INSTITUT ROYAL DES SCIENCES NATURELLES DE BELGIQUE

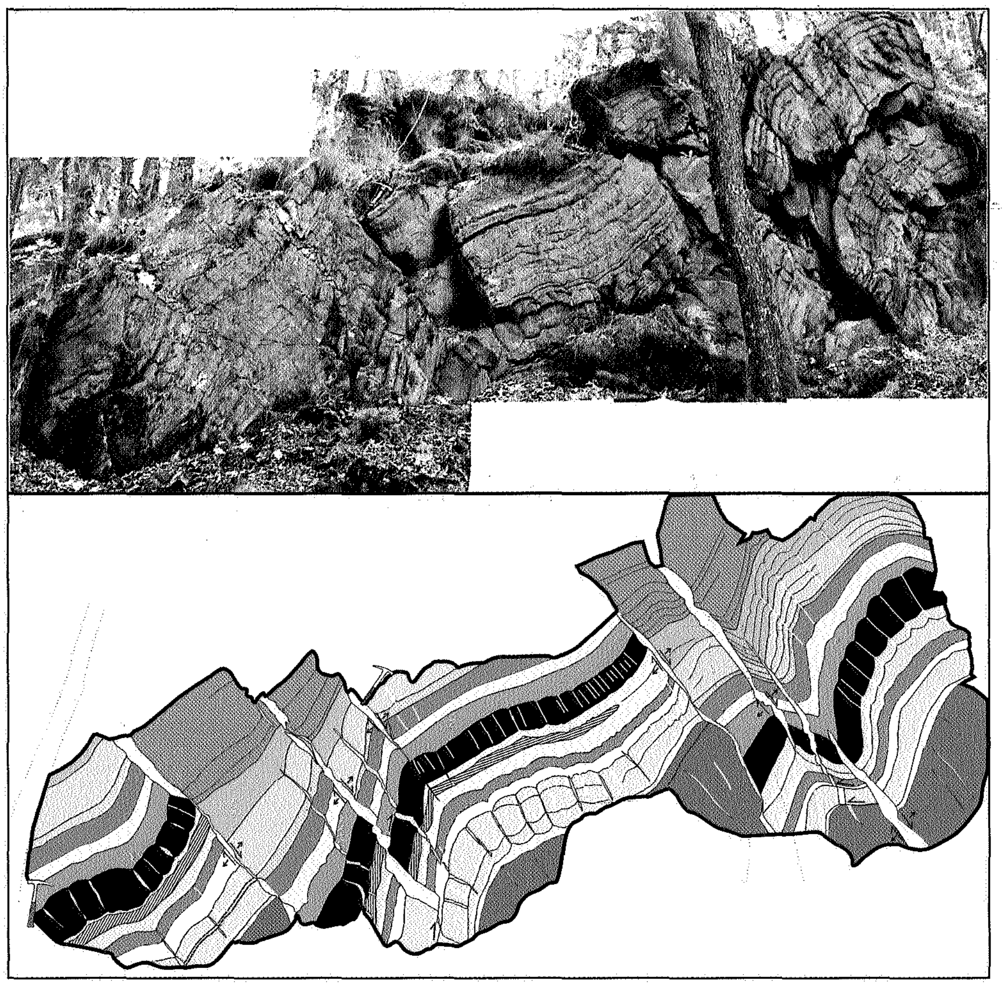
KONINKLIJK BELGISCH INSTITUUT VOOR NATUURWETENSCHAPPEN

ROYAL BELGIAN INSTITUTE OF NATURAL SCIENCES

MEMOIRS OF THE GEOLOGICAL SURVEY OF BELGIUM
N. 53 - 2006

Structural analysis of narrow reworked boudins and influence of sedimentary successions during a two-stage deformation sequence (Ardenne-Eifel region, Belgium-Germany)

Yves VANBRABANT & Léon DEJONGHE



SERVICE GEOLOGIQUE DE BELGIQUE
BELGISCHE GEOLOGISCHE DIENST

Geological Survey of Belgium

Rue Jenner 13 - 1000 Bruxelles
Jennerstraat 13 - 1000 Brussel

ISSN 0408-9510

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(38 figures)

Cover illustration: (Above) Picture of the "Ferme du Grand Vivier" section near Flamierge and Givry (Ardenne Anticlinorium). The section exhibits narrow reworked boudins and hybrid shear fractures. (Below) Stratigraphic interpretation of the section.

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STRUCTURAL ANALYSIS OF NARROW REWORKED BOUDINS AND INFLUENCE OF SEDIMENTARY SUCCESSIONS DURING A TWO-STAGE DEFORMATION SEQUENCE (ARDENNE-EIFEL REGION, BELGIUM-GERMANY)

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(38 figures)

ABSTRACT. The famous 'boudins' from the Ardenne and Eifel regions (Belgium, Germany) occur as regularly-spaced segments of Lower Devonian (meta-)sandstones separated by lens-shaped quartz veins. The whole is embedded in thick siltstone or shale horizons. Structural evidence throughout the Ardenne-Eifel region reveals a two-stage deformation sequence composed of a layer-parallel extension followed by a layer-parallel shortening. The latter results from the development of the Rhenohercynian fold-and-thrust belt during the Variscan orogeny (Carboniferous). During that period, the boudins inherited from the layer-parallel extension were strongly reworked and acquired their current extreme convex geometry, in parallel to a reduction of the aspect ratio (width/height) to ~0.5. We consider therefore that these structures should be named as 'narrow reworked boudins'. The prefix 'narrow' indicates that before the reworking period the boudin aspect ratio was already small (~ 1.0). In this memoir, evidences of unquestionable narrow boudins are illustrated. Their formation results from the opening of a joint set at a fracture saturation stage, in which any additional layer-parallel extension is accommodated by the opening of the existing joints instead of the development of new joints. We present a new model including all these aspects for the formation and reworking of boudins as those from the Ardenne-Eifel region.

The Lower Devonian formations from the Ardenne-Eifel region include not only thick siltstone or shale horizons with isolated sandstone layers that were boudinaged and then reworked, but also sandstone-dominant to massive sandstone units, where fine materials represent only cm- to mm-interlayers. Their deformation patterns differ from those richer in fine materials. During the period of layer-parallel extension, both sandstone-dominant and massive sandstone successions were affected by the growth of complex arrays of single- and multi-layered quartz veins. Single-layered veins correspond to pure open-mode fractures, while multi-layered veins frequently represent a hybrid-shear fracturation mode. During the layer-parallel shortening period, small-scale folds were developed in the sandstone-dominant units in close association with the occurrence of multi-layered quartz veins. By contrast, the quartz veins in massive sandstone units seem to have no influence during the layer-parallel shortening period. In this case, the shortening was accommodated by common structures, such as large-scale folds and reverse faulting (ramp).

KEYWORDS: associated structures, boudinage, hybrid shear fractures, layer-parallel extension, layer-parallel shortening, Lower Devonian, mullion.

1. Introduction

The term "boudin structures" was for the first time introduced in the Collignon Quarry (Bastogne, Belgium) by Lohest et al. about a century ago (1908). At that time, the term "boudin" described in the region of Bastogne a segment of a (meta-)sandstone layer with a barrel-shaped geometry. The individual boudins are separated from each other by lens shaped quartz veins (Fig. 1.1). Lohest et al.'s observations were carried out within the Lower Devonian meta-sedimentary rocks (mainly slate, siltstone and sandstone successions) belonging to the Ardenne Anticlinorium. This domain represents a tectonic province of the Rhenohercynian fold-and-thrust belt deformed during the Variscan orogeny in the Carboniferous. Similar observations to those made by Lohest et al. were conducted in numerous other localities throughout the Ardenne Anticlinorium as well as on the northern side of the Neufchâteau-Eifel Synclinorium (Fig. 1.2). This region will be referred in this memoir as the "**Ardenne-Eifel region**".

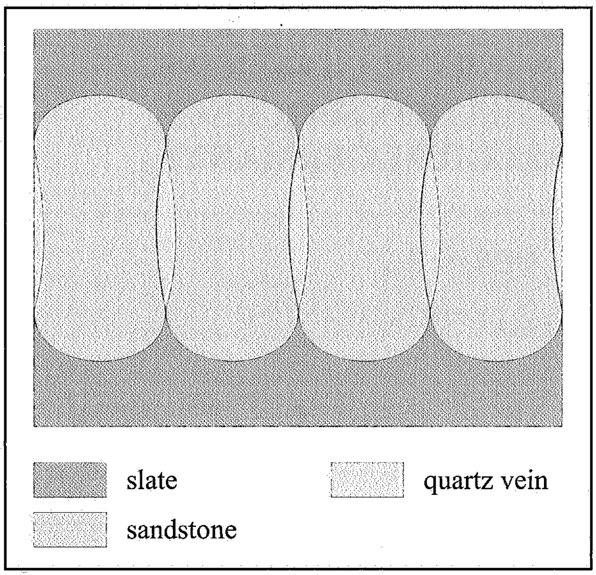


Figure 1.1 Simplified sketch of the "boudin" structures observed throughout the Ardenne-Eifel region. This representation is a vertical section.

Since Quirke's publication (1923) the origin of the boudins in the Ardenne-Eifel region has been a matter of debate. The problems relate among other things to: the relative age of quartz veining with respect to the cleavage within the slate units, the boudinage growth with respect to the fold development, the aspect ratio of the boudin blocks, the vein formation and the age of the metamorphism. Conflicting views and various models have been proposed to resolve these problems. In addition, there is a terminological problem, since a structure, only slightly different from the common segmented sandstone layers termed boudins, has been named "*mullion*" in Dedenborn (Germany) by Pilger & Schmidt (1957) and this has become a reference outcrop cited in many textbooks (e.g. Ramsay & Huber, 1987; Price & Cosgrove, 1990; Twiss & Moores, 1992). Consequently, two rather close structures bear different names, which further confuse the discussions.

Thus, the terms "boudin" and "mullion" have passed in the common language of structural geologists and numerous researches inspired by equivalent structures observed in

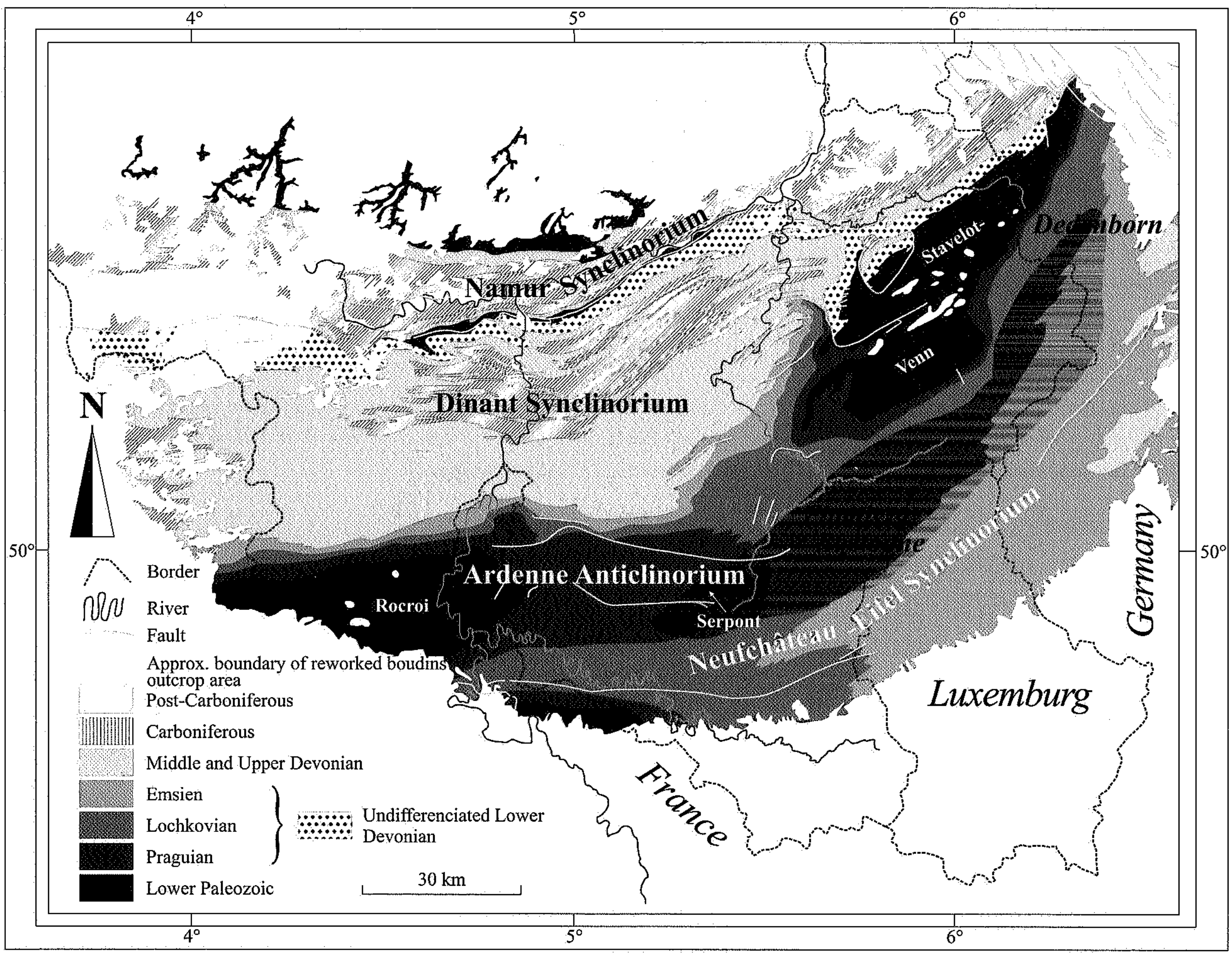


Figure 1.2 Geological map of southern Belgium and neighbouring regions. The study area belongs to the Ardenne Anticlinorium and the northern part of of the Neufchâteau-Eifel synclinorium.

many other terranes have been carried out to determine their mode of formation (e.g. for the boudins: Ramberg, 1955; Parterson & Weiss, 1968; Strömgård, 1973; Smith, 1975; Lloyd et al., 1982; Masuda & Kimura, 2004 – for the mullion structures: Smith, 1975; Fletcher, 1982; Sokoutis, 1987, 1990). The two terms are now frequently associated with a genetic definition. The boudins are regarded to form by a layer-parallel extension, while the mullion structures would result from layer-parallel shortening (e.g. Price & Cosgrove, 1990). With regard to the mullions, some authors do not agree or apply the genetic definition (Hobbs et al., 1976; Ramsay & Huber, 1987; Allaby & Allaby, 1990; Keary, 1996; amongst many others).

The main problem with the genetic definitions is that the field signatures identifying both processes (i.e. layer-parallel extension or shortening) are not always obvious and the structures observed throughout the Ardenne-Eifel region clearly demonstrate this problem. In fact, according to Jongmans and Cosgrove (1993) the region underwent two major deformation stages: the first one corresponds to a layer-parallel extension and then in a second period a layer-parallel shortening reworked the inherited structures. The distinction in the field of the structural features resulting from one or the other stage is a complex task, which is tackled in this contribution. The genetic facet of the definitions of "boudins" and "mullions" is however now so deeply anchored in structural geology literature that it would be difficult to reverse the situation. Furthermore, other problems are linked with the purely descriptive definitions. For these reasons, we also apply the genetic definitions for both terms.

This memoir is divided in two parts. In the first part, we present a model of development of the "boudin" structures throughout the Ardenne-Eifel region. Since the current structures result from a layer-parallel extension followed by a layer-parallel shortening, we term (Chapter 3) the layer segments as "**narrow reworked boudins**" or simply "**reworked boudins**" ("*boudins remaniés*" in French) in agreement with the recent nomenclature of the boudin structures by Goscombe et al. (2004). The aspect ratio (width/height) of the boudin before the layer-parallel shortening stage is then discussed and we show that narrow boudins do occur (Chapter 4) and can be related to the formation of joints (Chapter 5). The model of development of the narrow reworked boudins is then fully described in Chapter 6. The second part of this memoir is concentrated on "**associated structures**". This term encompasses all structural features that were formed by the same structural evolution as narrow reworked boudins, but contrast significantly from them especially in the architecture of the quartz veins. These differences are related to variations in the sedimentary successions in which the structures were developed. The associated structures are based on new field structural observations mainly conducted in the region of Flamierge and Bastogne (see Fig. 1.2 for location) and the mechanisms of formation of these structures will be the subject of future publications.

2. Geological setting

The Ardenne Anticlinorium and the northern part of the Neufchâteau-Eifel Synclinorium (Fig. 1.2) are situated in the Rhenohercynian fold-and-thrust belt (north-western Variscides) and are composed by lower Paleozoic and Lower Devonian (meta-) sedimentary rocks. The structures analyzed in this memoir affect only the Lower Devonian detrital (meta-) sedimentary rocks from the region of Flamierge and Bastogne. The rocks and quartz veins in this study zones are characterised by metamorphic assemblages and fluid inclusions indicative of pressure-temperature conditions equivalent to the green-schist facies (see e.g. Darimont, 1986; Beugnies, 1986; Fielitz and Mansy, 1999; Schroyen and Muchez, 2000; Kenis et al., 2005).

The Lower Devonian rocks are part of a thick (~10 km) Devono-Carboniferous passive margin sequence that was subsequently accreted during the Variscan orogeny between the end of middle-Mississippian to late-Pennsylvanian (e.g. Dittmar et al., 1994; Oncken et al., 1999; Vanbrabant et al., 2002). The involved rocks underwent therefore two major tectonic events: the first linked to the development of a passive margin during a global tectonic extension event, which began in the Lower Devonian times and the second linked to tectonic shortening during the Variscan orogeny.

The signature in the field of the Variscan orogeny is marked by trains of folds with axes mainly oriented E-W between the Rocroi Massif and the region of Bastogne and NE-SW to the east of Bastogne. An axial-plane slaty cleavage affects the finer material (i.e. shale). Recent mapping investigations show that the region of Flamierge (Dejonghe & Hance, 2001; Dejonghe, submitted) is characterised by longitudinal south-dipping thrusts cut in turn by transversal faults showing complex displacement vectors (i.e. left-lateral strike-slip with various vertical components). The quartz veins are another common structural feature of the Ardenne-Eifel region. They are mainly observed in the sandstone layers in association with the so-called "boudin" structures, which are typically encountered in fine-grained (i.e. slate or siltstone) sequences (Fig. 2.1). Nevertheless other sedimentary successions exist in the study area, such as the Mirwart Formation that is frequently observed in the region of Flamierge. This formation (formerly called the "Anor Formation") is mainly composed of a succession of grey shales and sandstone-quartzite units (Bultynck & Dejonghe, 2001). The latter outcrops as ten-meter thick massive bars. The role of the various sedimentary successions during the formation of the quartz veins and their subsequent shortening are part of the field observations presented in Chapter 7.

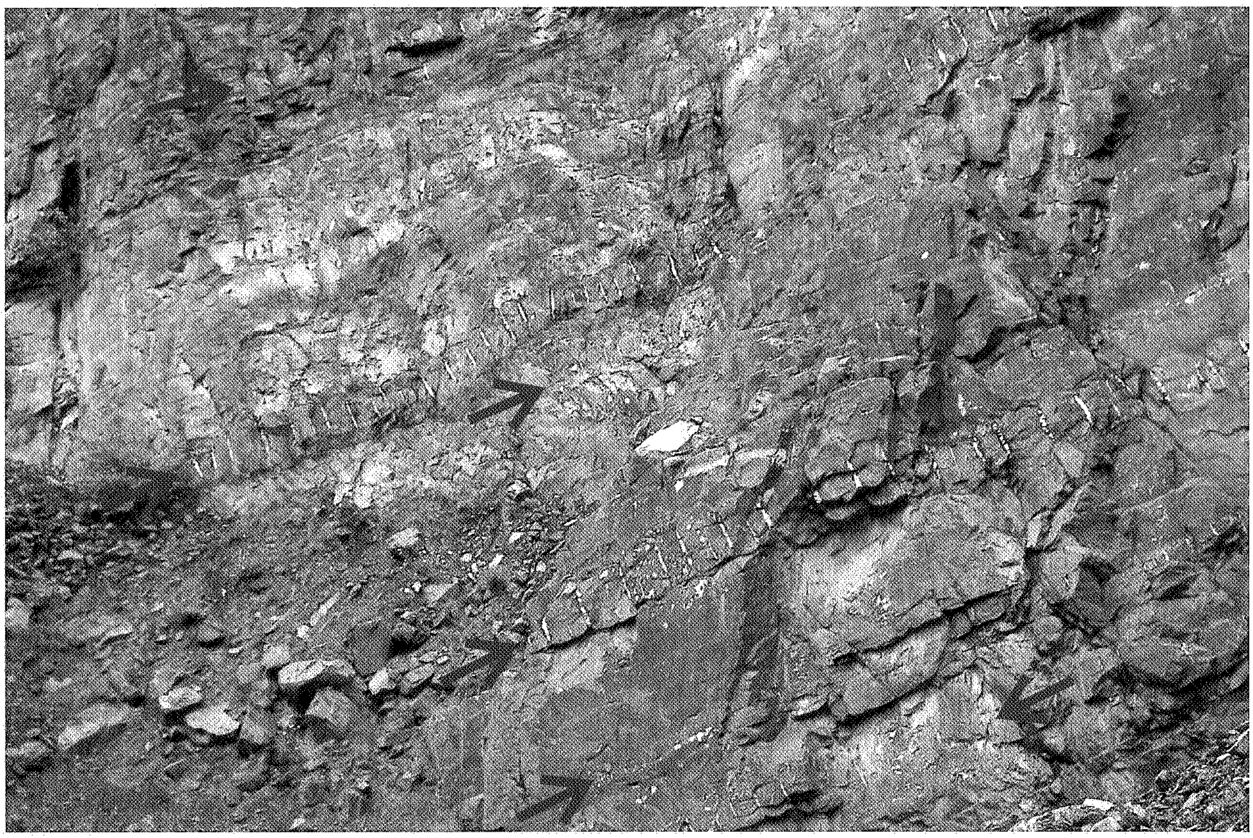


Figure 2.1 Example of boudinaged sandstone layers (see red arrows) embedded in thick siltstone units from Mardasson Quarry in Bastogne.

3. Narrow reworked boudins in the Ardenne-Eifel region

3.1 Segmented layers in the Ardenne-Eifel region

In the introduction we mention the problem of naming the segmented sandstone layers observed throughout the Ardenne-Eifel region. Observations from different authors have been considered and from these works a model of a typical segmented layer can be drawn. Its main characteristics are (Fig. 3.1):

- it is observed in well-individualized sandstone-quartzite layers embedded between fine material units (generally slate or siltstone);
- the segments are regularly spaced along the layers regardless to the position within a fold structure;
- each segment exhibits in section an extreme bi-convex geometry (e.g. barrel-shaped) and is separated to the next segment by lens shaped white quartz veins;
- within a segment the layering is flat in the central part, while it is curved at its top and bottom;
- the quartz vein tips are located at the sedimentary contacts with the fine material units;
- the segment height is twice its width, that is an aspect ratio (width/height) of 0.5;
- when viewed in plan view, the segments represent rock cylinders laying side by side;
- the cleavage plane is usually oblique to the bedding plane;
- the strike of the cleavage plane and the segment direction are usually not parallel;
- the cleavage plane is commonly refracted in the vicinity of the vein tips.

These features represent an idealisation of the structure (e.g. a model) and numerous exceptions exist. For instance, some veins may slightly penetrate within the fine materials or the regularity of spacing is in some cases not so obvious (Fig. 3.2). In addition, the relationship between the bedding and cleavage planes depends on the observation position within a fold structure. It is thus necessary during the analyses to take into account a degree of variability and an observation made in a particular point is perhaps not necessarily the same as those made at the next outcrop. Nevertheless the preceding characteristics represent the facts commonly observed.

