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# Evolution of mullion (formerly boudin) structures in the Variscan of the Ardennes and Eifel

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**Abstract:** Mullion and boudin structures in the Lower Devonian of the Ardennes and Eifel have been discussed in the literature in three languages since 1907. Two outcrops in Dedenborn, Germany, and Bastogne, Belgium served as examples in several textbooks for mullion and boudin type localities, respectively. Both structures are characterized by cylindrical cuspate-lobate structures on pelite-psammite contacts, with the regional slaty cleavage at a high angle to bedding. We review the confusing evolution of nomenclature, demonstrate the common origin of both structures and propose that all such structures in this area with a large angle between bedding and cleavage are from now on called mullions.

We review the most important observations of mullion (formerly boudin) structures and the models proposed for their evolution, and present data from a database of 150 outcrops containing mullion structures. Although most authors agree that these long, strikingly regular, cuspate-lobate structures formed during layer-parallel shortening, there is less agreement about the origin of the arrays of quartz veins, which are always present between individual mullions. An important observation is the angle between the mullion axis and the delta-lineation. This angle is generally non-zero but never more than 40<sup>3</sup>/<sub>4</sub>, strongly suggesting that the mullions did not form as buckling instabilities at the pelite-psammite interface.

We propose a two-phase development of these structures. First, at the late stages of burial to over 8 km depth in a passive continental margin, and after the development of close to lithostatic pore pressures, a regionally extensive series of closely spaced sub-parallel veins were formed in mode I fractures in the psammite layers at high angle to bedding. Then, during the early phases of sub-horizontal Variscan shortening, which happened to take place at high angles to the pre-existing veins, the cuspate-lobate structures were initiated at the vein tips due to the competence contrast (veins > psammite > pelite).

The shape of the lobes between mullions, which can be accurately measured, is a potential indicator of the power law exponent n in sand-shale sequences deforming under very low grade metamorphic conditions.



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## Nomenclature

The mullions shown in most modern structural geology textbooks (Hobbs et al., 1976; Ramsay and Huber, 1987; Pilger and Schmidt, 1957) are in many respects similar to structures found in nearby outcrops, which started their life in structural geology as the type example of boudins (Lohest et al., 1909).

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The reason for this confusing evolution in nomenclature is the inconsistent, multilingual usage of the initial morphological definition of the term boudin, which was based on a striking resemblance to the long, parallel strands in which blood-sausages are usually displayed in S-Belgium (Wilson, 1982) (Fig. 1). This nomenclature was originally strictly non-genetic, and the term boudinage was introduced for the (as yet unknown) process of formation of these structures (Lohest et al., 1909). Later usage of the term boudin became genetic, inspired by the extension during preparation of most other sausages and corresponding rock structures. The term boudin is now well established for structures formed by layer parallel extension of a competent layer in a less competent matrix, with veins or matrix emplaced in the boudin necks. In the second half of the last century some studies of the locus typicus for boudins at Bastogne concluded that the major part of the evolution of these structures was a shortening sub-parallel to bedding, instead of just extension. To solve the conflict in nomenclature the names K-boudin (K for the German word Kompression) and L-boudin (L for the German word Längung) were proposed (Bruhl, 1969). However, these terms never found general acceptance. After a "visit of English colleagues to Dedenborn" the name mullion was introduced (Pilger and Schmidt, 1957) and photographs of these structures found their way into the structural geology textbooks (Hobbs et al., 1976; Ramsay, 1967). Here, mullions are described as regular cuspate-lobate folds of an interface between two materials with a large competence contrast, the cusps poining towards the more competent material. This was interpreted (Ramsay, 1967) as being a compressional feature grown from an instability at the deforming interface.

#### Figure 1. The classic 'boudin' locality



(a) Morphology of the base of a psammite layer near Rouette, showing the characteristic cuspate-lobate structures of mullions. Width of picture is approximately 1 m. (b) Boudins in a shop near Bastogne, showing the characteristic morphology of sausages in this part of Belgium. Note the absence of pinch and swell structures along the sausage. Width of picture is approximately 20 cm. (Click for enlargement)

In other studies of the Bastogne boudins it was proposed that these structures were not initiated during a pronounced layer-parallel extension event and are therefore not boudins in the usual (extensional) sense, perhaps modified during later layer parallel shortening (Jongmans and Cosgrove, 1994; Rondeel and Voermans, 1975), although there is no general agreement.

