quartzophyllades*" (i.e. "an alternation of sandstone and claystone"), with "*passées gréseuses*" (i.e. "sandstone intercalations") (89E01). In addition, an examination by Herbosch (unpub. data) of a core of the Heverlee borehole (89E363) revealed the presence of centimetre-scale turbidite sequences, a facies which is rather different from the classical facies of the Mousty Formation, but quite similar to that of the Jodoigne unit (youngest unit of the Jodoigne Formation). Considering the older biostratigraphic age and the lithological and sedimentological resemblance with the Jodoigne Formation, it is possible and even likely that the aforementioned boreholes in the Leuven area contain the Jodoigne Formation instead of the Mousty Formation. Also cartographically this seems possible, as Leuven is situated only ~20km from Jodoigne, in a NW-SE-direction subparallel to the bedding trend within the northern part of the Brabant Massif (Fig. 9).

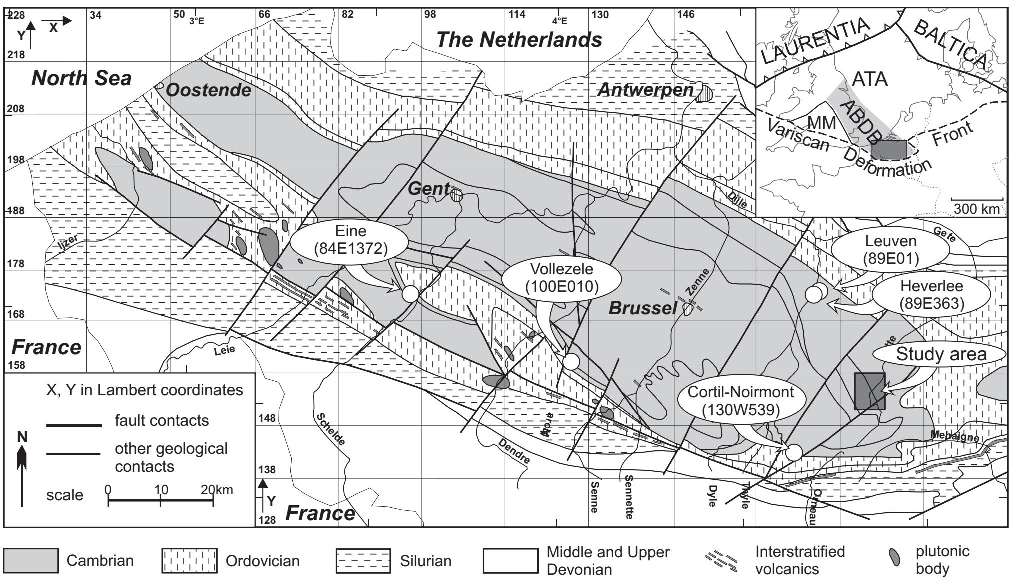

Figure 9 : Geological subcrop map of the Brabant Massif (after De Vos et al., 1993 and Van Grootel et al., 1997), showing the position of boreholes in which a facies attributed to the Mousty Formation was dated. See text for explanation.

8. Discussion

8.1. Suggested stratigraphic position

The combination of quite a number of arguments leads us to suggest that the Jodoigne Formation is not older than the Blanmont Formation, but is instead much younger, and probably has a Middle to Upper Cambrian age, close to or slightly below that of the Mousty Formation (Fig. 10). These arguments are: a) the lithological similarities between the Mousty Formation and the fine-grained parts of the Jodoigne Formation; b) the identical temperature-dependent variation of magnetic susceptibility of the Mousty Formation and the Jodoigne Formation, being exceptional with respect to that of the other investigated formations of the Brabant Massif; c) the younging sense within both the Blanmont Formation and the Jodoigne Formation in the study area, suggesting a younging from the former (WSW) towards the latter (ENE); d) its position in the northern part of the Brabant Massif, to the NE of the central axis occupied by the Blanmont Formation (Michot, 1980); e) the apparent stratigraphic hiatus, yet unexplained, between the basal Middle Cambrian (Oisquercq Formation) and the Upper Cambrian (Mousty Formation; see Verniers *et al.*, 2001); and f) the Middle Cambrian biostratigraphic age of deposits previously tentatively attributed to the Mousty Formation (base of Upper Cambrian to base of Tremadocian), but containing a facies quite distinct from that of the classical Mousty Formation and strongly resembling that of the youngest unit of the Jodoigne Formation. Although separately each of these arguments may be criticised, together they plead a case for a Middle (to Upper?) Cambrian stratigraphic position of the Jodoigne Formation (Fig. 10).

