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Tectonics and Structural Geology in Belgium

“a guideline to terminology and a better understanding of deformation structures”

14 May 2010

Contact Forum

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Folding and faulting in the Dinant fold-and-thrust belt

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L'allochtone ardennais, constitue l'une des trois unités structurales du front Nord de la Chaîne varisque. Ce front de chaîne est formé par une puissante série sédimentaire présentant des variations de la puissance et de la nature des séries associées à la dynamique extensive de marge passive qui a perdurée au moins jusqu'au Frasnien, puis compressive avec les premiers soubresauts de l'orogenèse dès la fin du Dévonien. La structuration de la pile sédimentaire est marquée par la formation de structures plissées et faillées dont la géométrie dépend de la position au sein du front de la chaîne et de la lithologie. Au cours de la déformation la couverture n'est pas décollée de son substrat, les déformations varisques affectant les deux ensembles de la même manière. La construction de la chaîne varisque est à l'origine, en Ardenne, d'un raccourcissement dont la direction principale est NNE-NNW. En carte, la mise en place des structures plissées faillées est progressive et s'organise dans un mouvement d'enroulement de l'allochtone autour du môle brabançon par la mise en place de larges bandes de virgation ou s'enregistrent des déformations compressives dextres orientées NNW-SSE et senestre orientée NNE-SSW. En coupe, la migration des déformations du Sud vers le Nord, participe à la complexité de la géométrie des structures et permet de mettre en évidence l'importance des niveaux de décollements au sein de la série. La zone de décollement majeure au sein de l'allochtone correspond au Frasnien. Elle est épaisse de près de 400 mètres au sud pour s'affiner puis disparaître vers le nord; elle permet le découplage de la pile sédimentaire de la partie méridionale de l'allochtone lors de la déformation. Une vision dynamique de mise en place de l'allochtone peut-être ainsi proposée. L'importance des niveaux de décollements est primordiale pour la compréhension du mode de déformation du prisme sédimentaire depuis l'échelle de l'affleurement à celui du front de chaîne. L'étude structurale de quelques plis en Ardennes, permet de mettre en évidence un mode de plissement où les décollements interstratifiés au sein des séries sont à l'origine de structures plissées dissymétriques à antiformes empilées qui, par exagération du cisaillement simple des flancs longs, permettent la formation de failles tronquant les flancs courts.

Folding and faulting in the High-Ardenne slate belt, example of the Noirefontaine fault zone.

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Within the scope of the Wallonia Geological Cartography Program financed by the Ministery of the Walloon region, the updating of the maps along the Semoy river has been made by the SGB team. The new mapping, based on lithostratigraphic principles, marks out the limits of lochkovian and praguian formations of siliciclastic sédiments such as Oignie (OIG), Saint-Hubert (STH), Mirwart (MIR), Villé (VIL) and Laroche (LAR).

Those sediments have undergone Variscan Orogeny. During this event, deformations were taking place such as E-W folds and faults which are often mentioned as longitudinal structures. The southern High-Ardenne region is dominated by the Givonne Anticline which overlaps the Neufchâteau Syncline by the Herbeumont fault.

The core of the Neufchâteau Syncline is composed of asymmetric inclined folds with a south dipping axial planar cleavage. Folds are tight with a low plunging (10°) axes toward SE to SW according to areas.

Cartography of Bouillon-Dohan (67/3-4) and surroundings shows several normal faults with a low angle dip to the south (20° to 30°). Their paths can be followed on more than 20 km from Pussemange meridien to the W to Herbeumont – Bertrix meridien toward the E. The normal slip can be estimated from 250 m to 500 m. The direction of the normal fautls is E – W, sub-parallel to the direction of the folds and axial planar cleavage which are crosscut by the faults. At map scale, the normal faults are crosscut by a set of NE – SW and NW – SE trending sub-vertical faults. Those last ones belong to a later event recognize as the Amerois event (reverse dextral, southern area of Bouillon).

On the field, the normal faults are recognized by the presence of shear zones of decimetric to metric thickness. The shear zone is limited by normal fault planes with a low dip to the south, sub-parallel to stratification/cleavage. Fault planes are covert by regular slightly marqued slikenslides.

The shear zones are mainly present in sediments with a predominantly laminar aspect which can conceal the cleavage. In homogeneous pelitic rocks it is the predominant slaty cleavage (which can conceal the bedding) that is deformed by the shear zones.