In the last decade of the twentieth century it was reemphasized (Spaeth, 1986) that all the cylindrical cuspatelobate structures in the areas (on both sides of the border between Germany and Belgium) belong to the same class as the original boudins at Bastogne.

In this paper, to keep nomenclature consistent with the present genetic usage and to avoid further confusion, we call all these compressional structures mullions (Kenis et al., 2001) although this is inconsistent with the original definition and is not yet generally accepted. In future

works, careful documentation of terminology will be required, because the term mullion is also not always clearly and consistently defined.

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# **Regional setting**

Mullion structures in the Ardennes and Eifel occur in a lower Devonian, shallow marine siliciclastic sequence, S and SE of the Stavelot-Venn Massif (Fig. 2), roughly between Dedenborn (Eifel) and SW of Bastogne (Ardennes). Mullion structures in the area are actually quite common. The most spectacular outcrops are well known from many publications.

# Figure 2. Geological map of the Ardennes and Northern Eifel

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metamorphism (from 350<sup>3</sup>/<sub>4</sub>C in the NE, up to 450-500<sup>3</sup>/<sub>4</sub>C and 200 MPa in the SW (Lielitz and Mansy, 1999; Kramm et al., 1985). This phase was accompanied by the development of close-to-lithostatic fluid pressure conditions (Sintubin et al., 2000; Hilgers et al., 2000).

In the late Devonian and Carboniferous, this sequence was inverted and thrust in a NW-direction to form a foreland fold- and thrust belt, which is now part of the Rhenohercynian zone of the Mid-European Variscides (Fig. 3). The important differences in sediment thickness and the involvement of basement massifs in the thrust sequence are the main factors influencing the typical outcrop pattern of the region (Adams and Vandenberghe, 1999; Fielitz, 1992; Hollman and von Winterfeld, 1992; Hollmann and Walter, 1995; Hance et al., 1999).

Figure 3. Figure modified after Hollmann and Winterfeld (1999)



Geological map of the Ardennes and Northern Eifel, showing the area where mullion structures occur (light brown) and the trace of the profile shown in Figure 3. Slightly modified after Fielitz and Mansy (1999). (Click for enlargement)

The rocks here were buried to 8 to 12 km depth in a passive continental margin in late Devonian times. During this burial phase the rocks underwent very low grade

### The Dedenborn outcrop

#### Figure 4. The Dedenborn outcrop

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Dedenborn



The Dedenborn outcrop. (a) The classic view of the outcrop, showing the characteristic cuspate-lobate structures at bedding contacts. (b) Overview of the outcrop, looking at high angle to bedding. (c) NW-SE profile of the fold structure in the area, showing bedding, cleavage and the location of mullions. Modifed after Pilger and Schmidt (1957). (d) Photograph of the outcrop in 1955, showing lateral variations in mullion morphology (arrows), which is not visible in (b) (from Pilger and Schmidt (1957)). (e) Overview of the outcrop, emphasizing the angle between mullion axis and delta lineation. (f) Side view of two mullions, showing the quartz vein terminating at the cusps (yellow, arrows) and the trace of cleavage. (g) Detailed drawing of several mullions in profile (from Pilger and Schmidt (1957)). (Click for enlargement)

A small roadside outcrop near the village of Dedenborn in the N-Eifel found its way into many structural geology textbooks as the type example of mullions (Fig. 4).

The outcrop is situated in the steep to overturned limb of a regional series of upright folds with well-developed axial planar cleavage. The rocks consist of alternating psammite-pelite layers. The classic view of the outcrop (Fig. 4a) shows the bottom of a sandstone layer, which broke along the contact to the adjacent shale. This surface forms a series of regular, highly cylindrical, asymmetrical cuspate-lobate structures (Fig. 4f,g) with the cusps pointing to the sandstone. In the sandstone layer cleavage is only weakly developed. The sandstone layer slowly grades upwards into a shale, and the backside of the outcrop consists of shale with a well-developed slaty cleavage. A very detailed description of this outcrop is given in (Pilger and Schmidt, 1957a; Pilger and Schmidt, 1957b; Pilger and Schmidt, 1957c; Pilger and Schmidt, 1957d).

