CLEAVAGE/FOLD RELATIONSHIP IN THE SILURIAN OF THE MÉHAIGNE-BURDINALE AREA, SOUTHEASTERN BRABANT MASSIF, BELGIUM

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(9 figures, 2 tables)

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ABSTRACT. New structural observations show that the Méhaigne-Burdinale area, situated along the southeastern rim of the Brabant Massif, below the Silurian-Devonian angular unconformity, does contain sub-horizontal to gently plunging, upright to steeply inclined folds characterised by convergent cleavage fans. As such, the Méhaigne-Burdinale area is analogous to the Silurian of the southern Orneau valley and the southern Sennette valley. In addition, like in the latter two areas, also the folds in the Méhaigne-Burdinale area are of an en-echelon periclinal nature, situated within a large-scale host synform. A periclinal nature is also proposed for the host synform. Although many folds show a small-angle clockwise cleavage transection, the sense and amount of cleavage transection are to a large extent influenced by the en-echelon periclinal nature of the folds.

There is no evidence for a ductile Variscan imprint, nor for a poly-phase deformation. Like in the other Silurian outcrop areas, the convergent cleavage fans formed prior to the Silurian-Devonian unconformity. Although the convergent cleavage fans might be explained by a continued fold amplification after cleavage development during a single progressive deformation, the question why these fans occupy such a specific position along the southern rim of the Brabant Massif remains unresolved.

KEYWORDS : convergent cleavage fans, periclinal folds, cleavage transection, mullions, kink bands, transverse fractures, Anglo-Brabant fold belt

1. Introduction

The Lower Palaeozoic Brabant Massif, N-Belgium, forms the southeastern part of the largely concealed Anglo-Brabant fold belt, one of the fold belts of eastern Avalonia. Currently, this fold belt is attributed to basin inversion within eastern Avalonia as a result of an anticlockwise rotation of the Midlands Microcraton between the Caradoc and the Middle Devonian (Debacker, 2001, Verniers *et al.*, in press). Along the southern rim of the Brabant Massif, deformed low-grade to very low-grade Silurian deposits are overlain with an angular unconformity by relatively undeformed sub-horizontal to gently dipping, diagenetic Givetian and younger deposits (Verniers & Van Grootel, 1991, Van Grootel *et al.*, 1997). Although in the more internal, Cambrian and Ordovician outcrop areas of the Brabant Massif, such as the northern Senne-Sennette valley and the Dyle-Thyle area, the cleavage dips moderately to steeply to the north, a S-dipping cleavage frequently occurs along the Silurian southern rim of the massif (cf. Fourmarier, 1914, 1921, Sintubin, 1997,

1999). As shown by Fourmarier (1914, 1921, cf. Kaisin, 1933, Mortelmans, 1953, Belmans, 2000, Herbosch *et al.*, 2001) in the southern Orneau valley and by Legrand (1967, cf. Debacker, 1996, Debacker *et al.*, 1999) in the southern Sennette valley, the local occurrence of a S-dipping cleavage is the result of a convergent cleavage fanning. These convergent cleavage fans were generally considered to reflect the presence of two deformation phases: a first phase forming the folds and the cleavage, followed by a minor second phase, accentuating the pre-existing folds thus giving rise to convergent cleavage fans (Kaisin, 1933, Mortelmans, 1953, Legrand, 1967, Michot, 1978, 1980). More recently, the convergent cleavage fans in the Sennette valley and the Orneau valley have been attributed to a single-phase progressive deformation (Debacker, 1996, Debacker *et al.*, 1999, Belmans, 2000, cf. Herbosch *et al.*, 2001).

From a structural point of view, the Méhaigne-Burdinale area (fig. 1), situated along the southeastern rim of the Brabant Massif, below the angular unconformity, is analogous to the southern Sennette valley and the southern
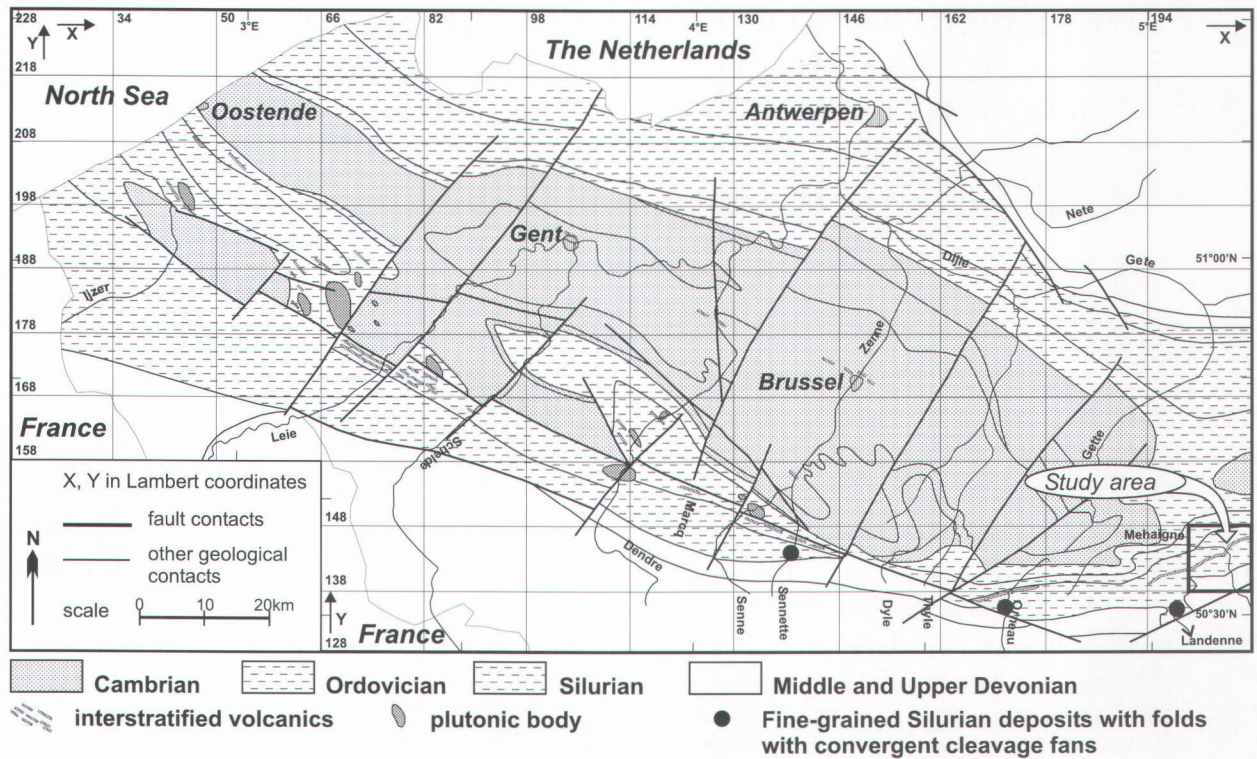
Fig. 1. Geological subcrop map of the Brabant Massif, after De Vos *et al.* (1993) and Van Grootel *et al.* (1997), showing the position of the study area. Also shown is the distribution of folds with convergent cleavage fans in fine-grained relatively incompetent deposits.

Orneau valley. Also the age and the nature of the deposits are similar to those in the latter outcrop areas. Because of the comparable structural position, also the folded fine-grained deposits of the Méhaigne-Burdinale area are expected to show a convergent cleavage fanning. However, judging from the literature (e.g. Fourmarier, 1921, Vandenven, 1967) this is not the case; instead of showing convergent cleavage fans the Méhaigne-Burdinale area seems to be dominated by a parallel cleavage. Still, seemingly in contradiction with the idea of a parallel cleavage, Verniers (1976, 1983) mentions the local occurrence of a steeply S-dipping cleavage. Unfortunately, this observation was never further investigated.

