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Linear to non-linear relationship between vein spacing and layer thickness in centimetre- to decimetre-scale siliciclastic multilayers from the High-Ardenne slate belt (Belgium, Germany)

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ABSTRACT

Typical spacing distributions have frequently been described for fractures in thin sedimentary layers (<1 m). Regularly spaced fractures often result from saturation during fracture development. Spatial distribution of veins is less commonly studied although it also can show regular patterns. This study focuses on the spatial distribution of quartz veins in Lower Devonian siliciclastic multilayer sequences from the High-Ardenne slate belt (Belgium, Germany) and compares the observed vein spacing with published fracture spacing in order (i) to investigate the effect of the layer thickness to vein spacing and (ii) to understand the processes of early vein development during the late stages of burial in a sedimentary basin at the onset of orogeny. The results show that a quasi linear relationship between vein spacing and layer thickness in thin (<40 cm) competent sandstone layers, embedded in a pelitic matrix, becomes non-linear in thicker sandstone layers (>40 cm). Vein spacing tends to increase to a maximum value becoming more or less independent of layer thickness. The resemblance with fracture spacing suggests that in an unfractured rock vein saturation can occur. High fluid pressures are responsible for vein nucleation but the stress state around the initial veins controls the spacing pattern. Subsequently, in a vein-saturated rock, or the existing veins will thicken by the process of crack-sealing, or a new cross-cutting vein generation will develop in case the regional stress field changes relatively with respect to the existing veins.

1. Introduction

Knowledge of the geometry of fracture and vein networks is essential in sub-surface research (e.g. oil reservoir research, mining geology). Discontinuities such as fractures, joints and veins are potential sites for fluid transport and have important implications for the hydraulic properties of rock (Clark et al., 1995; André-Mayer and Sausse, 2007).

Fracture spatial distribution has been studied in numerous papers commonly using statistical methods in search of the best fit between actual or numerical datasets and theoretical distribution laws. This theoretical approach not only provides a simplified image of the fracture set, but also enables a numerical definition (Huang and Angelier, 1989). Most fracture distributions, however, are not applicable to the spatial distribution of veins (Gillespie et al., 2001; Peacock, 2004). Although veins and joints initially are similar mechanically (e.g. Thomas and Pollard, 1993), there are important geometric, scaling and genetic differences and they should be considered separately (Gillespie et al., 2001). In this paper we refer to ‘joints’ or ‘fractures’ as unmineralised extension or opening (mode I) cracks across which host-rock minerals have been broken without any measurable displacement. Genetically, the term “joint” does not necessarily refer to fracture networks formed during uplift. We refer to ‘veins’ as mineral-filled fractures which usually form in vein arrays (cf. Twiss and Moores, 1992; Bai and Pollard, 2000b; Peacock, 2004).

In this field-based study we want to investigate if repetitive spacing of late burial quartz veins in the High-Ardenne slate belt (Belgium, Germany) is proportional to the layer thickness and if the observed spacing can be explained by one of the numerously published geomechanical models which are developed to predict fracture patterns in naturally fractured reservoirs. In order to do so, we firstly discuss some representative geomechanical models of fracture and vein spacing and show why there is still a need for new field data. Secondly, we compare the spacing of planar veins and the aspect ratios of fractured blocks in thin (<1 m) siliciclastic multilayer sequences with; (i) field examples of vein spacing in

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boudinaged layers; (ii) published fracture distributions for a range of lithologies; (iii) the spacing of lensoid veins in shortened sequences (i.e. mullions) in the central part of the slate belt in order to show the regional occurrence of vein spacing. It is interesting to examine the distribution of these stratabound veins to gain insight into a time-integrated history of compartmentalised fluid redistribution during low-grade metamorphism and to understand the initial development of veins (cf. Manning, 1994; Stowell et al., 1999). Working on veins rather than on fractures has moreover the advantage that the role of fluid pressure can be evaluated. This study could therefore serve as an analog for fracture or vein patterns in the sub-surface.

1.1. Fracture development

It is widely accepted that extensional fracture spacing is mainly controlled by lithological parameters of the host-rock and layer thickness. There is a large literature on the relationship between fracture spacing (*S*) and layer thickness (*T*) in which the mechanics of fracture spacing has been described by both field observations (Hobbs, 1967; Ladeira and Price, 1981; Pollard and Aydin, 1988; Huang and Angelier, 1989; Narr and Suppe, 1991; Engelder et al., 1997; Gillespie et al., 2001) and geomechanical or numerical modelling (Mandal et al., 2000; Fischer et al., 1995; Wu and Pollard, 1995; Ji and Saruwatari, 1998; Ji et al., 1998; Bai and Pollard, 2000a,b; Olson, 2004; Li and Yang, 2007). Both linear and non-linear relationships between fracture spacing and layer thickness have been described. Throughout these studies, spacing is often explained from a mechanical point of view without considering the role of pore-fluid pressure, although it is commonly accepted that high fluid pressures in combination with tectonic extension can induce opening fractures (Secor, 1965; Ladeira and Price, 1981; Simpson, 2000). Recent experimental results show that fracture spacing decreases progressively with increasing strain perpendicular to the fracture in such way that new fractures form between earlier fractures, with increasing bedding-plane friction and with increasing overburden pressure (cf. Arslan et al., 2010). The fractures are flanked by 'stress shadows' (Lachenbruch, 1961; Hobbs, 1967) in which new fractures are unlikely to form and the size of the stress shadow is directly proportional to the length of the fracture, i.e. the layer thickness (Pollard and Segall, 1987). In layered sequences, these fractures are usually prevented from further growth at the interface between competent and incompetent beds (Wu and Pollard, 1995; Engelder et al., 1997; Cooke et al., 2006). The final stage of fracture development is reached when no more 'freedom' exists for nucleating new fractures in between pre-existing ones and this stage is referred to as the 'saturation level' by Narr and Suppe (1991).

Recent modelling showed that the crack-normal stress between closely spaced fractures actually becomes compressive at certain fracture spacing so no more tensile fractures can form (Bai and Pollard, 2000b). This result dictates that at the saturation level, the opening of pre-existing fractures is preferred over nucleation of new additional fractures with increasing extensional strain (Olson, 2004; André-Mayer and Sausse, 2007). Bai and Pollard (2000a) defined a critical *S*/*T* ratio of 0.976 which gives a lower limit for fractures driven by extension in a material without significant flaws and defines the conditions of fracture saturation. This critical value increases non-linearly with increasing ratio of the Young's modulus of the fractured layer with respect to that of the neighbouring layers, with increasing Poisson's ratio of the fractured layer, and with increasing magnitude of the overburden stress (Bai and Pollard, 2000b). However, the effects of the elastic constants on the critical value are minor.

Spacing to thickness ratios less than the critical value have often been seen in outcrop. The concept of fracture saturation may break down if a local stress field exists due to the presence of flaws in between adjacent fractures, or due to a local mechanism such as high fluid pressures, which can overcome the compressive stress at the stage of fracture saturation in such way that new fractures are nucleated in the vicinity of pre-existing fractures (Simpson, 2000). This contrasts with a large body of work in which the nucleation of nearby fractures is prohibited at the stage of fracture saturation and the role of high fluid pressures has therefore been underexplored. These closely spaced infilling fractures are, moreover, more likely to initiate near the interfaces than in the middle of the layer.

Besides lithological parameters, fracture spacing is also dependent by the degree of pre-existing rock deformation (Harris et al., 1960) and the interference of adjacent competent layers (Ladeira and Price, 1981; Bai and Pollard, 1999). The effect of layer thickness variations may overshadow other variables, such as strain level, strain anisotropy and the subcritical crack index, which also influence fracture spacing. Experimental modelling (Olson, 1993, 2004) has shown that the subcritical crack index controls the degree of fracture organisation and depends on rock's microstructure (grain mineralogy, grain size, cement type, porosity; Atkinson, 1984) and the chemical environment. Moderate values of subcritical index (e.g. sandstones) result in more regularly fracture spacing that is roughly proportional to the mechanical layer thickness, whereas higher values (e.g. in carbonates) predict the occurrence of fracture swarms or clusters (Olson et al., 2002; Rijken, 2005).

1.2. Vein spacing

Clear examples of vein spacing distributions in literature are scarce. They have been described in limestones (e.g. Gillespie et al., 2001), or in pelites, in which veins for instance can occur in en-echelon arrays (Fisher et al., 1995) or axial planar (Simpson, 2000). Gillespie et al. (1999) and Foxford et al. (2000) give a detailed description of vein spacing for a range of lithologies. A fundamental distinction in spacing is apparent between stratabound vein arrays,

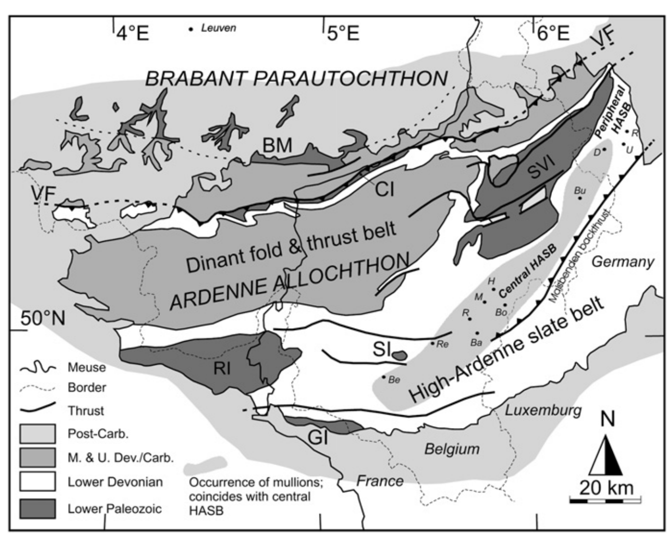

Fig. 1. Structural map of the Variscan external belt in the Ardenne-Eifel area showing the outcrops studied in the cHASB (Bu: Bütgenbach; Bo: Boeur; H: Houffalize; M: Mabompré; R: Rouette; Ba: Bastogne; Re: Remagne; Be: Bertrix; D, Dedenborn) and in the pHASB (U, Urftsee; R, Rursee). Lower Palaeozoic basement inliers: BM: Brabant Massif; CI: Condroz inlier; SVI: Stavelot-Venn inlier; SI: Serpont inlier; RI: Rocroi inlier; GI: Givonne inlier. VF: Variscan thrust front, separating the Brabant parautochthon from the Ardenne allochthon.

