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Deciphering the presence of axial-planar veins in tectonites

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ABSTRACT

Veins and dikes are often oriented subparallel to the axial surfaces of folds in the adjacent layered or foliated rocks. This implies an awkward situation, since veins would lay in planes close-to-parallel to the maximum stretching axis. A series of geometric models have been conceived in order to gain insight into the possible mechanisms for their formation. The models are based on the analysis of a varied selection of field structures and on the review of similar structures in the existing literature. A first categorization consists on distinguishing between axial-planar veins achieved by either progressive or polyphase deformation. Five models of axial-planar veins resulting from progressive deformation are described and discussed: (1) fold-related veins associated with the standard folding mechanisms, (2) fracture arrays localized along the short limbs of folds (asymmetric fold-related veins), (3) folds associated with rotation of extension veins (vein-related folds), (4) high strain and transposition of early veins, and (5) high strain and late veins parallel to axial planar foliations (axial planar foliation-related veins). The axial planar geometry is achieved through variable amounts of progressive rotational strain, except in model 5, in which the co-planarity is acquired at the time of vein intrusion. The possibility for axial-planar veins to have developed in two distinct phases in the context of polyphase or polyorogenic tectonics has also been explored and discussed. This study contributes to a better understanding of the intriguing interplays between deformation, metamorphic and magmatic processes in orogenic belts.

1. Introduction

Sheet-like bodies (veins and dikes) generated from melts or hydrothermal fluids commonly occur in close association with folds in naturally deformed rocks. This can be observed in many deformation zones under a wide range of metamorphic conditions, from very low-grade metamorphism under hydrothermal conditions (i.e. quartz or carbonate veins) to anatexis (i.e. migmatitic leucosomes). Magmatism can also be associated with regional folding, producing melts that are commonly emplaced as sheet- or lens-shaped bodies (Hutton and Reavy, 1992; Carreras and Druguet, 1994; Kisters, 2005; Brown, 2013). They can be subsequently folded and/or boudinaged depending on their orientation. These planar intrusives may be either concordant with the planar fabrics in the host rocks or discordant, crosscutting layering and other planar fabrics, such as a gneissic foliation, schistosity or crenulation cleavage (Vanderhaeghe, 1999; Marchildon and Brown, 2003). The structures developed in both veins and anisotropic host rocks and their mutual crosscutting relationships can be useful to determine regional strain and to reconstruct the relative and absolute timely tectonic history of a region (e.g. Hanmer and Passchier, 1991; Carosi et al., 1999; Short and Johnson, 2006; Druguet et al., 2008; Sassier et al., 2009; Bons et al., 2012; Maeder et al., 2014; Oriolo et al., 2018).

Veins are often oriented subparallel to the axial surfaces of folds in the adjacent layered or foliated materials (e.g. Edelman, 1973; Ramsay and Huber, 1987; Passchier et al., 1990; Rosenberg et al., 1995; Davidson et al., 1996; Brown et al., 2004; Craw et al., 2006; Skelton et al., 2015) or might even be restricted to fold hinge zones or short limbs of asymmetric folds (paired hook folds of Hudleston, 1989). Veins may also occur subparallel to a well-developed axial planar foliation in the host rocks, even if the foliation lies at a high angle to the instantaneous shortening axis (e.g. Lucas and St-Onge, 1995).

In the context of a single finite deformation, fold axial surfaces and associated axial-planar foliations tend to track the XY plane of the finite strain ellipsoid ($X \geq Y \geq Z$), while extension veins such as hydrofractures would eventually form closely parallel to the instantaneous shortening axis Z, i.e. at a high angle with coeval fold

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axial surfaces. Thus, an apparent contradiction arises between this theoretical concept and the ubiquitous cases observed in nature of veins that are subparallel to the fold axial surfaces. While in axial-planar foliations the relationship of subparallelism indicates that both, folds and foliations formed during the same deformation event and thus the term has a clear genetic connotation, this is not the case with axial-planar veins in which the observed geometrical relationship may have been developed by different processes.

Research specifically addressed to the question "how do axial surface-parallel veins develop?" has been performed since the early 1970s, e.g. Edelman (1973), Gayer et al. (1978), McLellan (1988), Hudleston (1989), Hand and Dirks (1992), Vernon and Paterson (2001), Weinberg and Mark (2008), Weinberg et al. (2015). These studies evidence the commonness of these structures in tectonites and that they are particularly abundant in high-grade metamorphic and migmatitic terrains. Almost all these works are based on field observations and analysis of natural structures from theoretical considerations. Experimental studies are less numerous, pioneered by Hudleston (1989) who performed some simple experimental models to explain the formation of a certain type of axial-planar veins (his paired hook folds). However, the mechanisms of formation of axial surface-subparallel veins remain somewhat enigmatic (Vernon and Paterson, 2001; Kisters, 2005) and difficult to model, largely because their inherent complexity, involving fluid flow, brittle and ductile deformation processes and generally significant amounts of stress and strain partitioning associated to rheological contrasts.

The present paper focuses on veins that are approximately parallel to fold axial surfaces, with the aim of gaining insight into the possible mechanisms for their formation. For the sake of simplicity, the term "axial-planar vein" will be used in the present paper, as used in previous works addressed to this structural type of veins (e.g. Edelman, 1973; Hudleston, 1989; Weinberg et al., 2013, 2015).

2. Conceptual and methodological approach to axial-planar veins

In order to deepen the understanding of the mechanisms that may give rise to different types of axial-planar veins, a series of geometric models have been conceived. They are based on the analysis of a varied selection of structures in tectonites and on the review of similar structures in the existing literature in terms of theoretical considerations, structural analysis and modelling.

The majority of the selected examples are from field areas where the author has done either previous extensive regional geological research (Variscan basement of NE Iberia, Rainy Lake zone in the Archean Superior Province of Canada) or sporadic field research (Variscan basement of NE Sardinia, Western Gneiss region of the Norwegian Caledonides).

It is not aimed to perform a systematic classification, but a qualitative categorization of axial-planar veins and the mechanisms for their formation, based on the combination of (i) structural and geometrical relationships obtained from observations mostly at the outcrop scale and (ii) theoretical constraints regarding strain, kinematics and rheological/mechanical parameters. Each model represents a particular situation, but different models are not mutually exclusive. They will be presented and illustrated with natural examples in the successive sections.

Because of their close link to fractures, most veins are typically regarded as tectonic structures. The majority of the veins described in this paper are not an exception as they have likely been originated by brittle fracturing. There is evidence, however, of veins that result from metamorphic subsolidus segregation or from coupled deformation and segregation (the so called "segregation veins" of Sawyer and Robin, 1986). The process can be extended to closed system partial melt segregation in stromatic migmatites (Oliver and Bons, 2001). This possibility will also be briefly considered.

A thoughtful question concerning the matter of this work and most cases of complex deformation structures is if the observed finite structure is the result of a single deformation event (formed either simultaneously or progressively) or, contrarily, can only be explained through different deformation phases (polyphase deformation). Both progressive and multiphase deformation histories are plausible in the context of mid- to low-crustal orogenic belts, although attempts should be made to integrate the different structures of a region in a single structural-kinematic model (Fossen et al., 2019). The key for deciphering this question largely lies on the structural/geometrical analysis of veins and folds, supported by a wide variety of additional evidences, such as the geometrical and kinematic analysis of other neighbouring regional structures (incorporated to this work) and petrological, geochemical and geochronological methods (outside the scope of this study). A first categorization consists on distinguishing between axial-planar veins achieved by either progressive or polyphase deformation.

3. Folds and axial-planar veins in progressive deformation

According to interpretations in the existing literature, penecontemporaneous folding and axial-planar veining during a single deformation phase is a commonly invoked scenario. The following situations are compatible with the development of veins subparallel to fold axial surfaces during progressive deformation.

3.1. Veining associated with the standard folding mechanisms

Tangential longitudinal strain (TLS) and flexural flow (FF) are standard folding mechanisms of single-layer folds (Ramsay, 1967; Fig. 1). TLS usually develops in homogeneous isotropic and FF in anisotropic layers. TLS is typical of competent layers within a multilayer sequence (Ramsay and Huber, 1987). A striking aspect is that, despite the two models have the same contour geometry (they are both parallel, class 1B folds), strain distribution in each model is totally different, since in TLS and FF folding the strain localizes in the hinges and limbs respectively.

Stress gradients and differences in strain distribution determine that the distribution of fracture and vein networks in each model will also be very different (Cosgrove, 2015). In TLS folding, extension veins are expected to form a radial array around the fold hinges from the neutral surface towards the outer arcs where layer-parallel extension dominates, while veins would grow parallel to layers and concentrically in the compressed zone of the inner arc (Fig. 1a). The veins in the outer arc of TLS folds are typically wedge-shaped (see e.g. Bastida et al., 2012; Jacques et al., 2014). Additionally, vein-filled saddle reef structures may form in the hinge regions of multilayer folds (Windh, 1995; Jacques et al., 2014). In contrast, fractures associated with FF folds will be heterogeneously distributed across the fold limbs, transverse to both the layering and the axial plane (Fig. 1b). Veins associated to both folding models usually have a low aspect ratio, since in TLS folds their lengths are limited to the thickness of the competent layers and in FF folds veins cannot cross from one limb to the other.

These fold-related veins can be deformed with subsequent progressive deformation and, in some instances, this may favour vein rotation into parallelism with the fold axial surface. A very common situation during fold evolution is the progressive change from buckling to homogeneous shortening as illustrated in Fig. 1. TLS fold model is more efficient to develop patterns of veins subparallel to the axial surface after progressive fold tightening (e.g.