Two observations not usually mentioned in textbooks (but documented in the literature) are: (1) The sandstone layer contains a series of spindle-shaped quartz veins which terminate in the cusps between the mullion lobes (Fig. 4f), and (2) the intersection lineation between cleavage and bedding (the delta lineation), best seen on another bedding plane which has not developed mullions) makes an angle of about 30 degrees with the long axes of the mullions (Fig. 4e).

# Morphology: Observations pertinent to the interpretation of the evolution of mullion structures

Data collected in this study come from about 150 outcrops containing mullion structures in lower Devonian shallow marine sands and shales (Fig. 5). In addition we report data from a smaller number of outcrops in the Bastogne area (Spaeth, 1986; Sippli, 1981).

#### Figure 5. Location of outcrops



Map showing the location of most of the outcrops used for the statistical analysis of this study. For location refer to Figure 2.

Most of our observations are consistent with earlier descriptions from the literature. We supplement these by a number of observations not yet reported. The observations are illustrated in a series of figures. Extensive descriptions are for example (Bruhl, 1969; Pilger and Schmidt, 1957a;





Jongmans and Cosgrove, 1994; Sintubin et al., 2000; Corin, 1933; Mukhopadhyay, 1972; Rondeel and Voermans, 1975; Tromme, 1997)

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• Mullions are visible as highly cylindrical cuspate-lobate structures of exposed psammite-pelite interfaces (Fig. 6). The cusps always point towards the psammitic layer. The higher the lithological contrast, the better defined the mullion.

#### Figure 6. Characteristic structures of the Eifel-Ardennes mullions



(a) 3D model showing the major characteristic structures of the Eifel-Ardennes mullions. The morphology of the structures is not strongly dependent on size: width of this model can be between 20 cm and 5 m. Click for Movie

• Mullions are always associated with quartz-rich veins in the psammite layers, terminating close to cusps. This association is very strong, over 99% of all observed cases contain this association. In psammitic layers the quartz veins are better developed. Sometimes these intra-mullion veins cross the psammite-pelite interface and terminate inside the pelite layer.

# Figure 7. Small outcrop near the village of Rouette, Belgium



Features in a small outcrop containing dm-size mullions, near the village of Rouette, Belgium. In this outcrop the angle between mullion axis and delta-lineation is approximately 20 degrees (only vaguely visible on the photographs). (a) Overview of the outcrop exposing the bottom of a psammite layer embedded in pelite. The mullions are developed at two wavelengths, at the m and dm scale. (b) Bottom of a relatively clay-rich psammite layer, with mullions less well developed. Note the lateral termination of some of the cusps, transforming two mullions into one. Width of image is about 1 m. (c) Profile view of the main psammite layer, with well developed mullions. Every cusp in this outcrop has an associated quartz vein. Width of image is approximately 50 cm. (d) Bottom of main mullion-containing layer. The image contains one of the first order mullions, with 7 smaller ones superimposed. (e) Sample cut perpendicular to the mullion axis, showing details of cleavage development in the cusps, and deformation of the veins. Width of image is 20 cm.

In layers without veins no mullions are observed, but in the same outcrop veins can be present without mullions. (Fig. 7).

Mullions are found on both limbs and in the hinge zones of regional folds. In mullions, cleavage and bedding intersect at angles more than 40 degrees. Mullions do not occur on fold limbs where the cleavage is sub-parallel to bedding. In these uncommon cases the psammite layers show the "normal, extensional" boudinage with cleavage that follows the curvature of bedding in the boudin necks.

When the psammite layer's boundary is well defined and bounded by pelite on both top and bottom, mullions are formed with cuspate-lobate folds on both upper and lower interface. The lobes point away from the psammite layer, with the intra-mullion veins connecting the cusps. In layers

with graded bedding mullions are present at one side of the layer only, with cusps associated with veins (Fig. 8).