The inside of a shear zone shows complex deformations with disharmonic aspect. Brechia can be observed from place to place but not always. Different styles and forms of folds, box folds, chevron folds, kinks (normal and reverse) and faults are present most of the time. Despite their different forms due to lithological variations, the structures show the same movement pattern which is a compressive stress close to the bedding/cleavage toward the South.

Folds and cleavage-fold relationship in the Brabant basement

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The Brabantian deformation event, which took place between the late Llandovery and the Middle Devonian, mainly resulted in the development of folds and a well-developed cleavage. On the basis of the cleavage-fold relationship, three main groups of folds can be recognised in the Brabant basement: post-cleavage folds, syn-cleavage folds and pre-cleavage folds.

Post-cleavage folds include kink folds and normal fault-related folds. Both have a rather restricted occurrence. Small-scale kink bands are restricted to the Silurian rim and to local high-strain zones, large-scale kink bands occur in the vicinity of large normal fault zones, and fault-related post-cleavage folds are situated in the damage zone of post-cleavage normal faults.

On the basis of the cleavage-fold relationship, three types of syn-cleavage folds are distinguished. Type A1 folds are upright to slightly asymmetric, subhorizontal to gently plunging, large-scale, multi-layer buckle folds, characterised by a convergent cleavage fanning. These folds are only observed within the Silurian rim above the Corroy Formation (lower Wenlock). Type A2 folds are asymmetric, S-verging, subhorizontal to gently plunging buckle folds, with a parallel or divergently fanning cleavage. Type A2 folds may be large multi-layer folds or small single-layer folds and often have a stepfold geometry. Large multi-layer type A2 folds are observed in the Cambrian core, and occur throughout the Ordovician up to the lower Silurian Corroy Formation. In the Silurian above the Corroy Formation, only small type A2 folds occur. Type B folds are upright, to steeply inclined, steeply plunging to reclined, asymmetric folds, usually with a divergent cleavage fanning. These folds have only been observed within the Cambrian core. In the central and western parts of the Cambrian core, type B folds are characterised by a dextral asymmetry.

Despite the large variation in fold style and orientation, all three types of syn-cleavage folds are cogenetic to the same cleavage, and are interpreted as being the result of a single, progressive deformation event, being the Brabantian deformation event. Comparison of structural outcrop data with geophysical data allows visualising the large-scale structural architecture, and allows unravelling the way in which the Brabant basement progressively deformed.

Pre-cleavage folds frequently occur, and are attributed to slumping. Such folds are common in the Cambrian Tubize Formation, the Cambrian Jodoigne Formation, the Ordovician Abbaye-de-Villers Formation and the Ordovician Ittre Formation. When combined with sedimentological and stratigraphic data, these pre-cleavage folds provide important information on the pre-inversion basin history of the Brabant basement.

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Fractures, faults and joints in chalk and limestones

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Brittle structures are characteristics of the upper structural level in the upper crust where deformation is considered to be quite low (Mattauer, 1973). Faults and joints are the typical structures of the sub-surface environment. Faults can be used to reconstruct paleo-stress, in particular the principal orientations of extension or compression. Joints can be used as an estimator of the principal orientations of main axis of stress tensor but are also associated to the principal mechanical properties of the rocks.

In the Mesocenozoic rocks, one important point of this work in terms of field analysis is that « Chalk » is a good marker of the palaeostress evolution in NW Europe, and then of the tectonic evolution of the European platform (Vandycke, 2002). The geometrical characteristic of different fault systems have been defined and the chronology between these faulting regimes has been established using synsedimentary, inherited or locked stratigraphically faults. The fault planes are striated and displacements of faults are metric. After an analysis in terms of stress tensor determination based on the direct inversion method, a succession of palaeostress is proposed for the Mons Basin, the NE of Belgium, the Boulonnais, the Kent, the Sussex and the Isle of Wight. A strike-slip regime has been correlated to the inversion phase well known in the North of the European platform and related to Alpine collision.

In the Cretaceous, in each case, inversion phases are related to crustal movements of main regional structure in transpression, the North Artois Shear Zone in the Mons Basin for example. Extensional periods are quite long and corresponding palaeostresses are not necessarily synchronous. The stress field was not homogeneous during the Mesocenozoic. The palaeostress analyses revealed a more complex tectonic history with development of neoformated mesofaults along crustal reactivated structures. The Chalk formations recorded well the palaeostress variations, resulting in development of numerous faults and joints. Compressional events related to inversion phases are accurately dated to the end of the Late Cretaceous (Maastrichtian) in Belgium. This observation leads to consider that inversion tectonics during the Cretaceous-Tertiary was active in a relay zone between Atlantic opening and Tethyan basin development. Evolution of palaeostress fields recorded by Cretaceous formations in NW Europe is mainly characterised by an extensional regime interrupted by strike-slip events related to inversion episodes. The Cretaceous was characterised by extensional events and strike-slip events. The post-Cretaceous period, except during the Tertiary inversion was predominantly in extension. In particular, the NE-SW extensional event is recorded in the whole NW Europe.