2. The outcrop area

The Méhaigne-Burdinale outcrop area is situated along the Méhaigne river and its tributary the Burdinale river (fig. 2). Although in size the Méhaigne-Burdinale area belongs to the largest outcrop areas of the Brabant Massif, large exposures, in size comparable to those in the Orneau and Sennette valleys, are scarce. A large number of small outcrops has been described by Verniers (1976, 1983). At present, many of these have disappeared, are completely covered by vegetation or are in a state unsuitable for structural analyses (e.g. creep). During this study 33 outcrops or groups of outcrops have been ex-

amined (fig. 2). Because of the size of the Méhaigne-Burdinale area, these outcrops are grouped into 8 outcrop areas. From south to north, the Méhaigne valley comprises the Fumal outcrop area (upper Wenlock), the Pitet outcrop area (lower Wenlock to upper Llandovery), the Fallais outcrop area (lower Wenlock to upper Llandovery) and the Latinne outcrop area (middle to upper Llandovery). From SE to NW, the Burdinale valley comprises the Huccorgne outcrop area (upper Wenlock), the Marneffe outcrop area (upper Wenlock), the Oteppe outcrop area (upper Wenlock) and the Lamontzé outcrop area (upper Llandovery to middle Wenlock). A detailed description of the outcrops in the area can be found in Verniers (1976, 1983).

The dominant lithology in the study area is a centimetric to decimetric alternation of mudstone and siltstone, occasionally with fine-grained sandstone intercalations (Verniers, 1976, 1983, Verniers *et al.*, 2001). Sedimentologically, the deposits are interpreted as distal turbidite deposits, usually consisting of Tde-sequences or, less frequently, Tcde-sequences (cf. Bouma, 1962), with intercalated laminated hemipelagites (Verniers, 1976, 1983, Verniers *et al.*, 2001). On the basis of the lithology and the number, type and thickness of sedimentary sequences eight formations are distinguished (Verniers, 1976, 1983, Verniers *et al.*, 2001). The lower four formations (the Latinne, the Hosdin, the Fallais and
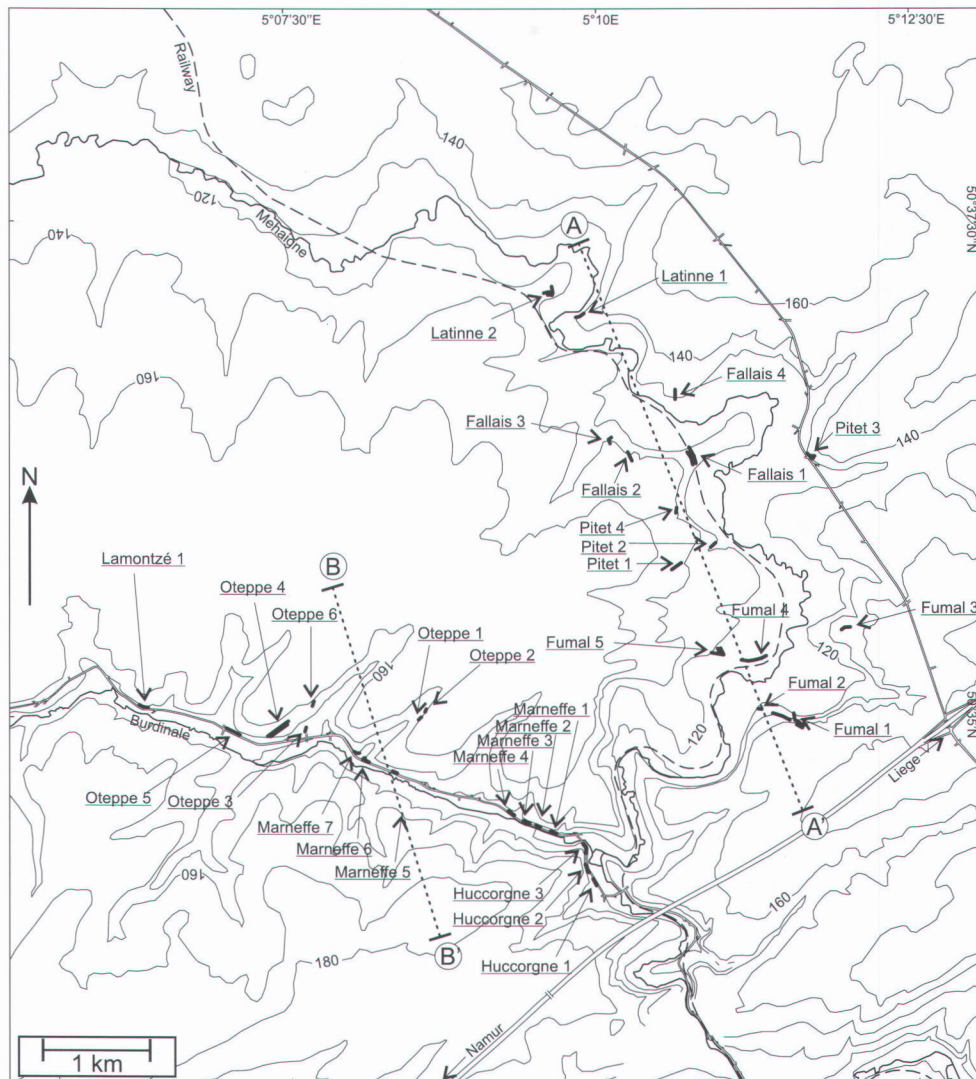
Fig. 2. Simplified topographic map of the Méhaigne-Burdinale area, showing the position of the studied outcrops. The section lines of the cross-sections A-A' and B-B' of figure 4 are indicated.

the Corroy Formation) are slightly more heterogeneous and generally contain more coarser-grained intervals (e.g. fine-sandy c-intervals, especially in the Corroy Formation; a volcano-sedimentary interval in the Fallais Formation) than the upper four formations (Les Vallées, the Vissoul, the Fumal and the Vichenet Formation) (Verniers *et al.*, 2001). In all formations bedding can relatively easily be distinguished. For an overview of the stratigraphy and the sedimentology of the different formations, the reader is referred to Verniers *et al.* (2001, cf. Verniers, 1976, 1983).

Orientations of planar elements are written as strike/dip, followed by an azimuth notation of the dip direction (e.g. 090/30 S for a plane dipping 30° to the south). Orientations of linear elements are written as plunge/plunge direction (e.g. 10/270 for a line plunging 10° to the west).

