GEOLOGICA BELGICA (2004) 8/3: 53-69.

THE SUPPOSED THRUST FAULT IN THE DYLE-THYLE OUTCROP AREA (SOUTHERN BRABANT MASSIF, BELGIUM) RE-INTERPRETED AS A FOLDED LOW-ANGLE EXTENSIONAL DETACHMENT.

Timothy N. DEBACKER[1], Alain HERBOSCH[2] & Manuel SINTUBIN[1]

(14 figures)

1. Structural Geology & Tectonics Group, Katholieke Universiteit Leuven, Redingenstraat 16, B-3000 Leuven, timothy.debacker@geo.kuleuven.ac.be, manuel.sintubin@geo.kuleuven.ac.be
2. Département des Sciences de la Terre et de l'environnement, Université Libre de Bruxelles, Avenue F. Roosevelt 50 CP160/02, B-1050 Bruxelles, herbosch@ulb.ac.be

ABSTRACT. Since 1943 the anomalous contact in the Dyle-Thyle area between the Lower Cambrian Tubize Formation and older deposits, on the one hand, and the Upper Cambrian Mousty Formation and younger deposits, on the other hand, has been interpreted as a gently N-dipping, large-displacement thrust, the Orne-Noirmont-Baudecet thrust. The irregular fault trace and the presence of a supposed klippe at Court-St.-Etienne are both ascribed to the very gentle fault dip. However, a review of outcrop, borehole and geophysical data shows that there are no convincing arguments for such a gently N-dipping thrust. An alternative model is proposed in which the Orne-Noirmont-Baudecet fault is considered a pre-cleavage and pre-folding low-angle extensional detachment, similar to the Asquempont fault *sensu* Debacker in the Senne-Sennette area. The irregular subcrop trace of the Orne-Noirmont-Baudecet fault is attributed to the strongly variable fold orientations, associated with a transition zone between steeply plunging and gently plunging folds, similar to what has recently been described in the Senne-Sennette area. Although also this model remains speculative, it is the only model which successfully combines all the data from the Dyle-Thyle area and which is compatible also with the structural architecture of other outcrop and subcrop areas of the Brabant Massif.

KEY-WORDS. Aeromagnetic, Anglo-Brabant deformation belt, extensional detachment, fold transition zone, slate belt, steeply plunging folds.

1. Introduction

The Lower Palaeozoic Brabant Massif (Fig. 1) forms the southeastern part of the Anglo-Brabant Deformation belt, one of the fold belts of eastern Avalonia (Van Grootel *et al*., 1997; Verniers *et al*., 2002). An angular unconformity separates the deformed, low-grade Lower Palaeozoic deposits of the Brabant Massif from overlying, diagenetic, undeformed Givetian and younger deposits (Legrand, 1967, 1968; De Vos *et al*., 1993a). At present, there is only evidence for one deformation phase, thought to have taken place between the Llandovery and the Eifelian (Debacker *et al*., 2002; Verniers *et al*., 2002). This deformation phase mainly resulted in the development of folds and a well-developed cogenetic cleavage (e.g. Sintubin, 1997a, 1999; Sintubin *et al*., 1998; Debacker *et al*., 1999, 2003, 2004a; Debacker, 1999, 2001). Although in the past, several studies have advocated the importance of thrusts in the deformation history of the Brabant Massif (e.g. Anthoine & Anthoine, 1943; Mortelmans, 1955; Legrand, 1967), recent studies have not found evidence for this (e.g. Giese *et al*., 1997). Instead, in the outcrop areas of the Brabant Massif, thrust faults appear to be scarce and have a rather limited effect on the stratigraphy in comparison to normal faults (e.g. Debacker, 2001; Debacker *et al*., 2003, 2004b). The few thrust structures that are observed have relatively small displacements, and usually show a direct relationship with folds and cleavage (e.g. Debacker, 1999, 2001; Debacker *et al*., 2003, 2004b).

However, seemingly in contrast with this, in the Dyle-Thyle outcrop area, an enigmatic contact exists between the Lower Cambrian Tubize and Blanmont formations on the one hand and the Mousty Formation and younger formations on the other hand (Figs 1-2), which, following the ideas of Anthoine & Anthoine (1943) is commonly interpreted as a gently N-dipping large-displacement thrust structure, the Orne-Noirmont-Baudecet thrust (e.g. see Herbosch *et al*., 2000, 2001, 2002a, 2002b; Herbosch & Lemonne, 2000; Delcambre *et al*., 2002; cf. Legrand, 1968, De Vos *et al*., 1993a). The trace of this supposed thrust fault has an E-W-trend near Ottignies, a N-S-trend to the east of Court-St.-Etienne, across the Orne valley, where it follows the Glory brook and is called Orne fault (Anthoine & Anthoine, 1943), and an E-W-trend again to the SE, approximately 2 km south of Chastre where it is called the Noirmont-Baudecet fault (Herbosch *et al*., 2001; Fig. 2). The apparently isolated body of rocks of the Tubize Formation at Court-St.-Etienne, amidst rocks of the Mousty Formation, is generally interpreted as a klippe, related to the same large thrust. However, as will become clear from the present paper, although indeed there is evidence for an anomalous contact between the aforementioned formations in the Dyle-Thyle outcrop area, there are remarkably few data in support of a gently N-dipping thrust. The present paper gives an outline of the reasoning behind and supposed arguments for the thrust fault hypothesis, gives an overview of the main problems associated with this hypothesis and finally suggests an alternative model in which all the data from

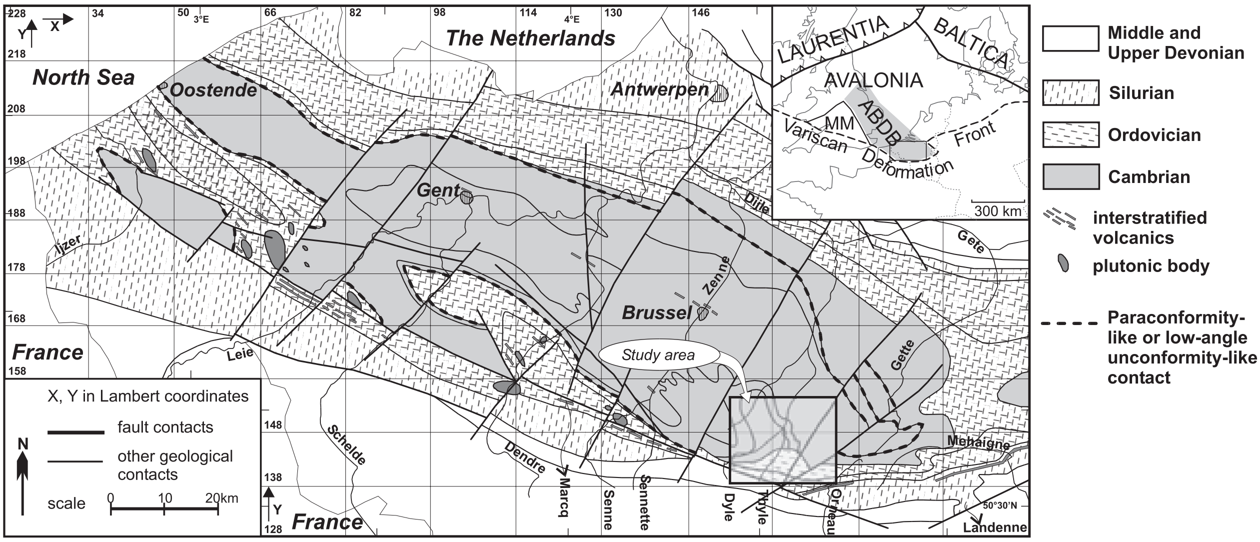

Figure 1. Geological subcrop map of the Brabant Massif, after De Vos *et al*. (1993a) and Van Grootel *et al*. (1997), with location of the study area (see also Fig. 2) and position of the Brabant Massif within Avalonia, as the southeastern part of the Anglo-Brabant Deformation belt (ABDB), flanking the Midlands Microcraton (MM) (upper right inset). The map shows an unexplained paraconformity-like or low-angle unconformity-like contact between the Lower Cambrian and the Ordovician (Middle to Upper Ordovician on top of Lower to lower Middle Cambrian in southwestern part of massif, Lower Ordovician on top of Lower to lower Middle Cambrian in northwestern part, Upper Cambrian on top of Lower Cambrian in northeastern and eastern part; cf. Debacker *et al*., in press). Along the southern part of the massif, between the Sennette valley and the Dendre valley, this contact is interpreted as the Asquempont fault, a pre-cleavage low-angle, extensional detachment (Debacker *et al*., 2003, in press).

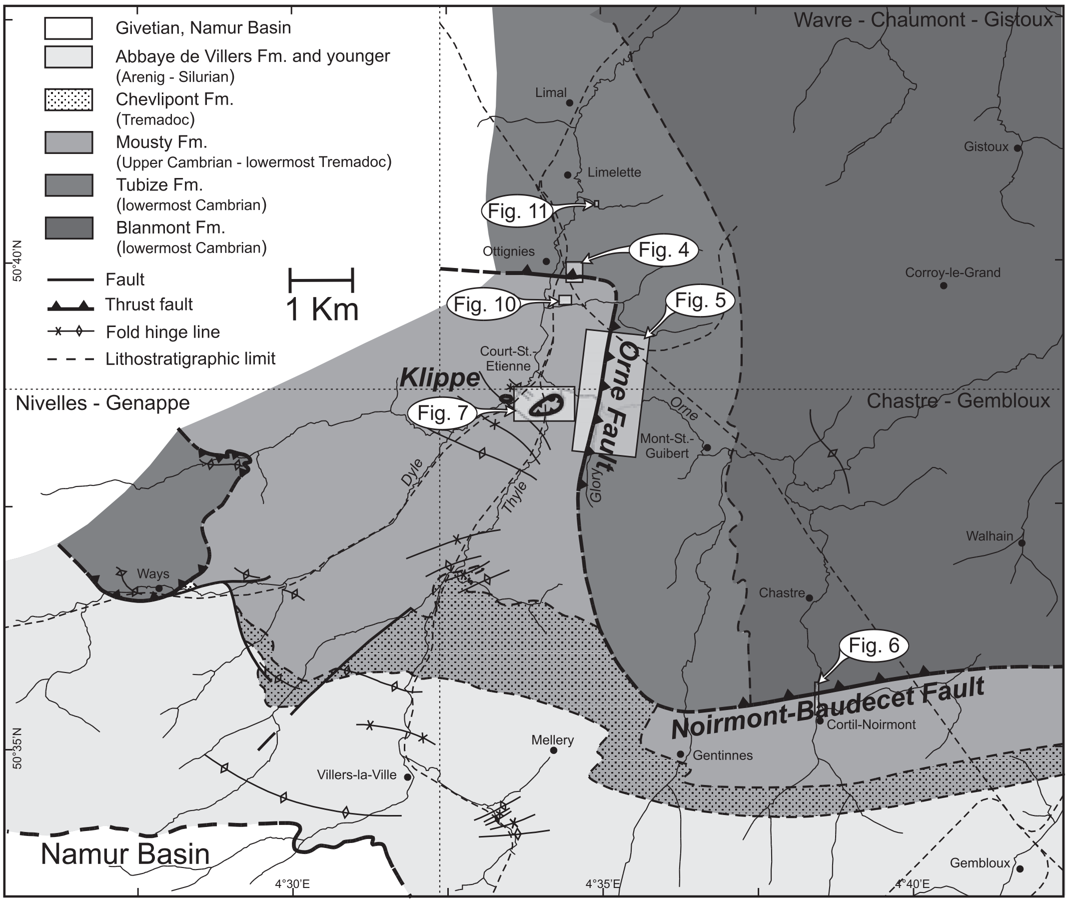

Figure 2. Simplified geological map of the Lower Palaeozoic of the Dyle-Thyle outcrop area, taken from Herbosch & Lemonne (2000), Herbosch *et al*. (2000, 2001, 2002a) and Delcambre *et al*. (2002). On this map, the Orne-Noirmont-Baudecet fault is interpreted as a gently N-dipping, large-displacement thrust, and the apparently isolated body of the Tubize Formation at Court-St.-Etienne as a "klippe" related to this thrust (e.g. Delcambre *et al*., 2002). The positions of Figs 4, 5, 6, 7, 10 & 11 are indicated.

the Dyle-Thyle outcrop area can be successfully integrated and which is more compatible with the structural architecture within the other outcrop areas of the Brabant Massif.