The Variscan front in the paleozoic basement makes the boundary between a folded part called Ardenne Allochtone in Belgium and North of France, and an almost undeformed part called Brabant Parautochtone. In the Paleozoic basement, Carboniferous and Givetian limestones have been investigated in terms of brittle tectonics, in Belgium. Faults and joints are well developed, with conjugated sets of strike-slip and reverse systems.

In the Ardennes, folded Givetian limestones are also affected by jointing. The main and effective system is the extensional joint in NE-SW extension. The maximum stress compression is compatible with the main direction of the Variscan Front propagation. There, Variscan folding in the Givetian limestones is accompanied by reverse faulting, strike-slip faults systems, tension gashes, stylolites and extrados normal faulting. Like in Wales, the maximum stress axis in compression is parallel to the direction of the Variscan propagation.

At the North of the Variscan Front, in the Brabant Parautochone, where limestones appear in monoclinal structures, four different types of structures have been differentiated. Reverse faults on the bedding planes and ramps can be directly attributed to the Hercynian thrusting tectonics. Two main strike-slip systems have been recognised in a pull-apart geometry. One of these transcurrent systems seems to be slightly older than the Variscan dynamics, the second one just younger. Hectometric tension gashes with metric spacing occur also in the Carboniferous limestones. There are abundant and some tension fibers can be observed in the calcite filling. But the main spectacular brittle structures are the extensional joints. Some of them are hydrogeologically active (Quinif et al., 1997).

It is observed that karstic networks are structured along some particular orientations related to recent tectonics, with extensional component. The NE-SW extension event, with NW-SE joints is the most developed brittle system. This system in NE-SW extension is related to the opening of the Rhin Graben and is present in the whole domain studied. It is still active today.

Finally, brittle tectonics analysis reveals that structural inheritance must be taken into account, not in terms of reactivation of old structures but in terms of permanent and recurrent dynamics, with stress fields evolution related to crustal activity.

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Mechanical principles of deformation in argillaceous sediments

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Fractures are common in many mudstones. The formation mechanism of these fractures is, due to the weak nature of these sediments, quite specific and can be different from the mechanics of fracturing in cemented rock. Due to their low strength and high water content, argillaceous sediments behave transitionally between brittle and ductile, with an interplay of internal and localized porosity reduction (bulk volume changes) and localized strain in stiffer conditions.

The nature of fractures typically observed in the field in several different mudstone formations has been studied in the lab using fabric, strain, paleostress and petrophysical analysis. Millimetre-scale ductile shear bands, meter-scale mixed-mode faults and brittle joints are commonly observed and develop at various moments in the stress path related to the burial/uplift history. The transition between the failure modes depends on the mean effective stress, the water content, the amount of strain and the burial-uplift history.

Mercury-porosimetry, P-wave velocity profiling and SEM analysis highlights the internal structural changes of the mudstone around the fractures. Small but consequent changes occur in the physical properties of the argillaceous matrix approaching a fault or shear zone, indicating compactional strain of the matrix in both foot-wall and hanging-wall.

In this mechanical framework, small differential stress induced by compaction and regional tectonic and gravitational forces is capable to induce small shear planes in nearly critically stressed weak mud. Subsequent matrix compaction provides an extension of endogenous origin, allowing further deformation. This ductile-brittle feedback can eventually lead to commonly observed intraformational collapse structures called polygonal fault systems.

In the case of the Boom Clay Formation, studied as a potential host rock for nuclear waste disposal, the specific stress path initially follows a K_0 path during burial that is left when differential stress increases, due to both uplift and compaction-induced endogenous forces, reflected by a decrease of effective confining pressure prior to failure, and far-field tectonic driving forces, reflected by the distinct and regular orientation of fractures. The related deformation is ductile and dis-tributed compacting micro shear zones are formed, up to the dilatancy boundary, beyond which extensional fractures develop.

This paper results from the study '*Faulting and jointing in clay*' sponsored by ONDRAF/NIRAS in collaboration with KULeuven Geodynamics and Geofluids Research Group and the Faculté Polytechnique de Mons.