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Figure 8. Large outcrop near Bastogne



(a) Large outcrop along the railway line North of Bastogne, showing mullions developed at two wavelengths. Note that in the cusps between the large mullions the quartz veins are thicker, too. Width of outcrop 50 m. Slightly modified after Brühl (1969). (b) A series of small mullions showing the very slender aspect ratios sometimes observed. Slightly modified after Brühl (1969). (c and d) Mullions showing the fans of cleavage convergent into the cusps. Slightly modified after Brühl (1969). (e) Sandstone layer with graded bedding, showing mullions developed only at the contact with high material contrast. Slightly modified after Brühl (1969). (Click for enlargement)

Cleavage is well developed in the slate layers, and is refracted across layer boundaries. Near the cusps between mullions, cleavage forms well-developed fans convergent into the cusps (Fig. 8c) (Mukhopadhyay, 1972).

Composite mullions with two wavelengths are sometimes found, usually the cusps between the larger first order lobes are connected to thicker quartz veins (Fig. 8a, Fig. 7a).

Mullion axes are oriented close to but usually not parallel to the delta lineation (Fig. 4e). Well-defined mullions with their axis at more than 40 degrees to delta lineation have not been documented. Delta lineation is rarely exactly parallel to mullion axis. Brühl (1969) quotes, based on 50 data, the angle between mullion axis and delta lineation to have values usually between 0 and 20 degrees. To further illustrate this point, outcrop data were grouped into subsets with similar structures. Figure 14 shows stereoplots of bedding, cleavage, mullion axis and delta lineation for two of these groups. It can be seen that in some outcrop groups the delta lineation is sub-parallel to the mullion axis, and in others the orientations are clearly different. In a compilation plot (Fig. 15) of all mullion axes and delta lineations, this distinction is not so clear due to the regional trends in orientations. For all outcrops we calculated the angle alpha between delta lineation and mullion axis. Figure 16 is a histogram of these data. There is a clear maximum at around 20 degrees, with no reliable measurement over 30 degrees. Frequency also decreases towards low values of alpha, but less rapidly than for high angles. This is consistent with the observed correlation between azimuth of mullion axis and delta lineation (Fig. 16). In rare cases mullions are folded across small-scale folds with the fold axis at an angle to the (folded) mullion axis (Bruhl, 1969), consistent with the above observation.

#### Figure 9. Microstructure of thin quartz vein



a) Microstructure of thin quartz vein at high angle to bedding, in a thin psammite layer containing mullions.b) Enlargement of this microstructure shows stretched crystals. (Click for enlargement)

In cross section, mullions show layering which is straight in the middle of the psammite layer, with the curvature increasing towards the outside. Bedding planes in the adjacent pelite layer follow the cuspate-lobate shape



until they are about one mullion-amplitude away from the layer contact (Fig. 7e). In thin sections of the psammite layers in mullions, the amount of solution-precipitation deformation is highest in the centre of the layer (Fig. 10) (Spaeth, 1986).

#### Figure 10. Microstructure in a small mullion



Urai et al., Fig. 6b

Microstructure of psammite at different locations in a small mullion. The amount of inferred solution transfer in the middle of the layer is higher than in the layer's boundary. (Click for enlargement)

Layer thickness correlates with the width of mullions (Jongmans and Cosgrove, 1994; Rondeel and Voermans, 1975). The aspect ratio H/W usually between 1 and 3 (Fig. 13). Several authors have noted that this is too slender in comparison with "normal" boudins formed by layer-parallel extension.

Mullions have orthorhombic symmetry when cleavage is normal to bedding, and are monoclinic on fold limbs (Fig. 4). In this case, symmetry is in agreement with the corresponding fold limb.

Mullions are highly cylindrical, with scatter in mullion axes typically less than 15 degrees in one large outcrop. Observations on cylindricity over more than 10 metres are much less frequent, as such outcrops are rare. In more detail, cusps between mullions sometimes end along strike, so that two mullions join into one (Fig. 7d, Fig. 13e).

#### Figure 11. Mullions with veins



Mullions with veins, which are clearly stretched at high angles to bedding, with the development of boudins. Note the difference in aspect ratio between the boudins and mullions. Slightly modified after Brühl (1969). (Click for enlargement)

Measured along the layering, veins comprise up to about 10% of bed length. This ratio gradually decreases towards the vein's tip.

Veins between mullions are normally spindle- or lens shaped. They are generally oriented at high angle to bedding and in profile view are sub-parallel to the weakly developed fracture cleavage in the psammite layers.

Vein microstructure is variable: in some cases fibres parallel to bedding are found. In other cases, the quartz has a blocky microstructure (Fig. 10).