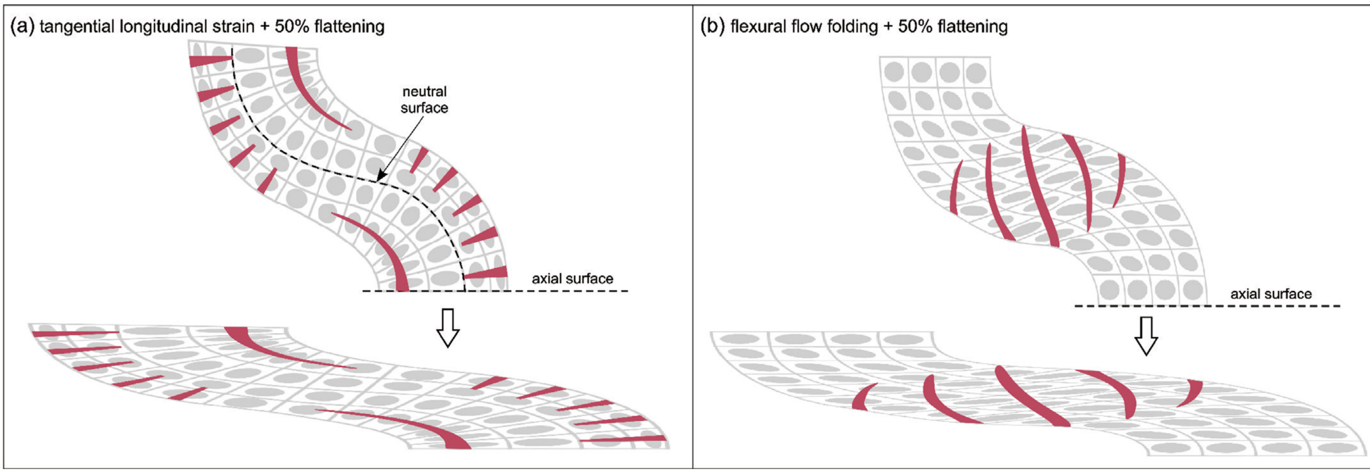

Figure 1. (a) Hypothetical distribution of vein sets developed during pure tangential longitudinal strain folding. With superimposed homogeneous flattening, the radial set of veins stretches and rotates into parallelism with the fold axial surface. (b) Hypothetical distribution of vein sets in pure flexural flow folding model. The superimposed 50% homogeneous flattening is not sufficient to reorient the veins formed in the fold limb into parallelism with the fold axial surface (modified after Ramsay and Huber, 1987).

Kruger and Kisters, 2016). However, examples of axial-planar veins in the literature strictly interpreted as derived from these basic folding mechanisms plus homogeneous strain are rather scarce.

3.2. Complex fracture arrays localized along the short limbs of folds (asymmetric fold-related veins)

Strain partitioning and localization processes may enhance the development of stepped veins or dilatant Riedel-type shears along the short limbs of regional asymmetric folds (Fig. 2). For this reason axial-planar veins formed by this process will be referred to as asymmetric fold-related veins.

The model is based on previous studies (Druguet et al., 1997; Bons et al., 2004) conducted in a high-grade metamorphic zone formed by sillimanite schists and pegmatite intrusions at the Lighthouse area in the Cap de Creus peninsula (Variscan basement of the Eastern Pyrenees). The area corresponds to the type locality for the "apparent boudins" of Bons et al. (2004). Pegmatite veins are aligned in form of strings of beads or lenses closely parallel to the axial surfaces of regional D_2 folds and crosscut the previous S_1 layer-parallel foliation in the alternating metagreywackes and metapelites (Fig. 3). D_2 folds are associated to a complex transpressional shear zone contemporaneous with pegmatite emplacement (Druguet et al., 1997).

The most characteristic pattern is the deflection of S_1 in the pegmatite-schists interfaces, giving rise to asymmetric "S"-shaped folds with the pegmatites occupying the short limbs. These folds do not differ much neither in orientation, nor in style from the D_2 asymmetric folds far from pegmatite dikes. Axial surfaces and pegmatite walls are oriented close to the average E–W trending D_2 folds (Fig. 3). In the rare cases where pegmatites are intruded at high angles to S_2 foliation, they have been folded. The folds in the dikes are coplanar with those in the country rocks but more open, indicating that some deformation had occurred before pegmatite emplacement and that it continued afterwards (Carreras and Druguet, 1994). No penetrative solid-state fabric is present in these pegmatites.

The isolated pegmatite segments are usually connected by surfaces of suture lacking pegmatite material (Fig. 3b,c), which could represent fracture segments collapsed just after pegmatite injection or, most likely, former discontinuous fractures (Bons et al., 2004; Bons and Druguet, 2007). S_1 is disrupted and or deflected along the sutures as well. A sinistral offset accompanied with shearing of the short limbs of the "S"-shaped folds is sometimes visible (Fig. 3c).

Occasionally, there is a continuity of layers and S_1 across the neck "inter-bead" regions devoid of suture (Fig. 3b), telling that the beaded shapes were already achieved at the time of pegmatite intrusion. In this case, pegmatites could have intruded in en-echelon opening fractures.

In addition, some pegmatites have wall-rock rims that are enriched in tourmaline (Fig. 3d,e). Tourmaline-rich rims (TRR) are preferentially developed in the micaschists, due to transformation of mica into tourmaline (Druguet et al., 1997). The TRR exhibit a more competent behaviour than the adjacent non-tourmalinized schists. The angular relationships between S_1 and pegmatite walls at the time of intrusion are fixed relative to the dikes in the TRR due to tourmalinization. This angle varies between 50° and 90° (Fig. 3d,e), indicating that pegmatites were emplaced at high angles to S_1 during D_2 folding and shearing. Bulk layering rotated dextrally up to 45° from the shortening field into the lengthening field (Druguet et al., 1997).

The orientation of the intrusive sites may have been primarily controlled by the S_1-parallel shear associated to flexural flow, rather than by the bulk D_2 transpressional flow. Folds in the schists, either those near the contacts with pegmatites or those further away, would initiate by S_1-parallel sinistral flexural flow and subsequent bulk oblique shortening, as shown in models of Fig. 2.

Flow partitioning between fold limbs would result into ductile stretching localized in the long limbs and, associated to the short limbs sited in the shortening field, a complex pattern of brittle or semi-brittle fractures that would enable pegmatite emplacement (Fig. 2). Such fractures could be composed of pull-aparts linked by shear fractures such in the models of Peacock and Sanderson (1995). Veins would fill the dilatant pull-aparts to form an array of lenses separated by shear fractures (e.g. Sawyer and Robin, 1986; Tikoff and Teyssier, 1992; Bons and Druguet, 2007). Other structures related to a process similar to the one here proposed are described in the context of en-echelon extension quartz-vein arrays associated to contractional kink bands (Ramsay and Huber, 1987; Sintubin et al., 2012).

Some thin axial-planar pegmatite veins of the Cap de Creus study case are very thin and sub-planar instead of lensoid-shape (e.g. Fig. 3d). In these cases, the intrusive sites could correspond to dilatant zones in the R_1-Riedel shear orientation (Fig. 2b). Dilatant Riedel-type shears have been reported and documented

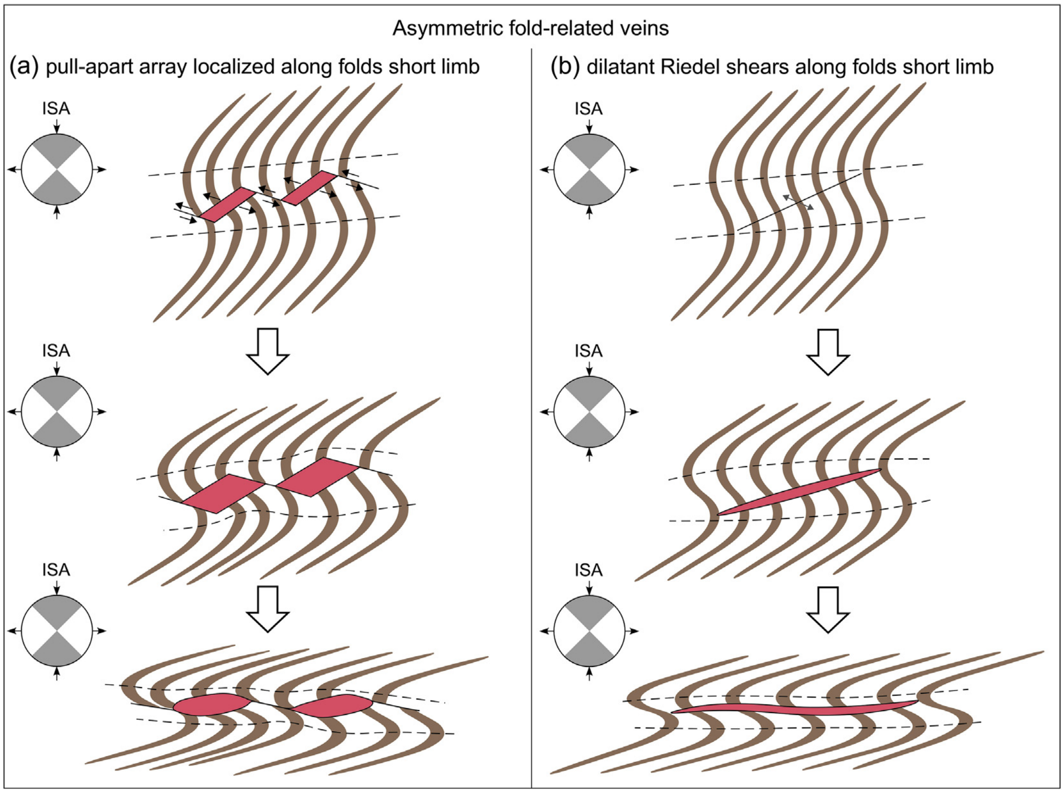

Figure 2. Models for the development of axial planar, low aspect ratio veins by fracture localization in the short limbs of asymmetric folds during progressive folding. The resulting string of beads have a strong resemblance to boudins, especially when progressive ductile deformation modifies their shape. Based on field observations in Cap de Creus and previous research (see Fig. 3; Druguet et al., 1997; Bons et al., 2004; Bons and Druguet, 2007; Carreras and Druguet, 2013). In (a) veins initiate as dilation jogs along a stepped fracture, while in (b) vein represents a dilatant R-type shear. ISA = bulk instantaneous stretching axes. Dashed lines represent fold axial surfaces.

experimentally by Rosenberg and Handy (2000), Holtzman et al. (2003), Holtzman (2005), Niemeijer et al. (2010) and J. Carrerast (personal communication, 2018).