Some characteristics in regard to the attribution of a name for the structure are clearly in favour of the "boudin" term, such as the regularly spaced segments with a barrel-shaped geometry and the lens-shaped quartz veins (see concave-

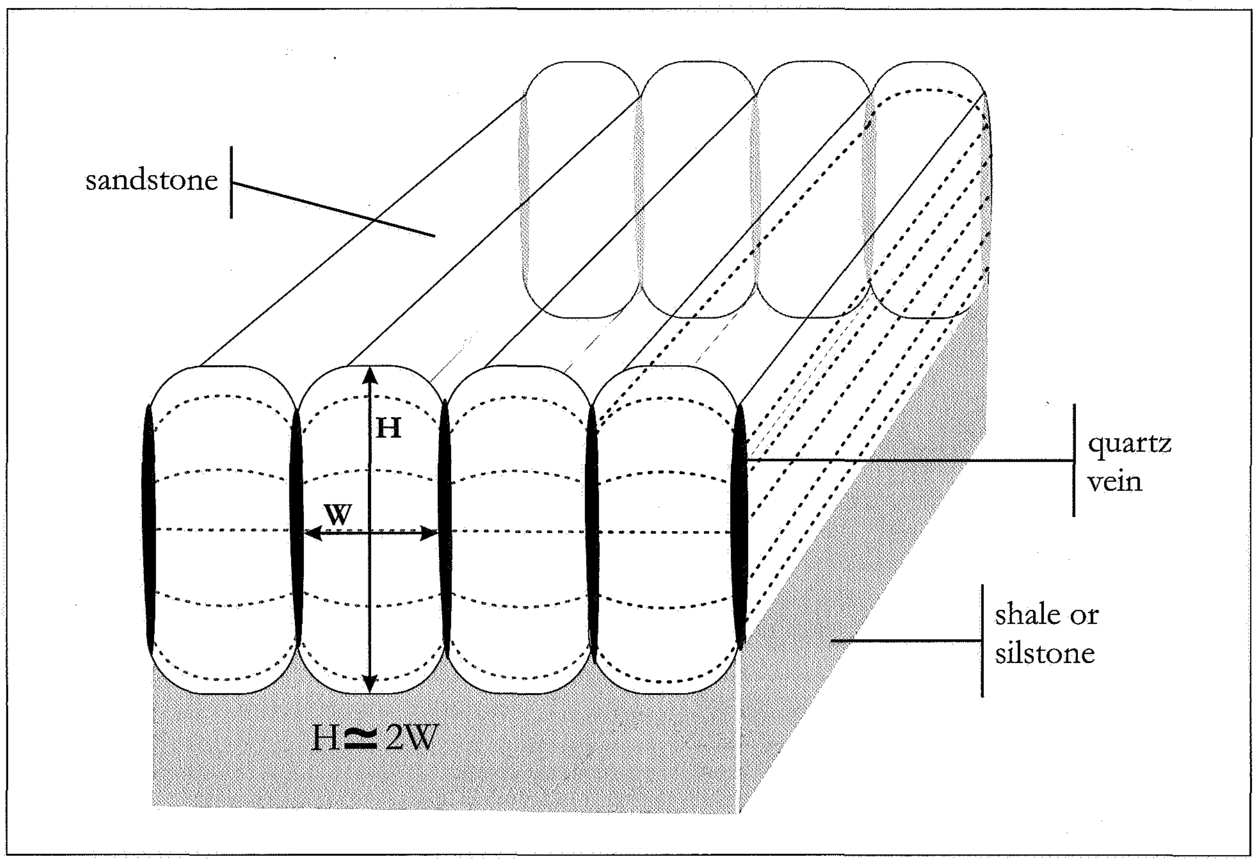


Figure 3.1 Three-dimensional representation of an idealized segmented sandstone layer as observed throughout the Ardenne-Eifel region (aspect ratio: W/H = 0.5, W: width and H: height).

face boudins in Fig. 3.3.a). However other features are different from the well-recognized and unquestionable boudin structures. For instance, the barrel-shaped boudins generally do not have such extreme convexity and the cleavage plane is usually sub-parallel to the boudinaged horizons. Finally, the aspect ratio of the boudin (width/height) is commonly considered to be higher than 2, while the one observed through the Ardenne-Eifel region is about 0.5.[1]

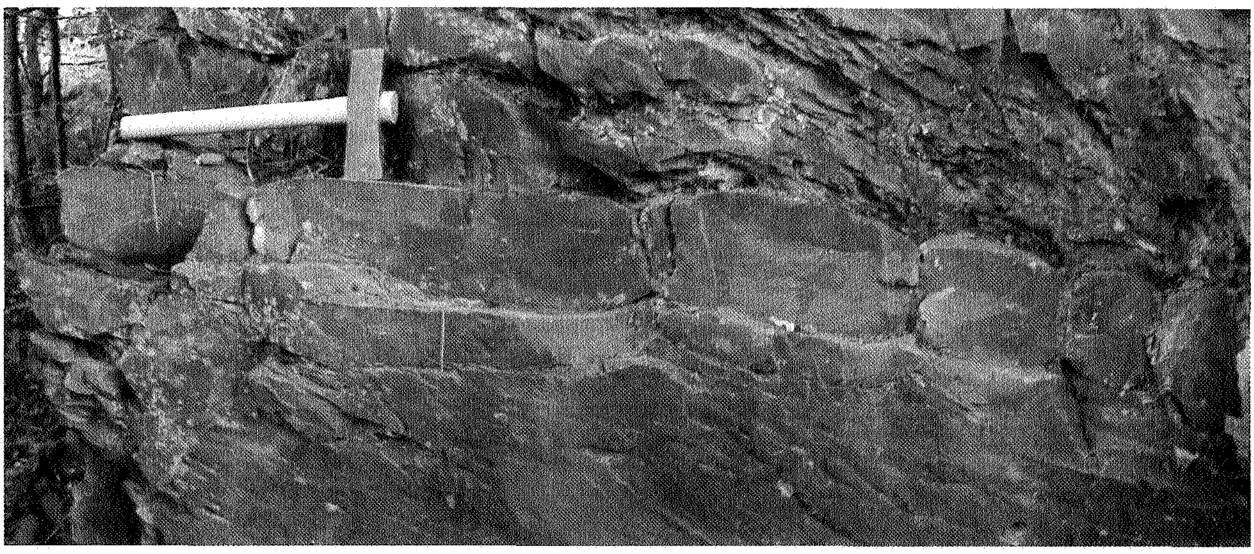


Figure 3.2 Example of irregularly spaced reworked boudins from the Collignon Quarry (Bastogne). On the left-hand side of the profile the segments are wide (aspect ratio = width/height ~2), while at the right-hand side they are narrow (aspect ration ~1).

[1] For the sake of clarity, we have to mention that some authors refer to the aspect ratio as height/width and not as width/height. Hence their values must be reversed in order to establish comparisons.

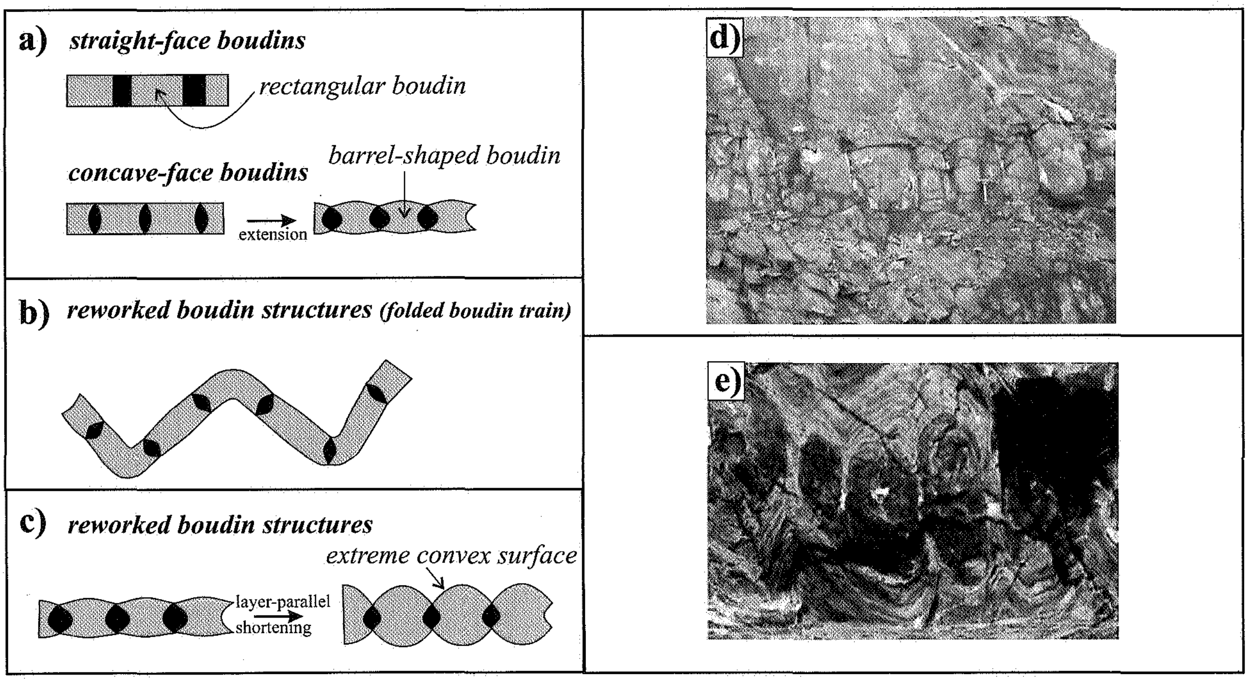


Figure 3.3 a) Straight- and concave-face boudins (grey) separated by vein infill (black). As layer extension increases concave-face boudin blocks adopt a barrel shape. A subsequent layer-parallel shortening leads to reworked boudin structures: b) by folding of boudin train and/or c) by reshaping of boudin blocks, which acquire an extreme convex surface. d) and e) Examples of reworked boudin from Bastogne (Belgium) and Mount Isa (Australia), respectively[2]. a), b), c) and e) are modified from Goscombe et al. (2004).

These deviations from the common boudin structures can be readily explained if a two-stage evolution is considered, namely a layer-parallel extension event responsible for the formation of boudin structures followed by a layer-parallel shortening period that transforms the boudin. This evolution has already been proposed by differents authors working in the study area (Jongmans & Cosgrove, 1993; Rondeel & Voermans, 1975). This case has also been extensively studied by Goscombe et al. (2004) for boudin structures from other terranes that the Ardenne-Eifel region. These multi-event structures were gathered under the term "reworked boudins". As a result of a layer-parallel shortening, the boudinaged layer can be either folded (Fig. 3.3.b) and/or each boudin block can be shortened (Fig. 3.3.c). During the shortening, each block is therefore transformed, namely its width is reduced and, if we assumed area conservation, its height should increase. In addition, the boudin envelope is further bent. The segmented layers through the Ardenne-Eifel (Fig. 3.3.d) clearly fit to this model and share numerous characteristics of other reworked boudins such those from Mount Isa in Australia (Fig. 3.3.e). Thereby the extreme convexity of segments can be readily explained by a subsequent shortening. The non-parallelism between the boudinaged horizon and the main cleavage plane corresponds to two dissociated events, with the cleavage formation during the shortening event. The low aspect ratio of the segments in the Ardenne-Eifel region could also be associated with this subsequent shortening. However the aspect ratio of the boudin structures has been the subject of numerous discussions, which are considered below.

3.2 Aspect ratio of boudins and reworked boudins

The reworking of boudin blocks is an elegant way explaining their current low aspect ratio in the Ardenne-Eifel region. However a related question concerns the initial geometry of the boudin blocks, that is, the aspect ratio before the layer-parallel shortening. As mentioned, the current value is about 0.5, while the commonly accepted value for unaffected boudins is above 2 (Voight, 1965; Smith, 1975; Price & Cosgrove, 1990). Using this last value as a first approximation requires a hypothetical shortening of 40 % to produce the currently observed aspect ratio.

The rare shortening values published in literature for the northern part of the Rhenohercynian fold-and-thrust belt evaluates it between 16-27 % (Dittmar et al., 1994) and 30-35 % (Raoult & Meilliez, 1987) and even 46 % (Hollmann, 1997). At first sight, the hypothetical shortening value is of the same order as the previous published values. However we should keep in mind that the published values are mainly based on the balanced cross-section technique, which is subjective. Furthermore, even if these values are correct they correspond the shortening by internal deformation of materials, by folding and by

[2] Reprinted from Journal of Structural Geology, 26, Goscombe, B.D., Passchier, C.W. & Hand, M., Boudinage classification: end-member boudin types and modified boudin structures, 739-763, Copyright (2004), with permission from Elsevier.

the displacements along the thrust faults. A large amount of the shortening evaluated by the balanced cross-section technique corresponds therefore to the folding and displacement along thrust faults. Both processes are usually assumed to represent the main shortening mechanisms within the fold-and-thrust belt and in particular in thin-skinned tectonic setting. By contrast in the internal domains of an orogenic belt, where a thick-skinned tectonic setting prevails, more internal deformation occurs (e.g. Twiss & Moores, 1992). The Ardenne-Eifel region represents however a transition zone between a thin- and thick- skinned tectonic (Dittmar et al., 1994). It is therefore delicate to clearly identify the main shortening process from the sole balanced cross-section technique.

Another approach consists into a direct measurement of the internal deformation. Different techniques are available. The internal deformation within an arenaceous rock can be evaluated in thin-sections by the EnFry method, which is a center-to-center based technique. Briefly, it consists of fitting ellipses on quartz grain boundaries and measuring the distances between theirs centers (for details see Erslev & Ge, 1990). A highly strain sample exhibits low distances between ellipses in a direction normal to the main flattening plane. This technique has been extensively applied along the DEKORP-seismic profile throughout the Rhenohercynian fold-and-thrust belt by von Winterfeld (1994) and Dittmar et al. (1994). Their results indicate that internal deformation is highly variable and depends on lithology and grain size, and also on the position of the sample with respect to the fold structures or proximity to a thrust fault. The temperature during deformation is also a significant factor. Hence a single value characterizing a small-scale structure such a boudin cannot be readily derivated from this large-scale study. The use of the EnFry method is certainly an interesting approach quantifying the strain within the reworked boudins, but it requires a significant amount of strain-mapping work within a boudin block and the need of repeating the measurements for different boudins in different positions throughout folds. Qualitative observations conducted by Urai et al. (2001), Kenis et al. (2002) and Kenis (2005) suggest that the internal deformation within the boudins should be small and is more likely lower than the one expected from a shortening of 40 %. These observations indicate that the boudin structures had a low aspect ratio (< 2) before the layer-parallel shortening period and a value of about 1 seems a more realistic value.

3.3 Summary

We consider that the segmented layers observed through the Ardenne-Eifel region should be named "narrow reworked boudins" or simply "reworked boudins". This term refers to the extensive nomenclature of boudin structures by Goscombe et al. (2004). We add the "narrow" prefix since it is likely that before their shortening the boudin blocks had a low aspect ratio (probably about 1), in contrast with a widespread idea that this parameter should be above 2. This problem will be discussed in the next chapter.

4. Narrow boudins

4.1 Introduction

Since there are indications of a low internal strain within the sandstone layers, a simple and rough estimation of the initial aspect ratio of the layer segments (i.e. before the layer-parallel shortening event) can be evaluated by a simple geometrical method. It simply consists into to the unfolding of buckled segments of the reworked torn boudins. Practically, the full length of the interfaces is measured and compared to the current width of the layer segments. Hence an amount of shortening can be derived and from that an initial aspect ratio computed. Brühl (1969) conducted such an evaluation and his results show that the initial ratios were in the range of about 1, which is smaller than the commonly recognized values for boudin structures. This element was utilized amongst others by Kenis et al. (2002) and Kenis (2005) to refute the term boudin for the structures observed through the Ardenne-Eifel region. However no definition of the boudin structure refers to the aspect ratio as a criterion to attribute or to refute the term to a structure. We do not share the opinion of Kenis et al. (2002) and we consider on the contrary that narrow boudins exist and were until now overlooked. Next, we will present examples of unquestionable narrow boudins.

4.2 Boudinage mechanisms and examples of narrow boudins

Boudin and pinch-and-swell structures have been widely recognised through the world in numerous different geological settings (see e.g. Goscombe et al., 2004). They are found in highly metamorphic terrains as well as in unmetamorphosed sedimentary rocks. The boudinage involves therefore a wide range of mechanical behaviours from a purely brittle in rectangle boudins (see Fig 3.3.a) to a ductile behaviour in pinch-and-swell structures. Ramberg (1955) considers that the boudin trains form by a succession of ruptures within a layer and separations of segments (Fig 4.1). As a result, the boudin blocks are separated from each other by various amounts depending of the total amount of strain (see Fig. 4.1.D). This model, named here "**successive rupture boudinage**", certainly fits some categories of boudin trains (e.g. Plate 1.D in Ramberg, 1955), but not all. Other types of trains are instead characterised by a remarkable regularity in repetition of the structures and those from the Ardenne-Eifel region follow this case (see Fig. 3.3.d). Consequently, the existence of a unique deformation mechanism for boudinage seems questionable and in the following chapters, we will discuss another mode of formation of these regularly-spaced narrow boudins.

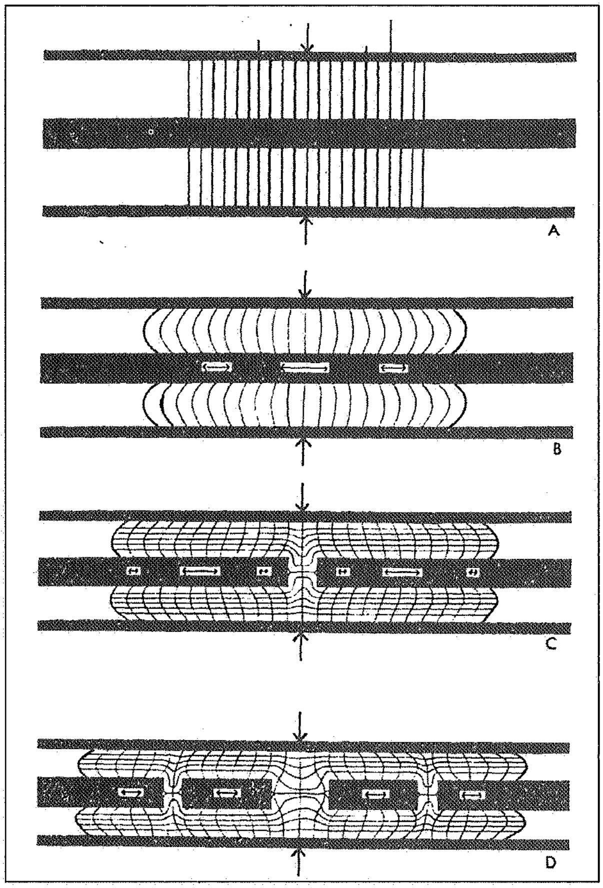
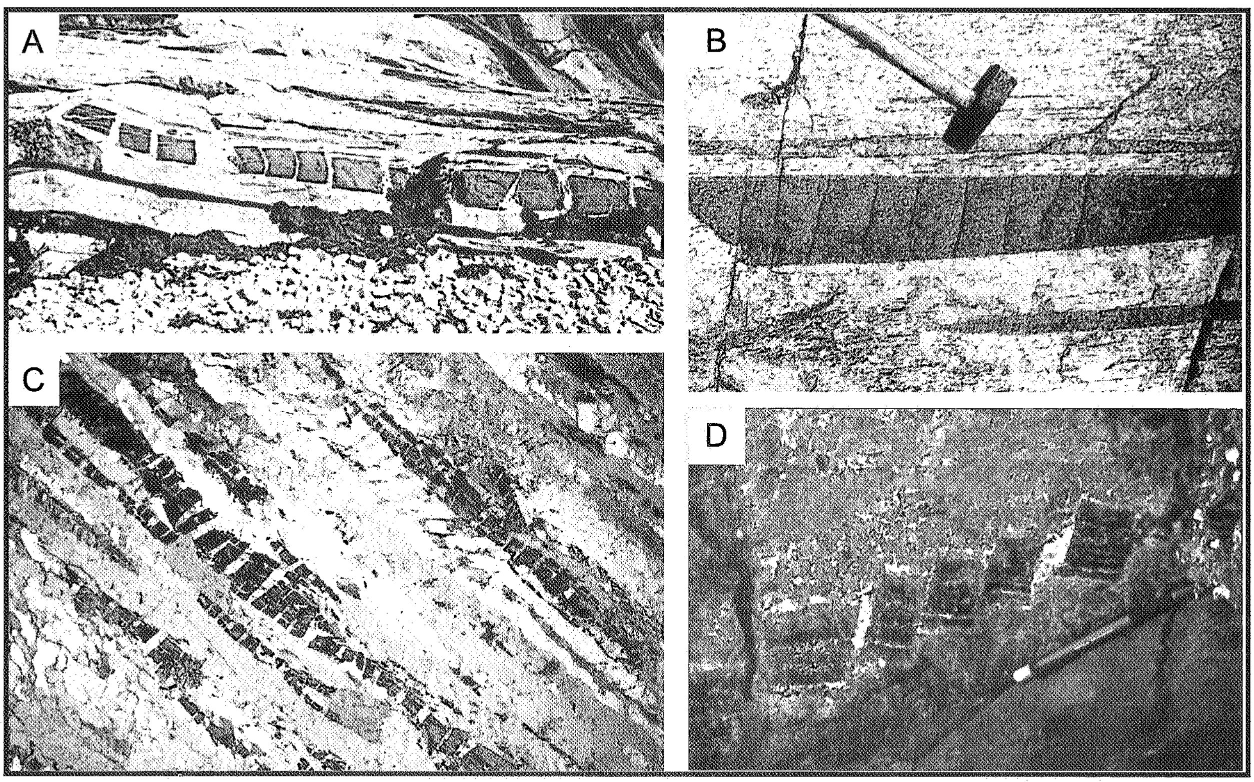


Figure 4.1. Kinematic model of boudinage by successive rupture-separation (from Ramberg, 1955)[3].

Examples of published descriptions of narrow boudins are not so uncommon: for instance, even in the paper by Ramberg (1955), an example of boudins with a low aspect ratio is presented (see the reproduction in Figure 4.2.A). In this case, they are separated by various lengths, which indicates that narrow boudins can also be formed by a successive rupture boudinage leading to a train of irregularly-spaced narrow boudins. In the same paper, Ramberg also presents an outcrop of a regularly-spaced joints affecting an amphibolite layer. The aspect ratio of segments is less than 1 (see reproduction in Figure 4.2.B). As it will be seen in the next chapter, veins and joints share numerous features. Passchier and Trouw (1998) exemplify the micro-boudinage with an instance

Figure 4.2 Example of narrow boudin structures. A) Boudinaged amphibolite in granitic gneiss, West Greenland (reproduction from Ramberg, 1955, Plate 2.B). B) Tension joints within amphibolite layer in quartz feldspar gneiss, West Greenland (reproduction from Ramberg, 1955, Plate 1.A). C) Microboudinage of tourmalines (dark) in a quartzite. Specimen courtesy Michel Arthaud (reproduction from Passchier & Trouw, 1998, p. 150)[4]. D) Dilational domino boudins in carbonate from Pakistan (reproduction from Goscombe et al., 2004, p. 750).



of very narrow (aspect ratio < 1) tourmaline segments (see reproduction in Figure 4.2.C) and Goscombe et al. (2004) presents an example of dilational domino boudin train (see reproduction in Fig. 4.2.D) from a carbonate in Pakistan with low aspect ratio blocks (ratio ranging between 0.6 and 0.8). The examples presented in Figure 4.2 are not unique. Other examples of narrow boudin can be found for instance in De Paor et al. (1991) and in their extensive analysis of boudinage Goscombe et al. (2004) gather numerous measurements of boudin aspect ratio among which narrow boudin with aspect ratio of about 1 or even less are frequent (see their figure 8.a and b). They seem to be particularly well represented by boudins exhibiting an open-mode fracturation (vein or matrix infill).

5. Hybrid shear fracture, veins and joints

5.1 Introduction

In this chapter, we first review some basics of rock mechanics paying special attention to hybrid shear fractures, then the stress conditions for the displacement and development of the different categories of fractures are described. The main characteristics of joints and veins are finally developed. All these elements will be used in the following chapters.

5.2 Structural and mechanical principles

Veins and joints are structural features commonly associated in the literature since they both represent open-mode fractures. The term "dilatational" fracture is also applied to these structures and they represent one of the three basic categories of fractures with shear and hybrid shear fractures (Price & Cosgrove, 1990). In the open-mode fractures, their walls separate without any shear (i.e. fracture-parallel) displacement. The opening is negligible for joints, while it can reach several meters for veins, which are filled by precipitation of mineral aggregates. A shear fracture exhibits only a significant shear displacement along a slip surface (i.e. a fault), while a hybrid shear fracture combines a shear displacement with an open-mode process. The hybrid shear fractures are also called: oblique shear fractures, conjugate hybrid joints, mixed-mode fractures, amongst many others (Engelder, 1999 and references therein).

