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"Boudins" in the High-Ardenne Slate Belt (Belgium): the state of the art

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ABSTRACT

The terms "boudin"♣ and "boudinage"⋆ were first introduced to describe particular geometric features associated with quartz veins in competent sandstone layers in the High-Ardenne Slate Belt (Belgium). A combined structural and fluid-inclusion study allows proposing a polyphase history for the development of the veins and associated structures. In this regard, microthermometry of primary fluid inclusions in the quartz veins suggests that hydraulic fracturing was responsible for the formation of the veins. Veining was followed by layer-parallel shortening which resulted in the development of mullions at both interfaces of the competent layer, pinned by pre-existing veins ("double-sided mullion"). Subsequently, these polyphase structures behaved passively during the Variscan deformation. Numeric modelling of the development of the mullions allows constraining the in-situ rheology of the sandstone layers under low-grade metamorphic conditions and imply very low value for the stress exponent of the power law.

KEYWORDS

Boudin, hydraulic fracturing, Lower Devonian, mullion, rheology

Introduction

The terms "boudins" and "boudinage" were first used to describe particular structures in the High-Ardenne Slate Belt which resemble to a series of sausages aligned side by side and separated by quartz veins (Lohest *et al*., 1908). Since boudinage refers to the process of layer-parallel extension of rather competent layers embedded in a more incompetent matrix it always remained a matter of controversy whether or not the latter kinematic definition applies to the "boudins" in the High-Ardenne Slate Belt. Even at the time of the first observations, it was recognised that both compressional (cleavage, curved nature of sandstones) and extensional elements (quartz veins) are present in association with the "boudin" structures. This conflicting coexistence basically led to two end-member models for the formation of the "boudin" structures. The first and most accepted model involves a layer-parallel extension during burial predating a layer-parallel compression during the Variscan orogeny (cf. Jongmans & Cosgrove, 1993). The second model calls upon an elastic recovery post-dating the compressional episode to explain the formation of the veins (cf. Quirke, 1932). Recently a new and more representative kinematic model for the development of the veins and associated structures has been proposed by Kenis *et al.* 2002 and Urai *et al*. 2001. The aim of this paper is to summarise the state of the art with respect to the particular structures in the High-Ardenne Slate Belt.

Geological setting

The Variscan Allochton can be subdivided into the Dinant Synclinorium, the Ardenne Anticlinorium and the Neufchâteau-Eifel Syncline (Fig. 1). The latter two zones consist of thick, predominantly pelitic, metasedimentary sequences of Early Devonian age, forming the High-Ardenne Slate Belt.

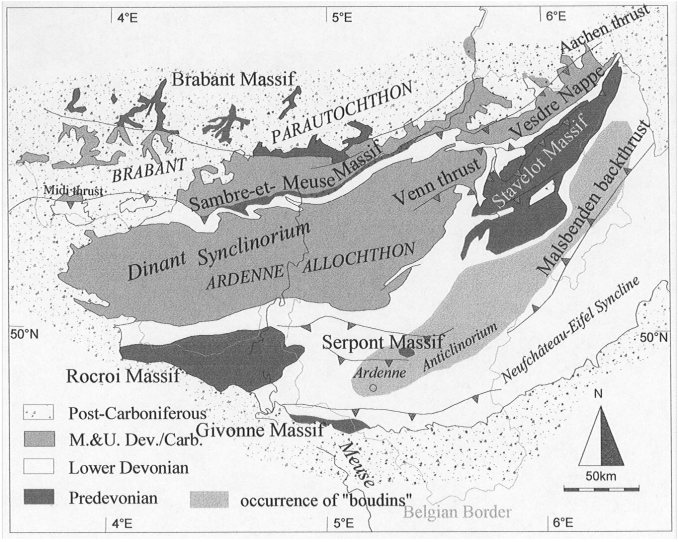


Fig. 1. Occurrence of the studied "boudin" structures.

The low-grade greenschist metamorphism present in the High-Ardenne Slate Belt is generally believed to be pre- to early synkinematic with respect to the prograding Variscan

♣ "Boudin", "boudinage", "interboudin": The terms between quotes apply to the particular structures in the High-Ardenne Slate Belt; the terms without quotes apply to the process of boudinage.

deformation and is considered to have a burial origin (Fielitz & Mansy, 1999; Schroyen & Muchez, 2000). The Variscan deformation is primarily characterised by a pervasive slaty cleavage. The occurrence of the particular "boudin" structures is limited to the low-grade metamorphic area within the southern limb of the Ardennen Anticlinorium. Stratigraphically the "boudins" occur in the Upper Lochkovian to Upper Pragian metasedimentary series.