2. Reasoning behind and supposed arguments for the thrust fault hypothesis

2.1. Stratigraphical studies

Malaise (1883), Fourmarier (1921) and de la Vallée Poussin (1931) all suggest a normal stratigraphic contact between the Mousty Formation and the Tubize Formation in the Dyle-Thyle outcrop area. Although Fourmarier (1921) was aware of the fact that in the Senne-Sennette area (Fig. 1) the Tubize Formation and the Lower Ordovician Chevlipont Formation are separated by the Oisquercq Formation, and not by the Mousty Formation, he saw the Mousty Formation as an eastern stratigraphical equivalent of the Oisquercq Formation. Previously, this idea had already been proposed by Malaise (1883), but later this was rejected again by the same author (Malaise, 1900, 1909, 1910), when he considered the Mousty Formation as stratigraphically overlying the Oisquercq Formation. However, also then, Malaise (1900, 1909, 1910) did not feel the need to propose the presence of an important fault. The reason for this probably lies in the claimed presence in the Dyle-Thyle outcrop area of rocks of the Oisquercq Formation in between the Tubize Formation and the Mousty Formation (Malaise, 1900), something which has never been confirmed by other authors.

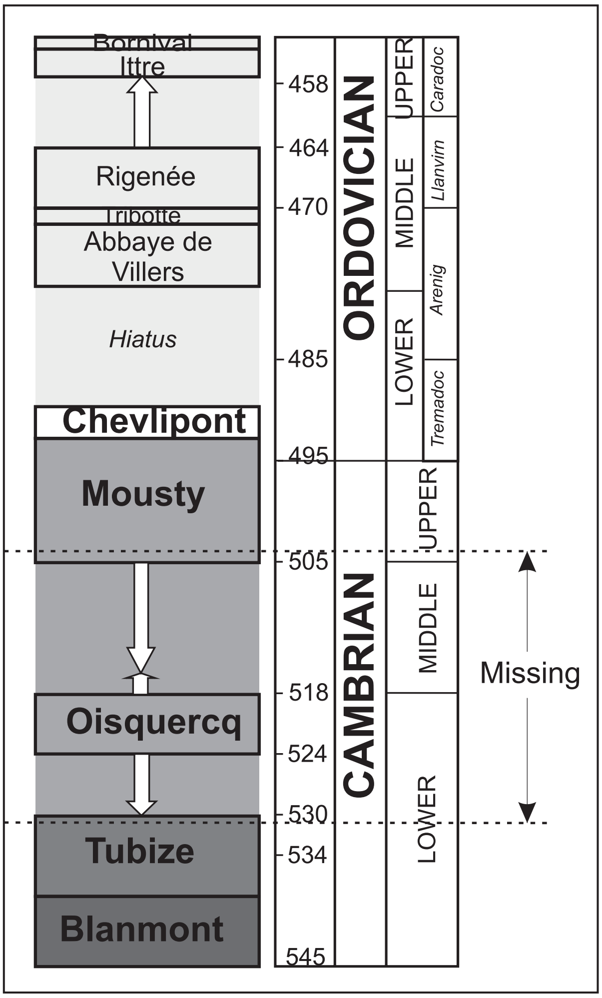

Figure 3. Synthetic chart of the chronostratigraphical position of the Lower Palaeozoic formations present in the study area, taken from Verniers *et al.* (2001). The absolute time-scale is that of Gradstein & Ogg (1996). In the Dyle-Thyle area, the Orne-Noirmont-Baudecet fault juxtaposes the Mousty Formation (and younger) and the Tubize Formation (and older), hereby removing the Oisquercq Formation and parts of the former two formations.

Largely on the basis of a modified stratigraphy (the Mousty Formation was considered to belong to the Arenig), Anthoine & Anthoine (1943) were the first to propose a thrust fault instead of a normal stratigraphic contact between the Tubize Formation and the Mousty Formation. This idea was favoured by Mortelmans (1955), and was also followed by Legrand (1967, 1968), who, like Malaise (1900, 1909, 1910), considered the Mousty Formation as stratigraphically overlying the Oisquercq Formation.

Hence, the interpretation of the contact between the aforementioned formations in the Dyle-Thyle area largely depended on the validity of the stratigraphy (Fig. 3). The two possibilities were that the Mousty Formation in the Dyle-Thyle area and the Oisquercq Formation in the Senne-Sennette area are lateral equivalents, not necessitating a (thrust) fault, or, alternatively, that both have a different age. Apparently, this discussion was ended by the dating of the Oisquercq Formation as Lower to lower Middle Cambrian by means of acritarchs (Vanguestaine, 1991). Previously acritarchs (Martin, 1976; Vanguestaine *et al.*, 1989; Vanguestaine, 1992) and graptolites (Lecompte, 1948, 1949) had already given an age-range of Middle Cambrian to early Tremadoc for the Mousty Formation, and also a gradual transition had been observed between the Mousty Formation and the lower Tremadoc Chevlipont Formation (e.g. Herbosch *et al.*, 2000). Hence, the Mousty Formation and the Oisquercq Formation are not two facies of the same formation but instead represent two consecutive units, the Mousty Formation being younger than the Oisquercq Formation (Herbosch *et al.*, 1991; Vanguestaine, 1991, 1992; De Vos *et al.*, 1993a; Verniers *et al.*, 2001). As a result, the absence of the Oisquercq Formation in the Dyle-Thyle area indeed suggests the existence of an anomalous contact between the Tubize Formation and the Mousty Formation. However, although this does not necessarily imply a thrust fault, the thrust fault hypothesis of Anthoine & Anthoine (1943) is generally used to explain the apparent juxtaposition of the Tubize Formation and older deposits on the one hand and the Mousty Formation and younger deposits on the other hand.

2.2. Mapping, boreholes and geophysical studies

The position of the contact between the Mousty Formation and younger Lower Palaeozoic formations on the one hand and the Tubize and Blanmont formations on the other hand could be positioned more accurately as a result of mapping, geophysical studies and new boreholes. However, as will become clear, none of these studies enabled a direct observation of the supposed thrust fault and not a single dataset yielded evidence for a gentle N-dip of this fault.

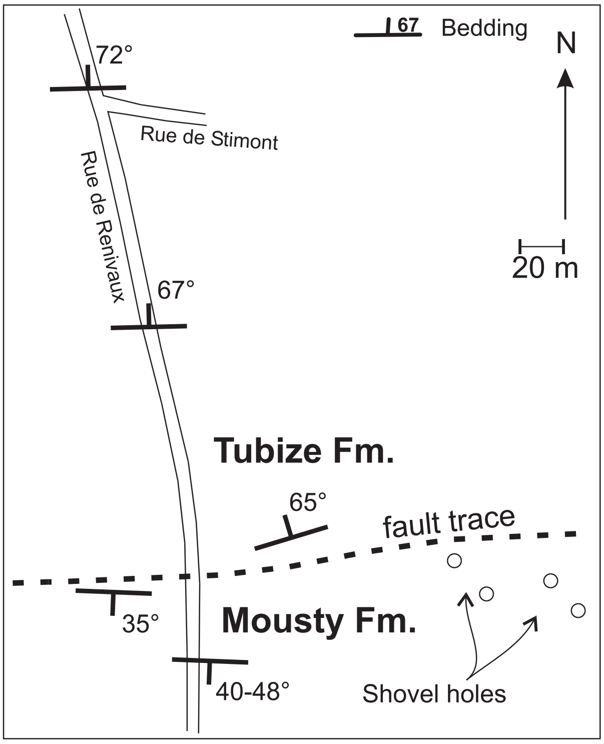

Figure 4. Observations of Van Tassel (1986) in the vicinity of Ottignies (see Fig. 2 for location), constraining the (unobserved) trace of the (fault) contact between the Tubize Formation to the north and the Mousty Formation to the south.

At Ottignies (Fig. 4), the contact between the Tubize Formation and the Mousty Formation, as depicted on Fig. 2, is mainly based on observations by Van Tassel (1986). Although in a N-S-direction, only ~20 metres separate the northernmost outcrops of the Mousty Formation from the southernmost outcrop of the Tubize Formation, and in an E-W-direction these outcrops are separated by only ~80 m (Fig. 4), the contact itself was never observed. Hence, although the trace is likely to be E-W-trending, as depicted by Van Tassel (1986), the dip of the contact remains unknown. The contact may indeed be gently N-dipping, but it may equally well be steeply N-dipping or S-dipping.

The N-S-directed trace of the Orne fault (Fig. 2), running within an unexposed zone of ~125 metres wide between the westernmost outcrops of the Tubize Formation and the easternmost outcrop of the Mousty Formation, is mainly based on the results of a magnetic study performed by de Magnée & Raynaud (1944). These authors observed an abrupt N-S-trending truncation of NNE-SSW-trending magnetic ridges of the Tubize Formation (Fig. 5). The close relationship between bedding orientation and the trend of the magnetic ridges led these authors to interpret the ridges as reflecting bedding. Indeed, several other studies in the Tubize Formation have confirmed the bedding-parallel nature of the magnetite-rich zones (e.g. de Magnée, 1943; Walraevens, 1984; Vander Auwera & André, 1985; De Vos *et al*., 1992). De Magnée & Raynaud (1944) interpret the ridge truncation as a N-S-directed fault. Importantly, they clearly state that they cannot ascertain whether this fault is gently E-dipping or steeply dipping. Hence, there is no evidence for a gentle E-dip. In addition, a recent (1995) destructive vertical borehole ("40/5-237": 130W527; see Fig. 5) of 87 metres deep, situated near the confluence of the Orne and the Glory brook, consists entirely of the Tubize Formation. Taking into account a distance of ~110 metres from the fault

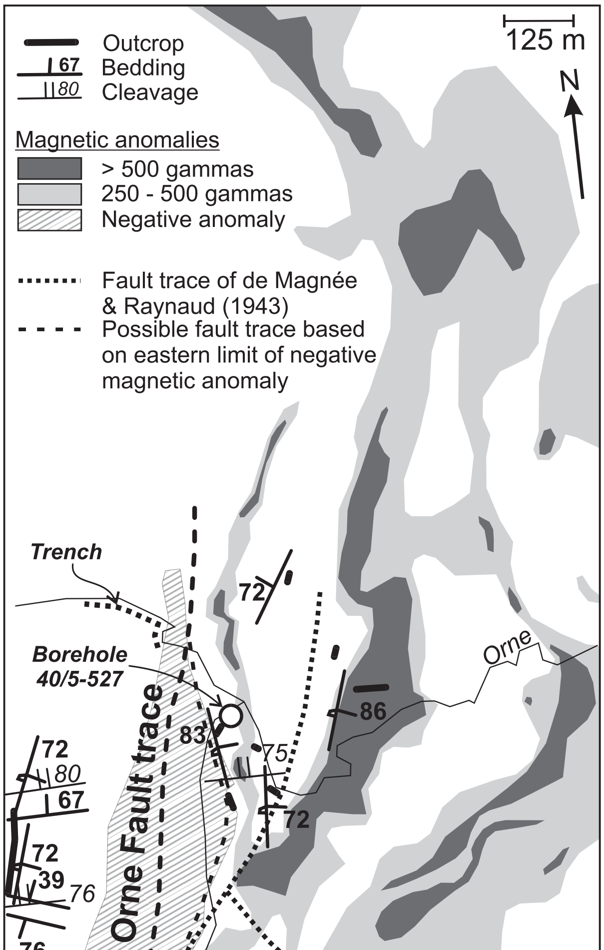

Figure 5. Magnetic anomaly data of de Magnée & Raynaud (1944) in the Orne valley to the east of Court-St.-Etienne (see Fig. 2 for location), with bedding and cleavage orientation data taken from Delcambre *et al*. (2002), fault traces of de Magnée & Raynaud (1944) and the Orne fault trace as currently depicted on recent geological maps (e.g. Delcambre *et al*., 2002). Note that the Orne fault trace, which was not depicted by de Magnée & Raynaud (1944), is constrained only by the truncation of the magnetic ridges in the southern part of the map, and, less accurately, by the eastern limit of the negative magnetic anomaly.

