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Shear zone-related folds

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Abstract

Folds in ductile shear zones are common structures that have a variety of origins. These can be pre-existing folds that become modified or folds developed during the shearing event. Among the syn-shearing folds, a second subdivision is based on the relative age of the folded surface, which can be pre-existing or newly formed during the shearing event. In each of the three categories final fold geometry and orientation show complex relationships with the kinematic frame. The final fold geometry depends on the vorticity within the shear zone, the rheology and the initial orientation of the folded surface relative to the kinematic framework. It follows that folds are complex structures, difficult to use as kinematic indicators. However, in shear zones where undeformed wall rocks with pre-shear structures are accessible and where kinematics can be well established, folds can provide a valuable natural means to understand the initiation and evolution of structures under non-coaxial regimes. We point to the need of discriminating among different plausible categories, based on the nature of the folded surface and on the inherent structural features of each category.

Keywords: Fold; Shear zone; Geometry; Kinematics; Cap de Creus

1. Introduction

Folds are common structures in many ductile shear zones. The origin of these folds is variable, as their development may predate, be contemporaneous with, or postdate the shearing event. The origin of folds in the interiors of some shear zones cannot always be determined, and they can be referred to as simply intramylonitic folds. However, many ductile shear zones display a complete transition from unsheared wall rock to highly strained domains and, in these, distinctions among different types of folds may be made. This is the case for the Cap de Creus shear zones (Eastern Pyrenees, Spain), on which this study is essentially based.

Folds and other common meso- and microstructures in shear zones (e.g. crenulations and boudins) are often asymmetric. This asymmetry is regarded as a kinematic indicator (Simpson and Schmid, 1983; White et al., 1986; Choukroune et al., 1987; Bjornerud, 1989; Hanmer and Passchier, 1991; Passchier and Trouw, 1996). However, the final geometry, symmetry and orientation of a shear-related fold are influenced by many variables other than the shear sense. In consequence, folds often have complex links with kinematics, as evidenced in shear zones where shear sense can be established from other kinematic criteria.

The aim of this work is to present in a systematic way different situations in which the geometry of folds inside a shear zone may be associated with the shearing event. These different situations are reviewed qualitatively to gain some understanding of the common problems associated with the genetic and kinematic interpretation of shear zone-related folds.

1.1. Shear zone-related folds: three main categories

Three different basic categories can be envisaged in which the final geometry of folds becomes intimately associated with the shearing event: sheared pre-existing folds, shear-related early folds and shear-related late folds (Fig. 1). Folds overprinting shear-related structures but unrelated to the shear event, although common in nature, will not be examined in this work.

The first category arises in which shear zones cut across a

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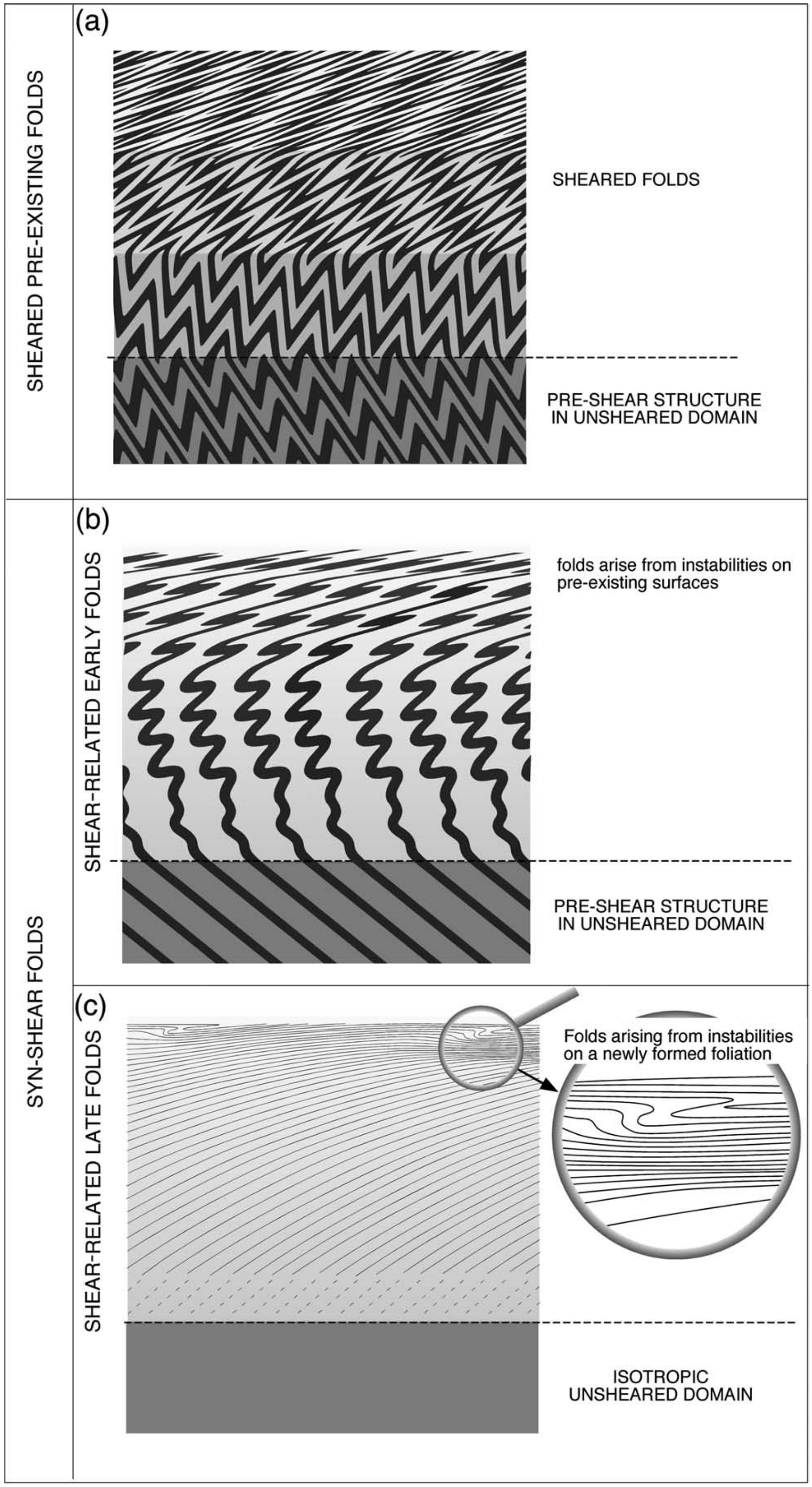

