GEOLOGICA BELGICA (2007) 10/1-2: 79-91.

ABOUT BOUDINS AND MULLIONS IN THE ARDENNE-EIFEL AREA (BELGIUM, GERMANY)

Ilse KENIS[1,2] & Manuel SINTUBIN[1,*]

(10 figures)

1. Geodynamics & Geofluids Research Group, Katholieke Universiteit Leuven, Celestijnenlaan 200E, B-3001 Leuven, E-mail: manuel.sintubin@geo.kuleuven.be
2. Geologie - Endogene Dynamik, RWTH Aachen, Lochnerstrasse 4-20, D-52056 Aachen. E-mail: i.kenis@ged.rwth-aachen.de
** corresponding author*

ABSTRACT. The terms 'boudin' and 'boudinage' have been coined in 1908 at Bastogne to describe the geometry of particular structures in Lower Devonian metasedimentary series, resembling an array of sausages lying side by side. Recent research shows that these structures are the expression of a polyphase deformation history in brittle-ductile deformation conditions in the middle crust. Hydraulic fracturing caused the formation of the vein arrays, while layer-parallel shortening is responsible for the cuspate-lobate morphology of both the lower and upper interface of the psammite layers. Taking into account the currently acknowledged geological nomenclature, particularly with respect to the terms boudin and mullion, the resulting structures should be described as mullions, or more particularly as double-sided mullions. Notwithstanding the fact that the kinematics giving rise to the particular structures in the Ardenne-Eifel area are not related to the process of boudinage, the Belgian geological community should strive for the creation of a heritage site at Bastogne, still the locality where the terms 'boudin' and 'boudinage' have been used for the first time.

KEYWORDS: Boudinage, Devonian, Palaeozoic, Variscides, geological heritage, Ardenne, Eifel.

1. Introduction

In the Ardenne-Eifel area (Belgium, Germany) there is a regional occurrence of well-organized arrays of lenticular veins, which are oriented at a high angle to the bedding and occur in the most competent parts of the sedimentary sequences, *i.e.* sandstones, psammites or quartzites (Figs 1, 2 & 3). They generally stop at the interface of the competent layer and the incompetent surrounding rocks, *i.e.* pelite or siltstone. The interfaces on both sides of the competent layer are characterized by a cylindrical cuspate-lobate geometry, pinned by layer-perpendicular quartz veins (Figs 2 & 3). These structures serve since nearly a century as type examples for the geological terms 'boudin' and 'boudinage' (†), primarily because a French-speaking group of geologists visited the type locality at Bastogne in 1908 (Lohest *et al.*, 1908; figs 1 & 2). A historical review clearly demonstrates that the terms 'boudin', 'boudinage' and 'pinch-and-swell' – at first all basically descriptive terms referring to a characteristic morphology of layers – got mixed up and gradually obtained a kinematic significance. This kinematic significance linked to boudinage (‡) is nowadays used worldwide by the geological community and refers to the disruption of layers, bodies or foliation planes within a rock mass in response to bulk extension along the enveloping surface (Goscombe *et al.*, 2004). Keeping in mind this kinematic definition the following questions can be asked. (1) Are the structures in the Ardenne-Eifel area that were at the origin of the terms 'boudins' and 'boudinage' (Lohest *et al.*, 1908), actually the result of the process of boudinage such as currently defined in literature? (2) If we have evidence that this is not the case, is there another process that can explain the formation of these structures? In that case, do we have to rename these structures? Or should the entire geological community adapt itself and redefine the term 'boudinage' such as nowadays generally accepted? (3) And if we agree that the entire international geological community should adapt itself, what should the new definition of 'boudinage' be, taking into account the structures at the type locality?

In our opinion, the answer to these questions should be inspired by some realism and pragmatism, and definitively not by a sort of fundamentalism. In this paper we want to demonstrate that we do have ample evidence that the particular structures that regionally occur in the Ardenne-Eifel area are not the result of the process of boudinage, *i.e.* disruption of layers within a rock mass in response to bulk extension, but are the result of a polyphase brittle-ductile deformation history in a setting that does

---

† the terms 'boudin' and 'boudinage' between quotes apply to the particular structures and their development in the Ardenne-Eifel area.

‡ the terms boudin and boudinage without quotes apply to the structures formed by the process of layer-parallel extension and to the process of layer-parallel extension.

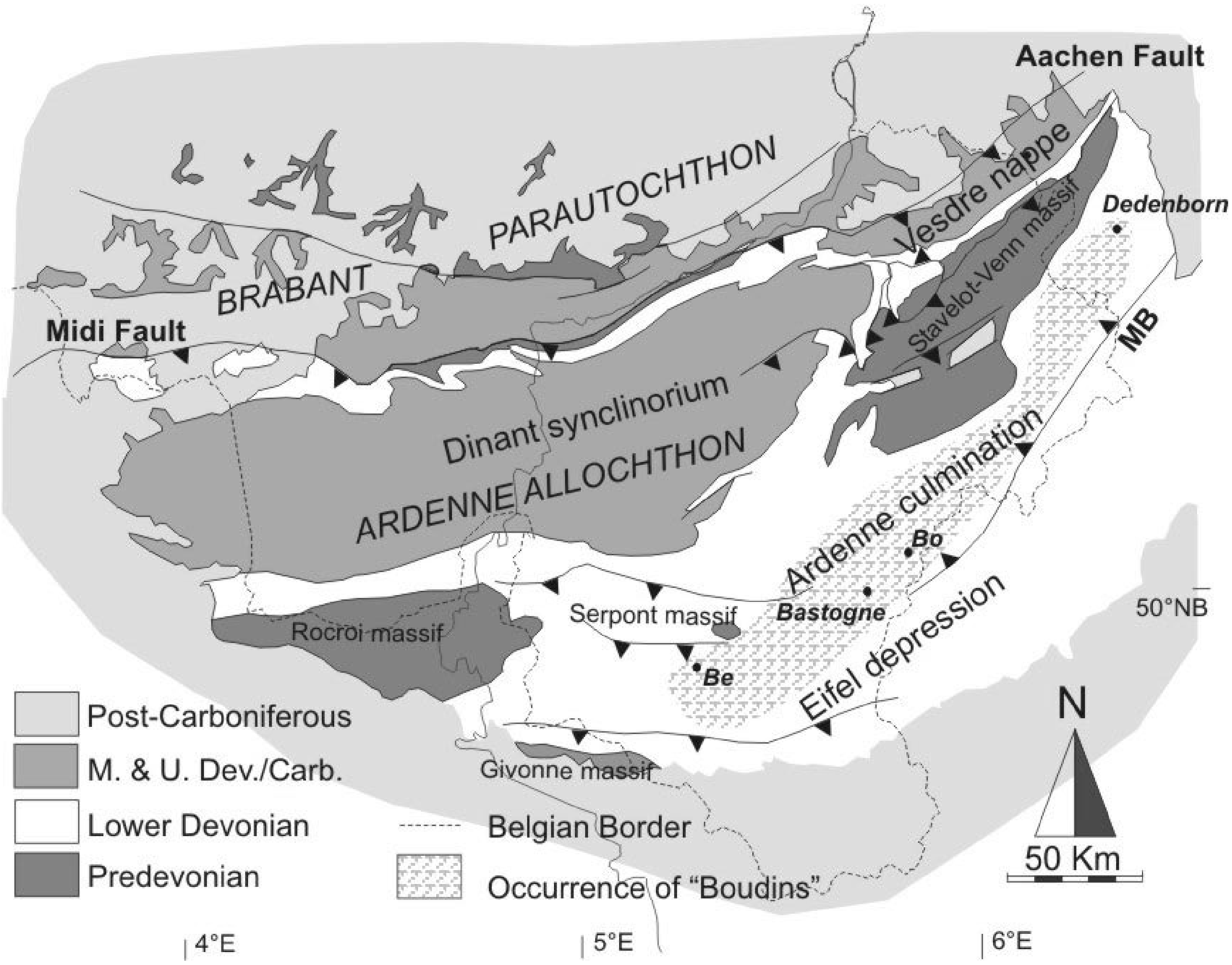


Figure 1: Geological map of the Ardenne-Eifel area (Belgium, Germany) with indication of major tectonostratigraphical domains. The occurrence of the structures investigated is limited to the culmination zone of the High-Ardenne slate belt. Dedenborn and Bastogne are indicated. Bo, Boeur; Be, Bertrix; MB, Malsbenden fault.

not require layer-parallel bulk extension. Furthermore, it will be demonstrated that the cuspate-lobate morphology of the structures is exemplary for the process of mullion formation. The term 'mullion' is used to describe particular cuspate-lobate folded interfaces due to layer-parallel shortening of competent layer embedded in a less competent matrix (van der Pluijm & Marshak, 2004). The textbook example of mullions (*e.g.* Price & Cosgrove, 1990) is also found in the Ardenne-Eifel area, on a small outcrop at the outskirts of Dedenborn and is for that reason a *'naturdenkmal'*, a natural heritage site (Figs 1 & 4). These mullions show the same characteristics (*e.g.* bedding-perpendicular quartz veins, cuspate-lobate geometry) as the 'boudins' and have a similar formation history, although according to textbooks the kinematics of both structures are opposite. This hampers the discussion on the 'boudins' in the Ardenne-Eifel area and calls for the introduction of an uniform nomenclature for both the mullions and 'boudins' in the Ardenne-Eifel area.