veins confined to competent rock in multilayered sequences, and non-stratabound vein arrays, in which veins occur in homogeneous rock. Veins often show well defined spacing statistics for a specific host-rock lithology, but comparing different studies remains difficult due to the regional variability of rock properties. Putz-Perrier and Sanderson (2008) statistically describe the decrease of vein spacing near faults and faulted blocks. Also Stowell et al. (1999) characterise a spacing distribution of veins cross-cutting folds and cleavage, caused by a late-orogenic uplift. They specifically discuss the distribution of late-orogenic veins in deformed multilayer sequences. Although the results of both latter case studies are applicable for the spacing of syntectonic veins, they cannot be compared to our study where veining is the result of an early deformation event, i.e. an event predating the main fold-and-cleavage development. Vein spacing distributions are thus difficult to compare since, despite from the vein-hosting lithology, the timing of fracturing influences vein spacing. Furthermore the different ways of how data may be represented in graphs can strongly influence the interpretation of results

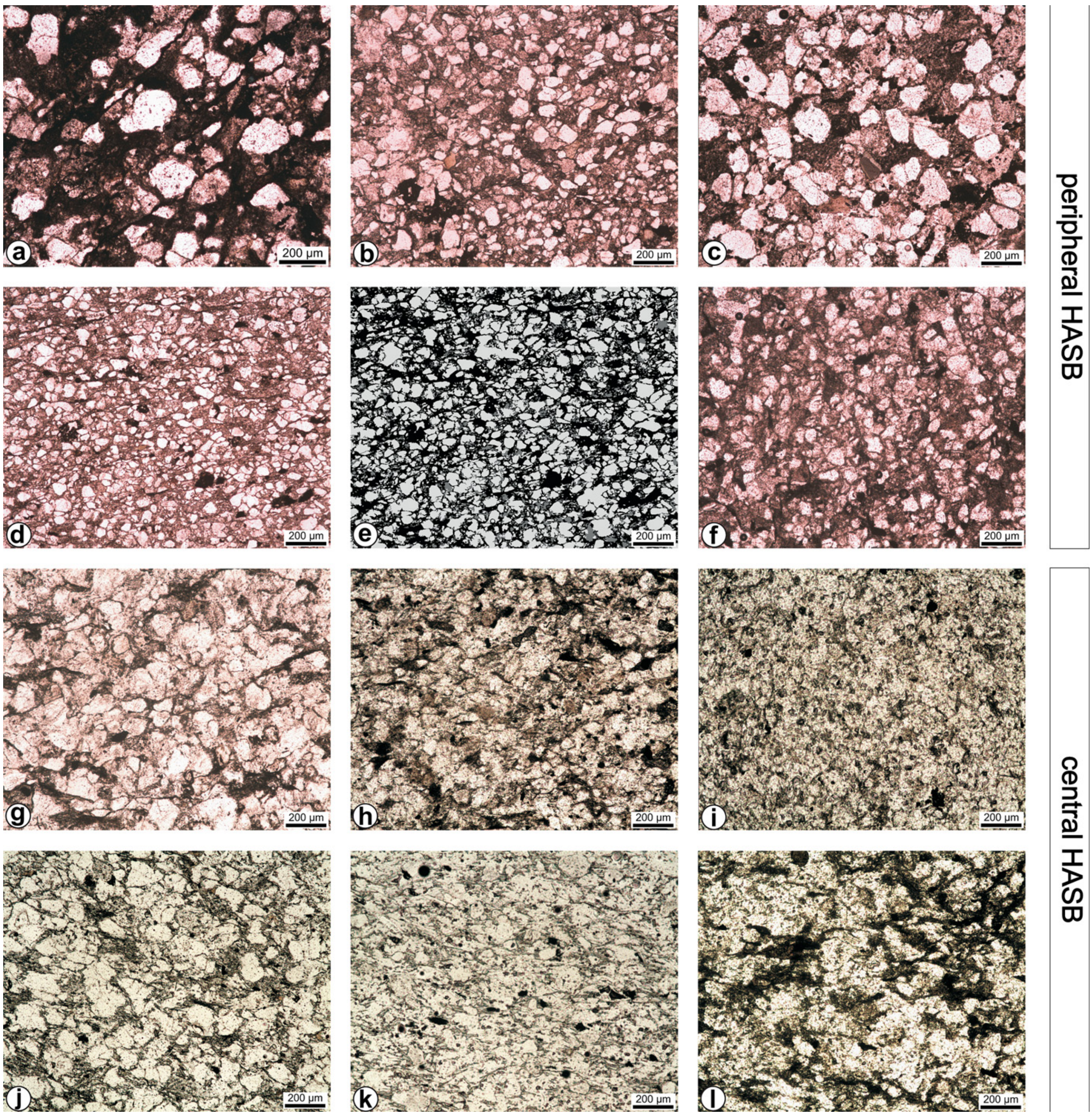

Fig. 2. Representative microphotographs of the host-rock lithologies of the different outcrops studied in the High-Ardenne slate belt (HASB). See Table 1 for description of the samples. (a) Wildenhof; (b) Schwammenauel; (c) Eschaulerberg; (d) Hubertus Höhe; (e) JMicrovision (Roduit, 2008) image of (d) used for estimating the percentage of quartz grains (light-grey) and quartz cement (dark grey) present in the host-rock; (f) Urftsee; (g) Dedenborn; (h) Boeur; (i) Bastogne Sur Les Roches; (j) Bastogne Mardasson; (k) Remagne; (l) Bertrix.

and complicates comparing case studies. Nevertheless the difficulty of comparing different vein spacing studies, it is still worthy to present new data from an interesting study area.

2. Late burial quartz veining in the High-Ardenne slate belt

2.1. Geological setting

The study area is situated in the northern extremity of the Central European Variscides: the so-called Rhenohercynian foreland fold-and-thrust belt (Oncken et al., 1999). The studied outcrops all belong to the High-Ardenne slate belt (Belgium, Germany; HASB; Fig. 1), forming a part of the Ardenne allochthon which was thrust over its foreland, the Brabant parautochthon, during the latest, Asturian, stage of the Variscan orogeny (late Carboniferous; Meilliez and Mansy, 1990). The slate belt consists of Lower Devonian siliciclastic metasediments, which were affected by a very low- (anchizonal) to low-grade (epizonal) burial-related metamorphism that was pre- to syn-kinematic with respect to the Variscan deformation (Fielitz and Mansy, 1999). The Lower Devonian sequences of the slate belt reflect the rapid syn-rift sedimentation of the Rhenohercynian basin, particularly active during the Pragian (Oncken et al., 1999), and predominantly consist of pelitic rock intercalated with sandstone layers. Maximum depth of burial varied between 7 and 10 km with a burial temperature variation ranging from 200 °C to 400 °C in the anchizonal and epizonal part respectively (von Winterfeld, 1994; Fielitz and Mansy, 1999). Quartz veining is a regional phenomenon in the slate belt and is related to the latest stages of the Rhenohercynian basin development (Ardenne-Eifel basin) and is synchronous with the burial-related metamorphism. In the entire slate belt, these late burial quartz veins predate the main compression phase of the Variscan fold-and-cleavage development and are mostly restricted to the competent layers in the siliciclastic multilayer sequences (Kenis et al., 2002; Van Noten et al., 2008). The early veins in the HASB can thus be considered as the earliest manifestations of the Variscan orogeny (cf. Van Noten et al., 2007).

Two areas can be outlined in the High-Ardenne slate belt (Fig. 1), each showing a characteristic vein pattern: the central part (i.e. cHASB: Bertix to Bütgenbach area, Belgium; Fig. 1) where mullions are pinned by bedding-perpendicular lensoid veins (see description in Urai et al., 2001; Kenis et al., 2002); and the peripheral part (i.e. pHASB: North Eifel, Germany; Fig. 1) exposing the higher structural levels of the Ardenne-Eifel basin, where planar veins occur in 'undeformed' segments which do not show mullion morphology (Van Noten et al., 2008). The quartz veins observed in the very low-grade metamorphic part of the HASB (pHASB) occur in several outcrops along the Rursee and Urftsee water reservoirs, situated in the North Eifel about 30 km ESE from Aachen (Germany). We refer to Van Noten et al. (2008) for a detailed location of the outcrops used in this paper.

2.2. Host-rock lithology

The host-rock lithology in the Eifel area (pHASB) can be classified as a fine- to medium-grained quartzwacke, in which the quartz grains mostly are subrounded to subangular and moderately to well sorted (Fig. 2a–f). The grains are single detrital crystals with uniform interference colors of which the grain size varies between 50 µm and 350 µm. The volume of quartz grains and quartz cement (Table 1) has been estimated by use of the image analysis software JMicroVision (Roduit, 2008). The very fine-grained matrix exists of minor muscovite, biotite and chlorite. The deposits studied belong to the Upper Rurberg Unit (upper Pragian) and Heimbach Unit (upper Pragian to Emsian). We refer to Van Noten et al. (2008) for the lithostratigraphical description of these units.

The host-rock in the cHASB varies from fine-grained sandstone in the anchizone to quartzite in the epizone of the HASB. The sandstone (cf. psammite; Kenis, 2004) shows a fine-grained matrix, consisting of mainly quartz grains (Fig. 2g–l; Table 1) and minor feldspar, biotite, muscovite, chlorite and ilmenite and is rich in

Table 1
Host-rock and adjacent lithologies of the different outcrops studied. See Bultynck and Dejonghe (2001) and Van Noten et al. (2008) for the lithostratigraphic descriptions of the formations in the Ardennes and Eifel, respectively. Common grain sizes have been used for description of layer lithology. The image analysis software JMicroVision (Roduit, 2008) has been used for an estimation of the volume of quartz in each representative sample. An error of ±5% has been estimated for this method. Sphericity (Sph): low (LS), medium (MS), high (HS); Roundness (Rnd): subangular (SA), subrounded (SR); Degree of sorting: moderate (Mod).