The existence of hybrid shear fractures naturally formed in rocks is however difficult to assess, since it can be the result either a simultaneous process composed of an open-mode and a shear displacement or alternatively a sequence including an initial separation of fracture planes followed by a shear displacement or a shear fracture that was in turn opened. The different processes cause in any case to the same structure, but in terms of stress states the differences between them are fundamental. (Micro)-structural investigations can help to distinguish between the different cases (Engelder, 1999).

During our observations, we have encountered structures that could be regarded as hybrid shear fractures. Briefly, they consist of blocky milky quartz veins exhibiting a shear displacement along their planes. As mentioned, it is difficult to clearly discriminate between the various aforementioned processes, and in Chapter 7 the term "hybrid shear fractures" must not be considered as a genetic definition, but rather as the description of a structure exhibiting both open-mode and shear displacements without assuming that both mechanisms are contemporaneous.

In terms of two-dimensional stress conditions the observed displacement for an existing fracture depends on the normal stress component (σ_n) acting perpendicular to the fracture planes and the shear stress component (τ), parallel to it. If σ_n is tensile (for convention tensile stress is negative), the fracture walls separate, while they remain joined if σ_n is compressive (> 0). On the other hand, if τ is different to zero a fracture-parallel displacement tends to occur, while no shear displacement is observed if $\tau = 0$. Consequently, a fracture is likely to (Fig. 5.1):

open as a joint or a vein if $\sigma_n < 0$ and $\tau = 0$;
slip as a fault if $\sigma_n > 0$ and $\tau \neq 0$;
open and slip as a hybrid shear fracture if $\sigma_n < 0$ and $\tau \neq 0$.

However the last structure can also result from a combination of the first two stress states without the conditions for the formation of a hybrid shear fracture having been satisfied.

The previous analysis does not consider the development of the fracture. Mechanical concepts and laboratory experiments on materials, such as rock, led to the fracturation theory, which aims to predict the stress conditions leading to the formation and growth of a fracture. This approach is closely linked with the failure envelope concept. For rock materials, this envelope is commonly referred as the Mohr-Coulomb failure envelope, which is usually represented as a parabola in a σ_n-τ plot (Fig. 5.1). This representation is useful for predicting which type of fracture is likely to develop for a given state of stress.

For a 2D problem, the state of stress at a given point within a material can be represent by the Mohr circle (Fig. 5.1). A fracture is likely to develop in this material, if the Mohr circle touches the material failure envelope. The coordinate of the contact point determines the values of σ_n and τ acting on this new fracture. For instance, if the contact point corresponds to point A in Figure 5.1 the conditions are encountered for the formation of a hybrid shear fracture, since σ_n is negative and τ is not

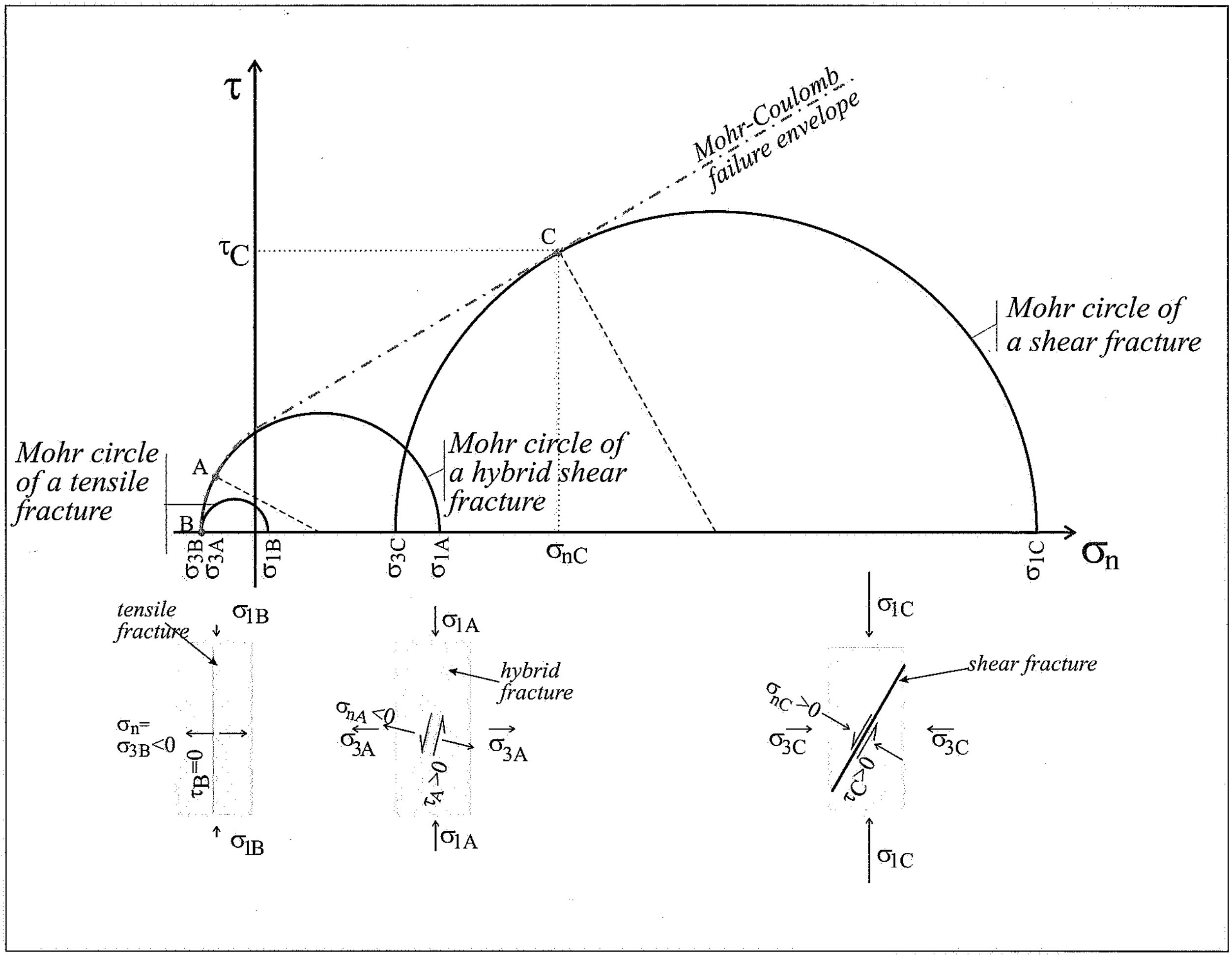


Figure 5.1 The three basic categories of fractures depends on the normal stress (σ_n) and the shear stress (τ). A new fracture will develop if the Mohr circle touches the Mohr-Coulomb failure envelope. The deformation mechanisms for this new fracture is related to the value of σ_n and τ of the contact point represented as red dots (see σ_{nA}, τ_A, τ_{nB}, ...).

equal to zero. A open-mode fracture forms when the corresponding state of stress is such that the Mohr circle meets the failure envelope at point B (see Fig. 5.1). In this case the normal stress σ_n equals σ_3 and the fracture is perpendicular to this stress component. Shear fracture grow in stress conditions of the type represented by the Mohr circle that touches the failure envelope at point C. This analysis predicts the conditions for a fracture to develop, but it does not take into account its growth. After the formation of a fracture the material state is altered because of the lost cohesion along the fracture planes. Hence the displacement along the existing fracture contrasts with the behaviour of an intact material. This aspect is however beyond the scope of this paper and the interested reader may refer to textbooks such as Jaeger and Cook (1979), Goodman (1989), Turcotte & Schubert (2002).

5.3 Characteristics, spacing and formation of joints

The water and oil industry, as well as slope stability engineering are interested in joints since they are a controlling factor of rock permeability and delimit potentially unstable rock bodies. In sedimentary sequences, joints form sets of parallel planes cutting the bedding plane at high angle (Price & Cosgrove, 1990; Narr & Suppe, 1991) and are frequently restricted to a single layer. Joint spacing is sensitive to rock type and layer thickness.

Joints are encountered in numerous environments and are generally associated in sedimentary rocks with folding linked to tectonism (Narr & Suppe, 1991) or with uplift and erosion. In the latter, the development of tensile stress is associated with elastic deformation and thermal effects (Twiss & Moores, 1992). Joints are also observed in flat lying sedimentary rocks, which apparently have not suffered any major deformation. Such fractures are called "**regional fractures**" and present according to Secor (1965 in Lorenz et al., 1991) an: "*...ultimate regularity and perfection in areas of near-horizontal sedimentary strata where other types of structural deformation are scarce or absent...*". Hence even for rocks deeply buried, regional joints are likely to exist before any major folding event. This observation is of significant importance for the current discussion of boudin formation through the Ardenne-Eifel region and is discussed further later.

The spacing between joints has been extensively studied, because of its influence on permeability and its control on the block dimensions, a factor relevant to the building stone industry. Numerous papers (see i.e. Sowers, 1972; Narr & Suppe, 1991; Bai & Pollard, 2000; Bai et al., 2000; Adda-Bedia & Ben Amar, 2001) show a direct relationship between the fracture spacing and the layer thickness. In addition, experimental works show that joint spacing decreases with the applied strain (Bai et al., 2000).

Wu & Pollard (1995) and Bai et al. (2000) show that there is a lower limit in the joint spacing, which is reached when the distance between two neighbouring joints is approximately equal to the layer thickness. Hence the aspect ratio (width/height) of the layer segments is equal to 1. Bai et al. (2000) call this stage the "**fracture saturation**" and it occurs as a result of a modification in the stress state in the central part of layer segment located between two joints. Before saturation a tensile stress ($\sigma_3 < 0$) may develop in this area and a new joint can potentially be formed. This additional joint implies in turn a decrease of the joint spacing, which tends thereby towards the fracturation saturation. When saturation is reached only compressive stress prevails within the layer segments and the formation of new joints is prevented. Any additional strain leads to opening of the joints instead of developing new joints (Bai et al., 2000).

In summary, the presence of joints within sedimentary layers is therefore a significant observation, since they indicate that the fracturated rock body underwent tensile stress conditions. The origin of the tensile stress is discussed in the next section. This fracturation event can occurred before any significant deformation such as folding and may produce a very regular pattern. The development of joints is however limited by the fracture saturation, which represents a minimum fracture spacing (i.e. an aspect ratio of approximately 1). Any additional strain is likely to be accommodated by the opening of the existing joints instead of the formation of new joints.

5.4 Tensile stress in the Earth's crust and vein formation

As well as joints, veins represent open-mode fracture resulting from a tensile stress. Veins are ubiquitous features in numerous geological settings and in particular within low-grade metamorphic rocks. Paragenetic associations, as well as the fluid inclusions and petrographic analyses indicate that the numerous veins were formed under the metamorphic conditions (Vidale, 1974; Norris & Henley, 1976; Etheridge, 1983; Yardley, 1983; Miller et al., 1992; Sibson & Scott, 1998). The interboudin veins observed throughout the Ardenne-Eifel region fit this observation, since various studies (see Chapter 3) have shown that these veins were formed in green-schist facies conditions.

In parallel, it is widely recognised in the literature that all stress components in the Earth crust are compressive ($\sigma_1 > 0$; $\sigma_2 > 0$; $\sigma_3 > 0$): see e.g. Twiss & Moores, 1992; Engelder, 1994). This notion is valid whatever the tectonic setting from a stable intraplate crust, to a global extension (e.g. graben) or shortening (e.g. orogenic belt). As a result, one might expect that no joint or vein could ever form within rocks, especially within deeply buried metamorphic rocks[5]. The solution to this problem is commonly solved by appealing to fluid pressure (P_f). The fluid pressure within a rock tends to counteract the effect of the applied compressive stress. This influence is translated in more formal terms by considering the effective stress components and one can write (see e.g. Jaeger and Cook, 1979; Twiss and Moores, 1992):

$$\sigma'_1 = \sigma_1 - P_f$$
$$\sigma'_2 = \sigma_2 - P_f$$
$$\sigma'_3 = \sigma_3 - P_f$$

where σ'_1, σ'_2 and σ'_3 represents the maximum, intermediate and minimum effective stress components, respectively. These equations show amongst other things that the influence of the fluid pressure is isotropic, since it counteracts all stress components with the same magnitude (i.e. $\sigma'_i = \sigma_i - P_f$). Graphically in a σ_n-τ plot, any increase of P_f induces in a shift of the Mohr circle towards lower stress values, while its size remains the same (Fig. 5.2). In other words, the differential stress is not affected by P_f ($\sigma'_1-\sigma'_3 = \sigma_1-\sigma_3$).

To illustrate this influence of the fluid pressure, we describe two cases: 1) the differential stress is large ($\sigma_1-\sigma_3 >$ 5.5T) and 2) the differential stress is low ($\sigma_1-\sigma_3 <$ 4T), where T is the rock tensile strength.

1) Large differential stress (see Fig. 5.2.a)
As already mentioned, a rock will fracture if the Mohr circle representing the state stress in a point touches the failure envelope of the material. The characteristics of this rupture depend on the position of the contact point (see Section 5.2). If the differential stress is large, the increase of the fluid pressure may cause the Mohr circle to reach the failure envelope in the compressive field. Hence shear fracture(s) form and no vein can develop when the differential stress is large.

[5] Tensile stress can locally develop at the outer arc of a fold or in very shallow depth conditions.

2) Small differential stress (see Fig. 5.2.b)
If the Mohr circle representing a state of stress is small, i.e. it has a diameter less than 4 times T (rock tensile strength), the Mohr circle can reach the tensile field if P_f is high and the rupture will correspond to an open-mode fracture that is, a joint or a vein. The condition of a low differential stress represents therefore a pre-request for the formation of a vein. Using this condition, Etheridge (1983) has suggested that the differential stress during regional deformation and metamorphism was as low as to 20 to 40 MPa.

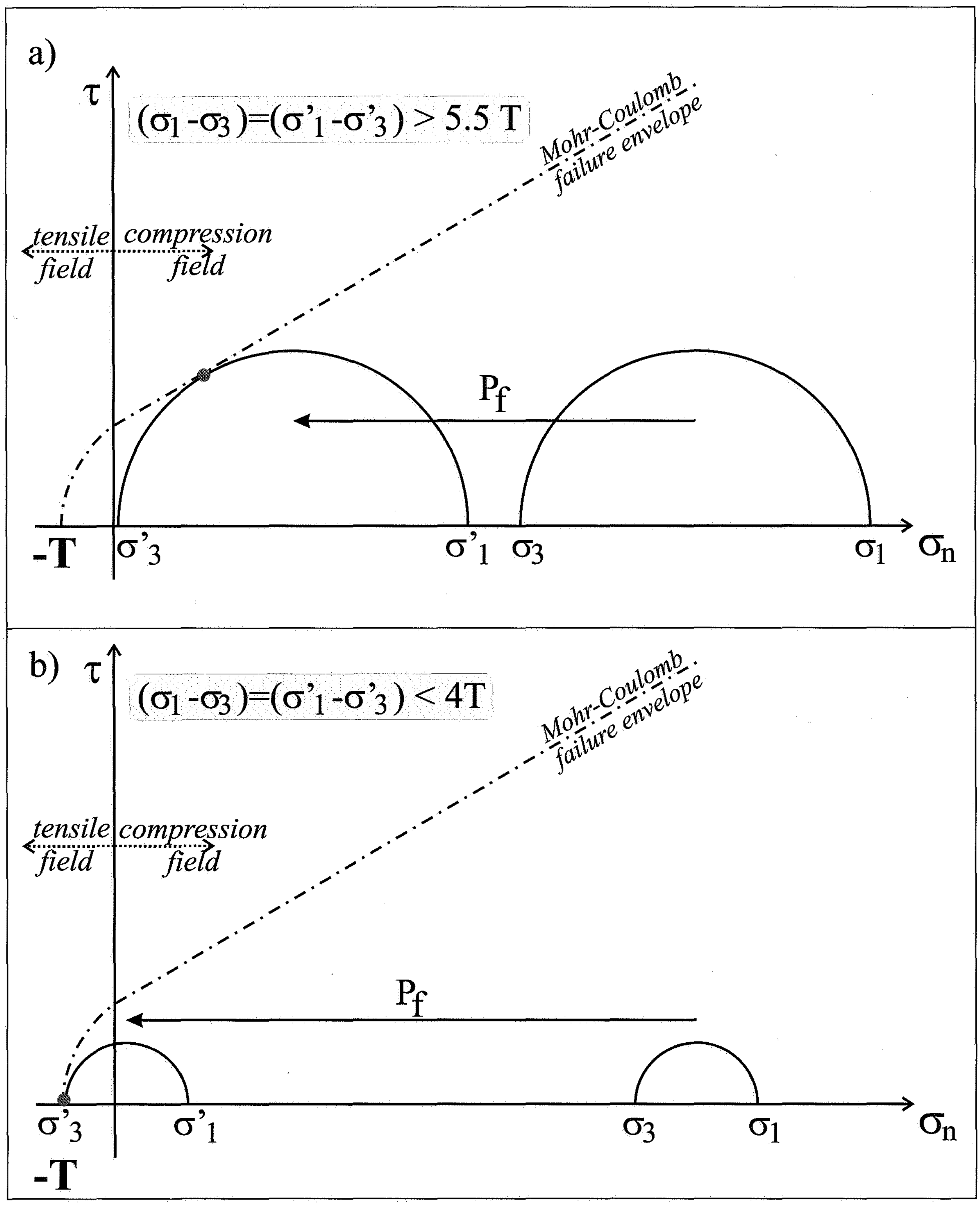


Figure 5.2 Influence of the fluid pressure (P_f) on the stress state. a) The shift of the Mohr circle due to the high fluid pressure in a high differential stress state can lead to the formation of shear fractures. b) If the differential stress is low, tensile fractures are likely to develop. *T* represents the rock tensile strength. Red dots represent the contact points between the Mohr circle and the Mohr-Coulomb failure envelope.

If the differential stress ranges between 4T and 5.5T a high fluid pressure may in theory induce the formation of a hybrid shear fracture.

The influence of the fluid pressure is therefore crucial in the understanding of fracturing. This process of fluid induced failure is called "hydraulic fracturation". This term should not be confused with the engineering term that designate a technique applied to induce new fractures within a rock body by injection of high-pressured water. Nevertheless both terms (*sensus* natural process and *sensus* engineering technique) describes the same phenomenon. Another important element to be mentioned is that if hydraulic fracturation induced the formation of veins or joints, that means that P_f overcame the least principal stress component ($P_f >> \sigma_3$). This situation is referred as a fluid overpressuring. As noted earlier, since the principal stress components within the Earth's crust are in compression (> 0), the observation of a vein in a rock is commonly interpreted as the result of a fluid overpressure and hence veins are frequently termed "hydrofractures". In contrast, if the differential stress is large, the development of a shear fractures during an increase of the fluid pressure is difficult to discriminate from a shear fracture develop without the influence of a high-fluid pressure. In fact, in both cases the structural features are the same, namely a fault. The presence of a fault in the field may or not necessarily indicate the involvement of a high-pressure fluid.

Veins are thought to develop from initial flaws within the rock and propagate by a stress concentration at the vein tips. However this progression is frequently interrupted by sharp rheological contrasts, such as a bedding plane separating two different lithologies. Veins observed between the reworked torn boudins throughout the Ardenne-Eifel region clearly follow this observation (see Section 3.1). Gudmundsson and Brenner (2001) show that in a sequence composed of stiff-soft-stiff layers, the tensile stress, which develops at a vein tip growing within a first stiff layer, is absent within the overlying soft layer, but is present again within the next stiff layer. Hence the formation of a vein within a layer may promote the formation of a new vein within another stiff layer. Since veins tend to form from existing flaws, the induced vein is not necessarily aligned with the source vein. Consequently, the development of veins within a stiff layers interbedded with thin soft layers is likely to follow a complex pattern with veins interrupted at sedimentary contacts but inducing new veins within other stiff layers.

6. Model of development for narrow reworked boudins

In this memoir, we suggest a new model for the development of narrow reworked torn boudins as those observed throughout the Ardenne-Eifel region. This model (Fig. 6.1) involves a sedimentary succession composed of a sandstone layer embedded between two finer-grain units (e.g. shale or siltstone). The deformation sequence involves two major deformation periods: first, a layer-parallel extension followed by a layer-parallel shortening.

During the early stage of the layer-parallel extension, very regularly joints ("regional fractures" *sensu* Lorenz et al. 1991) develop within the sandstone layer (Fig. 6.1.a). The joints are interrupted at the contacts with the finer materials. As the extension progresses, the number of joints increases until "fracturate saturation" is reached (see Bai et al., 2000 and section 5.2). At this stage, the aspect ratio (width/height) of the sandstone segments is about 1 (Fig. 6.1.b). Any additional extension strain cannot induce the formation of new joints due to the modification of stress conditions within the segments (see section 5.2). The subsequent deformation is accommodated by the opening of the existing joints. As a result of this, opening veins and narrow boudins develop. Following the works of Lloyd and Ferguson (1981), the shape of a boudin is determined by its hardness (Fig. 6.2). "Strong" boudins tend to keep their initial orthogonal shape, while ductile strain concentrates at the corners of "soft" boudins. In the latter case, the interboudin space acquires a lens-shaped geometry and the boudin envelope adopts the geometry of a barrel. The shape of the veins and of the boudin envelope are therefore related. This mechanism can lead to the formation of narrow barrel-shaped boudins separated by lens-shaped veins (Fig. 6.1.c) such as those observed throughout the Ardenne-Eifel region.

The barrel-shape geometry developed during the layer-parallel extension is likely to be of small amplitude. During the layer-parallel shortening, the boudin blocks were reworked by the passive amplification of this small perturbation. As a result of the layer-parallel shortening, the aspect ratio (width/height) of the boudin is further decreased (from 1 to ~0.5) and the inherited initial perturbation is strongly amplified into an extreme convex geometry as currently observed.

Our model differs with other recently published models concerning the Ardenne-Eifel study case on the following points of views:

- By contrast with the work of Jongmans and Cosgrove (1993), we consider that narrow boudins exist and that they develop firstly by jointing followed after "fracture saturation" by the opening (veining) of the existing joints.
- The sequence of deformation presented here is also in contracdiction with Kenis et al. (2002)'s model in that we consider a layer-parallel extension affected the region and a strain marker of this period is precisely the boudin structures. In addition, we consider that prior to the layer-parallel shortening, the boudin blocks

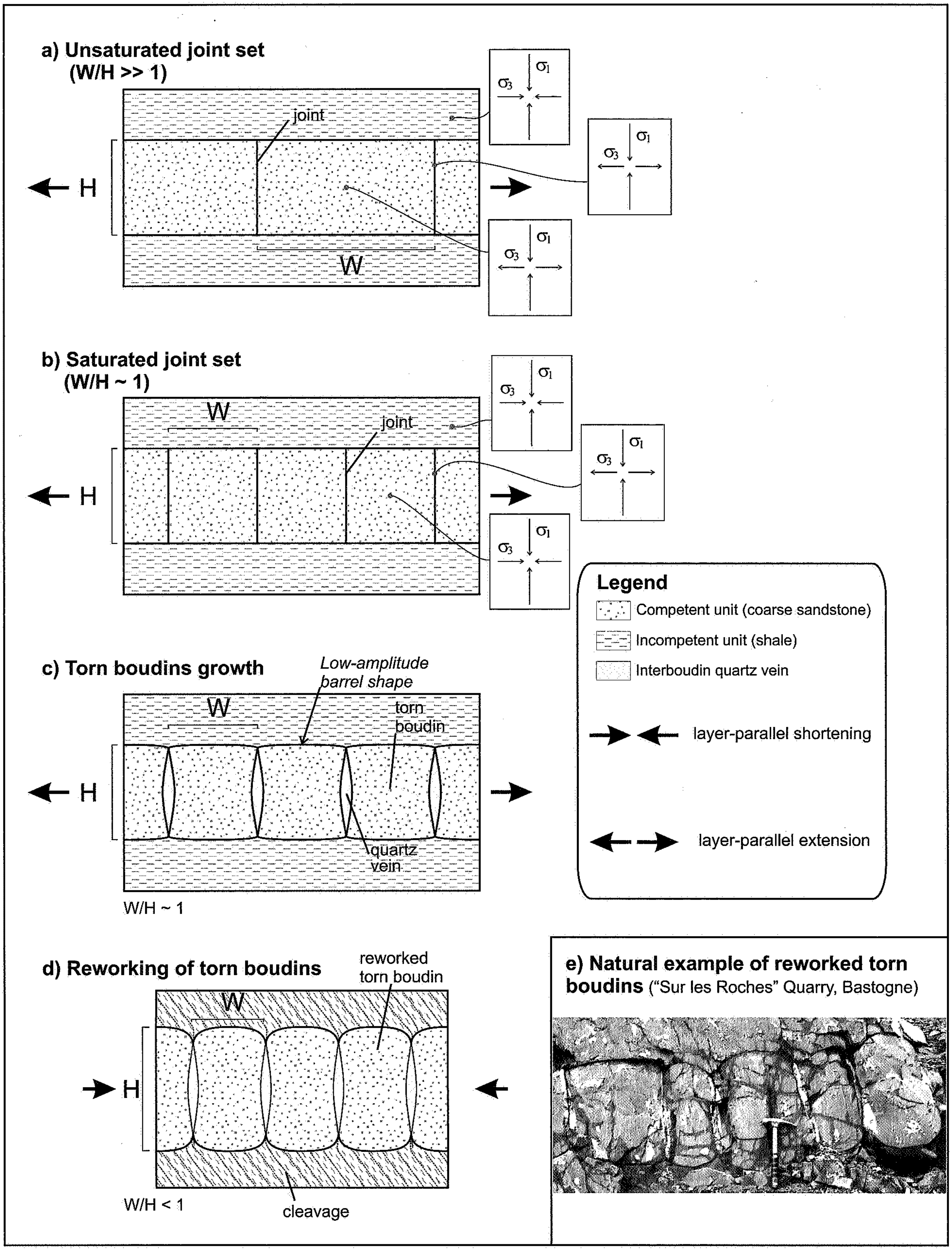


Figure 6.1 Model of the development of reworked boudins. W and H represent the boudin width and thickness, respectively. a)-c) Development stages of narrow boudins during a layer-parallel extension period, d) Reworking of the torn boudin during a layer-parallel shortening event. Note the modification of the stress conditions within a layer segment before and after fracture saturation (a-b).