2. A historical review

Already in the 19th century Belgian geologists were interested in the particular occurrence of the quartz veins in the Ardenne-Eifel area and their associated structures. Dumont (1848) was the first geologist to describe the quartz veins from a mineralogical point of view. However, it was Gosselet (1888) who, in his chapter on the metamorphism of the Ardenne, and more particularly on the *'cornéite des carrières de ballast à Bastogne'*, gave a first geometrical description of the veins. Stainier (1907), in his study on the origin of the metamorphic rocks in the Bastogne area, gave an extensive inventory of the occurrence and geometry of the veins. With this inventory he showed that the veins and associated structures in the Lower Devonian rocks had a regional occurrence and significance. To demonstrate the work of Stainier (1907) a field trip to the Bastogne area was organised by the Société Géologique de Belgique. On august 31st, 1908, at the Carrière Collignon at Bastogne (Fig. 2), Max Lohest introduced the terms 'boudinage' and 'boudins' in order to facilitate discussion on the particular vein occurrence described by Stainier (Lohest *et al.*, 1908). *'Lorsque l'on voit ces segments renflés sur une surface de stratification, on croirait voir une série d'énormes cylindres ou boudins alignés côte à côte; aussi, au cours de cette excursion, et sur l'initiative de M. Lohest on a fréquemment utilisé, pour la facilité du langage, les néologismes de boudiner et de boudinage'.* However, at this stage, the terms were used as purely descriptive terms without any kinematic

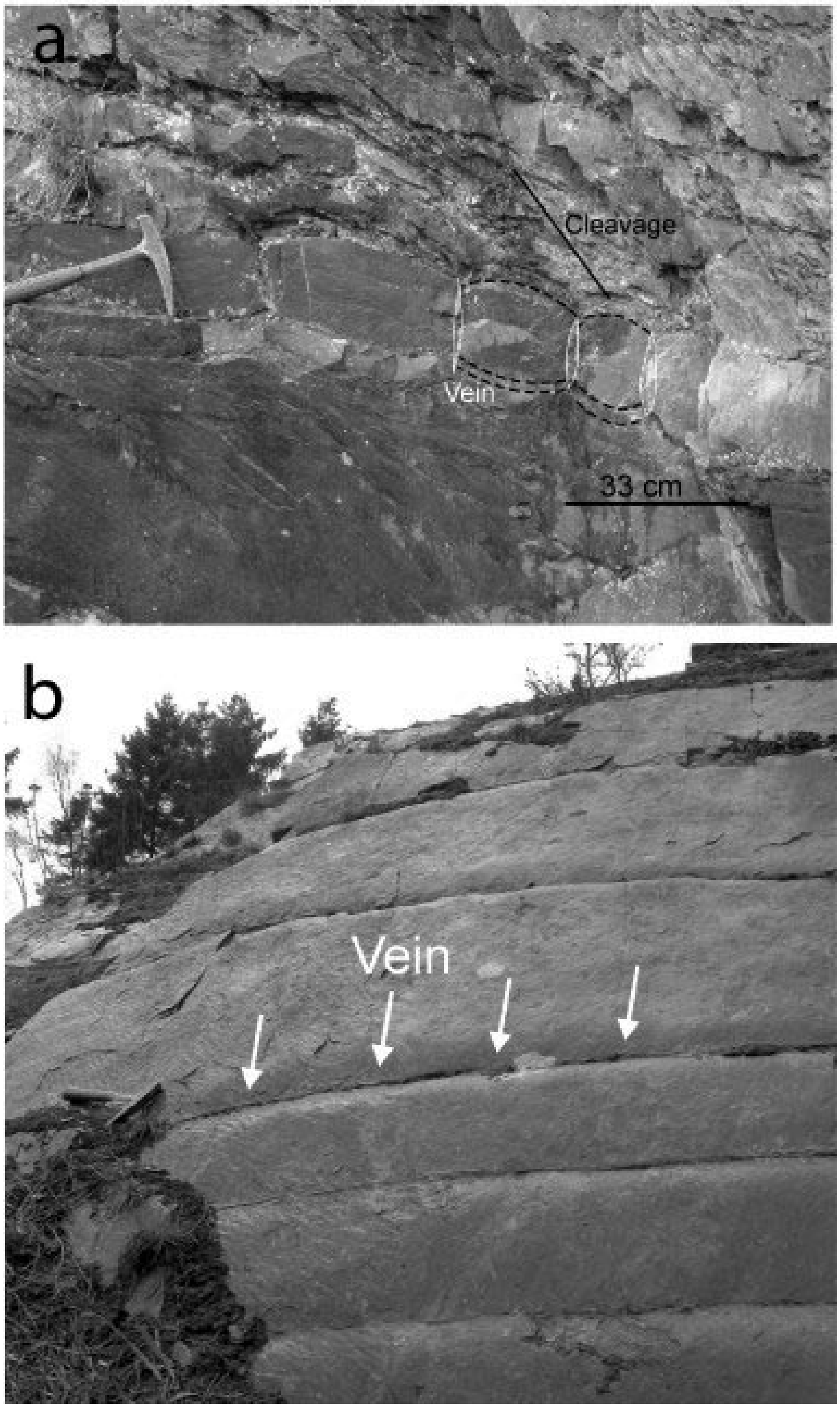


Figure 2: Photographs at the type locality at Bastogne (Carrière Collignon) (see Fig. 1 for locality). (a) Structures that were at the origin of the terms ‘boudins’ and ‘boudinage’. White line marks the occurrence of the veins, black dashed line corresponds to the cuspate-lobate geometry of the structures. Hammer length is 33 cm. (b) A bedding surface, on which the particular appearance of ‘sausages’ – ‘boudins’ in French – lying side by side becomes apparent. Hammer length is 33 cm.

significance. Moreover, during the field trip, a discussion unfolds on the relative timing of the compressional (cleavage, curved nature of competent layers) and extensional (quartz veins) features associated to the ‘boudins’. Since then a discussion started that led to numerous chronological models to explain the development of the structures (Quirke, 1923; Stainier, 1930; Holmquist, 1931; Corin, 1932; Wegmann, 1932; Eckelmans, 1961; Rondeel & Voermans, 1975; Lambert & Bellière, 1976; Jongmans & Cosgrove, 1993). Thanks to Cloos’ (1947) review on boudinage interest in boudins multiplied rapidly in the late 40’s and boudinage became recognized as one of the more common structure-forming processes in deformed rocks.

Although in the past it was often recognized that boudins and ‘pinch-and-swell’ structures of other areas (*e.g.* Holmquist, 1931; Walls, 1937) did not resemble the structures observed in the Bastogne area, Cloos (1947) makes no longer a distinction between ‘pinch-and-swell’ structures as described by *e.g.* Ramsay (1866) and Harker (1889) and the ‘boudins’ in the Ardenne-Eifel area. Boudinage obtains its current definition, in which it is

