Journal of Structural Geology 28 (2006) 1123–1138
JOURNAL OF STRUCTURAL GEOLOGY
www.elsevier.com/locate/jsg

Distinguishing syn-cleavage folds from pre-cleavage folds to which cleavage is virtually axial planar: examples from the Cambrian core of the Lower Palaeozoic Anglo-Brabant Deformation Belt (Belgium)

T.N. Debacker [a,*], M. van Noorden [b], M. Sintubin [b]

[a] *Geology and Pedology, Universiteit Gent, Krijgslaan 281, S8, B-9000 Gent, Belgium*
[b] *Geodynamics and Geofluids Research Group, Katholieke Universiteit Leuven, Celestijnenlaan 200E, B-3001 Leuven, Belgium*

Received 24 January 2006; received in revised form 21 March 2006; accepted 22 March 2006
Available online 6 May 2006

Abstract

Within the Cambrian Jodoigne Formation in the easternmost part of the Anglo-Brabant Deformation Belt, sub-horizontal to gently plunging folds occur within the limbs of steeply plunging folds. The latter folds are cogenetic with cleavage and are attributed to the Brabantian deformation event. In contrast, although cleavage is also (1) virtually axial planar to the sub-horizontal to gently plunging higher-order folds, shows (2) a well-developed divergent fanning across these folds, (3) an opposing sense of cleavage refraction on opposite fold limbs, and (4) only very small cleavage transection angles, an analysis of the cleavage/bedding intersection lineation suggests that these higher-order folds have a pre-cleavage origin. On the basis of a comparison of structural and sedimentological features these higher-order folds are interpreted as slump folds. The seemingly 'normal' cleavage/fold relationship across the slump folds within the limbs of the large steeply plunging folds is due to the very small angle between cleavage and bedding.

As such, a 'normal' cleavage/fold relationship is no guarantee for a syn-cleavage fold origin. It is not unlikely that also within undeformed, recumbent slump folds, a well-developed compaction fabric, formed parallel to the axial surface of the slump folds, may show fanning and contrasting senses of cleavage refraction on opposite fold limbs.

Keywords: Avalonia; Cleavage fanning; Cleavage refraction; Lower Palaeozoic; Slate belt; Slump fold

1. Introduction

In order to determine the tectonic nature of folds, geologists conventionally rely on the geometrical relationship with related small-scale tectonic structures such as cleavage, fractures and other associated structures (e.g. cleavage/bedding intersection lineations, boudins, mullions) (Wilson, 1961; Ramsay, 1967; Ramsay and Huber, 1987; Price and Cosgrove, 1990). Within the predominantly fine-grained deposits of slate belts, where fractures, being restricted to the few more competent beds, may be scarce, often geologists have to rely on the cleavage/fold relationship in order to establish the syn-cleavage, tectonic nature of the folds and distinguish these from pre-cleavage folds (e.g. Debacker et al., 2001). If a fold has an axial planar cleavage, give or take a small cleavage transection (e.g. Johnson, 1991; cf. Johnson and Woodcock, 1991), and if this cleavage remains parallel throughout the fold or shows a fanning, symmetrical about the fold hinges, and if opposing senses of cleavage refraction occur on opposite fold limbs, most geologists will conclude a syn-cleavage and hence tectonic fold origin (e.g. Wilson, 1961). However, the presence of an axial planar foliation is not diagnostic of tectonic folds (e.g. Elliott and Williams, 1988). By coincidence, cleavage may be virtually axial planar to pre-cleavage folds, in which case it becomes difficult to determine the pre-cleavage nature of these folds (e.g. see contrasting interpretations of early structures in the Newfoundland Appalachians by Helwig (1970), Pickering (1987), Elliott and Williams (1988) and Blewett (1991)). This difficulty is likely to increase with decreasing amount of exposure, with increasing number of tectonic deformation phases and with increasing amount of structural complexity. Probably because of this difficulty, there are hardly any studies that illustrate the behaviour of a cleavage being axial planar to pre-cleavage folds. If cleavage happens to

* Corresponding author. Tel.: +32 9 264 46 07; fax: +32 9 264 46 08.
E-mail addresses: timothy.debacker@UGent.be (T.N. Debacker), Michiel.vannoorden@geo.kuleuven.be (M. van Noorden), Manuel.sintubin@geo.kuleuven.be (M. Sintubin).

0191-8141/$ - see front matter
doi:10.1016/j.jsg.2006.03.027

be virtually axial planar to a pre-cleavage fold, whether tectonic or due to slumping, does it show opposing senses of cleavage refraction on opposite fold limbs and a cleavage fanning symmetrical about the fold hinge as in the case of the syn-cleavage folds? Similarly, does the cleavage transection angle have an upper limit, beyond which folds can definitely be labelled as having a pre-cleavage origin?

The present study documents close to tight pre-cleavage folds, with a virtually axial planar cleavage, that occur within the limbs of steeply plunging tectonic folds within a low-grade, single-phase deformed slate belt. As will become apparent, pre-cleavage folds may show opposing senses of cleavage refraction on opposite fold limbs and cleavage fans oriented symmetrical about the fold hinges. In the examples shown, in the absence of other criteria, it appears that the best indication of a pre-cleavage origin is the variation of the cleavage/bedding intersection lineation across the folds, even when the axial cleavage transection and profile cleavage transection (*sensu* Johnson, 1991) are almost negligible.

2. Outcrop location and geological setting

The study area is the Jodoigne area, situated in the Grande Gette valley, in the eastern part of the Lower Palaeozoic Brabant Massif, easternmost Anglo-Brabant Deformation Belt (Fig. 1). In recent years, significant progress has been made in the understanding of the structural architecture and the deformation history of the Brabant Massif (e.g. Sintubin, 1997, 1999; Debacker, 2001; Verniers et al., 2002; Debacker et al., 2004, 2005a). Thus far, within the Brabant Massif, there is only evidence for one single-phase progressive deformation, considered to have taken place from the early Silurian to the late Early Devonian (Debacker, 2001; Verniers et al., 2002; Debacker et al., 2005b; cf. Van Grootel et al., 1997). This deformation mainly resulted in the development of folds and a well-developed cogenetic cleavage (Sintubin, 1997, 1999; Debacker, 2001; Debacker et al., 2004). Within the outcrop areas, all situated in the southern part of the massif, two main tectonic fold types can be recognised (Debacker et al., 2004; cf. Sintubin, 1997, 1999). Type A folds consist of sub-horizontal to gently plunging, upright to moderately inclined folds, with a slight south-verging asymmetry and gentle to close, occasionally tight, interlimb angles (Fig. 2). These folds abound within the Silurian and Ordovician southern part of the massif and also occur within the steep Cambrian core. Type B folds (Lembeek fold type of Sintubin (1997, 1999) and Sintubin et al. (1998)) are upright to steeply inclined, steeply plunging to reclined folds, with open to tight interlimb angles and commonly reflect a step-fold geometry (Fig. 2). In contrast to the type A folds, the type B folds are only observed within the steep Cambrian core of the Brabant Massif. As recently demonstrated, within the Cambrian core the transition between the type A and type B folds, both being genetically related to the same cleavage, occurs in a gradual fashion (Debacker et al., 2004). However, the origin of the type B folds remains uncertain. As proposed by several authors (see Sintubin et al., 1998; Sintubin, 1999; Debacker et al., 2004; Piessens et al., 2004), these folds may result from dextral transpression, caused by non-orthogonal shortening against the steep, oblique side of a low-density gravimetric anomaly body situated in the subsurface of the SW-part of the Brabant Massif (cf. Everaerts et al., 1996; Sintubin and Everaerts, 2002). From this model, type B folds would be expected to become scarcer towards the east. However, Fourmarier (1921) already documented the occurrence of steeply plunging folds at Jodoigne, in the easternmost outcrop area of the Cambrian core of the Brabant Massif, but considered these as local features of relatively minor importance. The initial purpose of

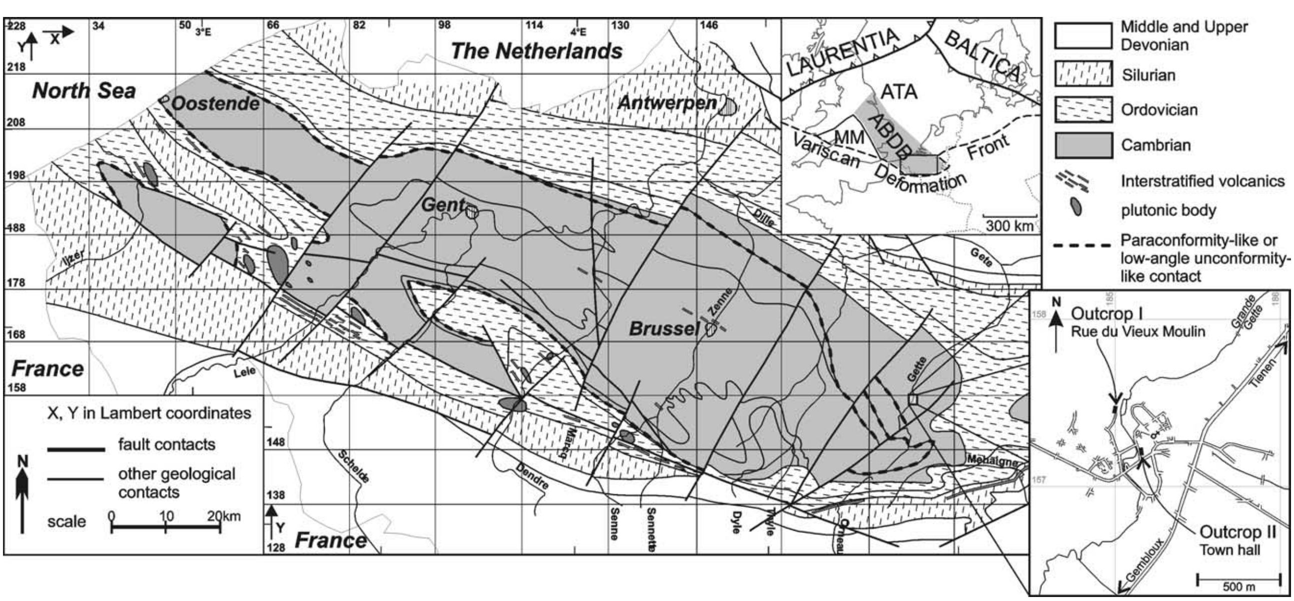

Fig. 1. Geological subcrop map of the Brabant Massif (after De Vos et al., 1993; Van Grootel et al., 1997) showing the position of the study area. The upper right inset shows the position of the Brabant Massif within the Anglo-Brabant Deformation Belt (ABDB) along the NE-side of the Midlands Microcraton (MM) in the context of Avalonia (ATA), Baltica and Laurentia. The lower right inset shows the location of the two studied outcrops at Jodoigne.