Structural analysis

Although a wide variety in morphology can be observed, all "boudin" structures can be defined by common geometric characteristics (Kenis *et al*., 2002; see also Fig. 5: 2). The veins are lensoid in shape and are mostly limited to the more competent parts of the sequence. They are oriented at high angles to the stratification. The veins predominantly consist of quartz with accessory chlorite, muscovite, bastonite (NH_4-rich dark mica) and albite. The veins are crosscut by bedding-parallel dissolution seams indicating that they formed before or during maximum burial. At the extremity of the competent parts the internal layering is buckled. This buckling is due to layer-parallel shortening during the Variscan compressional deformation posterior to veining.
The aspect ratio of the "boudins" in the Ardennes is commonly larger than 1 and up to 7, while the typical aspect ratio (height: width) of boudins is less than 0.5 (cf. Price & Cosgrove, 1990). To achieve such change in aspect ratio from 0.5 up to 7, a strong internal shortening up to 73% would be required. Considering a maximum shortening of 50% accommodated by slaty-cleavage development in the more pelitic parts of the sequence during the Variscan orogeny, it is suggested that the "boudins" had already atypical aspect ratios before shortening. This is not in agreement with the original definition of "boudinage".

Fluid inclusions

Microthermometric and Raman analyses have been performed on primary fluid inclusions in the "interboudin" veins from several localities to constrain P-T conditions at the time of veining and to determine the chemical composition of the palaeofluids. In growth zones, two major types of primary fluid inclusions can be observed (Kenis *et al.*, 2002).
The first type are gaseous CO_2-N_2 inclusions and the second type of fluid inclusions consists of two- and three-phase mixed aqueous/gaseous inclusions (H_2O-CO_2-NaCl). These gaseous and aqueous CO_2- and/or N_2-bearing primary fluid inclusions occur abundantly in the metamorphic zone of the High-Ardenne Slate Belt (Darimont *et al.*, 1988; Schroyen & Muchez, 2000). The relationship between pressure, temperature and bulk density has been calculated with the program FLINCOR (Brown, 1989).
Taking into account a temperature of 400°C at the time of veining constrained by chlorite geothermometry, maximum and minimum pressures can be calculated for both major fluid types (Fig. 2).
Since fluid pressures were very high (e.g. up to 260MPa; Kenis *et al.*, 2002) and fluctuated at the time of veining, hydraulic fracturing is likely responsible for vein formation (Fig. 2; cf. Boullier & Robert, 1992). The high fluid pressures, compared to maximal pressures reached during metamorphism (~250MPa) indicate that maximum fluid pressures were probably near-lithostatic.

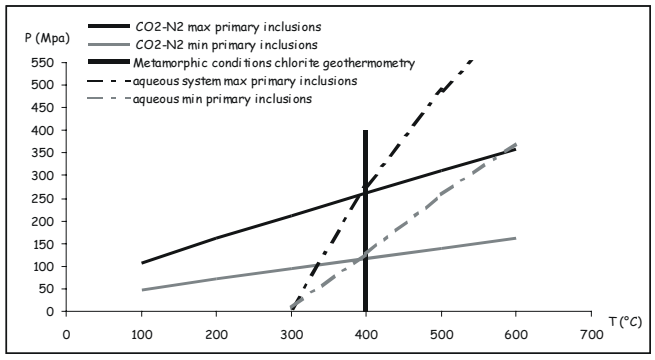


Fig. 2. Isochores of syngenetic gaseous and aqueous primary fluid inclusions of the "interboudin" vein quartz showing that fluid pressure at the time of veining fluctuated between 260 and 100 MPa.

The use of Mohr-circle and geometric analysis shows that the veins in the High-Ardenne Slate Belt formed under the influence of compressive horizontal forces (! σ_H (horizontal stress) still less then σ_V (vertical stress)) and high fluid pressures (hydraulic fracturing) rather then under the influence of crustal extension (boudinage) (Kenis *et al*., 2002; Fig. 3).