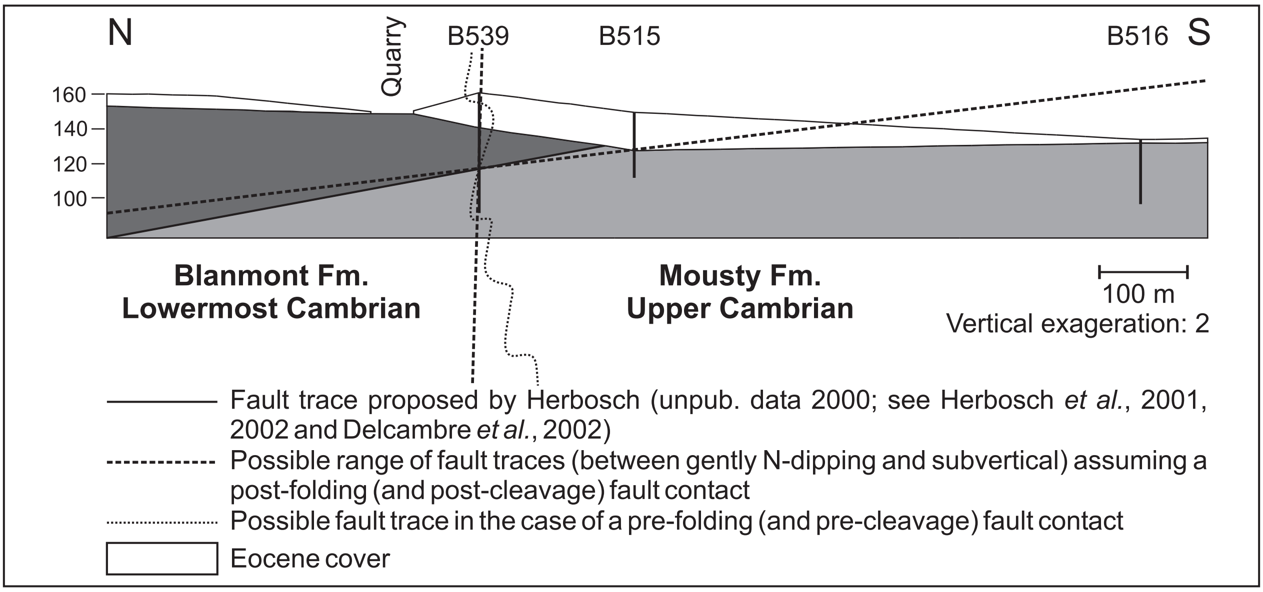

Figure 6. N-S-directed cross-section of the Noirmont area, after Herbosch *et al*. (2001, 2000a, 2000b) and Delcambre *et al*. (2002). B539, B515 and B516 are destructive boreholes. As shown, in the case of a post-cleavage fault, fault dips may range from subvertical to gently N-dipping, whereas in the case of a pre-cleavage fault an even bigger possible range of profile fault traces exists. See Fig. 2 for location.

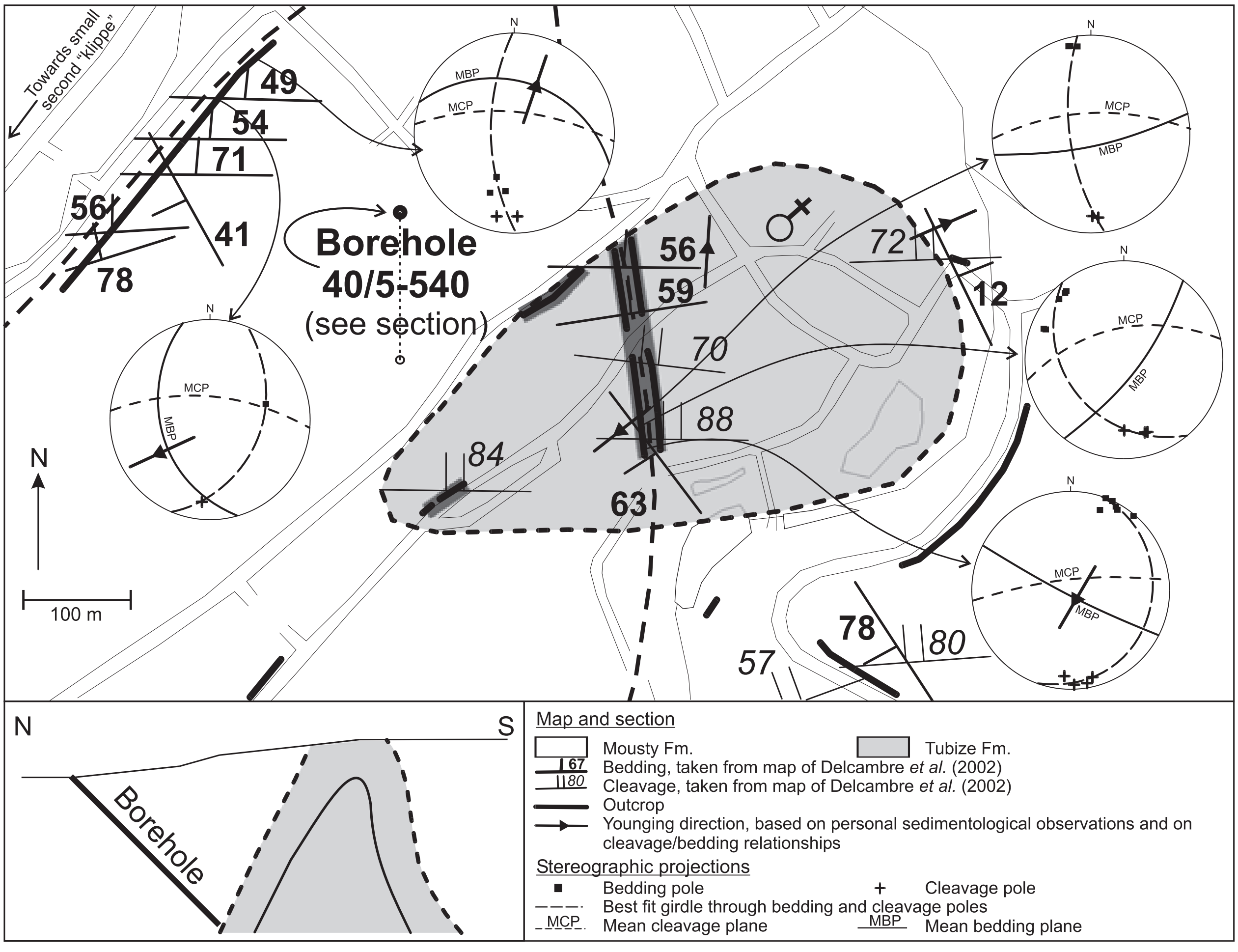

Figure 7. The supposed "klippe" of the Tubize Formation at Court-St.-Etienne, contoured (poorly constrained) after Delcambre *et al*. (2002) and Herbosch (unpub. data), with added cleavage and bedding data of Delcambre *et al*. (2002), and lower hemisphere equal-area projections of cleavage and bedding based on personal observations. The younging direction is based on personal (sedimentological) observations and on cleavage/bedding relationships. The data suggest a dome-like structure, younging outwards. As shown by the cross-section, an alternative hypothesis is possible for the "klippe", compatible with the dome-like architecture and the outward sense of younging. Note that the cleavage/bedding relationships suggest that steeply plunging and gently plunging folds occur both within (Tubize Formation) and surrounding (Mousty Formation) the "klippe". See Fig. 2 for location.

trace (cf. Delcambre *et al.*, 2002) and ~125 m from the easternmost documented occurrence of the Mousty Formation, the fault contact cannot have an E-ward dip of less than ~35°. Also the fault trace itself is not as well constrained as would appear from the recent geological maps, and although these maps do refer to de Magnée & Raynaud (1944), the trace shown generally does not reflect the ideas of these authors. A clear truncation of the magnetic ridges only occurs in the southern part of Fig. 5. It is only in this part of the area that de Magnée & Raynaud (1944) show a fault trace which coincides with the trace of the Orne fault found on the recent geological maps (cf. Fig. 2). Because of the absence of an obvious westward truncation of the magnetic ridges towards the north, de Magnée & Raynaud (1944) were unable to extend the limit between the Mousty Formation and the Tubize Formation towards the north and only show possible fault traces within the Tubize Formation. However, they do mention that the negative magnetic anomaly likely reflects the Mousty Formation, and hence that the fault is approximately parallel to the Glory brook, situated approximately 100 m to the west of the brook (Fig. 5). Further north, in the northern part of Fig. 5, the magnetic ridges markedly change trend, without being truncated, implying that the Orne fault should run to the west of these and hence is not as linear as generally depicted (Fig. 2; cf. Herbosch *et al.*, 2000, 2002a, 2002b; Delcambre *et al.*, 2002).

The trace of the Noirmont-Baudecet fault at Noirmont, approximately two kilometres to the south of Chastre (Fig. 6; cf. Fig. 2), is constrained by one outcrop of the Blanmont Formation and two destructive boreholes, of which the northernmost one (borehole 539) shows the Blanmont Formation in the upper parts and the Mousty Formation in the lower parts (below an altitude of 117 m; Herbosch & Lemonne, 2000; Delcambre *et al.*, 2002; Herbosch *et al.*, 2002b). Although this seems compatible with the thrust hypothesis, some reservations must be made. Since it is a destructive borehole, the nature and dip of the contact cannot be deduced from the borehole itself. Borehole 515, situated 175 m to the south of borehole 539, only shows the Mousty Formation (below altitude of 127 m). Although it is tentative to use this as an argument for a gently N-dipping contact (Herbosch *et al.*, 2000, 2001), these data only demonstrate that the contact may have a mean apparent dip between 3° and 89°N, as shown in Fig. 6 (cf. Delcambre *et al.*, 2002). Hence, although these data indeed suggest a mean N-dip for the anomalous contact between the Blanmont Formation and the Mousty Formation, there is no evidence for this being a gently N-dipping thrust.

The presumed "klippe" is proposed to explain the occurrence of a seemingly isolated body of the Tubize Formation amidst rocks of the Mousty Formation at Court-St.-Etienne (Anthoine & Anthoine, 1943;

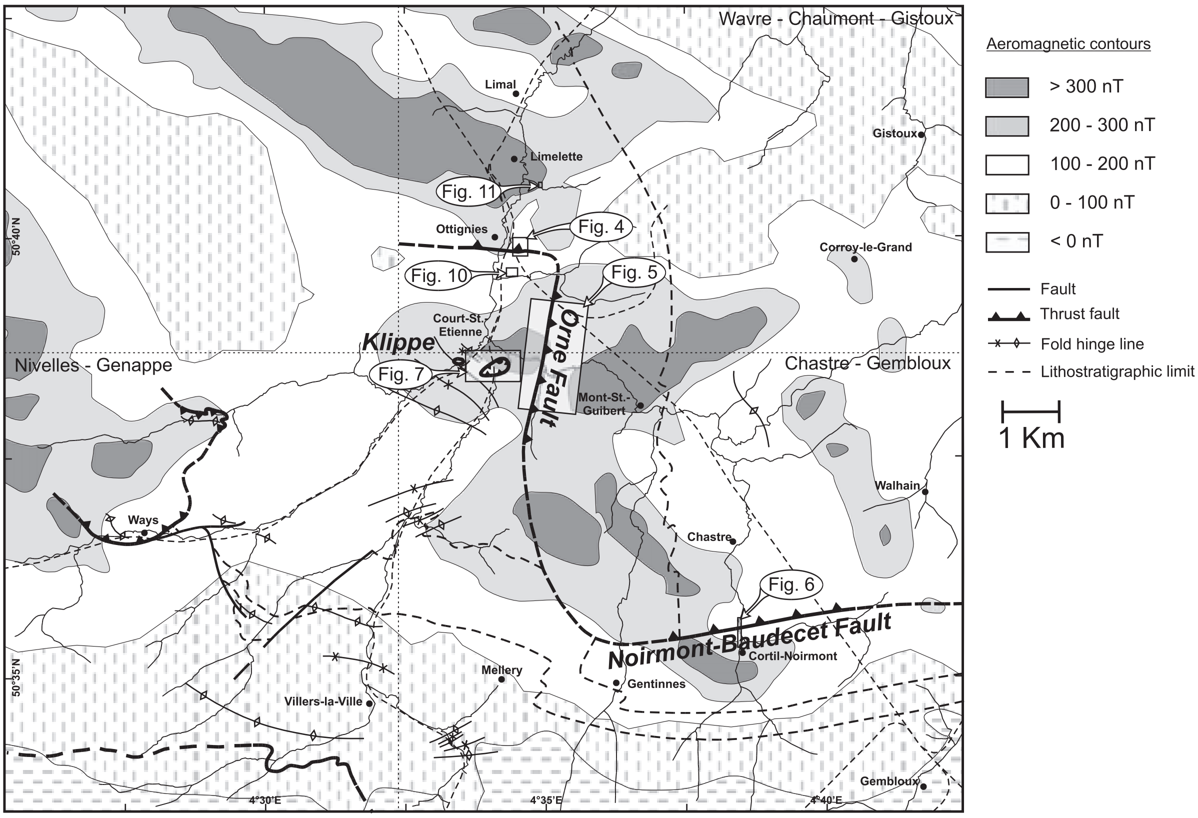

Figure 8. Map of the area, with the main lithostratigraphic limits of Fig. 2 and with added aeromagnetic contours taken from the Belgian Geological Survey (1994). The aeromagnetic highs correspond to the Tubize Formation (e.g. to the NW of Ways, to the N of Ottignies, at Mont-St.-Guibert) and also the "klippe" appears to be expressed aeromagnetically. However, the aeromagnetic highs extend from the Mont-St.-Guibert – Chastre area towards the west of the Orne fault trace where they, instead of being restricted to it, also occur around the "klippe".