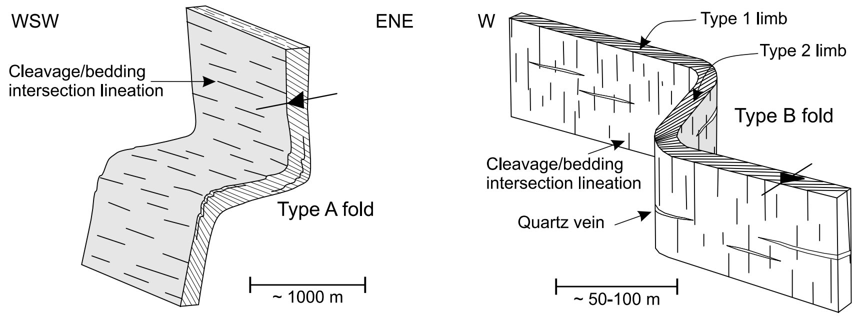

Fig. 2. The two main fold types in the Brabant Massif (type A folds and type B folds; after Debacker et al., 2004). The sense of younging is given by the arrows. See text.

the present study was to check whether or not the folds described by Fourmarier (1921) comply with the characteristics of type B folds.

In this paper, two well-exposed outcrops of the Cambrian Jodoigne Formation are examined at Jodoigne (Fig. 1). The first outcrop, 13 m long, is situated on the W-side of the Grande Gette valley, in the street 'Rue du vieux Moulin', facing the entrance of an old factory. This outcrop will be referred to below as outcrop I (Figs. 3 and 4). The second outcrop, referred to as outcrop II below, is a 25 m long outcrop situated on the E-side of the Grande Gette, below the W-wall of the town hall of Jodoigne (Fig. 5). The distance between both outcrops is ~250 m in a NW–SE-direction (327–147°).

3. Observations

3.1. Lithology

Both outcrops show the same lithology, consisting of very dark grey to black mudstone sequences, with intercalated pale grey to greenish grey siltstone and sandstone beds, often rich in pyrite, with a thickness ranging from a few millimetres to 1–3 dm. The sandstone and siltstone beds are usually cross-bedded, with the thicker beds (decimetric) often containing convolutions and showing a well-developed ripple lamination (Fig. 6). In both outcrops, current ripples and convolution axes are sub-parallel to the hinge lines of a system of steeply plunging folds. In outcrop I, the southern part is almost entirely composed of greenish grey, decimetric, cross-bedded sandstones, whereas the northern part is dominated by a mudstone sequence with a few intercalated sandstone beds. Some of these sandstone beds are dark grey to black, a facies regarded typical for the Jodoigne Formation (Verniers et al., 2001). Outcrop II is dominated by black mudstone, with relatively thin siltstone and sandstone beds. The thicker, convoluted beds seem restricted to the southernmost and northernmost parts of this outcrop.

In both outcrops, zones occur in which the mudstone sequences contain isolated, lens-shaped fragments of disrupted siltstone and sandstone beds, apparently being truncated and displaced by detachments oriented sub-parallel to bedding (Fig. 6). As observed in outcrop II, these lenses are sometimes rotated with respect to the surrounding beds and are associated occasionally with gently plunging, truncated folds (e.g. folds II11 and II07; Fig. 5). In a few locations, these isolated lenses are observed to be cross-cut by the cleavage, demonstrating their pre-cleavage origin (Fig. 6). In addition, the extent to which the sandstone and siltstone beds are dismembered in both outcrops, with the surrounding mudstone matrix being folded around it, suggests a pre-lithification origin. In outcrop I,

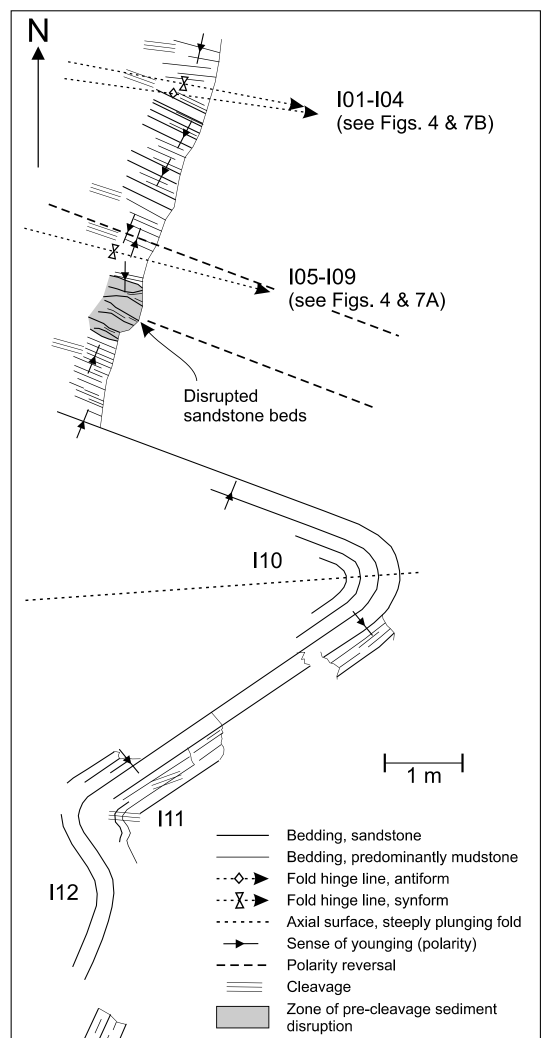

Fig. 3. Map view of outcrop I, showing bedding, cleavage, fold hinge lines, axial surfaces, younging sense and zones of pre-cleavage sediment disruption. Note the presence of sub-horizontal to gently plunging folds (folds I01–I09), within the northern limb of a steeply plunging fold (fold I10). See also Figs. 4 and 7.

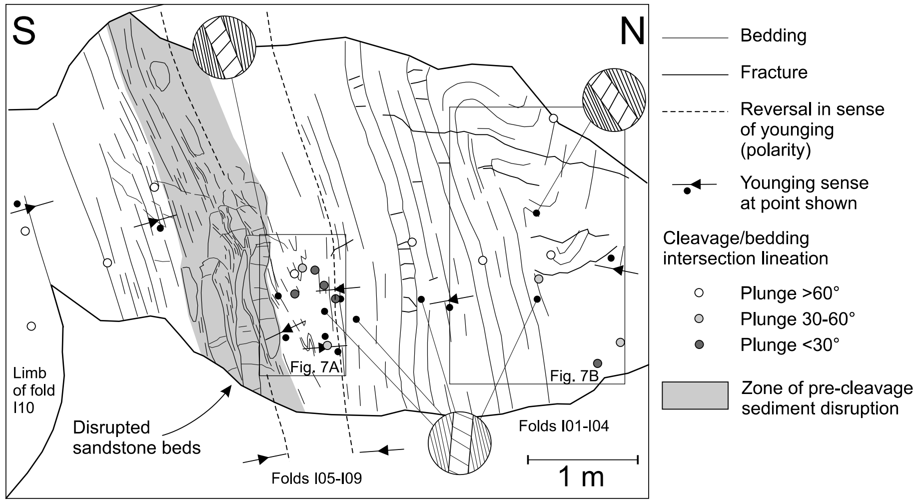

Fig. 4. Profile view of the northern part of outcrop I, showing the sub-horizontal to gently plunging folds (folds I01–I09), the sense of younging and the cleavage/bedding relationship within the northern limb of steeply plunging fold I10. See also Figs. 3 and 7.

such a zone, containing quite large sandstone fragments (several decimetres long and 2–3 dm wide), occurs in the northern part of the outcrop (see Figs. 3 and 4). In outcrop II, where, probably due to the overall more fine-grained lithology, the lenses are generally smaller (usually no more than 10 cm long and a few centimetres wide), several zones of pre-cleavage brecciation are recognised (see Fig. 5). The most important of these zones occurs in the central to northern part of the outcrop.

3.2. Cleavage/fold relationship and younging sense

Both outcrops are dominated by steeply plunging folds and contain sudden changes in younging sense, across almost uniformly dipping fold limbs.

Outcrop I is dominated by a decametre-scale, steeply N-plunging fold, with a step-fold geometry, a steeply N-dipping axial surface and a close interlimb angle (fold I10; Fig. 3). In the southern fold limb, two smaller steeply N-plunging folds are present, having gentle to open interlimb angles and an S-shaped asymmetry (folds I11 and I12). The cleavage/bedding intersection lineation is parallel to the fold hinge lines (Table 1). Although difficult to see in these cross-bedded sandstones, the cleavage is sub-parallel to the fold axial surfaces and shows a well-developed divergent cleavage fanning, with a symmetrical disposition about the fold hinges. Within this part of the outcrop, the folds face towards the E (younging sense).

In the northern part of outcrop I, in the northern limb of the steeply plunging fold (I10), two zones occur containing centimetre- to metre-scale, gently to moderately plunging folds (folds I1–I4 and folds I5–I9) (Figs. 3, 4 and 7). These folds have close to tight interlimb angles and steeply NNE-dipping, slightly curving axial surfaces. The cleavage, being at a very low angle to bedding, commonly shows a divergent cleavage fanning, symmetrical about the fold hinges and has an opposing sense of cleavage refraction on opposite fold limbs (Fig. 7). In addition, the cleavage only slightly transects the folds, with a transection angle that may vary from fold to fold (Table 1, Fig. 8). However, despite the seemingly almost perfect axial planar relationship between the cleavage and these folds, the cleavage/bedding intersection lineation is strongly variable (Fig. 8, Table 1). In the more or less uniform, steeply N-dipping beds in between these two fold zones, the intersection is steeply plunging, whereas in the fold zones, the intersection varies from steeply plunging to sub-horizontal (Figs. 4 and 7). Sub-horizontal to moderately plunging intersections are only observed where a relatively large angle exists between bedding and cleavage: in the hinge zones and in places where bedding is sub-vertical to steeply S-dipping. The sense of younging is downwards in the southern, synformal, fold zone and upwards to the south in the northern antiform–synform fold pair zone (Fig. 7). Hence, the overall younging direction of the northern part of the northern limb opposes that of the large steeply plunging fold to the south (I10) (see Figs. 3 and 4).

Outcrop II is dominated by a fold train of steeply plunging, decimetre- to metre-scale folds, with a Z-shaped fold asymmetry (Fig. 5). In the northernmost part of this outcrop (folds II01–II05) these folds have tight to close interlimb angles, steeply NE-dipping axial surfaces and steeply to moderately E-plunging fold hinge lines (Fig. 8). The plunge of the fold hinge lines varies along strike (up to 30°), seemingly reflecting curvilinear folds (see folds II04a,b,c and II05a,b,c,d; Table 1). Importantly, towards the south, the fold plunge decreases significantly (compare folds II01 and II02 with folds II04 and II05). Despite this variation in fold plunge, cleavage is sub-parallel to only slightly oblique to the fold axial surfaces and shows a divergent cleavage fanning, symmetrical about the fold hinges. The individual folds only show a small axial cleavage transection angle (<020°), of which the sense varies between the different folds (Table 1). Overall, the folds in this northernmost part of outcrop II have a small anticlockwise axial cleavage transection (013°), as well as a mean cleavage that is slightly anticlockwise (011°) with respect to the mean fold axial surface (Fig. 8). However, the cleavage/bedding