Vernon and Paterson (2001) proposed two similar mechanisms for magma injection subparallel to fold axial planes in migmatites. One consists on magma infilling dilational jogs in strongly asymmetric folds, and the other on injection of magma into extensional shear zones in fold limbs with an oblique extensional crenulation cleavage.

This model is also supported by analogue experiments performed by Barraud et al. (2001) in which partially molten material localizes in shear bands along the short limbs of syn-anatectic folds.

3.3. *Folds associated with rotation of extension veins (vein-related folds)*

Despite bearing geometric similarities with the previous model of asymmetric fold-related veins (Section 3.2), the present model responds to a very different deformation process. Rotation of a fracture (fault, join or vein) or a secondary shear zone towards the fabric attractor or shear direction during progressive deformation induces flow perturbations in the adjacent materials. In layered or foliated rocks, such perturbations may materialize as deflections or folds with their axial surfaces parallel to the rotating vein (Fig. 4).

The process leading to vein-related folds occurs under general flow conditions, either coaxial or non-coaxial deformation, although it is favoured in shear zones of prevailing rotational strain. The resulting structures have been extensively investigated in previous works by means of analogue and numerical modelling. They have been mostly interpreted as a result of progressive rotation of extension fractures (and the infilling vein) with respect to a foliation or layering during layer-parallel shearing, giving rise to a local deflection and folding of the planar fabric adjacent to the vein (Gayer et al., 1978; Hudleston, 1989; Swanson, 1992; Grasemann and Stüwe, 2001; Passchier, 2001; Carreras et al., 2005; Coelho et al., 2005; Exner and Dabrowski, 2010; Figs. 4 and 5).

Drag folds related to rotation of veins are typically asymmetric, with the vein located in the short limb (Figs. 4 and 5). Other geometrical features that usually accompany folds in the adjacent host rock are contractional or extensional offsets due to slip along the vein or fracture (Figs. 4 and 5b). Both folds and offsets in the adjacent host rocks do not extend much beyond the vein or fracture tips. In those cases where the regional structure is characterized by a folding pattern, the regional folds and the vein-related folds have no matching orientations.

The resulting structure was referred to as paired hook folds by Hudleston (1989). Passchier (2001) introduced the terminology flanking structure, flanking fold and flanking shear band for a wider set of structures. The associated slip can be synthetic or antithetic with regard to the overall shear sense, and drag folds can be normal or reverse with regard to the slip along the vein/fracture (Grasemann et al., 2018). The sense of slip along the vein/fracture can switch during progressive deformation and also the sense of drag can change from normal to reverse along the vein or fracture surface. The initial orientation, nature and mechanical behaviour of fractures and veins (frictional or viscous, stiff or soft) are among the most important factors controlling the final geometry of vein-related folds. Hudleston (1989) pointed to the particular effect of competence contrast between vein and host. Moreover, although in the examples shown and modelled by Gayer et al. (1978) and Hudleston (1989) layering deflects passively, it may also behave

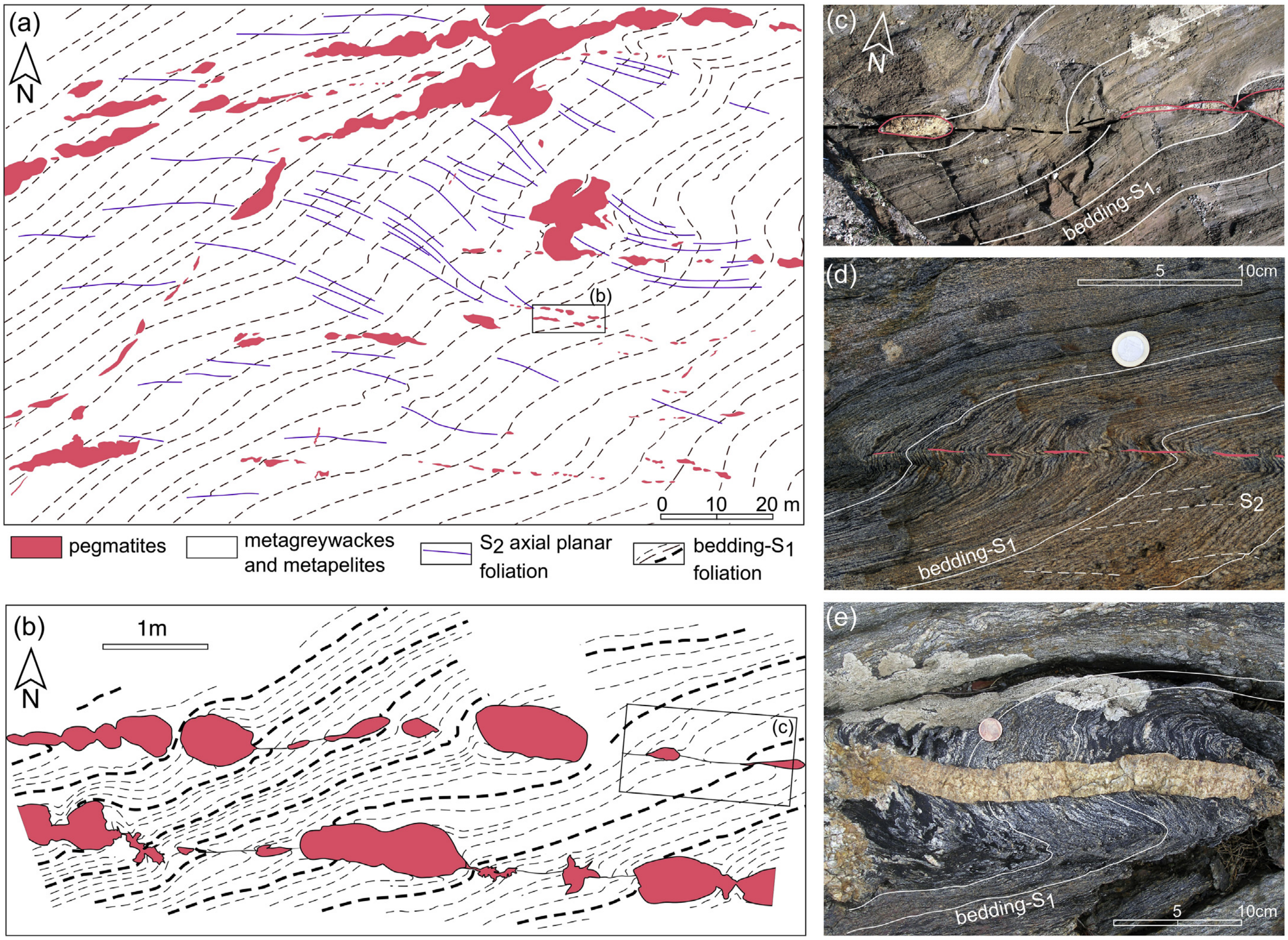

Figure 3. Pegmatite beads and veins aligned closely parallel to D_2 folds in high-grade schists from the Lighthouse area in Cap de Creus (Variscan of the Eastern Pyrenees). This is the type locality for the "apparent boudins" of Bons et al. (2004). (a) Structural map of the area. (b) Detail map of two strings of pegmatite beads. (c) Two pegmatite beads separated by a sinistral shear fracture. (d, e) Examples of pegmatite veins and associated tourmaline-rich rims preserving the original high angle between the veins and the bedding-S_1 foliation. Progressive ductile deformation of the schists outside the rigid tourmaline-rich rims gave rise to asymmetric "S"-shaped folds consistent with the overall D_2 fold pattern in the area.

mechanically active, giving rise to different types of folds. Progressive deformation up to large strains gives rise to tight folds and collapse structures around the veins. This is illustrated in the example of Fig. 5e corresponding to a high strain domain of the Canadian Rainy Lake transpressional deformation zone (Druguet et al., 2008). Flanking structures present in nearby domains of overall lower strain consistently indicate a lesser amount of rotation of competent veins (Fig. 5c,d).

Kocher and Mancktelow (2005), Gómez-Rivas et al. (2007) and Exner and Dabrowski (2010) developed methods and used them to estimate the finite strain and kinematics of deformation. In a recent review paper, Grasemann et al. (2018) catalogued flanking folds as complex structures and give some guidelines for their correct interpretation and use as kinematic indicators.

Finally, it is worth to note that vein-related folds are not exclusive of progressive deformation but can also be the result of polyphase deformation (see Section 4).

3.4. High strain and transposition of early veins

High strains can be attained when progressive deformation affects folded sequences and contemporary veins that were originally not necessarily axial-planar (e.g. the extension veins of Section 3.3). Folds tighten and become isoclinal, with thickened hinges and strongly sheared fold limbs, but also veins or vein segments are transposed into parallelism with fold axial surfaces and, when developed, with axial planar foliations (Figs. 6a and 7a).

This is a main mechanism for veins to achieve axial-planarity and can be observed in both non-metamorphic (Fig. 7a) and metamorphic environments, but are especially abundant in high-temperature, high-strain zones (e.g. Passchier et al., 1990), like in the boundaries of the Punta dels Farallons - Volt Andrau migmatitic complex at Cap de Creus (Druguet and Hutton, 1998; Fig. 7b,c, see the areas inside the white squares) or at the margins of shear zones in protomylonitic rocks such as in the Rainy Lake zone next to the Quetico fault in Ontario, Canada (Fig. 7d; Poulsen, 1986; Druguet et al., 2008). This type of veins whose axial-planarity is not an original feature but is achieved after a transposition process are obvious if different vein segments are exposed at the outcrop, like in Fig. 7. Otherwise, however, they may be easy to recognize and interpret for their characteristic structures. For vein/host high competence contrast, the stretched vein segments develop into boudinage structures (Fig. 7b). In the cases of incompetent veins or vein/host low competence contrast, veins become thin and record internal deformation fabrics, usually in the form of a solid-state foliation (Fig. 7c,d).