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Recent coseismic deformation recorded in near-surface sediments along active faults: Some examples from paleoseismic trenching in Belgium

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Since 1996, the Royal Observatory of Belgium is conducting paleoseismic research on the border faults of the Roer Valley graben (RVG), one of the seismically most active areas in intraplate NW Europe. Paleoseismology is the study of past large earthquakes capable of leaving a signature at the Earth's surface. The main objective is to identify individual paleoearthquakes, to estimate their size from their offset and/or rupture length, and to determine their timing. The fault that has been best studied so far is the Geleen fault, which is part of the Feldbiss fault zone, the SW border fault of the RVG. It extends NW-SE over a distance of ~30km between Bree (B) and Geleen (NL). The Geleen fault intersects Maas River terraces of different age, which is reflected in varying vertical topographic offset: on the Middle Pleistocene Main Terrace, the fault is expressed by a ~20 m high scarp, the Bree fault scarp, whereas on the Late Weichselian Maasmechelen terrace covering a large part of the Belgian Maas River valley, the relief is reduced to 1 m maximum. In the latter area, we mapped the surface trace of the Geleen fault using electric-resistivity tomography and georadar. We thus discovered a ~500 m wide stepover and a ~2 km wide bend with a more northerly strike. As the dimension of this stepover is generally considered to be too low to constitute a segment boundary, the Geleen fault likely defines a single fault segment that could rupture in one earthquake. Terrace offsets indicate a long-term slip rate of ~0.06 mm/yr. A total of eight paleoseismic trenches have been excavated across the Geleen fault, all of them revealing well-defined, near-vertical faults extending upward to just below the plough layer. In most cases, the fault zone is very narrow, consisting of a few fault strands. Fault strands are sharp in sand, but in gravel deformation is more distributed, showing a clear shear fabric. Commonly, fault strands have a bleached aspect down to a few m depth, which can be attributed to eluviation; fine particles including Fe and Mn are transported downward and redeposited near the water table, where the fault zone has a stained aspect. Individual paleoearthquakes can be identified in the stratigraphy by identifying the event horizon, this is the ground surface at the time of the earthquake. Layers below the event horizon have been faulted in the event, whereas layers above were deposited after the event. Primary, on-fault evidence for an event horizon typically consists of one or more of the following features: upward termination of fault strands and fissures, colluvial wedges resulting from degradation of a fault scarp, angular fault-zone unconformities produced by folding and tilting, stepwise downward increase in offset, buried soils, etc. Secondary evidence, produced by seismic shaking, both near the fault and in the far field, can be provided by liquefaction and fluidization features and other soft-sediment deformation features. By dating the deposits below and above an event horizon, we can obtain an age bracket for the event.

Almost all of the above-mentioned deformational features have been recognized in the trenches across the Geleen fault. Due to soil development and bioturbation down to 1 m depth, it is typically difficult to macroscopically identify the most recent event horizon. However, using thin sections we were able to confirm that a faintly visible horizon in two trenches near Rotem in the Maas River valley indeed corresponds to a paleoearthquake event horizon, by demonstrating the presence of an in situ soil below and colluvium with elements derived from this soil above. In one of these trenches, we could date the most recent paleoearthquake between 2.5 ± 0.3 and 3.1 ± 0.3 kyr. BP (OSL), and between 2790 ± 20 and 3770 ± 50 calibrated years before AD 2005 (radiocarbon). The time interval between the two most recent events has a range of 11,800 – 16,800 yr (2σ). In a trench across the Bree fault scarp in an interfluvial setting, we obtained a longer history of faulting. We could identify six paleoearthquakes, five of which occurred since ~125 kyr. The two most recent events are evidenced by downward stepwise increasing offset, the four older events by colluvial wedges that apparently formed in periglacial conditions.