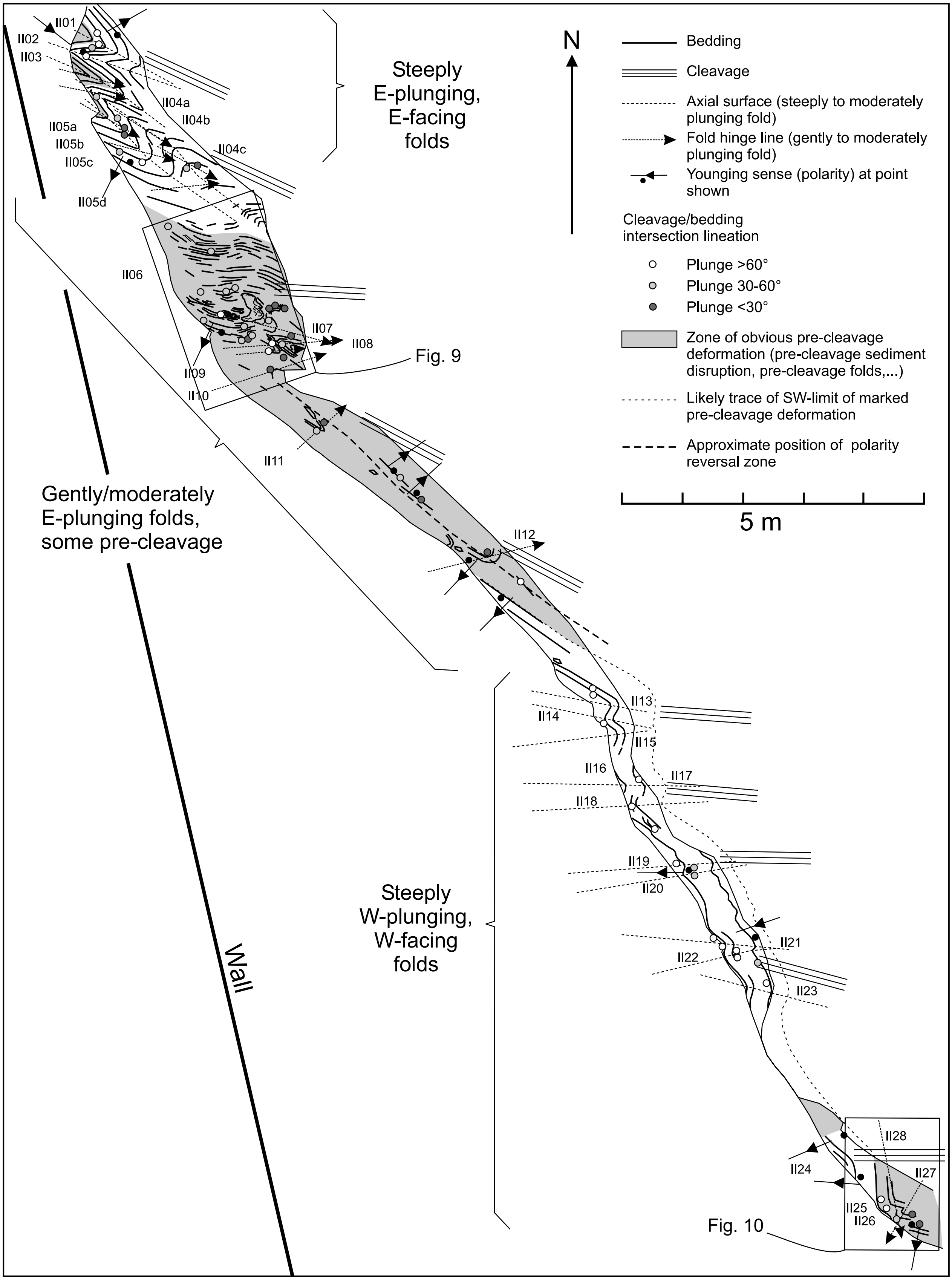

Fig. 5. Map view of outcrop II, showing bedding, cleavage, fold hinge lines, axial surfaces, cleavage/bedding intersection lineation plunges, younging sense and zones of pre-cleavage sediment deformation. Note the occurrence of zones of sub-horizontal to moderately plunging folds (folds II03–II12 and II27 and II28), in between zones of steeply plunging folds. See also Figs. 9 and 10.

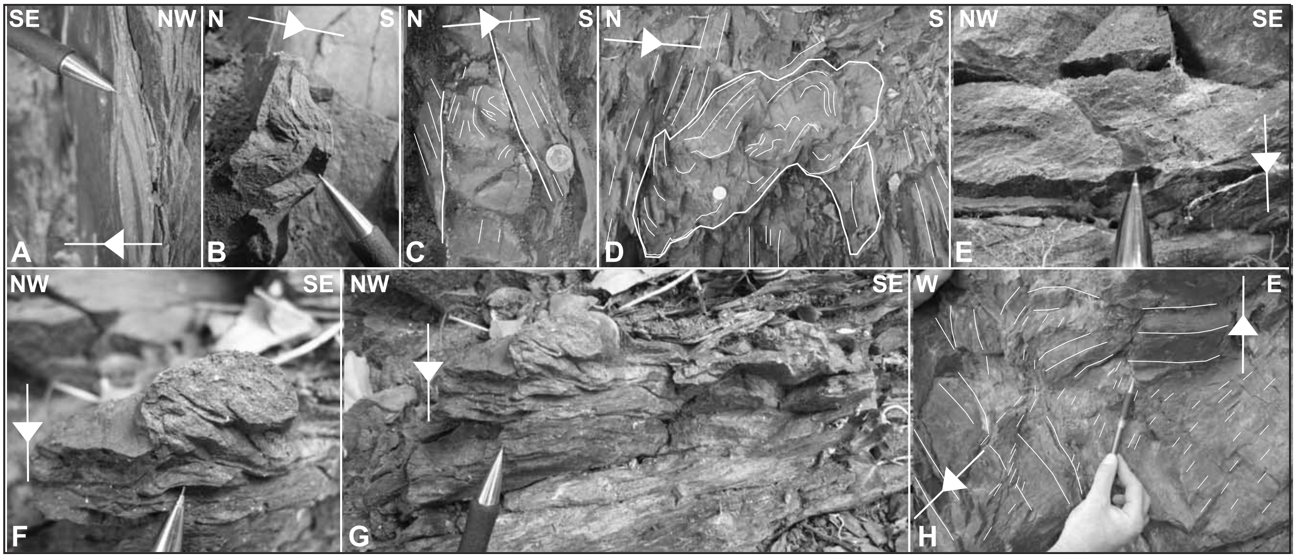

Fig. 6. Lithological, sedimentological and pre-cleavage deformation features within the Jodoigne Formation in outcrops I and II. Arrows indicate the sense of younging. (A) Crossbedded sandstone in the southeastern limb of fold I10 (outcrop I; pen tip for scale); (B) convoluted sandstone bed (zone of II06, outcrop II; pen tip for scale); (C) convoluted sandstone bed, truncating underlying beds and being truncated by overlying beds (zone of II06, outcrop II; 1 euro for scale); (D) isolated lens of thick convoluted sandstone, within seemingly almost undisturbed, fine-grained matrix (zone of II06, outcrop II; cf. Figs. 5 and 9; 1 euro for scale); (E) disrupted sandstone bed, consisting of ball-and-pillow-like structures and pronounced load casts being separated by upward intrusions of pelitic material (S-limb II12, outcrop II; pen tip for scale); (F) disrupted, rolled-up sandstone bed, forming a load cast-like structure into the older pelitic material (S-limb II12, outcrop II; pen tip for scale); (G) zoomed-out image of F, showing the strongly deformed sandstone bed and the disrupted, stratigraphically overlying (below) mudstone-siltstone sequence; (H) close-up of hinge of pre-cleavage fold II28; being cross-cut at high angles by the cleavage (top right to bottom left, sub-parallel to pen; outcrop II, cf. Figs. 5 and 10; pen for scale).

intersection lineation is sub-parallel to the fold hinge lines across the folds only in the northernmost folds (folds II01 and II02). Going towards the south, the plunge of the cleavage/bedding intersection lineation becomes highly variable (Table 1). Across the moderately to gently plunging folds II04 and II05, the cleavage/bedding intersection lineation shows gentle to moderate plunges in the fold hinges, but steep plunges in the steep limbs. Within this northernmost part of the outcrop, the folds face towards the E (younging sense).

Within the fine-grained zone to the south of fold II05 containing pre-cleavage and pre-lithification sediment deformation features, the overall NW–SE-trending bedding, essentially reflecting the southern limb of fold II05, shows a large change in trend (zone labelled II06; Figs. 5 and 9). This change in trend is cross-cut by the cleavage, thus demonstrating its pre-cleavage origin: in the west, bedding is oriented clockwise with respect to cleavage, whereas in the east bedding is oriented anticlockwise with respect to cleavage. Going towards the SE, NW–SE-trending, steeply to moderately NE-dipping beds contain several close (e.g. II07 and II12) to tight (e.g. II09 and II11), moderately (II08 and II09a) to gently (II07, II09b, II10, II11 and II12) E- to NE-plunging folds (Figs. 5, 8 and 9), some of which appear to occur as isolated lenses in the mudstone matrix (II11). Of all these folds, only fold II12 has a significantly large axial cleavage transection angle and a relatively large angle between its axial surface and the cleavage (Table 1). However, as suggested by the variation of the cleavage/bedding intersection lineation, folds II07 and II08 also have an anomalous cleavage/fold relationship (Table 1). Within this zone of NW–SE-trending bedding, the younging sense changes from NE-younging in the NW, to SW-younging in the SE. This polarity reversal appears to occur in the vicinity of fold II12 (Fig. 5).

In contrast to the northern and central parts of the outcrop, in the southern part of outcrop II the folds (II13–II26) have open to gentle interlimb angles, steeply N-dipping axial surfaces and steeply W-plunging fold hinge lines and, importantly, the younging sense is towards the W (Figs. 5 and 8, Table 1). However, despite these differences, the relationship with cleavage is quite similar to that in the northernmost part of the outcrop (e.g. folds II01 and II02). The cleavage/bedding intersection lineation is sub-parallel to the fold hinge lines. The cleavage is sub-parallel to only slightly oblique to the fold axial surfaces, shows a well-developed divergent cleavage fanning, symmetrical about the fold hinges and shows contrasting refraction patterns on opposite fold limbs. Similarly, the individual folds show a small axial cleavage transection angle ($<020°$), of which the sense varies in between the different folds, but the overall axial cleavage transection (004° anticlockwise) as well as the angular difference between cleavage and the mean fold axial surface (004° clockwise) can be neglected (Table 1, Fig. 8).

In the southernmost part of outcrop II, two gently S-plunging folds occur (II27 and II28), with a moderately E-dipping axial surface (Fig. 10, cf. Fig. 5). These folds are cross-cut at high angles by the cleavage (Table 1) and hence have a pre-cleavage origin. Within the gently S-dipping, upward younging eastern limb, the steeply plunging, gentle folds, present in the steeply dipping, W-ward younging western limb (II25 and II26) cannot be recognised.