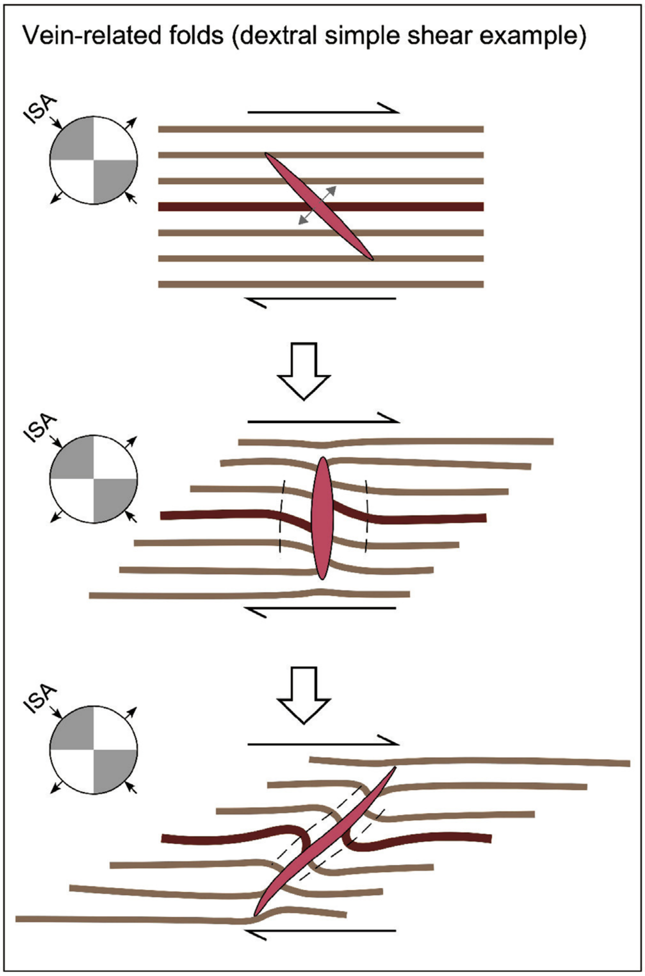

Figure 4. Model for the development of vein-related folds by progressive rotation of veins originally oriented within the instantaneous shortening field into parallelism with the shear plane. Based on experimental study under layer-parallel dextral shear conditions by Hudleston (1989). The final structure falls in the category of antithetic slip-reverse drag. ISA = bulk instantaneous stretching axes. Dashed lines represent fold axial surfaces.

3.5. High strain and late veins parallel to axial planar foliations (axial planar foliation-related veins)

As described above, progressive deformation causes fold tightening and transposition of pre-existing fabrics. Another well known effect of progressive deformation is the development of axial planar foliations and crenulation cleavages oriented parallel to the X–Y plane of the instantaneous strain ellipsoid. In folded sequences subjected to relative high strain, the new axial planar fabrics are well developed, displaying a variable degree of penetrativeness depending on the nature of the lithologies involved. These planar anisotropies represent planes of weakness which will have a strong influence on the orientation of the rock stresses (Price and Cosgrove, 1990).

Veins or dikes can form by hydrofracture in orientations close-to-parallel to the axial planar foliation, that is, in the plane perpendicular to the instantaneous shortening axis if fluid (or melt) pressure overcomes the maximum principal stress plus the tensile strength of the wall rock normal to the axial planar anisotropy (Wickham, 1987; Lucas and St-Onge, 1995; Vernon and Paterson, 2001; Brown, 2013). This process may operate under conditions of high fluid/magma pressure, a foliation surface of low tensile strength and low differential stresses (Gratier, 1987; Cosgrove, 1997). The resulting axial planar foliation-related veins are represented in the sketches of Fig. 6b and some natural examples from Cap de Creus and from the Central Pyrenees are shown in Fig. 8. This is the mechanism most invoked to explain axial-planar veins achieved directly, without necessity of any subsequent relative rotational strain of veins and fold axial surfaces into mutual parallelism (Oliver et al., 1990; Simpson, 2000; Vernon and Paterson, 2001; Arnaud et al., 2004; Weinberg and Mark, 2008). Obviously, this mechanism implies a late intrusion or injection of veins during progressive deformation, once the axial planar foliation is already developed. It can be easy to distinguish from the transposed veins described in the previous section if there is little or none further deformation that might affect the veins, or in presence of additional structural or geometrical criteria, such in the example shown in Fig. 8b of syntectonic leucogranites from the Volt Andrau high-strain zone in Cap de Creus. These leucogranites form a sub-vertical network of foliation-parallel and foliation-oblique dikes (Candami et al., 2013). In the detail of Fig. 8b, an apophysis normal to the axial planar foliation-dike is folded, but in a much more open form than the enclosing transposed metasediments, indicating that the intrusion of the interconnected network of leucogranites took place at the latest stages of folding.

Other models have postulated that the local stress and strain differences between the components of a rock can trigger metamorphic differentiation processes, with development of a compositional banding including subparallel segregation veins and mafic selvages. Such metamorphic or migmatitic banding could develop in an orientation perpendicular to the regional shortening direction (Robin, 1979; Sawyer and Robin, 1986). In this case, veins would form during continuous deformation, without brittle failure, by solution transfer of the soluble material that migrates to low pressure interfaces between layers of different competence. However, there are few examples in the literature of axial-planar veins interpreted as developed only by segregation (subsolidus or anatectic) processes without invoking brittle failure (Sawyer and Robin, 1986; Hand and Dirks, 1992; Le Hébel et al., 2002).

Finally, it is worth to point out that vertical crenulations, bandings and foliations represent ideal orientations for buoyancy-driven melt drainage (Hand and Dirks, 1992) or for tectonically driven extrusion (Lehmann et al., 2017).

4. Folds and axial-planar veins in polyphase or polyorogenic deformation

In polyphase or polyorogenic tectonic settings, vein formation and fold development in the neighbouring layered or foliated rocks belong to two distinct deformation events separated by a switch in orientation of the stress/strain fields. Thus, veins could either predate folds or folds could predate veins.

4.1. Veins predating folds

This setting consists on a superposed phase of shortening parallel to a pre-existing layering or foliation and at a high angle to also pre-existing veins. Such veins would have been intruded during a first deformation phase at a high angle to layering within the instantaneous shortening field (e.g., as an extension vein, Fig. 9). These veins may be deformed (folded if they are more competent than the host) or not (as in the example of Fig. 9) before the second deformation phase.

Throughout the second deformation event, defined by an important switch in the direction of regional shortening, the anisotropic host rocks, now laying in the shortening field, become folded, while the vein, now laying in the extensional field, becomes

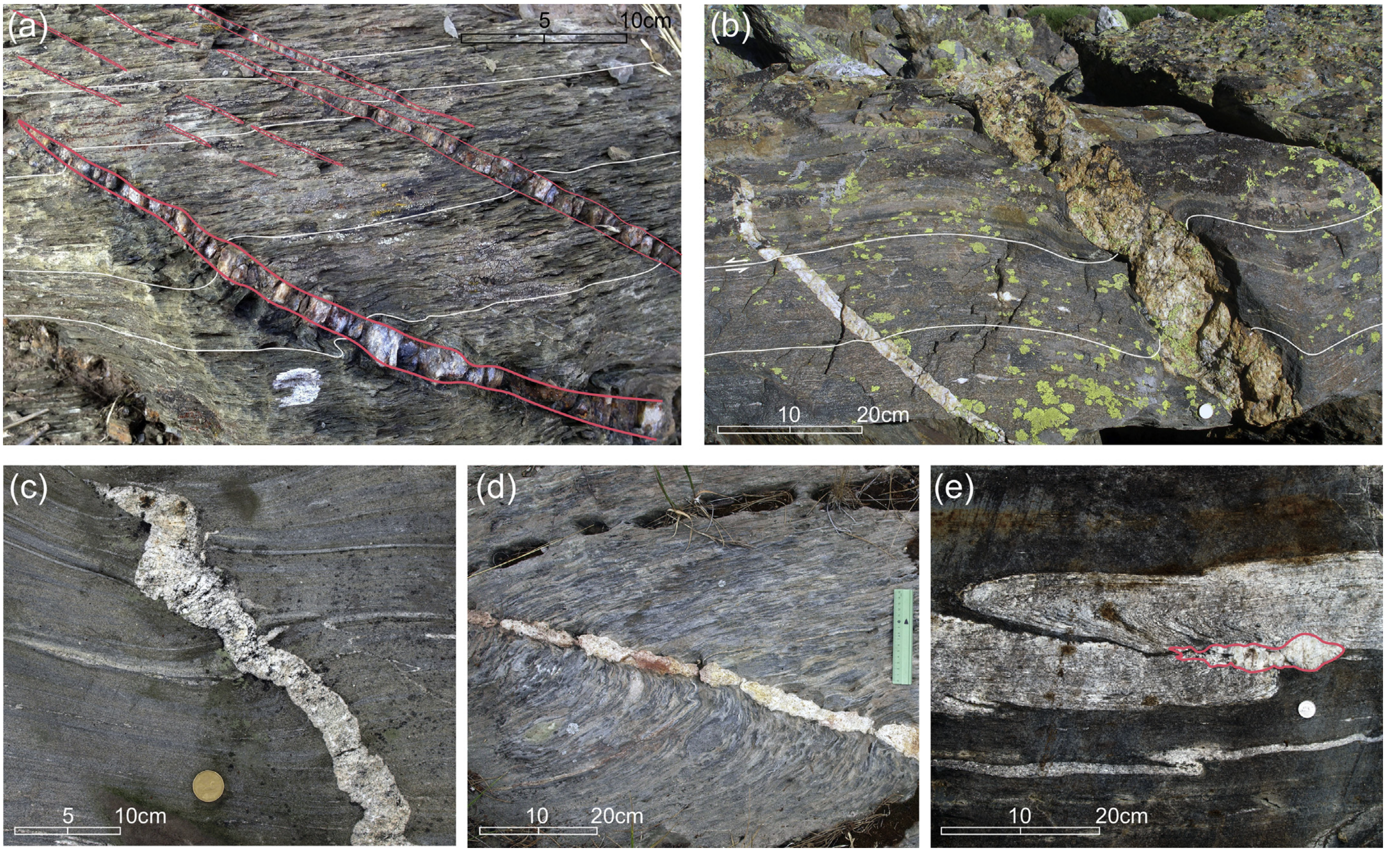

Figure 5. Examples of veins and associated drag folds (vein-related folds) that are likely formed by vein rotation during progressive deformation. All the structures fall in the category of synthetic slip normal drag. (a) Kink-band-like folds associated to quartz veins in slates (Coll de Jou, Variscan of the Central Pyrenees). (b) Rotated (anti-clockwise) cuspate-lobated pegmatite dike and associated drag folds affecting sheared mid-grade schists at Els Estanyols (Canigó massif, Variscan of the Eastern Pyrenees). Notice foliation-parallel sinistral shearing denoted by the thinner vein to the left. (c–e) Rotated (anti-clockwise) veins of leucogranite (c and d) and quartz (e) and associated drag folds affecting metavolcanic rocks from Rainy Lake zone (Superior Province of the Canadian Shield).