3. Macroscopic observations

3.1. Cleavage/fold relationship

Generally, apart from some gentle ondulations (e.g. outcrops Fumal 1A and Lamontzé 1) bedding orientation in individual outcrops remains fairly constant. Changes in bedding orientation between different outcrops, however, suggest the presence of several large, gentle to open, upright to steeply inclined, subhorizontal to gently plunging sinusoidal folds with wavelengths of 1 to 2.5 km (fig. 3, fig. 4). Because of the large scale of these folds as compared to the outcrop sizes, fold shape can only be deduced from stereographic projections and cross-sections. The gentle, gradual changes in bedding orientation between adjacent outcrops and the rounded shape of occasional small gentle ondulations observed in outcrop are suggestive of folds with wide, well-rounded hinge
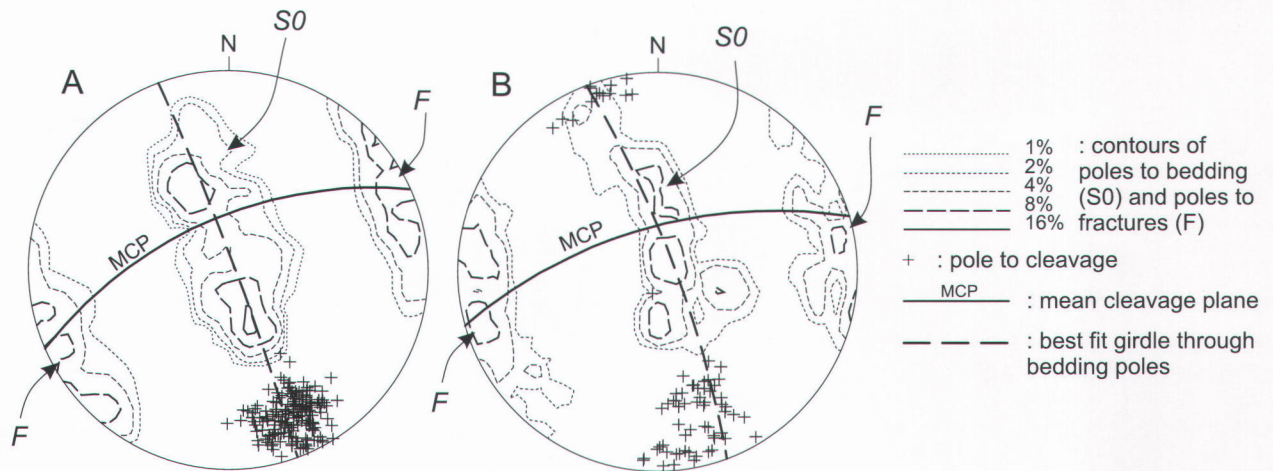
Fig. 3. Lower-hemisphere equal-area stereographic projections of bedding, cleavage and transverse fractures from the Méhaigne valley (A) and the Burdinale valley (B). See table 1 for number of measurements.
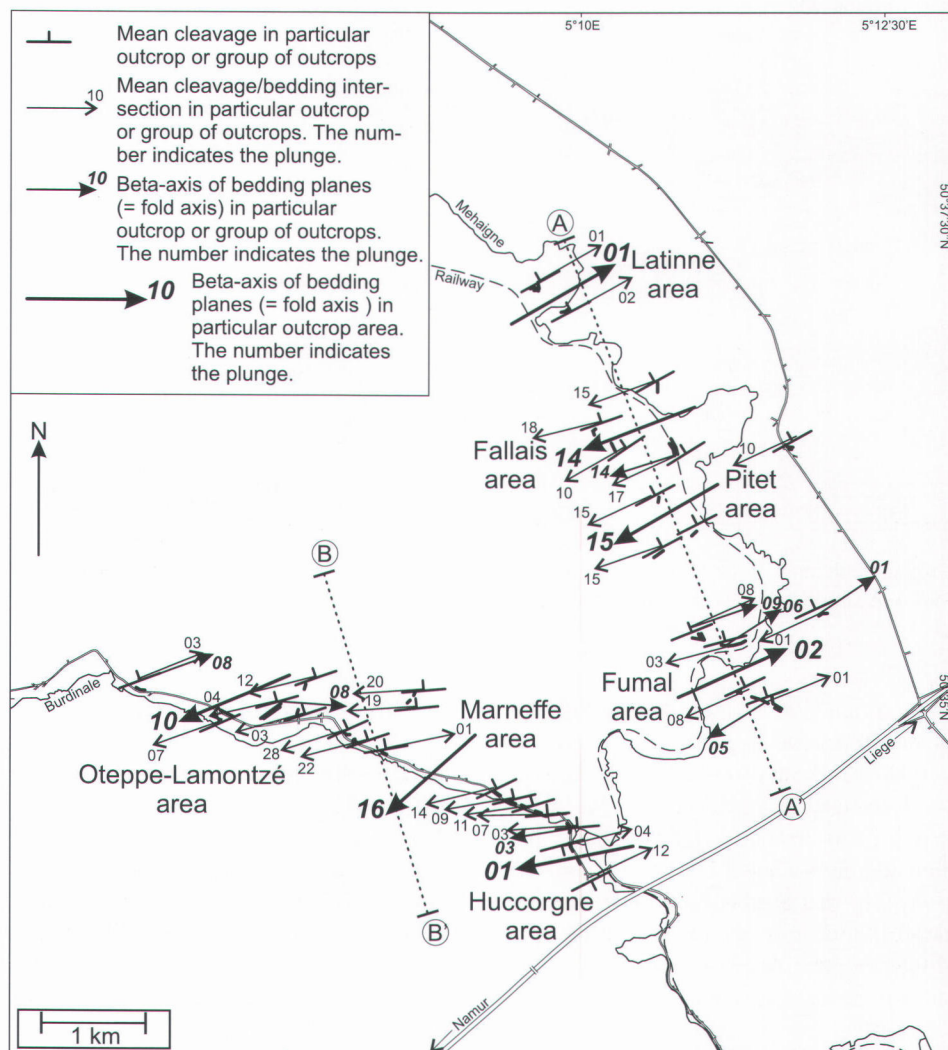