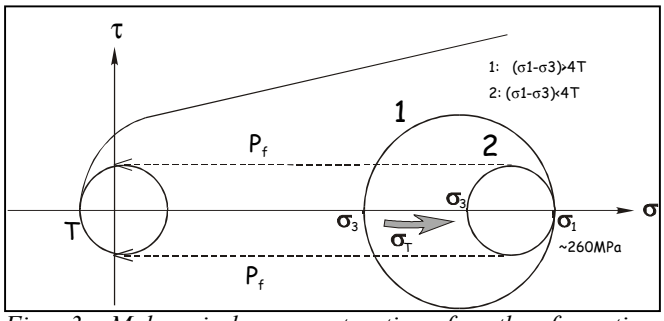


Fig. 3. Mohr circle reconstruction for the formation conditions of the veins (σ_1 is the maximal principal stress, σ_3 the minimal principal stress, Pf the fluid pressure; after Kenis et al., 2002) showing the need of an additional tectonic compressional stress to reduce the differential stress and obtain conditions for extensional cracking ($\sigma 1$-$\sigma 3 < 4T$ where T is the tensile strength). The presence of high fluid pressure is required to shift the Mohr-circle into the domain of tensile cracking.

Since the "interboudin" veins were formed before the buckling of the competent layers, they most probably acted as physical boundaries for this internal buckling. Therefore it is suggested that the "boudins" observed in the High-Ardenne Slate Belt, are the result of layer-parallel shortening of opposite interfaces pinned by pre-existing veins and should better be redefined as "double-sided mullions" (Kenis *et al*., 2002; Fig. 5).

Numerical modelling of rheological characteristics of the sandstones

As discussed above, the buckling of the sandstone layers between the veins is due to layer-parallel shortening. This compressional deformation took place at depths below a few kilometers where the behaviour of rocks can be defined by power law creep, relating strain rate to $(\sigma 1-\sigma 3)^n$ (n = stress exponent). Based on a simplified analytical model, Urai *et al.* (2001) suggested that the shape of the mullions in cross section is a strong function of the power law exponent n and thus a potential gauge for palaeorheology. Therefore, profiles of the buckled side of the competent sandstone layers were calculated with the non-linear finite element software Abaqus. The results of the numerical modelling confirmed that the stress exponent of the power law is indeed the most important parameter in determining the shape of the mullions. For materials which have a stress exponent = 1 the shape of the mullions is more or less parabolic and for increasing values of n, the shape becomes more angular to the side of the veins (Fig. 4).

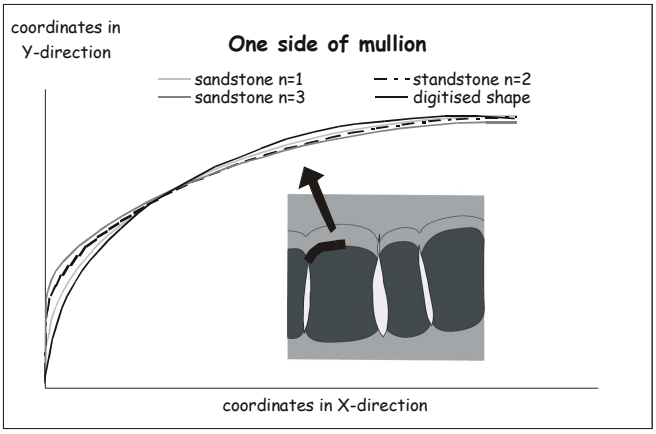


Fig. 4. Effect of stress exponent on the shape of the mullion.

Next to the stress exponent the shape of the mullions also shows a dependence on the original spacing between the veins, the thickness of the sandstone segments and the stresses in both the pelitic material and sandstones. The numeric model was therefore calibrated using strain-rates, shortening- and shape data of real boudins and average differential stresses of ~25 MPa calculated from the recrystallized grain size data of the vein quartz. The output of Abaqus shows profiles which can be compared with digitised profiles of real mullions. This comparison allows determining the in-situ rheology of the sandstones under low-grade greenschist metamorphic conditions and suggests a very low stress exponent of ~1 to develop the specific shape of the "double-sided" mullions (Fig. 4).
Although macroscopic rheological equation for silicates is usually of the power-law type, instances of Newtonian behaviour ($n \approx 1$) has been suggested in our samples by the microstructures in the sandstone indicative for pressure solution. Low stress exponent values (between 1 and 2) especially occur near the lower limit of the above stress interval and for very small grain sizes (Ranalli, 1995). Because deformation proceeds very slowly at these low stresses, it is difficult to investigate experimentally and therefore has been ignored by many researchers. Numerical analysis is capable of modelling deformation at very low strain-rates and can go beyond the limits of experiments. Therefore, it is a very good tool to perform a palaeorheological analyses of the mullions.