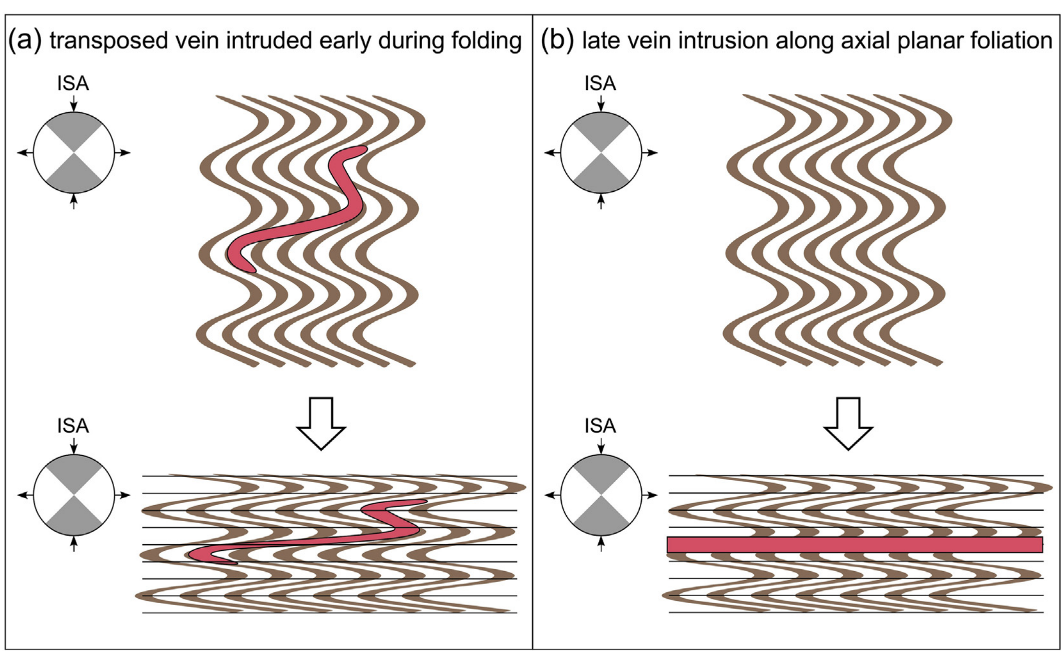

Figure 6. (a) Model of high strain deformation causing transposition of layers or foliations and a pre- or syn-folding vein in a case of progressive layer-parallel shortening. (b) Model for the formation of fold-related late veins in the same case of progressive layer-parallel shortening. Vein intrudes parallel to the axial planar foliation (black lines) developed after a considerable amount of deformation. ISA = bulk instantaneous stretching axes.

Figure 7. Field examples to illustrate the subparallelism between veins and fold axial surfaces due to intense folding and transposition. (a) Tight folds and associated axial planar cleavage (dashed lines) and axial-planar quartz veins affecting an anchimetamorphic sequence of slates and quartzitic sandstones (solid lines represent bedding surfaces). Collserola massif, 12 km NW from Barcelona (Catalan Coastal Ranges). (b) Folded and boudinaged quartz vein and crenulated sillimanite schists at Cala Prona (Cap de Creus). (c) Isoclinally folded leucogranite vein and sillimanite schists at Volt Andrau Area (Cap de Creus). (d) Tightly folded leucogranite veins and metavolcanic rocks at the margins of the Quetico Fault (Rainy Lake zone, Western Superior Province, Canada). White square areas in b, c and d indicate the areas of axial-planar vein segments.

stretched. The way vein-parallel extension is accommodated will depend on the competence contrast with the host rocks. Two end-member situations are depicted in Fig. 9: (i) vein homogeneous stretching for incompetent veins or low competence contrast between vein and host, in which case the vein would likely develop a foliation, and (ii) boudinage for higher competence contrast. At intermediate rheological conditions, pinch-and-swell structures could develop. Besides, as an intrinsic consequence of boudinage of competent veins, a precipitate or melt can fill the interboudin regions, progressively developing into a new generation of axial-planar vein (lower-right sketch in Fig. 9).

Moreover, the final structural patterns in the layered rocks will also reflect the effects of flow perturbations and strain localization due to the differences in mechanical behaviour between veins and host. As observed in the model of Fig. 9 and natural examples (Figs. 10, 11a and 12), more tighten folds, localized shears and kink-bands (e.g. Allan et al., 2017) or the typical foliation drag around boudins can develop in the host at the host-vein interfaces. This is a relevant difference with the relatively simpler or less heterogeneous fold pattern that usually characterizes the areas adjacent to axial planar foliation-related veins (Figs. 6b and 8). On the other hand, the present case of veins predating folds in a context of polyphase tectonics bears geometrical similarities with veins localized along the short limbs of folds (asymmetric fold-related veins of Figs. 2 and 3) and with folds associated with rotation of extension veins (vein-related folds of Figs. 4 and 5) during progressive deformation, from which they are not always easy to discriminate.

Three individual examples of axial-planar veins that could likely belong to this category will be now discussed. They are depicted in Figs. 10–12.

The first example consist in quartz veins embedded in low-grade, finely laminated metasedimentary rocks from the Central Pyrenees affected by polyphase Variscan tectonics (see microstructures in Fig. 10). Vein morphology varies between single high aspect ratio veinlets and arrays of stepped lenses. In both cases, the veins crosscut the dominant layer-parallel cleavage (Sd) at a high angle and are slightly folded with the axial planar of the folds. This feature evidences that the veins were likely injected during the development of the Sd. Later, during a subsequent deformation phase with shortening almost perpendicular to the veins, the dominant cleavage and parallel veins became respectively crenulated and folded. Notice in Fig. 10 that these late folds are not confined to areas where late axial-planar veins are present, but regularly extend over the rock sample. This is contrary to what happens in vein-related folds (Figs. 2 and 3) where the folds die out away from the vein.

The second example has been taken from the classical paper by Edelman (1973), and shows axial-planar quartz and granitic veins in high-grade gneisses and amphibolites from the Archipelago of SW Finland (Fig. 11). They were interpreted by Edelman (1973) as due to the release of elastic stresses perpendicular to the axial plane of folds, which would cause opening of tension fissures and formation of veins. Another plausible interpretation would be that veins predate folds, given the analogies with the previously described case from the Pyrenees. The vein segment encircled in Fig. 11a is folded with the gneissose foliation axial planar. A further evidence that polyphase tectonics may have operated in the SW Finland case is shown in Fig. 11b. The vein system associated to a folded amphibolite layer very much resembles a series of folds overprinting a previously boudinaged layer which contained thin

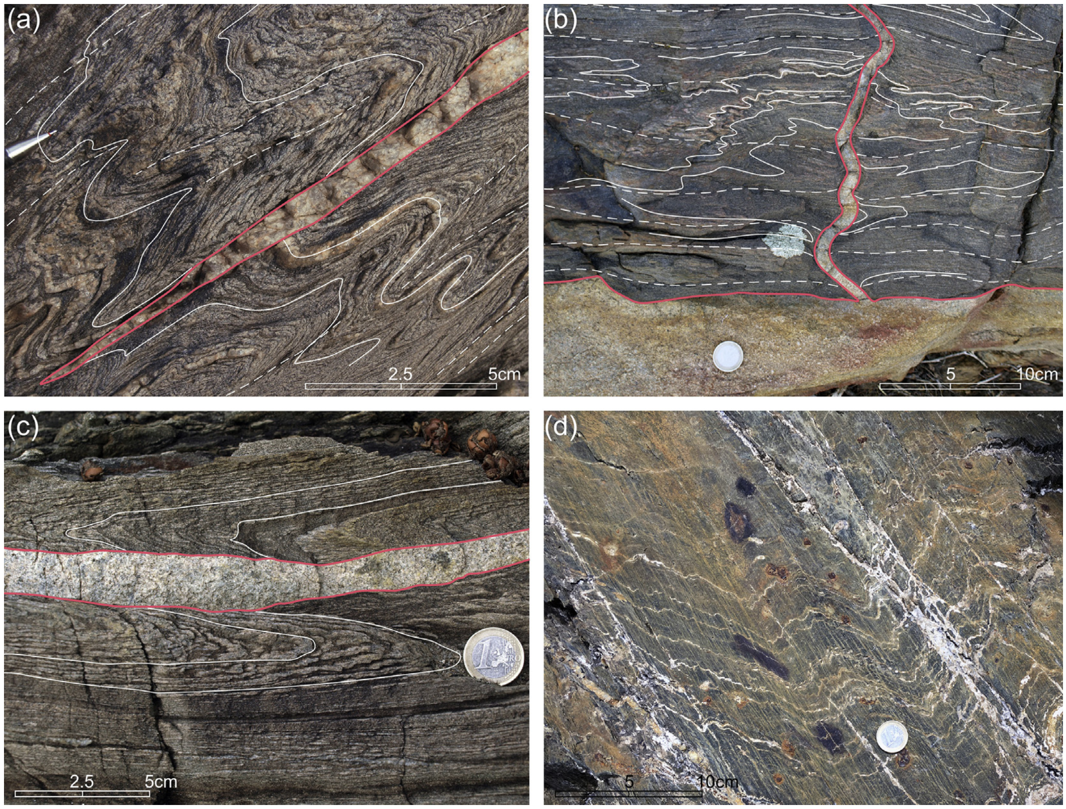

Figure 8. Examples of veins subparallel to an axial planar foliation (dashed traces). (a) Quartz vein from Cala Serena in Cap de Creus (Variscan of the Eastern Pyrenees). (b, c) Leucogranite dikes from Volt Andrau area in Cap de Creus. Notice in (b) the presence of a slightly folded apophysis normal to the main dike, indicating that leucogranite emplacement took place at the latest stages of regional folding. (d) Calcite veins parallel to a strongly developed crenulation cleavage in carbonatic slates from Son's road near Esterri d'Àneu (Variscan basement of the Central Pyrenees).