Fig. 1. Three basic categories of shear zone-related folds. (a) Pre-existing folds are passively deformed by shearing. (b) Pre-existing surfaces are modified and

country rock already containing folds. The final geometry of the folds is modified by the overprinting effect of shearing.

The second category occurs when shear zones cut across rocks containing planar fabrics (i.e. lithological layering or penetrative foliations). Such planes are deflected towards parallelism with the shear plane. Deflection of the pre-existing surface is commonly accompanied by the development of mechanical instabilities, leading to buckling structures that are subsequently modified by shear intensification (Ramsay, 1980; Skjernaa, 1980). Such folds are thus contemporaneous with the localization and development of the shear zone.

A third common category occurs when a newly formed shear zone-related foliation (e.g. a mylonitic foliation) or a stretched layer inside the shear zone becomes unstable during shearing (Carreras et al., 1977; Cobbold and Quinquis, 1980; Platt, 1983; Ghosh and Sengupta, 1984; Mies, 1991; Mandal et al., 2004). In consequence, a single fold or a train of folds nucleate inside the shear zone, and these are subsequently affected by continued shear. Although these are also syn-shear folds, their nucleation often starts after a considerable amount of deformation has taken place and, thus, they should be differentiated from the previously mentioned ones.

Combinations of the three basic categories are not only possible but common in nature. Despite the significant differences among the three categories, it is not always easy to differentiate one from another, and they are often not clearly distinguished in the literature. This difficulty appears both in distinguishing sheared pre-existing folds from shear-related early folds and also in separating this latter category from shear-related late folds. In the first case, the difficulty is greater if the deformation facies does not vary significantly with time, and a progressive shearing event initiates with the formation of cross-folds and ends with development of discrete shear zones (Sanderson, 1973; Williams, 1978; Skjernaa, 1989). This problem is documented for a variety of settings and scales, as shown by Graham (1978) when referring to folds in a shallow seated, wrench dominated domain. Iglesias and Choukroune (1980) also describe folds developed under progressive deformation associated with shear zones which cut across folded domains. In those settings where repeated folding occurs within non-discrete high strain zones or shear zones with no direct access to the undeformed wall rock and to the marginal zone (e.g. Ghosh and Sengupta, 1984, 1987), it is unrealistic to attempt to distinguish between the two categories of syn-shear folds. However, this is justified by the fact that in some settings two or three of these categories coexist and can be identified and distinguished.

In addition to these three basic categories, other complex shear-related folds can occur, such as folds and deflections in syn-tectonic veins or dykes. These other cases will be briefly treated separately from the three basic categories.

2. Sheared pre-existing folds

Although ductile shear zones typically develop in crystalline rocks with low internal competence contrast and/or a low mechanical anisotropy, some shear zones cut across rocks that already contain folded layers or foliations (Fig. 2). Some of the examples shown by Bell (1978, his fig. 5a), Minnigh (1979), Skjernaa (1989) and Ramsay (1997) can be identified as belonging to this category, although not all occur in discrete shear zones. Hypothetical examples of sheared folds are shown in figs. 22 and 24 in Ramsay (1980). A thorough analysis of the modification of chevron folds by simple shear accompanied by natural examples is presented by Lloyd and Whalley (1986, 1997), although their examples do not belong to discrete shear zones.

Folded rocks being non-isotropic, it is likely that their shearing will involve the development of mechanical instabilities. However, in a first approach, only passive deformation of pre-existing structures will be considered here. The resulting bulk geometry of heterogeneously sheared folds will be non-cylindrical folds, with the more theoretical than real exception of the case of folds with axes perpendicular to the shear direction, which would develop type 3 (Ramsay, 1967) interference patterns (see example in fig. 36.61 in Ramsay and Lisle (2000)).

2.1. Passive shearing of pre-existing folds

It is well established that when pre-existing folds are passively sheared their limbs will rotate according to the rules of rotation of planes under progressive deformation (Flinn, 1962; Talbot, 1970; Sanderson, 1973; Escher and Watterson, 1974; Ramsay, 1979; Skjernaa, 1980). The analysis of fold reorientation can be applied to any shear zone regardless of the type of flow, and the final orientation of sheared folds can be calculated if the initial orientation of the limbs and the shear zone are known and a given shear deformation is assumed.

In a hypothetical case (simple shear situations and for a given shear strain), the final structure will depend on the relative orientations and lengths of the fold limbs with regard to the shear zone kinematic frame. Due to different strain and rotation rates of differently oriented lines, fold profiles will generally become progressively asymmetric. Pre-existing folds can develop into tight folds, but also they can become unfolded if the inter-limb angle increases (Skjernaa, 1980). Common end results are isoclinal folds and sigmoidal structures with ‘S’ or ‘Z’ asymmetries

folding activated by shearing. The bulk geometry results in a drag-like structure, with folds nucleating on the pre-existing surfaces. Folds are subsequently affected by progressive shearing. (c) A newly generated shear-related foliation is subsequently folded. Note that while in (b) the folded surface is a previous fabric, in (c) the folded surface is a newly formed foliation (e.g. a mylonitic foliation).