Locality	Dataset	Formation	Sample	Layer lithology	% Q_z grains	% Q_z cement	% Q_z	Sph	Rnd	Degree of sorting	Adjacent layer lithology
pHASB/Rursee	Wildenhof 44a	Upper Rurberg	EI06VN08	Medium-grained sandstone	36	21	57	MS	SA	Poorly	Siltstone
pHASB/Rursee	Schwammenauel 93	Upper Rurberg	EI05VN43	Fine-grained sandstone	46	19	64	HS	SR	Well	Siltstone
pHASB/Rursee	Hubertus Höhe 72	Upper Rurberg	EI05VN36	Fine-grained sandstone	42	16	59	HS	SR	Well	Pelite
pHASB/Rursee	Eschaulerberg 64	Upper Rurberg	EI05VN34	Medium-grained sandstone	44	29	72	LS	SA	Mod	Siltstone
pHASB/Urftsee	27b	Heimbach	EI08VN26	Fine-grained sandstone	37	25	62	HS	SR	Well	Siltstone
pHASB	Dedenborn	Middle Rurberg	EI05VN17	Medium-grained sandstone	51	29	80	HS	SA	Mod	Pelite
cHASB	Bütgenbach	Neufchâteau	-	Fine-grained sandstone	–	–	–	–	–	–	Pelite
cHASB	Houffalize	Neufchâteau & Longlier	-	Sandstone	–	–	–	–	–	–	Pelite
cHASB	Boeur	Longlier	Boe 5	Sandstone	49	22	71	MS	SA	Well	Pelite
cHASB	Bastogne Collignon	Anlier	-	Quartzite	–	–	–	–	–	–	Siltstone/pelite
cHASB	Bastogne SLR	Anlier	SLR 10	Quartzite	46	28	73	HS	SR	Well	Siltstone
cHASB	Bastogne Mardasson	Anlier	BAMAR 8b	Quartzite	59	25	84	HS	SA	Well	Siltstone
cHASB	Rouette	Anlier	-	Psammite	–	–	–	LS	SA	Poorly	Siltstone
cHASB	Remagne	Oignies	Rem 3 A08	Quartzite	51	29	79	MS	SR	Well	Pelite
cHASB	Bertrix	Saint-Hubert	Ber 8b	Quartzite	35	30	65	HS	SR	Mod	Pelite

phyllosilicates. In general the quartz grains within the sandstone are mostly well sorted, subrounded to subangular and often show undulous extinction. The clastic shape of the grains can often be recognised, altered by preferential dissolution, and strain fringes with quartz overgrowths. Grain aggregates are frequently overgrown by phyllosilicate beards and phyllosilicate strain fringes are common (Kenis et al., 2005a). The percentage of quartz grains in the quartzites is much more difficult to estimate as individual grains are often overgrown by the recrystallised quartz cement.

2.3. Vein orientation

Opening mode fractures primarily propagate perpendicular to the least compressive principal stress σ_3 (Laubach et al., 2004). If veins, which initiated as fractures, are uniform in trend over a large area, then they can be used as indicators to decipher the palaeostress orientations at the time of veining (e.g. Laubach et al., 2004; Nüchter and Stöckhert, 2007). In order to evaluate the original vein orientation, the vein-hosting beds need to be restored to their original horizontal orientation prior to folding. The latter rotation was performed in two steps. Firstly, the plunge of the local fold hinge line was removed by rotation around a virtual axis perpendicular to the fold hinge line. Secondly, after untilting, the different fold limbs were unfolded towards the horizontal around the untilted local fold hinge line (e.g. Debacker et al., 2009). This method was evaluated by refolding the beds along the local intersection lineation in order to see if the original vein orientation could be restored (see Van Noten et al., 2008). The error is estimated to be less than 5°.

The geometric occurrence of the veins in the HASB suggests tensile fracturing with opening normal to σ_3. In the cHASB veining

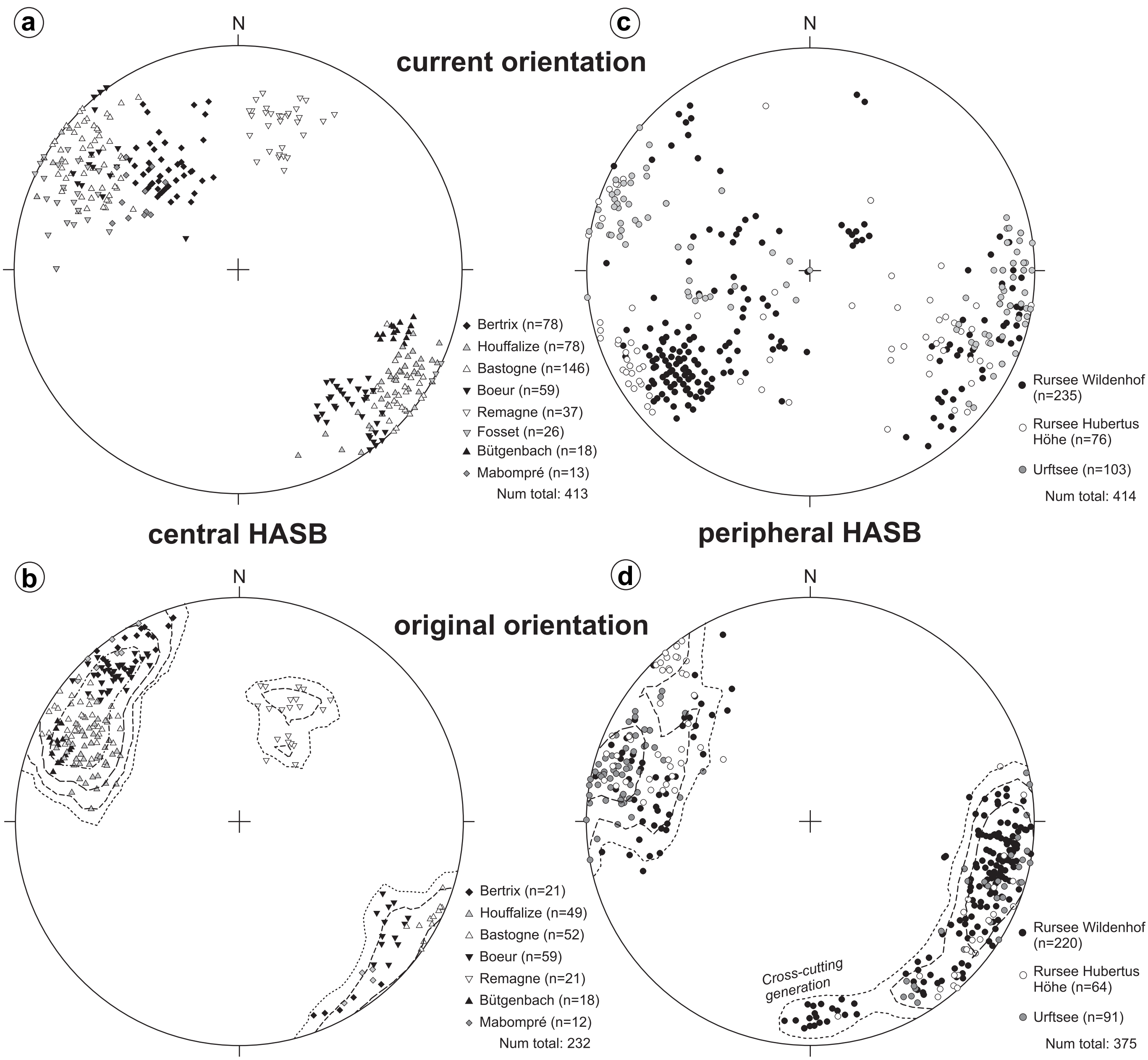

Fig. 3. Lower-hemisphere, equal-area projections of (a–b) bedding-normal quartz veins in the cHASB in their (a) current and (b) original unfolded orientation and (c–d) cross-cutting quartz vein generations in the pHASB in their (c) current and (d) original unfolded orientation. See text for discussion.

is expressed by the occurrence of a regular and consistent set of bedding-perpendicular veins (Kenis, 2004). Veins originally trend NE to NNE and are nearly vertical, indicating that veining occurred in an anisotropic stress field with a vertical σ_1 and a horizontal σ_2 corresponding to the tectonic stress (Fig. 3a and b). Towards the pHASB, quartz veining is still a regional phenomenon but is expressed differently by several cross-cutting vein generations (Fig. 4a and b). Veins originally show a variation in trend from NE to NNE for early generations, to ENE to E for cross-cutting generations (Fig. 3c and d). This cross-cutting relationship suggests that veining also occurred in an anisotropic stress with a vertical σ_1, but with a less obvious relationship between the intermediate and minimum principal stress. The change in orientation of cross-cutting veins could indicate that σ_2 equals σ_3 at a certain stage and that they switched locally during a short period. Differences between the areas notwithstanding, the original orientations of veins which are characterised by a repetitive spacing pattern are consistent in the whole High-Ardenne slate belt with a stress field characterised by a vertical maximum principal stress ($\sigma_1 = \sigma_{vertical}$) and a horizontal minimum principal stress (σ_3) oriented at about WNW–ESE to NW–SE at the time of veining.

2.4. Vein microstructures and veining conditions

The veins in the pHASB are oriented at a high angle to bedding, regardless of their position across the folds. They terminate at the interface with the adjacent incompetent pelitic material without changing in thickness indicating that interfacial, bedding-parallel slip must have taken place during veining. Sometimes the veins continue in the adjacent pelitic material, refracting at the competent–incompetent interface (Fig. 4c and d). Although straight, equally spaced axial planar veins have been described in slaty sequences (e.g. Simpson, 2000), veins in pelites in the pHASB are highly irregular with vein branching being a common feature. Vein thickness ranges from a few millimetres to several centimetres and their lengths vary between 10^{-1} m and 10^{1} m. The thickness distribution is not focussed upon in this paper, although thicker veins have rather been observed in thicker beds than in thinner.