Delcambre *et al.*, 2002; Figs 2 & 7). Also here the contacts between the different lithologies have never been observed and the circumference of the "klippe" is poorly constrained (Fig. 7). Instead of a "klippe", the structure might also be interpreted as a "window". In order to check this hypothesis, Herbosch, Pingot & Delcambre (unpub. data) drilled a 45°S-plunging cored borehole just north of the supposed "klippe" (borehole 40/5-540; it was impossible to drill it within the "klippe"). Along its entire length (161 m), this borehole remained within the Mousty Formation, and hence the "window"-hypothesis was abandoned. However, as shown in Fig. 7, these borehole results only rule out the presence of a "window" formed by a gently dipping contact between the Tubize Formation and the Mousty Formation. Because of the poorly constrained limit of the Tubize Formation at Court-St.-Etienne, it may be possible that the structure is a "window"-like antiformal structure of which the northern part is formed by a steep contact between the Mousty formation and the Tubize Formation (Fig. 7). According to this scenario the Mousty Formation would be situated on top of the Tubize Formation, being separated from it by a folded (fault) contact. Note that also on the W-bank of the Dyle river, at ~850 m due west of the church of Court-St.-Etienne, there is a local occurrence of the Tubize Formation amidst deposits of the Mousty Formation (Herbosch, unpub. data).

3. Problems associated with the thrust fault hypothesis

3.1. Map trace of the Orne-Noirmont-Baudecet fault

The straight fault trace segments depicted on the geological map (e.g. Delcambre *et al.*, 2002) do not seem compatible with the idea of a gently N-dipping thrust. Across the Orne valley, the Orne fault is drawn as a straight line, being more suggestive of a subvertical or steeply dipping fault instead of a gently dipping one. Similarly, at Ottignies the E-W-trending fault trace is drawn as a straight line across the Dyle-Thyle valley (Figs 2 & 8).

Theoretically, the above criticism might be refuted partly by arguing that a) the current topography does not reflect the predominantly flat basement topography, thus resulting in straight fault traces across valleys (e.g. at Ottignies), and b) the N-S-trending Orne segment does in fact represent a different, steep, dextral fault, displacing the predominantly E-W-trending Noirmont-Baudecet fault, as recently proposed by Herbosch *et al.* (2002b) and Herbosch & Blockmans (in press). However, although adequately explaining the suggested straight fault trace at Ottignies and across the Orne valley, these explanations are difficult to reconcile with the "klippe" at Court-St.-Etienne, without invoking significant changes in fault dip.

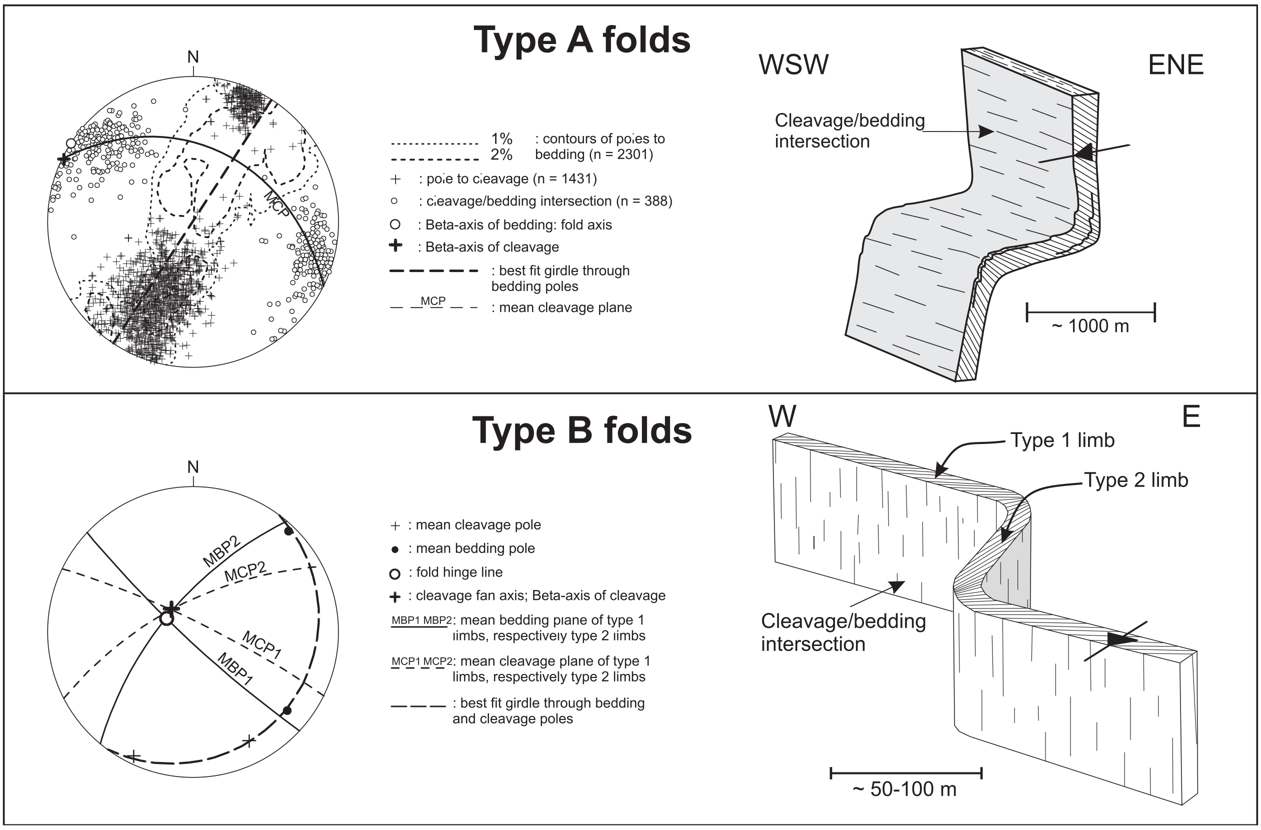

Figure 9. Two main fold types of the Brabant Massif, based on observations from the Sennette valley (after Debacker *et al.*, 2004). The type A folds are subhorizontal to gently plunging folds (data from Debacker, 2001; cf. Debacker *et al.*, 2004) and the type B folds steeply plunging folds (data from Sintubin *et al.*, 1998). Type B folds are only observed within the Cambrian core of the massif. The type A folds are omnipresent within the Ordovician and Silurian outcrop areas, but also occur in the Cambrian core (cf. Figs 11 & 13). A gradual transition exists between the type B folds and the type A folds (Debacker *et al.*, 2004; see also Fig. 12).

3.2. Aeromagnetic data

The aeromagnetic high in the core of the Brabant Massif (see De Vos *et al.*, 1993b, Belgian Geological Survey, 1994) is attributed to the magnetite-bearing Tubize Formation (De Vos *et al.*, 1992, 1993a; Chacksfield *et al.*, 1993). Indeed, to the northeast of the Orne-Noirmont-Baudecet fault trace, the aeromagnetic high coincides with the Tubize Formation (Fig. 8; e.g. see Ottignies, Mont-St.-Guibert).

In the assumption of an important, gently N-dipping thrust, of which the hanging wall is composed of the Tubize Formation and older deposits and the footwall of the Mousty Formation and younger deposits, no aeromagnetic highs would be expected to the south and to the west of the fault trace. However, to the west of the Orne fault, underlying and surrounding the supposed "klippe" at Court-St.-Etienne, high aeromagnetic values are present (Fig. 8). On the one hand, the aeromagnetic high at Court-St.-Etienne is compatible with the local presence of the Tubize Formation, such as in the "klippe". On the other hand, however, the high aeromagnetic values around the "klippe" suggest the presence of magnetite-bearing rocks of the Tubize Formation below the Mousty Formation, thus questioning the "klippe"-hypothesis. The aeromagnetic high of Court-St.-Etienne joins an aeromagnetic high to the east of the Orne fault trace, seemingly without interruption. Also ~3 kilometres to the south of Court-St.-Etienne, a similar aeromagnetic high is present to the west of the Orne fault trace that continues towards the SE below the supposed thrust, without any interruption. In addition, this high extends SE-ward to the south of the Noirmont-Baudecet trace. The fact that these highs, most likely reflecting the magnetite-bearing rocks of the Tubize Formation, extend across the fault traces without interruption, and also occur within the supposed footwall of the fault, seriously questions the hypothesis of a pluri-kilometric displacement along a gently N-dipping thrust.

3.3. Spatial relationship with steeply plunging and gently plunging folds

At present, two main fold types can be distinguished in

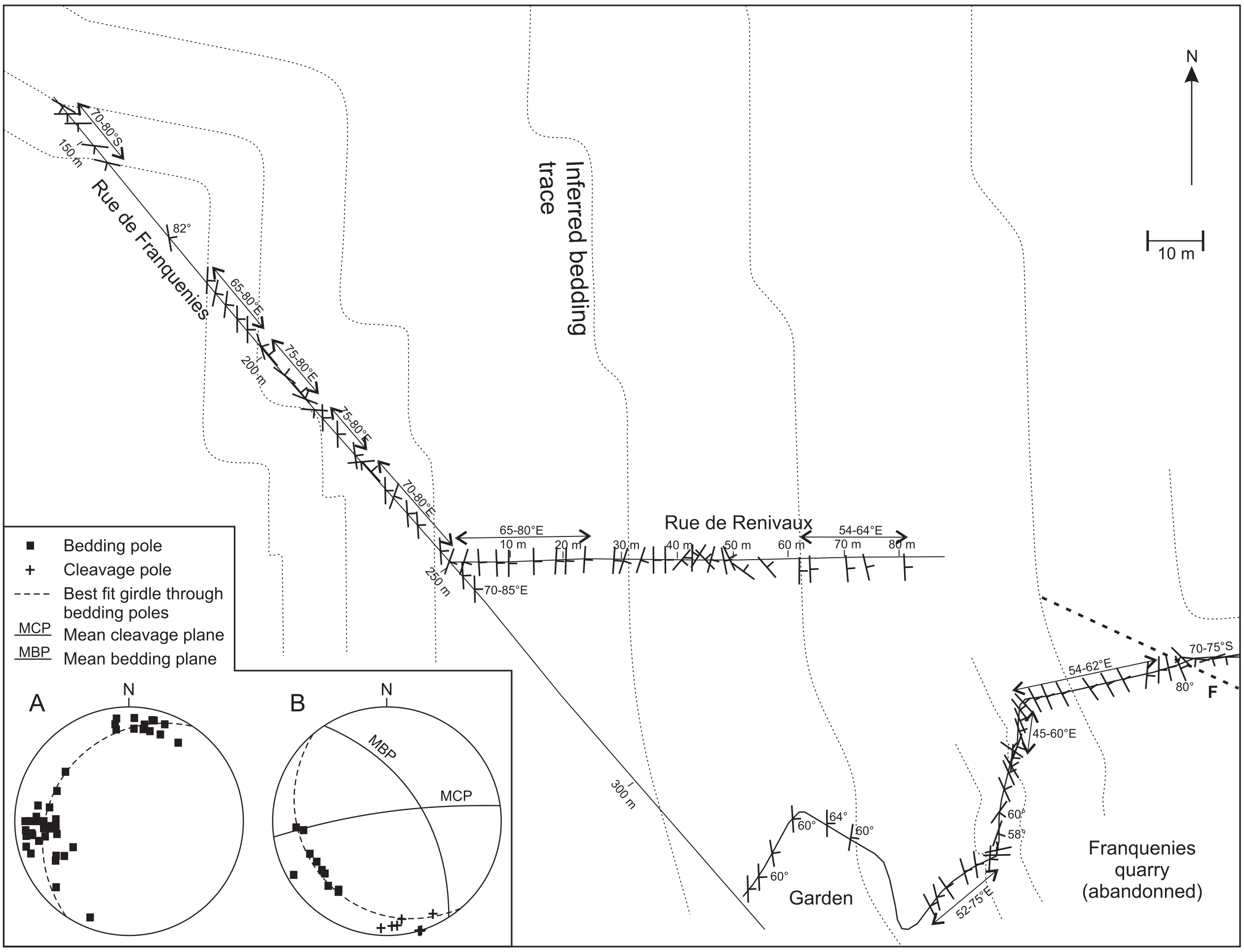

Figure 10. Bedding observations of Van Tassel (1986) within the Mousty Formation at Franquenies, with a personal geometrical interpretation of the probable bedding trace (constructed by means of kink band method). The inset (lower left) shows lower-hemisphere equal-area stereographic projections of (A) the bedding data of Van Tassel (1986) and (B) personal cleavage and bedding data from the SW-side of the Franquenies quarry (garden). Both data sets indicate the presence of type B folds: steeply plunging folds, with a steeply plunging cleavage/bedding intersection lineation. By analogy with Sintubin *et al.* (1998, 2002) the N-S-trending limbs are called type 2 limbs and the E-W-trending limbs type 1 limbs (see also Fig. 9). Note that the limbs in the Mousty Formation at Franquenies are subparallel to the limbs of the type B folds in the Tubize Formation at Beaurieux (type 1 and type 2 limbs; Debacker, 2001) and Mont-St.-Guibert (type 2 limb; Sintubin *et al.*, 2002). See Fig. 2 for location.