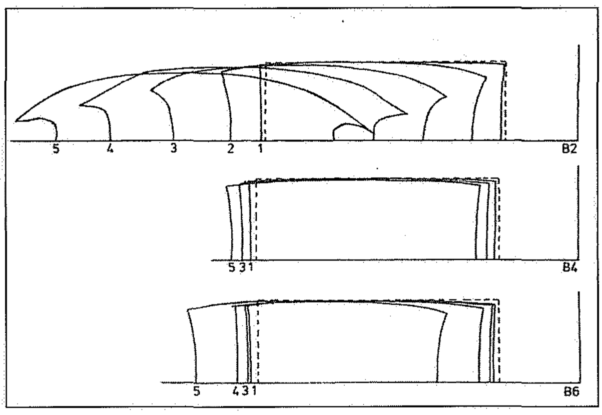


Figure 6.2 Variation in boudin shape according to its mechanical behaviour. "Soft" boudins (B2) adopt a significant barrel-shaped geometry, whereas "Strong" boudins (B4 & B6) show a low-amplitude barrel-shape. Note the relationship between the geometry of the interboudin space and the boudin envelope. Numbers 1 to 5 represents different deformation stage (from Lloyd & Ferguson, 1981).

had already acquired a small-amplitude barrel-shaped geometry, while Kenis et al. (2002, 2004) assumed an unperturbed segment envelope.

Our model does not follow the so-called model of boudinage by successive ruptures of Ramberg (1955, see also Section 4.2 and Figure 4.1). In Ramberg's model, the tensile fracture happens one by one with a period of separation of boudin blocs between the successive ruptures. As a result, irregularly-spaced boudins are formed (see Fig. 4.2.a). In our model, all tensile fractures (joints) are formed before the separation period, which is indicated by the opening and filling of the tensile fractures. The regularly-spaced boudins observed for instance throughout the Ardenne-Eifel region follows this second model. We consider that both boudinage processes exist, but reflect certainly different mechanical behaviours.

The difference between our model and other recent models will be further discussed in Chapter 8.

7. Field observations

7.1 Introduction

In this chapter, we present new field structural observations focused on structures associated with the reworked boudins from the Ardenne-Eifel region. They underwent the same tectonic evolution as the reworked boudins (e.g. a period of layer-parallel extension followed by a period of layer-parallel shortening), but do not share all their characteristics. The differences are related mainly to the sedimentary successions that contrast with the well-defined sandstone layer embedded between two thick shale or siltstone units. The lithologies are the same (i.e. sandstone-siltstone-shale), but the thickness of the fine grain size units may be relatively small and hence the sandstone layers start to influence one to other, especially during the layer-parallel extension period. As a result, the quartz veins exhibit a less-regular distribution. In addition, some veins propagate through the bulk of the sedimentary succession and other deformation processes such hybrid shear failure can occur.

Four categories of sedimentary assemblages have been encountered in the Bastogne-Flamierge area during our study. They are classified according to the relative amount of fine grain size lithologies with respect to the sandstone layers:

- a **shale unit** (Fig. 7.1.a) is composed of a thick succession (several meters to tens of meters) of shale layers (amount > 90 %) only interrupted occasionally by an isolated sandstone bed. The shale layers are possibly associated with cm-thick sandstone lenses (connected or not) in a lenticular bedding succession. The associated structures and even quartz veins are uncommon in such unit.
- a **shale-dominant unit** (Fig. 7.1.b) corresponds primarily to dm- to m-thick shale layers (> 50 to < 90 %) separating thinner well-individualized sandstone layers. In such units well-formed reworked boudins are commonly observed. Units mainly composed of siltstone layers instead of shale are for the sake of simplicity also designated as shale-dominant units.
- a **sandstone-dominant unit** (Fig. 7.1.c) involves cm- to dm-thick sandstone beds (amount > 50 and < 90 %) interlayered with thinner shale horizons. These assemblages favor the development of complex associated structures, even if some reworked boudin trains can also be found within individual sandstone beds.
- a **massive sandstone unit** (Fig. 7.1.d) is made up almost exclusively by dm- to m-thick sandstone layers (> 90 %) separated by very thin (often cm-thick) fine grain sedimentary contact. No reworked torn boudins are developed in this succession, but complex sets of quartz veins are observed.

The division of a sedimentary succession into units is sometimes subjective and so a shale-dominant succession can be subdivided for instance into a sequence composed of shale sub-units separated by sandstone-dominant or massive sandstone sub-units. Practically, we reserve the term "unit" to designate a sedimentary succession at least a few meters thick showing the distinctive characteristics of the other units. In some cases, this parting is obvious, while in others it is more subtler and will therefore be pointed out.

In the following section, we present first our observations in the Flamierge-Bertogne area and then those form the city of Bastogne. The studied sites are located on the geographical map of Figure 7.2.

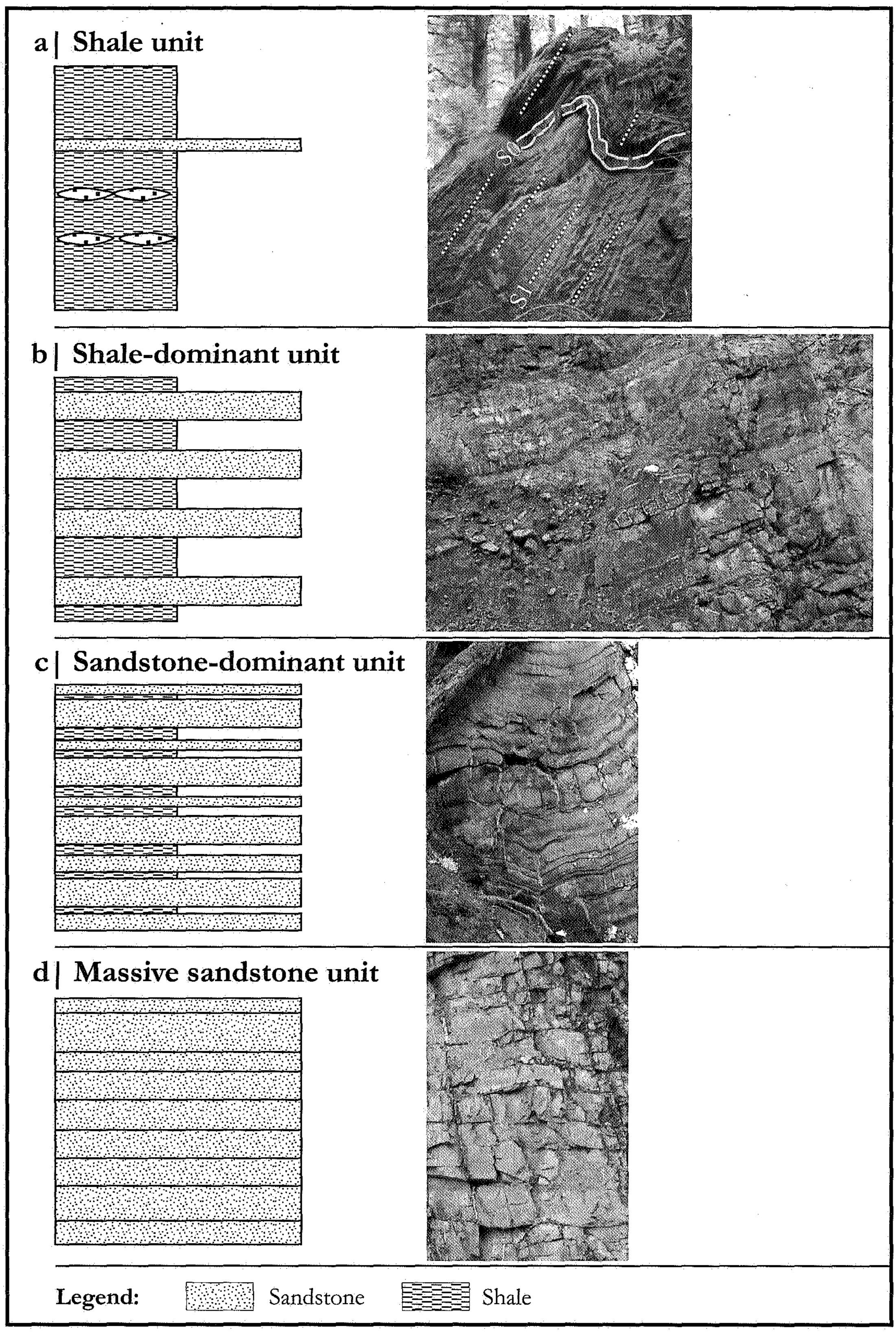


Figure 7.1 Models of the different sedimentary successions encountered during this study. Each model is exemplified with a real case. a) shale unit (example from the "Ferme du Grand Vivier" sections). S0: bedding plane marked by an isolated sandstone layer with yellow lines, inter-reworked boudins quartz veins are represented in red and S1: cleavage plane trace within the shale layers (white dashed lines). b) shale-dominant unit (example from the Mardasson Quarry, Bastogne; c) sandstone-dominant unit (from the "Ferme du Grand Vivier sections); d) massive sandstone unit (from the "Lambert Quarry"). These sites are described in the text and located in Figure 7.2.

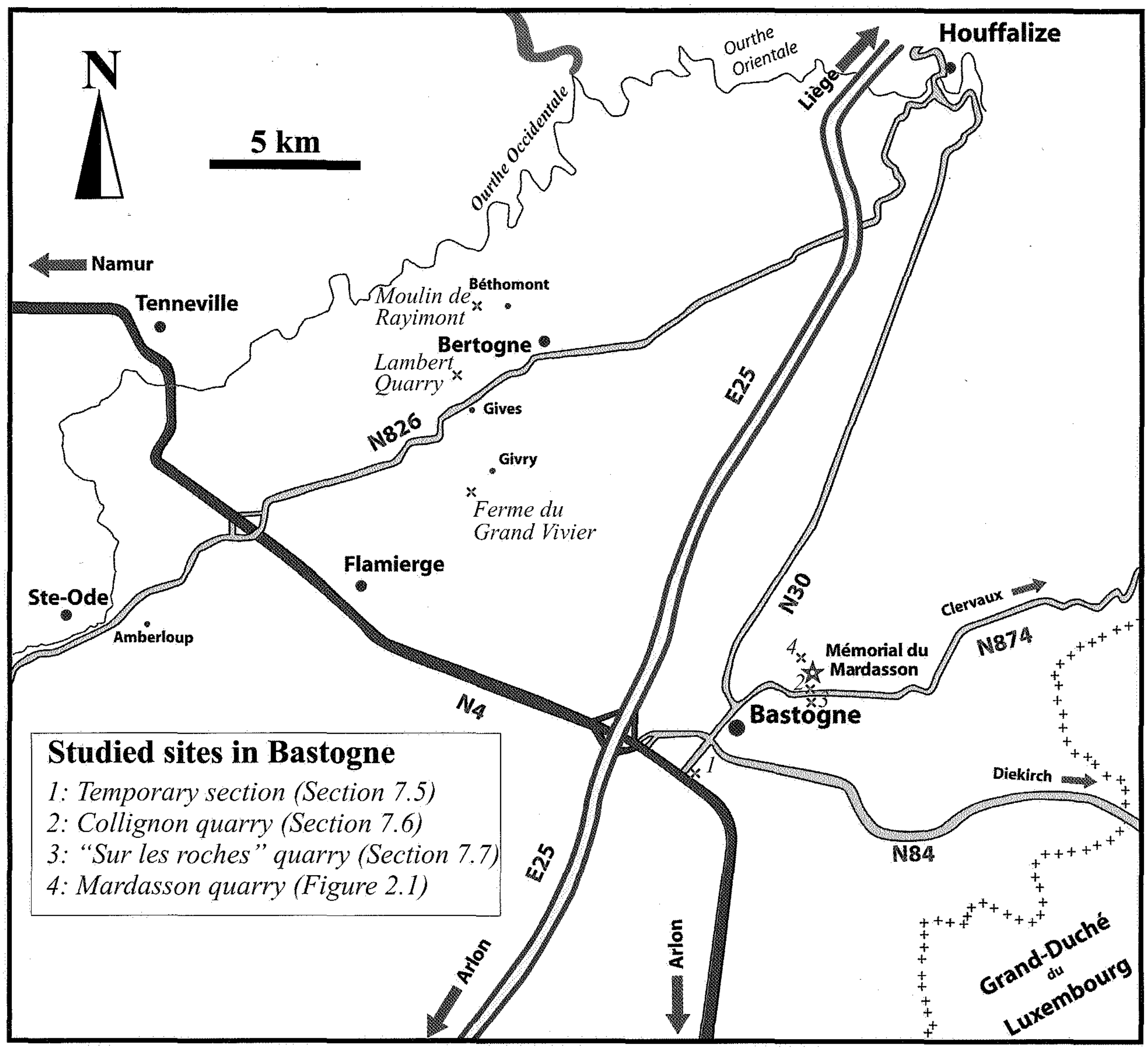


Figure 7.2 Location map of the studied sites in the Bastogne and Flamierge area.

7.2 "Ferme du Grand Vivier" sections

This outstanding outcrop zone (Geological Survey of Belgium:GSB points 196E338 and 196E340) is located 1 km SW to the village of Givry along both Givry stream banks (Fig. 7.3). The sections are composed of a set of separated outcrops usually ten meters long and three to four meters height.

The exposed rocks at this site belong to two major units: the first is a sandstone-dominant unit, while the second is a shale unit. The selected section (section A) exhibits rocks of the sandstone-dominant unit, which is composed of cm- to dm- thick sandstone beds interlayered with cm-thick shale beds. The sandstone beds are rich in sedimentary structures: cross-bedding, parallel-bedding, wavy-bedding in a flaser bedding sequence.

The slate unit is rather more uniform and is composed of a shale matrix interlayered with single or connected flat sandstone lenses (lenticular bedding). A mm- to cm-thick spaced cleavage is well-developed within this unit. The mean cleavage plane strikes N26°E and dips SE 51°. Only a few open and low-amplitude fold structures are observed. The quartz veins are rare and the reworked torn boudins are only observed into a dm-tick isolated sandstone layer (see Fig. 7.1.a). In the vicinity of this isolated sandstone layer fold structures show a smaller wavelength and larger amplitude than those observed in other parts of the shale-unit.

The main section presented in this memoir is located on the southeast riverbank. It is oriented WNW-ESE and is about 9 m-long for 3 m-height. The sedimentary sequence (Fig. 7.4) is composed of cm- to dm-thick sandstone beds interlayered with cm-thick slate beds including connected or single flat lenses of sandstone. The sandstone beds are frequently characterised by cross-bedding structures or less frequently by parallel-bedding structures.

This sedimentary succession is affected by a set of small-amplitude folds and undulations (Fig. 7.5.a-b) with a mean hinge direction of N32°E. The fold axes are horizontal or a plunge gently (~4-7°) toward the SW. A complex network of blocky and milky quartz veins cut the bedding planes at a high angle. Two major groups of veins can be distinguished. The veins of the first group are restricted to two beds (k and g layers in Fig. 7.4) and are linked with reworked boudins. These veins (oriented N34°E) are lens-shaped, normal to bedding and arrested at the sedimentary contacts with the surrounding shale beds. No significant offset can be observed parallel the vein walls and they are classified as tensile or open-mode fractures. On the ESE-side of the section, the quartz veins affect more than one layer and the resulting structures are multi-layered reworked boudins.

The second group of veins are oriented N30°E and dip ~60° SE. They are usually thicker than the interboudin veins and cut the bulk of the exposed sedimentary succession, i.e. these veins affect both the sandstone beds and the shales. Correlations between vein walls indicate that the fracturation involved both open-mode and vein-parallel offset. They are interpreted as "hybrid shear fracture" (see Section 5.1). No slickenside have been observed along these veins.

The vein thickness of the hybrid shear fractures is highly variable with a more or less "pinch-and-swell-like" geometry. It is however difficult to determine if the veins were boudinaged after their formation or if it is naturally developed geometry during the vein formation. In this latter case, the thickness variation could be influenced by the lithologies of the vein walls. In fact, there is a clear relationship between the vein thickness and the composition of the vein walls. Figure 7.6. shows examples of the relationship between the quartz vein thickness and the involved lithologies. In these examples, the relationship

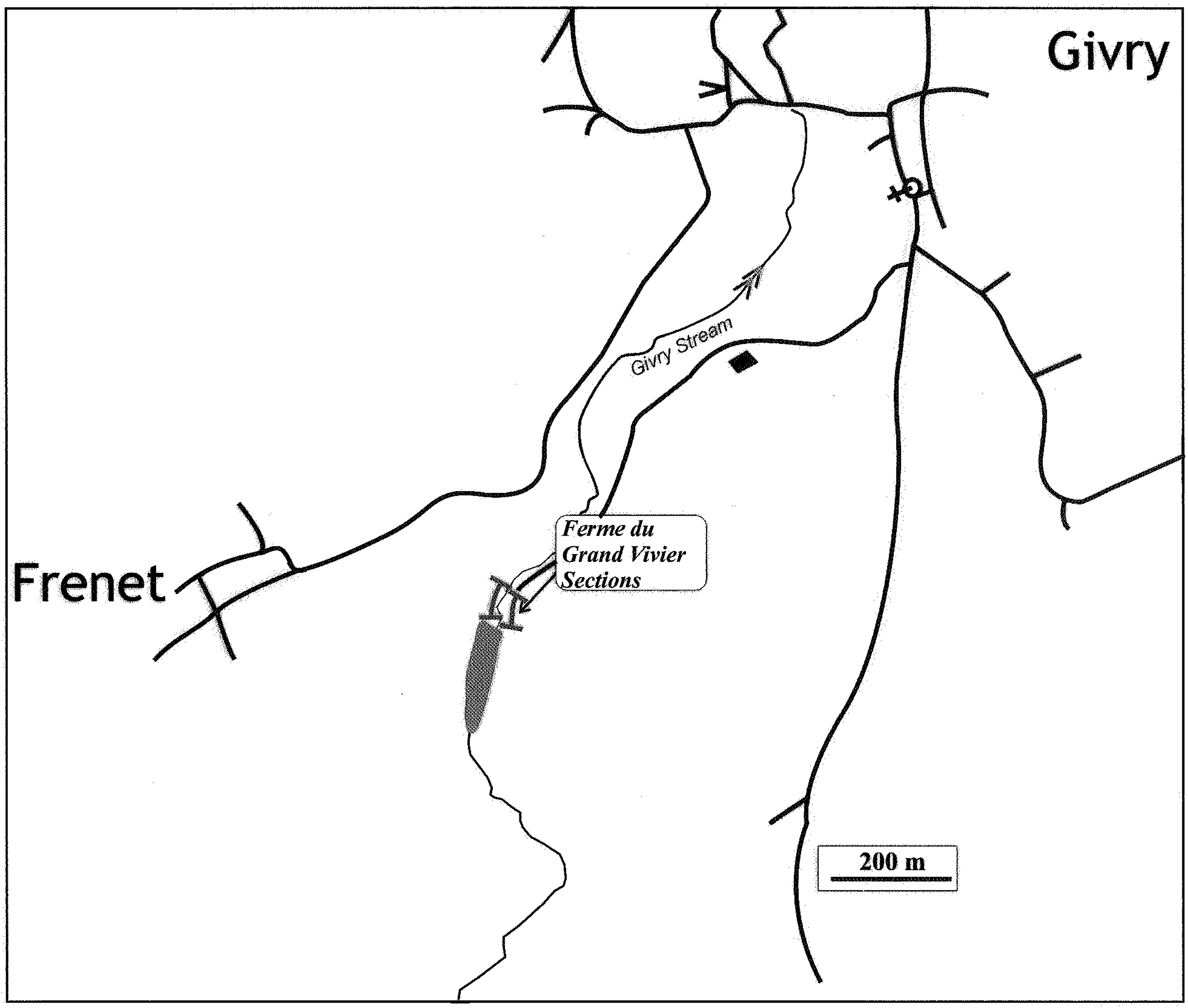


Figure 7.3 Topographic location map of the "Ferme du Grand Vivier" site.

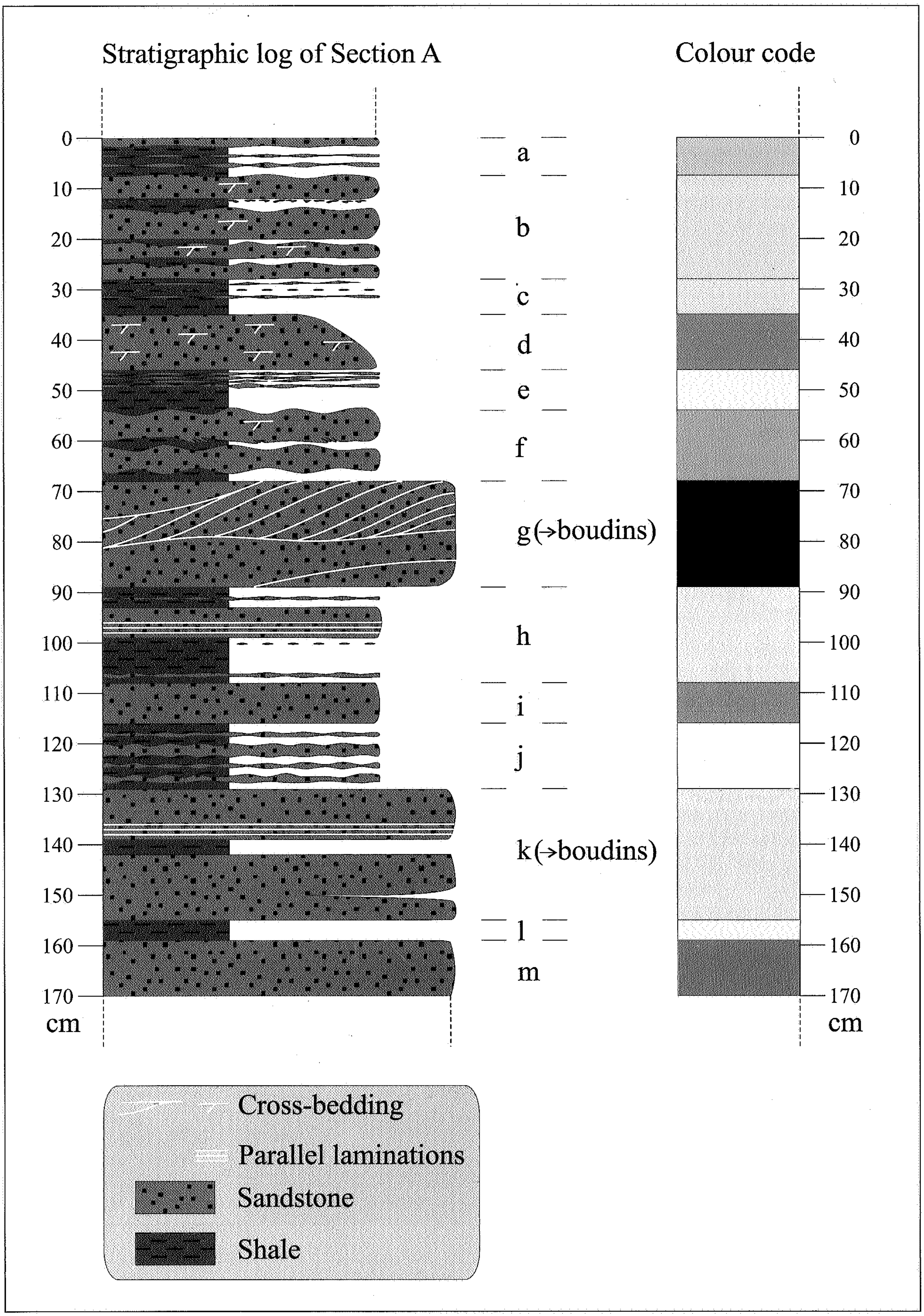


Figure 7.4 Stratigraphic log of the WNW end of Section A and the corresponding colour codes applied in Figure 7.5.