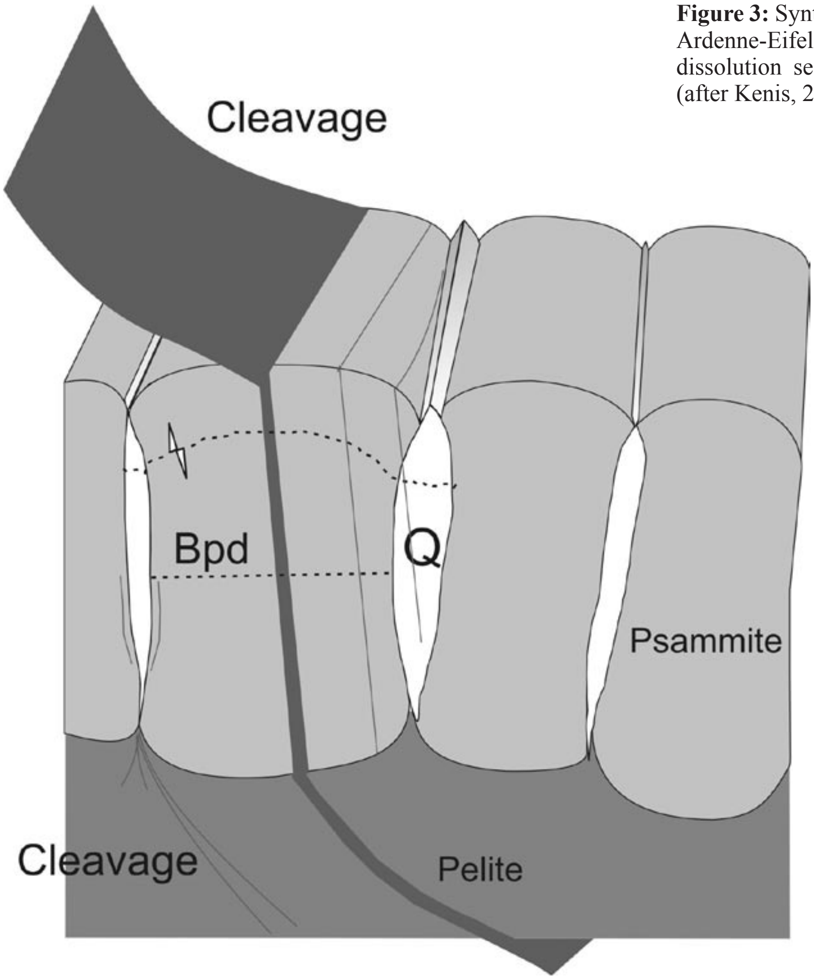
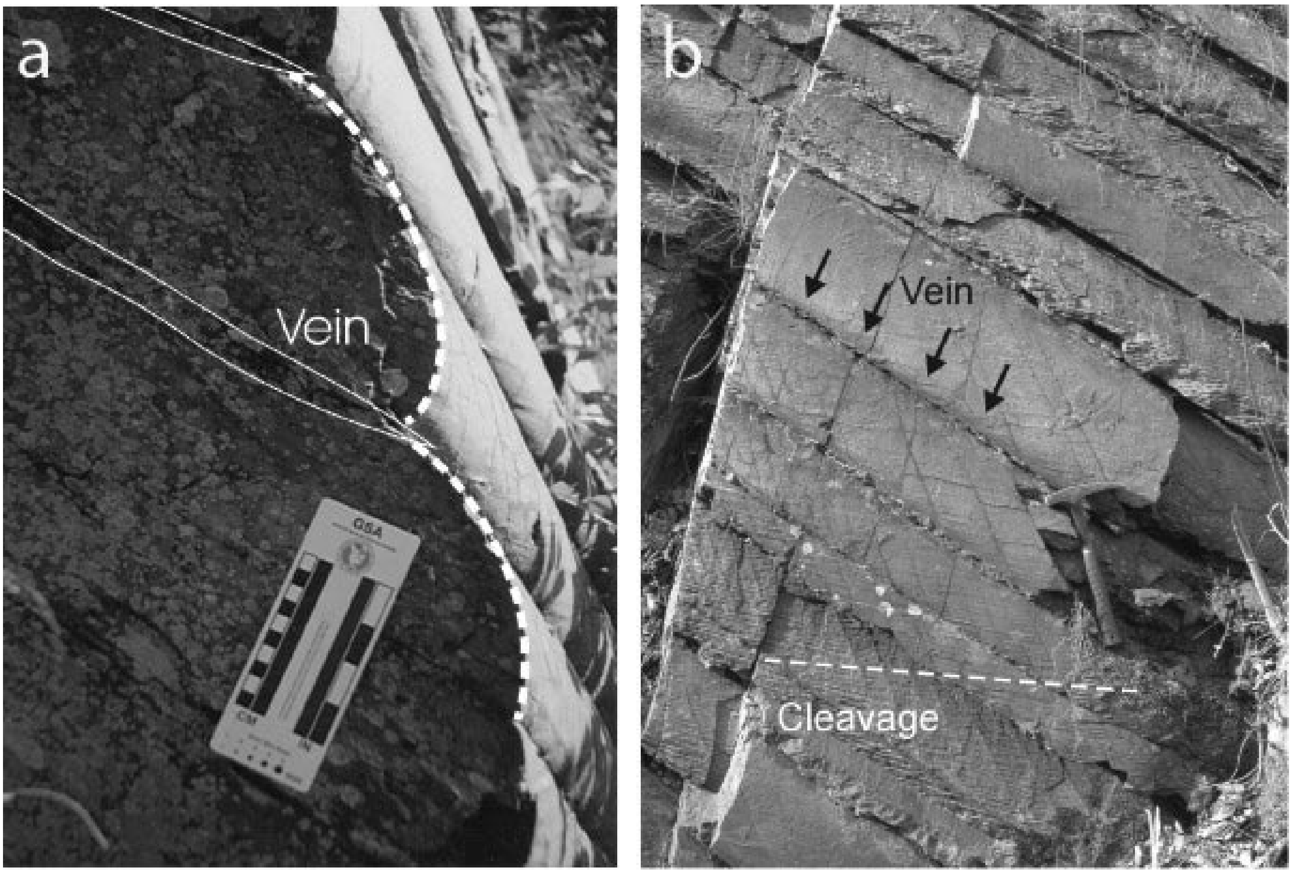


Figure 3: Synthetic figure of the cuspate-lobate structures in the Ardenne-Eifel area. Q, quartz vein; Bpd, Bedding-parallel dissolution seam. Grey lines represent the tectonic cleavage (after Kenis, 2004).

Figure 4: Photographs of the textbook example of mullions at Dedenborn (see Fig. 1 for locality). (a) Cuspate-lobate geometry of bedding interface (white dashed line) and quartz veins (white continuous line) in cross-section view. Scale bar is 10 cm. (b) A bedding surface, on which the mullions are apparent. Compare with figure 2b for the geometrical similarities. Hammer length is 33 cm.



ascribed to the process of layer-parallel extension of competent layers embedded in a less competent matrix. Since then, the terms 'pinch-and-swell' and 'boudins' are used within the same kinematic context (*e.g.* Ramberg, 1955; Fourmarier, 1956; De Sitter, 1958; Eckelmans, 1961). As an anecdote it can be mentioned that according to Wilson (1961) the confusion of the terms 'pinch-and-swell' and 'boudins' has undoubtedly arisen because of the different way sausages are displayed in butcher's shops in different countries. In continental Europe, large boudins are found lying side-by-side. In Britain and America a smaller type of sausages is more common and these are seen hanging in strings end-to-end (cf. *'allure en chapelet'*, Stainier, 1907; *'disposition amygdalaire'*, Gosselet, 1888).

Nearly 50 years after the terms 'boudin' and 'boudinage' were first used in Bastogne, confusion on the terms grew when similar structures were recognized in the North Eifel by Pilger & Schmidt (1957) and where described as mullions. These mullions have the same structural characteristics as the 'boudins' with the exception that veins occur at the bottom part of a thick competent sandstone layer and that cuspate-lobate structures only occur at the interface of this sandstone layer with the underlying pelitic material. The term mullion originates from the resemblance of these fold structures to vertical fluted architectural decorations, called mullions, in *e.g.* windows and on columns in Gothic cathedrals. At that time, Pilger & Schmidt (1957) proposed a genetic relationship between the mullions and the 'boudins' in the Ardenne-Eifel area and suggested a compressional origin for both structures. This idea was supported by Brühl (1969), who proposed that all related structures should be termed boudins since Bastogne was still the type locality for the 'boudins'. However, he proposed that, if the term 'boudins' was retained for the structures in the type locality, another term should be found for the extensional structures in literature described as boudins. As a solution, he introduced the terms L-boudin (*'auslängungs-boudins'*) for structures due to extension and K-boudin (*'verkürzungs-boudins'*) for the structures due to shortening. If the lithological difference