Fig. 5. Simplified map of the Méhaigne-Burdinale area, showing the orientation of the mean cleavage, the mean cleavage/bedding intersection and the fold axis in the studied outcrops or groups of outcrops and the overall fold axis within the different outcrop areas (cf. table 1 and fig. 2). Because of the gradual changes in bedding orientation a fold axis (beta-axis of bedding poles) could only be determined in a few outcrops or groups of outcrops. Note that the fold axes shown, calculated from the bedding orientations in the surrounding area, only reflect the probable orientation of the fold hinge lines. In general, their position does not coincide with the actual position of the fold hinge lines. The position of the fold hinge lines can be inferred from the cleavage/bedding relationship on the sections in figure 3 (cleavage perpendicular to bedding in fold hinge).
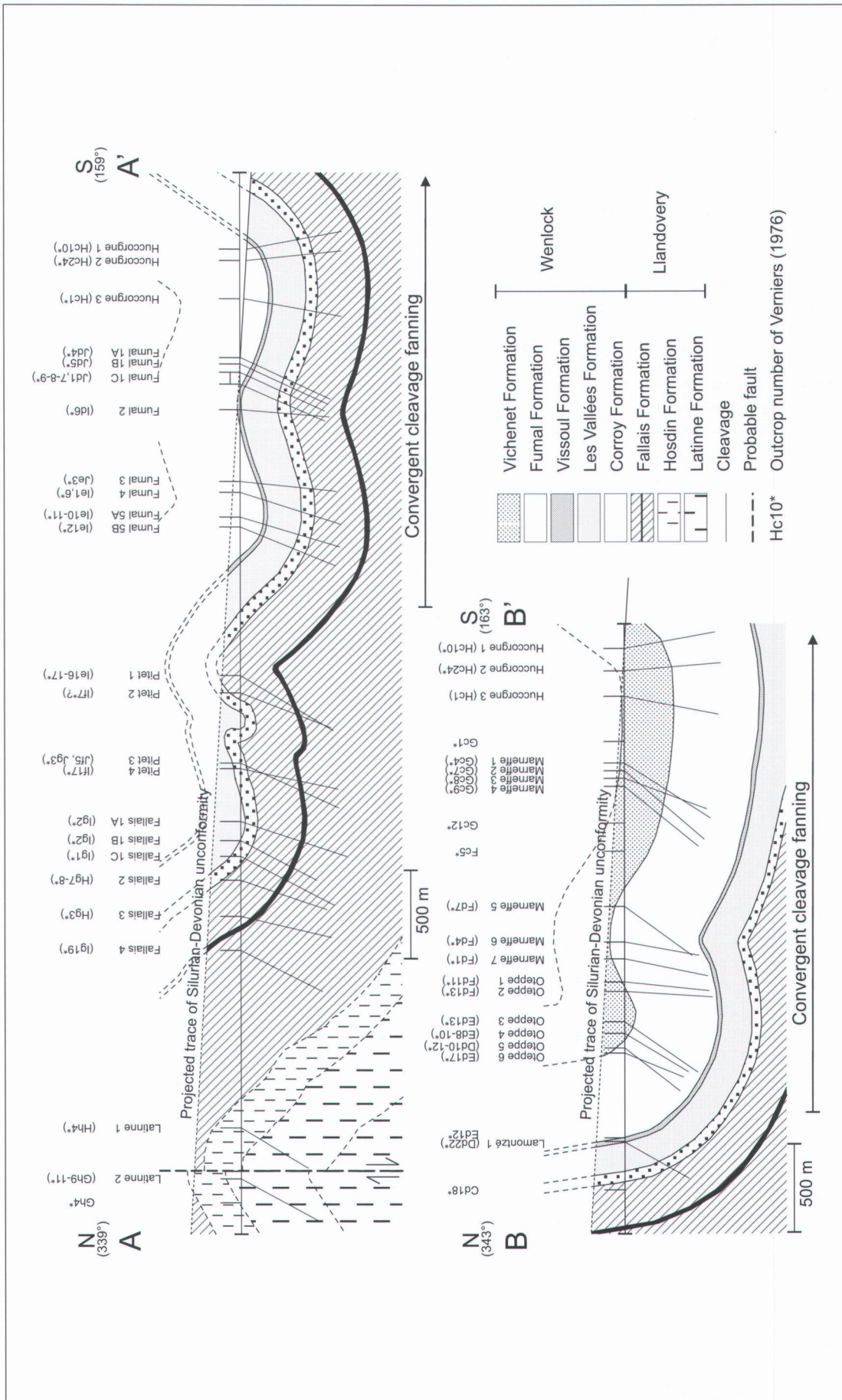
Fig. 4. Cross-sections along the Méhaigne valley (A-A'; 339-159°) and across the Burdinale valley (B-B'; 343-163°), showing the position of the convergent cleavage fans. The sections are constructed on the basis of personal observations, taking into account the data of Verniers (1976, 1983). Between outcrops Pitet 1 and Pitet 4, the small folds reflected by the Corroy Formation are entirely based on the data of the latter author. The bedding geometry above and below these folds was slightly changed in order to accommodate these folds. The fault in the northern part of the Méhaigne section is deduced on the basis of a comparison of the stratigraphy and bedding orientation. See figure 2 for section lines.

zones (amplitudes 1 to 2 and fold shapes B to E of Hudleston, 1973), favouring the use of a Busk construction (Busk, 1929). In figure 4 two cross-sections are shown, one along the Méhaigne valley and one across the Burdinale valley. The data from the Huccorgne area are incorporated in both sections because it occupies an intermediate position between both sections and, more importantly, it is the southern part of the Huccorgne area (outcrops Huccorgne 1 and 2) which hosts the steeply S-dipping cleavage observed by Verniers (1976, 1983).

As can be seen on the southern section parts, changes in bedding orientation describe a large synform, whereas the dip of the steeply S-dipping cleavage gradually increases towards the north, reaching a steep N-dip in outcrop Huccorgne 3. This progressive change in cleavage dip indicates a low-angle convergent cleavage fan. Although less pronounced, also further north, in the outcrop areas of Fumal, Marneffe and Oteppe, the changes in cleavage and bedding dip are compatible with a convergent cleavage fanning. However, in the northern parts of the sections, in the Pitet, Fallais, Latinne and Lamontzé outcrop areas, cleavage dip remains almost constant, occasionally showing a slightly divergent fanning. Like in the southern Sennette valley (Debacker, 1996, Debacker *et al.*, 1999), small folds and ondulations in the large host folds always show a parallel to divergently fanning cleavage, irrespective whether or not the host structures have a convergent, parallel or divergent cleavage fan.

As shown on the two cross-sections, the large folds in the Méhaigne-Burdinale area apparently form part of a large-scale synform (fig. 4). As previously noted by Verniers (1976, 1983) it is difficult to correlate the folds between the Méhaigne valley and the Burdinale valley. This also comes forward from a comparison of the fold hinge line orientations of the different outcrop areas. As can be seen in table 1 and figure 5, both the plunges and the plunge directions of the different folds vary from area to area in an apparently random fashion (e.g. the Marneffe area, fig. 5). Although also the strike of the cleavage slightly changes from area to area, this change is usually less pronounced and often does not reflect the changes in fold hinge line orientation. Therefore, although a large part of the Méhaigne-Burdinale area seems affected by a small clockwise axial cleavage transection (cf. Johnson, 1991), compatible with the observations of previous researchers (e.g. Sintubin, 1997), the new observations show that the angle of axial cleavage transection changes across the area, occasionally resulting in an anticlockwise cleavage transection (table 1). This changing cleavage transection angle is mainly a result of the changes in fold hinge line orientation.

3.2. Fractures and faults

Like in the other outcrop areas along the southern rim of the Brabant Massif (Debacker *et al.*, 1999, Debacker, 2001), regionally persistent fractures, sub-vertical to

Outcrop area	Bedding (S0)	Cleavage (S1)	S0 and S1 merged	S1-transection	Transverse fractures
Fumal (synform)	n = 122 Beta-axis : 02/066	n = 99; mean : 250/71N ± 007° Beta-axis : 17/064	n = 221 Beta-axis : 02/068	003°CW	n = 57 mean : 153 ± 020°
Pitet (antiform)	n = 22 Beta-axis : 15/240	n = 31; mean : 242/66NW ± 006° Beta-axis : 03/060	n = 53 Beta-axis : 14/248	008°CW	n = 14 mean : 150 ± 011°
Fallais (synform)	n = 32 Beta-axis : 14/249	n = 32; mean : 241/68NW ± 006° Beta-axis : 25/252	n = 64 Beta-axis : 16/247	002°ACW	n = 15 mean : 168 ± 017°
Latinne (antiform)	n = 12 Beta-axis : 01/060	n = 12; mean : 241/61NW ± 002° Beta-axis : 08/057	n = 24 Beta-axis : 01/060	001°CW	n = 11 mean : 154 ± 017°
Huccorgne (synform)	n = 30 Beta-axis : 01/259	n = 26; mean : 257/90N ± 010°	n = 56 Beta-axis : 00/257	001°ACW	n = 22 mean : 179 ± 019°
Marneffe (antiform)	n = 23 Beta-axis : 16/228	n = 22; mean : 252/64N ± 008° Beta-axis : 15/065	n = 45 Beta-axis : 15/255	030°CW	n = 4 mean : 156 ± 033°
Oteppe-Lamontzé (synform)	n = 30 Beta-axis : 10/247	n = 24; mean : 252/59N ± 010° Beta-axis : 13/259	n = 54 Beta-axis : 05/252	011°CW	n = 32 mean : 166 ± 018°
Méhaigne valley (Fumal - Latinne)	n = 188 Beta-axis : 03/250	n = 174 mean : 246/69NW ± 008° Beta-axis : 08/249	n = 362 Beta-axis : 03/248	003°ACW	n = 97 mean : 155 ± 019°
Burdinale valley (Huccorgne - Lamontzé)	n = 83 Beta-axis : 07/249	n = 72 mean : 254/72N ± 010° Beta-axis : 03/255	n = 155 Beta-axis : 06/254	008°CW	n = 58 mean : 171 ± 021°
Méhaigne-Burdinale area	n = 271 Beta-axis : 04/249	n = 246 mean : 248/70N ± 009° Beta-axis : 08/251	n = 517 Beta-axis : 04/250	001°CW	n = 155 mean : 161 ± 021°