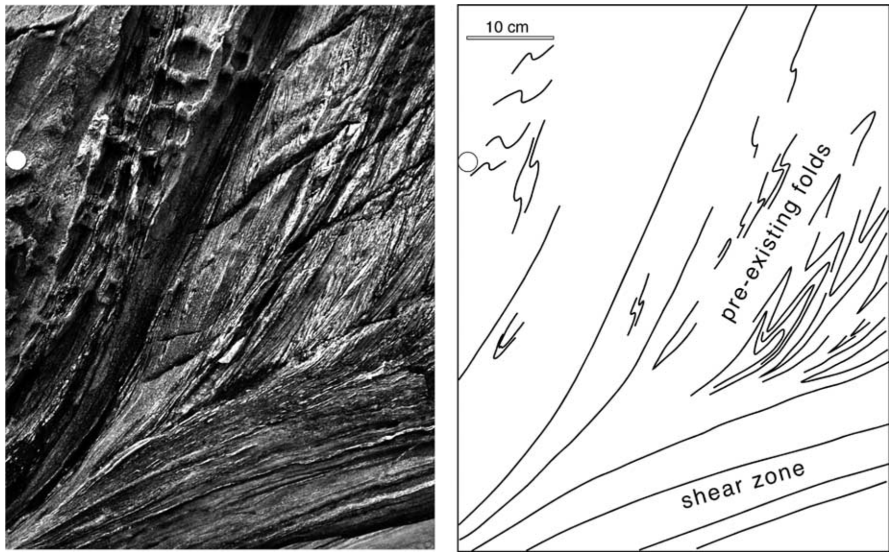

Fig. 2. Example of a shear zone cutting across pre-existing folds from the Cap de Creus. Sheared folds can be observed at the margins of the shear zone, while inside it, where shear strain values >20 are reached, pre-existing folds are completely transposed (see figs. 21 and 24 in Carreras (2001)).

(Fig. 3). Initial fold asymmetry can be reversed by progressive shearing for high shear strain (Fig. 1a).

The assumption that many shear zones cutting foliated rocks might deviate from the simple shear model also has an influence on the final geometry of folds. In a two-dimensional approach for general shear zones, the differences in geometry are the result of the relative orientation of pre-existing fold elements (hinges, limbs and axial planes) with regard to the flow eigenvectors. For identical pre-existing folds, the final asymmetry can be of opposite senses depending on the vorticity of the flow (Fig. 4). However, strain compatibility conditions for non-simple shear zones involve a change in vorticity along and across the shear zone that also causes a variation in geometry and sense of asymmetry of folds. The folds shown in Figs. 3 and 4 only represent true fold profiles if the initial fold axes are in the shear plane and perpendicular to the shear direction. In any other orientation, this two-dimensional section would only give apparent profiles.

In a three-dimensional analysis, the pre-existing limbs rotate about a line oblique to the previous fold axis, so that the initial orientation of fold axes is not preserved during shearing (except for those axes lying in the shear plane). Assuming simple shear, the rotation axis of a limb is given by the intersection of the limb and the shear surface. The fold hinge line, as a material line always remains coincident with the limb intersection line and, with the above exception, rotates towards the shear direction (Bryant and Reed, 1969; fig. 6.15 in Hobbs et al., 1976). This causes sections normal to the shear zone and parallel to the shear direction to give increasingly oblique profiles of structures as strain increases. In consequence, tight folds will appear tighter than they really are, while sigmoidal structures will appear more open than they are.

2.2. Non-passive shearing of pre-existing folds

In this situation, strain associated with rotation of folded layers or foliations may produce instabilities. Thus, in addition to the reorientation and area modifications, new structures (i.e. folds and boudinage) are expected to nucleate during the shearing event. This situation can be regarded as a particular and complex case of the category discussed in the forthcoming Section 3, as it deals with folds formed during the shearing event.

The expected non-cylindricity of sheared pre-existing folds does not exclude some segments of folds in the shear zone interior possessing quasi-cylindrical geometries. As stated above, fold axes in the shear plane should theoretically not rotate. However, this is unlikely to occur in nature because thickened hinges of pre-existing folds in crystalline metamorphic rocks may tend to behave as cylindrical rigid bodies and, in consequence, may rotate towards parallelism with the shear direction (Freeman, 1985; Passchier, 1987). Thus, regardless of the initial orientation of the previous folds, provided these are still preserved in the shear zone interior, they will come to lie in close parallelism with the shear direction. A peculiar example of this is shown in Fig. 5, where hinges of folded amphibolite layers are preserved in a pinch and swell structure in the shear zone interior. This structure develops due to the competent behaviour of amphibolite, demonstrating that shearing was not entirely passive.

For shear zones undergoing shear strains >10, pre-existing folds will be hardly recognizable and nearly completely transposed (Fig. 2), unless the pre-existing folds are delineated by markedly competent layers in which case they can be preserved in the shear zone interior, as in the example shown in Fig. 5a.