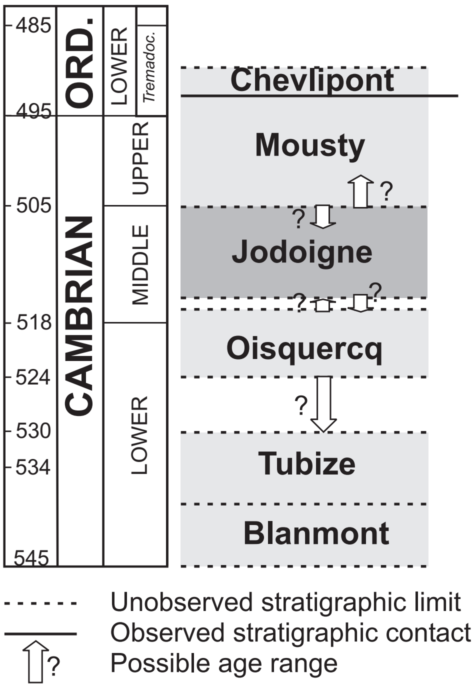

Figure 10: Stratigraphic subdivision of the Cambrian and lowermost Ordovician of the Brabant Massif, with the probable position of the Jodoigne Formation, as inferred from the current work. Note that the possible age range of the Jodoigne Formation, as represented by the arrows, allows for an overlap with the lower part of the Mousty Formation. Compare with Fig. 1.

Considering the lithology and stratigraphic position of the Mousty Formation (see above), we consider the main part of the Jodoigne Formation to be older than the Mousty Formation and significantly younger than the Oisquercq Formation, allowing a possible time-equivalence between the lower, more silty parts of the Mousty Formation and the younger, more fine-grained parts (Jodoigne unit) of the Jodoigne Formation. Although we admit that we cannot rule out the possibility that larger parts of the Jodoigne Formation and the Mousty Formation are lateral time-equivalents, deposited in different parts of the basin, the sum of the arguments above, not in the least the combination of biostratigraphic data, lithology and sedimentology, together with the close proximity between Jodoigne and Leuven, does seem convincing enough to place the largest part of the Jodoigne Formation (e.g. Jodoigne-Souveraine unit and older) below the Mousty Formation.

Despite the above, there are aspects that might be used to criticise the proposed stratigraphical position. In the Mousty Formation there is a high concentration of the element Mn, reflected a.o. by the presence of Mn-garnet and Mn-ilmenite (de Magnée & Anciaux, 1945; Herbosch *in* André *et al*. p. 291, 1991). Such a high concentration of Mn has not been observed in the Jodoigne Formation. Suffice to say that it is either absent, which can readily be explained by the suggested lower stratigraphic position, or that it has not been observed as yet, despite the examination of numerous thin sections (Herbosch, unpub. data). In this respect, it may be interesting to note some preliminary results of Robion (unpublished data) on the ferromagnetic (*s.l.*) mineralogy, based on thermal demagnetisation experiments using the Lowrie protocol (for method and applied fields, see Lowrie, 1990 and Debacker *et al.*, 2004b, 2005b). Besides pyrrhotite and magnetite, these preliminary results seemingly also indicate the presence of either ulvospinel-rich (Ti-rich) titanomagnetite (x of ~0.6 in $Fe_{3-x}Ti_xO_4$; Nagata, 1961; Butler, 1992) or ilmenite-rich (Ti-rich) titanohematite (x of ~0.5 - ~0.6 in $Fe_{2-x}Ti_xO_3$; Nagata, 1961; Stacey & Banerjee, 1974; Butler, 1992) for both the Mousty Formation and the Jodoigne Formation, something which may be compatible with the Mn-ilmenite reported in the Mousty Formation.

Another aspect which may seem difficult to explain in light of the suggested stratigraphic position of the Jodoigne Formation is the proximity of the Blanmont Formation and the Jodoigne Formation within the Gette outcrop area. This is explained below.

8.2. Proximity of Blanmont and Jodoigne formations in Gette outcrop area

The close proximity in the eastern part of the Brabant Massif between the Jodoigne Formation and the Blanmont Formation can be explained by means of the Asquempont