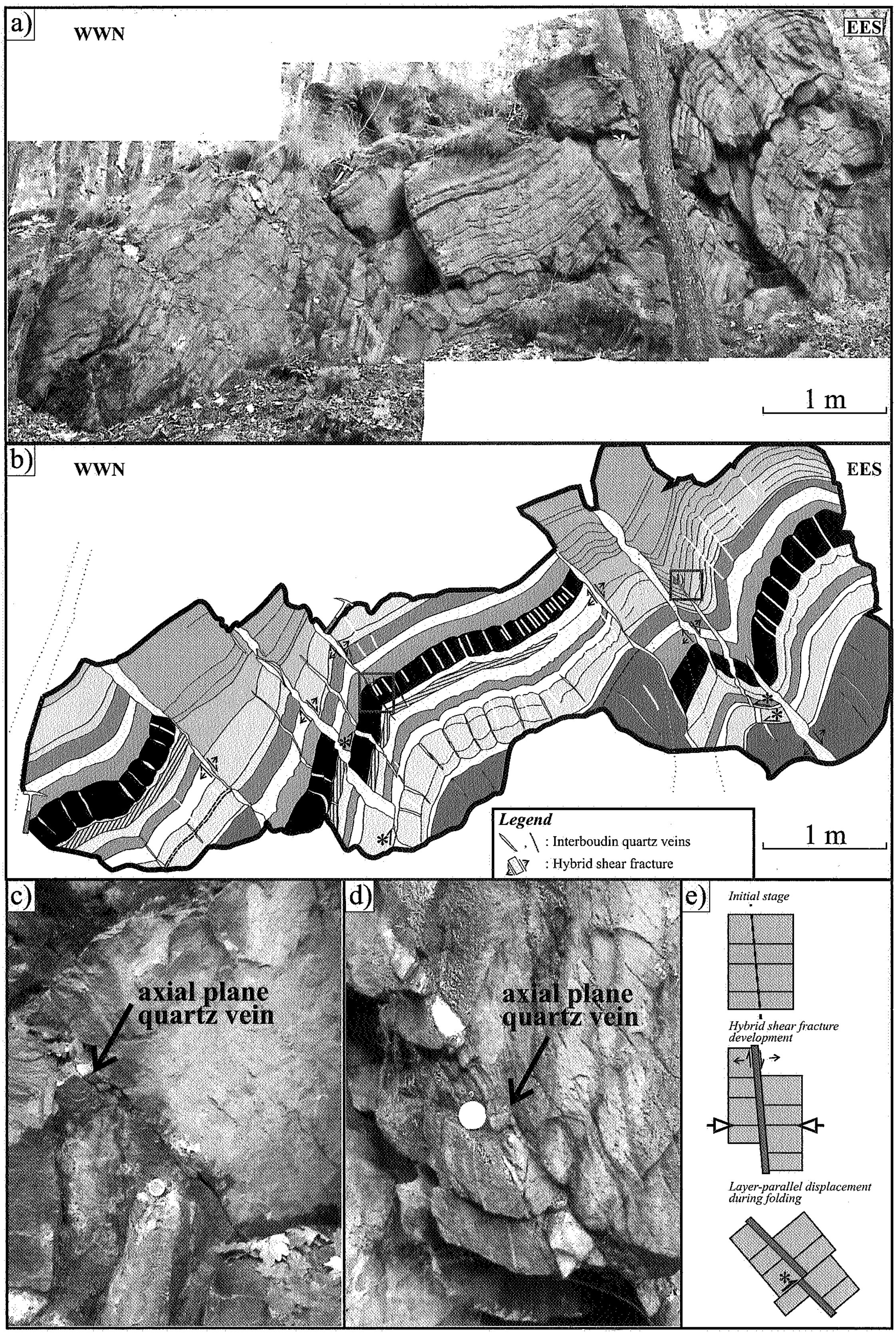


Figure 7.5 Ferme du Grand Vivier site. a) Picture of Section A, b) same section with the stratigraphic and structural interpretation, c) and d) details of axial plane quartz veins (see red squares in b for location), e) Sketch of development of an offset vein by layer-parallel displacement. The open arrows represent the only potential displacement plane due to the juxtaposition of layer contacts on both sides of the hybrid shear fractures (dark grey). These offset veins in Section A are indicated by the symbol (*) in b).

is clear, since the vein-parallel offsets are negligible. However in other instances, the composition of the vein walls changed constantly because of vein-parallel displacement and the vein thickness was strongly affected by this activity. The vein thickness variation can therefore reflect a variation of composition of the vein walls during apparent normal offset activity rather than a later vein-parallel stretching.

"Hybrid shear fractures" and fold structures

The hybrid shear fractures are observed in Section A as two swarms separating the portion of the section affected by reworked torn boudins (Fig. 7.5.a & b). In addition, both swarms are closely related to the fold structures. Some of the hybrid shear fractures, not all, are located within the fold axial planes (Fig. 7.5.c & d). This parallelism between fold structures and some veins is therefore a significant observation for the region and the implications will be discussed later.

Some hybrid shear fractures are clearly located within the axial fold planes and others are simply at a high angle to the bedding plane within the fold limbs. In addition, a layer-parallel displacement along some layer contacts cut some of these veins (see * in Figure 7.5.b). They were thus the sites of two different forms of displacements: first, a vein (or fracture)-parallel displacement with an apparent normal offset and then a layer-parallel displacement. The latter is concordant with flexural-slip model. The offset of the veins offers therefore a good example for this model. However an even more complex picture should be drawn from our observations. In fact, in a classical flexural-slip model, the shear displacement should be observed along all layer contacts, but in Section A, these displacements are only observed along some particular interfaces, i.e. some layer contacts have not undergone any displacement. This complexity is closely related to the sedimentary sequences on both sides of the veins. For instance, if a sedimentary contact on one side of fracture butts against the vein and the middle part of another layer of the opposite wall, it is unlikely that any displacement could occur along the interface during the fold formation (Fig. 7.5.e). In contrast, if the hybrid shear fracturation and the associated normal offset put face-to-face two layer interfaces on each side of veins (see open arrow in Figure 7.5.e), they will represent a potential slipping surface during the flexural-slip. The probability for two layer contacts being arranged face-to-face after the formation of the hybrid shear fracture is low and depends on the fracture-parallel displacement and the thickness of layers. However, the juxtaposition of a layer interface on one side with a weak shale bed on the other side of the fracture is likely to increase the probability of displacement along the bedding during folding.

The observation of offset veins by the layer-parallel displacements implies that the hybrid shear fractures and therefore the associated veins pre-date the fold formation. This relative age is the same as the one assumed in literature for the interboudin veins. In parallel, veins cut by the layer-parallel displacements have the same orientation as those within the axial plane and all these veins belongs to the same swarms. We therefore consider that axial plane veins also pre-date the fold formation. This result is significant since it is counter-intuitive. In fact, the presence of an axial plane quartz veins could reasonably be regarded as a late infill of an axial plane fracture or

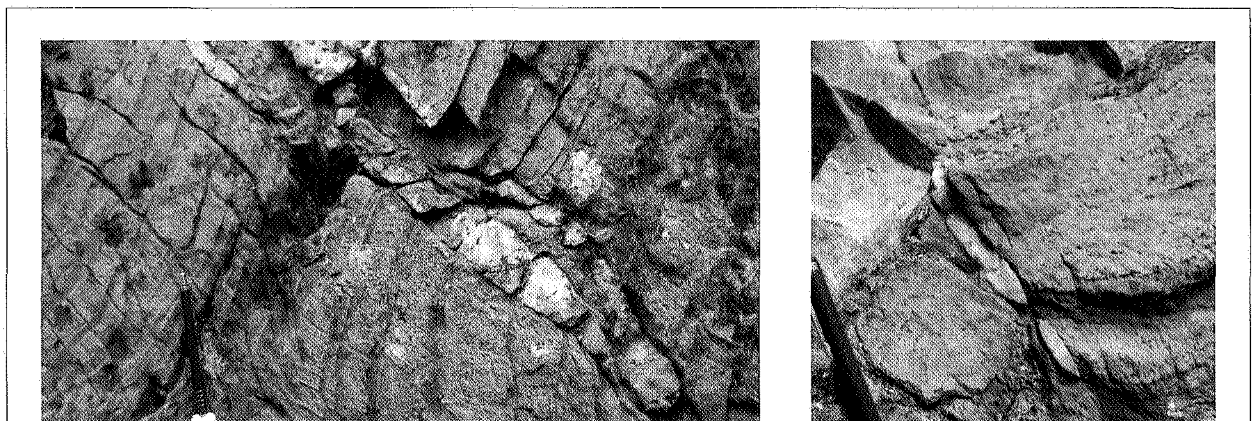


Figure 7.6 Examples of the relationship between the vein thickness and the rock types. Shale layers appear darker on the left picture and more eroded on the right one.

an open-mode fracturation as frequently observed at the outer arc of folds. It is actually the contrary situation, namely folds were formed around some veins or put differently some veins seem to localize the fold formation. During the folding, others veins (i.e. those not located in the hinge zones) were possibly cut by the layer-parallel displacements due to the flexural-slip.

"Hybrid shear fractures" and reworked torn boudins

As noticed earlier, section A exposed two major categories of quartz veins: hybrid shear fractures and those associated with reworked boudins. From the sole observation of section A the relationship between the two sets of veins is not apparent, since they do not occupied the same position.

Nevertheless it is noticed that both types of veins pre-date the folding. The main argument for the hybrid shear fractures is the bedding-parallel displacements (see previous section). The geometry of the layer segments constitutes indirect argument that leads us to also consider inter-boudin veins as older than folding. In fact, they present all the elements of classical reworked boudins with the extreme bi-convex geometry.

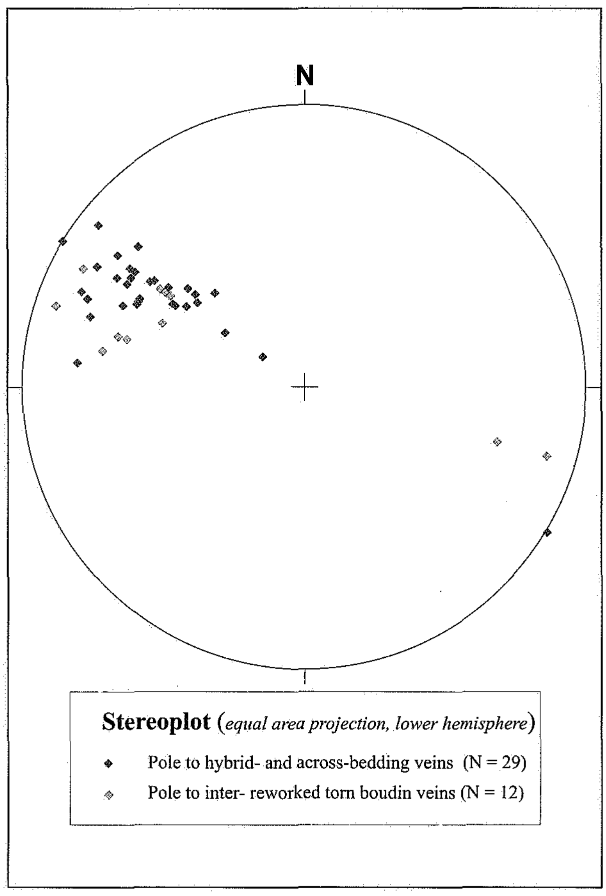


Figure 7.7 Stereoplot of poles to hybrid shear fractures and across-bedding veins (blue diamond) and reworked boudins (red diamond) from the "Ferme du Grand Vivier" sections.

The different location for both types of veins through the section does not allow the establishment of a relative age, since there is no intersection between the various veins. Nevertheless the veins are more likely related to the same tectonic event, since they show the same orientation (Fig. 7.7). The coexistence of both single-layered open fracture and across-bedding hybrid shear fractures during the same tectonic event should be investigated in the future.

7.3 Lambert quarry

This outstanding outcrop (GSB point: 196E263) is located about 1250 m NNE of the village of Gives (see Fig. 7.2 for location). Goemaere and Dejonghe (2005) have recently studied this quarry mainly for its sedimentary and paleoenvironment content. The sedimentary sequences and structures reveal a tidal flat paleoenvironment with a vertical stacking of sub-environments. The subsidence rate was high with a constant influx of clastics (Goemaere and Dejonghe, 2005).

Observations described in this memoir were carried out for the structural geology interest of the quarry. The same numbering of lithological units as Goemaere and Dejonghe (2005) was used. However some of their units have been subdivided into sub-units.

Our investigations focus mainly along the larger face of the quarry (Fig. 7.8) that is oriented NW-SE and is about 130 m long. The section is characterised by a uniformly dipping bedding plane with a strike N30°E and a dip of 25° towards SSE.

The sedimentary sequence along the main face can be divided from bottom to top into:
unit 3: a ~9 m-thick **shale unit** associated with siltstone layers
unit 4: a 11-12 m-thick sandstone succession exploited for building stones and aggregates. This unit can be separated into a lower **massive sandstone sub-unit** composed of dm-thick sandstone beds interlayered with mm- to cm-thick shale-siltstone beds, whereas the upper part of the succession is richer in fine-grain material with sandstone beds interlayered with siltstone horizons. The latter should be regarded as a **siltstone-dominant sub-unit**.
unit 5: a 3 m-thick blue **shale unit**.
unit 6: a 10 m-thick composite entity including a lower **siltstone-dominant sub-unit** overlain by a **sandstone-dominant sub-unit**.
unit 7: a 9 m-thick **shale unit**
units 8 and 9: represent the SSE-end of the face and are composed of a 2 m-thick **sandstone bed** and a **shale unit**, respectively.

These units are represented by white numbers in Figure 7.8. Detailed sedimentary description of each member

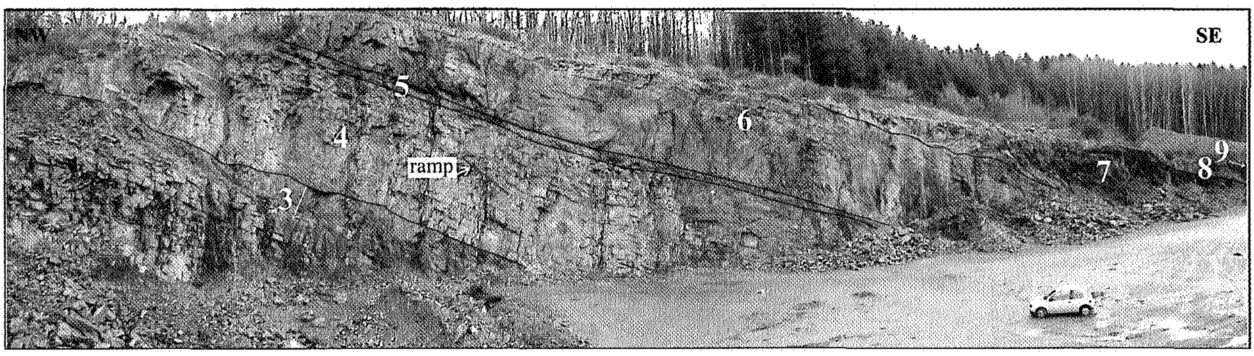


Figure 7.8 Main face of the Lambert Quarry. White numbers refer to the various sedimentary units as defined by Goemaere and Dejonghe (2005). See text for details.

(including members 1 and 2 located along a lateral profile and not developed in this work) can be found in Goemaere and Dejonghe (2005).

This division of the sedimentary successions into units or sub-units is based on the structural geology and mainly on the quartz veins. The latter are mainly restricted to the massive sandstone and sandstone-dominant units that is, mainly the lower half of member 4 and the upper part of member 6, while within the other parts of those members the quartz veins are confined to the sole sandstone layers. By contrast, mudstone-siltstone units (No. 3, 5, 7 and 9) are almost devoid of quartz veins. Observations of some structures within units 4 and 6 are discussed.

7.3.1 Structures of unit 4

The sparseness of fine material in the lower unit corresponds to the development of an outstanding number of milky quartz veins cutting the bedding plane at a high angle. Different categories of veins are observed. Some are limited to a single bed, namely they terminate at the sedimentary contacts, while other veins affect the bulk of this massive sequence. The deformation patterns and mechanisms of formation of the different sets of veins and fractures are first discussed. Then a particular structure located at the interface between units 3 and 4 is analysed. Finally, a ramp structure in the middle part of the unit 4 is described.

Veins and fractures

The through going veins cutting the bulk of the massive-sandstone sub-unit represent the most striking structural features observed in this sedimentary succession (Fig. 7.9). They are perpendicular to the bedding planes and can be grouped into en-échelon sets with some sigmoidal veins. Some of these veins can be also classified as "hybrid shear fractures", since in addition to the open-mode fracturation they clearly exhibit a vein-parallel offset. The apparent displacement is normal, but the presence of quartz fibrous within some veins indicates a significant strike-slip component.

The single-layered veins are scattered across the profile and there is no clear regular distribution, which usually characterised boudinaged layers. In addition, the veins are not associated with reworked torn boudins and they actually divide the sandstone layers into orthogonal segments. Some of these veins cut 2 or 3 layers, but their path are interrupted by the fine-grain interlayers. The veins appear therefore as a dashed line. The vein thickness ranges between mm- and few cm. A few of these single-layered veins are cut by "hybrid shear fractures" (Fig. 7.9),

Figure 7.9 Example of a single-layered vein (see red arrow) cut by a "hybrid shear fracture". Note the presence of a "single-layered" vein to the right (see green arrow). The latter induced the formation of an aligned vein within the underlying bed (see yellow arrow) and a slightly offset vein above (see orange arrow).

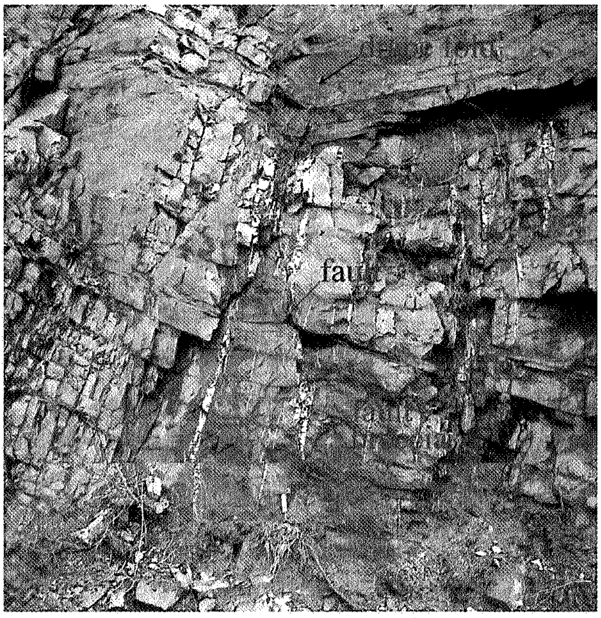


Figure 7.10 "Normal" fault cutting a hybrid shear fracture. The fault is associated with a fault breccia at the outcrop bottom, while upward the fault is replaced by a drape fold.

which indicates a two-stage vein development, beginning with single-layered veins followed by the hybrid shear fractures. The mean strike of all these veins is N43°E, but the values range between N20°E and N56°E. The mean dip angle is NW 81°.

The random distribution of the single-layered veins is restricted to the massive sandstone sub-unit, while regular-spaced single-layered veins affect the sandstone beds belonging to the overlying siltstone-dominant sub-unit. These veins are associated with reworked boudins. We consider that the lack of boudins within the massive sandstone unit is not the result of a different generation of veins, but it is more likely to be related to the lack of incompetent materials, which is one pre-request for the boudin development.

In addition to the single-layered veins and the hybrid shear fractures, some faults within the massive-sandstone sub-unit cut the bedding planes with a high angle, but lower than the quartz veins. Figure 7.10 shows an example of such a fault with a mean strike of N40°E. Its path is however irregular. The dip angle in the lower part of the profile is steep (82° towards NW) and is associated with fault breccia composed of quartz cement and fragments of sandstone beds, while in the middle part the dip angle is 76° towards SE and the fault corresponds to a single slip surface cutting single-layered veins and hybrid shear fractures. Hence the fault should be regarded as a late event within the deformation sequence with respect to the vein formation. Finally, the fault dies out upward passing into a drape fold (for definition see Price & Cosgrove, 1990) within the overlying siltstone-dominant sub-unit.

Sedimentary contact structure

All the veins observed within unit 4 disappear downward before or at the contact with underlying unit 3, which is devoid of any veins. The general trend of this contact is flat, but a set of small-amplitude undulations can be observed. An example of these undulations (Fig. 7.11) is particularly well-developed in the NNW-end of the main quarry face. The envelope exhibits there a trapezoidal shape associated with a set of cusps and lobates. In parallel, a series of quartz veins exhibiting a fan distribution affects the lower part of unit 4.

This structure indicates that even if the quartz veins observed within lower part of unit 4 are not associated with boudin, they are present because of the lack of fine-grained material within the unit. Where the quartz veins reach the contact between the massive sandstone sub-unit and the underlying shale unit the sedimentary interface displays the common cusp and lobate geometry. The architecture is however slightly different, since in commonly observed reworked boudin trains, the cusps and lobates are regularly-spaced, while in this case, all cusps and lobates are located in a single zone. The latter also corresponds to an area of high-density in quartz veins in unit 4. Such high density of in quartz veins and related deformed contact are however rare along the contact, which is mainly flat (see Fig. 7.8). The dying

Figure 7.11 Deformed sedimentary contact between units 3 and 4 (see white numbers). The contact exhibits a series of cusps and lobes.