Table 1. Bedding, cleavage and fracture data from the Méhaigne-Burdinale area. The Beta-axis is the line of intersection of all planar features under consideration. In the case of bedding, the Beta-axis represents the fold axis, which, in the case of perfectly cylindrical folds corresponds to the fold hinge line. In the case of cleavage, the Beta-axis represents the cleavage fan axis. When bedding and cleavage planes are merged, the resulting Beta-axis approximates the mean cleavage/bedding intersection. ACW: anticlockwise cleavage transection; CW: clockwise cleavage transection. n: number of measurements. Note the strong clockwise cleavage transection in the Marneffe area, caused by obliquely oriented bedding in outcrops Marneffe 1 to Marneffe 4.

steeply dipping, are oriented sub-perpendicular to the trend of the fold hinge lines (fig. 3, table 1). Similar fractures, with a similar orientation, are encountered in the Frasnian limestones directly overlying the angular unconformity (e.g. outcrops Fumal 1, Huccorgne 1).

Possibly because of the relatively small outcrop size, fault observations are scarce. Outcrop Huccorgne 3 contains a small, gently S-dipping apparently reverse fault (103/33S, n = 7; n: number of measurements), post-dating cleavage, with an apparent displacement of 10 cm. However, fault striations are not observed. In outcrop Fumal 5B, a 3 m thick fracturation zone is observed, containing small reverse post-cleavage faults with a gentle WNW-dip (202/28NW, n = 1 and 209/41NW, n = 4). As suggested by the sections, there is no evidence of large faults in the southern part of the Méhaigne-Burdinale area. In the northern part of the Méhaigne valley, however, a comparison of the distribution of the Llandovery formations on map and on cross-section indicates the presence of a fault with an apparent down-throw towards the south of minimum 100 metres. Also in the NW-part of the Burdinale valley, on the basis of stratigraphy, Verniers (1976, 1983) suggested the presence of relatively important faults.

3.3. Kink bands

As previously observed by Vandenven (1967), the cleavage in the Méhaigne-Burdinale area is affected by a large number of kink bands (table 2, fig. 6). During the present study, kink bands have been encountered in three outcrops (Fumal 4, Huccorgne 3 and Latinne 2). Like in the Orneau valley (Belmans, 2000, Debacker, 2001, Herbosch et al., 2001) the kink bands are of a contractional type, with an internal geometry suggestive of a slight volume increase due to kink band development (table 2, fig. 7; cf. Ramsay, 1967, Ramsay & Huber, 1987). However, as previously pointed out by Vandenven (1967), two important differences occur with respect to the kink bands in the southern Orneau valley (cf. Belmans, 2000, Herbosch et al., 2001). Firstly, whereas the latter area is characterised by sub-horizontal to gently dipping kink bands, with sub-horizontal to gently plunging E-W-trending axes, the kink bands in the Méhaigne-Burdinale area generally have steeply dipping to sub-vertical kink band boundaries with steeply plunging kink axes (fig. 6, table 2). Secondly, in contrast to the two main sets encountered in the Orneau valley, apparently forming conjugate sets (cf. Belmans, 2000, Herbosch et al., 2001), only one set is encountered

Outcrop	Kink band boundary	Cleavage in kink band	Cleavage surrounding kink band	Kink axis	a	b	c (~ a + b)	Volume change
Fumal 4	206/71NW (n = 3)	310/88NE (n = 1)	260/60N (n = 1)	66/326 (n = 9*)	50°	77°	125°	+ 27,2%
Latinne 2	173/60W (n = 3)	273/73N (n = 6)	244/59NW (n = 4)	53/296 (n = 13)	60°	90°	150°	+ 15,5%
Huccorgne 3	202/78W (n = 10)	302/84NE (n = 20)	266/80N (n = 31)	79/348 (n = 65*)	63°	82°	144°	+ 11,1%
All kink bands	197/73NW (n = 16)	296/82NE (n = 27)	264/77N (n = 36)	72/321 (n = 87*)	65°	84°	148°	+ 9,7%

Table 2. Kink band orientation and geometry in the Méhaigne-Burdinale area. All kink bands are dextral contractional kink bands with an internal geometry suggestive of dilation (a < b; volume increase given by sin b/sin a - 1). a: angle between kink band boundary and cleavage outside the kink band; b: angle between kink band boundary and cleavage inside the kink band; c: angle between cleavage inside and outside the kink band. See figure 5 for geological significance of angles a and b. * : includes additional cleavage orientation data from kink bands with rather rounded hinge zones. n: number of measurements.
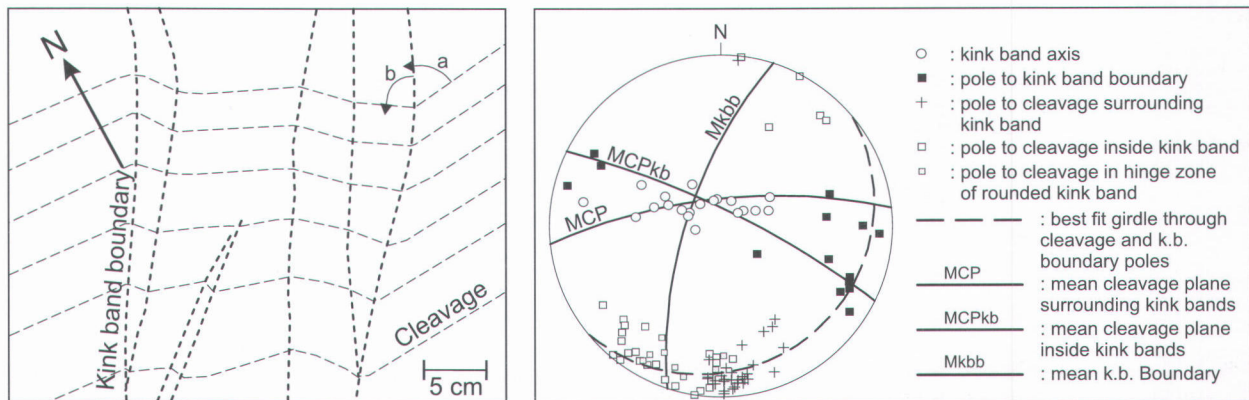

Fig. 6. Contractional kink band geometry in the Méhaigne valley. Left: drawing of the kink band geometry in outcrop Huccorgne 3 (see fig. 2 for location). Right: Lower-hemisphere equal-area stereographic projection showing the kink band axes, the kink band boundaries and the cleavage within and surrounding the kink bands in the Méhaigne-Burdinale area. See table 2 for number of data.
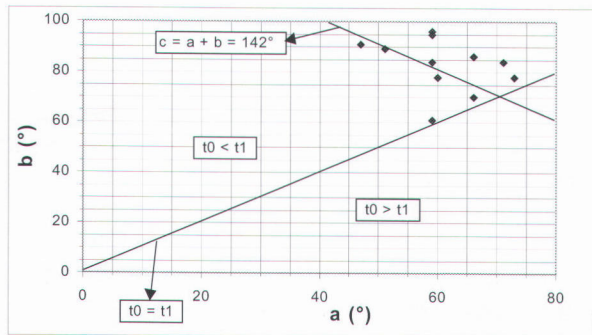
Fig. 7. Plot of angles a and b for the contractional kink bands in the Méhaigne-Burdinale area. The kink band geometry indicates a volume increase, reflected by a thickness increase inside the kink band (t1) relative to the thickness outside the kink band (t0). The volume change inside the kink band is given by sin b/sin a − 1 (Ramsay, 1967, Ramsay & Huber, 1987). See figure 6 for the geological significance of angles a and b.

in the Méhaigne-Burdinale area. Here, all kink bands have NNE-SSW-trending kink band boundaries, with a dextral geometry, indicating development during ENE-WSW-directed shortening.