Discussion and conclusion

In the High-Ardenne Slate Belt, structures formerly described as "boudins" (Lohest *et al*., 1908) are redefined as "double-sided mullions" (Kenis *et al*., 2002; Urai *et al*., 2001). The development of the "double-sided mullions" resulted from a complex polyphase history (Fig. 5).

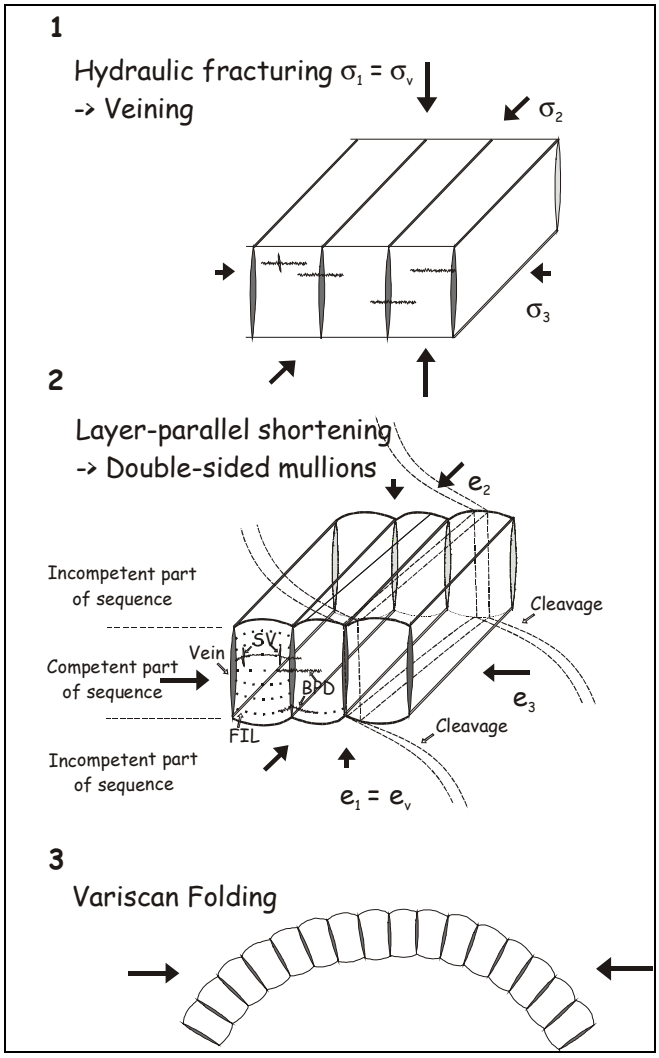


Fig. 5. Polyphase history of double-sided mullions (σ_1 is the maximal principal stress, σ_3 the minimal principal stress, σ_2 the intermediary stress; σ_v is the vertical stress, e1, e2, e3 are respectively maximum, intermediate and minimum stretch directions) (1) Hydraulic fracturing causing veining; (2) Layer-parallel shortening causing buckling and structural characteristics of the "boudin" structures. SV: smaller veins; FIL: folded internal layering; BPD: bedding-parallel dissolution seams; (3) Variscan folding and cleavage development (after Kenis et al., 2002).

Fluid inclusions demonstrated that the motor for vein development was hydraulic fracturing in an already compressional setting rather than layer-parallel extension by

the process of boudinage (Kenis *et al.*, 2002). In this respect, the surrounding pelitic material was an efficient barrier to fluid flow so that it could retain very large potentiometric pressure heads in the sandstones. Regions of a sedimentary basin that are isolated from their surroundings by an envelope of low-permeability rock and have an interior of sufficiently high permeability to maintain a consistent internal static fluid pressure gradient are named fluid (or pressure) compartments (Ortoleva, 1994). Such fluid compartments and associated abnormal high pressures are shown to be a world-wide phenomenon and are important in oil industry (Ortoleva, 1994). Therefore the knowledge of the "double-sided mullions" which are fossil high-pressure fluid compartments, can be very interesting in understanding basin flow regimes, which control diagenesis, hydrocarbon migration and the process of hydraulic fracturing.

The vein development of the structures was followed by a layer-parallel shortening resulting in the buckling of both the interfaces of the competent layer. The rheological characteristics of the competent layer during buckling can be determined by means of numerical modelling and indicate very low power law stress exponent values corresponding to Newtonian behaviour of the sandstones.

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