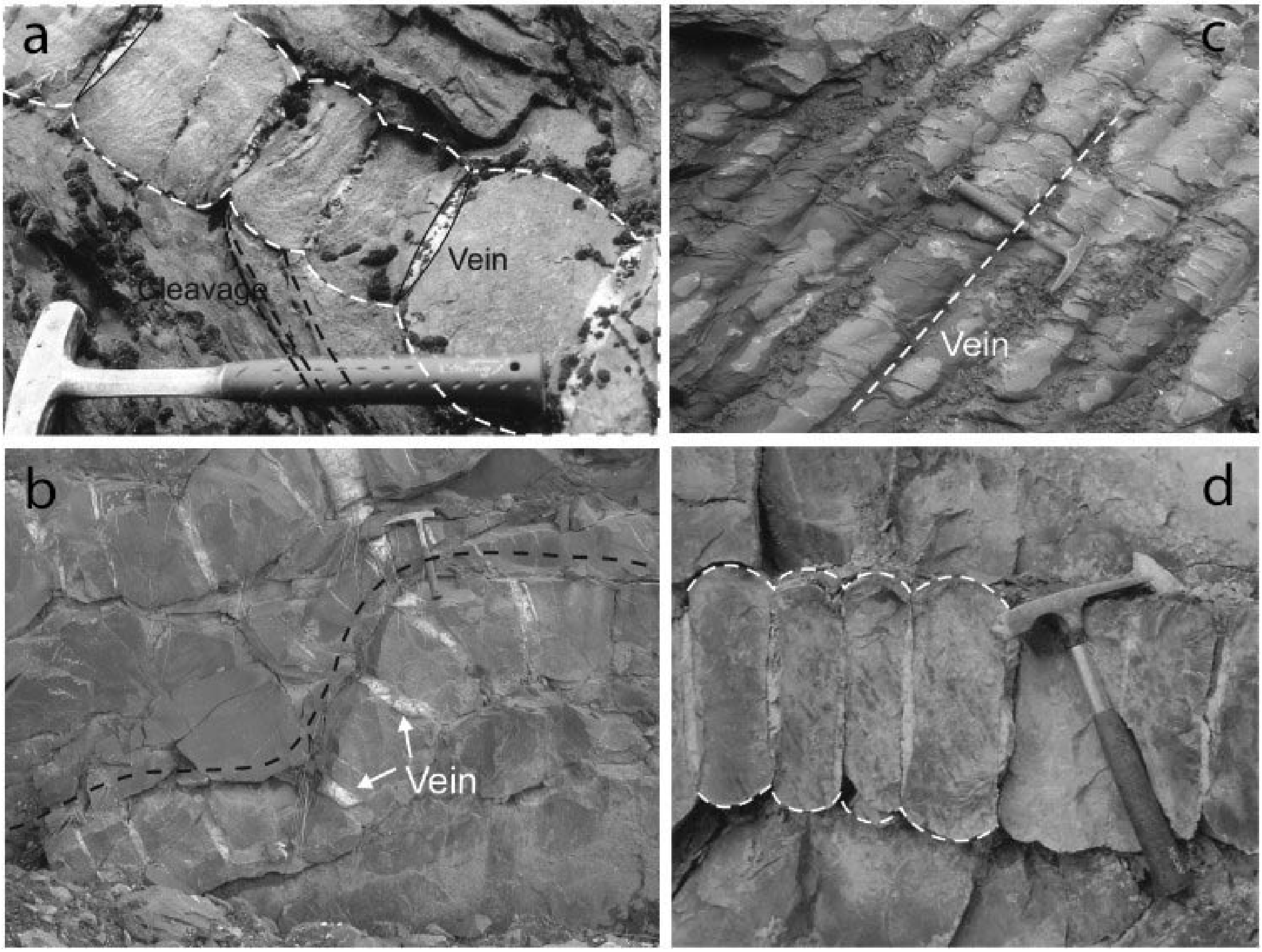


Figure 5: Different geometrical aspects of the particular structures in the Ardenne-Eifel area. (a) 'double-sided mullions' at Boeur (see Fig. 1 for locality). White dashed line represents the cuspate-lobate geometry in between the veins of the psammite-pelite interface. Black dashed lines indicate cleavage in pelite. Hammer length is 33 cm. (b) A small-scale Variscan fold (black dashed line) of a segmented sandstone layer (Carrière Mardasson, Bastogne, see Fig. 1 for locality). Hammer length is 33 cm. (c) Continuous occurrence of veins (white dashed line) in the bedding plane (Carrière Mardasson, Bastogne, see Fig. 1 for locality). Hammer length is 33 cm. (d) Particular aspect ratio of the 'sausage'-like structures in the Ardenne-Eifel area (Carrières de la Flèche, Bertrix, see Fig. 1 for locality).

is only present at one plane of the bedding, 'half-boudins' sensu Brühl (1969) result, *i.e.* mullions sensu Pilger & Schmidt (1957).

Since the association of the term boudinage with bulk extension was already too deeply entrenched in English literature, Mukhopadhyay (1972) did not find this new terminology of L- and K-boudins a solution to the confusion. In stead, he proposed to keep using the terms boudinage and mullion formation in order to make a distinction between the process of layer-parallel extension of competent layers enclosed in a less competent matrix, and the formation of cusp-like corrugations at the interface of units of different competencies in a multilayer sequence affected by layer-parallel shortening respectively. To date, both kinematic definitions are worldwide acknowledged as exemplified in most manuals on structural geology (*e.g.* Ramsay & Huber, 1983; Ramsay & Huber, 1987; Price & Cosgrove, 1990; Twiss & Moores, 1992; Ghosh, 1993; van der Pluijm & Marshak, 2004).

Mukhopadhyay (1972), however, agreed with the ideas of Pilger & Schmidt (1957) and Brühl (1969) of a compressional origin for the particular cuspate-lobate structures in the Ardenne-Eifel area and therefore suggested that all related structures in this region should be called mullions. Apart from Spaeth (1986), the association of the cuspate-lobate structures with mullions again disappeared in literature and only supporters of an extensional origin for the structures, *i.e.* boudinage followed by compression, performed new work on the 'boudins' (*e.g.* Rondeel & Voermans, 1975; Lambert & Bellière, 1976; Jongmans & Cosgrove, 1993). They consider the structures as examples of 'shortened boudins' (see also classification of Goscombe *et al.*, 2004). The latter are vein structures that formed due to bulk extension of competent layers and subsequently underwent a shortening history.

Recently, extensive research efforts (Kenis *et al.*, 2002, 2004, 2005a, 2005b; Kenis, 2004; Sintubin *et al.*, 2000; Urai *et al.*, 2001) reveals that these particular structures reflect a brittle-ductile, polyphase deformation history. A synthesis of the main findings of these studies is further reported in this paper.

3. The structures in the Ardenne-Eifel area

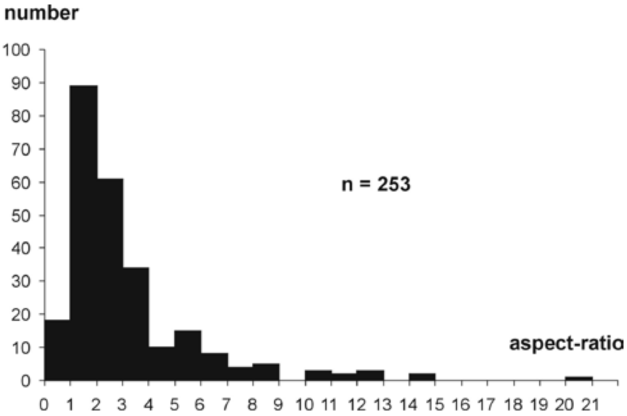


Figure 6: Histogram representing the aspect ratio (heigth/width) of the segments in between veins in the Ardenne-Eifel area. Number of measurements n=253.

As a starting point in the description and interpretation of the particular structures in the Ardenne-Eifel area, we make a clear distinction between two distinct structural features: (1) the veins and (2) the cuspate-lobate geometry of the bedding interfaces. Although we consider both structural features separately, a regional survey clearly indicates that both features are spatially closely related and kinematically linked (Hilgers *et al.* 2000, Urai *et al.*, 2001; Kenis *et al.*, 2002; Kenis, 2004). If veins are not present, the cuspate-lobate morphology is lacking. Another obvious observation is that the occurrence of both structural features is limited both in space and time. They only occur in formations of Upper Lochkovian to Pragian age. Regionally, their occurrence is limited to the southern limb of the Ardenne culmination (Fig. 1), coinciding with the part of the High-Ardenne slate belt with the highest metamorphic degree (Fielitz & Mansy 1999), and representing the deepest parts of the Eifel-Ardenne rift basin (cf. Oncken *et al.* 1999).

3.1. Veins

The veins predominantly consist of quartz, but also contain minerals such as chlorite, muscovite, biotite, pyrite, chalcopyrite, ilmenite and feldspar. In the veins at Bastogne a special dark mica can, moreover, be observed.

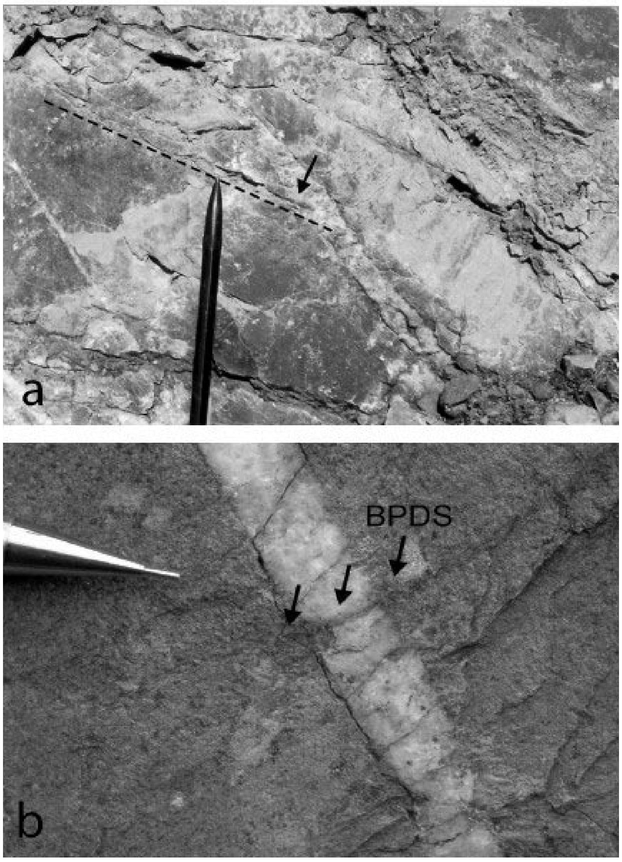


Figure 7: (a) Variscan cleavage (black dashed line) crosscuts the veins (Carrières de la Flèche, Bertrix, see Fig. 1 for locality). Pencil is 15 cm. (b) Bedding-parallel dissolution seam (BPDS) crosscutting the veins (Carrière Mardasson, Bastogne, see Fig. 1 for locality). Width of photograph is 7 cm.

This mica is describes as extremely poor in potassium (Klement, 1888) and is named bastonite after its type locality. According to Bos *et al.* (1987) it is one of the richest NH_4^+-dark micas encountered so far. The NH_4^+ content is well above the maximum content for metamorphic rocks.