Figure 12. Microstructure of a deformed intra-mullion quartz vein showing evidence for crystal plasticity and incipient recrystallization. (Click for enlargement)

In thin sections, micro-scale veins parallel to the intramullion veins are occasionally found, with a stretched crystal microstructure indicating transgranular fracturing in a strong rock (Hilgers et al., 2000) (Fig. 9, Fig. 11).

Not unfrequently the intra-mullion veins have a pinchand-swell structure (stretched in a direction sub-normal to bedding); these structures have the usual aspect ratios and are quite different from the Mullions (Bruhl, 1969; Jongmans and Cosgrove, 1994).

In thin sections of deformed veins the vein quartz shows evidence for plastic deformation, with subgrain formation and incipient recrystallisation (Fig. 12).

## Figure 13. Structures from the Bastogne quarry

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Structures from the Bastogne quarry. (a) Mullions developed in a thick psammite layer. Note the unusual aspect ratios. Width of outcrop about 10 m. (b) Detail of (a). (c) Regular series of mullions in a thick sand layer. Width of outcrop is approximately 10 m. (d) Detail from a mullion similar to (c), showing the convergent cleavage fan in the cusp. Width approximately 10 cm. (e) Photograph of the bottom of a psammite layer, showing cylindrical mullions. Note cleavage approximately parallel to bedding. Note the lateral termination of the mullions. Width of outcrop about 15 m.

Fluids in intramullion veins have variable composition but can be H2O, N2 and/or CO2 – rich as has been documented in extensive studies (Fielitz and Mansy, 1999; Sintubin et al., 2000; Schroyen and Muchez, 2000; Darimont et al., 1988).

# Models

Models to explain the evolution of the Eifel-Ardennes mullion structures fall into a number of classes summarised below. This is not a complete list, but a summary of the main classes.

Model (1): The structures formed by layer-parallel extension only (Corin, 1933; Wegmann, 1932).

This model fails to explain many of the observations, for example the high angle between bedding and cleavage, and was rejected long ago.

Model (2): The intra-mullion veins are formed late, after the formation of the cuspate-lobate structures (Quirke, 1923)

This calls for spontaneous nucleation of the cuspatelobate structures at the layer interface (Ramsay and Huber, 1987; Ramberg, 1979) or at load cast structures (Jongmans and Cosgrove, 1994). This phase is followed by further shortening and formation of cleavage. At a later stage, formation of veins is initiated at the cusps, perhaps during a stress relaxation event (Mukhopadhyay, 1972). This model does not explain the deformation features in the veins (pinch-and-swell structures, undulose extinction) (Sintubin et al., 2000), the layer thickness dependence of the size of the mullions (cf. Tromme, 1997), and the shape of the mullions with cuspate-lobate folds symmetric on both sides of the layer. Also, it is not clear why in this model the veins should stop at the psammite-pelite interface (the cleavage has already developed in the pelite). In addition, the nonzero angle between mullion axes and the delta lineation is a strong argument against this model.

#### Figure 14. Structural data



a - scale bar 0.3 mm

b - scale bar 0.1 mm

Structural data (lower hemisphere, equal area) from selected groups of outcrops from the study area. (a) Outcrops with delta lineation close to the mullion axis. (b) Example of a case where these two lineations are clearly distinct. Lower hemisphere, equal area projections. Legend: open circles- Mullion axis; open triangles- poles to intramullion veins; open squares- poles to bedding; crosses- poles to cleavage in pelite; dots- delta lineation (intersection of bedding and cleavage). (Click for enlargement)

Model (3): The intra-mullion veins formed during the early stages of layer-parallel shortening, before the main development of folds and cleavage (Bruhl, 1969; Sintubin et al., 2000).

In the model of Brühl, the growth of crystals in the veins is thought to occur due to the force of crystallization. Although this is an exciting idea which recently has been further developed (Wiltschko and Morse, 2001), in our case it seems unlikely because the orientation of intra-boudin veins implies opening of the vein against the largest principal stress, and parallel to the largest tensile strength. It is much more likely that the force of crystallization would have opened the veins parallel to layering. In addition, the vein microstructure (syntaxial) does not agree with the force of crystallization arguments either. Final arguments The Virtual Explorer

against this model are the regularity of the structures and the nonzero angle between intra-mullion veins and cleavage.