In the vein fills, quartz commonly occurs as fibrous to elongate-blocky, ataxial to syntaxial crystals (Fig. 4e and f), of which the fibres are oriented sub-perpendicular to perpendicular to both vein walls. Sometimes clear vein wall parallel host-rock inclusions (Fig. 4g) are torn from the vein walls during episodical opening of the vein by the crack-seal mechanism (cf. Ramsay, 1980), marking former positions of the vein walls. These host-rock inclusions indicate that these veins initiated as opening mode fractures and that the rate of cementation was higher than the opening rate. If chlorite is present, it only occurs near both vein walls. Undulose extinction, deformation lamellae and bulging of the crystal walls (Fig. 4g) are observed in the quartz crystals, implying that limited deformation of the host crystals has taken place. Primary microstructures such as fibrous crystals are still present and were not

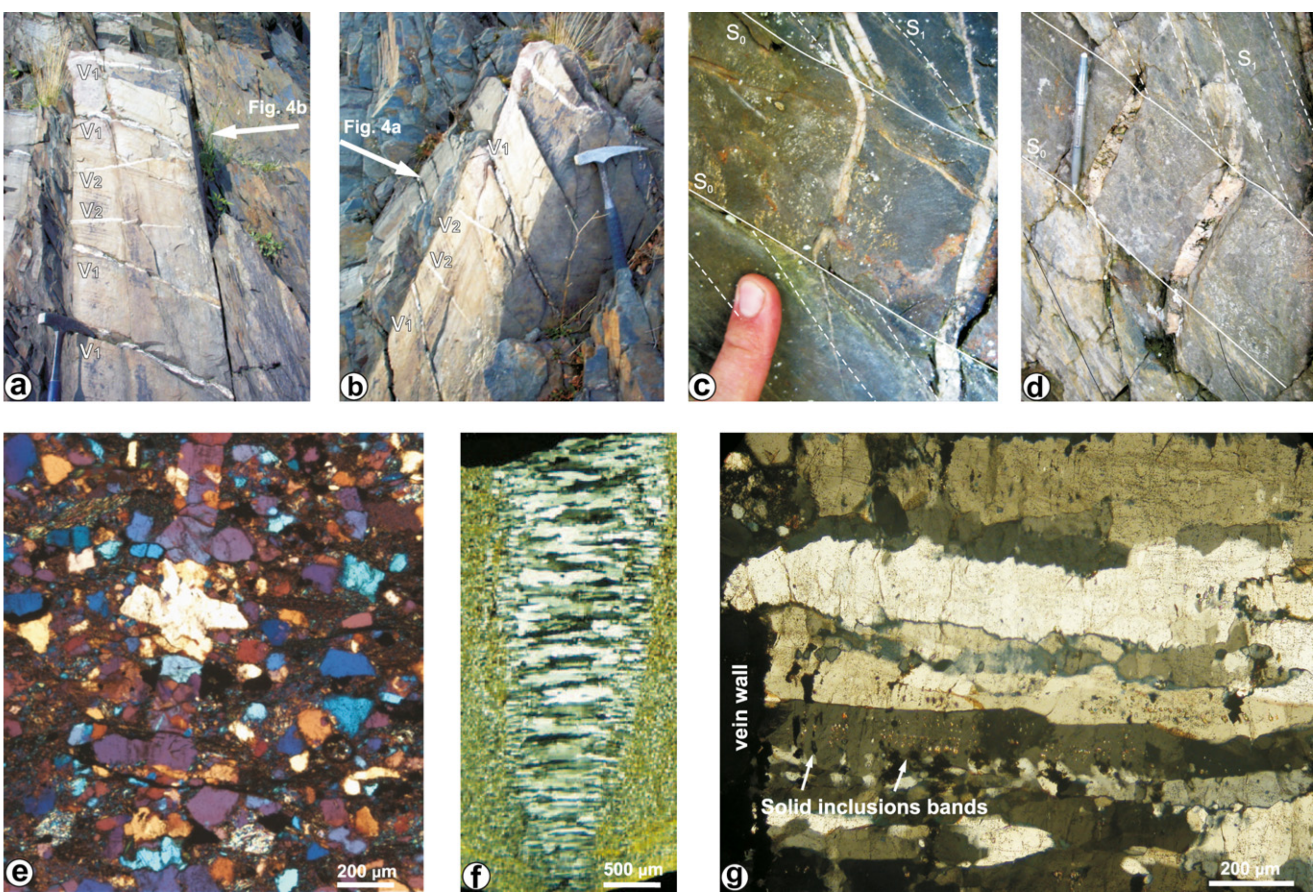

Fig. 4. Photographs and characteristics of quartz veins in the pHASB (Rursee and Urftsee, North Eifel). (a–b) Cross-cutting vein generations (early V_1 and cross-cutting V_2). Hammer (32 cm) for scale. (c–d) Quartz veins refracting at the competent–incompetent interface. Fingernail and pencil (15 cm) for scale. (e) Transgranular microvein fracturing through the host-rock quartz grains indicating the low porosity at time of fracture initiation; (f) vein tip showing elongate-blocky crystals oriented perpendicular to the vein wall. Two phases are visible: an early phase at the edges of the vein and one late phase in the middle of the vein supporting syntaxial vein growth. (g) Crack-seal microstructures with repetitive host-rock inclusions parallel to the vein wall. Elongate crystals track the opening trajectory. The crystal margins are recrystallised.

destroyed during subsequent progressive Variscan deformation. The metamorphic (burial) conditions recorded in the veins were thus not exceeded during Variscan fold-and-cleavage development. Microthermometry of pseudosecondary fluid inclusions measured in undeformed crystals, reveals that the veins contain aqueous (H_2O–NaCl) inclusions with low salinities (2–6 eq.wt% NaCl) and yield homogenisation temperatures (Th) in the range of 140 °C to 220 °C with a peak Th of 160 °C (Van Noten et al., 2009). The reflectivity of vitrinite grains measured in pelitic layers is at about 4.5–5.5% R_{max} (von Winterfeld, 1994; Fielitz and Mansy, 1999; Vinzelberg, 2002; Ribbert and Vieth, 2005). By using this vitrinite reflectance range as an independent geothermometer for pressure correction and taking an effective heating time of 20 Ma (Muchez et al., 1991) into account, Van Noten et al. (2009) deduced a maximum burial temperature of 235 °C to 250 °C for the veins in the pHASB. The variation of homogenisation temperatures can be explained by fluid pressures fluctuating between suprahydrostatic and lithostatic (Van Noten et al., 2009), although lithostatic pressures were most likely during vein formation, and by necking-down and leakage during Variscan deformation. Secondary inclusions oriented parallel to the vein walls indicate that the veins repeatedly re-opened during late burial. Impermeable layers, such as shales, can compartmentalise the pore-fluid system during burial, allowing the pore-fluid pressure to rise within the sandstone without any vertical connectivity between the compartmentalised competent units.

The microstructures and conditions of veining in the cHASB have already been studied extensively (Kenis et al., 2002; Kenis, 2004), demonstrating by means of a.o. fluid inclusion studies that the mechanism of veining is hydraulic fracturing at low differential stresses.

2.5. Mullion formation

A century long discussion exists in literature on the development of mullion structures in the cHASB (see references in Kenis et al., 2002; Kenis, 2004; Kenis and Sintubin, 2007; Sintubin, 2008). The discussion was primarily based on the conflicting coexistence of extensional (veins) and compressional (mullions) structures. It remained a controversy as to whether the mullions in the cHASB were formed by the process of layer-parallel extension (boudinage) or purely by shortening (mullion). Although these structures originally were described as the classical rectangular boudins (Lohest et al., 1908), recent studies (Urai et al., 2001; Kenis, 2004) have determined that these structures are in fact mullions developed during a two-phased history: first, extension veins developed during progressive burial with σ_1 still vertical, and second, as quartz veins become more competent than the host-rock, a cuspate-lobate geometry of the pelite–psammite interface (mullions) formed during layer-parallel shortening during tectonic inversion ($\sigma_1 = \sigma_{horizontal}$) at the early stages of the Variscan orogeny. In particular, the unusual high aspect ratio of the structures in the cHASB caused reconsideration of boudinage as a mechanism for veining (Kenis et al., 2002; Kenis, 2004).

Fig. 5. Parameters influencing vein spacing. (a) cHASB: variability in intermullion vein spacing due to irregular layer thickness. Upper left: veins are equally spaced in a layer with a uniform thickness (Bastogne Mardasson, Belgium; scale bar = 50 cm). (b) pHASB: the presence of older vein generations (V_1) could influence the spacing pattern (white arrows) of a younger (V_2) vein generation (Rursee, North Eifel; pencil = 15 cm). (c) pHASB: variability in vein spacing in a heterogeneous sandstone due to the interference of adjacent competent layers. The veins refract at the competent–incompetent interface and are oriented oblique to bedding as a result of flexural slip folding (Rursee, North Eifel; knife = 10 cm). (d) pHASB: veins cross-cutting multiple competent layers, which are separated by thin incompetent units (Urftsee, North Eifel; fingernails for scale).

3. Parameters influencing vein spacing

In order to investigate the effect of the layer thickness to vein spacing and to compare it properly with published fracture distributions, we have to exclude possible parameters which could influence the spatial distribution and which are determinable in the field (Fig. 5). Following parameters have an influence on the spacing pattern and are well accepted in literature.

Firstly, fracture and vein spacing strongly depends on the lithological properties and on rock permeability. In order to avoid the influence of lithology and permeability on the spacing distribution, we only measured spacing of veins which are confined to competent sandstones (pHASB) and quartzites (cHASB) and did not consider measuring veins in other lithologies. Material properties of sandstone need to be constant in an area in order to demonstrate the true effect of the layer thickness. This is extremely difficult as there is a substantial rock property change (change of subcritical crack index; Olson et al., 2002) from initial composition through diagenisis and metamorphism. Bedding-normal veins, however, are not affected by grain-scale mechanical heterogeneity of the host-rock, as evidenced by transgranular microveins with low tortuosity (Fig. 3e) and by absence of compaction features associated with the veins (cf. Hilgers et al., 2006), indicating that the veins formed in an already low-porous rock at maximum burial. So the material properties solely depend on the initial composition of the host-rock and not on the grain/cement ratio. A change in subcritical crack index of sandstone will thus determine the variability in fracture spacing. This change in crack index in between the cHASB and pHASB, however, will be rather small as both areas contain sandstones which are deposited in a shallow marine, deltaic to tidal environment with an identical mineral source (Van Noten et al., 2008). Correlating the percentage of quartz (grains and cement; see Section 2.2.; Table 1; Fig. 2) with experimental tests on a wide range of sandstones (Rijken, 2005), supports intermediate subcritical crack indices between 50 and 60, which are indicative for regular spacing proportional to bed thickness (Olson et al., 2002; Rijken, 2005) with a minor spacing variability regionally.

Secondly, because we want to investigate the influence of the layer thickness, measurements of vein spacing in outcrops with an irregular bedding surface or with varying layer thicknesses are not taken into account. After all, vein spacing is strongly variable within a single competent layer which shows an irregular bed continuity (Fig. 5a), and this will influence the correlation of layer thickness and vein spacing.