Table 1

Cleavage and fold data of the investigated folds. See Figs. 3, 5, 7 and 9 for location. The orientation of planar features (cleavage: S1, axial surface: AS) is written as strike/dip with an indication of dip direction (e.g. 270/70N for a plane dipping 70° due north) and the orientation of linear features (fold hinge line: FHL, cleavage/bedding intersection lineation: S1/S0 intersection: $I_{S1/S0}$) as plunge/plunge direction (e.g. 60/090 for a line plunging 60° due east). In the columns of S1, FHL (β-axis of bedding) and $I_{S1/S0}$, the number of measurements is given between brackets. In the column of $I_{S1/S0}$ also the angular difference between the two extreme values is given. The cleavage transection angle is determined by removing the fold plunge and comparing the fold trend with the cleavage trend (axial cleavage transection; *sensu* Johnson, 1991). ACW and CW signify that cleavage transects the fold in an anticlockwise, respectively, clockwise fashion. The angular difference between cleavage (S1) and the axial surface (AS) is given in terms of strike (000°) and dip (00°), + (−) implying that S1 trends clockwise (anticlockwise) with respect to AS or is steeper (less steep) than the AS. Entries in bold correspond to values (and folds) of which, judging from the geometrical analysis, the cleavage/fold relationship seems suspicious (very large spread in $I_{S1/S0}$, large angular difference between $I_{S1/S0}$ and FHL, large difference in orientation between AS and S1, or large axial cleavage transection)

Fold	Cleavage (S1)	Fold hinge line (FHL: β-axis of bedding (S0))	S1/S0 intersection lineation ($I_{S1/S0}$)	Angle FHL–$I_{S1/S0}$	Axial surface (AS)	Cleavage transection angle	Angular difference S1–AS
Outcrop I: W-side of Rue du Vieux Moulin, Jodoigne							
I10–I12	260/67N (3)	66/009 (44)	68/023 (13), 20°	6°	266/67N	001° ACW	−006°, 00°
I01	285/75N (3)	31/094 (5)		**51°**	280/80N	001° CW	+005°, −05°
I02	285/81N (4)	39/093 (12) 39/096 (24)	**76/043 (6), >90°**	**43°** **44°**	291/69N	004° CW	−006°, +12°
I03	282/82N (2)	36/101 (6)		**48°**	283/88N	004° ACW	−001°, −06°
I04	304/74NE (1)	51/098 (6)		**33°**	294/78N	003° CW	+010°, −04°
I05	–	22/118 (2)		**43°**	306/66NE	–	–
I06	314/68NE (1)	03/306 (4) **33/104 (13)**	**20/308 (10), >90°**	17°	305/77NE	009°CW	+009°, −09°
I07	290/70N (2)	26/099 (3)		**54°** **58°**	–	001°CW	–
I08	290/78N (1)	19/294 (2)		13°	–	000°	–
I09	284/66N (2)	10/289 (3)		21°	285/66N	000°	−001°, 00°
Outcrop II: below W-wall of town hall, Jodoigne							
II01	299/69NE (2)	69/074 (5)	74/018 (2), 22°	18°	296/76NE	008° ACW	+003°, −07°
II02	279/71N (2)	75/085 (5)	72/020 (1)	18°	282/86N	016° ACW	−003°, −15°
II03	296/86NE (1)	49/105 (4)	–	–	320/71NE	004° CW	**−024°, +15°**
II04a	308/69NE (3)	46/101 (6)		**37°**	307/67NE	003° CW	+001°, +02°
II04b	–	56/123 (3) 46/110 (14)	**51/045 (5), 84°**	**44°** **42°**	–	–	–
II04c	094/82S (2)	52/119 (5)		**44°**	–	009° ACW	–
II05a	300/62NE (4)	23/120 (6)		**55°**	315/57NE	012° ACW	−015°, +05°
II05b	–	31/104 (5) 34/106 (20)	**61/062 (6), >90°**	**41°** **39°**	324/50NE	–	–
II05c	288/63N (1)	42/106 (6)		**32°**	–	017° ACW	–
II05d	260/87N (2)	44/084 (3)		21°	–	005° ACW	–
II06	270/65N (8)	50/081 (13)	**65/007 (14), >90°**	**40°**	–	015° ACW	–
II07	276/69N (3)	04/105 (6)	**05/092 (4), 55°**	13°	–	010° ACW	–
II08	280/71N (2)	44/086 (3)	**11/097 (2), 58°**	**34°**	284/73N	004° ACW	−004°, −02°
II09a	273/79N (2)	48/081 (2)	62/052 (3), 15°	21°	269/80N	000°	+004°, −01°
II09b	273/79N (2)	24/088 (2)	23/079 (1)	8°	270/81N	000°	+003°, −02°
II10	264/60N (1)	20/072 (3)	24/069 (1)	5°	–	000°	–
II11	260/47N (1)	20/048 (2)	29/041 (2), 22°	11°	260/32N	012° CW	000°, +15°
II12	298/49NE (4)	13/076 (3)	10/069 (1)	7°	271/71N	**032° CW**	**+027°, −22°**
II13	284/85N (1)	75/326 (4)	63/101 (2), 9°	**39°**	280/80N	007° ACW	+004°, +05°
II14	291/76N (1)	66/339 (2)	75/359 (1)	11°	284/70N	006° ACW	+007°, +06°
II15	/	64/337 (3)	–	–	263/67N	–	–
II16	285/89N (1)	78/288 (3)	–	–	–	000°	–
II17	285/89N (1)	65/293 (5)	79/290 (1)	14°	271/80N	002° ACW	+014°, +09°
II18	272/73N (3)	66/330 (5)	79/335 (2), 21°	13°	267/68N	007° ACW	+005°, +05°
II19	255/79N (2)	65/312 (3)	68/281 (2), 31°	13°	267/72N	018° ACW	−012°, +07°
II20	266/80N (2)	72/336 (4)	63/283 (2), 31°	21°	260/76N	020° ACW	+006°, +04°
II21	277/78N (2)	71/308 (4)	71/324 (3), 20°	5°	277/80N	002° CW	000°, −02°
II22	285/75N (2)	73/353 (5)	74/350 (4), 31°	1°	254/73N	002° ACW	**+031°, +02°**
II23	285/76N (2)	76/336 (4)	–	–	291/80N	005° CW	−006°, −04°
II24	295/72NE (1)	72/346 (4)	–	–	–	–	–
II25	262/72N (1)	83/016 (3)	68/006 (2), 8°	15°	–	–	–
II26	270/57N (2)	73/340 (3)	57/356 (2), 17°	17°	–	–	–
II27	257/74N (2)	31/210 (3)	**49/299 (6), 90°**	**67°**	028/53SE	**049° CW**	**+049°, +53°**
II28	275/61N (1)	53/169 (3)		**70°**	044/59SE	**075° ACW**	**+051°, +60°**

3.3. Quartz veins

The same two quartz vein sets are recognised in both outcrops. Both vein sets are generally restricted to the coarser beds. Because of the predominantly coarser lithology in outcrop I, the veins are much better developed in that outcrop (Fig. 11).

A first set consists of sub-vertical veins, of which the intersection with bedding is sub-parallel to the fold hinge line

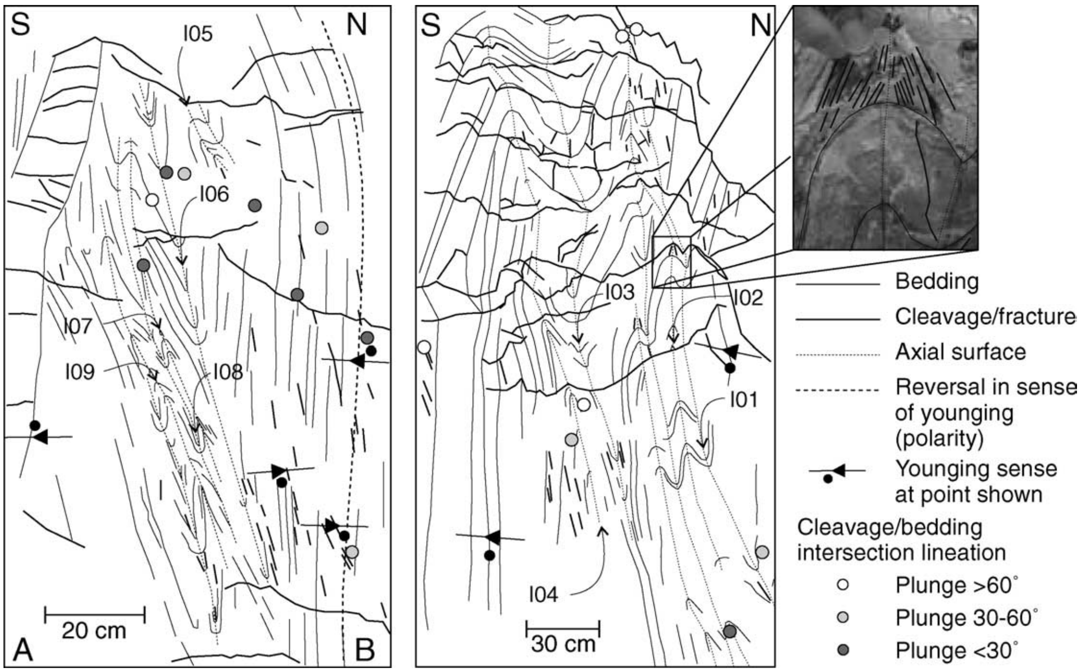

Fig. 7. Detailed profile views of fold trains I05–I09 (A) and I01–I04 (B) in the northern part of outcrop I, showing the sense of younging and the cleavage/bedding relationship. In (A) the truncation of bedding by the overlying sandstone bed to the south of I09 should be noted, as well as the bedding-parallel, probably welded nature (not recognisable in outcrop) of the inferred polarity reversal zone in the northern part of outcrop I. Also note the pronounced divergent cleavage fanning, symmetrical about the fold hinges, as shown in the inset of (B). See also Figs. 3 and 4.