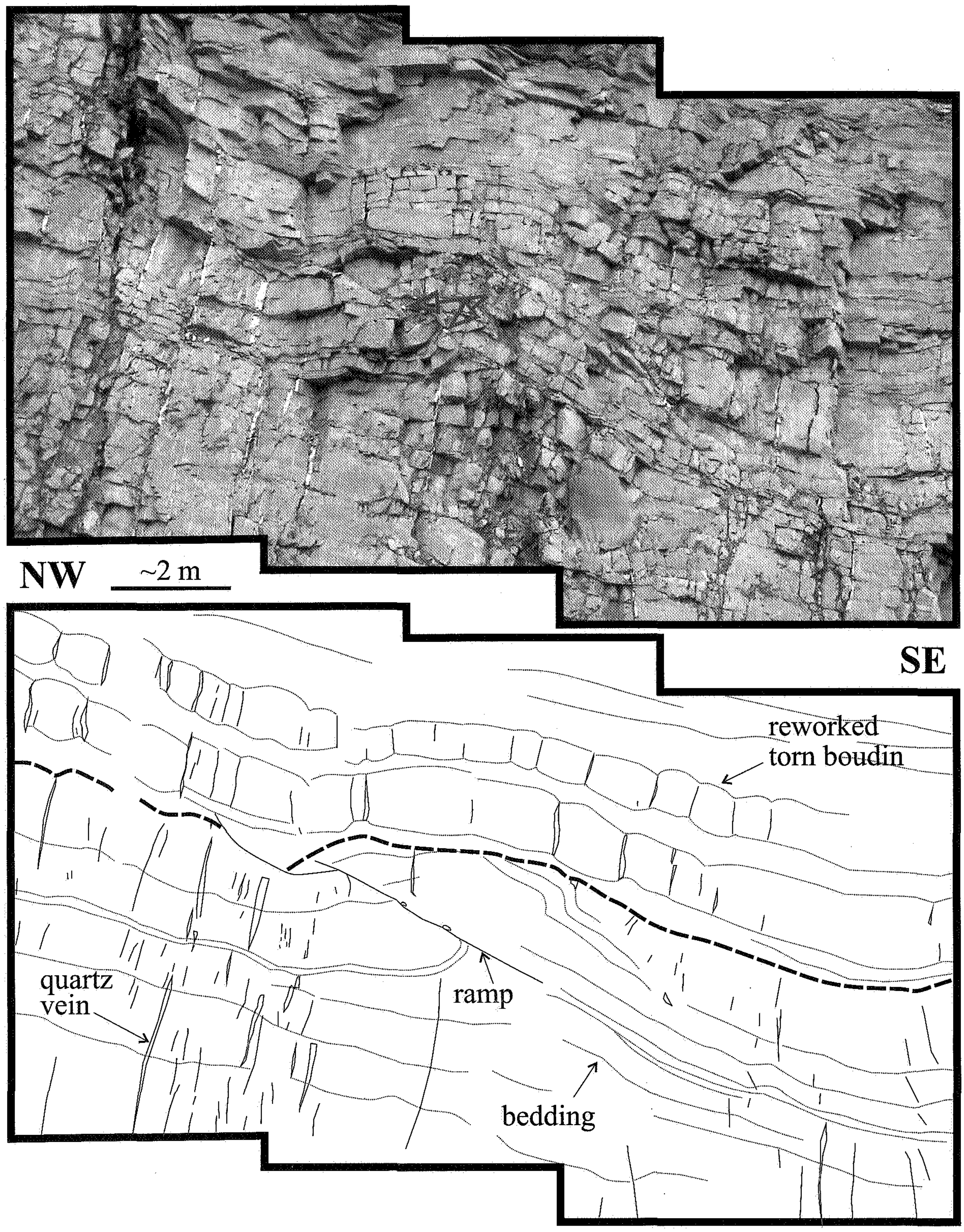


Figure 7.12 Picture and line drawing of the ramp structure at the top of the massive sandstone sub-unit. The limit between this sub-unit and the overlying siltstone-dominant sub-unit is indicated by the thick dashed line. Note the presence of two reworked torn boudin trains developed into two particular sandstone layers belonging to the siltstone-dominant sub-unit. The two red open arrows in the picture indicate the location of small quartz vein lenses.

out downward of most of the veins before they reach the contact explains this scarcity of the deformed contact. The significance of this structure will be further discussed later in this memoir (Section 7.7).

Ramp structure

The next structural feature described is not directly related to the formation of the reworked boudins or the associated structures, but its analysis constrains the deformation sequence. It consists of a flat and ramp structure affecting the middle domain of unit 4 (Fig. 7.12 and see Fig. 7.8 for location), that is, the boundary between the massive sandstone lower sub-unit and the upper siltstone-dominant sub-unit. The south-dipping ramp cuts the massive sandstone layers at an angle of ~13°. Downward, the fault becomes parallel to the bedding plane along a thin mixed siltstone-sandstone bed. The ramp climbs upward in the form of breaching faults affecting the first siltstone beds of the upper sub-unit. Quartz vein lenses are located along the ramp surface and are interpreted as previous quartz veins cut and displaced during the ramp growth (see arrows in Figure 7.12). Other veins seem to have undergone a deformation linked to a shearing along the ramp. The latter is also responsible for the development of an open and small-amplitude anticline structure.

Figure 7.12 clearly demonstrates the difference into the quartz vein distribution between the two sub-units. Below the boundary (see thick dashed line in Figure 7.12) the quartz veins do not show any clear distribution, while they are more regularly-spaced within the two overlying sandstone layers of the siltstone-dominant sub-unit. In addition, the reworked torn boudins are only observed within the upper sub-unit and below the limit the layer segments are orthogonal.

7.3.2 Structures of unit 6

Unit 6 exhibits a sedimentary succession opposite to that of unit 4, i.e. the coarser material is located in the upper part of the unit. Hence, it is not surprising to observe the quartz veins at the top of the member (Fig. 7.13). By contrast, the lower siltstone-dominant sub-unit is devoid of quartz veins, except in a few very thin (few-cm) sandstone layers. The latter are associated with small reworked torn boudin trains. The interface between units 6 and 7 exhibits a clear cusps and lobate architecture, while the undulations die out progressively downward. This structure should be therefore considered a "reworked torn half-boudins".

7.4 « Moulin de Rayimont » exposures

The outcrops of the Rayimont Valley (Fig. 7.14 & GSB point: 196E243) close to the locality of Bethomont (see Fig. 7.2 for location) exhibit deformation features affecting slate-sandstone sequences of the Mirwart Formation. The exposures are mainly concentrated along the eastern riverbank close to the Rayimont water mill. The outcropping conditions are relatively good composed of numerous small-scale outcrops in the lower part of the valley and some medium-amplitude cliffs (~10-20 m) in the upper part. The structural features presented in this section represent a selection from numerous exposures, mainly located at the limit between the discontinuous outcrop zone and the cliffs.

The local stratigraphic succession can be divided into three units, which are from bottom to top:

- a shale-dominant unit only interrupted by m-scale sandstone beds. The outcrop area is in the lowest part of the valley;
- a middle unit composed of numerous dm-thick sandstone beds separated by thin (cm-scale) shale layers. Following our classification (see Fig. 7.1), this unit should be named as a sandstone-dominant unit;
- a massive sandstone unit forming the upper of the cliffs.

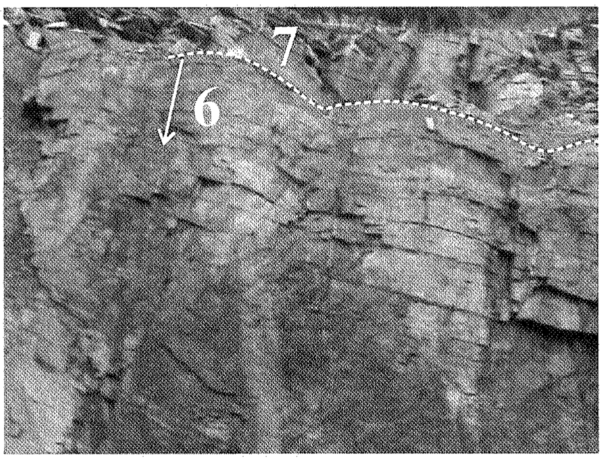


Figure 7.13 Picture of "reworked half-boudins" at the upper part of unit 6.

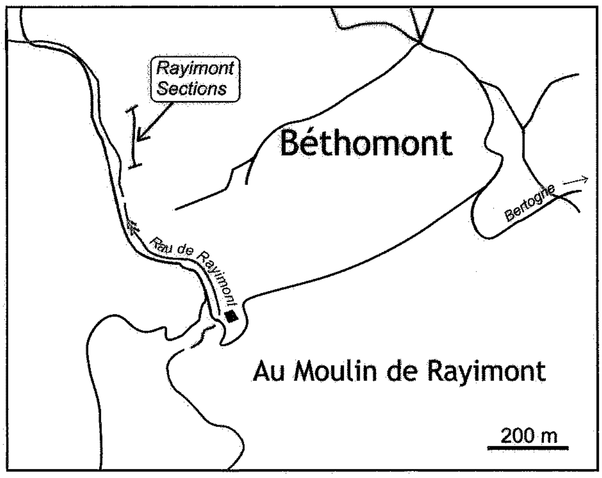


Figure 7.14 Topographic location map of the Rayimont Valley sections.

This site allows a simultaneous observation of deformation features (i.e. veins and folds) for two different units, which are the sandstone-dominant unit and the massive sandstone unit. In the previous sections, both sedimentary assemblages were analysed separately.

The bedding plane envelope in the area of Rayimont water mill is only slightly folded with a minimum wavelength of more than a few tens of meters and the bedding plane dip in the massive sandstone unit is usually of only few degrees. In contrast, the sandstone-dominant unit exhibits numerous small-scale folds with amplitudes of few-dm and with an irregular wavelength. There is therefore a clear disharmonic folding between the sandstone units.

There is also a clear relationship between the presence of small-scale folds and the occurrence of quartz veins. For instance, at the contact between the middle unit and the underlying shale-dominant unit, the sandstone layers are affected by numerous small anticlines (Fig. 7.15.a), each one having a quartz vein along its axial plane. The latter disappear at the contact between the shale-dominant unit and the middle unit. In addition, each anticline is bounded by two small syncline structures devoid of any quartz veins. Such complex fold trains (e.g. an anticline with its quartz vein and the associated two synclines) is observed only locally. Between these points the bedding plane is unfolded and follows the regional bedding plane envelope. Where the spacing between the veins decreases the bedding plane may even adopt a camelback shape (Fig. 7.15.b).

As at the "Ferme du Grand Vivier" locality, there are numerous different structures reflecting specific conditions including sedimentary variations. For instance, the anticlines observed at the contact between the lower and middle units dies out upward in the vicinity of the massif sandstone unit (see Fig. 7.15.c). The quartz veins also change their position as the folds are traced upward moving from the axial plane to the fold limb. In addition, some quartz veins swarms can be followed from the middle unit to the massif sandstone unit. There, the quartz veins thicken and are normal to the flat bedding plane. In other words, the small-scale folds disappear in the massive sandstone unit, but the quartz veins remain present. The association between a quartz vein and a small anticline structure is not the only case and synclines can also be observed in association with a quartz vein. Figure 7.15. d shows an example of a box-shape syncline associated with a complex swarm of quartz veins. This structure is observed within the upper part of the middle unit. Interestingly, the quartz veins at the edges of the swarm are located within the syncline limbs and are sheared along the thin shale interlayers, while the veins in the hinge zone (e.g. middle part of the swarm) are intact. The shear senses are always oriented toward the anticline structures, an observation compatible with the flexural-slip model of folding. Figure 7.15.e shows another example of an axial plane quartz vein in association with a syncline structure. The adjacent anticlines present similar interlimb angle to the syncline, but are devoid of any quartz veins. Along the NW-limb between the syncline and the anticline another very thin quartz vein exhibits a shearing within the shale layers, the sense of which is compatible with the flexural-slip model (see Fig. 7.15.e-inset).

The association between an axial plane quartz vein and a fold structure could be considered at first sight as the result of open-mode fracturation as commonly observed at the outer arc of the fold (i.e. extrados fractures). However this assumption can be rejected, since folds characterised by a quartz vein are bounded by folds with a similar interlimb angle, but without any quartz veins. If the open-mode fracturation was associated with the formation of the folds, one could expect similar veins both in the synclines and anticlines. In addition, the veins cut several layers, while veins formed at the outer arc of folds are restricted the outer part of one single layer. Such observations are incompatible with vein formation by outer arc extension. The change in position of the quartz veins from the fold axial to fold limb seems to be related to the dying out of the fold structures. This reduction of fold amplitude may in some cases be the result of the disappearance of the quartz veins in the vicinity of the massif sandstone unit that was unable to be folded with the same wavelength as the layers of the middle unit (disharmonic folding). Where the veins reach the massive sandstone unit they are not related to any small fold.

The analysis of the observations indicates that the veins pre-date the formation of the folds and the presence of the quartz veins acts as a seed for the localisation of small-amplitude folds. The two main arguments leading to this conclusion are that:

- the veins observed within the axial plane are intact, while those observed along the fold limbs are sheared according to a flexural-slip model;
- at the contact between the shale-dominant unit and the middle unit the position of all anticlines correspond to the tip of quartz veins. Where quartz veins are absent the bedding plane remains flat.

The formation of an anticline or a syncline structure around a quartz vein is not random. At the contact between the slate-dominant and middle units all folds linked to the veins are anticlines (see Fig. 7.15.a-b). At this locality, all the veins taper downward. We therefore suggest that if the vein tip is oriented downward an anticline structure tends to grow around the vein, while a syncline structure develop around a vein ending upward. We suggest a simple model involving to the geometry of the sedimentary contact during the formation of the vein. As already explained in Chapter 6, the formation of lens-shaped vein is associated with a perturbation of the

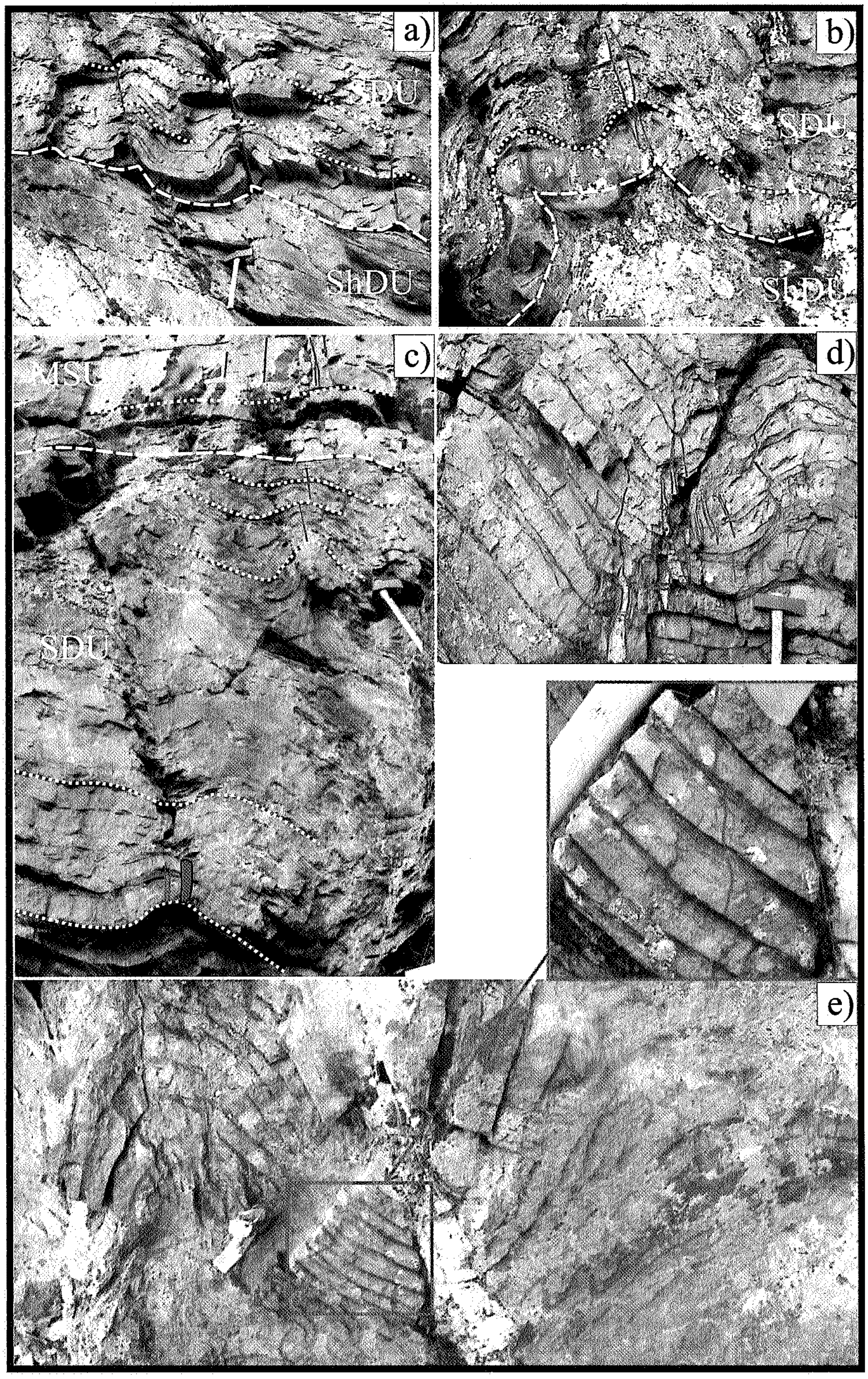


Figure 7.15 Structural features observed in the Rayimont Valley sections. a) Series of small anticlines associated with axial plane quartz veins and the bounding synclines devoid of any quartz veins. The picture shows the contact between the shale- (ShDU) and sandstone-dominant (SDU) units. b) A camelback structure observed at the same contact as in a). c) Dieing out upwards of two anticlines. The anticline in the lower left part of the picture initiates on a quartz vein disappearing upward, while the second one (up-right) dies out in the vicinity of the massif sandstone unit (MSU). The quartz veins associated with the second anticline extend to the overlying massive sandstone unit. In the latter, no small-scale fold is observed. d) Example of a box syncline associated with a quartz vein swarm in SDU. Veins located along the limb are sheared according to a flexural-slip model, whereas those in the hinge zone are intact. e) Another example of a syncline in SDU associated with an axial plane quartz vein. Along the NW-limb (see inset) a very thin quartz vein is sheared toward the anticline hinge. The boundaries of quartz veins are represented as red lines, some bedding planes as dotted white lines and the contacts between the various units as white dashed lines.

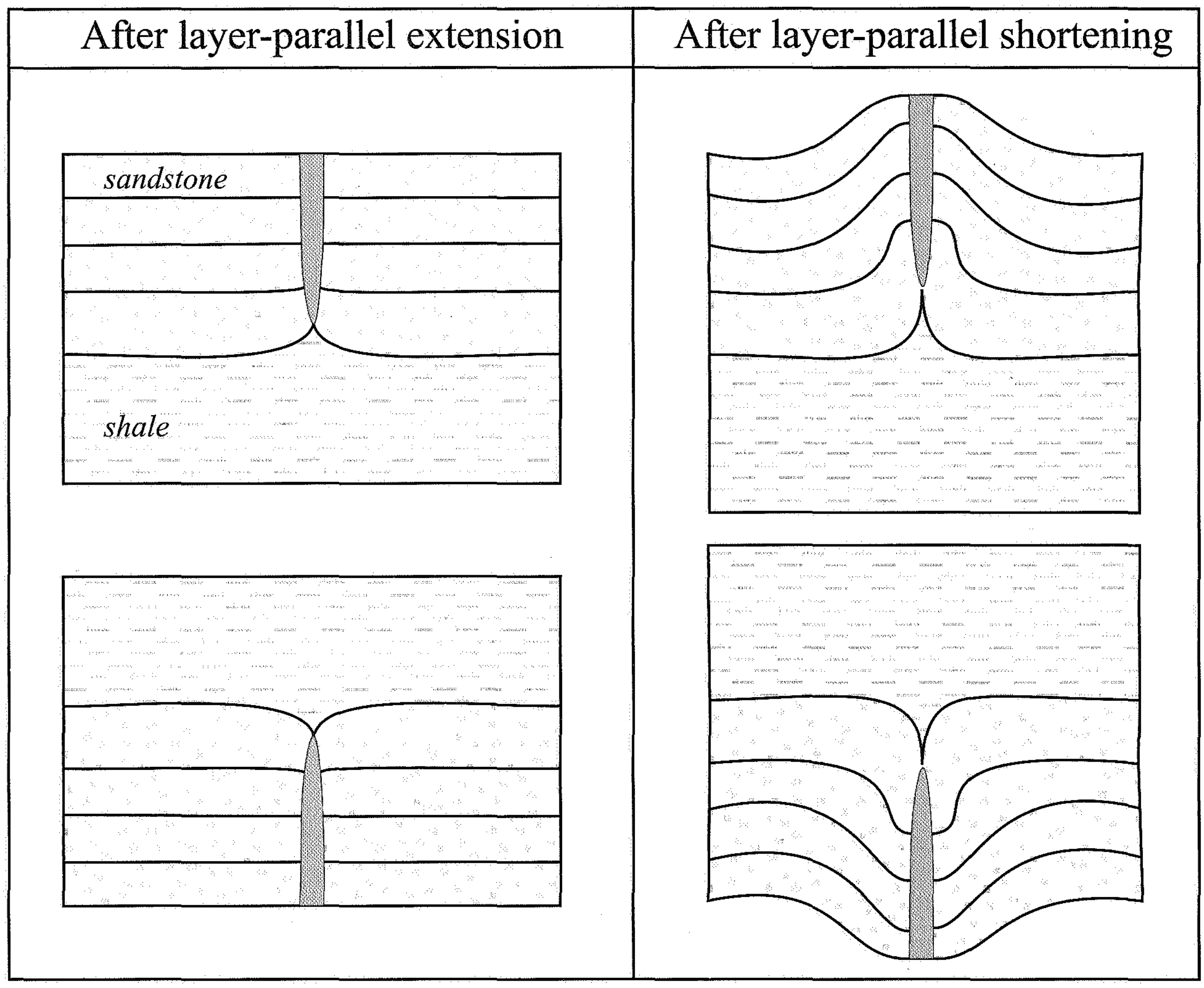


Figure 7.16 Model of development of an anticline or a syncline with an axial plane quartz vein. The cusps structures opposite to the vein tips and are inherited from the layer-parallel extension. They act as nucleuses for the fold development.

sedimentary contact (see also Fig. 6.2). This deformation takes a cusp shape pointing in the opposite direction to the vein tip and during a layer-parallel shortening this small perturbation acted as the nucleus for the formation of folds (Fig. 7.16). As a result, the localisation of deformation is not necessarily a direct consequence of the presence of quartz veins, but can also be related to the inherited deformation along the sedimentary contact. A syncline or an anticline structure is formed if the vein ends upward or downward, respectively (see Fig. 7.16). This model contrasts with Kenis et al.'s (2002, 2004) model and this issue will be further discussed in Chapter 8.

7.5 Temporary exposure in Bastogne city centre

During the winter of 2004-2005, the foundation works for a new building in the city centre ("Rue Joseph Renquin, 36") exposed a temporary section (Fig. 7.17). The studied section (GSB point: 205W203) is ~28 m-long and 2 to 3 m-height. The sedimentary sequence is composed of interlayered slate-siltstone-sandstone beds, which are cut by numerous quartz veins. In its central part, a large quartz vein divides the section into two parts between which no stratigraphic correlation was recognised. Hence the profile includes two sedimentary successions (**a** and **b**). Succession '**a**' is located to the north of the quartz vein and 12 levels have been recognised, while to the south 5 levels make up succession '**b**'.

7.5.1 Details of succession 'a'

a1: Intermediate grey to dark blue shaly sandstone with lighter greenish grey laminae. A poorly developed cleavage can be distinguished in this unit (thickness unknown).
a2: Homogeneous dark grey slate with a well-developed cleavage. The bedding plane is difficult to observe. This level shows mid-brown olive alteration fringes at the contacts with a1 and a3 (thickness: 1.40 m).
a3: Greenish-grey sandstone with fine black laminae. (thickness: 0.14 m).