3.4. Other structural features

As observed in outcrops Fumal 1B and Huccorgne 3, dm-thick fine-sandy convoluted beds (c-intervals, Bouma, 1962) locally occur interstratified in the sub-horizontal to gently S-dipping upper Wenlock clayey to fine-silty deposits (cf. Verniers, 1976, 1983). In contrast to normal convoluted bedding, however, in which the convolutions are restricted to the internal parts of the sandy beds, these convolutions also involve the interface with the surrounding fine-grained deposits (fig. 8). The geometry of the interfaces shows a cuspate shape. This occurs both at the upper and lower interfaces, resulting in a barrel-shaped geometry, the barrels corresponding to one or more con-
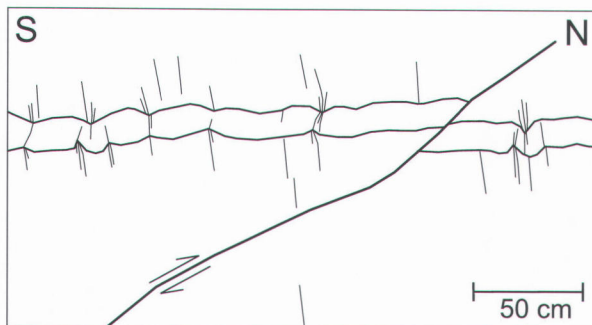

Fig. 8. Drawing of tectonically induced thickness changes of the competent convolute turbidite c-intervals in outcrop Huccorgne 3. A well-developed cleavage occurs around the cusps forming the limits of these barrel-shaped structures. These structures are interpreted as mullions. Note the S-dipping reverse fault affecting the beds (cf. Fourmarier, 1921).

volutions. The limits between the barrels usually coincide with the antiformal convolutions. Although generally the cleavage is hardly observable in these competent beds, the limits between the barrel-shaped structures show a rather well developed cleavage.

4. Microscopic observations

Thin sections of fine-grained deposits (laminated hemipelagites and d- and e-turbidite intervals) show a spaced, disjunctive cleavage, with anastomosing cleavage domains rich in opaque material. Microlithon width ranges between 15 and 40 microns, whereas the cleavage domains are generally less than 15 microns wide. The limits between microlithons and cleavage domains are gradual. White mica is abundant in the cleavage domains, oriented parallel to the cleavage. Chlorite-mica stacks, with variable orientations, predominantly occur in the microlithons. In some cases they are oriented parallel to bedding, in other cases parallel to cleavage.

Although the hinge zones of the kink bands are generally well rounded, small fractures, filled with iron oxides/hydroxides, occur along the kink band boundaries (cf. Vandenven, 1967). The most abundant fractures, however, are oriented parallel to the cleavage fabric and are generally restricted to the kink band (cf. Vandenven, 1967). Also these fractures have an infill of oxides/hydroxides. In one example remnants of a quartz infill are observed between the oxide/hydroxide infill. Although these fractures demonstrate the dilation deduced from the kink band geometry (fig. 7), the extension suggested by the fractures in the microscopically investigated kink band (maximum 6%; outcrop Fumal 4) is much lower than the dilation expected from the kink band geometry (~ 27,2%; see table 2).

5. Discussion

5.1. Bedding-parallel shortening

Since both the upper and lower limit of the convoluted sandy turbidite c-intervals have a cuspate shape, a sedimentological, density-controlled origin (e.g. load casts) is not likely. Instead, the barrel-shaped structures are interpreted as mullions, formed by shortening parallel to the interface between competent and incompetent beds. The geometry of the interfaces is compatible with the isolated occurrence of the convoluted beds (cf. Verniers, 1976, 1983). Because of the strong competence contrast across these surfaces in combination with the localised occurrence of the convoluted beds in the surrounding matrix of fine-grained relatively incompetent hemipelagic and distal turbidite deposits, the interfaces will essentially behave as free surfaces. During buckling

of a free surface intense strain localisation will occur around the cusp points (limits of the barrel-shaped structures) (Price & Cosgrove, 1990). This strain localisation is reflected by the presence of a cleavage delimiting the different barrels, thus connecting the cusp points of the upper and lower interfaces. It remains uncertain whether these mullions formed during initial, pre-folding bedding-parallel shortening or as a result of shortening in the fold hinge zone during fold development.

5.2. Cleavage/fold relationship

Like in the other Silurian outcrop areas along the southern rim of the Brabant Massif (see fig. 1), the cleavage/fold relationship (fanning, sense of cleavage refraction, low cleavage transection angles) indicates a cogenetic relationship between folding and cleavage development. As suggested by the cross-sections and stereographic projections, the plunges and plunge directions of the fold hinge lines change across the area. Although the stereographic projections of the individual folds generally do not reflect a non-cylindricity, the changes in fold hinge line orientations do suggest the presence of en-echelon periclinal folds. This is identical to the observations in the Silurian of the southern Sennette valley (Debacker et al., 1999) and the southern Orneau valley (Belmans, 2000). Hence, it seems that en-echelon periclinal folds form a common feature along the Silurian, southern rim of the Brabant Massif. In addition, the Silurian parts of the southern Sennette valley, the southern Orneau valley and the Méhaigne-Burdinale area have a similar architecture, essentially consisting of a large-scale, pluri-kilometric synform of which the central parts contain several smaller en-echelon periclinal folds.

Possibly also the large-scale host structures have a periclinal shape. A comparison of the folding-related shortening across the large host synforms, and of the geometries of the smaller folds in the Silurian deposits along the southern rim of the massif appears to support this hypothesis. The folding-related shortening, reflected by the fold interlimb angles, was determined on cross-section by means of line-length balancing. Note that, because of dealing with unbalanced sections (cf. Dahlstrom, 1969, Hossack, 1979), these shortening values should merely be considered as approximations. The highest amount of shortening characterises the large-scale synform in the southern Orneau valley (~ 50% shortening), in which the folds have open to close interlimb angles and a chevron-like geometry (Belmans, 2000, Debacker, 2001, cf. Herbosch et al., 2001). The smallest amount of shortening occurs in the large-scale synform in the Méhaigne-Burdinale area (~ 15% shortening), in which folds have gentle to open interlimb angles and a rounded, sinusoidal shape. Across the large-scale synform in the southern Sennette valley, in which sinusoidal folds as well as chevron-like folds occur, with rather rounded

hinges and gentle to close interlimb angles, intermediate shortening values are obtained (Debacker et al., 1999, Debacker, 1996, 2001). The difference in amount of shortening between the three outcrop areas considered may be related to the relative position within large-scale periclines, the higher shortening occurring near the central parts of the periclines (e.g. southern Orneau valley) and the lower shortening occurring near the peripheral parts of the periclines (e.g. Méhaigne-Burdinale area, see fig. 9). Because of the sizes of the large-scale host structures, with wavelengths from 3 to 8 kilometre, a considerable lateral extent is expected. On the basis of a 1 to 5 ratio between the pericline maximum wavelength and the extent of the pericline measured along the fold hinge line (Price & Cosgrove, 1990), a lateral extent of 15 to 40 kilometres, or even more, may be expected, thus supporting the possibility to correlate the large-scale host fold structures between different outcrop areas (fig. 9).