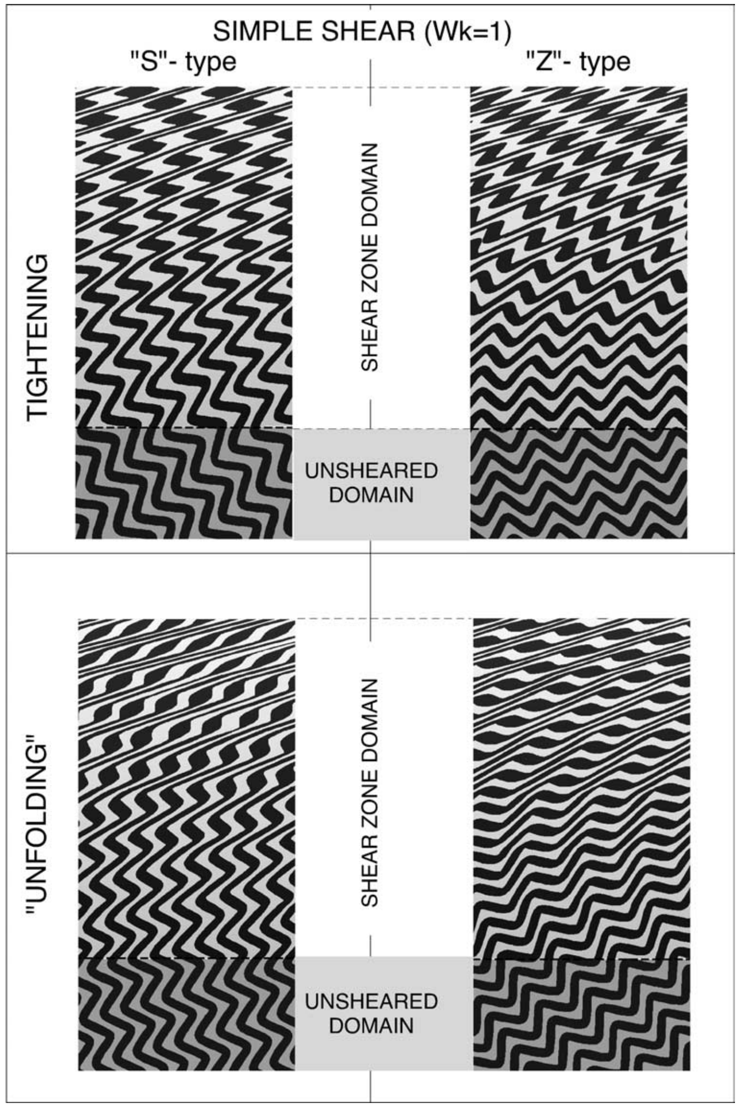

Fig. 3. Two-dimensional idealized examples of sheared pre-existing folds, showing the effect of initial orientation of folds. In all cases folds are originally symmetric and shear strain increases exponentially towards the top, which represents the shear zone interior of a heterogeneous simple shear zone. The maximum shear strain is 2.75. Note that the folds or sigmoids display different asymmetries at the interior of each shear zone. The development of sigmoid structures can be preceded by early stages of slight tightening. Also a stage of sigmoid development might be followed by a final stage of tightening.

Although it is suggested that sheath folds form as a result of shearing of pre-existing folds bearing a slightly curved hinge (fig. 16 in Ramsay, 1980) or double plunging folds (fig. 4 in Williams and Zwart, 1977; Minnigh, 1979; Skjernaa, 1989), a great majority of sheath folds found in the interior of shear zones are formed by the evolution of folds nucleated during the shearing event, and thus developed on foliation or layers lying in close parallelism with the shear zone (Carreras et al., 1977; Rhodes and Gayer, 1977; Bell, 1978; Quinquis et al., 1978; Henderson, 1981; Jiang and Williams, 1999).

3. Shear-related early folds

In this category shearing implies both rotation and strain of lithological or mechanical discontinuities (Ramsay, 1980; Skjernaa, 1980). The contrast in rheological properties between rock layers (Ramberg, 1959; Biot, 1961; Fletcher, 1974; Neurath and Smith, 1982; Hudleston and Lan, 1993, 1995; Mancktelow, 1999) or the presence of mechanical anisotropies (Cobbold et al., 1971; Cobbold, 1976; Cosgrove, 1976, 1989; Mühlhaus et al., 2002) give rise to perturbations in flow which can result in folding. The resulting structures form a continuous spectrum that largely depends on the passive or non-passive behaviour of lithological and/or mechanical discontinuities. At one end of the spectrum, the surfaces are passively deformed and the resulting structure will be a sigmoidal-shaped deflection delineated by the rotation of the pre-existing surface about an axis forming a variable angle (90–0°) with the shear direction (Fig. 6). At the other end of the spectrum, shearing