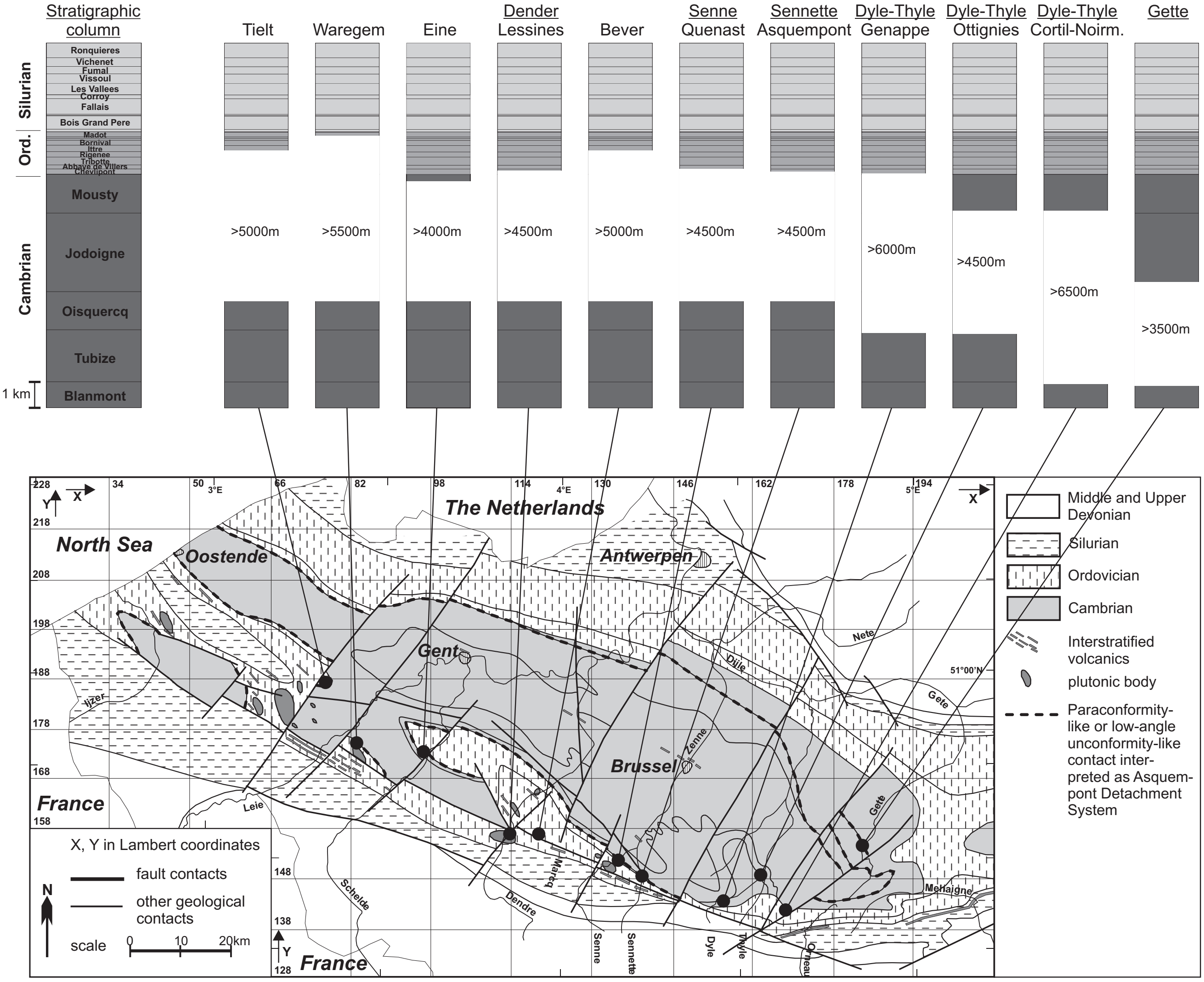

Figure 11: Geological subcrop map of the Brabant Massif (after De Vos et al., 1993 and Van Grootel et al., 1997), showing the effect of the Asquempont Detachment System on the newly proposed stratigraphy at different observation points. For comparative purposes, for each of these points the same composite stratigraphic column is used as shown in the upper left corner. On these stratigraphic columns, the part considered to be removed by the Asquempont Detachment System is shown in white, together with a minimum thickness estimate. The thickness of the individual formations is based on Verniers et al. (2001), Piessens et al. (2005) and Herbosch et al. (in press) and for the Jodoigne Formation on the present work. Tielt, Waregem, Eine, Lessines (Dender valley) and Bever are borehole observations, whereas the columns for the Senne, the Sennette, the Dyle-Thyle and the Gette are based on outcrop observations. Data are taken from Debacker (2001), Debacker et al. (2004a, 2005a), Piessens et al. (2005) and from this work (cf. Herbosch et al., submitted). See text for explanation.

Detachment System. The Asquempont Detachment System, named after the Asquempont fault at Asquempont, is a low-angle extensional detachment system that formed prior to folding and cleavage development (Debacker *et al.*, 2004c, 2005a; cf. Debacker, 2001). At present, the presence of this detachment system has been demonstrated or deduced in at least three areas along the S-side of the Brabant Massif (Fig. 11).

In the Senne-Sennette outcrop area, where it was defined, this detachment system places Lower Ordovician strata on top of the Oisquercq Formation (Debacker, 2001; Debacker *et al.*, 2004c; cf. Legrand, 1967; Mortelmans, 1955). In the unexposed parts of the Brabant Massif to the WNW of the Senne-Sennette outcrop area, this detachment system places the Lower to Upper Ordovician on top of the Oisquercq Formation, as observed in several boreholes (from E to W: Bever 114W73, 114W93; Lessines 113E1015; Schendelbeke 100W181; Eine 84E1372; Waregem 84W1385; at Eine: contact between Mousty Formation and Oisquercq Formation) (Piessens *et al.*, 2005; cf. Debacker *et al.*, 2004c). To the east, in the Dyle-Thyle outcrop area, the presence of the Asquempont Detachment System forms the most plausible explanation for the enigmatic contact between the Mousty Formation (detachment hanging wall) on the one hand and the Tubize and Blanmont formations (detachment footwall) on the other hand (Debacker *et al.*, 2005a).