Model (4a): The intra-mullion veins formed before the start of layer-parallel veins, as boudin-necks during an extension event (Jongmans and Cosgrove, 1994; Rondeel and Voermans, 1975; Tromme, 1997). The present shape of the structures is a deformed equivalent of the early boudins, but the cuspate-lobate shape is caused by the early boudinage. This was presumably the argument of Jongmans and Cosgrove (1994) for using the term boudin.

#### Figure 15. Stereogram



a, c - scale bar: 0.1 mm b, d - scale bar: 0.3 mm

Stereogram showing all delta lineation and mullion axis data from the study area. Insert shows a cross-plot of the azimuth of these two datasets. Lower hemisphere, equal area projection. (Click for enlargement)

This model is consistent with the location of veins in the sandstone layers, the deformed veins, the cleavage patterns and the angle between veins and delta-lineation. It has problems, however, with the aspect ratio of the mullions, which would require unrealistically high shortening strains (Sintubin et al., 2000). In addition, the 3D shape of boudinaged layers is usually much more irregular than observed in this study, even considering the later deformation which tends to make structures more cylindrical.

Model (4b): The intra-mullion veins formed before the start of layer-parallel shortening, in a regionally developed joint system during events of hydraulic fracturing (Sintubin et al., 2000; Hilgers et al., 2000). During later shortening the veins were mechanically stronger than the sandstone, and the veins acted as stress guides for extrusion of the sand normal to the layers (Fig. 17). During later shortening, the folds and the cleavage were formed, and the mullions became asymmetric in the fold limbs.

The key elements of his model were developed simultaneously and independently in early 2001 by Kenis et al. (2001) and Urai et al. (2001), see also Kenis et al. (in press).

#### Figure 16. Histogram



Histogram of the angle between delta lineation and mullion axis. (Click for enlargement)

This model does not disagree with the observations published so far, including our dataset. In what follows, we discuss some aspects of this model in some detail.

Regular, narrow-spaced fracture sets perpendicular to bedding in layered siliciclastic sequences are a common feature. They can be locally very regularly spaced, and evolve into vein sets in the presence of supersaturated fluids. Examples are given in Price and Cosgrove (1990). Their preferred location in psammite layers is consistent with stresses measured in sandstone-shale sequences in sedimentary basins during burial, which consistently indicate lower horizontal stresses in sand than in clay. This means that with progressively decreasing horizontal effective stress during periods of pore pressure increase, mode I fractures and subsequent veins first develop in the sand layers, only occasionally penetrating into the slate. The lateral teminations of the mullions, which can be occasionally observed, are similar to the vein terminations observed in field studies. A more detailed discussion of the stress path in this region is presented in (Hilgers et al., 2000).

Microstructures (stretched crystals, layer parallel fibres) in the sandstone indicate that the sand was lithified before the fractures developed in a high fluid pressure

environment. This overpressure event (Sintubin et al., 2000; Hilgers et al., 2000) was extensive and long-lived and was accompanied by a slight (5-10%) horizontal extension as indicated by the total amount of vein quartz in the psammite layers.

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# Figure 17. Model for the development of mullion structures



scale bar: 0.3 mm

Model proposed for the development of mullion structures: (a) An illustration of the model proposed for the development of mullion structures.

The right hand diagram is a trace of the sample shown in Fig. 7e. The left-hand diagram shows an interpretation of the geometry of this structure at the beginning of layer parallel shortening. The image was constructed assuming constant volume deformation and no deformation of the quartz veins. As argued for in the text, at this point there was a clear competence contrast (vein quartz > psammite > pelite). The quartz veins thus reduced the vertical stretching in the psammite along their margins, causing the psammite to be extruded perpendicular to the layers. See text for discussion.

(b) Schematic illustration of the process by which mullions become asymmetric during progressive folding.

The mullions were then initiated during the early stages of sub-horizontal Variscan shortening. In this period, the strong veins acted as stress guides for extrusion of the sand normal to the layers. Arguments for the vein quartz being stronger than the sandstone are the fine grain-size of the sand and the evidence for solution transfer processes, and the CO2 and N2 - rich fluids in the quartz. It has been shown experimentally that milky vein quartz containing CO2 rich fluids is much stronger than milky vein quartz containing H2O-rich fluids (Dijkstra, 1990).