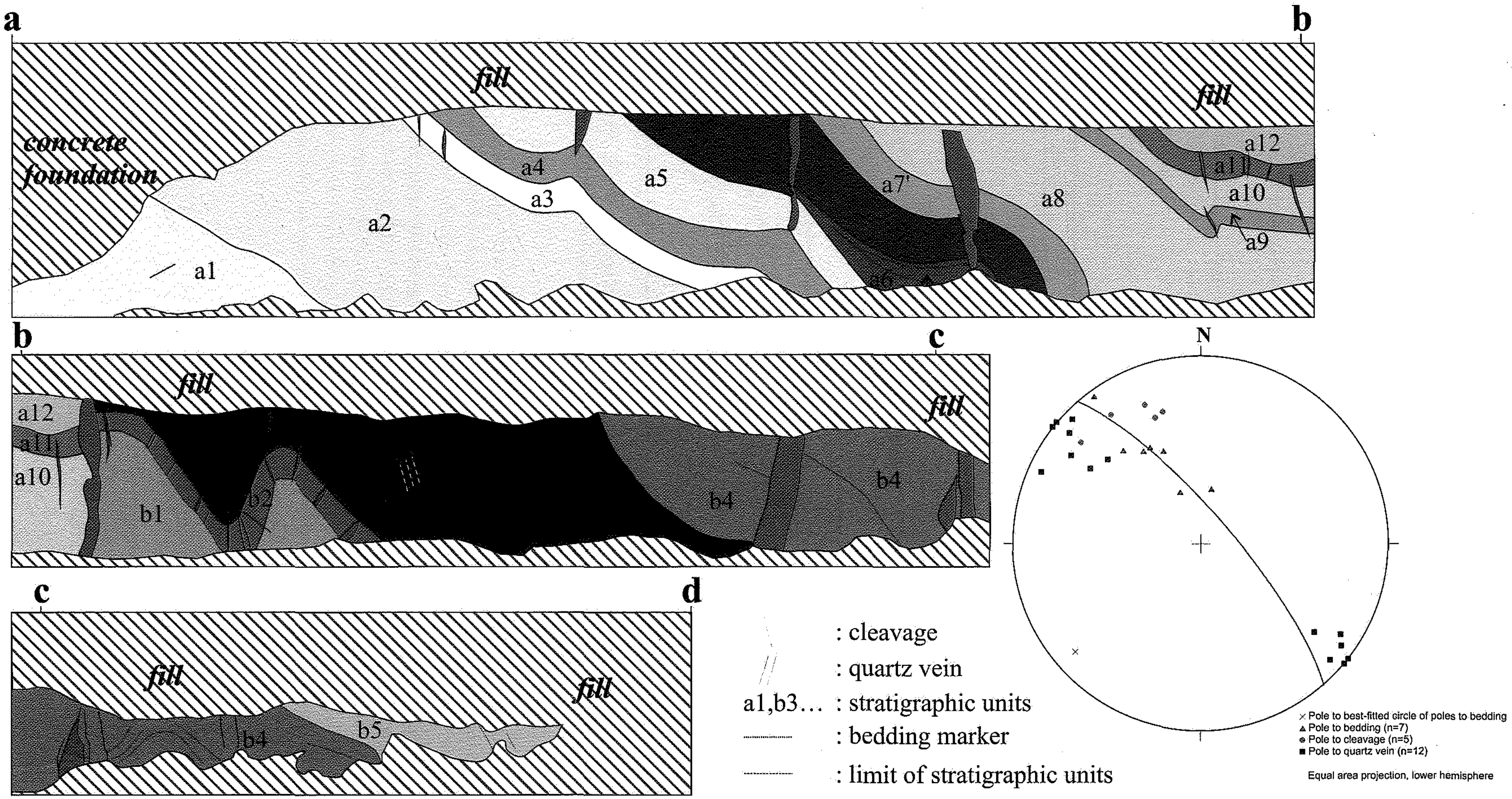


Figure 7.17 Sketch of a temporary exposure in Bastogne city centre.

a4: Mixed level composed of alternations of shale and sandstone layers at the base changing upwards into a homogeneous, dark blue shale (thickness: 0.31 m).
a5: Strongly altered micaceous green-olive sandstone (thickness: 0.40 m – 0.20 m).
a6: Lens-shaped level composed of micaceous, dark grey sandstone (thickness: 0.00 to 0.30 m). Another lens of coarser green sandstone rich in mud chips is included within the level.
a7: Blue-grey and green shaly sandstone layers showing alteration fringes in the vicinity of a vein (thickness: 0.80 m).
a8: Homogeneous blue-grey sandstone. In the upper third, numerous fine, grey-green laminea are observed (thickness: 0.90 m).
a9: Green sandstone (thickness: 0.11 m).
a10: Blue sandstone (thickness: 0.32 m).
a11: Green sandstone (thickness: 0.21 m).
a12: Altered olive green shale level (thickness: unknown).

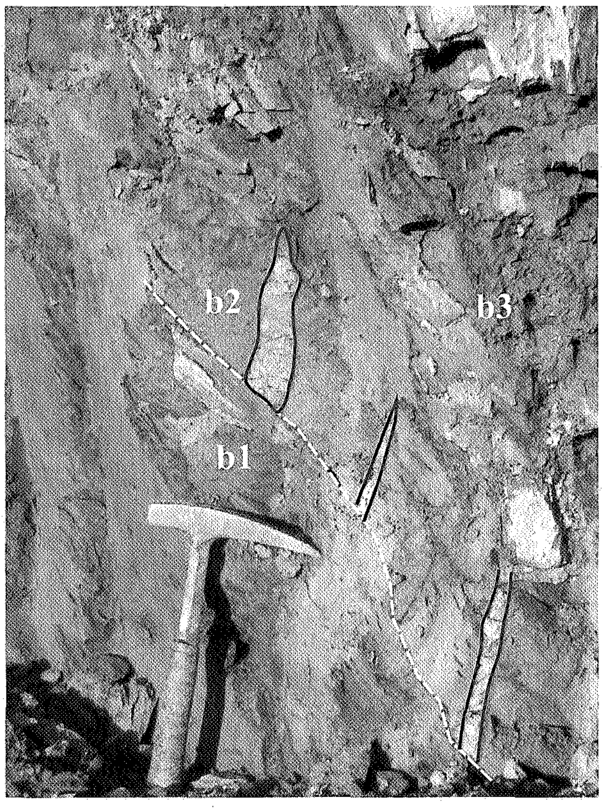


Figure 7.18 Isolated sandstone layer (b2) within a shale unit (b1 & b3). No reworked boudin is observed and the veins (red contours) are abruptly interrupted at the contact between b1 and b2 (white dashed line). These veins separate rectangular boudins. The boundary between layer b2 and b3 is gradual and the quartz veins taper upward.

7.5.2 Details of succession 'b'

b1: Homogeneous black shale-siltstone level (thickness: > 0.95 m).
b2: Green sandstone (thickness: 0.12 – 0.18 m). The contact with b3 is gradational.
b3: Homogeneous black shale-siltstone level (thickness: ~ 1.9 m).
b4: Green sandstone level with numerous laminae in its upper part (thickness unknown due to the intense deformation).
b5: Shaly bluish dark grey sandstone with parallel laminae (thickness: unknown).

7.5.3 Structural observations

The bedding plane envelope dips towards the southeast, but a series of small amplitude folds are observed. They trend NE-SW (N49°E) and plunge gently towards the SW (Fig. 7.17). The fold axial planes are vertical or slightly vary around this orientation. A steep southeast-dipping slaty cleavage is developed within the finer material. Its mean strike is N60°E, while the quartz veins strike on average N37°E.

Four main sedimentary units can be distinguished from this small section:

- levels a1 to a2 are almost devoid of any quartz veins.
- levels a3 to a11 represent a sandstone-dominant unit composed of irregular quartz veins cutting several levels. In addition, the veins are clearly associated with the presence of small-scale anticlines formed around veins ending downward.
- levels b1 to b3 is a shale unit including a thin sandstone layer (b2). This layer is folded and divided into a series layer segments separated by single-layer quartz veins. Interestingly, no reworked torn boudins have been observed along this layer. The shape of the veins is also particular, since most of them do not show the common lens-shaped geometry, but instead they are sharply interrupted at a sedimentary contact (Fig. 7.18).
- levels b4 to b5 corresponds to a sandstone-dominant unit presenting a good relationship between small-amplitude folds and the presence of quartz veins (Fig. 7.19).

This section gathers thus several observations presented in the previous sections. First, there is a close relationship between the presence of small-scale folds and axial plane quartz; second, the boudins are observed into an isolated sandstone layer. However, these boudins are very particular, since they are rectangular and were not reworked during the layer-parallel deformation stage.

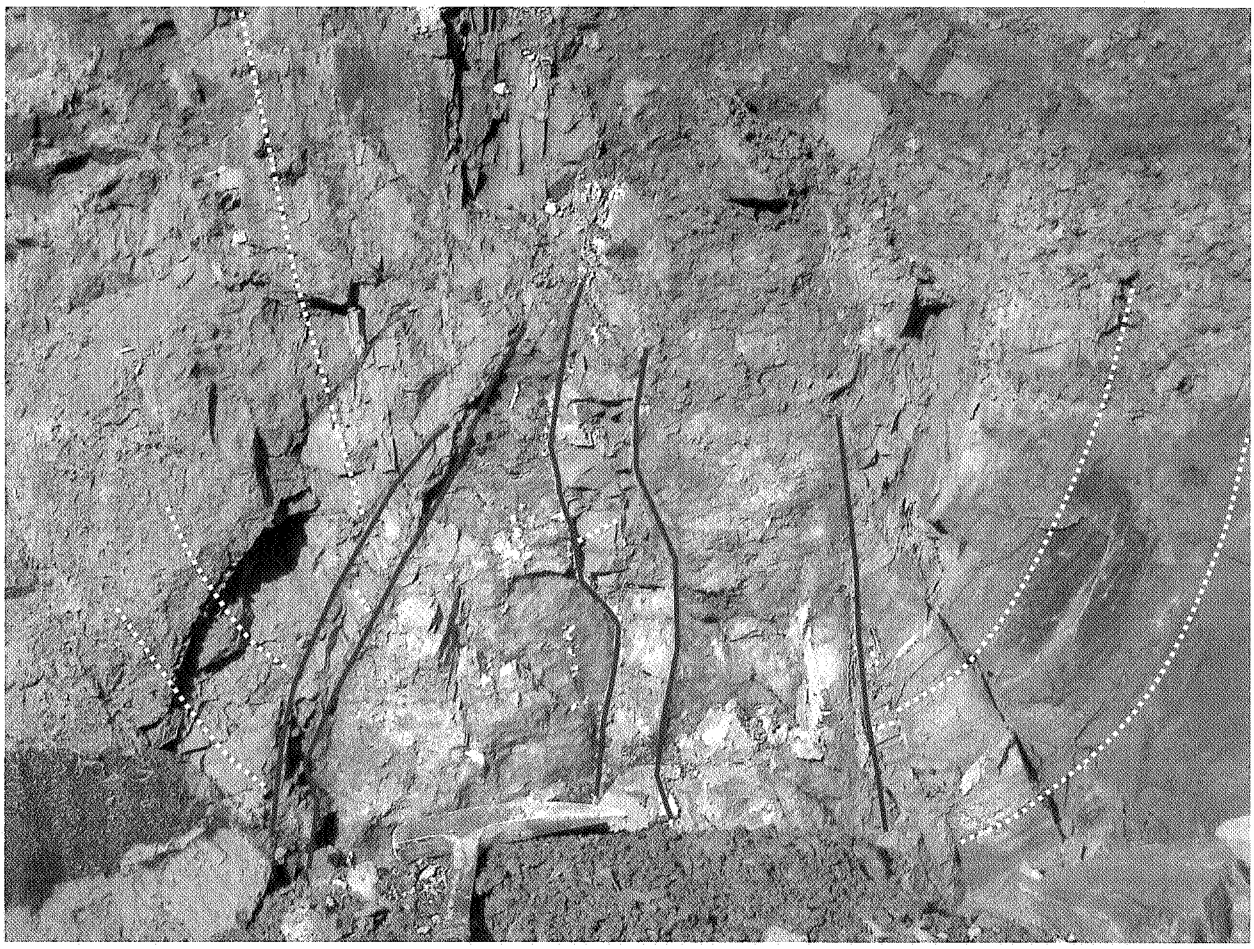


Figure 7.19 Example of the association between a syncline structure affecting level b4 and two dm-thick quartz veins (red contours). Some bedding planes are indicated by the white doted lines.

7.6 The Collignon quarry and Dedenborn outcrop

The Collignon quarry (GSB point 197W005) to the east of Bastogne city has already been studied and reported in numerous papers, such as the inaugural paper of Lohest et al. (1908) or in other works such as that by Jongmans and Cosgrove (1993). It is in this quarry that the boudin structures were named for the first time.

It is not our aim to detail again this quarry, but we simply revisit one particular structure (Fig. 7.20) already extensively studied by Jongmans and Cosgrove (1993). It is located at the contact between a slate unit and a sandstone unit, but the latter is characterised by fining upward and becomes progressively a fine sandstone and then a siltstone. The interface between both units is affected by a series of lobes and cusps and thin quartz veins are connected to the cusps. The lack of any sharp material contrast upward prevented to the formation of equivalent deformation feature upward. Following our classification, such structures should be referred as half-reworked torn boudins.

As already mentioned, the Dedenborn outcrop (Fig. 7.21) represents the current reference exposure of the "mullion" structure (Wilson, 1961; Price & Cosgrove, 1990; Twiss & Moores, 1992). The outcrop exhibits the contact between a slate unit and a sandstone unit becoming progressively a siltstone. Therefore the sedimentary succession is exactly the same as the one observed in the Collignon quarry and, in the line of Goscombe et al.'s (2004) classification, we should name this structure as half-reworked boudins.

7.7 "Sur les Roches" quarry

The last locality to be presented in this memoir is opposite to the Collignon quarry. The bulk of the sedimentary sequence in the quarry is composed of siltstone-dominant units associated with dm- to m-thick sandstone layers. The latter are characterised by the common reworked torn boudin structures, such as the one presented in Figure 6.1.e. The siltstone-dominant succession is locally interrupted by a single massive sandstone unit, several meters thick.

Figure 7.20 Reworked half-boudins from the Collignon quarry.

Figure 7.21 The "mullion" structure of Dedenborn (Germany) becomes, in the classification of Goscombe et al. (2004), an example of reworked half-boudins. In this exposure the slate material has been removed by erosion. Note that each quartz vein (red contours) is associated with each cusp.

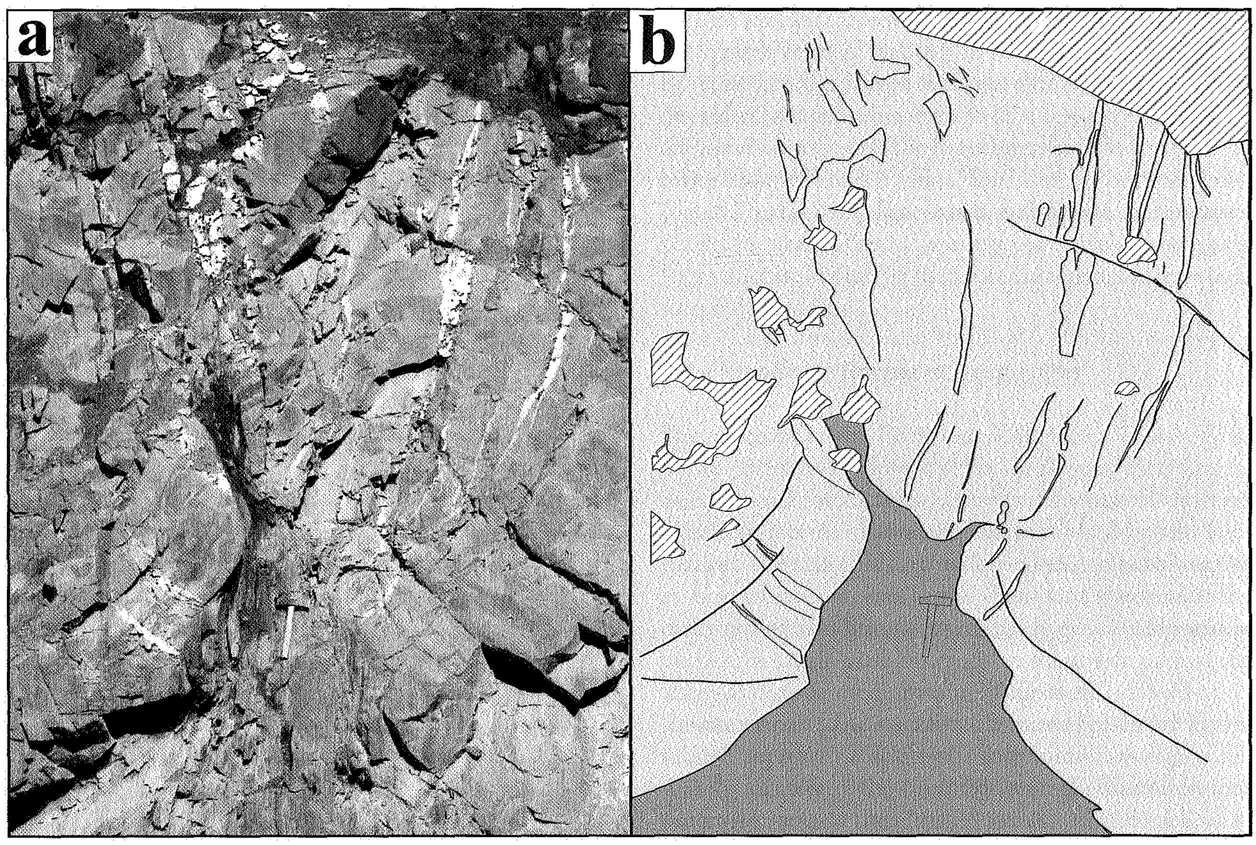


Figure 7.22 Fish-tail injection of shale material into a massive sandstone unit. a) Picture of the structure, b) sketch of the structure, the outline of veins is in red, the siltstone-dominant and massive sandstone units are in purple and light brown colour, respectively. The left branch of the injection is partly obscured by drift material (hatched fill). Note the presence of a small T-shaped quartz veins on the right side of the quartz vein network.

Besides the reworked torn boudin trains two particular structures can be observed. The first structure (Fig. 7.22) is located at the contact between a siltstone-dominant unit and a massive sandstone unit. The shale material appears as a fish-tail injection within the sandstone unit, which is associated with a complex network of quartz veins. The latter spread as fan around the injection. Interestingly, the tips of the injection are not directly related with a particular vein. Unfortunately, the left-branch of the injection is partly obscured by drift material. A particular quartz vein on the right-hand side of the network exhibits a T-shape geometry. The formation of such structure implies a local reorientation of the stress field (Gudmundsson and Brenner, 2001). In this case, the reorientation is to be linked with the presence of a sedimentary contact.

The second remarkable structure (Fig. 7.23) observed in the quarry is located in the deeper part of the current extraction face. The sedimentary succession is composed of fine sandstone layers embedded into siltstone units. There is no sharp sedimentary contact between the different lithologies and the transition between the different materials is progressive. The coarser material is nevertheless emphasized by the presence of lens-shaped quartz veins normal to the bedding plane. In addition, a very thin (< 1 cm) quartz vein occurs parallel to the bedding plane. This vein is also slightly shortened into round-shaped folds. The association between quartz veins normal to bedding and the layer-parallel vein can be followed to few tens of meters. This folded vein may also be interpreted as the horizontal branch of a major T-shape vein. In our deformation sequence, this layer-parallel veins should be also regarded as an event before the layer-parallel period, since the horizontal branch was folded.

8. Synthesis of the observations

The Lower Devonian formations in the area of Flamierge-Bastogne exhibit a wide spectrum of sedimentary compositions. We have distinguished four different sedimentary successions (Fig. 7.1) on the basis of the relative amount of sandstone and shale-siltstone lithology: 1) shale-unit mainly composed of shale or siltstone layers with occasionally a well-individualized sandstone horizon; 2) shale-dominant unit in which well-individualized sandstone layers are more frequent, but do not represent the dominant lithology; 3) sandstone-dominant unit composed of numerous cm- to dm-thick sandstone layers separated by thin shale interlayers; 4) massive sandstone unit com-

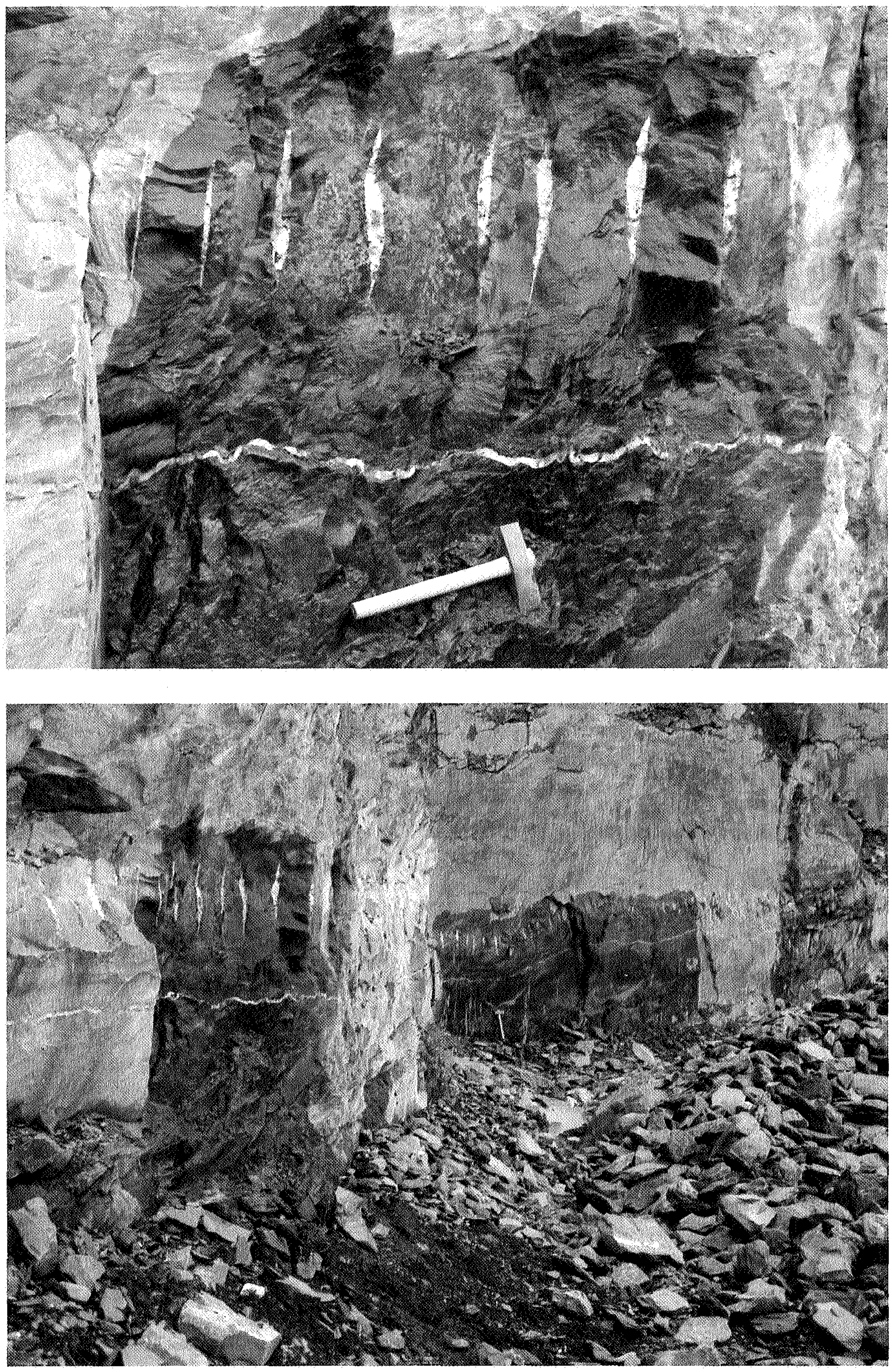


Figure 7.23 Association of lens-shaped quartz veins normal to the bedding plane and a layer-parallel quartz vein slightly folded.

posed almost entirely of sandstone layers separated by mm- to cm-thick shale beds. The discrimination between the sedimentary successions is in some cases subjective. Nevertheless these units acted differently to deformation, which occurred as a result of a layer-parallel extension followed by a layer-parallel shortening. The extensional period is characterised by the presence of single-layered quartz veins, hybrid shear fracture and faults, while the reworking of the inherited structures represents a major accommodation of layer-parallel shortening. The different deformation processes led to a variety of structures, from the famous boudin structures to numerous other structures called here the 'associated structures'.

The shale-units have been observed in numerous localities. In all cases, the quartz veins are scare and the deformation markers of the layer-parallel extension are not directly observed within the shale-siltstone layers. The presence of boudins within few well-individualized sandstone layers represents the sole and readily accessible marker of the layer-parallel extension. During the layer-parallel shortening event, the inherited boudins were strongly reworked and the boudin trains were deformed into folds with a meter-scale wavelength and amplitude. This case was observed for instance in the "Ferme du Grand Vivier" sections (see Fig. 7.1.a). Similar folds were observed in a temporary section in Bastogne city centre (see layer b2 in Fig. 7.17). In the latter case, the folded sandstone layer is not associated with reworked boudins. This issue will be discussed in the following chapter. If the shale unit is devoid of any sandstone layer, the sole observed structures are very low-amplitude open folds (see text Section 7.2) or the shale unit follows the envelope imposed by other, more competent units (see text Section 7.3 and Fig. 7.8).