A geometrical analysis of the veins shows the following general characteristics. The veins are commonly lens-shaped (Figs 3 & 5a). They are oriented nearly perpendicular with respect to bedding, independent of the geometrical disposition, *i.e.* the orientation of the bedding (Fig. 5b). The veins are commonly limited to the most competent parts, *i.e.* the most silty and sandy parts, of the multilayer sequence. They form a systematic array of parallel veins, very continuous in the longitudinal direction. In the transverse direction the array is characterized by a rather regular spacing (Figs 2b & 5c). Mostly the veins are limited to one single bed but sometimes veins spanning several beds can be observed. The aspect ratio (height versus width) of the segments in between two adjacent veins ranges from 1 to 7 even up to 20 (Figs 5d & 6).

A number of features allow constraining the relative timing of the veining. Veining definitively predates Variscan folding and cleavage development. Independent of the geometrical disposition of the beds, the angular relationship between veins and bedding remains constant. This suggests that veining occurred in beds in a horizontal, depositional, disposition. No observations allow suggesting that veining and folding are kinematically linked. The Variscan cleavage moreover transects the veins, clearly suggesting that cleavage development, which is kinematically linked to the folding, postdates the veining (Fig. 7a). A crucial observation with respect to the relative timing of the veining is the observation of bedding-parallel dissolution seams cross-cutting the veins (Fig. 7b). This observation suggests that veining occurred at deepest burial conditions. No observations suggest that veining occurred during uplift. Based on the above-mentioned observations, it is fair to assume that veining occurred during the deep stages of the burial history within the Eifel-Ardenne rift basin, thus during the early Viséan (~340Ma).

To decipher the mechanism of veining we performed an extensive mineralogical, geochemical and fluid-inclusion study of the vein quartz (Kenis *et al.*, 2002; 2005a; Kenis, 2004). It does not lie in the scope of this paper to elaborate on the detailed results, which have been published elsewhere (Kenis *et al.*, 2002; 2005a; Kenis, 2004). Both mineralogy and fluid-inclusion data indicate that the vein material precipitated from metamorphic fluids present in the rocks. As shown by chlorite geothermometry, precipitation occurred at local peak metamorphic conditions in thermal equilibrium with the host rock (Verhaert, 2001). These local metamorphic temperatures correspond to 300-400 ºC. (see also Darimont *et al.*, 1988; Theye & Fransolet, 1993; Beugnies, 1986). In combination with the microthermometrical study of the fluid inclusions, pressure-temperature conditions at the time of veining could be determined (300-400 ºC, 190-255 MPa; Kenis, 2004). This analysis demonstrates that high fluid pressures were present at the time of veining (see also Darimont *et al.*, 1988). Fluid pressures moreover fluctuated between near-lithostatic to near-hydrostatic (between 255-115 MPa at 400 ºC and between 100-190 MPa at 350 ºC; Kenis, 2004). This apparent fluid-pressure fluctuation and the near-lithostatic fluid pressures infers that the mechanism of veining was hydraulic fracturing (cf. Cosgrove, 1997).

3.2. Cuspate-lobate geometry

The second structural feature of the particular structures in the Ardenne-Eifel area is the cuspate-lobate geometry of the interface between materials of different composition/competency (Figs 3 & 5a). The layer-parallel dissolution seams, which crosscut the veins, follow this cuspate-lobate geometry clearly indicating that the cuspate-lobate geometry formed after veining and can be considered as a separate event with respect to the formation of the veins (Kenis *et al.*, 2002; Kenis *et al.*, 2004). In addition, internal cleavage fanning inside pelitic layers of multilayer structures demonstrates that the cuspate-lobate geometry is a consequence of layer-parallel shortening, occurring at the onset of Variscan shortening (Ramsay & Huber, 1987; Fig. 8). This layer-parallel shortening is in agreement with lattice preferred orientation and shape preferred orientation present within the vein-quartz fabric (Kenis, 2004). The

Figure 8: Divergent cleavage pattern (white dashed lines) in pelitic part of a multilayer cuspate-lobate structure (Boeur, see Fig. 1 for locality). Height of photograph is 20 cm.

formation mechanism of a cuspate-lobate geometry of interfaces between sandstones and pelites due to layer-parallel shortening complies with the kinematic definition of mullions as nowadays acknowledged by the geological community. Therefore, the cuspate-lobate geometry of the structures currently observed in the Ardenne-Eifel area can be considered as the effect of mullion formation at the interfaces of the competent (sandstone/psammite/quartzite) and incompetent (siltstone/pelite) parts of the sequence.

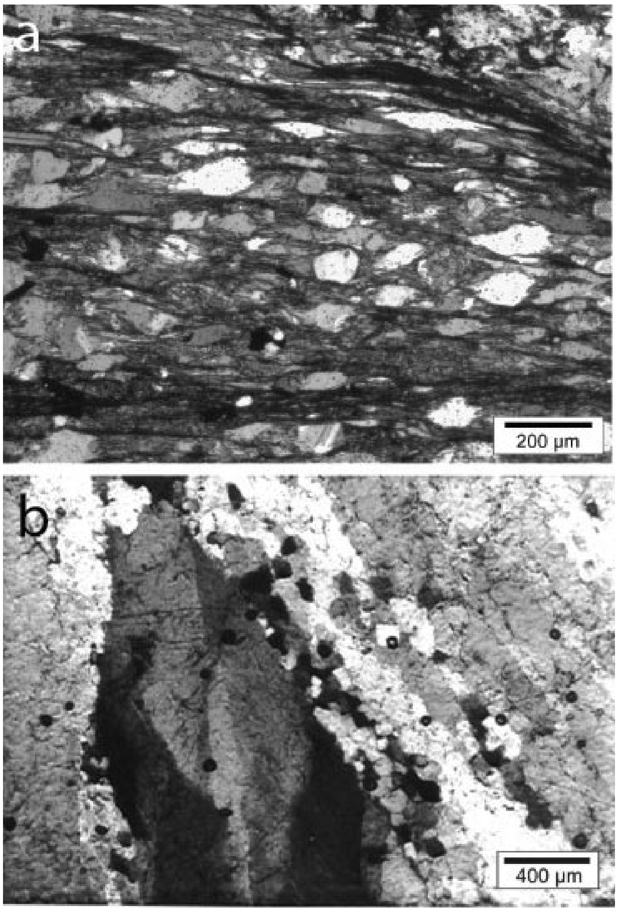


Figure 9: (a) Psammite matrix with microstructures characteristic for solution-precipitation creep. The original clastic shape of the grains can often be recognized, altered by preferential dissolution. (b) Microstructures of vein quartz characteristic for dislocation creep. Large elongate-blocky quartz grains (500µm to 1cm) show undulose extinction with the formation of subgrains. Dynamic recrystallization occurs by progressive rotation of subgrains and grain-boundary migration.

Although vein and mullion formation are considered as separate events, the cuspate-lobate morphology is entirely constrained by the presence of the veins. Without the presence of the veins, no cuspate-lobate geometry will occur at the interfaces of the psammite layers. This model for the cuspate-lobate morphology is based on the knowledge that vein formation occurred due to hydraulic fracturing and that this brittle process does not initiate a cuspate-lobate geometry of the segment interfaces between the veins such as the ductile process of boudinage would generate. Therefore it is suggested that interfaces between psammite and pelite were still straight after formation of the veins. The contribution of the veins to the formation of mullions is evidenced by microstructural observations of both the vein quartz and the siltstones/sandstones, and, moreover, corroborated by numerical work (Kenis *et al.*, 2004, 2005b). The microstructural observations indicate that solution-precipitation creep was the dominant deformation mechanism active during mullion formation in the sandstones (Fig. 9a). The absence of notable deformation by dislocation creep of quartz in the sandstones indicates that the differential stress remained too low for this deformation mechanism to be competitive with solution-precipitation creep (cf. Rutter, 1976; 1983; Schwarz & Stöckhert, 1996; Stöckhert *et al.*, 1999). In contrast, the vein quartz is dominantly deformed by dislocation creep (Fig. 9b), indicating higher flow stress in these parts and causing an inhomogeneous stress field in the different lithologies (quartz versus sandstone). The latter has led to the process of mullion formation at the onset of Variscan shortening. The formation of the cuspate-lobate geometry and thus the formation of mullions in the sandstone layers of the Ardenne-Eifel area can, therefore, be reduced to a matter of rheological