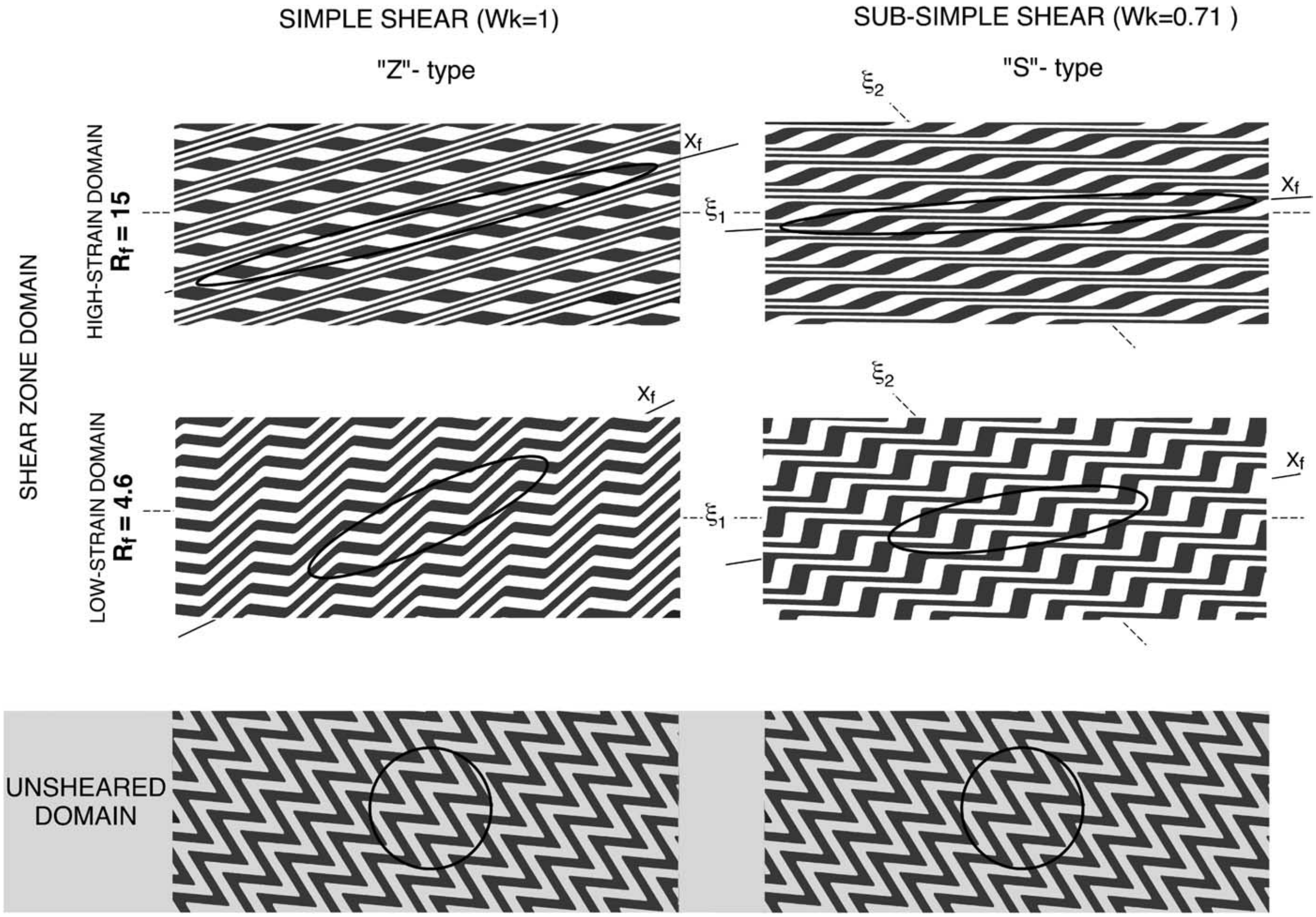

Fig. 4. Two-dimensional idealized examples of sheared pre-existing folds showing the effect of vorticity on identically orientated folds affected by simple and sub-simple shear. The geometry of folds in two different homogeneously deformed domains ($Rf=4.6$ and 15) is shown. Note that sigmoids display different asymmetries at the top, which represents the interior of the shear zone. *Wk* is the kinematic vorticity number and *Rf* is the axial ratio of the imposed finite strain. The strain ellipses are outlined in black. The position of the direction of maximum finite stretch is marked by *Xf* and the positions of the flow apophyses by $\xi 1$ and $\xi 2$.

of pre-existing surfaces leads to growth of instabilities which will lead to contractional structures (folds and/or crenulations), extensional structures (e.g. boudins, extensional crenulations or shear bands) or both (simultaneously or successively). The orientation of these structures depends on the main stretching and shortening directions in the sheared surface (Ramberg and Ghosh, 1977; Ramsay, 1980; Skjernaa, 1980; Treagus and Treagus, 1981). Thus, the developing structures will vary for differently oriented surfaces (Fig. 6). For simple shear, the rotation axis remains constant, while the structures nucleating on the sheared surface rotate, unless they formed in close parallelism to the shear direction. Natural examples of a pre-existing foliation being deflected and crenulated obliquely to the deflection axis are abundant in the Cap de Creus shear belt. For the sake of simplicity, passive and non-passive categories will be treated separately.

3.1. Passive shearing of foliation and/or layering

Assuming heterogeneous simple shear, the main way in which shearing of pre-existing surfaces differ from shearing of isotropic materials is that the resulting sigmoidal structure has a variable orientation with regard to the shear direction (Carreras, 1997). If the unsheared rock is penetratively foliated, the shear zone-related foliation will only closely approach the *XY* plane of strain for high shear strain values (Ramsay, 1967; Bayly, 1974; Carreras, 1975; Ghosh, 1982). If the unsheared rocks contain non-foliated layers, dykes or any kind of lithological boundary, the foliation will theoretically cut across these lithological discontinuities, except for specific initial orientations. This last situation occurs when dykes and wall rocks of low viscosity contrast become sheared, as in the examples shown in Escher et al. (1975) or in the smaller-sized examples in Simpson et al. (1982), Ramsay and Huber (1983) and in Fig. 7. In the case of sheared layers or dykes, because of the complex three-dimensional relations between geometry, kinematics and outcrop surface, the geometry of the resulting two-dimensional structures can be in apparent contradiction to the sense of shear (Wheeler, 1987; Passchier and Williams, 1996; Carreras, 1997). Passive