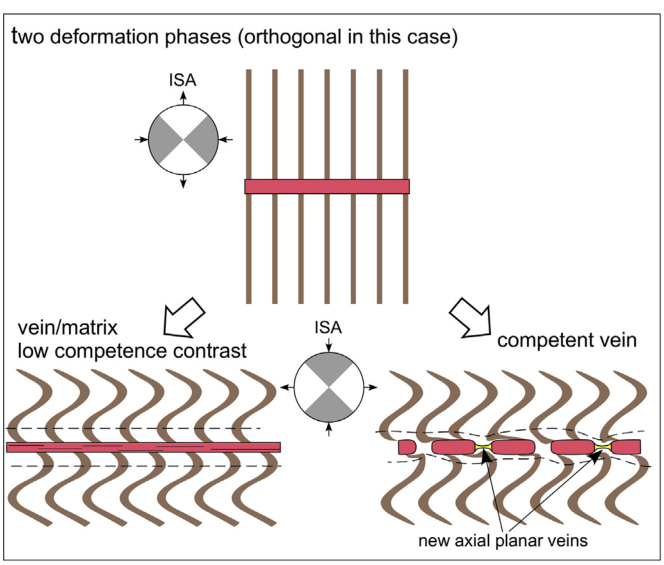

Figure 9. Model for the development of axial planar veins throughout polyphase deformation. Extension veins intrude at a high angle to the foliation associated to a first deformation phase and are subsequently stretched homogeneously or boudinaged (depending of competence contrasts) during a second phase of folding. Dashed lines represent fold axial surfaces.

interboudin veins. This example is strikingly similar to natural and experimental examples of folded boudins in Sengupta (1983).

The third example also meets the conditions described for a setting in which veins achieve their axial planarity in a second phase of folding. The field area is located in the Cap de Creus peninsula (Eastern Pyrenees), on a beach slope north of El Port de la Selva (Fig. 12; Carreras and Druguet, 2013). There, orthogneisses with a prominent gneissic foliation are cut at a high angle by a set of quartz veins. Whilst at the same time the veins are oriented subparallel to the axial surfaces of late folds and crenulations (Fig. 12a), and display signs of vein-parallel shearing and stretching (Fig. 12b,c). Structural correlations at the regional scale reveals that the dominant gneissic foliation is a composite $S_{1/2}$ axial planar transposition foliation to which quartz veins are probably syntectonic, and that the late folds and crenulations (D_3) are widespread at the regional scale (not restricted to sites of vein presence). The overprinting D_3 folds locally produced type 3 fold interference patterns (Fig. 12d).

Finally, vein-related folds can also develop in polyphase deformation in those cases where vein formation and rotation correspond to separate tectonic phases. An example could be the formation of veins in interboudin partings during a first phase of extension parallel to competent layers, followed by a second phase of layer folding/rotation. These could be the case of Fig. 5e.

4.2. Folds predating veins

This setting consists on the injection of veins parallel to the axial surfaces of pre-existing folds or crenulations. A common occurrence is that an axial-planar cleavage or foliation is already developed associated to the previous folding event, so it acts as a weakness surface along which hydrofractures may form irrespective of the orientation of the regional stress/strain field, just as

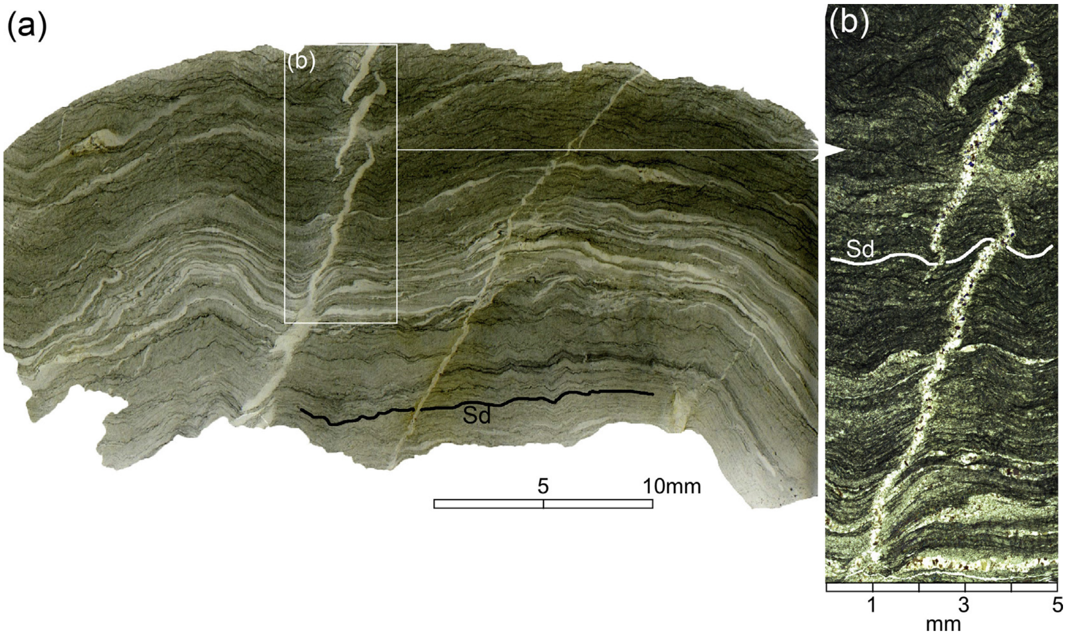

Figure 10. Quartz veins injected into finely foliated low-grade metarhythmite (Pica d'Estats summit, Variscan of the Central Pyrenees). (a) Polished hand specimen. (b) Microphotograph of the en-echelon vein array indicated in (a). The veins are at a low angle to the axial surfaces of the widespread crenulation. The open folds present in the vein segments indicate syntectonic injection with the deformation event that gave rise to the closely spaced dominant cleavage (Sd). Thus, the veins likely predate the crenulation event.

it occurs with late veins in progressive high strain deformation (Section 3.5; Fig. 6b). Distinction between the two scenarios (late veins in progressive deformation vs. a first event of folding and a second of axial-planar vein formation) is not structurally straightforward (with limited exceptions such as in the field example shown in Fig. 8b) and may require performing petrological correlations or applying geochronological criteria.

5. The particular case of migmatites

Migmatitic terrains represent a paradigm for the study of the interplay between deformation, metamorphism, anatexis and magmatism and thus for the recognition and interpretation of the structures that are object of this study. The presence of interconnected systems of leucosomes subparallel to the migmatitic foliation or banding, melt-bearing shear bands and axial planar leucosomes is a very common feature in many folded migmatitic domains (e.g. Sawyer, 2008; Pawley et al., 2015). This has entailed a large number of studies in which aspects related to this issue have been explored on the macro- to micro-scale by means of field analysis and experimental modelling (McLellan, 1988; Hand and Dirks, 1992; Brown, 1994, 2013; Druguet and Hutton, 1998; Vanderhaeghe, 1999; Barraud et al., 2001, 2004; Vernon and Paterson, 2001; Weinberg and Mark, 2008; Weinberg et al., 2013; Lehmann et al., 2017).

The low cooling rates prevailing at anatectic conditions allow interaction between the partially crystallized veins and the hot wall rocks during folding. Deformation tends to localize around melts, producing a range of structures from melt bearing to solid-state stages, separated by the reversal of competence contrast between leucosome and host rock (Druguet and Carreras, 2006).

Based on the analysis of natural migmatites, Hand and Dirks (1992) proposed a model in which melt reactions initially take place in high strain zones where the melting reaction activation energy is first overstepped. The generated leucosomes, as incompetent material, would elongate in a plane normal to the direction of maximum compression and parallel to the axial surfaces of crenulations. Pervasive melting would result into an interconnected vein network. Partial melt segregation processes that lead to the formation of stromatic migmatites consisting on layers of leucosome and melanosome is comparable to metamorphic segregation referred to in Section 3.5 (Oliver and Bons, 2001).

Rosenberg and Handy (2000, 2001) performed a series of experiments on syntectonic partial melting with very interesting results. Under simple shear conditions, melt pathways were distributed along interconnected dilatant shear bands at low angles to the shear zone boundary. Under pure shear, transient melt pockets developed parallel to the stretching direction. The results from the experiments by Barraud et al. (2001) and Holtzman et al. (2003) also confirmed the reliability of leucosomes to localize in shear bands along the short limbs of folds (model of asymmetric fold-related veins; see Section 3.2).

Most of the models suggested in the present paper match the mechanisms proposed by Vernon and Paterson (2001) for the formation of axial planar veins in migmatites. Six of their mechanisms apply to magma injection and the other three to in situ formation of leucosomes.

Weinberg and Mark (2008) argued that synchronous folding and melt migration enhances transposition, and Weinberg et al. (2013) explained the common occurrence of layer-parallel and axial planar leucosomes in migmatites as the result of melt extraction along funnel-shaped channels subparallel to fold hinges, driven either by magma buoyancy or by pressure gradients arisen during deformation. In a more recent paper, Weinberg et al. (2015) emphasized the role of stress-driven ductile compaction instabilities in the formation of such axial-planar melt channels.