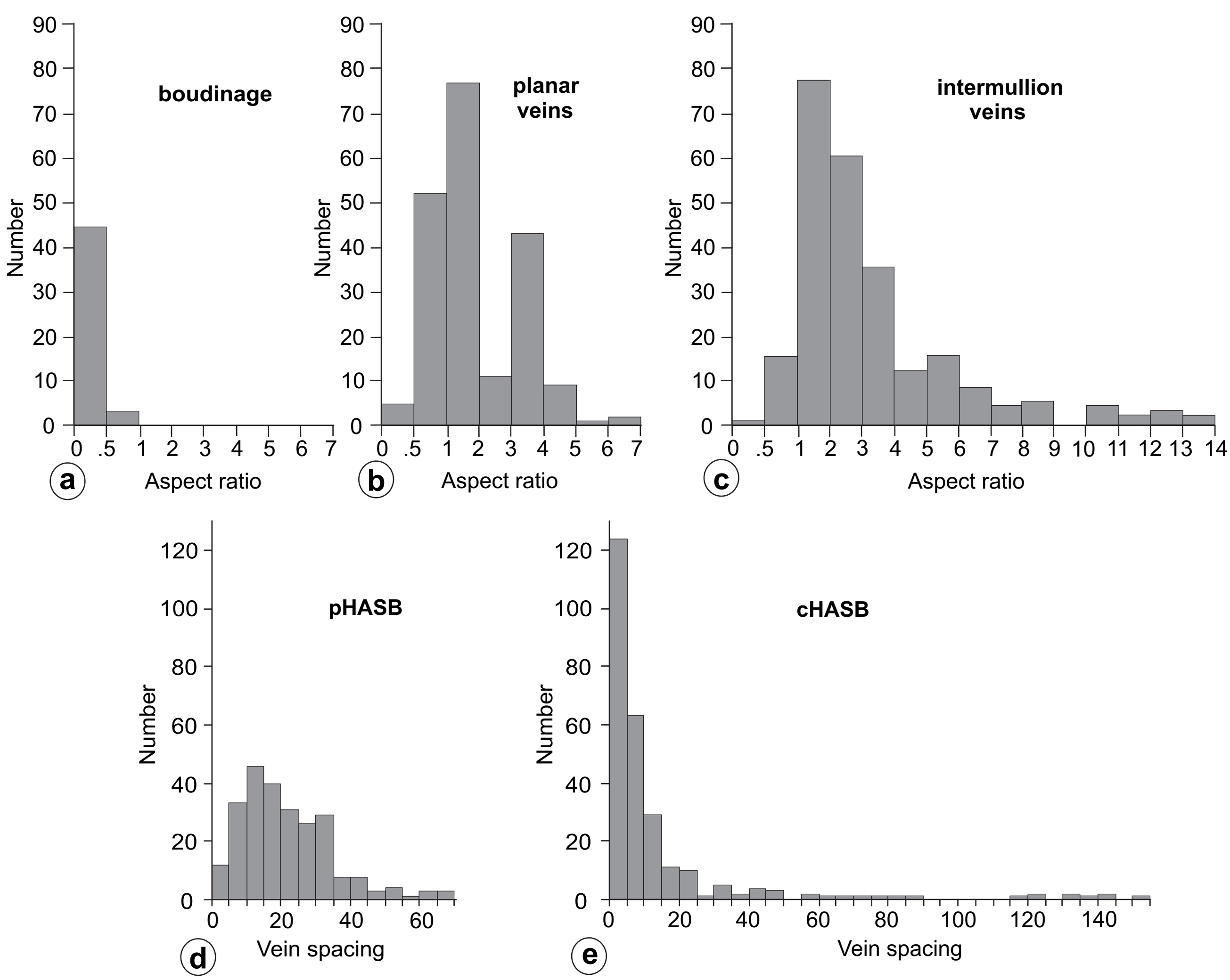

Fig. 6. Block aspect ratio reflecting vein spacing in (a) boudinaged layers (examples from Price and Cosgrove, 1990; Van Baelen and Sintubin, 2008); (b) 'undeformed' segments in the Eifel area, pHASB; (c) mullions, cHASB. (d–e) Histograms showing the vein spacing frequency in the pHASB and cHASB.

Thirdly, besides lithology and layer thickness another parameter known to influence fracture spacing is the degree of deformation experienced by rock prior to fracturing (Harris et al., 1960). Yet, the variation in spacing due to the deformation of rock will in no way mask the fundamental variation of fracture spacing exhibited due to layer thickness and lithology (e.g. Ladeira and Price, 1981). As mentioned before, several vein generations in the pHASB mutually cross-cut (Fig. 5b). In order to avoid the influence of earlier veining events and on the basis that the mechanical properties of the rock would be different when veins are already present (Caputo and Hancock, 1999), only the spacing of the oldest generation is used for the vein spacing distribution.

Finally, the influence of the thickness of adjacent incompetent units bounding the fractured layer and thus nearby competent layers play also a minor role in fracture/vein spacing (Ladeira and Price, 1981; Fischer et al., 1995; Bai and Pollard, 1999; Cooke et al., 2006). In outcrops where competent layers are omnipresent, fractures will 'jump' from one layer to the other, which makes it very difficult to determine the effect of a single layer thickness to the spacing pattern. Moreover, when two competent layers are only separated with a thin incompetent layer, with the interlayer by convention smaller than 5 centimetre (Ladeira and Price, 1981), fractures are more closely spaced than if they are separated by a thick incompetent layer (Ji et al., 1998). Bai and Pollard (1999), moreover, calculated that as the adjacent layers are 1.5 times thicker than the fractured layer, the fractured layer does not have any influence of nearby competent layers and the system can be treated as an infinitely thick top and bottom layer. Similar observations have been made in our study area (Fig. 5c and d). We therefore neglected all measurements in competent beds which are surrounded by thin incompetent beds in order to avoid the influence of adjacent competent beds.

4. Vein spacing distribution

4.1. Aspect ratio

Besides describing the absolute vein spacing as a function of the layer thickness, the aspect ratio of each segment is given (Fig. 6). This ratio represents the ratio of the layer thickness relative to the median spacing of the veins (which is a better and more stable estimator of the centre of the spacing population that the arithmetic mean) and is referred to as the fracture spacing ratio (FSR) by Gross (1993). The FSR is useful to compare spacing patterns of different outcrops and has been used in the past to determine if boudinage can be invoked as a mechanism for veining (e.g. Kenis et al., 2002).

Aspect ratios in the HASB (Fig. 6) vary between 1 and 21 in the cHASB and between 0.7 and 6 in the pHASB. A small percentage of the aspect ratios is lower than 1, with mean values of 0.7 in the cHASB and 0.8 in the pHASB. The aspect ratios of rectangular boudins (i.e. those boudins considered to develop by tensile fracturing of brittle layers at right angles to layering) are commonly less than 0.55 (Price and Cosgrove, 1990; Ghosh and Sengupta, 1999; Mandal et al., 2000; Van Baelen and Sintubin, 2008). The difference in aspect ratios of the veins in the slate belt with respect to the low ratios of rectangular boudins clearly shows that boudinage was not the mechanism for veining and is not responsible for the regular spacing pattern (see Section 2.5).

Despite the widely used FSR, its inverse is often used in geomechanical modelling. Based on this S/T ratio in the HASB (see mean S/T in Tables 2 and 3), vein spacing in the HASB can mostly be classified into Range III of Bai and Pollard (2000b), i.e. the regime in which spacings have ratios less than the critical value of 0.976. This indicates that the veins developed at distances closer than those

Table 2
Summary of vein spacing data from the Eifel area (pHASB). Mean original vein strike represents vein orientation prior to folding. Convention used: dip direction/dip; Min: minimum spacing; Mean: arithmetic average; Max: maximum spacing; σ: standard deviation; C_v: coefficient of variation of all veins in the measured bed; C_v^*: modified version of C_v. Mean S/T determined by average of spacing/thickness ratio.

Locality	Data set	Mean original vein strike	Line length (cm)	Nr of values (n)	Thickness (T)	Min	Median (S)	Mean	Max	σ	C_v	C_v^*	Mean S/T
Eifel/Rursee	Wildenhof 45a	282/78	26	8	3	1	3	3.1	4	0.99	0.32	0.36	0.88
Eifel/Rursee	Wildenhof 45b	280/70	64	5	7	10	13	12.8	16	2.77	0.22	0.27	1.76
Eifel/Rursee	Wildenhof 39a	276/73	84	6	10	7	12	14.0	28	7.72	0.55	0.65	1.13
Eifel/Rursee	Wildenhof 46b	285/74	25	3	12	10	12	12.3	15	2.52	0.20	0.29	1.00
Eifel/Rursee	Wildenhof 5	310/89	85	6	17	9	13.5	14.2	21	5.12	0.36	0.43	0.75
Eifel/Rursee	Wildenhof 50	286/76	203	8	18	12	24	25.4	34	6.84	0.27	0.31	1.28
Eifel/Rursee	Wildenhof 39b	276/73	58	5	23	7	12	11.6	18	4.72	0.41	0.50	0.44
Eifel/Rursee	Wildenhof 44b	282/77	536	24	28	12	22	22.3	35	6.53	0.29	0.30	0.73
Eifel/Rursee	Wildenhof 40	293/77	410	15	28	21	25	27.3	35	5.19	0.19	0.20	0.95
Eifel/Rursee	Wildenhof 44a	284/76	539	23	35	10	23	23.4	44	8.95	0.38	0.40	0.58
Eifel/Rursee	Wildenhof 46a	285/74	98	3	44	30	30	32.7	38	4.62	0.14	0.20	0.73
Eifel/Rursee	Wildenhof 19b	089/60	460	11	56	31	38	41.8	62	11.69	0.28	0.31	0.70
Eifel/Rursee	Wildenhof 42	273/74	573	11	93.5	20	53	52.2	70	14.27	0.27	0.30	0.50
Eifel/Rursee	Schwammenauel 94	254/88	29	4	22	6	8	7.3	9	1.50	0.21	0.27	0.32
Eifel/Rursee	Schwammenauel 93	254/88	75	3	60.5	12	31	25.0	32	11.27	0.45	0.64	0.34
Eifel/Rursee	Hubertus Höhe 71	337/85	65	10	9	3	6.5	6.5	10	2.37	0.36	0.40	0.58
Eifel/Rursee	Hubertus Höhe	106/76	42	6	15	5	6.25	6.9	13	3.17	0.46	0.54	0.40
Eifel/Rursee	Hubertus Höhe 72	140/83	84	6	31	9	15	14.0	18	3.90	0.28	0.33	0.42
Eifel/Rursee	Hubertus Höhe	108/78	177	4	52	12	20.5	21.7	31	6.38	0.29	0.38	0.39
Eifel/Rursee	Hubertus Höhe	109/62	133	8	55	21	35	33.3	40	9.71	0.29	0.33	0.56
Eifel/Rursee	Hubertus Höhe	114/82	117	5	72	17	26	25.4	31	5.32	0.21	0.26	0.31
Eifel/Rursee	Eschaulerberg 64	294/65	294	13	75	10	25	22.6	33	7.50	0.33	0.36	0.30
Eifel/Urftsee	27b	108/83	57	7	9	7	8	8.1	10	1.21	0.15	0.17	0.95
Eifel/Urftsee	27b	105/77	26	3	12	12	12	12.7	14	1.15	0.09	0.13	1.05
Eifel/Urftsee	27b	292/78	265	24	13	7	11	11.0	17	2.66	0.24	0.25	0.80
Eifel/Urftsee	27a	109/71	237	14	16	12	17.5	16.9	22	3.02	0.18	0.19	1.10
Eifel/Urftsee	28b	105/87	152	7	31	11	22	21.7	33	7.30	0.34	0.39	0.57
Eifel/Urftsee	6	330/77	185	5	60	20	43	37.0	45	10.93	0.30	0.36	0.56
			Total measurements:	*247*						Mean C_v:	*0.29*	*0.34*	*0.72*