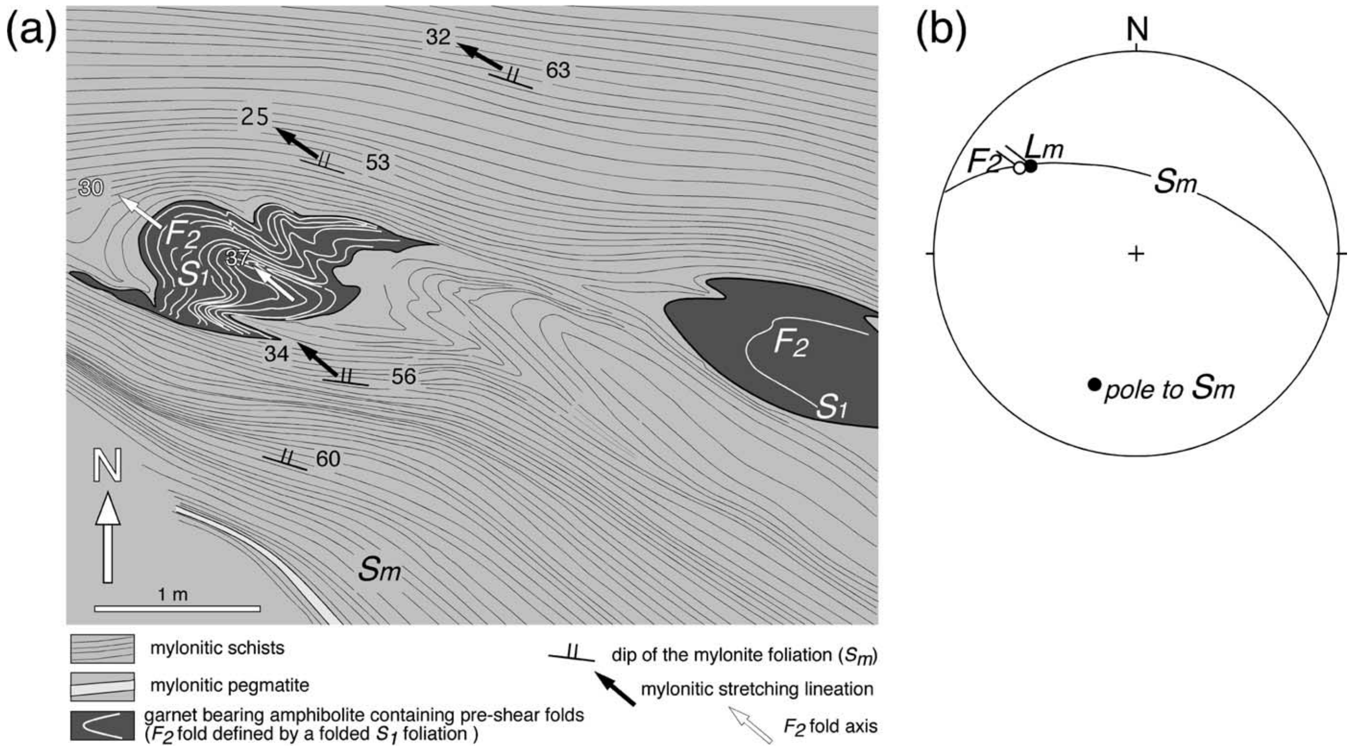

Fig. 5. Folds wrapped inside a shear zone. (a) Rods consist of fold hinges of amphibolites enclosed in a pelitic–psammitic mylonite. Folds (*F2*) affecting a *S*1 layer-parallel foliation, pre-date the shearing event. Mylonitic foliation (*Sm*) is associated with post-*D*2 shearing. (b) Stereoplot showing the parallelism between mean *F*2 fold hinges and the mean mylonitic stretching lineation, *Lm*.

shearing by simple shear of planar surfaces will develop cylindrical deflections (Ramsay, 1967). In general shear zones, the shear plane might not be a plane of no finite longitudinal strain. In consequence, the orientation of the rotation axis (the *R* axis in Fig. 6) will change during the progress of deformation, leading to the development of non-cylindrical deflections. For deformations close to simple shear a low degree of non-cylindricity can be assumed.

Finally, passive folds formed by differential simple shear along the axial plane with no shortening normal to the shear flow direction have been considered in the literature (Carey, 1962; O'Driscoll, 1964; Ramsay, 1980). However, the change in shear sense required by this model to explain fold development seems improbable for the majority of syn-shear buckle folds.

3.2. Non-passive shearing of foliation and/or layering

Mechanical instabilities leading to contractional and/or extensional structures develop in layers or foliations behaving non-passively (fig. 13 in Ramsay, 1980). It is a common situation in shear zones cutting across uniformly foliated rocks that folds appear in the margins of the shear zone (Fig. 8a). However, in the literature, this category of folds is rarely treated separately from the other types of shear zone-related folds. Natural examples of folds belonging to this category are described in Bell (1978), Carreras and Cirés (1986) and Carreras and Casas (1987).

In general, folds increase in tightness and frequency towards the centre of the shear zone (Figs. 8b and c and 9), and they are also more frequent at the boundaries of lozenges (sigmoidal bodies of lower strain) wrapped inside shear zones (fig. 7 in Ghosh and Sengupta, 1987; Hazra, 1997). Especially remarkable examples are the folds that often form at the tails of schistose lozenges (Fig. 9b and c). In the interior of the shear zone these folds are hardly recognisable, except where preserved in lower strain lozenges.

Experimental work on nucleation and development of folds under simple shear conditions has been carried out by Ramberg (1959), Ghosh (1966), Manz and Wickham (1978), Williams and Price (1990) and Mawer and Williams (1991). Experiments with more complex deformational histories, involving layer parallel shortening followed by shearing are described in Reches and Johnson (1976). Remarkable experimental folding of layered rocks submitted to sub-simple shearing was succinctly reported by Hoeppener et al. (1983), showing the variable relations between fold asymmetry and degree of non-coaxiality. In a two-dimensional approach, folds would form if the line representing the previous layering or anisotropy was subjected to shortening at the onset of shearing. This can be extended to plane strain three-dimensional situations if layers intersect the shear plane perpendicular to the shear direction.