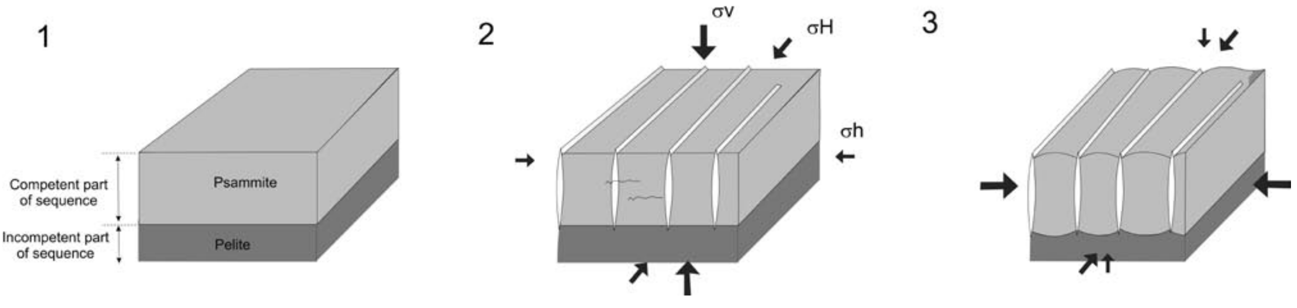


Figure 10: Schematic illustration of the development of the particular structures in the Ardenne-Eifel area. (1) Layers of psammite and pelite are deposited and compacted during burial in the subsiding Ardenne-Eifel basin. (2) Veins are formed in psammite layers due to hydraulic fracturing in a high fluid-pressure compartments at the final stages of burial. σV: maximum vertical stress; σH: maximum horizontal stress; σh: minimum horizontal stress. (3) Layer-parallel shortening resulted in the formation of cuspate-lobate geometries of the pelite-psammite interface, *i.e.* mullion formation, at the onset of Variscan shortening. Vein quartz is stronger than psammite, which is in turn stronger than pelite. The strength contrast between the vein quartz and psammite causes the formation of mullions in the layer interface of the psammite and pelite (Kenis *et al.*, 2004, 2005b). Size of arrows is indicative for the relative magnitude of the finite strain.

difference between the vein quartz and the sandstones during Variscan layer-parallel shortening. Without this difference no cuspate-lobate geometry, or mullions, would have formed. Fluid-inclusion analysis and microstructural analysis demonstrate that mullion formation occurred at relatively similar conditions as the formation of the veins (*i.e.* 350-400°C, Kenis, 2004; Kenis *et al.*, 2005a.). The formation of the mullions is, moreover, only dependent on the presence of the veins, and not at all dependent on the structural-geometrical disposition. Mullions across the Variscan folds all show the same morphology and orientation with respect to the bedding. It is thus clear that the development of the cuspate-lobate morphology predated the Variscan folding and cleavage development.

In summary our work demonstrated that the 'boudins' in the Ardenne-Eifel area can be considered as the result of two completely distinct events (Fig. 10): (1) the brittle emplacement of the veins due to hydraulic fracturing during the latest stages of the burial history in the Ardenne-Eifel basin and (2) the formation of mullions due to layer-parallel buckling of the psammite-pelite interface pinned by the pre-existing quartz veins at the onset of the Variscan shortening (Kenis *et al.*, 2002; 2004; Kenis, 2004). Although veining and mullion formation are clearly distinct, very similar P-T conditions are suggested (Kenis, 2004). This suggestion implies that the structures in the Ardenne-Eifel area are exemplary of the deformation behaviour in the brittle-ductile transition zone in the middle crust, *i.e.* at about 7 to 10 km depth. Taking into account the above, the Ardenne-Eifel area serves as a natural laboratory for the brittle-ductile transitional deformation behaviour in the middle crust. The cuspate-lobate morphology has, moreover, proven to be a palaeorheological gauge, indicative of a weak middle crust (Kenis *et al.*, 2004, 2005b).

4. Discussion

4.1. The boudinage question

The structures discussed in this paper served since nearly a century as type examples for the geological terms 'boudin' and 'boudinage'. In current literature boudinage refers to the disruption of layers, bodies or foliation planes within a rock mass in response to bulk extension along the enveloping surface (cf. Goscombe *et al.*, 2004). Boudinage, and subsequently the occurrence of boudins, occurs in all possible kinematic settings, both coaxial and non-coaxial, and in all possible geometrical settings (*e.g.* in folds, shear zones) (Goscombe & Passchier, 2003; Goscombe *et al.*, 2004). The occurrence of boudins will, however, always be indicative of a finite extension. While layer-parallel extension of competent layers commonly results in pinch-and-swell structures and boudins, layer-parallel shortening of layers and interfaces gives rise to a wide range of structures, such as folds and mullions. The latter refers to particular cuspate-lobate folded interfaces between layers of different competency (van der Pluijm & Marshak 2004). Cuspate-lobate folding also occurs in a wide range of kinematic and geometrical settings (*e.g.* hinge zones of folded multilayer sequences). Their occurrence is, however, always indicative of finite shortening.

The 'boudins' in the Ardenne-Eifel area can be considered as the result of a polyphase history involving a brittle (*i.e.* formation of veins) and ductile (*i.e.* formation of cuspate-lobate geometry) deformation event. Already from structural observations, it is clear that the ductile deformation event corresponds to the formation of mullions at the onset of Variscan shortening. The crucial question to be asked, however, concerns the formation of the veins, *i.e.* the 'boudinage question'. When only based on structural observations, the vein development is, indeed, commonly linked to the process of boudinage (*e. g.* Jongmans & Cosgrove, 1993).

The answer to the 'boudinage question' has to be found in the conclusion that hydraulic fracturing was at the origin for vein formation rather than bulk extension (Kenis *et al.*, 2002; Kenis, 2004). It is a common misconception that the result of hydraulic fracturing in sediments and rocks is the formation of randomly oriented extension fractures and the generation of breccia structures (cf. Cosgrove, 1997). Perfectly aligned arrays of veins also result from this process. It should, therefore, be clearly stated that mechanical failure of the compentent siliciclastic layers in the Ardenne-Eifel area occurred due to the consequence of high fluid pressures. In this respect the Ardenne-Eifel area can be considered exposing a 340 million year old fracture reservoir (Hilgers *et al.* 2000; Sintubin *et al.*, in prep.). Hydraulic fracturing in this way causes local tensile failure. Veining is the result of very confined stress-induced diffusional redistribution processes of quartz from the psammite to the fracture. The latter implies that the process of boudinage, or bulk extension of the enveloping surface of the layer in which the veins develops, is not the initiator to the formation of veins. This initiator is represented by the high fluid pressures within the sandstone fluid-pressure compartments. On the one hand, the occurrence of tensile fractures formed at depths such as constrained for the veins in the Ardenne-Eifel area, requires small differential stresses, which are more likely in a stress regime where some tectonic loading is involved. This tectonic loading also gives a good explanation for the perfectly aligned orientation of the veins, implying, on the other hand, the existence of substantial differential stresses (Kenis *et al.*, 2002; Kenis, 2004). Although we assume a certain horizontal tectonic loading, we want to emphasize that the stress due to overburden is still the major principal stress (σ_1 vertical) during vein formation and that the veins are still formed during the burial stage in an overall extensional stress regime, following Anderson's theory of faulting (Anderson, 1951). The horizontal tectonic loading will eventually lead an inversion from a burial stress regime (σ_1 vertical) to a compressional regime (σ_1 horizontal). It is widely recognized that such an inversion in stress regime can play a key factor for triggering hydraulic fracturing (Sibson, 2000; Van Ruth *et al.*, 2003).

The suggestion that the veins of the structures are not formed due to the process of boudinage and that we are not facing 'shortened boudins' is, moreover, supported by the particular geometry of the structures. While boudins classically shows aspect ratios (H/W) smaller than 0.5 (Goscombe *et al.*, 2004; Price & Cosgrove, 1990), the aspect ratios observed for the structures in the Ardenne-

Eifel area typically range from 1 to 7, even up to 20, which is completely atypical (Figs 5d & 6). However, as recognized in literature, boudins can be reworked and modified to varying degrees by later deformation (*e.g.* Weiss, 1972; Ramsay & Huber, 1983; Malavielle & Lacassin, 1988; Hanmer & Passchier, 1991; Swanson, 1992; Carreras & Druguet, 1994; Goscombe *et al.*, 2004). The coaxial shortening of boudins can lead to curious oval shapes with extreme barreling effects when compared to normal boudins (cf. Goscombe *et al.*, 2004). In this context, many authors (*e.g.* Jongmans & Cosgrove 1993) explained the occurrence of the atypical aspect ratio of the structures in the Ardenne-Eifel area. However, keeping in mind typical aspect ratios for boudins (0.5), the atypical aspect ratios (1 to 7, up to 20) would imply tremendous degrees of shortening, for which no indications whatsoever can be found in the rock fabric. Moreover, another discriminating criteria of shortened boudins is the fact that the boudin height should be significantly greater than the relict undeformed inter-boudin vein material (cf. Goscombe *et al.*, 2004). Again, this does not apply to the structures in the Ardenne-Eifel area. Therefore, in addition with the evidence of high fluid pressures, the atypical aspect ratio of the structures in the Ardenne-Eifel area demonstrates that the formation process of the veins is not at all in compliance with the process of boudinage, *i.e.* the disruption of a layer due to bulk extension. Also the extensive modeling efforts (Kenis *et al.*, 2004, 2005b) corroborate this conclusion.

4.2. A matter of nomenclature

The structures in the Ardenne-Eifel area show a cuspate-lobate geometry of the bedding interface on both sides of the competent layers (sandstone/quartzite/psammite). This double-sided cuspate-lobate geometry is bounded by quartz veins and was at the origin of the specific names of the structures, namely ‘boudins’ (Lohest *et al.*, 1908). It is clear that at that stage the term ‘boudin’ and its associated formation process ‘boudinage’ were used as purely descriptive terms referring to the cuspate-lobate characteristic geometry of the layers rather than to the veins. Gradually both terms obtained a kinematic significance, nowadays used worldwide by the geological community to describe the disruption of layers within a rock mass in response to bulk extension along the enveloping surface (Goscombe *et al.*, 2004). However, structural and fluid-inclusion evidence show that this kinematic process can not explain the formation of the original ‘boudins’ in the Ardenne-Eifel area. The inconsistency between the kinematic definition of boudinage, as currently acknowledged by the geological community, and its type example remains problematic and needs a solution. Depending on ones point of view, this problem can be solved in two ways.