A large part of the Méhaigne-Burdinale area shows a small clockwise axial cleavage transection, partly confirming the observations of previous researchers (Fourmarier, 1914, 1921, cf. Sintubin, 1997). However, because of the changes in fold hinge line orientation, the angle of cleavage transection may strongly vary across the area. Hence, also in this respect the Méhaigne-Burdinale area can be regarded as similar to the southern Sennette valley (Debacker, 1996, Debacker et al., 1999) and the southern Orneau valley (Belmans, 2000, cf. Herbosch et al., 2001). It differs from the southern Sennette valley, however, on the basis of the sense of cleavage transection. Whereas the predominant sense of cleavage transection in the latter area is zero to slightly anticlockwise (Debacker et al., 1999, Debacker, 1996, 2001), the predominant transection sense in the Méhaigne-Burdinale area is slightly clockwise (table 1). On the basis of isolated cleavage and bedding measurements, several authors (Fourmarier, 1921, Sintubin, 1997) put forward a difference in curvature of the fold hinge line trajectories with respect to the cleavage trajectories along the southern rim of the Brabant Massif, the former having a stronger curvature than the latter. This difference in curvature is believed to result in a clockwise cleavage transection in the eastern outcrop areas (Méhaigne-Burdinale area) and an anticlockwise transection in the western outcrop areas (Senne-Sennette area) (Sintubin, 1997). Although not contradicting this opinion, a comparison of the data from the Méhaigne-Burdinale area with those from the other Silurian outcrop areas (Debacker et al., 1999, Debacker, 2001) shows that the difference in cleavage transection between the eastern outcrop areas and the western outcrop areas is less pronounced than suggested by previous authors (e.g. Sintubin, 1997) and that, to a large extent, the sense and amount of cleavage transection are influenced by the en-echelon periclinal nature of the folds. Hence, considering the common occurrence of en-echelon periclinal folds,

of different sizes (Price & Cosgrove, 1990, Treagus & Treagus, 1981, Debacker, 2001), care should be taken when concluding a regional cleavage transection on the basis of only a few observations. In addition, it should be emphasised that, in order to determine cleavage transection, also the plunge and plunge direction of the fold hinge lines and the dip of the cleavage should be considered (Johnson, 1991). Cleavage transection should not be determined by means of simply comparing the trend of the cleavage with the trend of the fold hinge lines (e.g. Sintubin, 1997).

In contrast to previous views (Vandenven, 1967, Sintubin, 1997) a low-angle convergent cleavage fanning does occur in the Méhaigne area. As such, also in this respect the Méhaigne-Burdinale area is similar to the southern Sennette valley (Legrand, 1967, Debacker, 1996, Debacker et al., 1999) and the southern Orneau valley (Mortelmans, 1953, Belmans, 2000). Also the Wenlock-Ludlow deposits of the Landenne area, situated in between the Orneau valley and the Méhaigne-Burdinale area (De Winter, 1998), appear to be deformed by folds with convergent cleavage fans.

Like in the Orneau valley and the Sennette valley, there is no evidence for a Variscan overprint nor for a polyphase deformation in the Méhaigne-Burdinale area. Hence, a two-phase deformation explanation for the convergent cleavage fans, as previously put forward by Mortelmans (1953; pre-Givetian deformation followed by Variscan deformation), Legrand (1967; two pre-Givetian phases) and Michot (1978; two pre-Givetian phases), is avoided. By analogy with the southern Sennette valley (Debacker, 1996, Debacker et al., 1999) and the southern Orneau valley (Belmans, 2000), also here a single pre-Givetian progressive deformation phase might offer a geometrical explanation for the convergent cleavage fans. Continued fold amplification during and after cleavage development may cause a passive rotation of the cleavage, hereby generating the convergent cleavage fans (cf. Debacker, 1996, Debacker et al., 1999, Belmans, 2000). However, having outlined the particular location of the convergent cleavage fans, the question rises why these convergent cleavage fans are restricted to the Silurian southern rim and, if formed by a continued fold amplification during and after cleavage development, why this did not happen in the more central, Cambrian and Ordovician parts of the massif. Michot (1978) argued that pre-Middle Devonian, northward upthrusting along the Mosane fault in the Condroz inlier ("Bollandian phase") was responsible for the convergent cleavage fans along the southern rim of the Brabant Massif. For two reasons this explanation is rather unlikely. Firstly, it invokes two separate pre-Givetian deformation phases, a first one from the north, a second one from the south. Secondly, although the Méhaigne-Burdinale area is the most closely situated outcrop area of the Brabant Massif to the Condroz inlier, it has the lowest degree of convergent cleavage fanning. Possibly the restricted occurrence of the convergent cleavage fans is linked to a particular deformation style within the large-scale periclinal synforms along the southern rim of the Brabant Massif. Alternatively, it should be taken into account that the restricted (geographical) occurrence of the conver-
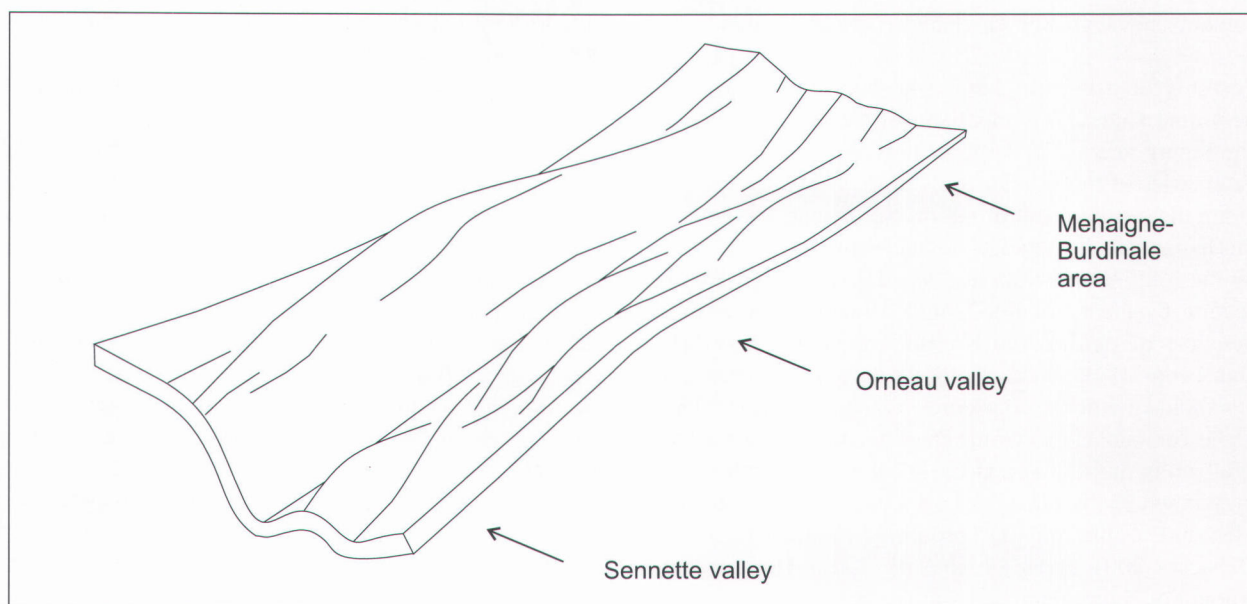

Fig. 9. Conceptual drawing of the Silurian southern rim of the Brabant Massif, interpreted as a large-scale periclinal fold assemblage with a synformal shape. The approximate positions of the southern Sennette valley, the Orneau valley and the Méhaigne/Burdinale area are added. Note the low amount of shortening across the Méhaigne/Burdinale area as compared to the southern Sennette valley and the Orneau valley. The highest amounts of shortening occur across the Orneau valley and between the Orneau valley and the southern Sennette valley.

gent cleavage fans is not necessarily a result of the actual structural position, but instead may be considered as a restricted stratigraphical occurrence. As shown by several authors (e.g. Ramsay & Huber, 1987, Price & Cosgrove, 1990, and references therein) lithology influences the folding mechanism and the way folds initiate and amplify. Hence, perhaps the convergent cleavage fans are related to the homogeneous fine-grained lithology of the Silurian deposits (cf. Verniers *et al.*, 2001).