In almost all trenches we observed one or more types of soft-sediment deformation. The most prominent features can be attributed to liquefaction of sand, and associated fluidization or water escape. Liquefaction is commonly caused by earthquakes due to cyclic loading by shear waves. If a low-permeability cap is present above a liquefied sand layer, the water expelled from the liquefied zone can create sand blows, these are intrusions of fluidized sand into the overlying cap through feeder dikes (fractures created by hydraulic fracturing or lateral spreading). Sand blows are widely regarded as the type of soft-sediment deformation that is most indicative of seismic shaking. In the investigated area, it appears that the Late Glacial coversands that lie atop the fluvial terraces are very susceptible to liquefaction. In one trench, we identified unequivocal sand blows intersecting a soil profile, the top of which can be correlated with an event horizon in the fault zone. In a second trench, we even observed a gravel dike rising ~0.9 m from the otherwise horizontal top of the Maasmechelen terrace. In a third trench, we observed small-scale intrusions of sand laminae into silt laminae. In trenches situated on relatively steeper slopes, we observed several other features that can be attributed to deformation of a liquefied sand layer under the influence of gravity. These features include: folding due to a combination of downward flow and differential settling, small-scale intraformational upslope-dipping faults accommodating downslope flow of a liquefied sand layer, and a detachment slide with harmonica-like folding of sand and pebble horizons at its toe. Although it is not always possible to exclude an alternative origin, it is not likely that these features represent cryogenic deformation, which was common when periglacial conditions existed in the region. Collectively, the abundant features of soft-sediment deformation corroborate the coseismic nature of faulting in the RVG.

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Veins in the High-Ardenne slate belt: useful instruments to define early and late orogenic rock failure

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Given the objective of this study day, it is clear from the most titles of lectures that the greater part of deformation structures, such as folds, cleavage, fold-cleavage relationships and faults, observed in the Brabant Massif or in the Ardennes are related to the contraction-dominated main stages of either the Brabantian or Variscan orogeny respectively affecting Palaeozoic sediments deposited in Belgium. Especially in the High-Ardenne slate belt the formation of folds and cleavage, which occurred during the Sudetic stage of the Variscan orogeny, is rarely accompanied by large or obvious fluid flow motions, indicating that fold-and-cleavage development occurred in a 'seemingly dry crust' without any significant fluid redistribution. Quartz veins, however, are omnipresent in Lower Devonian sediments of the High-Ardenne slate belt and their occurrence ranges from restricted to the competent sandstone/quartzites, interbedded between lithologies or embedded in slaty sequences. It is clear from ongoing research at the *Geodynamics and Geofluids Research Group* (K.U.Leuven) that these different vein-types have major implications both on the incipient development of a slate belt, prior to the main contractional stage and on the late destabilisation of the orogen, posterior to the contractional stage. In this lecture, different vein types from three different regions will be shown and from a detailed structural, microstructural and microthermometric analysis, the regional significance of pre- to early tectonic and late tectonic quartz veins and their importance to the transition between tectonic stress regimes will be discussed.

In the northeastern part of the High-Ardenne slate belt (Eifel, Germany), two successive types of quartz veins, oriented normal and parallel to bedding chronologically, are interpreted to reflect the late Carboniferous tectonic inversion affecting upper crustal levels (around 7 km depth) (Van Noten et al., 2008; Van Noten and Sintubin, 2010; Van Noten et al., in prep.). This compressional tectonic inversion represents the switch from the latest stage of the extensional stress regime, during which bedding-normal extension veins developed regionally at near-lithostatic fluid pressures under low-grade, anchizonal metamorphic conditions, to the early stage of the compressional stress regime. Bedding-parallel veins are the first evidence demonstrating the latter stress regime and they precipitated from lithostatic to supralithostatic fluid pressures present at the time of veining and needed to uplift the overburden rock column.

The latter purely brittle kinematic history during compressional tectonic inversion differs from a mixed brittle–ductile deformation observed in deeper parts of the Ardenne-Eifel basin (i.e. Bertrix to Bütgenbach region) which is currently expressed as lens-shaped veins with a blocky infill, followed by the development of mullion structures. These particular structures developed during a two-phased history (Kenis et al., 2002, 2004, 2005a, 2005b;

Kenis & Sintubin, 2007): first, bedding-normal extension veins developed during progressive burial and second, as veins become more competent than the host-rock, a cuspate-lobate geometry at the incompetent-competent interface formed during layer-parallel shortening after the tectonic inversion reflecting the compressional stress regime.

Evidence of the reverse - extensional - tectonic switch, i.e. transition from compression to extension, is found in the Herbeumont-Bertrix area (Van Baelen, 2010), of which the inversion is related to the destabilisation of the Variscan orogen as expressed by south-verging folds, kink bands and discordant quartz veins that cross-cut the main Variscan cleavage. These veins with complex geometries are interpreted as extension fractures which formed initially shortly after the inversion and which underwent a shape-modification during increasing differential stress and ongoing extensional shearing.

These examples show how veins in particular can contribute to the reconstruction of the geodynamic history recorded in the High-Ardenne slate belt and how they have implications to the incipient shortening or late destabilisation of slate belts.