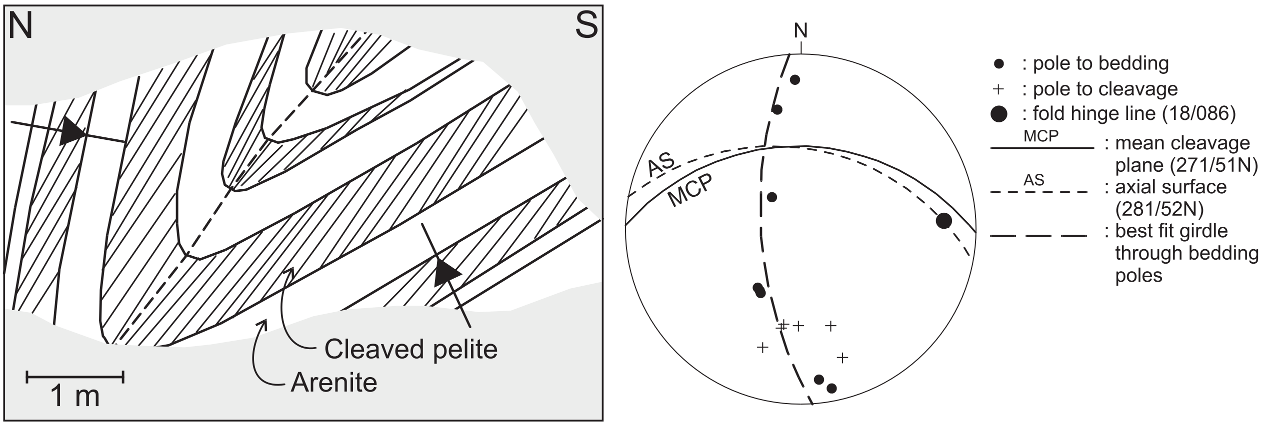

Figure 11. Structural observations at Blanc Ri, to the NE of Ottignies (see Fig. 2 for location), demonstrating the presence of type A folds in the Tubize Formation to the north of the Orne-Noirmont-Baudecet fault (after Debacker, 2001). The younging sense is shown by the arrows.

the Brabant Massif: type A folds and type B folds (Debacker *et al*., 2004a; cf. Sintubin, 1997a, 1999). Both of these are cogenetic with cleavage. As shown in Fig. 9, the main distinction between these is the fold plunge. The type A folds are subhorizontal to gently plunging folds, with gentle to close interlimb angles, rounded to subangular hinges, upright to moderately inclined, slightly asymmetric to the south, often with a stepfold geometry (e.g. Fourmarier, 1921; Sintubin, 1997a; Debacker *et al*., 1999, 2001, 2004a; Debacker, 2001; Beckers, 2003). The type B folds are steeply plunging to reclined folds, upright to steeply inclined, with open to close interlimb angles, subangular hinges and upright to steeply dipping limbs (Fourmarier, 1921; Sintubin, 1997a; Sintubin *et al*., 1998; Debacker, 2001; Debacker *et al*., 2004a). The latter folds were described in detail by Sintubin *et al*. (1998) within deposits of the Tubize Formation at Lembeek, Sennette valley (Fig. 1). There, these folds have a Z-shaped ("dextral") geometry, with NW-SE-trending long limbs and NE-SW-trending short limbs. The former limbs are termed type 1 limbs, the latter limbs type 2 limbs. These type B folds have never been observed outside the Cambrian core of the massif (Fourmarier, 1921; Sintubin, 1997a, 1999; Debacker, 2001; Debacker *et al*., 2004a).

In the Dyle-Thyle outcrop area, known examples of type B folds and type B cleavage/bedding relationships (steeply plunging cleavage/bedding intersection lineation) occur in the Tubize Formation at Mont-St.-Guibert (type 2 limb; Sintubin *et al*., 2002) and at Beaurieux (type 1 limb and type 2 limb; Debacker, 2001; Delcambre *et al*., 2002). Classical examples of type A folds and cleavage/bedding relationships (gently plunging intersection lineation) occur in the Abbaye de Villers Formation in the Thyle valley, along the road Court-St.-Etienne – Villers-la-Ville in the vicinity of the abbey of Villers (Michot, 1977; Debacker, 2001; Beckers, 2003).

The apparently particular occurrence of type B folds and type A folds in the Dyle-Thyle area, the former folds seemingly restricted to the Cambrian core to the NE of the Orne-Noirmont-Baudecet fault, the latter folds to the Ordovician and Silurian to the SW of this fault, is sometimes used as an additional argument for the importance of the Orne-Noirmont-Baudecet fault (Herbosch & Lemonne, 2000; Herbosch *et al*., 2001). However, as can be seen in Fig. 10 (cf. Fig. 2), the data of Van Tassel (1986) demonstrate the presence of steeply plunging folds (type B folds) in the Mousty Formation in the supposed footwall of the fault. In addition, at Ottignies, subhorizontal folds (type A folds) occur in the Tubize Formation, in the supposed hanging wall of the fault (Fig. 11, cf. Fig. 2). Finally, as shown on Fig. 7, both within and surrounding the "klippe" both steeply and gently plunging cleavage/bedding intersections occur, respectively suggesting type B and type A folds. All these observations demonstrate that the contact between the Mousty Formation (and younger deposits) and the Tubize Formation (and older deposits) in the Dyle-Thyle area cannot account for a separation between type A folds and type B folds.

3.4. Structural style

Although Mortelmans (1955) and others strongly favoured the importance of large-displacement thrusts in the Brabant Massif, these structures have never been observed (e.g. Giese *et al*., 1997). In the Senne-Sennette area, normal faults appear to be much more common and have a more significant effect on the distribution of the different stratigraphic levels than thrust faults (Debacker *et al*., 2003, 2004b). In fact, thus far, the only known structure in the Brabant Massif that comes close to a relatively important thrust structure is the low-angle reverse shear zone in the Marcq area (Fig. 1; Debacker, 1999; see also Piessens *et al*., 2000, 2002). However, in the Marcq area, the fold geometry and the cleavage are intimately linked with the low-angle reverse shear zone (Debacker, 1999; Piessens *et al*., 2000, 2002), the stratigraphic displacement appears to be small (Debacker, 1999, Vanguestaine, unpub. data), and there is a plausible cause for the development of the low-angle reverse shear zone, namely an overthrusting of sediments above the rather shallow roof of the low-density gravimetric anomaly body at depth (Debacker, 1999; cf. Everaerts *et al*., 1996, De Vos, 1997; Sintubin, 1999). In contrast, the presumed gently N-dipping thrust in the Dyle-Thyle area does not show any relationship with the folds and the cleavage, is thought to have a displacement of several kilometres (e.g. Herbosch & Lemonne, 2000; Delcambre *et al*., 2002), and there is no likely cause for its development.

4. Reasoning behind an alternative model

Having outlined the reasoning behind the thrust fault hypothesis and the problems associated with it, it becomes clear that an alternative model is welcome in which all the data can be combined and which is more compatible with the structural architecture of the other outcrop areas of the Brabant Massif.

Two recent structural discoveries in the Senne-Sennette area can be used to develop a model for the Dyle-Thyle area: the fold transition zone between steeply plunging and gently plunging folds on the one hand (Debacker *et al*., 2004a), and the redefined Asquempont fault on the other hand (Debacker *et al*., 2003, 2004b). Importantly, both these features are unrelated (Debacker *et al*., 2004a, 2004b).

4.1. Fold transition between steeply plunging and gently plunging folds in the Sennette valley

In the Sennette valley (Fig. 1), Debacker *et al*. (2004a; cf. Debacker, 2001) were able to locate and to characterise a transition zone between the type B folds, considered typical for the steep Cambrian core of the massif (cf. Sintubin *et al*., 1998), and the type A folds, omnipresent in the Ordovician and Silurian southern part of the massif (Fig. 12). Both fold types are cogenetic with cleavage development and there is no evidence for a poly-phase deformation across the transition zone. In contrast to previous opinions (e.g. Sintubin *et al*., 1998), the transition between both fold types occurs rather gradually and repeatedly in a NW-SE-trending zone of 1 to 1.5 kilometres wide, overlying the aeromagnetic Asquempont lineament (*sensu* Sintubin & Everaerts, 2002). Within this zone, both steeply plunging and gently plunging folds are present, with variable fold plunges and facing directions, suggestive of curvilinear fold hinge lines. As shown schematically in Fig. 12, within this fold transition zone, a complex subcrop pattern is expected.

4.2. The Asquempont fault in the Sennette valley

On the basis of outcrop data, combined with borehole data, Debacker *et al*. (2003, 2004b; cf. Debacker, 2001) redefined the Asquempont fault as a pre-cleavage and pre-folding, low-angle extensional detachment, thus contradicting the original idea of a steep, reverse fault put forward by Legrand (1967). As a result of its pre-folding and pre-cleavage nature, the Asquempont fault itself is folded and crosscut by the cleavage. Hence, considering its small angle with bedding and its pre-folding nature, it will almost follow bedding across folds, with the same amplitude, and the same interlimb angle, but will be oriented slightly oblique to bedding. In the Senne-Sennette outcrop area and in subcrop towards the west, this fault places Lower, Middle and Upper Ordovician deposits on top of the Lower to lower Middle Cambrian Oisquercq Formation (Debacker *et al*., 2003, 2004b). This contact is visible on the geological map of De Vos *et al*. (1993a) as a paraconformity-like contact. On this map, similar seemingly laterally continuous paraconformity-like contacts are shown all around the Cambrian core of the Brabant Massif. In the western

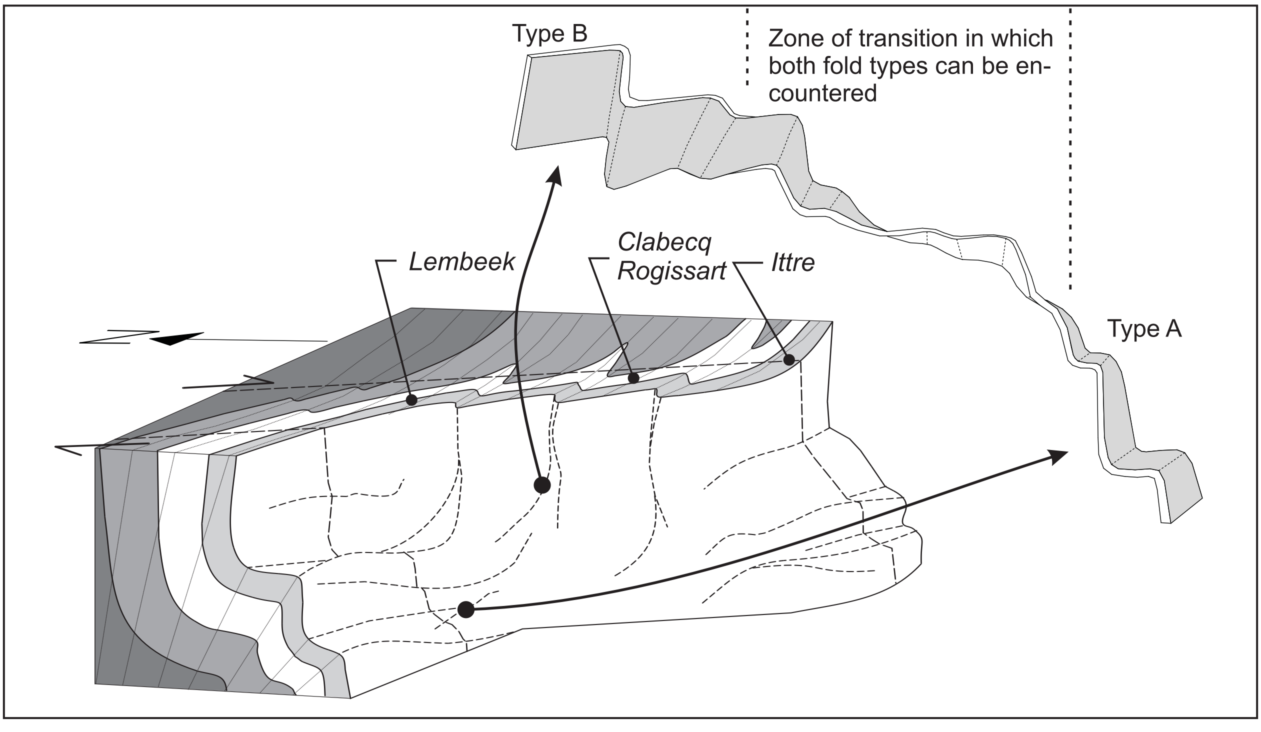

Figure 12. Schematic representation of the transition zone between type A and type B folds in the Sennette valley (taken from Debacker *et al*., 2004). The transition between type A and type B folds occurs gradually and repeatedly in a zone several kilometres wide. Within this transition zone, folds show marked changes in plunge and facing, reflecting curvilinear fold hinge lines.

parts of the massif such a contact forms the limit between the Ordovician and the Oisquercq Formation, whereas to the east, this contact forms the limit between the Mousty Formation and the Oisquercq Formation, and further east between the Tubize Formation and the Mousty Formation (Fig. 1).