A deduction of the studies discussed above is that migmatitic terrains are frequently characterized by their structural complexity. Many of the resulting structures are interpreted as a consequence of the coupling between polyphase deformation and multiple melting pulses (e.g. Talbot, 2008; Weinberg et al., 2013; Barbey et al., 2015). Thus, it is reasonable to consider the abundance of axial planar veins as an inherent phenomenon in anatectic domains, and that they can likely form by various or

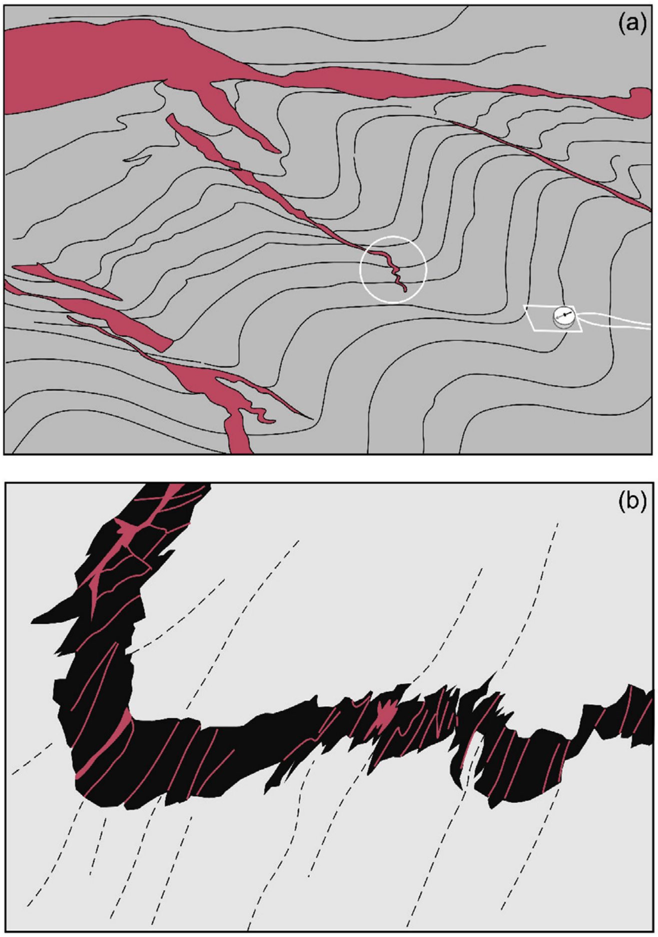

Figure 11. Sketches of two field photographs from the Archipelago of SW Finland from Edelman (1973). The structures suggest formation of axial-planar veins by two superposed deformation phases. (a) Line drawing of Fig. 3 of Edelman (1973). Pegmatite veins (pink) are subparallel to the axial surfaces of folds in the layered gneisses (grey). The tip of the central vein (white circle) is folded with the main gneissose foliation as axial surface. Like in the example showed in Fig. 10 of this article, this would indicate that the veins are pre- or syn-tectonic with the foliation that was later folded during a superimposed tectonic event. (b) Sketch of Fig. 5 of Edelman (1973). A layer or dike of amphibolite (black) is folded within a gneissose matrix (pale grey) and includes a set of granite veins (pink) parallel to the axial surface of folds (dashed lines). The structure resembles folded boudins originated by two deformation phases, a first phase of layer-parallel extension and granite vein formation and a second phase of layer-parallel shortening that would have produced the folds.

different combinations of the predicted mechanisms. A variety of patterns of axial-planar or quasi-axial-planar leucosomes from different world regions are shown in Fig. 13. In Fig. 13a, an isolated diffuse melt patch seems to have migrated from the fold limbs and hinges to the axial surface, while in Fig. 13b,c leucosomes are more elongated and occupy the sheared limbs of the asymmetric folds. Fold transposition and the development of leucosomes along the axial planar migmatitic fabric characterize the examples shown in Fig. 13d and e. The last example of straight leucocratic veins parallel to the axial planes of the folds in migmatitic schists from Loch Monar (Scotland) is particularly intringuing (Fig. 13f). These veins have been interpreted by Ramsay and Huber (1987) and Hudleston (1989) as the product of local melt segregation during folding, which appears difficult to explain by any of the proposed simple mechanism. Most likely, fold transposition after melt infill is needed to account for the extreme parallelism of the veins with fold axial surfaces.

6. Final discussion and conclusions

Axial-planar veins are common in tectonites and respond to a large variety of metamorphic, deformational and tectonic settings. Interpretation of the finite structures observed in the field has lead to previous and present studies to establish certain correlation between the resulting finite structures and formation mechanisms, that is, a correspondence between geometrical types and genetic models of axial-planar veins. Some particular geometrical and overprinting relationships are attributable to specific development mechanisms. Other structural relationships are not as straightforward, either because they are the complicated result of coupled processes, or because similar final geometries can be achieved by different mechanisms. Nevertheless, we have seen that coplanar folds and veins can be grouped into two main settings depending on the sequence of deformation processes that lead to their formation, that is, progressive and polyphase deformation settings (Fig. 14), Whilst polyphase deformation is the apparent best explanation for the occurrence of axial-planar veins (provided a switch in orientation of the kinematic framework), it has been demonstrated that many of these finite structures can be better explained as a consequence of progressive deformation. Also, there are specific complex cases whose analysis transcends the progressive or polyphase deformation histories. This is the case of some migmatitic terrains dominated by a complex coupling of interacting deformation, metamorphic and fluid/melt flow phenomena (e.g. model 8 in Fig. 14).

6.1. Models of progressive deformation

Five particular settings have been investigated, here summarized with some of their characteristic features (Fig. 14):

(1) Veining associated with the standard folding mechanisms. Tangential longitudinal strain (TLS) folding is more efficient than pure flexural flow folding as a mechanism to develop axial-planar veins. However, in the case of TLS, the process requires a multilayer with high competence contrast and veins that form are usually very discontinuous and limited to the fold outer arc.

(2) Complex fracture arrays localized along the short limbs of folds (asymmetric fold-related veins). Veins are localized in the short limbs of asymmetric folds, generally as stepped dilatant pull-aparts between shears or along Riedel-type shears. The vein-bearing folds are co-relatable with regional folds.

(3) Folds associated with rotation of extension veins (vein-related folds). Complex flanking folds develop as a result of vein rotation. Generally, these local folds do not match with regional folds in orientation and they die out progressively away from the vein. The veins themselves may record a rather complex deformation history, especially if they are more competent than the host, as they can be progressively folded and boudinaged.

(4) High strain and transposition of early veins. In this case, the coplanarity of veins with folds is achieved after a transposition process which is usually discernible in the rocks by the tight folding of the layered/foliated host and the presence of boudinage or internal foliation in the veins (depending on competence contrast).

(5) High strain and late veins parallel to axial planar foliations (axial planar foliation-related veins). In this case, an axial planar foliation is already developed and this controls the orientation of late-tectonic veins. Veins are expected to record little deformation compared to the high strain fabrics in the host.

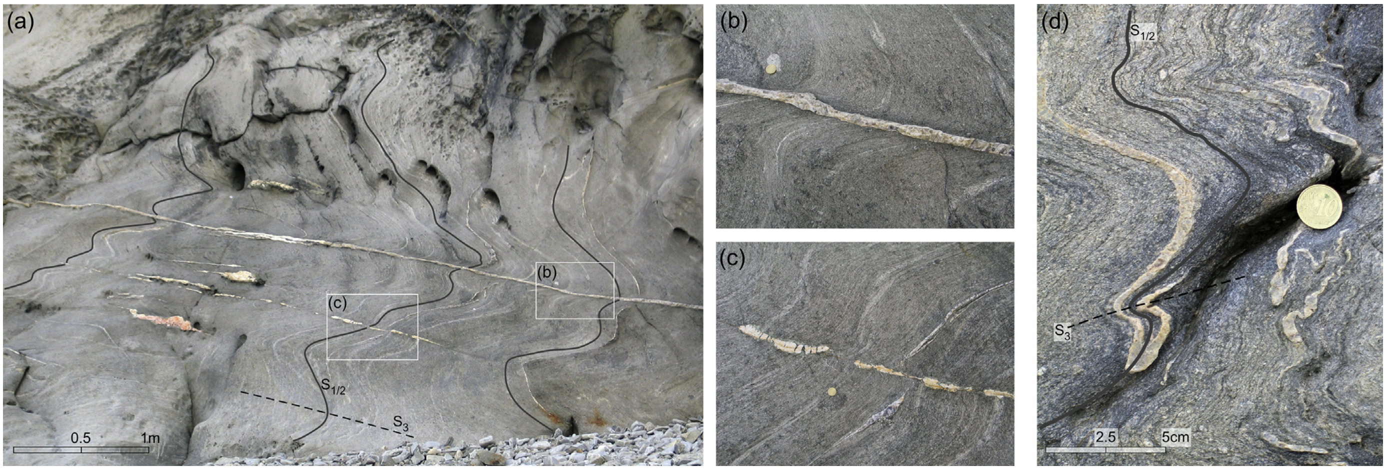

Figure 12. (a) Field example of quartz veins subparallel to axial surfaces of folds and crenulations (S_3) affecting El Port de la Selva orthogneiss (Les Clisques beach, NW Cap de Creus). Veins that vary in shape between planar and continuous (b) and irregular and segmented (c) are located along sheared fold limbs. See main text for discussion. (d) Refolded folds in quartz veins of an earlier generation are evidence that the region was affected by polyphase tectonics.