On the basis of the stratigraphic position of the hanging wall and footwall rocks in boreholes in the unexposed western part of the Brabant Massif, Piessens *et al.* (2005)

deduced an initially (i.e. pre-folding) gentle NNE-dip for the Asquempont Detachment System. The apparent eastward stratigraphic ageing of both the hanging wall and footwall rocks from the western unexposed areas to the Dyle-Thyle outcrop area along the S-side of the Brabant Massif (Fig. 11) is fully compatible with the results of Piessens *et al.* (2005). Extrapolating this trend towards the Gette outcrop area, we would expect a hanging wall composed of the Mousty Formation or older and a footwall composed of the Blanmont Formation or older. As indicated by our observations (this work), the presence of eastward younging deposits of the Jodoigne Formation, seemingly directly overlying eastward younging deposits of the lowermost Cambrian Blanmont Formation, necessitates the presence of a discontinuity (hiatus, fault or unconformity) between both formations in the Gette outcrop area. This discontinuity is the Asquempont Detachment System, with the Jodoigne Formation in the hanging wall and the Blanmont Formation in the footwall (Fig. 11). Hence, the Asquempont Detachment System, the NNE-dip of this detachment system and the newly suggested stratigraphic position of the Jodoigne Formation (just below the Mousty Formation, possibly partly overlapping) are fully compatible. In addition, besides seemingly confirming the NNE-dip of the Asquempont Detachment System, the new geological interpretation of the Gette outcrop area forms the first strong indication for the presence of the Asquempont Detachment System along the N-side of the Brabant Massif, a hypothesis previously already suggested on cartographic grounds by Debacker *et al.* (2004c, 2005a) and Piessens *et al.* (2005).

8.3. Inferred thickness of the Jodoigne Formation

Assuming overall type B fold geometry in the study area, a stratigraphic thickness of at least 4 km would be inferred for the Jodoigne Formation (see Fig. 5). Such a thickness is nearly half the inferred thickness of the entire Cambrian within the Brabant Massif. However, also type A folds often occur within the study area, indicating that the stratigraphic thickness should be less. In addition, several relatively large, poorly exposed zones occur, especially in between the Jodoigne unit and the Jodoigne-Souveraine unit. As pointed out above, these zones coincide, at least partly, with the more fine-grained units of the Jodoigne Formation. Although we do not have indications for a fault-controlled repetition, in these unexposed areas the presence of faults affecting the apparent stratigraphic thickness cannot be excluded. Moreover, it is possible that (the lower) parts of the Mousty Formation and (the upper) parts of the Jodoigne Formation are lateral equivalents. These considerations suggest that the thickness of the Jodoigne Formation is likely to be less than 4 km. Therefore, we tentatively propose a thickness in the order of 3 km for the Jodoigne Formation. This is also the thickness used in the composite stratigraphic columns in Fig. 11.

8.4. Comparison with the Middle and Upper Cambrian of the Ardennes Inliers

Despite the fact that the Middle Cambrian within the Brabant Massif was unknown at that time, Verniers *et al.* (2002) concluded a similar Cambrian basin evolution for the Brabant Massif and the Ardennes Inliers, especially for the Middle and Late Cambrian. If so, and considering the stratigraphic position proposed in the present work, the Jodoigne Formation should bear some resemblance to the Middle to Upper Cambrian deposits of the Ardennes Inliers. These deposits are the deposits of the Revin Group.

As pointed out by de la Vallée-Poussin (1931), the lithology of the Jodoigne Formation strongly resembles that of the Revin Group of the Ardennes Inliers. This group, consisting of several formations, is mainly composed of alternations of black slate, mudstone, grey sandstone and grey to occasionally black quartzite of variable thickness (e.g. Verniers *et al.*, 2001). Indeed, this general description is very similar to that of the Jodoigne Formation. According to the stratigraphic position of the Jodoigne Formation proposed in the present work, in the Rocroi Inlier the Jodoigne Formation should be time-equivalent to the Rocher de l'Uf Formation (Rv1) and/or the La Roche à 7 heures Formation (Rv2). In addition, considering the possible time-equivalence with the lower parts of the Mousty Formation, the Jodoigne Formation possibly overlaps also with the Anchamps Formation (Rv3) and maybe even also with part of the Petite-Commune Formation (Rv4-Rv5) (e.g. Vanguestaine, 1992; Verniers *et al.*, 2001). Similarly, for the Stavelot Inlier, the Jodoigne Formation is expected to be time-equivalent to the Wanne Formation (Rv1-Rv2) and, because of the possible time-equivalence with the lower parts of the Mousty Formation, possibly overlaps with the La Venne Formation (Rv3-Rv4) (e.g. Vanguestaine, 1992; Verniers *et al.*, 2001). Several of these formations have facies resembling the different facies of the Jodoigne Formation. Both the La Venne Formation and the La Roche à 7 heures Formation, for instance, contain massive grey quartzite, resembling the Maka unit of the Jodoigne Formation, whereas black sandstone and quartzite like in the Jodoigne-Souveraine unit of the Jodoigne Formation are present also in the Anchamps Formation, the Petite-Commune Formation and the Wanne Formation (e.g. Verniers *et al.*, 2001). Hence, although a detailed correlation between the different units of the Jodoigne Formation and the different lithostratigraphic units of the Revin Group in the Ardennes Inliers is not possible, the lithological similarities between the Jodoigne Formation and the lower and middle parts of the Revin Group are compatible with the proposed stratigraphic position. Moreover, these similarities seem to support the similar Middle to Late Cambrian basin evolution for the Ardennes Inliers and the Brabant Massif suggested by Verniers *et al.* (2002).