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Systematic inventory and hierarchisation of the Belgian faults

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The study of faults in Belgium has interested and concerned still nowadays many structural investigations. A census of the faults appears essential to clear, as the literature is large and scattered. The programme “Faults” is actually based on bibliographic researches. The aim is to provide an inventory compiling the main structural features (*i.e.* direction and length of the trace, nature and length of the throw(s) …) and suggesting a brief tectonic interpretation. The divergent views are taken in account. The results will be brought out as a memoirs of the Geological Survey of Belgium and a national-scale map of the Belgian fault network. An electronic open access database will be considered.

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Tectonites and related structures
Measuring palaeostrain and palaeorheology

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A **tectonite** is a tectonic rock resulting from a homogeneous, penetrative or continuous, finite strain. Strain is defined as the component of deformation reflecting the change of shape. Finite strain is the strain comparing the initial and final configuration of the deformed body. Homogeneous strain is a strain in which any two portions of a rock body similar in form and orientation before strain remain similar in form and orientation after strain. Finally, a penetrative or continuous strain affects the whole rock body on a mesoscopic or (sub-)microscopic scale respectively. This means that a tectonite can serve as a **strain gauge**. A tectonites reveals (1) the orientation of the principal strain axes, (2) the relative magnitude of the principal strain axes, and (3) the type of finite strain (i.e. constriction, plane strain, flattening). Recognizing tectonites in the field is therefore a powerful tool in any attempt to reconstruct the geodynamic history of a terrain.

Basically three types of tectonite can be distinguished. An **S tectonite** (and S-l tectonite) shows a dominant planar fabric. It reflects primarily a flattening strain. Typical S tectonites are e.g. cleavage fabrics, a schistosity, a gneissic foliation. An **L tectonite** (and L-s tectonite), on the other hand, shows a dominant linear fabric. Such tectonites commonly occur in metamorphic terrains. It reflects primarily a constructional strain. An **S-L tectonite** shows both planar and linear fabric elements. It commonly reflects a plane strain and is typical for mylonitic foliations.

The planar fabric of an S tectonite is classically interpreted to represent the XY plane of the finite strain ellipsoid, while the linear fabric of an L tectonite represents the X axis of the finite strain ellipsoid.

The common tectonite in low-grade metamorphic sedimentary rocks is a **cleavage**. A cleavage can be defined as a secondary foliation formed by the statistical preferred orientation of plate fabric elements, i.e. phyllosilicates. It is therefore the common tectonite in predominantly argillaceous metasediments. Different types of cleavage fabric can be described. A **shale fabric** is a bedding-parallel cleavage fabric, primarily caused by compaction due to overburden. An early tectonic deformation, resulting in layer-parallel shortening, eventually gives rise to a **pencil cleavage**, an L tectonite. Ongoing tectonic deformation eventually results in a **slaty cleavage**, with (S-l tectonite) or without (S tectonite) a developed mineral lineation.

A number of related structures can also serve as strain gauges. With respect to **folds**, the associated cleavage materialises the axial plane of the fold. The axial plane cleavage thus represents the XY plane of the strain ellipsoid, while the Y axis of the strain ellipsoid commonly coincides with the fold hinge line (and intersection lineation in the case of concentric folds). In the case of **boudins** the boudin axis can be seen as the Y axis of the strain ellipsoid. The boudins result from a foliation-parallel extension. The tectonic foliation, materialising the XY plane of the finite strain ellipsoid, occurs parallel to the aligned boudins. **Mullions**, on the other hand, are the result of foliation-parallel shortening – i.e. cuspate-lobate folding. The mullion axis again represents the Y axis of the strain ellipsoid. The tectonic foliation, resulting from the foliation-parallel shortening, occurs perpendicular to the interface affected by the cuspate-lobate folding.

The relation between cleavage and related structures can also serve as **rheology gauges**. High viscosity contrasts lead to fold amplification, resulting in e.g. **ptygmatic folds**. High viscosity contrasts in multilayer sequences also leads to **cleavage fanning** across fold hinges and **cleavage refraction** at the foliation interfaces. In the case of boudins the boudinaged layer is composed of the more competent material embedded in a less compentent matrix. In the case of cuspate-lobate folding – or mullions – the viscosity contrast is relatively low at both sides of the affected interface, not giving rise to any fold amplification. The cusps point towards the more competent material, while the lobes point towards the less competent material.