The angle between mullion axes and delta-lineations is a consequence of a coincidence between the early veins and the Variscan shortening direction. This was oriented close to but not exactly parallel to the opening directions of the early veins: In this orientation the mullions could easily form. According to the model mullions do not form when the shortening is at a small angle to the veins. Therefore a critical observation to falsify the model would be mullion axes at very high angle to the delta lineation. To date such outcrops have not yet been described.

Mullions thus formed early in the Variscan shortening, and became asymmetric during the later folding. In areas of the regional folds where bedding became sub-parallel to cleavage, the psammite layers which first developed the mullions presumably underwent a later phase of stretching, forming the boudins observed in these locations (Fig. 4c) (Spaeth, 1986).

The development in two different tectonic phases is consistent with the variable nonzero angle between mullion axis and the cleavage. During shortening the veins were effective in controlling the local strain field and perhaps had a small effect on the local orientation of the fold axes, but the direction of shortening and the development of regional fold sets and cleavage were controlled by regional forces.

Not all observations are equally well explained so far. For example, the spindle shape of the intra-mullion veins is not like the veins found in their undeformed equivalents. This is one of the questions which requires further study.

## Discussion

The model presented above can be considered, in a highly simplified first approximation, as a consequence of flow between two rigid plates, which are moved closer to each other. The process is similar to the deformation in triaxial deformation machines where a ductile sample is shortened between two rigid pistons without lubrication between piston and sample.

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Further simplifying, this can be considered as flow of a fluid between two stationary plates (Fig. 18). Using this approximation, we calculated a number of profiles of material deformed in this system. Results of this model show that the expected shape of the lobes is a strong function of the power law exponent n. For linear viscous materials the shape is parabolic, and for increasing values of n the deformation is more and more concentrated at the layer's boundaries.

The profiles calculated can be compared with the shape of the mullions in profile. The exact shape of these can be determined accurately, but was not yet studied extensively so far. As an example one can compare Figure 18 with Figure 7. This comparison suggests that, as first estimate, the value of the stress exponent n in these rocks is between 2 and 5. We note that much more work is needed here, using non-linear finite element techniques. Such a study will also require careful calibration of the models against volume change due to pressure solution, the strain in the intra-mullion veins, and require removal of later deformation. Obviously this is not a simple process. On the other hand our understanding of the in-situ rheology of psammites under very low-grade metamorphic conditions is very limited and additional information from naturally deformed rocks would be quite valuable.

An interesting consequence of the model is that wider initial vein spacing results in faster deformation in the corresponding sandstone segment. In other words, this effect will tend to make the spacing between mullions more regular. This prediction can be tested in the field, using observations in multiple mullions.

- (a)
- (b)

Figure 18. Mullions calculated based on the model for flow between parallel plates



(a) Profile of mullions calculated based on the model for flow between parallel plates, showing the effect of power law stress exponent n on the expected shape of the mullions.

(b) Click for movie Cinema 4D model illustrating the effect shown in (a) for three different mullions evolving in materials having n= 1,3 and 5 respectively. The kinematics of the model are based on the velocity profile of a power law fluid flowing between parallel plates, and a shortening rate chosen such that volume is approximately constant.

## Conclusions

• The structures in Dedenborn and Bastogne are both of the same origin, and should be given the same name. The original term boudin was used first and it was a perfectly adequate name for these structures. Even today mullion and boudin are both used for these compressional structures. To end the confusion in terminology, we propose the consistent usage of mullion for all the structures described in this paper, based on the genetic definitions of the terms mullions and boudins given in recent structural geology textbooks.

• Mullions formed during the first phases of Variscan shortening as response to the mechanical structure of veined layers with the competence contrast (vein > psammite > pelite). Vein quartz was the strongest element of the system due to its coarse grain size and due to its CO2 - rich fluid content.

• Mullion shape in cross section is a potential gauge for paleo-rheology: It depends on the power law creep exponent n. Initial, highly simplified modelling indicates a value



between 2 and 5. Further work using non-linear finite element models and detailed study of samples is in progress.

• At peak burial this part of the lower Devonian passive continental margin a regional scale vein set perpendicular to bedding was developed in a high fluid pressure cell.

• Basin inversion occurred sub-parallel to the extension direction in the continental margin, in an approximately 100 km wide zone.

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