predicted for fracture saturation and that it is reasonable to seek other mechanisms to overcome the stress transition around fractures at the stage of fracture saturation.

4.2. Coefficient of variation

There are a lot of analytical methods to characterise the spatial distribution of veins. The standard deviation (σ) represents the quality of the measurements; the lower σ is, the more representative the median will be. This largely depends on the amount of measurements (n) taken. A more suitable measure is the coefficient of variation (C_v): the ratio of the standard deviation (σ) to the mean spacing (S). The C_v characterises the variability in a dataset from anticlustered to clustered and has been used developed to determine the spatial distribution of modelled fault populations (Gillespie, 2003), but also works for opening mode fractures and veins (Gillespie et al., 1999, 2001; Foxford et al., 2000; André-Mayer and Sausse, 2007). Gillespie et al. (1999) calculated that for $C_v > 1$ veins are clustered, i.e. power-law; for $C_v = 1$ veins are randomly distributed; $C_v < 1$ the spacings are anticlustered or periodic and for $C_v = 0$ the veins are equally spaced. Fracture saturation is therefore characterised by $C_v < 1$. A modified coefficient of variance $C_v^* = C_v((n+1)/(n-1))^{1/2}$ needs sometimes to be calculated due to the small amount of measurements (n) taken along a fractured bed (Gillespie, 2003). This modified value C_v^* has been calculated in Tables 2 and 3, but only cause a minor change in the estimated C_v and does not influence our interpretation.

At the pHASB and the cHASB, the vein arrays have low values of C_v ranging between 0.09–0.55 and 0.01–0.70 with an average C_v of 0.29 and 0.27, respectively. This indicates anticlustered, periodic spacing distributions in the whole HASB and although spacings sometimes seem to be varied, they often appear to have some regularity in outcrop. Characteristic regularly spaced vein clusters are typical for stratabound vein arrays in sandstones (e.g. Foxford et al., 2000; Gillespie et al., 2001). The histograms (Fig. 6d and e), moreover, show a normal to power-law vein spacing population in the pHASB and the cHASB respectively.

4.3. Influence of layer thickness

The term ‘spacing’ is used for the distance between two neighbouring, parallel veins, measured perpendicular to the vein walls. Vein spacing was measured between veins cross-cutting the

Table 3
Summary of intermullion vein spacing data from the Ardennes (cHASB). Mean original vein strike represents vein orientation prior to folding. Convention used: dip direction/dip; Min: minimum spacing; Mean: arithmetic average; Max: maximum spacing; σ: standard deviation; C_v: coefficient of variation of all veins in the specified layer; C_v^*: modified version of C_v. Mean S/T constructed by average of spacing/thickness ratio.

Locality	Dataset	Mean original vein strike	Line length (cm)	Nr of values (n)	Thickness (T)	Min	Median (S)	Mean	Max	σ	C_v	C_v*	Mean S/T	% of shorte ning
Eifel	Dedenborn	346/52	278	14	28	16	21	19.9	24	3.18	0.16	0.17	0.75	29.7
Ardennes	Bütgenbach	112/77	12	8	2.1	0.9	1	1.5	2.2	0.45	0.30	0.34	0.64	
Ardennes	Bütgenbach	112/77	24	5	7	4.3	4	4.5	5	0.40	0.09	0.11	0.59	
Ardennes	Bütgenbach	112/77	937	16	86	41	57	58.6	88	14.07	0.24	0.26	0.63	11.8
Ardennes	Houffalize	114/64	12	7	6	1	1	1.6	2	0.53	0.32	0.37	0.13	
Ardennes	Houffalize	114/64	163	26	10	2	6	6.2	11	4.35	*0.70*	0.72	0.24	
Ardennes	Houffalize	114/64	36	6	11	3	7	5.9	8	2.20	0.37	0.44	0.47	
Ardennes	Houffalize	114/64	27	3	13	7	9	9.0	11	2.00	0.22	0.31	0.67	
Ardennes	Boeur	140/75	13	13	2	0.8	1	1.0	1.5	0.32	0.32	0.35	0.50	
Ardennes	Boeur	140/75	9	6	4	0.8	1	1.3	2	0.40	0.31	0.37	0.31	
Ardennes	Boeur	304/72	10	8	5	1	1	1.3	2	0.40	0.31	0.35	0.24	28.4[a]
Ardennes	Boeur	140/75	153	26	7	2.3	6	5.9	10	1.95	0.33	0.35	0.70	20.4[a]
Ardennes	Boeur	140/75	36	7	9	2.5	5	5.2	9	2.27	0.45	0.52	0.56	
Ardennes	Bastogne Collignon	121/62	12	6	1.3	1.1	1	1.9	2.6	0.61	0.41	0.48	1.12	
Ardennes	Bastogne SLR	149/78	6	7	1.5	0.5	0.65	0.8	1.6	0.35	0.46	0.53	0.48	
Ardennes	Bastogne Mardasson	125/81	3	3	2.1	0.5	1.1	1.1	2	0.21	0.19	0.27	0.50	
Ardennes	Bastogne Mardasson	125/81	21	10	3.5	1.1	1.7	1.7	2.4	0.37	0.22	0.24	0.50	28.0[a]
Ardennes	Bastogne Mardasson	125/81	16	6	5	4	2.7	2.6	3.8	0.96	0.37	0.44	0.49	23.1[a]
Ardennes	Bastogne Collignon	121/61	7	4	5	1	1.7	1.6	2.1	0.46	0.29	0.37	0.28	
Ardennes	Bastogne SLR	149/78	102	8	26.5	14	12	12.8	16	2.42	0.19	0.21	0.47	
Ardennes	Bastogne Collignon	121/61	142	4	40	33	34.5	35.5	40	3.11	0.09	0.11	0.85	
Ardennes	Bastogne SLR	149/78	186	6	50	24	32.5	31.0	36	4.29	0.14	0.16	0.61	
Ardennes	Bastogne SLR	149/78	130	3	92	40	43	43.3	48	1.53	0.04	0.05	0.47	32.3[a]
Ardennes	Bastogne SLR	149/78	203	4	100	40	45	42.0	45	15.02	0.36	0.46	0.48	29.5[a]
Ardennes	Bastogne SLR	149/78	270	5	110	65	55	55.0	65	4.24	0.08	0.09	0.59	25.4[a]
Ardennes	Rouette	142/82	38	9	9	3.5	6	5.5	7.2	2.23	0.41	0.45	0.67	27.6[a]
Ardennes	Rouette	142/82	51	3	26	10	17	16.7	17	0.58	0.03	0.05	0.65	31.0[a]
Ardennes	Remagne	207/44	7	5	3	1	1	1.3	1.8	0.37	0.29	0.36	0.37	
Ardennes	Remagne	207/44	15	9	8	1.2	1	1.6	2.8	0.60	0.37	0.41	0.23	
Ardennes	Bertrix	148/85	20	3	15	5	5	6.7	10	2.89	0.43	0.61	0.40	19.8[a]
Ardennes	Bertrix	148/85	38	7	17	5	6	6.9	13	2.79	0.40	0.47	0.36	
Ardennes	Bertrix	148/85	88	12	23	4	9	7.3	10	2.43	0.33	0.36	0.28	
Ardennes	Bertrix	148/85	35	4	26	8	8	8.6	14	3.77	0.44	0.56	0.30	26.4[a]
Ardennes	Bertrix	148/85	58	7	34	5	9	8.3	10	2.01	0.24	0.28	0.23	
Ardennes	Bertrix	148/85	164	14	70	12	17	16.4	20	4.40	0.27	0.29	0.15	
Ardennes	Bertrix	148/85	228	4	200	50	57	55.3	58	1.98	0.04	0.05	0.29	
Ardennes	Bertrix	148/85	195	3	229	60	68	67.5	75	8.66	0.13	0.18	0.29	
Ardennes	Bertrix	148/85	399	3	250	108	108	108.3	109	0.58	0.01	0.01	0.52	
Ardennes	Bertrix	148/85	500	4	500	80	125	119.6	130	23.65	0.20	0.26	0.27	
Ardennes	Bertrix	148/85	780	6	800	89	137.5	130.0	155	22.17	0.17	0.20	0.16	
			Total measurements:	*304*						Mean C_v:	*0.27*	*0.32*	*0.46*	

[a] Data from Kenis et al. (2004, 2005b).

whole competent bed and terminating at the competent–incompetent interface. Hairline veinlets or thin microveins, which are sometimes present in between the vein arrays, are ignored, although they are also formed due to fracturing. Median vein spacing to layer thickness relationship in thin (<1 m; Figs. 7 and 8) as well as in thick layers (>1 m; Fig. 9) is shown. The range of spacing along a single bed is indicated by minimum and maximum error bars and the data are represented both on a linear scale, so that the relationship between spacing and thickness may readily be seen (Fig. 7a–d), and on log–log axes (Fig. 7e and f) in order to obviate the problem relating to the unresolvable data near the origin.