In order to amplify fold instabilities, a certain amount of

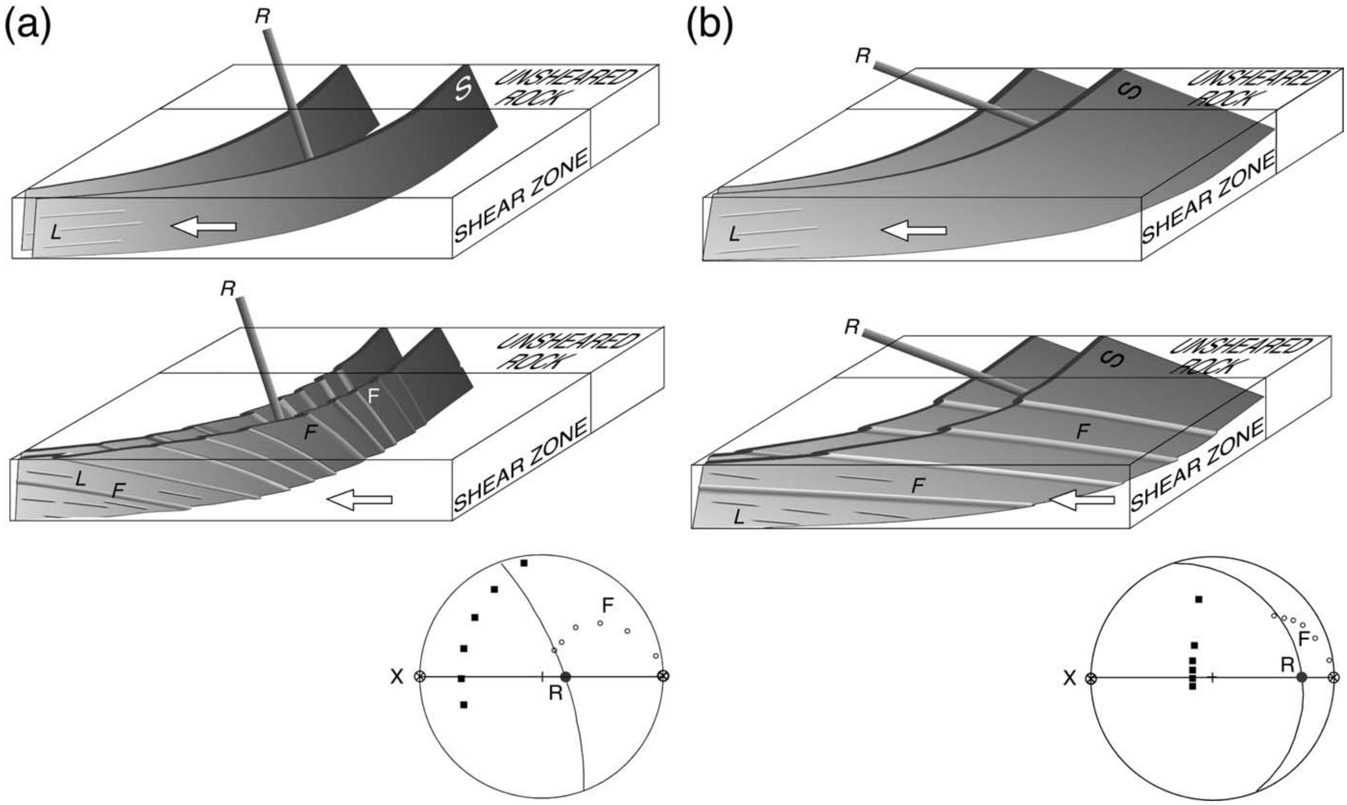

Fig. 6. Sketch showing the effect in three-dimensions of passive and non-passive shearing of a pre-existing surface under heterogeneous simple shear. (a) The rotation axis *R* lies at a high angle to the shear direction. In the upper sketch the surface rotates passively around *R*, which makes an angle of 70° with the shear direction *X*. *L* is the stretching lineation on the sheared surface. In the lower sketch the orientation of fold axes *F*, developed parallel or close to parallel to the maximum stretch on the shear plane, is shown. The stereoplot shows the attitude of the poles of the sheared surface (black squares) and the fold axes (circles). (b) Same as in (a) for a plane with a rotation axis at a low angle (20°) to the shear direction.

shortening, depending on the effective viscosity contrast and the sectional strain history, is required before planes enter the instantaneous extension field. Thus, for simple shear, planes need to make a large obtuse angle with the shear direction in order that folds develop. However, for highly anisotropic materials, even for planes oriented close to the extension field, some instabilities arise, inducing the development of structures such as kinks (fig. 4 in Williams and Price, 1990).

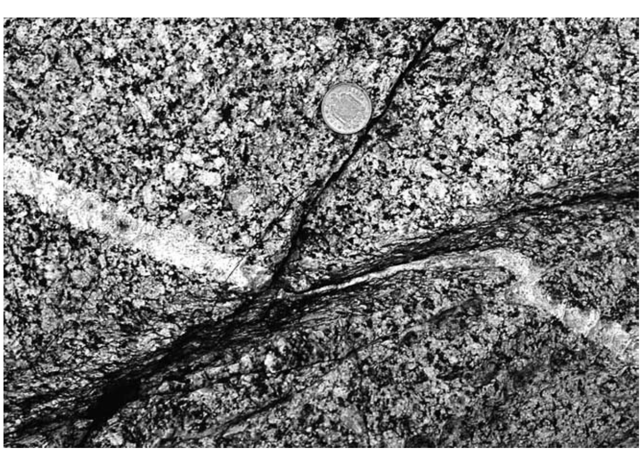

Fig. 7. Example of a drag-like structure developed in a sheared leucocratic dyke in a granodiorite (Roses shear zones, Cap de Creus). Width of view is 25 cm.