A first approach starts from the point of view that ‘boudins’ in the Ardenne-Eifel area remain the type example and that, therefore, a redefinition of the process of boudinage is required. The redefinition of boudinage needs to be done in such a way that it corresponds to the formation mechanism of the ‘boudins’ in its type locality, *i.e.* the Ardenne-Eifel area. Some considerations should, however, be made with respect to this approach. Firstly, the association of boudinage with bulk extension is generally accepted and very deeply entrenched in literature. A redefinition of the term boudinage would not only imply that the entire geological community should adapt itself but also that all previous publications on structures formed by the disruption of layers or bodies by bulk extension along the enclosing envelope should be reconsidered. Secondly, bulk extension of layers or bodies and associated disruption has been witnessed frequently in the field (*e.g.* Lacassin, 1988; Ghosh & Sengupta, 1999; Goscombe & Everard, 2000). If the term boudinage can no longer be used in this context, one should look for a new term explaining this mechanical process. Thirdly, if we want to go back to redefine boudinage according to the formation process of the structures in the Ardenne-Eifel area, we have to be aware that we are dealing with a polyphase deformation process, *i.e.* brittle veining followed by ductile shortening. This polyphase deformation process does not facilitate the redefinition of boudinage. And, last but not least, this approach becomes even more complex due to the occurrence of similar structures at Dedenborn, with veins and a cuspate-lobate geometry, but this time strictly limited to the bottom side of a fining-upward sequence and thus to one side of a competent layer. Structural analysis shows that these structures have identical formation mechanism as the ‘boudins’ in the Ardenne-Eifel area (Kenis, 2004). However, the Dedenborn structures serve as the textbook example for mullions. For that reason the outcrop of Dedenborn is a *‘naturdenkmal’*, a natural heritage site. If we want to keep boudinage linked to the ‘boudins’ in the Ardenne-Eifel area and redefine boudinage in such a way that it corresponds to the formation mechanism of the structures in the Ardenne-Eifel area, boudinage will also correspond to the formation mechanism of the Dedenborn structures. The latter infers that we have to omit the term mullion, also deeply entrenched in literature. Since this approach is a rather fundamentalist approach and is largely based on a ‘who was first’ philosophy, the omission of the term mullion will be a logical consequence, since the term mullions was only introduced in the late 50’s. All previous publications on mullions will have to be reconsidered too. As clearly evidenced from the above this approach is completely unrealistic and even a bit absurd. However, this discussion also reveals the need for clear agreements when considering structural terminology.

A second approach starts from the kinematic definitions of mullion formation and boudinage as currently acknowledged by the geological community and suggests to rename the structures in the Ardenne-Eifel area accordingly. According to these kinematic definitions, the cuspate-lobate morphology of the structures in the Ardenne-Eifel area, is exemplary for the process of mullion formation, which corresponds to the formation of cuspate-lobate folded interfaces due to layer-parallel shortening. These mullions formed due to the presence of the veins that originated by the process of hydraulic fracturing. Therefore, we propose to rename the structures with a double-sided cuspate-lobate geometry, formerly termed ‘boudins’, double-sided mullions, or mullions that form at both interfaces pinned by quartz veins. Structures that only show a cuspate-lobate geometry on one side of the competent layer, are termed mullions, such as in Dedenborn. The arguments in favor of mullions is strengthened by a numerical modeling approach (Kenis *et al.*, 2004). This approach even lead to the use of the particular structures in the Ardenne-Eifel area as a gauge to determine the palaeorheology of the deforming middle crust (Kenis *et al.*, 2004). Recently, the application of the numerical modeling approach has been extended to bone-shaped structures (Kenis *et al.*, 2006).

5. Closing remarks

Notwithstanding the fact that the kinematics giving rise to the exceptional structures in the Ardenne-Eifel area has nothing to do with the process of boudinage, the Belgian geological community should definitively not forget the Bastogne area as the original site where the terms 'boudin' and 'boudinage' were first used in a geological context. It is clear that without the structures in the Ardenne-Eifel area these terms would not have existed. It is, therefore, our opinion that the Belgian geological community needs to strive for the creation of a heritage site at Bastogne for those particular and historically significant structures. This site would preferably be the Carrière Collignon (Fig. 2). In addition to the specific structures, the veins at Bastogne also contain a specific type of dark mica, named Bastonite (Klement, 1888), only strengthening our belief of a geological heritage site at Bastogne. Moreover, as shown by our research, the exceptional structures and their occurrence in the Ardenne-Eifel area needs extensive national and international scientific exposure (literature, conferences, field trips, …) to promote the Ardenne-Eifel area as a natural laboratory for the study of the brittle-ductile deformation behaviour in the middle crust.

6. Acknowledgements

This work frames in the research project KAN 1.5.128.05 *'The structural architecture of a slate belt'* of the F.W.O.-Vlaanderen. Manuel Sintubin is Research Associate of the Onderzoeksfonds – K.U.Leuven. This work has benefited from intensive discussions with Janos L. Urai (RWTH Aachen) and Philippe Muchez (K.U.Leuven). We would also like to thank Olivier Bolle and Jacques Touret for their helpful and constructive reviews.

References

ANDERSON, E.M., 1951. *The Dynamics of Faulting*. Oliver and Boyd, Edinburgh.

BEUGNIES, A., 1986. Le métamorphisme de l'aire anticlinale de l'Ardenne. *Hercynica*, 2(1): 17-33.

BOS, A., DE HAAS, G.J.L.M., VONCKEN, J.H.L., VAN DER EERDEN, A.M.J. & JANSEN, J.B.H., 1987. Hydrothermal synthesis of ammonium-phlogopite. *Geologie en Mijnbouw*, 66: 251-258.

BRÜHL, H., 1969. Boudinage in den Ardennen und in der Nordeifel als Ergebnis der inneren Deformation. *Geologische Mitteilungen*, 8: 263-308.

CARRERAS, J. & DRUGUET, E., 1994. Structural zonation as a result of inhomogeneous non-coaxial deformation and its control on syntectonic intrusions: an example from the Cap de Creus area, eastern-Pyrenees. *Journal of Structural Geology*, 16: 1525-1534.

CLOOS, E., 1947. Boudinage. *Transactions, American Geophysical Union*, 28: 628-632.

CORIN, F., 1932. A propos du boudinage en ardenne. *Bulletin de la Société belge de Géologie*, 42: 101-117.

COSGROVE, J.W. ,1997. Hydraulic fractures and their implications regarding the state of stress in a sedimentary sequence during burial. *In*: Sengupta, S. (ed.) *Evolution of Geological Structures in Micro- to Macro-scales*. Chapman & Hall, London, 11-25.

DARIMONT, A., BURKE, E.A.J. & TOURET, J.L.R., 1988. Nitrogen-rich metamorphic fluids in devonian metasediments from Bastogne, Belgium. *Bulletin de Minéralogie*, 111: 321-330.

DE SITTER, L.U., 1958. Boudins and parasitic folds in relation to cleavage and folding. *Geologie en Mijnbouw*, 20: 277-286.

DUMONT, A., 1848. Mémoire sur les terrains ardennais et rhénan de l'Ardenne, du Rhin, du Brabant et du Condros. II: Terrain Rhénan. *Mémoire de l'Académie royal de Belgique*, 22: 1-451.

ECKELMANS, V., 1961. *Contribution à l'Etude du Métamorphisme et du Boudinage dans les roches du Siegenien inférieur de Bastogne*. Unpublished Licence thesis, Université de Liège.

FIELITZ, W. & MANSY, J.-L. 1999. Pre- and synorogenic burial metamorphism in the Ardenne and neighbouring areas (Rhenohercynian zone, central European Variscides). *Tectonophysics,* 309: 227-256.

FOURMARIER, P., 1956. A propos d'un article sur le "boudinage". *Annales de la Société géologique de Belgique*, 79: B135-140.

GHOSH, S.K., 1993. *Structural Geology: fundamentals and modern developments*. Pergamon.

GHOSH, S.K. & SENGUPTA, S., 1999. Boudinage and composite boudinage in superimposed deformations and syntectonic migmatization. *Journal of Structural Geology*, 21: 97–110.

GOSCOMBE, B. & EVERARD, J.L., 2000. Tectonic evolution of Macquarie Island: extensional structures and block rotations in oceanic crust. *Journal of Structural Geology*, 23: 639–673.

GOSCOMBE, B. & PASSCHIER, C.W., 2003. Asymmetric boudins as shear sense indicators-an assessment from field data. *Journal of Structural Geology*, 23: 639-673.

GOSCOMBE, B.D., PASSCHIER, C.W. & HAND, M., 2004. Boudinage classification: end-member boudin types and modified boudin structures. *Journal of Structural Geology*, 26: 739-763.