Interestingly, judging from the literature, the estimated stratigraphic thickness of the Middle and Upper Cambrian is about three times less in the Ardennes Inliers (~1500 m) than in the Brabant Massif (~4500 m). When the entire Cambrian is taken into account, the estimated thickness appears to be even more than four times thinner in the Ardennes Inliers than in the Brabant Massif. In combination with results of palaeocurrent analysis and good stratigraphic constraints, such a consistent difference in thickness could provide valuable information for the basin evolution during the Cambrian. However, it should be realised that, because of the locally very intense deformation, stratigraphic thicknesses in the Ardennes Inliers are much less well constrained than in the Brabant Massif, and that the Cambrian in the Ardennes Inliers may be much thicker than estimated. In addition, to the author's knowledge, no large-scale palaeocurrent analyses have been performed in the Cambrian of the Ardennes Inliers and the Brabant Massif. Hence, although a difference in thickness may exist between the Brabant Massif and the Ardennes, the exact amount remains unknown, and hence cannot be used yet for further interpretation.

9. Conclusions

On the basis of an analysis of pre-existing data and new data from various sources we suggest that the Jodoigne Formation should not be considered as the oldest formation of the Brabant Massif, but instead has a significantly younger age, probably corresponding to the Middle Cambrian and possibly extending into the lower Upper Cambrian. These data are: 1) the resemblance between the black mudstone-dominated parts of the Jodoigne Formation and the rocks of the Mousty Formation; 2) the similar anomaly in terms of temperature-dependent variation of magnetic susceptibility for the Jodoigne Formation and the Mousty Formation; 3) the apparent stratigraphic hiatus, yet unexplained, between the basal Middle Cambrian (Oisquercq Fm.) and the Upper Cambrian (Mousty Fm.); 4) the overall E-ward younging sense within the Jodoigne Formation in its type area (Grande Gette valley), away from the seemingly adjacent, E-ward younging lowermost Cambrian Blanmont Formation; 5) the lower Middle Cambrian biostratigraphic position (acritarchs by Vanguestaine, 1992) of rocks said to belong to the Mousty Formation (Leuven, 89E01), but having a lithology reflecting a turbiditic sedimentology, thus far only encountered within the youngest two observed units of the Jodoigne Formation at Jodoigne (Jodoigne unit and Jodoigne-Souveraine unit). In addition, the presence of the stratigraphically revised Jodoigne Formation seemingly adjacent to the Blanmont Formation, can adequately be explained by means of the Asquempont Detachment System, and, in turn, this explanation appears to confirm the initial NNE-dip of this detachment system proposed by Piessens *et al.* (2005). Moreover, it forms the first direct indication for the presence of the Asquempont Detachment System along the N-side of the Brabant Massif (cf. Debacker *et al.*, 2004c; Piessens *et al.*, 2005).

We cannot rule out the possibility that the Jodoigne Formation partly overlaps in time with the Upper Cambrian Mousty Formation, and that for instance (the younger) parts of the Jodoigne Formation represent a more proximal, more energetic facies of (the older) parts of the Mousty Formation. However, considering the apparent homogeneity within the Mousty Formation over relatively large areas (Herbosch & Lemonne, 2000; Delcambre *et al.*, 2002; Herbosch *& Verniers,* 2002), the lower Middle Cambrian biostratigraphic age at Leuven (89E01; Vanguestaine, 1992) of fine-grained turbiditic deposits strongly resembling the deposits in the younger units of the Jodoigne Formation, and the relatively short distance between Jodoigne and Leuven, in a direction subparallel to the large-scale bedding trend, we feel that at least the largest part of the Jodoigne Formation should be situated below the Mousty Formation.

Acknowledgements

We kindly acknowledge W. De Vos, J. Bellière and P. Ryan for their constructive remarks on the manuscript. We are most grateful to Manuel Sintubin (Geodynamics & Geofluids Research Group, Katholieke Universiteit Leuven) for allowing us to use the KLY3S kappabridge. We would also like to express our gratitude to Philippe Robion (*Département des Sciences de la Terre et de l'Environnement, Université de Cergy Pontoise*) for the fruitful discussions and for performing thermal demagnetisation experiments on some of our samples not included in Debacker *et al.* (2004b, 2005b). Also Fátima Martín-Hernández is thanked for the stimulating discussions. We warmly thank Michel Vanguestaine, who passed away too soon, for having read our interpretation of his biostratigraphic data, and for the new acritarch dating attempts on the black pelites of the Jodoigne Formation. The revised stratigraphic position of the Jodoigne Formation is an idea of A. Herbosch. A. Herbosch also did the mapping, distinguished the different units, did the literature review, examined the existing data and constructed a facies distribution map. T. Debacker did the structural field measurements, made the structural interpretation, performed magnetic analyses, and constructed a geologically feasible map. The application of the Asquempont Detachment model to the Jodoigne area is the work of T. Debacker and K. Piessens. K. Piessens also checked the existing borehole data. T.N. Debacker is a Postdoctoral Fellow of the Fund for Scientific Research-Flanders (F.W.O.-Vlaanderen). Part of this research was done when T. Debacker was at the Geodynamics & Geofluids Research Group (K.U.Leuven). This work forms part of research projects G.0274.99, G.0094.01 and G.0271.05 of the F.W.O.-Vlaanderen. Data on the subcrop part of the Brabant Massif were revised during the project VLA03-1.1, funded by the Flemish Community (*Afdeling Land en Bodembescherming, Ondergrond en Natuurlijke Rijkdommen - ALBON* and *Databank Ondergrond Vlaanderen - DOV*).