5.3. Post-cleavage deformation

The apparent discrepancy between the expected dilation based on kink band geometry and the, much lower, extension suggested by cleavage-parallel fractures inside the kink band may partly have been accommodated by a loss of cohesion along the kink band boundaries. This is compatible with the abundance of fractures running along the kink band boundaries. Alternatively, instead of being concentrated on isolated, easily recognisable fractures within the kink bands, a large part of the dilation may have occurred along the cleavage domains, as such resulting in a more homogeneously distributed, and therefore less obvious, extension.

The kink bands suggest development during ENE-WSW-directed compression, at high angles to the shortening responsible for fold and cleavage development (cf. Vandenven, 1967). Taking into account the relatively high confining pressures necessary for kink band development (Anderson, 1974, Ramsay & Huber, 1987) and the apparent absence of Givetian and younger compressional features inside the Brabant Massif, the kink bands are considered to have formed prior to the Givetian, during the late stages of compression. On the one hand, the constant orientation of the kink bands and the large distance between the outcrops containing them suggests a large-scale occurrence, which is difficult to attribute to a local deviation of strain trajectories such as encountered around large objects offering more resistance to deformation (e.g. plutonic bodies). On the other hand, however, the position of these structures, apparently restricted to the eastern part of the Méhaigne-Burdinale area, does suggest a large-scale strain partitioning, resulting in an additional post-cleavage ENE-WSW-directed shortening component. Possibly this additional shortening component, responsible for kink band development, is related to the last increments of the eastward escape of the core of the Brabant Massif put forward by Sintubin (1999, cf. Debacker, 2001).

Although reverse faulting in outcrop Huccorgne 3 is readily compatible with the fold and cleavage orientation, the small apparently reverse faults in the fracturation zone in outcrop Fumal 5B are dipping moderately towards the WNW, oriented oblique to the structural trend (strike difference of 35 to 50°). On the one hand, taking into account the general structural trend, these faults may have experienced an oblique-slip displacement, with a relatively important sinistral component. On the other hand, however, in the case of a dip-slip or dextral oblique-slip movement, these small reverse faults may be compatible with the shortening direction responsible for kink band development.

The regionally consistent transverse fractures reflect a small extension sub-parallel to the fold hinge lines. Although the spread in orientation of these transverse fractures seemingly suggests conjugate sets with a steeply plunging intersection lineation and NNW-SSE-facing acute angles, consistent with development during NNW-SSE-directed shortening, true conjugate sets have not been observed. In addition, fractures with a similar orientation have also been observed in the Frasnian limestone above the unconformity. An analogous situation has been observed in the Silurian of the southern Sennette valley (Debacker *et al.*, 1999, Debacker, 1996, 2001): steeply dipping to sub-vertical fractures, oriented at high angles to the fold hinge lines, have a similar orientation and appearance as the fractures in the relatively undeformed Givetian deposits above the unconformity. In addition, also there, the spread in fracture orientation seemingly reflects conjugate sets with a steeply plunging intersection lineation and NE-SW-facing acute angles. However, the observed conjugate sets in the southern Sennette valley reflect a NW-SE-directed extension and a vertical shortening under the influence of a vertical load (Debacker, 2001, cf. Debacker *et al.*, 1999), thus suggesting development after compression. This could explain why fractures with a similar appearance and orientation occur both above and below the angular unconformity. Using this assumption, it seems strange to find that the orientation of the fractures, unrelated to compression, shows such an intimate relationship with the fold hinge line orientations, especially when considering the difference in fold hinge line orientation between the Méhaigne-Burdinale area (WSW-ENE-trend) and the Sennette valley (NW-SE-trend). This may be explained, however, by the suggestion of Lisle (2001). As put forward by this author, layered rocks, upon deformation, acquire a material anisotropy which will polarise later strains in a direction parallel or perpendicular to the initial fold hinge lines. In the case of the Brabant Massif, the anisotropy of the deformed Lower Palaeozoic basement may have polarised the small strains induced by the vertical load after compression, hence giving rise to fractures at high angles to the fold hinge lines, irrespective of the absolute orientation of the fold hinge lines.

6. Conclusions

Although several authors (e.g. Fourmarier, 1921, Vandenven, 1967, Sintubin, 1997) have stated that the Méhaigne-Burdinale area is characterised by folds with

a parallel cleavage, and therefore markedly differs from the other Silurian outcrop areas of the Brabant Massif, characterised by folds with convergent cleavage fans (the Sennette valley, the Orneau valley and the Landenne area), new outcrop observations also demonstrate the presence of folds with convergent cleavage fans in the southern part of the Méhaigne-Burdinale area. Apparently, a gradual transition exists towards folds without such fans in the Silurian deposits in the northern part of this outcrop area.

Similar to the Silurian of the Orneau valley and the Sennette valley, also the Méhaigne-Burdinale area can be considered as consisting of a pluri-kilometric host synform, probably of a periclinal nature, of which the core contains an en-echelon periclinal fold train. The gentle to open fold interlimb angles and the sinusoidal, rounded fold shapes of the Méhaigne-Burdinale area may be attributed to a peripheral position within a large-scale periclinal host synform. Although a small clockwise cleavage transection dominates the area, both the sense and amount of cleavage transection are to a large extent influenced by the en-echelon periclinal fold shapes.

Like in the other outcrop areas of the Brabant Massif, there is only evidence for one single pre-Givetian deformation. The dextral, NNE-SSW-trending kink bands likely formed prior to the Givetian and possibly result from the lateral, E-ward escape of the Cambrian core of the Brabant Massif put forward by Sintubin (1999). Only the transverse fractures may have formed after the Givetian. Their close geometrical relationship with the folds probably results from strain polarisation due to the anisotropy of the deformed Lower Palaeozoic basement.

By analogy with the Sennette valley and the Orneau valley (cf. Debacker, 1996, Debacker *et al.*, 1999, Belmans, 2000), also the convergent cleavage fans in the Méhaigne-Burdinale area might be explained by a small post-cleavage fold amplification during a single-phase progressive deformation. However, the question why these convergent cleavage fans seem restricted to the Silurian southern rim of the Brabant Massif remains unanswered. Possibly this is related to a particular deformation style within the large-scale host synform or it is a result of the homogeneous fine-grained lithology of the Silurian deposits. Further studies to the origin of the convergent cleavage fans should consider both options and will have to take into account the currently recognised similarities in deformation style within all Silurian outcrop areas along the southern rim of the Brabant Massif.

7. Acknowledgements

8. References

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