The shale-dominant units follow more or less the same evolution as the shale units. They represent the typical sedimentary succession in which reworked boudins are observed. For instance, they are observed in the Bastogne quarries (see Fig. 7.1.b). The formation of the boudin (see Fig. 6.1) is considered here as the result of first the formation of a regular-spaced joint set. The individual joints were in turn opened leading to the formation of lens-shaped veins separating low-amplitude barrel-shaped boudins. During the layer-parallel shortening these low-amplitude perturbations were passively amplified (reworked) to develop the current extreme-convex geometry of the reworked boudins. Besides these structures, the layer-parallel shortening led to the formation of open folds with a wavelength of tens of meters, which contrasts to the small-scale folds observed in the shale units.

The presence of a gradual grain size variation in a sandstone layer led to the formation of an associated structure that should be qualified as "reworked half-boudins", that have already been described in the Collignon Quarry (Fig. 7.20), as well as in Dedenborn (Fig. 7.21). The latter outcrop represents a reference outcrop for the mullion structure, but we consider that it rather represents an 'associated structure' resulting from a two-stage deformation sequence.

If the thickness of the fine material in a shale-dominant unit decreases, the different sandstone layers start to interact and the development of a regularly-spaced joint set starts to be perturbated. In this case, we may observe the development of multi-layered reworked boudins. They have been observed for instance in the Ferme du Grand-Vivier locality (see text Section 7.2). This deformation feature corresponds to a transition between the very common reworked boudins observed in the shale-dominant unit and the structures observed in the sandstone-dominant unit.

The interaction of the sandstone layers in the sandstone-dominant unit modifies the deformation pattern resulting from the layer-parallel extension. The numerous quartz veins are not restricted to isolated sandstone layers. The quartz veins cut the bulk of the sedimentary sequence and show in some cases a shear-displacement in addition to the opening of vein walls. These structures have been called "hybrid shear fractures" (see Fig. 7.5.a & b). Veins without fracture-parallel offset have been named as "across-sequence veins". The presence of the veins and/or the deformation of the sedimentary contacts in the vicinity of vein tips played a key role during the layer-parallel shortening. In fact, small-amplitude folds structures were initiated upon those structures. These folds are characterised by a quartz vein within the axial plane (see Fig. 7.5.c, 7.5.d, 7.15, 7.17 & 7.19). On the other hand, some of these veins are not associated with a fold axial plane and are in this case cut by the layer-parallel displacement following a flexural-slip model (see Fig. 7.5.a & b, 7.15.e-inset).

In massive sandstone units, the layer-parallel extension period led to the formation of complex sets of quartz veins frequently organised as *en-échelon* sets. The deformation sequence during the layer-parallel extension is composed first by the formation of single-layered quartz veins, then hybrid shear fractures and finally normal faulting. The contact between the massive sandstone unit and the shale unit show rare zones of high-concentration in quartz veins and significant cusps or "injection" structures of the shale material into the sandstone layers (see Fig. 7.11 & 7.22). The presence of extensional structures within the massive sandstone units did not localise significantly the subsequent layer-parallel shortening. The latter was accommodated by other processes, such as the formation of small-scale ramps (see Fig. 7.12). An example of this lack of reworked structures in the "Moulin de Rayimont" exposures is the dying out of small-scale folds in the vicinity of a massive sandstone unit. These folds were formed around quartz veins within a sandstone-dominant unit (see Fig. 7.15.c).

9. Discussion

All field observations made during this study clearly indicate that before the layer-parallel shortening related to the Variscan orogeny, a significant layer-parallel extension period segmented the sandstone layers (i.e. boudinage) and induced the formation of complex sets of quartz veins within the sandstone-dominant and massive units. During the layer-parallel shortening, these inherited structural features were more or less reworked. Our observations are therefore in good agreement with some previous models, such the one by Rondeel & Voermans (1975) and Jongmans & Cosgrove (1993), whom applied to the term "**boudinage**" to designate the segmentation of sandstone layers, though they recognised that the boudins suffered a significant layer-parallel shortening after their formation. The same problem is encountered with the term "mullion" or "double-sided mullion" (Kenis et al., 2002), who invokes only a layer-parallel shortening event. We prefer the use of the term "**reworked boudins**"[6], which avoid confusion concerning a multi-stage origin for the formation of those structures.

Our observations of the associated structures in sandstone-dominant units show a strong relationship between the occurrence of quartz veins and some small-scale fold structures. For instance, some folds were clearly moulded around some quartz veins. Other veins show however a different behaviour, since they appear along fold limbs. Nevertheless both categories of veins were formed during the same structural period (i.e. layer-parallel extension). There are also indications that the **initial perturbation** along the sedimentary contacts in the vicinity of a quartz veins may also play a key role during the reworking of the structures. We refer to the initial perturbation as the small-amplitude perturbation created during the layer-parallel extension along the layer contacts between sandstone and fine material layers or units.

The initial shape of the boudins before their reworking was already addressed in Chapter 6. We have indicated that previous studies on the subject (e.g. Lloyd and Ferguson, 1981; Ramberg, 1955) shows a clear relationship between the shape of the interboudin space and the one of the boudin envelope: the growth of a lens-shaped vein is associated with barrel geometry, while rectangular boudin are separated by orthogonal interboudin space. In the Ardenne-Eifel region, the vast majority of the reworked boudins are separated by lens-shaped quartz veins. It is therefore more likely that the boudins had already low-amplitude barrel geometry before the subsequent shortening. This result is clearly in contradiction with the model suggested by Kenis et al. (2002, 2004, 2005) in which the sandstone layers are separated by lens-shaped quartz veins and flat sedimentary contacts. In their model, the barrel-shaped geometry was only acquired by the layer-parallel shortening and the quartz veins act as rigid platens between which the layer segments are

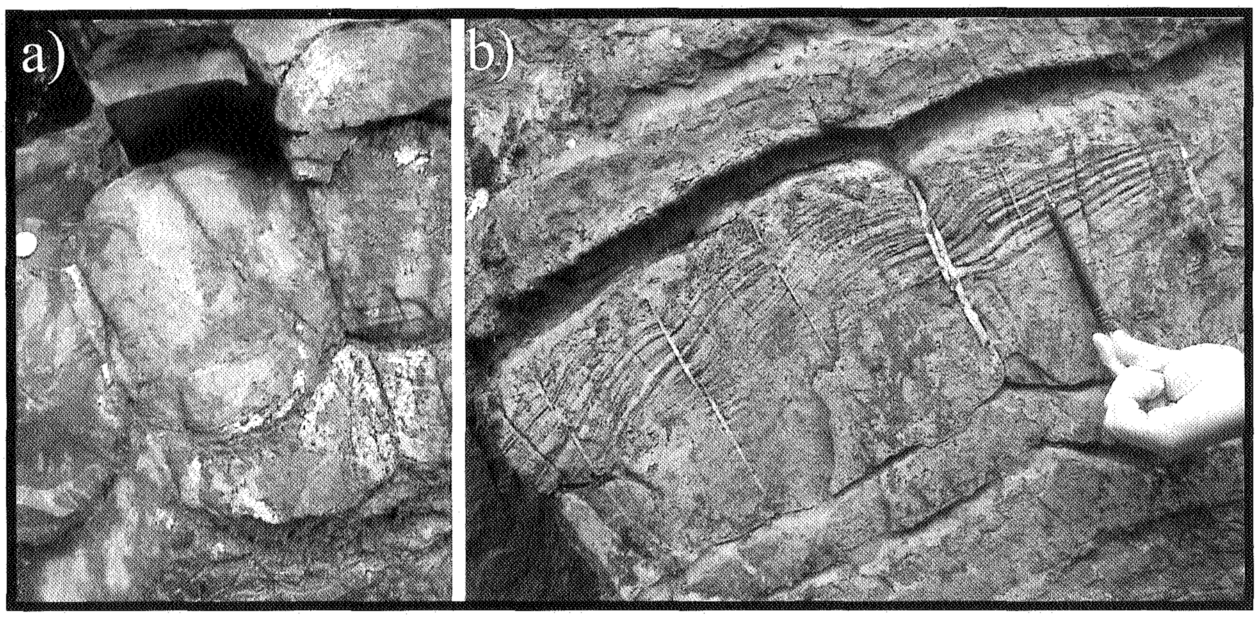


Figure 9.1 Relationship between the development of reworked boudins and the quartz vein width. a) Example of a well-developed reworked boudin with cm-thick quartz vein ("Ferme du Grand Vivier" section A: see layer k in Figs 7.4 & 7.5). b) poorly-developed reworked torn boudins associated with mm-thick quartz vein from the same section (layer g).

[6] This term was first introduced in literature by Goscombe et al. (2004) to designate modified boudins observed from other terranes through the world.

shortened. The solution to this contradiction cannot be readily solved by the examination of the classical reworked torn boudins. Other parameters or structures should therefore be considered.

In the section A of the "Ferme du Grand Vivier" locality, we mention that reworked torn boudin trains affect two particular sandstone horizons with similar thickness (see layers g and k in Fig. 7.4 and Fig. 7.5). Layer g (Fig. 9.1.a) is characterised by well-developed reworked torn boudins separated by quartz veins between 1 and 2 cm wide in their central part. By contrast, in layer k the quartz veins are thinner (Fig. 9.1.b) and the reworked torn boudins are poorly-developed. In addition, we can notice that the low-amplitude barrel geometry is only associated with a thicker vein (1 cm thick). The other veins are only 1 to 3 mm wide and the boudin envelope is not affected by their presence. There is therefore a strong relationship between the development of the reworked boudin (i.e. their current amplitude) and the quartz vein width. This observation cannot readily be explained from the model of Kenis et al. (op. cit.), since if the quartz veins would act as rigid platens all layer segments should be evenly shortened. By contrast, if the layer contacts were deformed (i.e. perturbated) during the layer-parallel extension, the wider the veins are, the bigger was the initial perturbation. The mm-thick veins were unable to produce any perturbation of the sedimentary contacts. During the layer-parallel shortening, the sole initial perturbations in the vicinity of the wider veins were passively amplified.

Another indication of the significant role played by the initial perturbations is this unique example of rectangular boudins observed in a temporary section in Bastogne city centre (see Fig. 7.18). By contrast with all other outcrops, the quartz veins are there abruptly interrupted by a sedimentary contact and exhibit an angular anatomy along the lower contact. In other words, they do not exhibit the usual lens geometry and the boudin envelope remained flat. During the layer-parallel shortening, the boudin blocs were not reworked due to the lack of initial barrel geometry and the convergence had to be accommodated by another process, such the significant folding of the boudin train. The model of rigid platens of the quartz veins cannot explain this observation. The other ends of the veins in the temporary section exhibit a lens-shaped. The lack of buckled contact on the upper side of the layer can be interpreted by a combination of two features. First, the transition between the boudinaged layer and the overlying unit is gradual and hence the vein tapering is also progressively compensated by internal deformation within the material and not by the perturbation of a gradual contact. The second feature is that the lack of initial perturbation along the lower contact hindered the shortening of the boudin blocs and the upper contact remained therefore unaffected.

The association between a pertubated contact and the lens geometry of a vein needs however to be further discussed, since single-layered lens-shaped veins can also exist without any perturbation of the bedding planes. One case has been encountered during this study. It is observed within the massive sandstone units where the lens-shaped quartz veins within a sandstone layer are not associated with the formation of barrel-shaped boudins (Fig. 9.2.a). In fact, the formation of the boudins requires the presence of significant rheological contrasts, which is missing in massive sandstone units. Gudmundsson and

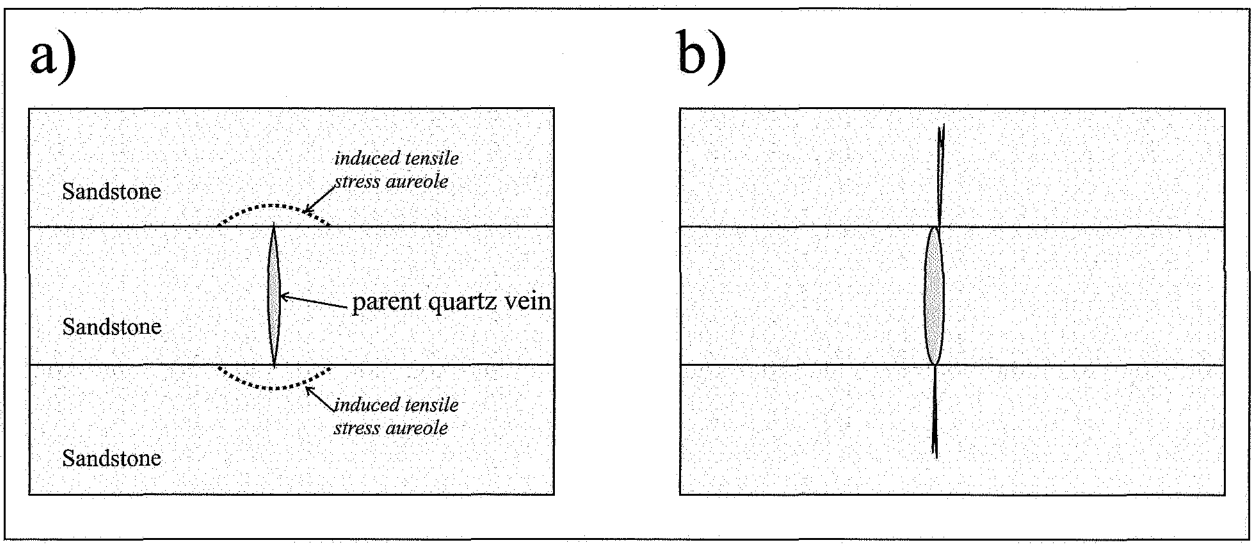


Figure 9.2 a) Sketch of a lens-shaped quartz vein in flat lying layers. Note that the layer contacts are not pertubated by the tapering of the quartz veins, but instead a tensile stress builds up within the surrounding layers. b) The increase of the extension can induce new veins within the surrounding layers, which are aligned or not with the mother vein (see e.g. Fig. 7.9).

Brenner (2001) have shown that the growth of a open-mode fracture may induce the development of tensile stress aureole within the unfracturated competent layers (see Fig. 9.2.a). As layer-parallel extension increases the induced stress can ultimately cause the formation of new veins within the surrounding layers (Fig. 9.2.b). These new veins will be aligned or not with their parent vein (see Fig. 7.9).

A major unknown in our study and in all other previous researches is the age of this layer-parallel extension that is, also the age of the quartz veins and the metamorphism. Since we are studying Lochkonian sedimentary rocks that underwent low-grade metamorphism conditions (green-schist facies) during the layer-parallel extension, it implies that the rocks were deeply buried (~8-10 km) during the layer-parallel extension. Hence the latter is more likely younger than the end of Lower Devonian times (~398 Ma). The other constraint for the age is the onset of the Variscan orogeny and layer-parallel shortening, which ranges in the Ardenne-Eifel region between 330 Ma (Vanbrabant et al., 2002) and 300 Ma (Oncken et al., 1999). The time span ranges therefore between 68 and 98 Ma. Some researchers (Dittmar et al., 1994; Fielitz and Mansy, 1999) consider however that the metamorphism is due to the burial of sediments during the basin formation and give it a pre-Carboniferous age. On the other hand, Kenis et al. (2002, 2004) assume that veining occurred just before the onset of Variscan shortening and the age of veining is between 335 and 325 Ma. They attribute this age since they refute in their model the layer-parallel extension period. As we shall discuss next, the Kenis et al. model must be regarded with some circumspection. On the other hand, if we agree that the layers underwent a layer-parallel extension, a simple and elegant explanation for this deformation process would be to relate it with the formation and growth of the Rhenohercynian passive margin. Interestingly, we have to point out that the Ardenne-Eifel region, that is the outcrop zone of the boudinaged layers, corresponds to the former transition zone between the Old Red Sandstone platform and Eifel rift basin (e.g. Dittmar et al., 1994; Oncken et al., 1999). Hence this area underwent a major extensional period between Lower Devonian and Lower Carboniferous period. In this context, the boudinaged layer represents a good candidate as a strain marker of this extensional period.

In their model, Kenis et al. (2002) calculate a state of stress for rocks before the onset of the Variscan deformation. They show that the differential stress (σ_1-σ_3) was bigger that 4 times the tensile strength (T). Hence they consider that the conditions were not fulfilled for the formation of quartz veins (see circle I in Figure 9.3, see also Section 5.4 and Fig. 5.2.a). They recognise however that the maximum stress component (σ_1) was vertical before shortening, whereas the minimum component (σ_3) was horizontal. The additional horizontal stress (σ_T in Figure 9.3) resulting from the onset of shortening would in turn increase σ_3, thus reducing the differential stress (i.e. decrease of the Mohr circle size). The latter (circle II in Figure 9.3) becomes then lower than 4T and the presence of an overpressured fluid (Pf >> σ_3) leads to the shift of the Mohr circle and hydraulic fracturation and veining (see Figure 5.2.b).

We have serious doubts about this model for several reasons:

1. the additional horizontal stress seems an elegant way to explain the reduction of the Mohr circle. However, the influence of the fluid pressure before the Variscan orogeny is not taken into account in Kenis et al.'s model. The presence of overpressured fluids (Pf >> σ_3) should have already shifted the Mohr circle I (see Fig. 9.3) towards the low stress values and shear fractures must develop in a similar way as represented in Figure 5.2.a. These shear fractures in nature should correspond to sets of conjugate normal faults at about 60° with respect to the bedding plane. None of these faults have been observed. The rare small-scale "normal" faults observed in this study are late structures, since they clearly cut the various categories of veins (see Fig. 7.10). Neither the so-called hybrid shear fractures are an expression of these hypothetical faults, since the hybrid shear fractures cut the bedding plane at a high angle (more than 60°).

2. Another problem in the Kenis et al. model is related to the strain and stress concepts. In fact, the veining by hydraulic fracturation occurs while σ_1 was vertical and σ_3 was horizontal. However, Kenis et al. (2002, p.107) wrote that: "*hydraulic fracturing occurred at the earliest onset of the Variscan deformation (late Visean) in an overall compressional setting (0 < σ_3<σ_2<σ_1; σ_h still smaller than σ_v).*", and later conclude (p108) that: "*the motor for vein development was hydraulic fracturing in an already compressional setting rather than layer-parallel extension by the process of boudinage*". We completely disagree with their opinion for several reasons. First, the boudinage refers to a deformation by layer-parallel extension and not a mechanical state. No definition of boudinage has ever stated the stress conditions for the formation of the structures. Secondly, a compressional setting as assumed by Kenis et al. in 2002 (i.e. σ_1 > σ_2 > σ_3 > 0, with σ_1 vertical, σ_2 and σ_3 horizontal) is not incompatible with a layer-parallel extension for flat-lying horizons. It actually represents the perfect stress conditions for the development of boudinage or conjugate normal faults. The selection between both deformation processes depends on the state of stress and the fluid pressure. If the differential stress (σ_1-σ_3)

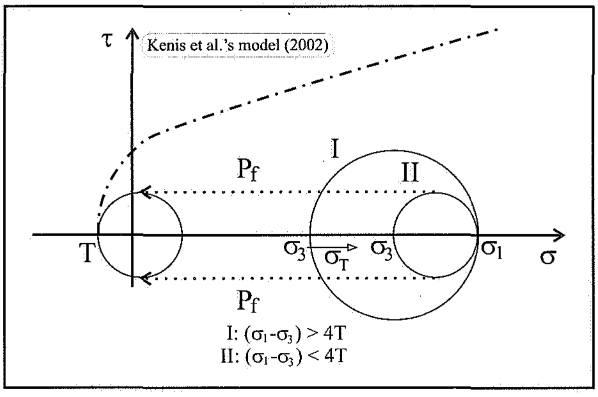


Figure 9.3 Stress conditions assumed in the model of Kenis et al. (2002). σ_T represents the additional horizontal stress resulting from the onset of Variscan shortening. I: State of stress in a relaxed basin; II: state of stress due to the influence of σ_T. P_f is the fluid pressure.

is low (< 4T) and fluid pressure high ($P_f >> \sigma_3$), the layer-parallel extension will happen by tensile fracturation resulting into boudins. By contrast, if (σ_1-σ_3) is larger than 5.5T (see Figure 5.2.a) with overpressured fluid, the layer-parallel extension will occur as sets of inclined normal faults.

3. As we already pointed out, the stress conditions within the Earth crust are basically compressive and yet the boudinage process and other layer-parallel deformation features are ubiquitous. According to the Kenis et al's model, the formation of boudin structures should be impossible within the Earth crust stress conditions. Unfortunately, Kenis et al. do not explain the stress state relative to the formation of what they call "real" boudin.

10. Conclusion

The Lower Devonian sedimentary rocks of the Ardenne-Eifel region (Belgium, Germany) underwent two major deformation periods. The first was a layer-parallel extension and the second a layer-parallel shortening. The latter arose from the Variscan orogeny, which occurred during Carboniferous times and was responsible for the accretion of the Devono-Carboniferous Rhenohercynian passive margin. The age of the layer-parallel extension is unconstrained, but could be as old as a mature stage of development of the passive margin.

The famous "boudin" structures observed in the region of Bastogne and elsewhere through the Ardenne-Eifel region and the reference "mullion" structure from the Dedenborn outcrop (Germany) were developed in this two-stage deformation sequence that have affected various sedimentary successions composed of sandstone-siltstone and shale layers.

In this memoir, we show that:

- narrow boudins with an aspect ratio (width/heigth) of ~1 exist contrary to a widespread statement in literature;
- narrow boudins through the Ardenne-Eifel region form initially as a set of regularly-spaced joints within the sandstone layers. The number of joints increases with the layer-parallel extension until a "fracture saturation" stage is reached and subsequently the additional strain is accommodated by the opening of joints and the formation of lens-shaped quartz veins separating boudins;
- the structure resulting from the layer-parallel extension is a train of low-amplitude barrel-shaped boudins with an aspect ratio of 1;
- the low-amplitude barrel geometry played the role of initial perturbations during the subsequent layer-parallel shortening. These perturbations were passively amplified. The boudins were therefore shortened and acquired their current extreme convex geometry and low aspect ratio (~ 0.5);
- these layer segments should be named "narrow reworked boudins" or simply "reworked boudins" following the recent nomenclature of Goscombe et al. (2004), since they result from a two-stage deformation sequence;
- the type structures in the reference outcrop of the "mullion" structures in Dedenborn (Germany) should be called "reworked half-boudins";

Besides the reworked boudins, a complete spectrum of associated structures are described for the first time. They develop in the same two-stage deformation sequence as reworked boudins, but show significant differences. Our study shows that the presence of different sedimentary successions played a key role on the development of extension structures during the layer-parallel extension on the development of extension structures. These structures in turn generally controlled the location of structures formed during the layer-parallel shortening period.

Four sedimentary successions have been encountered: the so-called shale, shale-dominant, sandstone-dominant and massive sandstone units. The first two represent the typical units in which regularly-spaced reworked boudins are observed. In sandstone-dominant and massive sandstone units, the layer-parallel extension results into the formation of complex sets of single-layered quartz veins and hybrid shear fractures, the later cutting the bulk of the sedimentary succession. During the layer-parallel shortening, the presence of the quartz veins in association with an initial perturbation of the unit contacts led to the formation of small-amplitude folds within the sandstone-dominant units. They were moulded around some quartz veins, which are now parallel to the axial plane. Other veins, located along the fold limbs, were cut by the layer-parallel displacements. Our observations clearly indicate that care should be given when interpreting axial plane quartz veins, since they could be formed before the fold formation and not after, as it could be intuitively assumed. The presence of the quartz veins within the massive sandstone units does not seem to have a major influence during the layer-parallel shortening. Other processes, such as the folding or the development of ramp structures, accommodated the convergence.

Acknowledgments

Prof. John Cosgrove and André Delmer are sincerely thanked for their fruitful reviews. We also thank M. Quentin Ketelaers for the realisation of some figures.

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Manuscript received 04.04.2006 and accepted for publication 09.11.2006.

ISSN 0408-9510

Guide for authors: see website Geologica Belgica
http://www.ulg.ac.be/geolsed/GB
List of publications and sale: see website Geological Survey of Belgium
http://www.naturalsciences.be/geology/homepage/

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Jennerstraat 13, 1000 Brussel
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Verantwoordelijke uitgever
Camille PISANI
Koninklijk Belgisch Instituut
voor Natuurwetenschappen
Vautierstraat 29
B-1000 Brussel

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Camille PISANI
Institut royal des Sciences naturelles
de Belgique
29, rue Vautier
B-1000 Bruxelles

Impression: Service public fédéral Economie,
P.M.E., Classes moyennes et Energie

Drukwerk: Federale Overheidsdienst Economie,
K.M.O., Middenstand en Energie