References

André, L., Herbosch, A., Vanguestaine, M., Servais, T., Van Grootel, G., Louwye, S. & Verniers, J. 1991. Guidebook of the excursion on the stratigraphy and magmatic rocks of the Brabant Massif, Belgium. In: *Proceedings of the international meeting on the Calidonides of the Midlands and the Brabant Massif (Brussels, 20-23 september 1989)* (L. André, A. Herbosch, M. Vanguestaine & J. Verniers, eds.). *Annales de la Société géologique de la Belgique* **114**, 283-323.

Asselberghs, E. 1918. Gîtes nouveaux d'Oldhamia radiata à Oisquercq (vallée de la Sennette). *Bulletin de la Société belge de Géologie* **24**, 102-103.

Bouma, A. H. 1962. *Sedimentology of some flysch deposits*. Amsterdam, Elsevier.

Butler, R.F. 1992. *Paleomagnetism: magnetic domains to geologic terranes.* Blackwell Scientific Publications, Boston, 319p.

Debacker, T.N. 2001. *Palaeozoic deformation of the Brabant Massif within eastern Avalonia: how, when and why?* Unpublished Ph.D.-thesis, Laboratorium voor Paleontologie, Universiteit Gent.

Debacker, T.N., Dewaele, S., Sintubin, M., Verniers, J., Muchez, Ph. & Boven, A. 2005. Timing and duration of the progressive deformation of the Brabant Massif, Belgium. *Geologica Belgica* **8**, 20-34.

Debacker, T.N., Herbosch, A. & Sintubin, M. 2005a. The supposed thrust fault in the Dyle-Thyle outcrop area (southern Brabant Massif, Belgium) re-interpreted as a folded low-angle extensional detachment. *Geologica Belgica* **8**, 53-69.

Debacker, T.N., Herbosch, A., Verniers, J. & Sintubin, M. 2004c. Faults in the Asquempont area, southern Brabant Massif, Belgium. *Netherlands Journal of Geosciences/Geologie en Mijnbouw* **83**, 49-65.

Debacker, T.N., Robion, P. & Sintubin, M. 2004b. The anisotropy of magnetic susceptibility (AMS) in low-grade, cleaved pelitic rocks: influence of cleavage/bedding angle and type and relative orientation of magnetic carriers. In: *Magnetic Fabric: Methods and Applications* (Martin-Hernandez, F., Lüneburg, C.M., Aubourg, C. & Jackson, M., Eds.). *Geological Society, London, Special Publications* **238**, 77-107.

Debacker, T.N., Robion, P. & Sintubin, M. 2005b. Complexity of the Anisotropy of Magnetic Susceptibilitiy in Single-Phase Deformed, Low-Grade, Cleaved Mudstone. *Materials Science Forum* **495-497**, 45-50.

Debacker, T.N., Sintubin, M. & Verniers, J. 2004a. Transitional geometries between gently plunging and steeply plunging folds: an example from the Lower Palaeozoic Brabant Massif, Anglo-Brabant deformation belt, Belgium. *Journal of the Geological Society, London* **161**, 641-652.

Debacker, T. N., van Noorden, M., Sintubin, M. 2006. Distinguishing syn-cleavage folds from pre-cleavage folds to which cleavage is virtually axial planar: examples from the Cambrian core of the Lower Palaeozoic Anglo-Brabant Deformation Belt (Belgium). *Journal of Structural Geology* **28**, 1123-1138.

Delcambre, B. & Pingot, J.-L. 2002. *Notice explicative de la carte Chastres-Gembloux*, 72 p; Ministère de la Région wallonne. Namur.

Delcambre, B., Pingot, J.-L. & Herbosch, A. 2002. *Carte Chastre-Gembloux n° 40/5-6, Carte géologique de Wallonie, échelle 1/25000*. Namur: Ministère de la Région Wallonne.

de la Vallée-Poussin, J. 1931 Contribution à l'étude du massif Cambrien dans les vallées de la Dyle et de la Gette. *Mémoire de l'Institut de géologie, Université de Louvain* **6**, 319-353.

De Magnée, I. & Anciaux, P. 1945 Note préliminaire sur le métamorphisme à grenats du Brabant. *Bulletin de la Société Belge de Géologie* **14**, 77-85.