4.3. Relevance for the Dyle-Thyle area

The Dyle-Thyle area contains an anomalous contact between the Mousty Formation and the Tubize Formation. A similar contact between these two formations is shown on the map of De Vos *et al.* (1993a) in the eastern part of the Brabant massif, where it follows the curvature of the core of the massif, implying that this contact is folded.

Since both type A folds and type B folds are observed in the Dyle-Thyle area (see above; Van Tassel, 1986; Sintubin, 1997a; Sintubin *et al.*, 2002; Debacker, 2001; Herbosch *et al.*, 2000, 2001, 2002a, 2002b; Delcambre *et al.*, 2002), the presence of a transition zone between these, as observed in the Sennette valley, is likely.

If a pre-cleavage and pre-folding tectonic contact, like the Asquempont fault, would be situated in a transition zone between type A folds and type B folds (Fig. 12), this would give rise to a very irregular fault trace. We feel that this is what happens in the Dyle-Thyle area.

5. Development of the extensional detachment model

5.1. Cleavage/fold relationships in the Dyle-Thyle area

In the case of a large-displacement thrust fault, the folds in the hanging wall and those in the footwall do not need to have the same style or younging sense and obvious mismatches may be expected between the hanging wall and the footwall. However, in the case of a pre-folding extensional detachment, with the Mousty Formation directly on top of the Tubize Formation, the fold styles should not be restricted to either side of the fault, but are expected to extend across the contact, the folds are expected to deform the contact, and in all cases should the younging sense of the beds correspond to the younging sense across the detachment (i.e. towards the Mousty Formation). All three conditions seem to occur in the Dyle-Thyle area.

Figure 13 shows the distribution of the two fold types or cleavage/bedding dispositions across the Dyle-Thyle outcrop area, using a plunge of 35° as a limit between the type A and type B folds (type B > 35°; see also Figs 9 & 12). This distribution is based on personal data (e.g. Court-St.-Etienne, Mont-St.-Guibert, Beaurieux, Franquenies, Ottignies, Ways, Thy; see above) and to a large extent on data from the literature (Van Tassel, 1986; de Magnée & Raynaud, 1944) and on data from geological maps (Herbosch & Lemonne, 2000; Delcambre *et al.*, 2002). In the latter case, the presence of type B folds and type B cleavage/bedding relationships was inferred on the basis of a comparison of bedding data with neighbouring cleavage data, and on the basis of the occurrence of steeply dipping N-S-trending beds, striking at high angles to the structural trend given by the type A folds, cleavage and lithostratigraphic contacts. As can be seen on this map, type A and type B folds occur on both sides of the Orne-Noirmont-Baudecet fault (Fig. 13). In the Lower Cambrian deposits in the northeast of the area, type B folds predominate (e.g. Beaurieux, Mont-St.-Guibert; Debacker 2001, Sintubin *et al.*, 2002,), but also type A folds occur (e.g. Ottignies; see Fig. 11). Similarly, also in the Tubize Formation in the western part of the area, both type B folds (to the W of Ways) and type A folds occur (at Ways and at ~2 km to the NNE Ways; Fig. 13). At Ways, we observed type A cleavage/bedding relationships within the Tubize Formation, which, over a short distance (~20 m), indicate a change in fold plunge from ~20° W in the west to ~30°E in the east, towards Thy (~1.5 km east of Ways; cf. Herbosch & Lemonne, 2000). Such a marked variation in plunge of type A folds over short distances is one of the characteristic features of the fold transition zone observed at Asquempont (Debacker *et al.*, 2004a; Fig. 12). Hence, also at Ways possibly a fold transition zone occurs. The presence of both type A and type B folds in the Tubize Formation in the Ways area supports this idea. As shown above, also the data from the "klippe" suggest the presence of both fold types (see Fig. 7). Although in the Mousty Formation and the Ordovician deposits type A folds predominate, type B folds also occur in the Mousty Formation in the area of Court-St.-Etienne, Franquenies (see Figs 7 & 10) and Thy (Fig. 13). Also the data from the deposits of the Abbaye de Villers Formation and the Tribotte Formation at Thy and to the east of Villers-la-Ville appear to reflect type B folds (Fig. 13). However, in the latter case some caution is necessary. Whereas at Thy, judging from the vicinity of the type B folds in the Tubize Formation and the Mousty Formation, the data may indeed reflect tectonic type B folds, the cleavage/bedding data to the east of Villers-la-Ville point to moderate fold plunges, possibly resulting from slumping. As recently demonstrated, slump folds are quite common in the Abbaye de Villers Formation, and may result in strong variations in plunge and plunge direction (Beckers, 2003; cf. Michot, 1977).

Judging from the distribution of the type A folds and the type B folds across the Dyle-Thyle area, two large zones can be outlined in which a transition occurs from type B folds to type A folds, strongly resembling the fold transition zone at Asquempont (see Fig. 12; cf. Debacker *et al.*, 2004a). A first zone, apparently several kilometres wide, occurs from Ottignies in the NW to Cortil-Noirmont in the SE, and a second zone occurs in the vicinity of Genappe (Ways, Thy) (Fig. 13).

The marked change in trend of the Orne-Noirmont-Baudecet fault to the SE of Ottignies (Fig. 13) may be explained by the data of Van Tassel (1986) from the Mousty Formation at Franquenies (Fig. 10), which demonstrate the presence of type B folds. The eastern part of the area of Fig. 10 is dominated by a steep, N-S-trending type 2 limb, subparallel to the type 2 limbs in the Tubize and Blanmont formations to the east of the Orne fault (e.g. Sintubin *et al.*, 2002; Delcambre *et al.*, 2002; Debacker, 2001), whereas the northwestern part

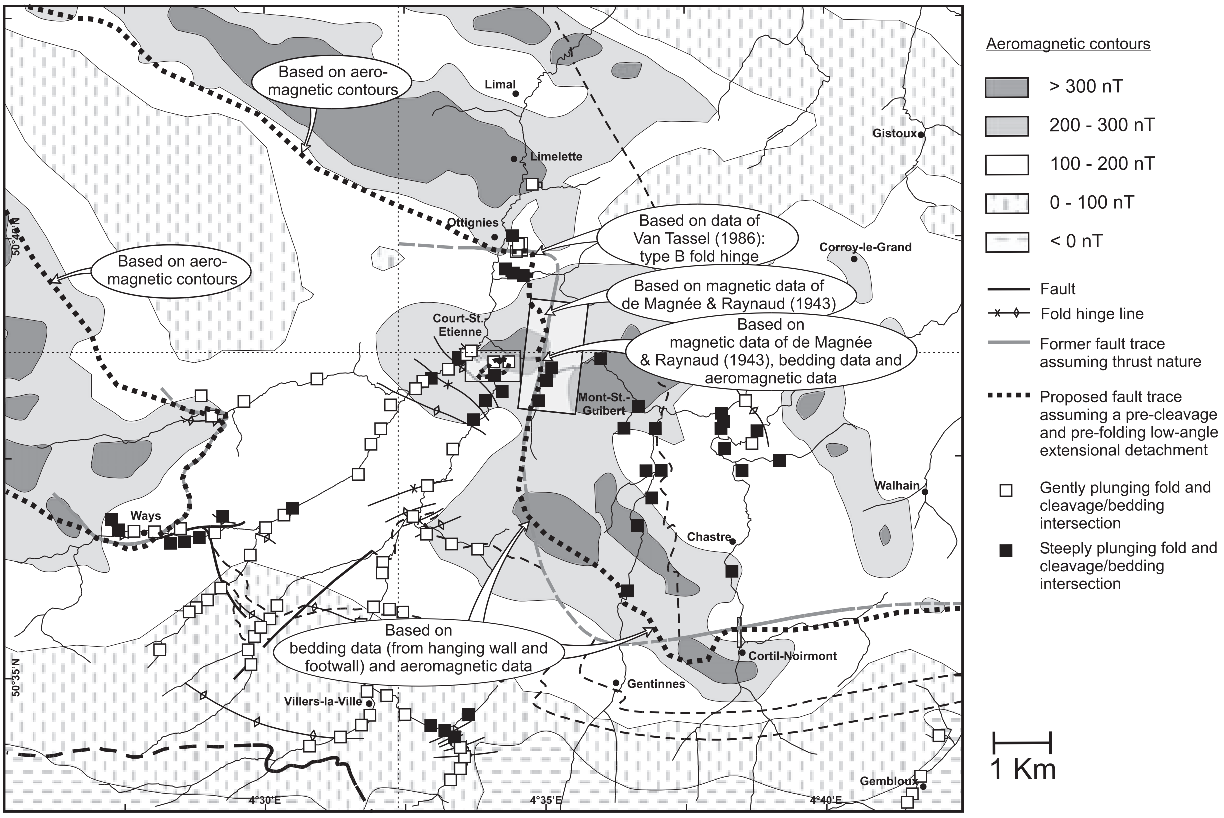

Figure 13. Map of Fig. 8, with the distribution of type A and type B folds. The distribution of type A and type B folds is based on personal observations and on an interpretation of bedding and cleavage orientations of Delcambre *et al.* (2002) and Herbosch & Lemonne (2000), using a plunge divide of 35° (type A < 35°; type B > 35°). Also shown is the newly proposed fault trace, assuming it to be a pre-cleavage and pre-folding low-angle extensional detachment. The fault trace is based on mapping (e.g. Herbosch & Lemonne, 2000; Delcambre *et al.*, 2002), aeromagnetic contours (Belgian Geological Survey, 1994), magnetic data (de Magnée & Raynaud, 1944) and personal and published (Van Tassel, 1986; Herbosch & Lemonne, 2000; Delcambre *et al.*, 2002) bedding and cleavage data, and is drawn as closely as possible to the trace proposed by Delcambre *et al.* (2002) and previous workers (Herbosch *et al.*, 2000, 2001, 2002a, 2002b).

of the area of Fig. 10 is occupied by a steep, E-W-trending type 1 limb. Hence, the area of Fig. 10 reflects one large, steeply plunging type B fold (cf. Figs 9 & 12). The axial surface of this type B fold has a NE-SW trend. If the axial surface is continued towards the NE, one arrives close to the point where the N-S-trending Orne fault changes its direction and continues in an E-W-direction towards Ottignies (Fig. 13; cf. Fig. 8). At Ottignies (Fig. 4; cf. Figs 8 & 13), the data of Van Tassel (1986) suggest that the fault trace runs subparallel to bedding. Hence, around a large-scale steeply plunging open fold, the fault trace appears to remain at low angles to the steeply dipping bedding (Fig. 13). In addition, across this large-scale type B fold, the younging sense inferred from the cleavage/bedding relationship is identical to that across the fault contact, being S-ward younging in the steep limb at Ottignies (Fig. 4; steep limb of type A fold changing E-ward into a type 1 limb of a type B fold) and W-ward in the type 2 limb, with bedding in the Mousty Formation to the west of the Orne fault being subparallel to that in the Tubize Formation to the east of the Orne fault and being at low angles to the Orne fault trace (see Fig. 5; cf. Mont-St.-Guibert, Sintubin *et al.*, 2002).

Also the data from the "klippe" suggest that the contact is folded and that the sense of younging within the Tubize Formation and the Mousty Formation matches the younging sense across the contact (Fig. 7). Although the situation is quite complex, due to the presence of both type A and type B folds, the cleavage and bedding data in combination with the stratigraphic polarity (where possible) within the Tubize Formation point to a dome-shaped structure, younging outwards towards the Mousty Formation (to the north in the N, to the south in the S; Fig. 7). Hence, these data are compatible with an anticlinal culmination of the Tubize Formation amidst overlying rocks of the Mousty Formation. Taking into account the 45°S- plunging borehole to the north of the "klippe" and the poorly constrained trace of the "klippe", the northern limit may be steeply N-dipping (~70°; type A cleavage/bedding relationship; see Fig. 7).

Finally, as suggested by the data on the geological map (Herbosch & Lemonne, 2000; Delcambre *et al.*, 2002), also around Ways and to the north of Gentinnes does the younging sense, inferred from the cleavage/bedding data, match the younging sense across the fault. To the west of Ways, the type 2 limbs of the type B folds suggest a WSW-ward younging, compatible with the presence of the Ordovician to the SW, whereas at Ways and to the east of Ways, the limbs of the type A folds and the E-ward fold plunge suggest a SE-ward younging, compatible with the presence of the Ordovician to the SE. Also ~2 km to the NNE of Ways, the type A cleavage/bedding relationship within the Tubize Formation suggests a N-ward younging of the deposits, towards the Mousty Formation (cf. Herbosch & Lemonne, 2000). To the north of Gentinnes, in the SE-part of the area, the same situation occurs as across the Orne fault (cf. Fig. 5).