Finally, the cleavage fabric (or tectonic foliation) serves as a **time marker**. Geological structures predating cleavage development are commonly cross-cut by the cleavage fabric. Multiple cleavage fabrics, such as extensional shear cleavage, can develop during a single progressive deformation. Different cleavage fabrics can also be superposed, leading to a (multiple) **crenulation**. And finally, cleavage fabrics can be affected by subsequent deformations (e.g. kinking, faulting).

Tectonites and related structures hold valuable information on different aspects of the geodynamic history of a terrain. Already in the field special attention should be devoted to these geological structures.

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Influence of Lower Devonian sedimentary sequences on reworked boudins and associated structures (Ardenne)

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Lower Devonian meta-sedimentary rocks from the Ardenne Anticlinorium and the surrounding areas in Belgium and Germany outcrop in a wide spectrum of sedimentary sequences. The latter can be classified according to the relative thickness of meta-pelite and sandstone layers. The aim of this talk is to present the influence of different sedimentary assemblages during a multi-event deformation sequence, which affected the Rhenohercynian basin before and during the Variscan orogeny (~330-300 Ma). The main deformation periods include first a layer-parallel extension followed during the Variscan orogeny by a layer-parallel shortening period.

The main stress marker of the layer-parallel extensional period is shown by sets of lens-shaped quartz veins within the sandstone layers. These veins are commonly interrupted at the contact with meta-pelite horizons. If the thickness of the latter (e.g. closely-packed sandstone layers) is relatively small the sandstone layers influence each other resulting into a perturbed stress field marked by complex sets of quartz veins. By contrast, the development of quartz veins in well-individualized sandstone layers follows a regular pattern associated with the deformation of sandstone-pelite interfaces as a cuspate and lobate geometry. The individual sandstone layer segments adopt a barrel-shaped structure: the boudins (see figure).

During the layer-parallel shortening period (Variscan orogeny) the boudins were shortened (reworked) and the cuspate-lobate geometry was further magnified by passive amplification. In closely-packed sandstone layers the complex sets of quartz veins are associated with irregular sedimentary contacts. The latter were also passively amplified during the Variscan layer-parallel shortening resulting notably into complex fold structures.

The model of reworked structures is globally in good agreement with the one of Jongmans & Cosgrove (1993) and with the classification of boudin structures by Goscombe et al. (2004). It provides also new insights on the discussions regarding the aspect ratio (height/width) of the reworked boudins from the Ardenne Anticlinorium area. The passive amplification of pre-existing structures during the Variscan orogeny contradict the ‘doubled-sided mullions’ model of Kenis et al. (2002) which attempted to reject the layer-parallel extension period and consider that the quartz veins could act as rigid-platens.