De Vos, W., Verniers, J., Herbosch, A. & Vanguestaine, M. 1993. A new geological map of the Brabant Massif, Belgium. *Geological Magazine* **130**, 605-611.

Dumont, A. 1848. Mémoire sur les terrains ardennais et rhénan de l'Ardenne, du Rhin, du Brabant et du Condros: seconde partie: terrain rhénan. *Mémoires de l'Académie royale de la Belgique, Classe des Sciences* **22**, 1-451.

Fourmarier, P. 1921. La tectonique du Brabant et des régions voisines. *Mémoires de l'Académie royale de la Belgique, Classe Sciences (2è sér.)* **4**, 1-95.

Hennebert, M. & Eggermont, B. 2002. *Carte Braine-le-Comte - Feluy n° 39/5-6, Carte géologique de Wallonie, échelle 1/25000*. Namur, Ministère de la Région Wallonne.

Herbosch, A., Dumoulin, V., Blockmans, S. & Debacker, T. (in press). *Carte Rebecq-Ittre n° 39/1-2, Carte géologique de Wallonie, échelle 1/25000.* Namur, Ministère de la Région Wallonne.

Herbosch, A., Dumoulin, V., Blockmans, S. & Debacker, T. (submitted). *Carte Jodoigne-Jauche n° 40/3-4, Carte géologique de Wallonie, échelle 1/25000.* Namur, Ministère de la Région Wallonne.

Herbosch, A. & Lemonne, E. 2000. *Carte Nivelles-Genappe n° 39/7-8, Carte géologique de Wallonie, échelle 1/25000.* Namur, Ministère de la Région Wallonne.

Herbosch, A & Verniers, J. 2002. The Lower Paleozoic Stratigraphy and Sedimentology of the Brabant Massif in the Dyle and Orneau valleys and the Condroz Inlier at Fosses: an Excursion Guidebook. *Geologica Belgica* **5**, 71-142.

Hunt, C.P., Moskowitz, B.M. & Banerjee, S.K. 1995. Magnetic properties of rocks and minerals. In: *A Handbook of Physical Constants, vol. 3* (T.J. Ahrens, ed.). American Geophysical Union, Washington, DC, pp. 189–204.

Jelinek, V. & Pokorny, J. 1997. Some new concepts in technology of transformer bridges for measuring susceptibility anisotropy of rocks. *Physics and Chemistry of the Earth* **22**, 179-181.

Kaisin, F. 1919. *Esquisse sommaire d'une description géologique de la Belgique*. Uystpruyst, Louvain, 154p.

Lecompte, M. 1948. Existence du Trémadoc dans le Massif du Brabant. *Bulletin de l'Académie Royale de Belgique, Classe des Sciences* **34**, 677-687.

Lecompte, M. 1949. Découverte de nouveaux gites à Dictyonema dans le Tremadocien du massif du Brabant. *Bulletin de l'Institut Royal des Sciences Naturelles de Belgique, Sciences de la Terre* **25**, 1-8.

Lecompte, M. 1957. Schistes et quartzites de Jodoigne. In: *Lexique stratigraphique International. Volume 1: Europe, fascicule 4a1: France, Belgique, pays-Bas, Luxembourg, Antécambrien et Paléozoïque Inférieur* (P. Pruvost, & G. Waterlot, eds.), 268 p.

Legrand, R. 1967. Ronquières, documents géologiques. *Mémoires pour servir à l'Explication des Cartes géologiques et minières de la Belgique* **6**, 1-60.

Legrand, R. 1968. Le Massif du Brabant. *Mémoires pour servir à l'Explication des Cartes géologiques et minières de la Belgique* **9**, 1-148.

Lowrie, W. 1990. Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties. *Geophysical Research Letters* **17**, 159-162.

Malaise, C. 1873. *Description du terrain silurien du centre de la Belgique*. Bruxelles, Imprimerie F. Hayez.

Malaise, C. 1883. Sur la constitution du massif du Brabant. *Bulletin de l'Académie royale de la Belgique*. **5**, 1-184.

Malaise, C. 1900. Etat actuel de nos connaissances sur le Silurien de la Belgique. *Annales de la Société Géologique de Belgique* **25(bis)**, 179-221.

Malaise, C. 1911. Sur l'évolution de l'échelle stratigraphique du Siluro-Cambrien de Belgique. *Annales de la Société Géologique de Belgique* **38**, 7-28.

Martin, F. 1968. Ordovicien et Silurien belge: données nouvelles apportées par l'étude des acritarches. *Bulletin de la Société belge de Géologie, de Paléontologie et d'Hydrologie* **77**, 175-181.

Martin, F. 1976. Acritarches du Cambro-Ordovicien du Massif du Brabant, Belgique. *Bulletin de l'Institut Royal des Sciences Naturelles de Belgique, Sciences de la Terre* **51**, 1-33.

Michot, P. 1980. Le segment tectogénique calédonien belge. *Mémoires de l'Académie Royale de la Belgique, Classe des Sciences (2e série)* **43**, 1-61.