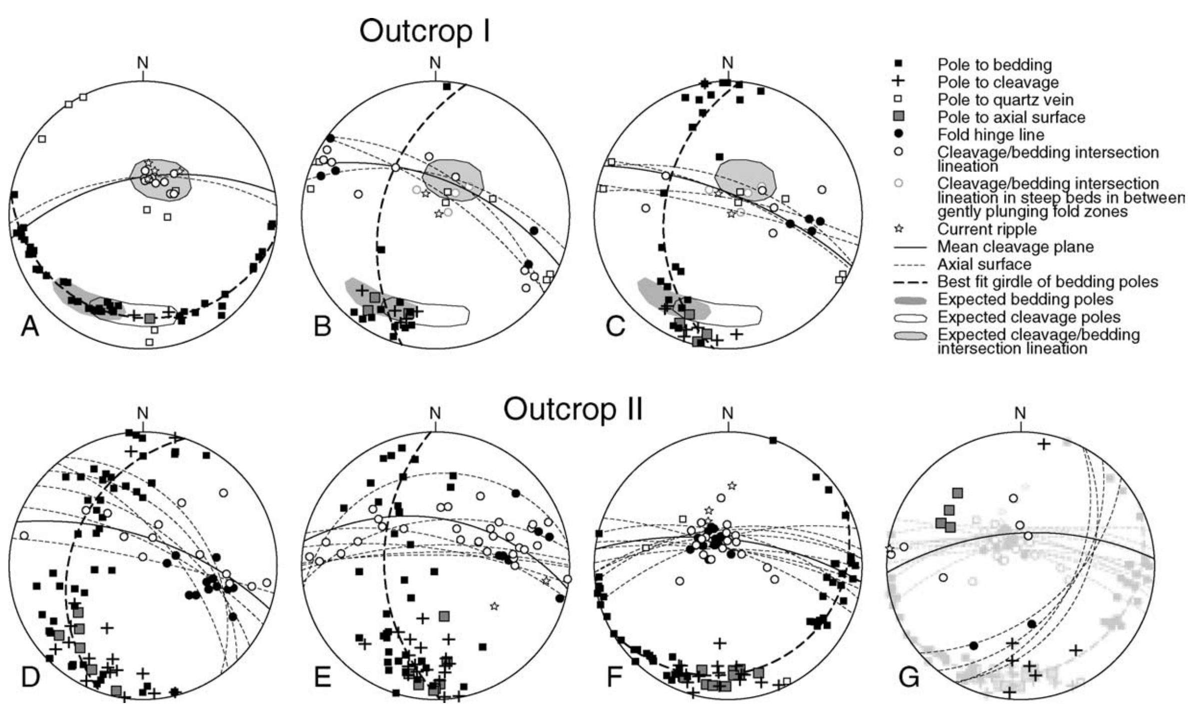

Fig. 8. Lower-hemisphere equal-area projections showing bedding, cleavage, veins, cleavage/bedding intersection lineation, fold hinge lines, axial surfaces and current ripples within outcrops I ((A)–(C)) and II ((D)–(G)). (A) Data from the steeply plunging folds I10–I12; (B) data from the sub-horizontal to gently plunging folds I05–I09; (C) data from the gently to moderately plunging folds I01–I04; (D) data from the steeply to moderately E-plunging folds II01–II05 in the northern part of outcrop II; (E) data from the pre-cleavage deformation zone containing folds II06–II12; (F) data from the steeply W-plunging folds II13–II26 in the southern part of outcrop II; (G) data from the pre-cleavage folds II27 and II28 in the southernmost part of outcrop II. For comparison, in plots (B) and (C) the position of the cleavage/bedding intersection lineation, bedding poles and cleavage poles have been added, as expected from the position of folds I01–I09 within the steep northern limb of fold I10 (see plot (A)). Also for comparative purposes, in plot (G) the data of plot (F) have been added as a grey background. Note the strong spread in cleavage/bedding intersection lineation orientations in plots (B)–(E) and (G). In plot (D), this strong spread is mainly observed within folds II04 and II05; folds II01 and II02 do not show a significant spread. See also Table 1.

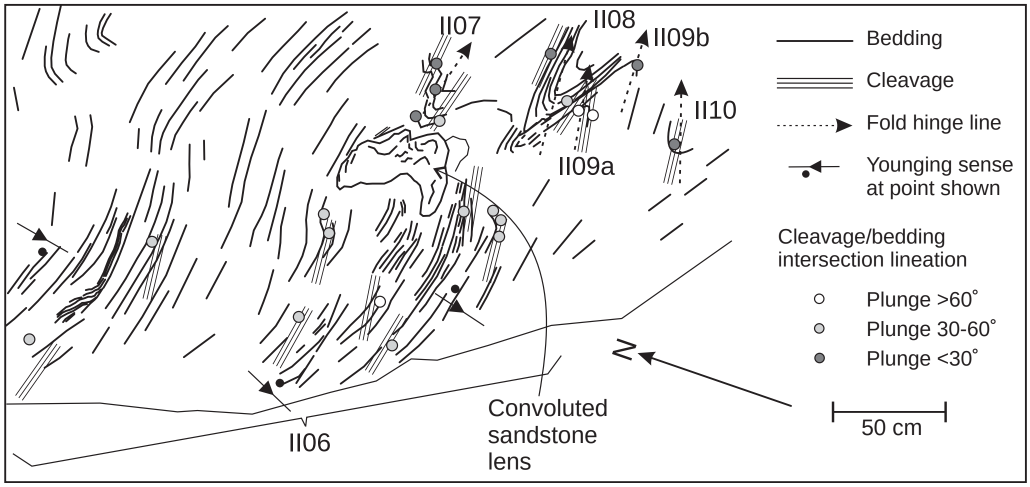

Fig. 9. Detailed plan view of the pre-cleavage deformation zone in the northern part of outcrop II, showing bedding, cleavage, fold hinge lines, axial surfaces, sense of younging and the plunge of the cleavage/bedding intersection lineation (see also Fig. 5). From W to E, the trend of the bedding relative to that of the cleavage changes from clockwise to anticlockwise, thus demonstrating the pre-cleavage nature of the change in bedding orientation.

and to the cleavage/bedding intersection lineation in the large, steeply plunging folds in outcrop I (Fig. 11A and B). Often, these veins are lined by pyrite. Around the steeply plunging folds, their orientation remains sub-perpendicular to bedding, suggesting a pre- or syn-folding origin. In the NW–SE-trending northern fold limb, the orientation of these veins remains the same, irrespective of the younging sense of the beds.

In outcrop I, the second set, cross-cutting the first, consists of sub-horizontal to gently SW-dipping veins, oriented sub-perpendicular to the fold hinge lines and cleavage/bedding intersection lineation of the steeply plunging folds (Figs. 8 and 11). Their orientation remains the same across the steeply plunging folds. These veins reflect extension along the fold axis and probably have a late syn-folding origin (e.g. Price and Cosgrove, 1990). In the NW–SE-trending northern fold limb, this set is locally slightly folded and gives rise to bone-shaped structures (e.g. Kenis et al., in press), thus reflecting a shortening at high angles to bedding after vein development (Fig. 11C). Judging from the bedding thickness, relative to the vein length, this shortening was in the order of ∼20% within the fine-grained sandstone. In the NW–SE-trending northern fold limb, the vein orientation remains the same, irrespective of the younging sense of the beds (Fig. 8).

Although, because of the scarcity of veins, much less easy to observe, in outcrop II a similar relationship exists between these two vein sets and the steeply plunging folds (southern part; Fig. 8). Interestingly, the slight difference in fold orientation between outcrop I (steeply N-plunging) and the southern part of outcrop II (steeply NW-plunging) appears reflected by the orientation of vein set 2: sub-horizontal to gently SW-dipping in outcrop I and gently SE-dipping in the southern part of outcrop II (Fig. 8).

In stark contrast to the clear geometrical relationship between the two vein sets and the steeply plunging folds, the two vein sets do not show any geometrical relationship with the gently plunging folds in outcrops I and II (folds I01–I09, II04–II12, II27 and II28).

4. Interpreting the different folds and related features

4.1. Steeply plunging folds and related features

The marked divergent cleavage fanning symmetrical about the fold hinge (outcrops I and II), together with the parallelism between the cleavage/bedding intersection lineation and the fold hinge lines (outcrops I and II), the geometrical relationship with the two vein sets (outcrops I and II) and the asymmetry of

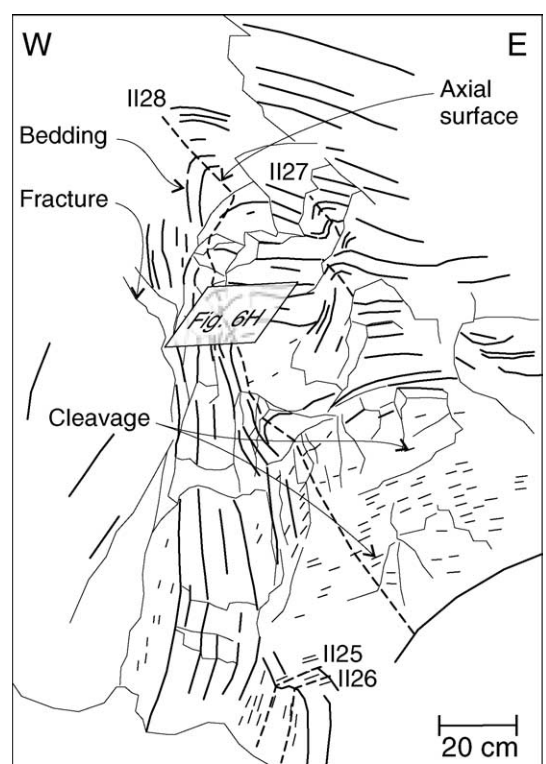

Fig. 10. Pre-cleavage folds II27 and II28 and their relationship with cleavage (southernmost part of outcrop II; see also Fig. 5). The approximate position of photograph 6H is indicated.

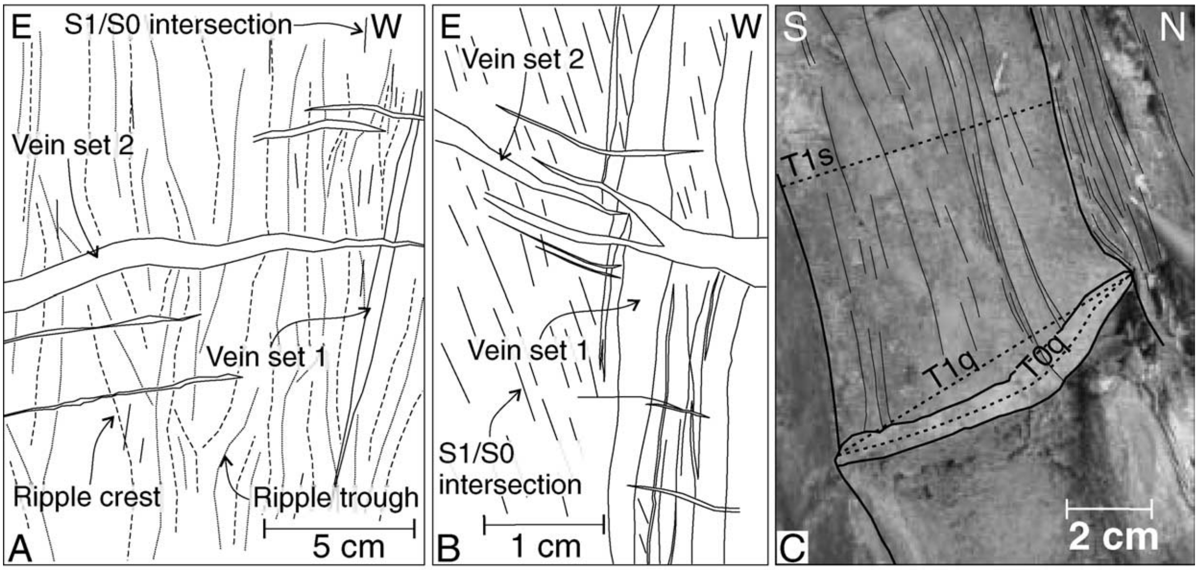

Fig. 11. The two main quartz vein sets within outcrop I, their mutual relationship and their relationship with respect to other features. (A) Relationship between the two vein sets, the current ripples and the cleavage/bedding intersection lineation (S1/S0 intersection) in the hinge of fold I10; (B) relationship between the two vein sets and the cleavage/bedding intersection lineation in the northern limb of fold I10, stratigraphically ∼10 cm above the beds depicted in (A); (C) fine-grained sandstone bed, within the northern limb of fold I10, stratigraphically ∼1 m above the beds depicted in (B), containing a curved vein of vein set 2. Assuming that the vein was initially straight (length t0q), and received its curved shape (length t1q) due to later shortening at high angles to bedding, the shortening of the quartz vein can be estimated at ∼2%. Similarly, assuming that the sandstone beds had a constant initial thickness equal to the initial length of the quartz vein (t0q), the present thickness of the sandstone bed (t1s) suggests a flattening of the sandstone bed by ∼20%.

the smaller folds, being compatible with their position on the limb of the larger fold (outcrop I) suggests that the steeply plunging folds in outcrops I and II have a tectonic, syn-cleavage origin (Fig. 8, Table 1). Similar steeply plunging tectonic folds have been described in the more western outcrop areas of the Cambrian core of the Brabant Massif, where they are termed type B folds (Lembeek fold type of Sintubin (1997, 1999) and Sintubin et al. (1998); see also Debacker et al., 2004, 2005a; Piessens et al., 2004). These folds are characterised by steep fold plunges, a step-fold geometry, with relatively long, straight limbs, sub-angular to sub-rounded hinges, open to tight interlimb angles and a pronounced divergent cleavage fanning (Fig. 2). Generally, these folds have quite consistent limb orientations, one having an E–W- to NW–SE-trend, referred to as type 1 limb, and the other having a NE–SW- to N–S-trend, referred to as type 2 limb. Because of these similarities, also the steeply plunging folds in outcrops I and II at Jodoigne are considered as type B folds. Geometrically, the northern part of outcrop I represents a type 1 limb and the southern part represents a type 2 limb (Fig. 3). In outcrop II, the southward decrease in 'z-shaped' asymmetry of the small type B folds (compare folds II01–II03 with folds II13–II26), together with an anticlockwise change in cleavage trend towards the south (Fig. 5), may be explained by considering outcrop II as representing the transition between a type 1 limb and a hinge zone of a large-scale type B fold. However, although significant variations in plunge (in the order of 30–50°) are not exceptional for the type B folds (e.g. Debacker et al., 2004), this does not readily explain the change in fold plunge together with the change in younging sense between the northern part (plunge ∼80–30E, younging E) and the southern part (plunge ∼60–90NW, younging W) of outcrop II.