GOSSELET, J., 1888. L'ardenne. *Mémoires Explicatives de la Carte Géologique de France*.

HANMER, S. & PASSCHIER, C., 1991. Shear-sense indicators: a review. *Geological Survey of Canada. Paper*, 90-17.

HARKER, A., 1889. On the local thickening of dikes and beds by folding. *Geological Magazine New Series*, 6: 69-70.

HILGERS, C., BÜKER, C., URAI, J. L., LITTKE, R., POST, A., VAN DER ZEE, W. & KRAUS, J. 2000. Field study of an exhumed lower Devonian high pressure reservoir. *Geophysical Research Abstracts* 2(SE34): 47.

HOLMQUIST, P.J., 1931. On the relations of the “boudinage-structure”. *Geol. Fören. Förhandl*, 53: 193-208.

JONGMANS, D. & COSGROVE, J. W., 1993. Observations structurales dans la région de Bastogne. *Annales de la Société géologique de Belgique,* 116: 129-136.

KENIS, I., 2004. Brittle-Ductile Deformation behaviour in the middle crust as exemplified by mullions (former “boudins”) in the High Ardenne Slate Belt. *Aardkundige Mededelingen*, 14.

KENIS, I., MUCHEZ, PH., VERHAERT, G., BOYCE, A. & SINTUBIN, M., 2005a. Fluid evolution during burial and Variscan deformation in the Lower Devonian rocks of the High-Ardenne slate belt (Belgium). *Contributions to Mineralogy and Petrology*, 150: 102-118.

KENIS, I., SINTUBIN, M., MUCHEZ, PH. & BURKE, E.A.J., 2002. The “boudinage” question in the High-Ardenne slate belt (Belgium): a combined structural and fluid inclusion approach. *Tectonophysics*, 348: 93-110.

KENIS, I., URAI, J.L. & SINTUBIN, M., 2006. The development of bone-shaped structures in initially segmented layers during layer-parallel extension: numerical modelling and parameter sensitivity analysis. *Journal of Structural Geology*, 28: 1183-1192.

KENIS, I., URAI, J.L., VAN DER ZEE, W., HILGERS, C. & SINTUBIN, M., 2005b. Rheology of fine grained siliciclastic rocks deforming in the middle crust. *Earth and Planetary Science Letters*, 233: 351-360.

KENIS, I., URAI, J.L., VAN DER ZEE, W. & SINTUBIN, M. , 2004. Mullions in the High-Ardenne Slate Belt (Belgium). Numerical model and Parameter Sensitivity Analysis. *Journal of Structural Geology*, 26: 1677-1692.

KLEMENT, C., 1888. Analyse chimique de quelques minéraux et roches de Belgique et de l’Ardenne française. *Bulletin de Musée royale de l’Histoire naturelle de Belgique*, 5: 159.

LACASSIN, R., 1988. Large-scale foliation boudinage in gneisses. *Journal of Structural Geology*, 10: 643–647.

LAMBERT, A. & BELLIÈRE, J., 1976. Caractères structuraux de l’éodévonien aux environs de Bastogne. *Annales de la Société géologique de Belgique*, 99: 283-297.

LOHEST, M., STAINIER, X. & FOURMARIER, P., 1908. Compte rendu de la session extraordinaire de la Société géologique de Belgique, tenue à Eupen et Bastogne les 29, 30 et 31 août et le 1,2 et 3 septembre 1908. *Annales de la Société géologique de Belgique*, 36: 275-282.

MALAVIELLE, J. & LACASSIN, R., 1988. ‘Bone-shaped’ boudins in progressive shearing. *Journal of Structural Geology*, 10: 335-345.

MUKHOPADHYAY, D., 1972. A note on the mullion structures from the Ardennes and North Eifel. *Geologische Rundschau*, 61: 1037-1049.

ONCKEN, O., VON WINTERFELD, C. & DITTMAR, U., 1999. Accretion of a rifted passive margin: The Late Paleozoic Rhenohercynian fold and thrust belt (Middle European Variscides). *Tectonics*, 18: 75-91.

PILGER, A. & SCHMIDT, W., 1957. Definition des begriffes ‚mullion-struktur‘ (mullion structure). *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen*, 1: 24-28.

PRICE, N.J. & COSGROVE, J.W., 1990. *Analysis of geological structures*. Cambridge University Press, Cambridge.

QUIRKE, T.T., 1923. Boudinage, an unusual structural phenomenon. *Geological Society of America Bulletin*, 34: 649-660.

RAMBERG, H., 1955. Natural and experimental boudinage and pinch-and-swell structures. *Journal of Geology*, 63: 512-526.

RAMSAY, A.C., 1866. The Geology of North Wales. *Memoirs of the Geological Survey of Great Britain*, 3.

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.

RONDEEL, H.E. & VOERMANS, F.M., 1975. Data pertinent on the phenomenon of boudinage at Bastogne in the Ardennes. *Geologische Rundschau*, 64: 807-818.

RUTTER, E.H., 1976. The kinetics of rock deformation by pressure solution. *Philosophical Transactions of the Royal Society A*, 283: 203-219.

RUTTER, E.H., 1983. Pressure solution in nature, theory and experiment. *Journal of the Geological Society of London*, 140: 725-740.

SCHWARZ, S. & STÖCKHERT, B., 1996. Pressure solution in siliciclastic HP-LT metamorphic rocks – constraints on the state of stress in deep levels of accretionary complexes. *Tectonophysics*, 255: 203-209.

SIBSON, R.H., 2000. Tectonic controls on maximum sustainable overpressure: fluid redistribution from stress transitions. *Journal of Geochemical Exploration*, 69-70: 471-475.

SINTUBIN, M., KENIS, I. & MUCHEZ, P., in preparation. The Lower Devonian in the Ardenne-Eifel area (Belgium, Germany). An exposed example of a 340 million year old fractured reservoir. *Geologica Belgica*.

SINTUBIN, M., KENIS, I., SCHROYEN, K., MUCHEZ, P. & BURKE, E.A., 2000. „Boudinage“ in the High-Ardenne slate belt (Belgium), reconsidered from the perspective of the „interboudin“ veins. *Journal of Geochemical Exploration* 69-70: 511-516.

SPAETH, G., 1986. Boudins and Mullions in devonischen Schichtfolgen der Nordeifel und Ardennen - Erscheinungsbild, Entstehung und Umformung. *Nachrichten Deutsche Geologische Gesellschaft*, 35: 74-75.

STAINIER, X., 1907. Sur le mode de gisement et l'origine des roches métamorphiques de la région de Bastogne (Belgique). *Mémoire de l'Académie royale de Belgique*, 4.

STAINIER, X., 1930. Le métamorphisme des régions de Bastogne et de Vielsalm. *Bulletin de la Société belge de Géologie*, 39: 112-156.

STÖCKHERT, B., WACHMANN, M., KÜSTER, M. & BIMMERMAN, S., 1999. Low effective viscosity during high-pressure metamorphism due to dissolution precipitation creep: the record of HP-LT metamorphic carbonates and siliciclastic rocks from Crete. *Tectonophysics*, 303: 299-319.

SWANSON, M.T., 1992. Late Acadian-Alleghenian transpressional deformation: evidence from asymmetric boudinage in the Casco Bay area, coastal Maine. *Journal of Structural Geology*, 14: 323-341.

THEYE, T. & FRANSOLET, A.-M., 1993. Amphibolitfazielle Metamorphite im Rhenoherzynikum der Ardennen. *Berichte der Deutschen Mineralogische Gesellschaft, Beiheft zum European Journal of Mineralogy*, 5: 255.

TWISS, R.J. & MOORES, E.M., 1992. *Structural Geology*. W. H. Freeman and Company, New York.

URAI, J.L., SPAETH, G., VAN DER ZEE, W. & HILGERS, C., 2001. Evolution of mullion (formerly boudin) structures in the Variscan of the Ardennes and Eifel. *Journal of the Virtual Explorer*, 3: 1-15.

VAN DER PLUIJM, B. A. & MARSHAK, S., 2004. *Earth Structure. An introduction to structural geology and tectonics*. W.W. Norton & Company, New York.

VAN RUTH, P., HILLIS, R. R., TINGATE, P. & SWARBRICK, R. E., 2003. The origin of overpressure in 'old' sedimentary basins: an example from the Cooper Basin, Australia. *Geofluids*, 3: 125-131.

VERHAERT, G., 2001. *Kwartsaders en dubbelzijdige mullions in de Lochkoviaanmetasedimenten in de Hoge-Ardennenleisteengordel (groeve La Flèche, Bertrix, België)*. Unpublished Master thesis, Katholieke Universiteit Leuven.

WALLS, R., 1937. A new record of boudinage-structure from Scotland. *Geological Magazine*, 74: 325-332.

WEGMANN, C.E., 1932. Note sur le boudinage. *Bulletin de la Société géologique de France*, 52: 477-492.

WEISS, L.E., 1972. *The minor structures of deformed rocks*. Springer Verlag, Berlin.

WILSON, G., 1961. Boudinage. *Annales de la Société géologique de Belgique*, 84: 423-548.

(Manuscript received 03.05.2005, accepted 26.07.2006)