Mortelmans, G. 1955. Considérations sur la structure tectonique et la stratigraphie du Massif du Brabant. *Bulletin de la Société belge de Géologie, de Paléontologie et d'Hydrologie* **64**, 179-218.

Mortelmans, G. 1977. Le groupe Devillien: Cambrien ou Précambrien? *Annales des Mines de Belgique* **1977**, 309-334.

Nagata, T. 1961. *Rock magnetism*. Maruzen Ltd., Tokyo, 350p.

Piessens, K., De Vos, W., Beckers, R., Vancampenhout, P. & De Ceukelaire, M. 2005. *Project VLA03-1.1: Opmaak van de pre-Krijt subcropkaart van het Massief van Brabant voor invoering in de Databank Ondergrond Vlaanderen.* Unpublished end-report, Koninklijk Belgisch Instituut voor Natuurwetenschappen, Belgische Geologische Dienst, 90 p.

Piessens, K., De Vos, W., Herbosch, A., Debacker, T. & Verniers, J. 2004. Lithostratigraphy and geological structure of the Cambrian rocks at Halle-Lembeek (Zenne Valley, Belgium). *Geological Survey of Belgium Professional Paper* **300**, 1-166.

Piper, J.D.A. 1987. *Palaeomagnetism and the continental crust.* Open University Press, Milton Keynes, U.K., 434p.

Raynaud, J. 1952. Contribution magnétique à la connaissance géologique du massif de la Gette. *Annales de la Société Géologique de Belgique* **75**, B283-B291.

Rutot, A. & Van den Broeck, E. 1890. Matériaux pour servir à la connaissance de la composition chimique des eaux artésiennes du sous-sol de la Belgique dans leurs rapports avec les couches géologiques qui les renferment. *Bulletin de la Société belge de géologie* **4,** 170-220.

Sintubin, M., Brodkom, F. & Laduron, D. 1998. Cleavage-fold relationships in the Lower Cambrian Tubize Group, southeast Anglo-Brabant Fold Belt (Lembeek, Belgium). *Geological Magazine* **135**, 217-226.

Sintubin, M., Lemonne, E. & Herbosch, A. 2002. Some structural particularities on a Tubize-Formation outcrop at Mont-Saint-Guibert (Brabant Massif, Belgium). *Geologica Belgica* **5**, 51-53.

Stacy, F.D. & Banerjee, S.K. 1974. *The physical principles of rock magnetism.* Elsevier, Amsterdam, 195p.

Vander Auwera, J. 1983. *Étude pétrographique, sédimentologique et géochimique de l'Assise de Tubize (DV2) - Massif du Brabant - Belgique.* Unpublished M. Sc.-thesis, Département des Sciences de la Terre, Université Libre de Bruxelles.

Van Grootel, G., Verniers, J., Geerkens, B., Laduron, D., Verhaeren, M., Hertogen, J. & De Vos, W. 1997. Timing of magmatism, foreland basin development, metamorphism and inversion in the Anglo-Brabant fold belt. *Geological Magazine* **134**, 607-616.

Vanguestaine, M. 1973. Etude palynologique du Cambro-Ordovicien de la Belgique et de l'Ardenne française. Thèse de doctorat inédite, Université de Liège.

Vanguestaine, M. 1991. Datation par acritarches des couches cambro-trémadociennes les plus profondes du sondage de Lessines., *Annales de la Société Géologique de Belgique* **114**, 213-231.

Vanguestaine, M. 1992. Biostratigraphie par acritarches du Cambro-Ordovicien de Belgique et des regions limitrophes: synthèse et perspectives d'avenir. *Annales de la Société Géologique de Belgique* **115**, 1-18.

Vanguestaine, M., Servais, T. & Steemans, P. 1989. Biostratigraphy of 28 boreholes in the Brabant Massif. Abstracts of the International Meeting on the Caledonides of the Midlands and the Brabant Massif, p. 46.

Verniers, J., Herbosch, A., Vanguestaine, M., Geukens, F., Delcambre, B. Pingot, J.L., Belanger, I., Hennebert, Debacker, T., Sintubin, M. & De Vos, W. 2001. Cambrian-Ordovician-Silurian lithostratigraphical units (Belgium). *Geologica Belgica* **4**, 5-38.

Verniers, J., Pharaoh, T., André, L., Debacker, T., De Vos, W., Everaerts, M., Herbosch, A., Samuelsson, J., Sintubin, M. & Vecoli, M. 2002. Lower Palaeozoic basin development and Caledonian deformation history in and around Belgium in the framework of Eastern Avalonia. In: *Palaeozoic Amalgamation of Central Europe* (J. Winchester, T. Pharaoh & J. Verniers, eds.). *Geological Society, London, Special Publication* **201**, 47-93.

Von Hoegen J., Kramm U. & Walter R. 1990. The Brabant Massif as part of Armorica/Gondwana: U-Pb isotopic evidence from detrital zircons. *Tectonophysics* **185**, 37-50.

Walz, F. 2002. The Verwey transition-a topical review. *Journal of Physics: Condensed Matter* **14**, R285-R340.

(Manuscript received 04.09.2007 and accepted 29.11.2007, published on line 01.02.2008)