One of the characteristic features of the type B folds is the small angle between cleavage and bedding (∼20°, or less) and the pronounced divergent cleavage fanning, even within relatively competent sandstone or siltstone beds (Sintubin et al., 1998; Piessens et al., 2004). This is exactly what is observed in outcrop II and in the siltstone and sandstone sequences in the steeply plunging folds in outcrop I (Fig. 3). However, within the relatively incompetent, mudstone-rich NW–SE-trending type 1 fold limb in the northern part of outcrop I, bedding and cleavage are often nearly parallel.

As mentioned above, the orientation of vein set 1 suggests a pre- or syn-folding origin. For a pre-folding origin, vertical compaction during burial is a possible cause, whereas for a syn-folding origin, extension in the outer part ('above' the neutral surface) of a longitudinal strain fold might be invoked (e.g. Ramsay, 1967; Ramsay and Huber, 1987). Considering that these veins are present not only in the hinges but also in the straight limbs, the first possibility seems more likely. Vein set 2 probably has a late syn-folding origin. Considering their low dips, these veins likely result from hydraulic fracturing, when, during folding, fluid pressures exceeded lithostatic pressure. As outlined above, within the NW–SE-trending northern fold limb of outcrop I, vein set 2 is locally folded and gives rise to bone-shaped structures within the fine-grained sandstone, thus reflecting a shortening of ∼20% after vein development, at high angles to bedding. Considering the late syn-folding origin of this vein set, this reflects a post-buckle flattening of the NW–SE-trending type 1 fold limb. Possibly this post-buckle flattening is partly responsible for the extremely small angle between cleavage and bedding in the NW–SE-trending type 1 limb in the northern part of outcrop I. Likely, the post-buckle flattening attained in the mudstone sequences was even higher than the 20% estimated within the fine-grained sandstone. Starting off with an angle of 20° (α_0) between cleavage and bedding, and assuming no change in length (l) measured along the cleavage, a post-buckle flattening of 20% (new bed thickness $t_1=0{,}8t_0$) would, taking into account the relationship $\sin\alpha_0=t_0/l$, result in a cleavage-bedding angle of ~16° ($\alpha_1=A\sin(t_1/l)=A\sin(0.8t_0/l)$ and $t_0=lA\sin\alpha_0$) whereas a shortening of 30% (new bed thickness $t_2=0{,}7t_0$) would give rise to an angle of only ~14°.

4.2. Sub-horizontal to gently plunging folds and related features

In outcrop II, in the southern part of the outcrop, the cleavage cross-cuts the gently S-plunging folds (II27 and II28) at very high angles, indicating a pre-cleavage origin. Within this outcrop, at several locations breccias occur that are cross-cut by the cleavage, as well as local changes in bedding trend that are cross-cut by the cleavage (e.g. II06). Similarly, cleavage folds itself around, and cross-cuts isolated sandstone lenses and disrupted and truncated sandstone beds, without the truncation surfaces and detachments affecting cleavage. All these features appear to have a pre-cleavage origin.

In outcrop I, cleavage shows a divergent cleavage fanning, symmetrical about the fold hinges of the tight to close sub-horizontal to moderately plunging folds (I01–I09), and only slightly transects these folds, with a transection angle comparable with, or even smaller than that observed in the steeply plunging type B folds in outcrops I and II (Table 1). Seemingly, this would suggest a syn-cleavage origin. However, across these sub-horizontal to gently plunging folds, the cleavage/bedding intersection lineation strongly varies: within the fold hinges, the intersection lineation is sub-parallel to the fold hinge lines, but within the limbs, the intersection lineation may change over short distances from gently plunging to steeply plunging (Table 1, Figs. 4, 7 and 8). Apparently, this change entirely depends on the orientation of bedding with respect to the N-dipping cleavage: in the steeply N-dipping beds, the intersection lineation is always steep, whereas in the sub-vertical to S-dipping beds and in the fold hinges, moderately to gently plunging intersection lineations are observed. Being situated within the type 1 limb of a large type B fold, steep intersection lineations (and fold hinge lines) would be expected. Taking into account the possibility of curvilinear hinge lines, changing N-ward from steeply plunging type B folds to sub-horizontal folds, the cleavage/bedding intersection lineation would be expected to reflect this change rather progressively and not reflect the fold hinge line orientation only in the hinge of the gently plunging folds (e.g. see Holdsworth et al., 2002; Debacker et al., 2004, 2005a). In addition, in the assumption of curvilinear hinge lines, a change in fold plunge well exceeding 90° would be necessary, instead of the 'easier' ~40–50° (from ~60–70°N to ~50–30°E), in order to match the asymmetry of the gently plunging folds ('s-asymmetry') to that expected within the type 1 limb of the type B fold ('z-asymmetry'). Finally, within this northern part of outcrop I, the same two vein sets are observed, of which the orientation could be related to the steeply plunging type B folds. Their orientation remains unmodified and cannot be related to the sub-horizontal to gently plunging folds.

All these observations imply that, despite the virtually axial planar cleavage and the divergent cleavage fanning, these sub-horizontal to steeply plunging folds within the type 1 limb of the type B fold pre-date cleavage, cleavage-related folding and vein development. The same reasoning can be applied to most of the moderately to gently E-plunging folds in outcrop II (folds II04, II05, II07, II08 and II12). Although cleavage is almost axial planar to the folds, shows a divergent cleavage fanning symmetrical about the fold hinges and shows contrasting senses of cleavage refraction on opposite fold limbs, the strong variation in cleavage/bedding intersection lineation orientation across these folds, in combination with the occurrence within or in the direct vicinity of a pre-cleavage sediment deformation zone, suggests a pre-cleavage nature.

Hence, both outcrops contain pre-cleavage folds. An analysis of the asymmetry and relative orientation of these pre-cleavage folds with respect to other features shows that they may be related. In both outcrops, the pre-cleavage fold hinges are at high angles to the ripple marks and convolution axes: in outcrop II the angle is 52° in fold II12 and ranges between 67 and 105°, with a mean of 83° ($n=8$) in folds II27 and II28, whereas in outcrop I, the angle ranges between 37 and 119°, with a mean of 74° ($n=18$). In addition, the asymmetry reflected by the pre-cleavage folds in the southernmost part of outcrop II (folds II27 and II28) perfectly matches that of fold II12 in the central part of outcrop II, and that within the northern fold zone in outcrop I (folds I03 and I04). By trial and error we attempted to match up the pre-cleavage folds of both outcrops, by rotating those from one outcrop around the steeply plunging type B fold hinge lines. Rotating the bedding (~005/88E) and the pre-cleavage folds of the southern part of outcrop II by ~70° anticlockwise around a sub-vertical to steeply NE-plunging axis (87/044), in order to match the bedding with the type 1 limb of outcrop I (~295/87N) results in pre-cleavage fold hinge lines (50/099, 28/139) of which the orientation is sub-parallel to those in the northern part of outcrop I, but of which the axial surfaces are slightly less steep (on average 25°; 13–37°; $n=8$) and rotated slightly clockwise (on average 38°; 22–53°; $n=8$) (Table 1). Although this procedure is rather crude, the obtained sub-parallelism complies with the idea that the pre-cleavage folds in both outcrops may be related. The slight mismatch in trend and dip of the axial surfaces may eventually result from an initial curvilinear shape of the pre-cleavage folds, from variations in shear strain during development of the type B folds and from variations in post-buckle flattening across the folds.

4.3. Cause for the sudden changes in younging sense

In outcrop I, the cleavage/bedding disposition remains virtually identical across the polarity reversal zones, implying that overturning occurred prior to cleavage development. In addition, the current ripples and convolution axes in the southern, N-ward younging part of the type 1 limb of the type B fold (I10) are sub-parallel to those in the northern, S-ward younging part of this limb. This indicates that the axis of overturning was either sub-parallel or sub-perpendicular to the ripple marks and convolution axes. As the type B folds, having hinge lines sub-parallel to the ripple marks and convolution axes, are cogenetic with cleavage development, they cannot be held responsible for the change in polarity. In contrast, considering their local downward-facing nature and their pre-cleavage origin, the sub-horizontal to gently plunging folds, being oriented at high angles to the ripple marks and convolution axes (see above), are likely candidates. Hence, we suggest that the sudden changes in polarity in outcrop I occur around pre-cleavage detachments that are intimately related to the sub-horizontal to gently plunging pre-cleavage folds. Also the pre-cleavage disruptions and truncations of the sandstone beds are likely related to this deformation. As pointed out above, within outcrop II, the younging sense finally changes from E-younging to W-younging in the pre-cleavage deformation zone in the central part of the outcrop, somewhere around fold II12. As the structural style in the northern part of this outcrop is, except for the sense of younging and the fold plunge, almost identical to that in the southern part, also here the change in younging sense should have a pre-cleavage origin. Hence, the change in polarity is either directly related to II12, having a pre-cleavage origin, or changes across an unobserved pre-cleavage detachment.

4.4. Geological significance of the pre-cleavage folds

At present, within the Brabant Massif, there is only evidence for one progressive deformation event, which is considered to have taken place from the early Silurian to the late Early Devonian (Verniers et al., 2002; Debacker et al., 2005b; cf. Van Grootel et al., 1997) and which mainly resulted in the development of folds and a well-developed cogenetic cleavage. Hence, the pre-cleavage deformation at Jodoigne either reflects an older, yet unknown tectonic deformation event, or alternatively, it is related to slumping. Considering the largely bedding-parallel disposition of the pre-cleavage folds, their rather isolated occurrence, being surrounded by relatively undeformed zones, and their occurrence in the direct vicinity of pre-cleavage detachments, pre-cleavage brecciation zones and zones containing disrupted and truncated sandstone beds and sandstone lenses floating within a mudstone mass, we attribute these folds, and the sudden changes in younging sense, to slumping (cf. Debacker et al., 2001).