The following features are characteristic:

(i) vein spacing increases with increasing layer thickness;
(ii) in the realm of thin layers (<40 cm) a linear relationship can be assumed for an individual outcrop. There is, however, a small variation in between different outcrop localities in the pHASB: veins show for example a wider spacing in the Urftsee outcrop than in the Hubertus Höhe outcrop, although quartz

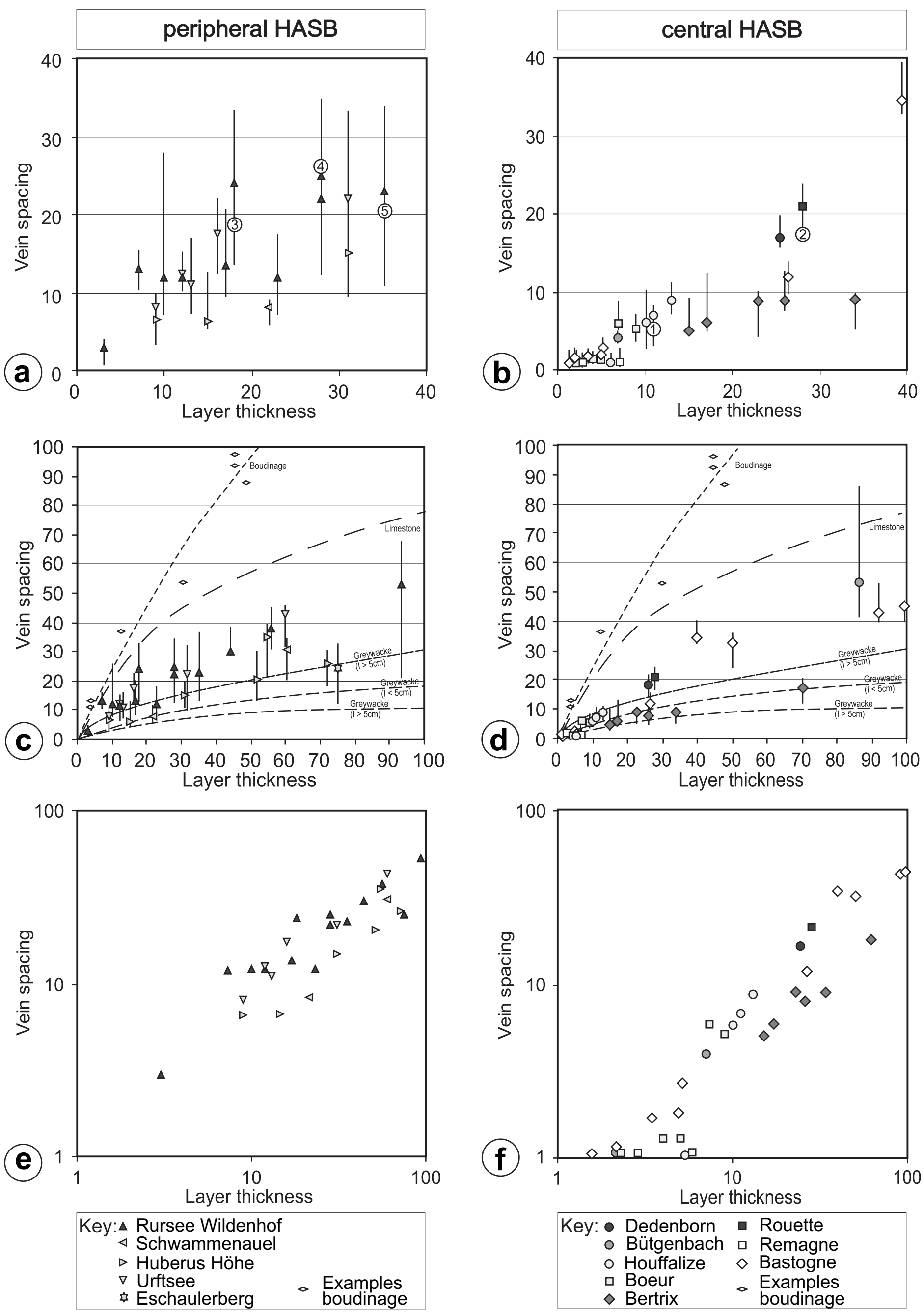

Fig. 7. Vein spacing (in cm) versus layer thickness (in cm) relationship for veins from the pHASB in (a) thin and in (c) thicker siliciclastic multilayer sequences compared to the spatial distribution (b and d) of intermullion veins in the cHASB. The intermullion veins are narrower spaced in thin layers than the veins in the pHASB. The numbers in circles refer to the examples shown in Fig 8. (c)–(d) Vein spacing is also compared to published fracture spacing in greywackes (examples from the U.K. and Portugal) and in limestone (Ladeira and Price, 1981), of which fracture spacing in greywacke shows a comparable non-linear relationship (I = thickness of interlayers in between two competent beds). Some examples of boudinaged layers (Price and Cosgrove, 1990; Van Baelen and Sintubin, 2008) clearly have wider spacings. (e)–(f) Vein spacing versus layer thickness data presented on a log–log scale, showing a power-law S/T relationship.

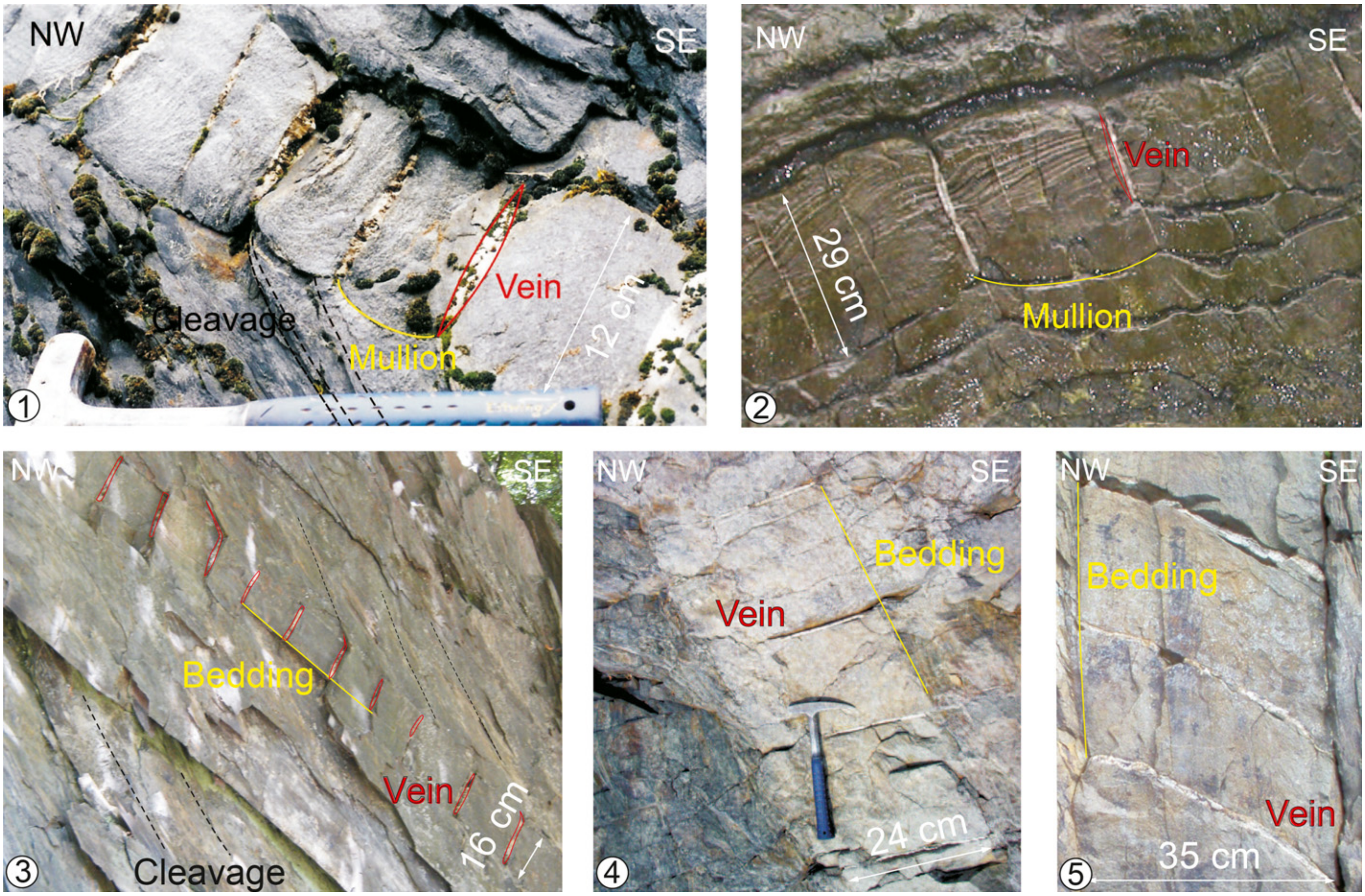

Fig. 8. Examples of intermullion vein spacing (1–2) from the cHASB and spacing of planar veins (3–5) from the pHASB. Numbers correspond with numbers on Fig. 7a and b.

content of the host-rock (Table 1) and thus subcritical crack index in both localities is nearly the same. This variation in spacing in between different outcrops is smaller in the cHASB;

(iii) the assumed linear relationship in thin layers becomes non-linear in thicker layers (>100 cm) and tends to evolve towards a maximum value (Fig. 9) indicating that the layer thickness becomes decreasingly important in controlling vein spacing. Variation in vein density along a single bed (expressed by the error bars in Fig. 9) increases towards thicker units. The latter however could be a sampling artefact; large veins in thick units are only observed in two quarries in the cHASB (Bastogne and Bertrix; Table 1). With thicker beds and wider spacings, the number of veins sampled is smaller than for thin layers with narrow spacings. These results therefore have to be carefully interpreted due to under-sampling in thick layers and a lack of comparable units in the pHASB. Extrapolation of the results to larger scales using fractal statistics may be possible, but probably may be flawed