Hence, not only do the cleavage/bedding relationships suggest the presence of a fold transition zone between type A and type B folds, but a comparison with the fault trace also suggests that a) the fault does not delimit the different fold styles, b) that this fault is folded, both by type A and type B folds, and hence is affected by at least one fold transition zone, c) that this fault has a relatively low bedding cut-off angle, and d) that the sense of younging below and above the fault matches the sense of younging across the fault, implying a normal sense of younging, and hence a normal, extensional nature of the fault. In short, the data are fully compatible with this fault being a pre-cleavage and pre-folding, extensional detachment, similar to the Asquempont fault in the Senne-Sennette outcrop area, which is folded both by type A and type B folds.

5.2. Comparison with (aero-)magnetic data

The aeromagnetic (Belgian Geological Survey, 1994) and magnetic data (de Magnée & Raynaud, 1944) are perfectly compatible with the above deductions.

Near Ottignies, the E-W-trace of the fault, being subparallel to the bedding trend in both the steep limb of a type A fold (to the W; Fig. 4) and the type 1 limb of a steeply plunging type B fold (to the E; cf. Fig. 10), is reflected by the southern margin of the aeromagnetic high of the Tubize Formation (Fig. 13). In addition, towards the east, the change in fault trace from E-W-trending to N-S-trending, which, as shown above, also appears to be reflected by the bedding, coincides with a marked change in trend of the southern limit of the aeromagnetic high.

As argued above, the supposed "klippe" is likely to have a predominantly periclinal structure (mainly type A folds). A periclinal structure may also explain the aeromagnetic pattern. As can be observed in Fig. 13, the "klippe" coincides with an aeromagnetic high. However, relatively high aeromagnetic values are not restricted to the "klippe", but occur all around it, and continue towards the east to join the larger aeromagnetic high of the Tubize Formation east of the Orne fault trace (Mont-St.-Guibert). These high values around the "klippe" most likely reflect deposits of the Tubize Formation below a relatively thin sequence of the Mousty Formation. Towards the west, these values drop, probably because of an increasing thickness of the overlying Mousty Formation, due to a marked W-ward plunge of the pericline. Towards the east, the pericline plunges gently east (type A fold?), again resulting in a shallowly buried detachment. The detachment surfaces again as the Orne fault in the N-S-trending type 2 limb of a large-scale type B fold (cf. Fig. 5; de Magnée & Raynaud, 1944). A likely reason for the apparent mismatch between the magnetic data of de Magnée & Raynaud (1944), which do reflect the Orne fault, and the aeromagnetic data, which show a completely different pattern, lies in the greater penetration depth and lower resolution of the latter method with respect to the former, in combination with the depth to the magnetite-bearing deposits.

To the south of the aeromagnetic high of the supposed "klippe", a similar high occurs, continuing SE-wards towards Chastre – Cortil-Noirmont. Also here, the continuation of high aeromagnetic values to the west of the fault trace can be interpreted as resulting from a relatively shallow Tubize Formation, which, likely due to a W-ward fold plunge (type B in east towards type A in west?), becomes more deeply buried towards the west, below the Mousty Formation.

5.3. The folded extensional detachment model

We re-interpret the Orne-Noirmont-Baudecet fault, the anomalous contact between the Tubize Formation and older deposits on the one hand, and the Mousty Formation and younger deposits on the other hand, as an Asquempont fault-like pre-cleavage and pre-folding, extensional detachment (cf. Debacker *et al.* 2003, 2004b), of which the irregular trace is essentially due to the complex deformation style related to the transition between gently plunging (type A) and steeply plunging folds (type B) (cf. Debacker *et al.*, 2004a). The suggested map trace of this folded detachment is shown on Fig. 13. The proposed trace is drawn as closely as possible to the trace depicted on recent geological maps (Herbosch & Lemonne, 2000; Delcambre *et al.*, 2002; Herbosch *et al.*, 2001, 2002a, 2002b; Herbosch & Blockmans, in press), and is constrained by the mapped distribution of the different formations, cleavage/bedding relationships based on personal and published data (fold style and orientation of cleavage and bedding), and (aero-)magnetic data.

In the area of Ways, we mainly followed the original trace (Herbosch & Lemonne, 2000). In this area the detachment is affected by both type A and type B folds, which suggests a possibly complex trace. To the NNE of Ways, the detachment (northern limit of Tubize Formation) is affected by type A folds and the trace is based on the aeromagnetic contours. The aeromagnetic low to the north of this trace coincides with an area composed entirely of the Mousty Formation (cf. Sintubin, 1997b). In our hypothesis, this aeromagnetic low is caused by a thick sequence of the Mousty Formation, thus strongly reducing the aeromagnetic signal of the underlying Tubize Formation, below the detachment. Because of the predominance of type A cleavage/bedding relationships, and the aeromagnetic image, this area is interpreted as a large-scale, asymmetric synform (steep N-limb, moderate S-limb).

To the north of the aeromagnetic low, considered to reflect the Mousty Formation, towards Ottignies in the east, the detachment is traced along the steep, WNW-ESE-trending aeromagnetic gradient forming the S-side of the aeromagnetic high of the Tubize Formation. In this zone, we interpret bedding to be steep, representing the northern limb of the supposed large-scale type A synform, or being situated within a steep shear zone. Within this WNW-ESE-trending zone, both type A and type B folds are possible. In our hypothesis, the aeromagnetic lineament entirely results from the detachment, which truncates the deposits of the Tubize

Formation, whereas the abruptness of the gradient is interpreted as reflecting a steep disposition (bedding and detachment), possibly due to a steep shear zone (cf. Sintubin, 1997b). Hence, in this respect it slightly differs from the Asquempont lineament in the Senne-Sennette area (*sensu* Sintubin & Everaerts, 2002; see Debacker *et al*., 2003, 2004a, 2004b).

As already explained above, the marked change in fault trend to the southeast of Ottignies is attributed to the presence of a large-scale type B fold. The N-S-trending trace depicted on the geological maps (e.g. Herbosch *et al*., 2000, 2001, 2002a, 2002b; Delcambre *et al*., 2002; Herbosch & Blockmans, in press) is moved westward so as to make the axial surface of the large-scale type B fold, evident from the data of Van Tassel (1986), responsible for the change in fault trend. Towards the south, the detachment trace is based on the magnetic data of de Magnée & Raynaud (1944), following the curvature of the magnetic ridges (type 2 limbs of type B fold), and taking into account also the aeromagnetic high to the west of the Orne trace, underlying the "klippe".

As pointed out above, the "klippe" is re-interpreted as a periclinal culmination of the detachment, within a fold transition zone between type A and type B folds. To the west, it plunges underneath the deposits of the Mousty Formation, likely with moderate plunges. In this respect, the NE-SW-trending aeromagnetic contour segments may correspond to "type 2 limbs", and the NW-SE-trending segments to "type 1 limbs" of moderately W plunging folds. This is also thought to occur in the aeromagnetic high ~3 km to the south of Court-St.-Etienne.

Towards the southeast, where the N-S-trending Orne segment changes into the E-W-trending Cortil-Noirmont segment, the detachment trace is modified with respect to the trace on the geological maps (e.g. Delcambre *et al*., 2002) so as to show more resemblance to the aeromagnetic contours, and to better match bedding traces and bedding orientations. Also here, type B folds are expected, which, to the southeast, may become rotated anticlockwise with respect to the type B folds further north. Note that, judging from the aeromagnetic contours, the unobserved limit between the Tubize Formation and the Blanmont Formation to the south of Chastre is better moved to the east (by means of stepfolds, of which the plunge decreases towards the SE and changes into type A folds to the east of Cortil-Noirmont), in order to be compatible with the aeromagnetic contours and to reduce the apparent cut-off angle with the detachment. Judging from the aeromagnetic contours and the stratigraphy and bedding trends in the Ordovician around Gembloux, the trace around Cortil-Noirmont is expected to be steep, changing from a type 1 limb of a type B fold in the west towards a steep limb of a type A fold towards the east.

A tentative three-dimensional image of the probable nature of the detachment surface is shown in Fig. 14.

6. Conclusion

A literature review shows that there are no convincing arguments for a gently N-dipping large-displacement thrust fault in the Dyle-Thyle area. An alternative model is presented, in which the anomalous contact between the Tubize Formation and older deposits on the one hand and the Mousty Formation and younger deposits on the other hand, is re-interpreted as a pre-cleavage and pre-folding low-angle extensional detachment, similar to the

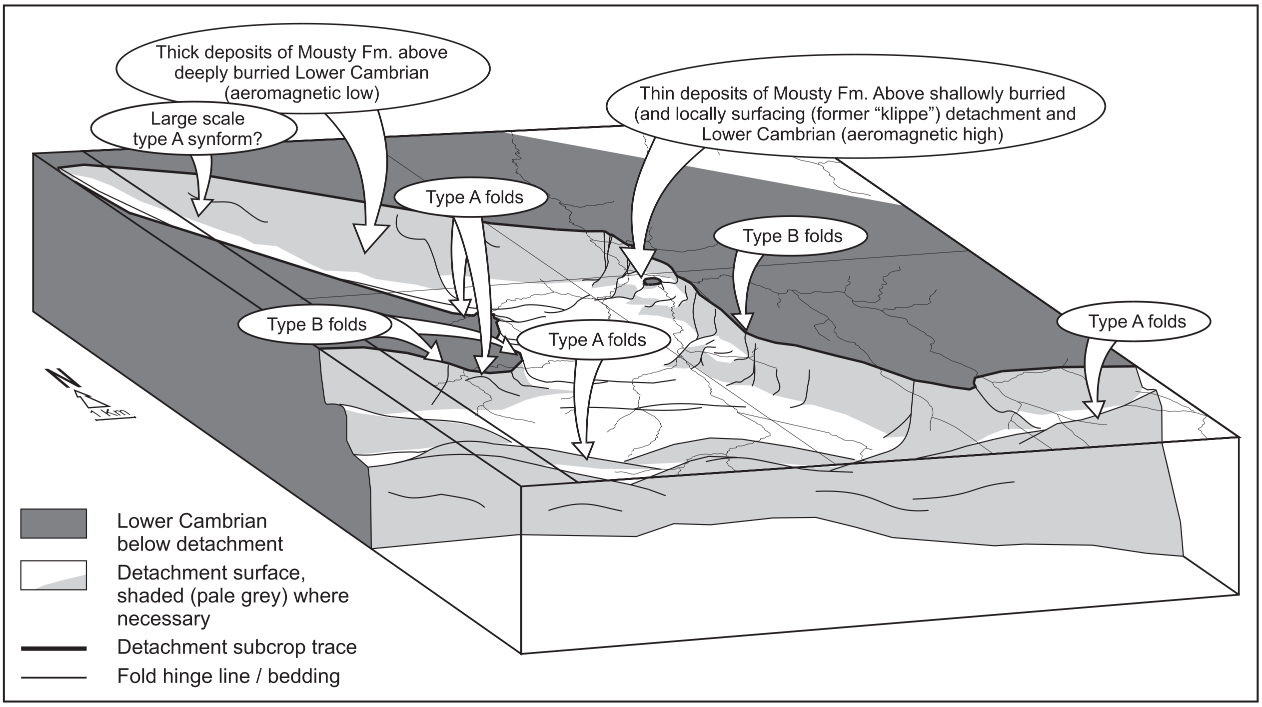

Figure 14. Schematic 3-D representation of the Orne-Noirmont-Baudecet fault, re-interpreted as a pre-cleavage and pre-folding low-angle extensional detachment (see also Fig. 13). The irregular nature and subcrop trace can be attributed entirely to its pre-folding nature and its position within a large-scale transition zone between type A and type B folds.

Asquempont fault in the Senne-Sennette area (cf. Debacker *et al.*, 2003, 2004b). The irregular subcrop trace of the detachment in the Dyle-Thyle area is a result of it being affected by fold transition zones and hence being folded by both steeply plunging and gently plunging folds (cf. Debacker *et al.*, 2004a). In this respect, the supposed "klippe" at Court-St.-Etienne can easily be re-interpreted as an anticlinal culmination with a periclinal shape.

Although also this model remains hypothetical, and the traces shown are likely to be modified in the future, it is the only model which adequately combines all data and explains all observations from the Dyle-Thyle area, and, importantly, is compatible with the structural architecture of the other outcrop areas of the Brabant Massif.

Considering that an Asquempont fault-like pre-cleavage extensional detachment is observed in the Senne outcrop area, in the Sennette outcrop area and in several boreholes in the southwestern part of the massif (see Debacker *et al.*, 2003, 2004b), and also allows explaining the anomalous contact within the Dyle-Thyle outcrop area, it seems that such detachments have a wide-spread distribution. As previously suggested (Debacker *et al.*, 2003, 2004b), possibly also other paraconformity-like or low-angle unconformity-like contacts depicted by De Vos *et al.* (1993a), represent similar low-angle extensional detachments (cf. Fig. 1). We therefore suggest that the entire Lower Cambrian core of the Brabant Massif is outlined by a system of pre-cleavage and pre-folding, low-angle extensional detachments, which we define as the Asquempont Detachment System. Based on outcrop and borehole observations (see Debacker *et al.*, 2003, 2004b), this detachment system formed between the Caradoc and the timing of cleavage development.