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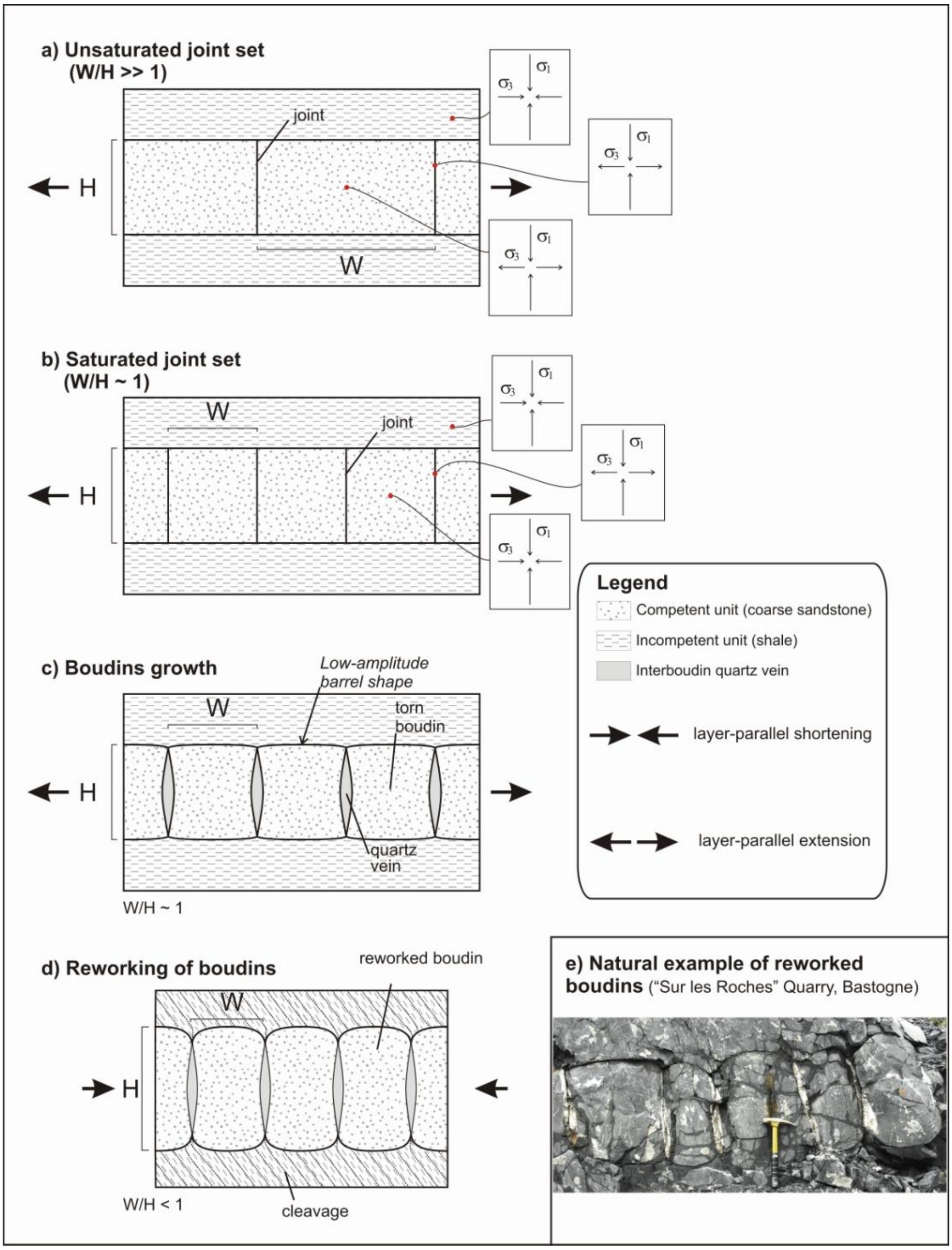

Figure – Model of development of narrow reworked boudins from the Ardenne Anticlinorium area (from Vanbrabant, Y. & Dejonghe, L. 2006. Structural analysis of narrow reworked boudins and influence of sedimentary successions during a two-stage deformation sequence (Ardenne-Eifel region, Belgium-Germany). Memoirs of the Geological Survey of Belgium 53, 1-43.)

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Kink bands

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Kink bands are narrow zones (bands) of angular, straight-limbed folds (kinks), forming on a well-developed, pre-existing planar anisotropy. Despite the fact that kink bands are essentially folds, and therefore should not be linked to stress, experimental work pointed out a direct relationship between kink band geometry and the principal stress directions (e.g. Paterson and Weiss, 1962, 1966; Donath, 1968; Anderson, 1974; Gay and Weiss, 1974). Moreover, several field studies have linked kink bands to stress orientations of nearby faults. Because of these experimental results and supporting field studies, kink bands have often been used to determine paleostress orientations.

Within the type A1 folds in the Silurian rim of the Brabant Massif, small-scale kink bands occur, with a geometry suggestive of a post-cleavage subvertical shortening. Because of the convergent cleavage fanning, different kink bands are observed on opposite fold limbs. However, the observed kink band geometries do not match those expected on theoretical grounds, and suggest a strong influence of bedding and/or cleavage orientation on the final kink band geometries.

We observed similar problems in two other areas. In the Silurian Hawick Group in the southwestern part of the Southern Uplands Terrane (Scotland), upright syn-cleavage folds experienced later subvertical shortening. Although cleavage remains parallel throughout the folds, kink bands with opposite asymmetries occur on opposite fold limbs, and conjugate systems are rarely observed. The kink band geometries point to a strong influence of bedding geometry on the kink band geometries. Also in the Silurian – Carboniferous of the Macin zone in the N-Dobrogea orogen (Romania), two subhorizontal kink band sets occur, forming part of a conjugate system formed under the influence of a vertical, post-cleavage shortening. Although cleavage orientation changes significantly across the area, conjugate systems seem to occur in all outcrops. This suggests a strong influence of cleavage on local stress orientation, and hence on kink band geometry.

In all three areas studied, an influence of pre-existing fabrics (bedding and/or cleavage) on final kink band geometries is inferred. This, combined with the occasional occurrence of curvilinear kink axes, strongly questions the use of kink bands for determining paleostress orientation. We suggest that, as long as the mechanism of kink band development is not fully understood, kink bands should not be interpreted in terms of stress directions, but should be interpreted only in terms of strain.