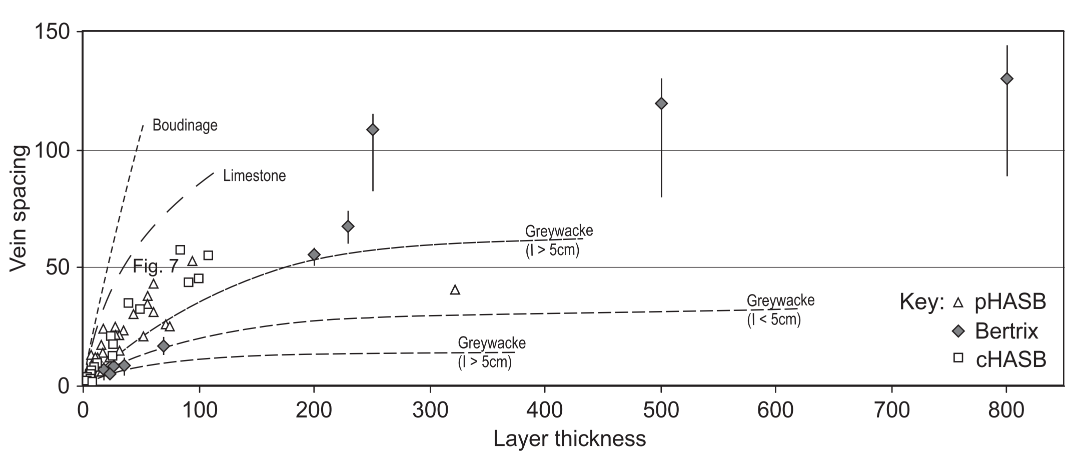

Fig. 9. Vein spacing (in cm) versus layer thickness (in cm) relationship for quartz veins in thick metasedimentary multilayer sequences (data from Bertrix; cHASB). Compared to fracture spacing (data from Ladeira and Price, 1981), vein spacing is wider in thick units although a lack of measurements may obscure these results. See text for discussion. Axes have a different scale.

Table 4
Restoration of the degree of mullion shortening by means of methods explained in the text. The original vein spacing (S_0) versus initial layer thickness (T_0) ratio increases after restoration. Entries in italic correspond with data which are rather exceptional in the slate belt.

Locality	Dataset	Median (S)	Thickness (T)	S/T	% of shorte ning	S_0	T_0	S_0/T_0
Eifel	Dedenborn	21	28	0.75	29.7	29.9	23.8	1.26
Ardennes	Bütgenbach	57	86	0.63	*11.8*	71.0	81.0	0.86
Ardennes	Boeur	6	7	0.70	20.4[a]	5.7	5.7	1.00
Ardennes	Boeur	5	9	0.56	25.7	6.7	9.2	0.73
Ardennes	Boeur	13	27	0.48	22.0[a]	16.5	19.1	0.87
Ardennes	Bastogne Mardasson	21	49	0.48	26.9	26.8	39.0	0.68
Ardennes	Bastogne Mardasson	24	23	1.05	*14.2*	28.0	17.2	1.60
Ardennes	Rouette	6	9	0.67	27.6[a]	6.7	6.9	0.97
Ardennes	Rouette	17	26	0.65	31.0[a]	23.3	18.6	1.25
Ardennes	Bertrix	7	24	0.30	25.5[a]	9.4	17.2	0.57

[a] Data from Kenis et al. (2004, 2005b).

because the mechanics of vein formation may be governed by different dominant processes at larger scales (Cowie et al., 1996).

4.4. Restoration of mullion shortening

For a given layer thickness smaller than 40 cm, intermullion veins in the cHASB are closer spaced than planar veins in the pHASB. This is represented by smaller S/T values in Table 3 and on Fig. 7b. As mullions are compression features developed due to early Variscan layer-parallel shortening, it would be interesting comparing the original spacing to layer thickness ratio (S_0/T_0) with the S/T ratio in the pHASB, in order to show consistency of vein spacing in the slate belt. Based on field observations incipient layer-parallel shortening mainly varies between 19% and 33% (Kenis et al., 2005b). This variation has no correlation with the increase of metamorphic grade towards the epizone in the cHASB. The percentage of layer-parallel shortening (see Tables 3 and 4) has been calculated by converting the area of host-rock between two veins to a rectangle with thickness equal to 95% of the length of the vein with strain of quartz of 5% to correct deformation of the vein, thereby assuming no volume change has taken place during shortening (Kenis et al., 2004, 2005b). In order to estimate S_0/T_0, a small number of mullions of different localities in the cHASB were reconstructed into their initial shape (Table 4). We firstly measured bedding length between the vein tips along the lobate bedding to estimate the initial spacing of the veins (S_0). Secondly, the original layer thickness (T_0) was deduced by measuring the distance between the vein tips minus 5% shortening to correct elongation of the vein during mullion formation.

This restoration of mullion shortening causes an increase of the S_0/T_0 ratio, with spacings into the realm of the vein spacing measured in the pHASB (Fig. 10), with even wider spaced veins for a small amount of outcrops. Due to the small amount of measurements no interpretations can be made on the variation of vein spacing in function of the metamorphic grade or on variability of the host-rock parameters in between the cHASB and the pHASB.

We also have to keep in mind that the S_0/T_0 ratio in the pHASB was most probably also higher than the present measured S/T ratio due to – macroscopically not observable – Variscan layer-parallel shortening at the onset of cleavage development. The amount of shortening in sandstones during cleavage development, however, is not known.

5. Discussion

Comparing the vein spacing to layer thickness relationship with various fracture distributions serves as a useful indicator of the processes which may have been responsible for controlling the observed regular vein spacing in the High-Ardenne slate belt. Vein spacing increases linearly with layer thickness in thin sedimentary sequences (<40 cm) but tends to increase non-linearly in thick layers. The pattern looks similar to published fracture spacings (e.g. Ladeira and Price, 1981; Mandal et al., 2000) with the minor difference that veins are wider spaced than fractures in thick layers. The resemblance of vein spacing with fracture spacing could imply that initial vein development in an unfractured rock occurs similar way to fracture development.

Regularly spaced fractures have been evidenced to form at the stage of fracture saturation (cf. Bai and Pollard, 2000b). The low coefficient of variation ($C_v < 1$) calculated for our examples indicates that saturation could have been reached during initial vein development. Some of the S/T- and calculated S_0/T_0 ratios are, however, below the critical value for fracture saturation (see Tables 2 and 3) supporting a mechanism to overcome the compressive stress state around saturated fractures. The latter has been explained by pre-existing flaws which cut through the compressive region existing in between the saturated fractures (e.g. Bai and Pollard, 2000b) or by jointing due to hydraulic fracturing (e.g. Ladeira and Price, 1981). The presence of pre-existing flaws is very difficult to determine and largely depends on the heterogeneity of the rock. High pore-fluid pressures are recorded both in regularly as in closely spaced veins, indicating that these high pressures can account for vein nucleation rather than that they control vein spacing.

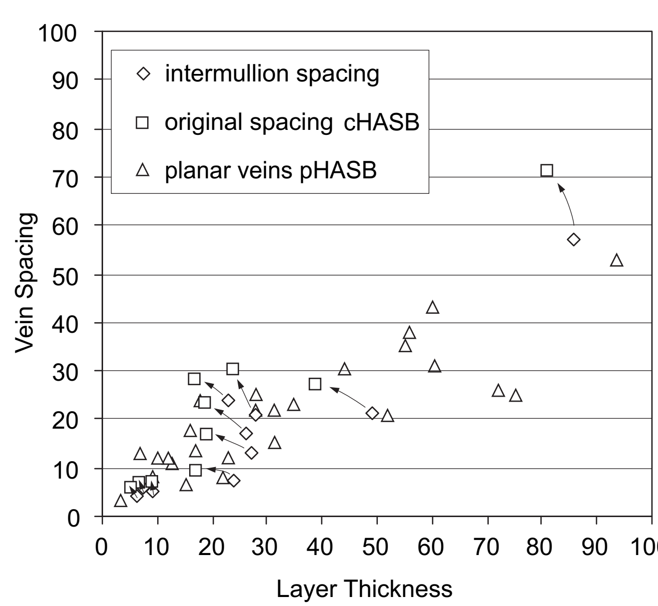

Fig. 10. S/T- versus S_0/T_0 relationship of intermullion veins for some examples from the cHASB, compared to the S/T relationship of planar veins from the pHASB.

The regular spacing pattern may thus suggest that initial veins are 'aware' of adjacent veins during the initial development and that the process of spacing is still favoured by stress distributions around fractures. Despite a lack of constraints on the timing of the initial veins relative to each other, the spacing pattern suggests that a rock can be saturated by the presence of initial veins. The latter is in contrast with the crack-jump model of Caputo and Hancock (1999) who state that once vein formation has commenced, the local stress conditions around incipient veins are fully restored due to sealing of the host rock, with new cracks being 'unaware' of the existence of any pre-existing ones. They moreover argue that the factors leading to a layer becoming saturated by the presence of joints do not apply for veins if the vein filling is more resistant to tension than the host rock. The presence of crack-seal host-rock bands in the veins, however, evidences that the quartz crystals in the veins are weaker than the host rock and that successive cracking and sealing was responsible for thickening of the initial veins.

In the pHASB cross-cutting quartz vein generations evidence a less regular stress field during vein formation than in the cHASB. In contrast with the cross-cutting generations, which were formed due to a switch of σ_2 and σ_3 in the stress field, only the first generation in an unfractured rock shows a clear, regularly distributed pattern. The absence of any pattern in late generations indicates that it is only possible to create a stage of saturation in an unfractured rock and not in an already deformed rock (cf. Caputo and Hancock, 1999).

6. Conclusions

This comparative field-based study demonstrates that vein spacing within a single rock type is strongly influenced by layer thickness in thin sedimentary sequences (<40 cm) but will become less dependent on layer thickness in thicker units. The spacing pattern observed in our examples shows similarities with fracture spacing distributions, supporting the idea that individual veins inhibit the formation of new adjacent veins at a certain distance during initial development and that the rock can be saturated by the presence of initial veins, although this may be in contrast with the previously published crack-jump model. High fluid pressures are responsible for vein initiation, but the spacing pattern is probably determined by the stress state around fractures. At the stage of fracture saturation, high fluid pressures can overcome the compressive stresses in between the saturated initial veins causing regularly spaced veins smaller than those predicted at fracture saturation. The presence of crack-seal microstructures moreover supports the fact that vein-filling material is weaker than the host rock itself and indicating that the initial veins will rather thicken by the process of crack-sealing, than that new veins will form near pre-existing ones. Whether a single consistent set of veins or cross-cutting generations will develop, with only the oldest generation regularly spaced, depends largely on the consistency of the regional stress field.

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