7. Acknowledgements

The authors wish to acknowledge the careful reviews by W. De Vos and O. Bolle. T.N. Debacker is a Postdoctoral Fellow of the F.W.O.-Vlaanderen. M. Sintubin is a Research Associate of the Onderzoeksfonds K.U.Leuven. Part of the work of A. Herbosch was sponsored by F.N.R.S. project 2.4506.97. This work forms part of research project G.0094.01 of the F.W.O.-Vlaanderen.

8. References

ANTHOINE, R. & ANTHOINE, P., 1943. Les assises de Mousty et de Villers-la-Ville du bassin supérieur de la Dyle. *Annales de la Société Géologique de Belgique*, **66**: M53-170.

BECKERS, R., 2003. *Vergelijking van de plooien in de Abbaye de Villers en Chevlipont formaties (Ordovicium) in de omgeving van de Abdij van Villers, Thyle-vallei, Massief van Brabant*. Unpublished M.Sc. thesis, Laboratorium voor Paleontologie, Universiteit Gent.

BELGIAN GEOLOGICAL SURVEY, 1994. *Aeromagnetic map of the Brabant Massif: residual total field reduced to the pole. Scale 1/100000.*

CHACKSFIELD, B.C., DE VOS, W., D'HOOGE, L., DUSAR, M., LEE, M.K., POITEVIN, C., ROYLES, C.P. & VERNIERS, J., 1993. A new look at Belgian aeromagnetic and gravity data through image-based display and integrated modelling techniques. *Geological Magazine*, **130**: 583-591.

DEBACKER, T.N., 1999. Folds trending at various angles to the transport direction in the Marcq area, Brabant Massif, Belgium. *Geologica Belgica*, **2**: 159-172.

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., HERBOSCH, A., SINTUBIN, M., & VERNIERS, J., 2003. Palaeozoic deformation history of the Asquempont-Virginal area (Brabant Massif, Belgium): large-scale slumping, low-angle extensional detachment development (the Asquempont Fault redefined) and normal faulting (The Nieuwpoort-Asquempont fault zone). *Memoirs of the Geological Survey of Belgium*, **49**: 1-30.

DEBACKER, T.N., HERBOSCH, A., VERNIERS, J. & SINTUBIN, M., 2004b. Faults in the Asquempont area, southern Brabant Massif, Belgium. Netherlands Journal of Geosciences, 83: 49-65.

DEBACKER, T.N., SINTUBIN, M. & VERNIERS, J., 1999. Cleavage/fold relationships in the Silurian metapelites, southeastern Anglo-Brabant fold belt (Ronquières, Belgium). *Geologie & Mijnbouw*, **78**: 47-56.

DEBACKER, T. N., SINTUBIN, M. & VERNIERS, J., 2001. Large-scale slumping deduced from structural and sedimentary features in the Lower Palaeozoic Anglo-Brabant fold belt, Belgium. *Journal of the Geological Society, London* **158**: 341-352.

DEBACKER, T.N., SINTUBIN, M. & VERNIERS, J., 2002. Timing and duration of the progressive deformation of the Brabant Massif, Belgium. *Aardkundige Mededelingen*, **12**: 73-76.

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.

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.

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 MAGNÉE, I., 1943. Etude magnétique de la tectonique du Cambrien du Brabant à l'est de Court-St-Etienne. *Bulletin de la Société belge de Géologie*, **52**: 242-253.

de MAGNÉE, I. & RAYNAUD, J., 1944. Etude magnétique de la tectonique du Cambrien du Brabant à l'est de Court-St-Etienne. *Annales de la Société Géologique de Belgique*, **67**: 495-546.

DE VOS, W., 1997. Influence of the granitic batholith of Flanders on Acadian and later deformation (Brabant Massif, Belgium). *Aardkundige Mededelingen*, **8**: 49-52.

DE VOS, W., CHACKSFIELD, B.C., D'HOOGE, L., DUSAR, M., LEE, M.K., POITEVIN, C., ROYLES, C.P., VANDENBORGH, T., VAN EYCK, J. & VERNIERS, J., 1993b. Image-based display of Belgian digital aeromagnetic and gravity data. *Professional Paper, Geological Survey of Belgium*, **263**: 1-8.

DE VOS, W., POOT, B., HUS, J. & El KHAYATI, M., 1992. Geophysical characterization of lithologies from the Brabant Massif as a contribution to gravimetric and magnetic modelling. *Bulletin de la Société belge de Géologie*, **101**: 173-180.

DE VOS, W., VERNIERS, J., HERBOSCH, A. & VANGUESTAINE, M., 1993a. A new geological map of the Brabant Massif, Belgium. *Geological Magazine*, **130**: 605-611.

EVERAERTS, M., POITEVIN, C., DE VOS, W. & STERPIN, M., 1996. Integrated geophysical/geological modelling of the western Brabant Massif and structural implications. *Bulletin de la Société belge de Géologie*, **105**: 41-59.

FOURMARIER, P., 1921. La tectonique du Brabant et des régions voisines. *Mémoires de l'Académie Royale de Belgique, Classe des Sciences, 2ème série*, **4**: 1-95.

GIESE, U., KATZUNG, G., WALTER, R. & WEBER, J., 1997. The Caledonian deformation of the Brabant Massif and the Early Palaeozoic in northeast Germany: compared. *Geological Magazine*, **134**: 637-652.

GRADSTEIN, F. M. & OGG, J., 1996. A Phanerozoic time scale. *Episodes*, **19**: 3-6.

HERBOSCH, A. & BLOCKMANS, S. (in press). *Carte Wavre – Chaumont-Gistoux n° 40/1-2, 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., PINGOT, J.L. & DELCAMBRE, B., VANGUESTAINE, M., VERNIERS, J. & SAMUELSSON, J., 2000. *Stratigraphie, sédimentologie et cartographie du socle cambro-ordovicien du bassin de la Dyle (cartes Chastre-Gembloux, Nivelles-Genape et Wavre)*. Excursion guidebook of excursion "Geologica Belgica et Groupe de Contact FNRS Caledonides, Micropaléontologie" (20 mai 2000).

HERBOSCH, A., VANGUESTAINE, M., DEGARDIN, J.M., DEJONGHE, L., FAGEL, N. & SERVAIS, T., 1991. Etude lithostratigraphique, biostratigraphique et sédimentologique du sondage de Lessines (bord méridional du Massif du Brabant, Belgique). *Annales de la Société géologique de Belgique*, **114**: 195-212.

HERBOSCH, A., VERNIERS, J., DEBACKER, T.N., BILLIAERT, B., DE SCHEPPER, S., BELMANS, M., 2001. *The Lower Palaeozoic stratigraphy and sedimentology of the Brabant Massif in the Dyle and Orneau valleys and of the Condroz Inlier at Fosses: an excursion guidebook*. Pre-symposium excursion of symposium Early Palaeozoic palaeogeographies and biogeographies of Western Europe and North Africa, Université des Sciences et Technologies de Lille, Villeneuve d'Ascq, 24-26 September 2001**:** 59p.

HERBOSCH, A., VERNIERS, J., DEBACKER, T.N., BILLIAERT, B., DE SCHEPPER, S., BELMANS, M., 2002a. *The Lower Palaeozoic stratigraphy and sedimentology of the Brabant Massif in the Dyle and Orneau valleys and of the Condroz Inlier at Fosses: an excursion guidebook*. Post-symposium excursion of the International Meeting and Workshops of the "Commission Internationale pour l'étude de la Microflore du Paléozoique (C.I.M.P.)": Palaeozoic palynology in the third millenium: new directions in acritarch, chitinozoan and miospore research**:** 58p.

HERBOSCH, A., VERNIERS, J., DEBACKER, T.N., BILLIAERT, B., DE SCHEPPER, S., BELMANS, M., 2002b. The Lower Palaeozoic stratigraphy and sedimentology of the Brabant Massif in the Dyle and Orneau valleys and of the Condroz Inlier at Fosses: an excursion guidebook. *Geologica Belgica*, **5**: 71-142.

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.

LECOMPTE, M., 1948. Existence du Trémadocien dans le Massif du Brabant. *Bulletin de l'Académie Royale des Sciences, Lettres et Beaux Arts de la Belgique, Classe des Sciences (5è série)*, **34**: 677-687.

LECOMPTE, M., 1949. Découverte de nouveaux gites à Dictyonema dans le Trémadocien du Massif du Brabant. *Bulletin de l'Institut Royal des Sciences Naturelles de Belgique*, **25**: 1-8.

MALAISE, C., 1883. Sur la constitution du Massif du Brabant. *Bulletin de l'Académie Royale de Belgique, 3ème série*, **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., 1909. Echelle stratigraphique du Silurien de Belgique et âge géologique des Schistes noirs de Mousty. *Annales de la Société géologique de Belgique*, **36**: M31-39.

MALAISE, C., 1910. Sur l'évolution de l'échelle stratigraphique du Siluro-Cambrien de Belgique. *Bulletin de la Société belge de Géologie, de Paléontologie et d'Hydrologie*, **24**: 415-437.

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

MICHOT, P., 1977. L'Ordovicien de la vallée de la Thyle (Brabant): structure tectonique, stratigraphie et lithologie. *Annales de la Société géologique de Belgique*, **100**: 223-231.

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.

PIESSENS, K., MUCHEZ, PH., DEWAELE, S., BOYCE, A., DE VOS, W. SINTUBIN, M., DEBACKER, T., BURKE, E. & VIAENE, W., 2002. Fluid flow, alteration and polysulphide mineralisation associated with a low-angle reverse shear zone in the Lower Palaeozoic of the Anglo-Brabant fold belt, Belgium. *Tectonophysics*, **348**: 73-92.

PIESSENS, K., VIAENE, W. & MUCHEZ, PH., 2000. *Laboratoriumstudie van Boorkernen in het Massief van Brabant. Rapport VLA98-3-6. In opdracht van het Ministerie van de Vlaamse Gemeenschap, Afdeling Natuurlijke Rijkdommen en Energie (ANRE)*. Leuven: Katholieke Universiteit Leuven (Afdeling Fysico-chemische Geologie): 121 p.

SINTUBIN, M., 1997a. Cleavage-fold relationships in the Lower Palaeozoic Brabant Massif (Belgium). *Aardkundige Mededelingen*, **8**: 161-164.

SINTUBIN, M., 1997b. Structural implications of the aeromagnetic lineament geometry in the Lower Paleozoic Brabant Massif (Belgium). *Aardkundige Mededelingen*, **8**: 165-168.

SINTUBIN, M., 1999. Arcuate fold and cleavage patterns in the southeastern part of the Anglo-Brabant fold belt (Belgium): tectonic implications. *Tectonophysics*, **309**: 81-97.

SINTUBIN, M. & EVERAERTS, M., 2002. A compressional wedge model for the Lower Palaeozoic Anglo-Brabant Belt (Belgium) based on Potential Field Data. *In*: J. Winchester, J. Verniers & T. Pharaoh (Eds.) *Palaeozoic Amalgamation of Central Europe*. Geological Society, London, Special Publications, **201**: 327-343.

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.

VANDER AUWERA, J. & ANDRÉ, L., 1985. Sur le milieu de dépôt, l'origine des matériaux et le faciès métamorphique de l'Assise de Tubize (Massif du Brabant, Belgique). *Bulletin de la Société belge de Géologie*, **94**: 171-184.

VAN GROOTEL, G., VERNIERS, J., GEERKENS, B., LADURON, D., VERHAEREN, M., HERTOGEN, J. & DE VOS, W., 1997. Timing of subsidence-related magmatism, foreland basin development, metamorphism and inversion in the Anglo-Brabant fold belt. *Geological Magazine*, **134**: 607-616.

VANGUESTAINE, M., 1991. Datation par acritarches des couches Cambro-Tremadociennes les plus profondes du sondage de Lessines (bord méridional du Massif du Brabant, Belgique). *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.

VAN TASSEL, R., 1986. Contribution à la lithologie du segment calédonien des vallées de la Dyle et de la Thyle, Brabant, Belgique. *Aardkundige Mededelingen*, **3**: 239-268.

VERNIERS, J., HERBOSCH, A., VANGUESTAINE, M., GEUKENS, F., DELCAMBRE, B. PINGOT, J.L., BELLANGER, 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 Amalgamatien of Central Europe* (J. WINCHESTER, J. VERNIERS & T. PHARAOH, eds). Geological Society, London, Special Publications, **201**: 47-93.

WALRAEVENS, P., 1984. Levé magnétique du compartiment de schistes à magnétite devilliens de Ways-Ruart (Bassin de la Dyle, Brabant). *Bulletin de la Société belge de Géologie*, **93**: 151-159.

Manuscript received on 11.08.2004 ; accepted for publication on 21.03.2005.