The lithology suggests that both outcrops do not contain the same stratigraphic levels. In terms of the cleavage/fold relationship and younging sense, the northernmost folds of outcrop II (II01 and II02) are virtually identical to the type B folds in outcrop I (I10–I12). Likewise, the sense of younging of the type B folds in the southern part of outcrop II (folds II13–II26), opposing that of the northernmost folds of outcrop II, is similar to that in the northernmost part of outcrop I (zone containing folds I01–I09). For the current purpose, in both outcrops the former, NE-younging zone is referred to as zone 1, whereas the latter, SW-younging zone is referred to as zone 2 (Fig. 12). In outcrop I, the beds in zones 1 and 2 are younging towards each other, giving the polarity reversal zone a syncline-like nature on map. In contrast, in outcrop II, the beds in zones 1 and 2 are younging away from each other, giving the polarity reversal zone an anticline-like nature on map (cf. fold II12). Hence, at least two different polarity reversal zones are present. Because of the relative position with respect to the two polarity zones, in combination with the inferred slightly different stratigraphic position, it becomes clear that, despite the similar size and asymmetry, the slump folds in zone 2 in outcrop II (II27 and II28) are unlikely to belong to the same slump sheet as the slump folds in zone 2 in outcrop I. In addition, it is possible that the beds of zone 1 (zone 2) in one outcrop closely overlay those of the same zone in the other outcrop. If this were the case for zone 1, this would imply the presence of at least two zones 2, whereas if this were the case for zone 2, this would imply the presence of at least two zones 1. All this suggests that slump-related deformation zones and changes in younging sense may be quite common in, at least this part of, the Jodoigne Formation.

5. Discussion

5.1. Cause of the geometrical relationship between cleavage and the pre-cleavage folds

Because of their nature, slump fold hinge lines are situated within the bedding plane (e.g. Maltman, 1994). For a given lithology and water content, the angle between the initially horizontal bedding plane and the slump fold axial surfaces is likely to be controlled by the shear strain during slumping, the compaction strain during burial and the later tectonic shortening strain. As the amount of shear strain and compaction strain increase, the angle between bedding and slump fold axial surface is expected to decrease, whereas the influence of later tectonic strain will depend upon the position within the tectonic folds. For a given lithology, the angle between cleavage and bedding in tectonic folds largely depends on the folding mechanism and on the position within the tectonic folds, but also depends on the amount of bedding-perpendicular compaction during burial and on the occurrence of post-buckle flattening (e.g. Ramsay and Huber, 1987).

A characteristic feature of the type B folds is the pronounced divergent cleavage fanning and the small angle between cleavage and bedding within the fold limbs, even within relatively competent sequences (Sintubin et al., 1998; Piessens et al., 2004). This has been interpreted to result from flexural folding of beds that underwent a significant amount of pre-tectonic burial strain (Sintubin et al., 1998). Within the type 1 limb in the northern part of outcrop I, a very small angle exists between bedding and cleavage. This very small angle may be a combined effect of flexural folding of beds that underwent a significant compaction during burial (cf. Sintubin et al., 1998), of the predominantly fine-grained lithology and of a significant amount of post-buckle flattening (∼20% in

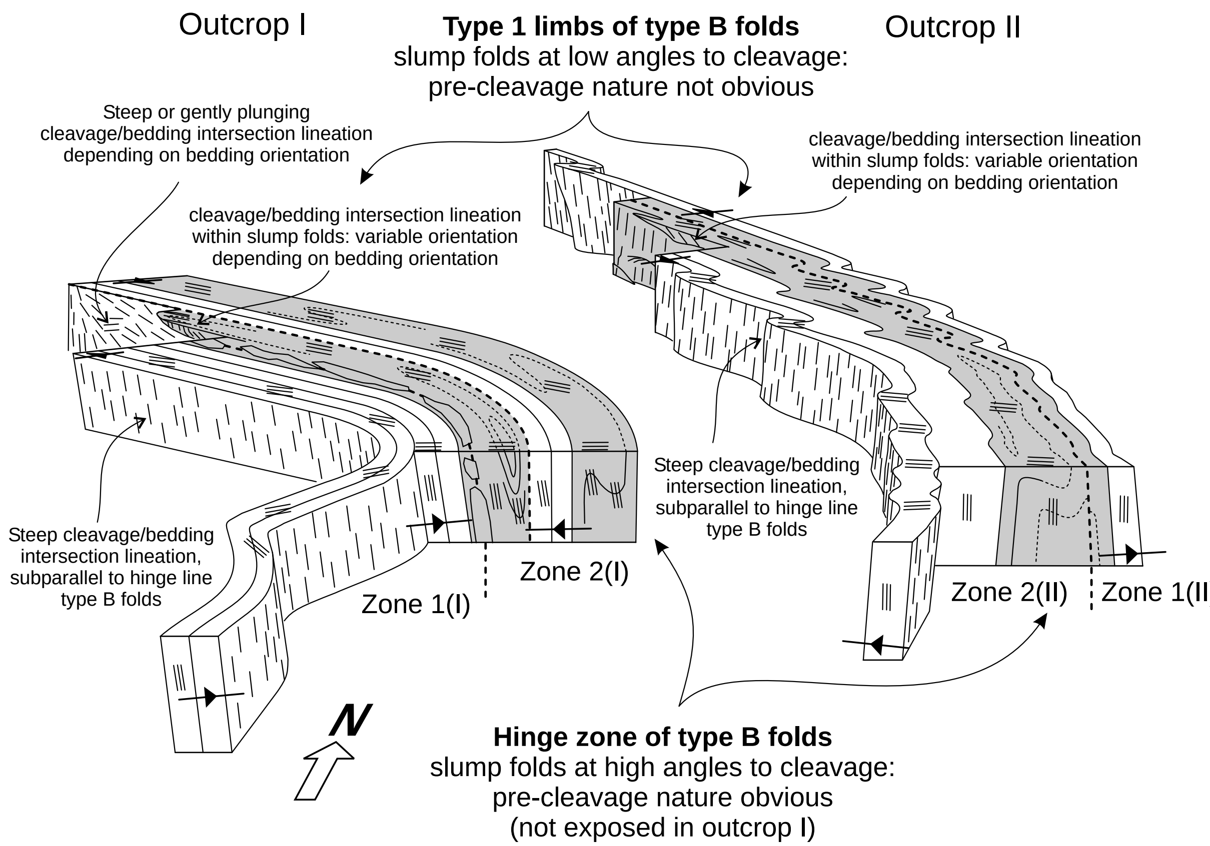

Fig. 12. Conceptual block diagrams of outcrops I and II, in which the pre-cleavage deformation zones are marked in grey (not to scale). In the hinge of the large type B folds (E-ward closing in both outcrops), due to the large angle between bedding and cleavage, the pre-cleavage nature of the sub-horizontal to gently plunging folds is obvious, whereas, because of the small angle between cleavage and the slump fold axial surfaces, this is not the case within the NW–SE-trending type 1 limbs of the type B folds. Within these limbs, it is mainly (if not only) the strong variation of the cleavage/bedding intersection lineation orientation across the folds that gives away the pre-cleavage fold origin (cf. Table 1). In both outcrops, zone 1 refers to NE-ward younging beds and zone 2 to SW-ward younging beds (sense of younging shown by arrows). Note that the relative stratigraphic position of the beds of outcrop II with respect to those of outcrop I is unknown: the beds of outcrop I may be situated to the west of those of outcrop II (as depicted), or it may be the other way around. Also note the change in overall bedding dip across the polarity reversal zones (between zones 1 and 2), which is attributed to pre-cleavage deformation (slumping) and may have a profound effect on the (local) plunge of the type B folds. Compare with Figs. 1, 3 and 5.

fine-grained sandstone in the type 1 limb). In addition, within this limb, small (pre-cleavage) changes in bedding orientation relative to the mean bedding orientation may have further decreased this angle. Going northward along the type 1 limb in outcrop I, mean bedding dip increases across the sandstone-rich pre-cleavage disruption zone (Figs. 4, 8 and 12), resulting in a larger difference in dip between the relatively undisturbed beds and the N-dipping cleavage in the northern part of this limb (in the southern part of this limb, the strike difference is more important than the dip difference). By coincidence, the slump fold asymmetry and the angle between slump fold axial surface and bedding after compaction are compatible with this dip difference, resulting in slump folds to which the tectonic cleavage is approximately axial planar. In addition, the post-buckle flattening experienced by this limb not only resulted in a decrease of the angle between cleavage and bedding, but also resulted in a further tightening of the slump folds, further decreasing any slight angular differences between cleavage and the slump fold axial surfaces.

A similar scenario can be proposed for outcrop II (Fig. 12). The difference in plunge of the syn-cleavage folds between the northernmost part of the outcrop (II01 and II02; E-facing, E-plunging) and the southern part of the outcrop (II13–II26; W-facing, NW-plunging) is attributed to a pre-cleavage change in bedding dip, similar to what is observed across the disrupted sandstone beds in the northern part of outcrop I and is likely a result of slumping. Within the northern part of outcrop II, the syn-cleavage folds are difficult to distinguish from the slump folds, mainly because of the inferred position within the type I limb of a large-scale type B fold, in which bedding and cleavage are at a very small angle to one another, and partly because of the relatively small difference in plunge between the syn-cleavage (steeply E-plunging) and pre-cleavage folds (gently E-plunging), which can partly be attributed to a pre-cleavage change in bedding dip. In contrast, within the southernmost part of outcrop II, although apparently belonging to the same slump sheet and having the same asymmetry as in the northern part of the outcrop, the slump folds can easily be recognised. The main reason for this is the inferred position within the hinge of a large-scale type B fold, in which cleavage is at high angles to the overall bedding and the (bedding-parallel) slump folds.

Hence, in both outcrops, the apparent geometrical relationship between cleavage and the pre-cleavage slump folds is a direct result of the particular slump fold asymmetry and slump fold axial surface orientation after compaction on the one hand and of the small cleavage/bedding angle within the limbs of the later tectonic folds on the other hand.

5.2. Cleavage refraction and cleavage fanning in pre-cleavage folds

The concept of cleavage refraction has been known for a long time (e.g. Sorby, 1853). As pointed out by Treagus (1983), although cleavage refraction is commonly described with respect to folding, folding is not a necessity for cleavage and strain refraction. This is supported by the fact that cleavage also refracts across competent bodies that are unrelated to the beds experiencing syn-cleavage folding. Examples of bodies experiencing such a 'passive' (i.e. implying no relationship with the folding mechanism) cleavage refraction are dykes (e.g. Ramsay and Lisle, 2000) and competent beds in slump folds of which the axial surface is oblique to cleavage (e.g. fig. 6 in Debacker et al., 2001). Hence, also within slump folds where the axial surface is very close to parallel to cleavage, as in the present study, cleavage is expected to show cleavage refraction across interfaces between beds of different competency. In this case the contrasting sense of cleavage refraction on opposite slump fold limbs entirely results from the fact that cleavage is virtually axial planar to the folds. If in the profile plane the mismatch between cleavage and the slump fold axial surface were larger than the half interlimb angle of the fold (assuming the axial surface bisects the interlimb angle), the same sense of cleavage refraction would be observed on both fold limbs.

Because of the pre-cleavage nature, and the marked difference in orientation in outcrop I between the pre-cleavage folds and the syn-cleavage folds, the observed cleavage fanning across the hinge zone of the pre-cleavage folds is unlikely to be related to strain refraction patterns obtained from card deck experiments (e.g. Ramsay and Huber, 1987). It is more likely that the observed fanning is more related to cleavage patterns around isolated competent bodies in a less competent matrix. Due to shortening during cleavage development, within the limbs of the steeply plunging type B folds the pre-existing slump folds will be shortened also, and this being sub-perpendicular to their axial surfaces, which, by coincidence, are at very low angles to cleavage. Most likely, the competent beds in the hinges of the slump folds experienced less shortening than the less competent mudstone sequences, thus giving rise to a divergent cleavage fanning within the more incompetent beds, quite similar to the cleavage pattern shown around isolated competent bodies in a mudstone sequence (e.g. fig. 10.20 in Ramsay and Huber, 1983).