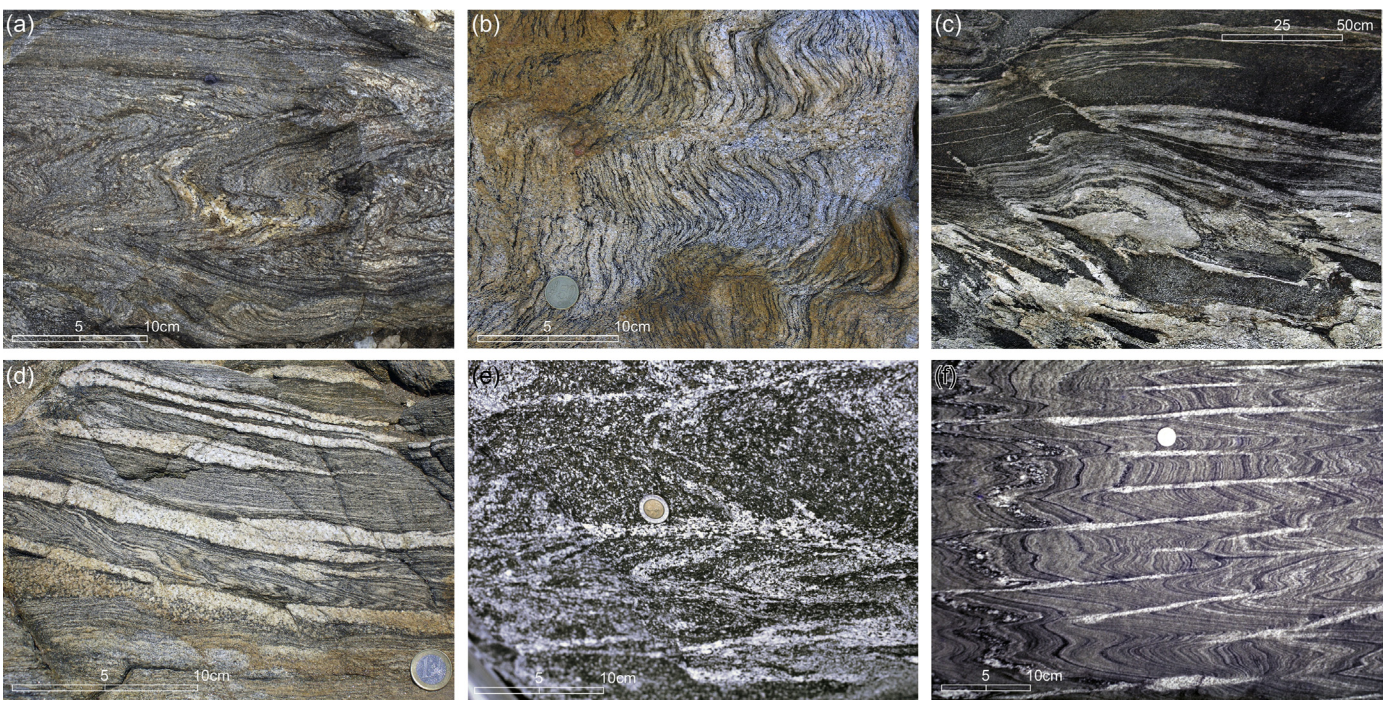

Figure 13. Field examples of folded migmatitic rocks with leucosomes closely parallel or at a low angle to sheared fold limbs and fold axial surfaces. (a) Migmatitic schists from Volt Andrau migmatitic complex at Cap de Creus. Irregular leucosome is roughly parallel to the axial surface of the folds. (b) Migmatitic orthogneiss with leucosome-filled sheared limb (Porto Ottiolu, Variscan basement of NE Sardinia, Elter et al., 1990). (c) Folded stromatic migmatites with cross-cutting axial planar leucosome veins (Osvatnet, Western gneiss region, Norway). (d) Highly transposed mesocratic migmatitic gneiss with axial-planar granitic leucosomes (Porto Ainu, Variscan basement of NE Sardinia, Carosi et al., 2006). (e) Veins of leucotonalite parallel to the axial surfaces of folds affecting banded tonalites from the floor of the Bergell pluton in the Central Alps (Rosenberg et al., 1995; Davidson et al., 1996). Photograph courtesy of C. Rosenberg. (f) Multilayer folds produced under near-migmatitic conditions in the Moine Series rocks at Loch Monar (NW Scotland), with pegmatite veins parallel to the folds axial surface (analogue to Fig. 20.12, p. 416 of Ramsay and Huber, 1987; and to Fig. 2d of Hudleston, 1989). Photograph courtesy of J. Carreras.

Within this category of progressive deformation, distinction can be made between those mechanisms by which the axial planar geometry is achieved at the time of vein intrusion (model 5), and those by which the geometry is achieved throughout the relative rotation (by different degrees) of the veins and the anisotropy in the host rocks (all the other models, 1 to 4).

In models 1 and 2, axial-planar veins are already intruded into the regional instantaneous extensional field, responding to mechanisms which are strongly controlled by strain partitioning processes. Strain partitioning across lithological/rheological boundaries (banding or layering with competence contrast) dominates the setting associated to tangential longitudinal strain folding, whereas partitioning between different limbs of asymmetric folds, either by deformation with a shear component or by pure shear oblique to layering/foliation, dominates other fold-related axial planar veins.

In models 3 and 4, veins that are originally emplaced as extension fractures into the regional instantaneous shortening field

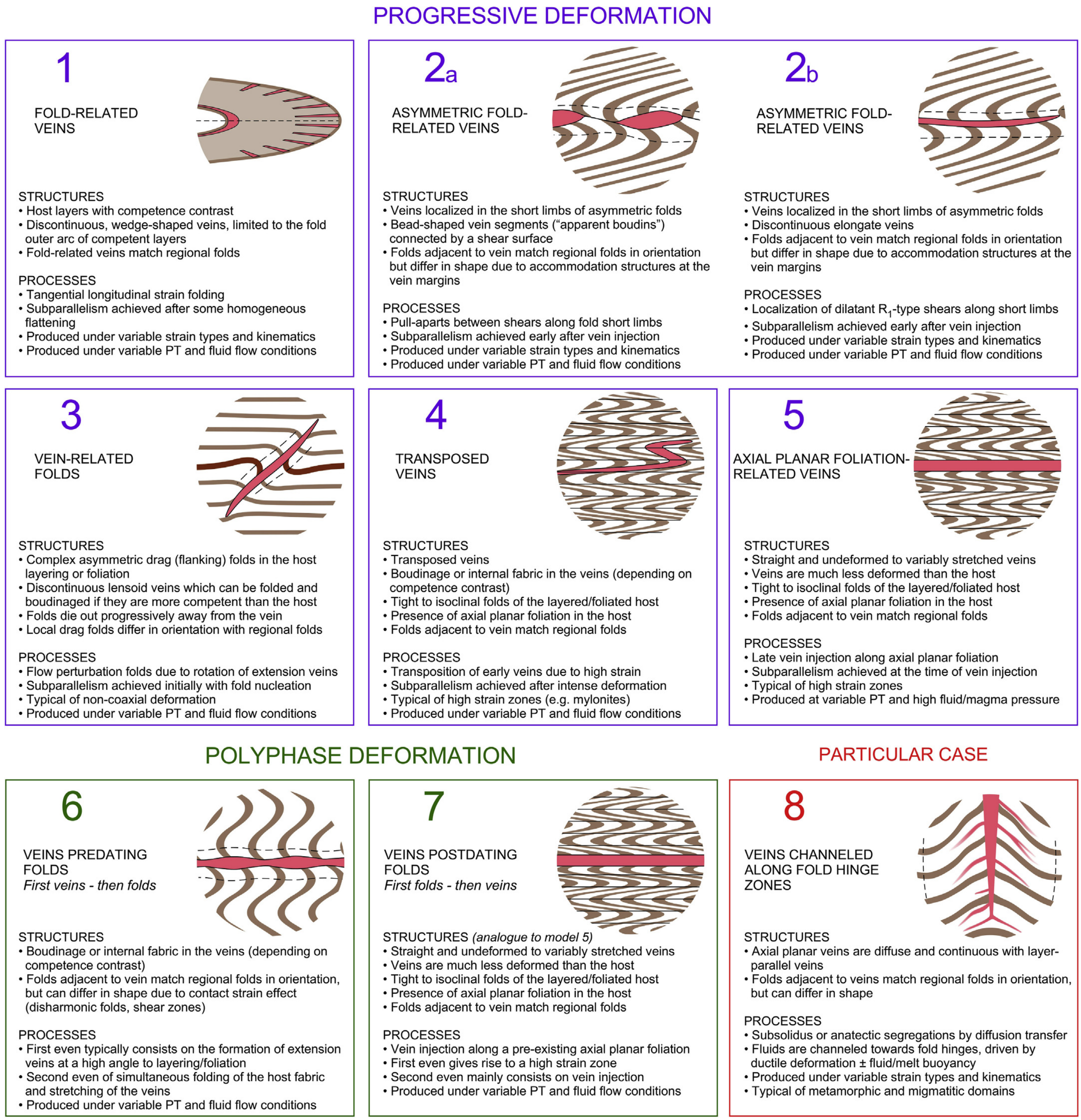

Figure 14. Scheme summarizing the diagnostic characteristics of models leading to the axial-planar veins considered in this study. The drawings represent finite structures. Model 8 represents a specific case based on Weinberg et al. (2013) model for axial-planar leucosomes in migmatites.

progressively rotate into the extensional field. This can be achieved by different ways. In the case of model 3, folds are the consequence of vein rotation, whereas in model 4 the coplanarity is the result of high strain and transposition.

6.2. Models of polyphase deformation

Discriminating between axial-planar veins formed by polyphase or progressive deformation is not always clear and usually requires to be contrasted with independent indicators. Some useful evidence for mechanisms associated to polyphasic tectonics, although not always univocal, are the presence of fold superposition structures such as folded boudins or fold interference patterns, or the record of two or more generations of crenulations, foliations and mineral assemblages. Where regional polyphase tectonics is in evidence, the possibility for axial-planar veins to have developed in two distinct phases should not be underestimated. In this context, and depending on the sequence of the events, veins would either predate folds (model 6, Fig. 14) or folds would predate veins (model 7, structurally equivalent to model 5).

6.3. Final remarks

Axial-planar veins are specific but quite abundant structures in metamorphic and magmatic terrains. Deciphering the feasible mechanism for their development has been determinant for gaining insight into the interplays between deformation, metamorphic and magmatic processes during the evolution of orogenic belts. For instance, the recognition that certain mechanism has operated to form one of these structures can be useful to formulate hypothesis about the relative age of veins and the associated structures and, once this is done, proceed with dating veins by geochronology techniques (e.g. Kontak and Smith, 1990; Fletcher et al., 2002; Cottle et al., 2009). The present work provides some guidelines for the recognition of such mechanisms. Careful structural analysis may provide useful insight into the processes leading to the development of these still somewhat intriguing structures. Some of these processes are rather obvious; while others are so complex that demand the use of additional criteria, including tectonic and kinematic correlations at the regional scale, microstructural analysis and petrological and geochemical studies. Different models are not mutually exclusive, as they represent end-member situations that can coexist in a single region and even in a single vein system. This is particularly manifest in complexly deformed hydrothermal, migmatitic and magmatic vein networks.

Finally, this study serves as a basic 2D context from which to develop more complex and systematic physical and numerical models of the interactions between deformation, fluid or magma flow and anatexis that lead to coplanar folds and veins in crustal rocks.

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