5.3. Slump folds with an axial planar cleavage

Although the presence of an axial planar foliation is not regarded as a common feature in slump folds (e.g. Helwig, 1970; Beutner, 1975; Stone, 1976; Elliott and Williams, 1988; Maltman, 1994; Bradley and Hanson, 1998), quite a number of reports exist of slump folds with an axial planar cleavage (e.g. Williams et al., 1969; Helwig, 1970; Corbett, 1973; Woodcock, 1976; cf. Elliott and Williams, 1988; Maltman, 1994). In addition, Helwig (1970, p. 174) even mentions the presence of a "secondary cleavage consistently in divergent fans", along with other criteria such as "secondary cleavage(s) non-parallel to fold axial surfaces", as one of the features commonly associated with slump-folded beds. However, unfortunately, no evidence is given for this and, judging from later publications, for at least some of these folds the slump origin is quite controversial (see Pickering, 1987; Elliott and Williams, 1988; Blewett, 1991). In contrast, Maltman (1994) states that flatlying folds with *non-fanning foliations* are not necessarily of syn-cleavage origin, seemingly giving the impression, by explicitly mentioning 'non-fanning', that if cleavage were to fan, a syn-cleavage origin would be beyond reasonable doubt.

According to Maltman (1994) and Elliott and Williams (1988), in many cases, the presence of a flatlying pervasive fabric being axial planar to flatlying slump folds within a sub-horizontal bedding sequence is more likely a result of later compaction than it is a result of the actual slumping process (cf. Maltman, 1981). In this respect, the association of undeformed, flatlying slump folds with a sub-horizontal, axial planar foliation is quite comparable with the examples shown in the present paper, as in both cases, the pervasive fabric (compaction fabric for flatlying slump folds, tectonic fabric in the present case) post-dates the slump folds to which, by coincidence, it is axial planar. Judging from the present observations, it is very likely that a pervasive bedding-parallel compaction fabric, being axial planar to flatlying slump folds, will also show opposing senses of cleavage refraction on opposite fold limbs. In addition, however, taking into account the significantly different amount of compaction between sandy layers and their pelitic matrix (e.g. Paterson et al., 1995), we suggest that it may be possible to find a pervasive bedding-parallel compaction fabric showing a divergent cleavage fanning symmetrical about a slump fold hinge (cf. Helwig, 1970).

6. Conclusions

The present observations at Jodoigne, situated in the Grande Gette valley, forming the easternmost outcrop area of the Cambrian of the single-phase deformed Anglo-Brabant Deformation Belt (Belgium), demonstrate the occurrence of steeply plunging syn-cleavage folds, well to the east of their type area (Lembeek, Sennette valley; Sintubin et al., 1998), where they are currently referred to as type B folds (Debacker et al., 2004). Apart from their steep plunge, these folds are characterised by a well developed divergent cleavage fanning, symmetrical about the fold hinges, and a very small angle between cleavage and bedding in the fold limbs.

Within the steep limbs of these type B folds at Jodoigne, locally sub-horizontal to gently plunging folds occur. Within the NW–SE-trending limbs of the type B folds, these sub-horizontal to gently plunging folds show an axial planar cleavage and a divergent cleavage fanning, symmetrical about the fold hinges, seemingly suggestive of a syn-cleavage origin. However, a careful analysis of the cleavage/bedding intersection lineation across these folds within the limbs of the type B folds suggests an anomalous relationship with cleavage. A pre-cleavage nature is further corroborated by an analysis of quartz veins of which the geometry shows a relationship with the steeply plunging type B folds. Finally, these sub-horizontal to gently plunging folds, situated within the limbs of the type B folds, can be related to similar folds occurring in the hinge zone of large type B folds, where, due to the large cleavage/bedding angle, the pre-cleavage nature is obvious. By means of a comparison of structural and sedimentological observations, these sub-horizontal to gently plunging pre-cleavage folds can be interpreted as slump folds. Also the sudden changes in younging sense across almost uniformly dipping tectonic fold limbs is attributed to slumping.

The extreme difficulty in recognising the pre-cleavage origin of the slump folds within the steep limb of a steeply plunging type B fold is a result of the near-coincidence between cleavage and the pre-cleavage slump axial surfaces. Due to this near-coincidence, cleavage shows contrasting senses of cleavage refraction on opposite slump fold limbs and a divergent cleavage fanning within the incompetent beds, symmetrical about the fold hinges. Hence, as it turns out, the presence of a virtually axial planar cleavage, showing only a minor axial or profile transection (*sensu* Johnson, 1991), showing contrasting senses of cleavage refraction on opposite fold limbs and showing a fanning, symmetrical about the fold hinge, is no guarantee for the syn-cleavage origin of the folds. In this respect, it may be possible that also within undeformed slump beds, a pervasive compaction fabric exists that, although essentially post-dating slumping, is axial planar to the recumbent slump folds (see also Maltman, 1994) and shows a fanning across the slump folds, symmetric about the fold hinges (cf. Helwig, 1970).

Acknowledgements

The authors are most grateful to Alex Maltman and Enrico Tavarnelli for their constructive remarks on the manuscript and wish to acknowledge A. Herbosch for the stimulating discussions. T.N. Debacker is a Postdoctoral Fellow of the Fund for Scientific Research-Flanders (F.W.O.-Vlaanderen), M. van Noorden a Research Assistant and M. Sintubin a Research Associate of the "Onderzoeksfonds, K.U.Leuven". At the time of this study, T. Debacker was at the Geodynamics and Geofluids Research Group, Katholieke Universiteit Leuven. This work forms part of research projects G.0274.99, G.0094.01 and G.0271.05 of the F.W.O.-Vlaanderen.

References

Beutner, E.C., 1975. Did the worm turn? Deformed burrow as a slump movement indicator. Journal of Sedimentary Petrology 45, 212–214.

Blewett, R.S., 1991. Slump folds and early structures, northeastern Newfoundland Appalachians: re-examined. Journal of Geology 99, 547–557.

Bradley, D., Hanson, L., 1998. Paleoslope analysis of slump folds in the Devonian flysch of Maine. Journal of Geology 106, 305–318.

Corbett, K.D., 1973. Open-cast slump sheets and their relationship to sandstone beds in an Upper Cambrian flysch sequence, Tasmania. Journal of Sedimentary Petrology 43, 147–159.

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

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., 2004. Transitional geometries between gently plunging and steeply plunging folds: an example from the Lower Palaeozoic Brabant Massif, Anglo-Brabant deformation belt, Belgium. Journal of the Geological Society, London 161, 641–652.

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

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

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

Elliott, C.G., Williams, P.F., 1988. Sediment slump structures: a review of diagnostic criteria and application to an example from Newfoundland. Journal of Structural Geology 10, 171–182.

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 2 (4), 1–95.

Helwig, J., 1970. Slump folds and early structures, northeastern Newfoundland Appalachians. Journal of Geology 78, 172–187.

Holdsworth, R.E., Tavarnelli, E., Clegg, P., Pinheiro, R.V.L., Jones, R.R., McCaffrey, K.J.W., 2002. Domainal deformation patterns and strain partitioning during transpression: examples from the Southern Uplands terrane, Scotland. Journal of the Geological Society, London 159, 401–415.

Johnson, T.E., 1991. Nomenclature and geometric classification of cleavage-transected folds. Journal of Structural Geology 13, 261–274.

Johnson, T.E., Woodcock, N.H., 1991. Detecting cleavage-transected folds using cleavage–bedding intersections. Journal of Structural Geology 13, 919–925.

Kenis, I., Urai, J.L., Sintubin, M., in press. The development of bone-shaped structures in initially segmented layers during layer-parallel extension: numerical modelling and parameter sensitivity analysis. Journal of Structural Geology, in press.

Maltman, A.J., 1981. Primary bedding-parallel fabrics in structural geology. Journal of the Geological Society of London 138, 475–483.

Maltman, A.J., 1994. The Geological Deformation of Sediments. Chapman and Hall, London.

Paterson, S.R., Yu, H., Oertel, G., 1995. Primary and tectonic fabric intensities in mudrocks. Tectonophysics 247, 105–119.

Pickering, K.T., 1987. Wet-sediment deformation in the Upper Ordovician Point Leamington Formation: an active thrust-imbricate system during sedimentation, Notre Dame Bay, north-central Newfoundland. In: Jones, M.E., Preston, R.M.F. (Eds.), Deformation of Sediments and Sedimentary Rocks. Geological Society, London, Special Publications 29, pp. 213–239.

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

Price, N.J., Cosgrove, J.W., 1990. Analysis of Geological Structures. Cambridge University Press, Cambridge.

Ramsay, J.G., 1967. Folding and Fracturing of Rocks. McGraw-Hill, New York.

Ramsay, J.G., Huber, M.I., 1983. The Techniques of Modern Structural Geology: Volume 1: Strain Analysis. Academic Press, London.

Ramsay, J.G., Huber, M.I., 1987. The Techniques of Modern Structural Geology: Volume 2: Folds and Fractures. Academic Press, London.

Ramsay, J.G., Lisle, R.J., 2000. The Techniques of Modern Structural Geology: Volume 3: Applications of Continuum Mechanics in Structural Geology. Academic Press, London.

Sintubin, M., 1997. Cleavage–fold relationships in the Lower Palaeozoic Brabant Massif (Belgium). Aardkundige Mededelingen 8, 161–164.

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: Winchester, J., Verniers, J., Pharaoh, T. (Eds.), Palaeozoic Amalgamation of Central Europe. Geological Society, London, Special Publications 201, pp. 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.

Sorby, H.C., 1853. On the origin of slaty cleavage. New Philosophical Journal 55, 137–148.

Stone, B.D., 1976. Analysis of slump slip lines and deformation fabric in slumped Pleistocene lake beds. Journal of Sedimentary Petrology 46, 313–325.

Treagus, S.H., 1983. A theory of finite strain variation through contrasting layers, and its bearing on cleavage refraction. Journal of Structural Geology 5, 351–368.

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

Verniers, J., Herbosch, A., Vanguestaine, M., Geukens, F., Delcambre, B., Pingot, J.L., Belanger, I., Hennebert, M., 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. The Cambrian to mid Devonian basin development and deformation history of Eastern Avalonia, east of the Midlands Microcraton: new data and a review. In: Winchester, J., Verniers, J., Pharaoh, T. (Eds.), Palaeozoic Amalgamation of Central Europe. Geological Society, London, Special Publications 201, pp. 47–93.

Williams, P.F., Collins, A.R., Wiltshire, R.G., 1969. Cleavage and penecontemporaneous deformation structures in sedimentary rocks. Journal of Geology 77, 415–425.

Wilson, G., 1961. The tectonic significance of small scale structures and their importance to the geologist in the field. Annales de la Société Géologique de Belgique 84, 423–548.

Woodcock, N.H., 1976. Structural style in slump sheets: Ludlow Series, Powys, Wales. Journal of the Geological Society of London 132, 399–415.