3.2.1. Shape and asymmetry of folds

There are several variables controlling the initial geometry and, in consequence, the final geometry of shear-related early folds. The initial wavelength, amplitude and shape of the fold instability depend on the angular relationship between layering/foliation and the shear plane, the rheology (i.e. viscosity contrasts and mechanical anisotropy) (Fig. 10a) and the vorticity number of the flow (*Wk*, Fig. 10b).

The initial orientation of layering/foliation controls the early sense of fold asymmetry, both S and Z asymmetries being possible (Hazra, 1997), as are also symmetric folds (Manz and Wickham, 1978). With progression of shear, structures tend towards a dominant asymmetry, either if the fold tightens or unfolds. This dominant asymmetry can be achieved either by transformation of initial symmetric structures or by preserving or reversing the sense of asymmetry of initially asymmetric structures. For simple shear, the development of a tight fold, or a sigmoid, depends respectively on whether or not one of the limbs of an active fold crosses the extensional flow plane (Fig. 10).

The viscosity contrast between layer and host material

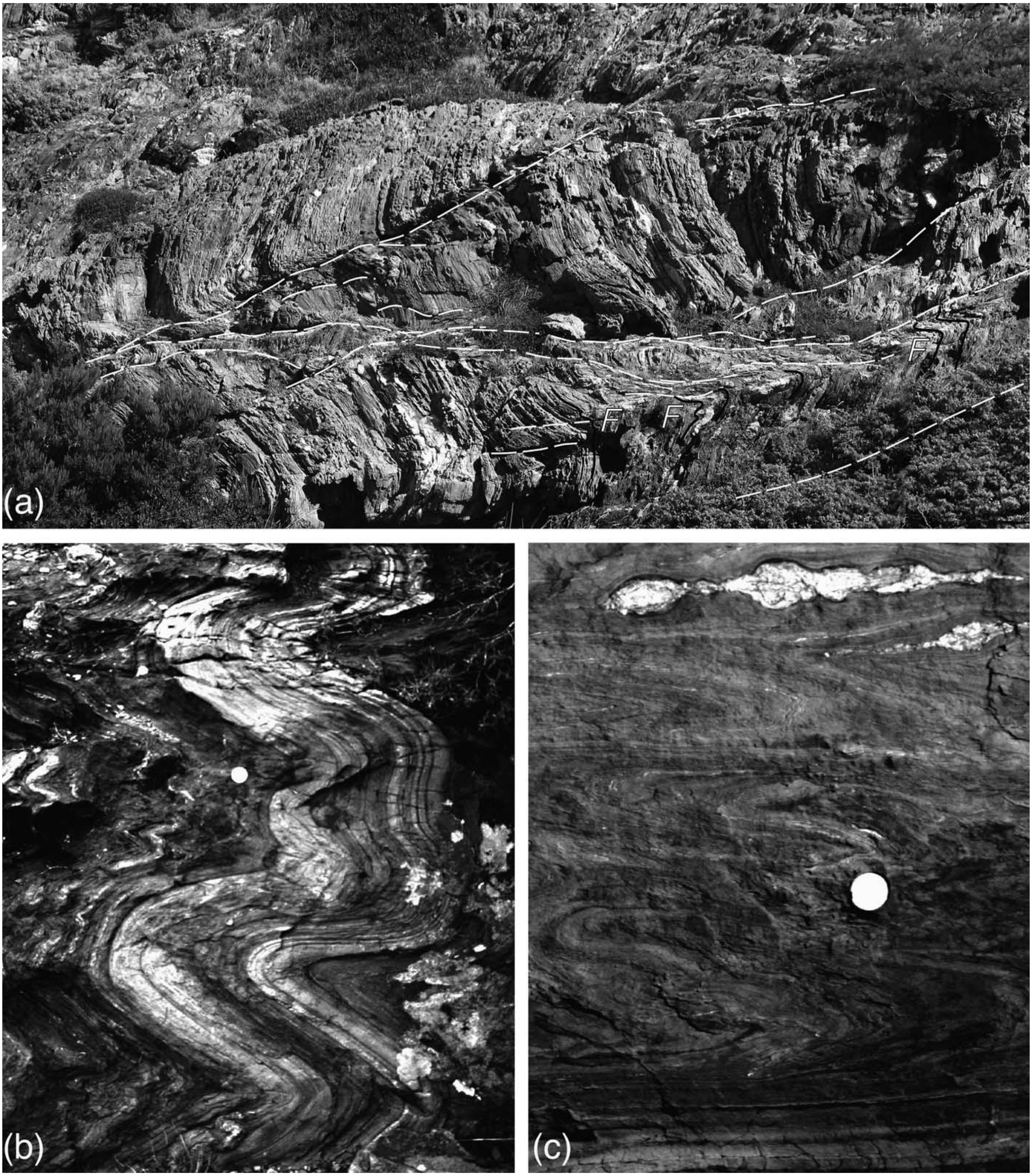

Fig. 8. Field photographs of folds developed on a pre-existing foliation involved in a shearing event in the Cap de Creus shear belt. (a) Folds (*F*) developed at the margins of shear zones (dashed lines) cutting across foliated rocks. These folds developed as a result of deflection, strain and folding of the sheared pre-existing foliation. Width of view is 12 cm. (b) Open folds developed at the marginal domains of a shear zone. Width of view is 75 cm. (c) Tight folds in the interior of a shear zone which could have resulted from increasing strain affecting folds analogous to those shown in (b). Width of view is 30 cm.

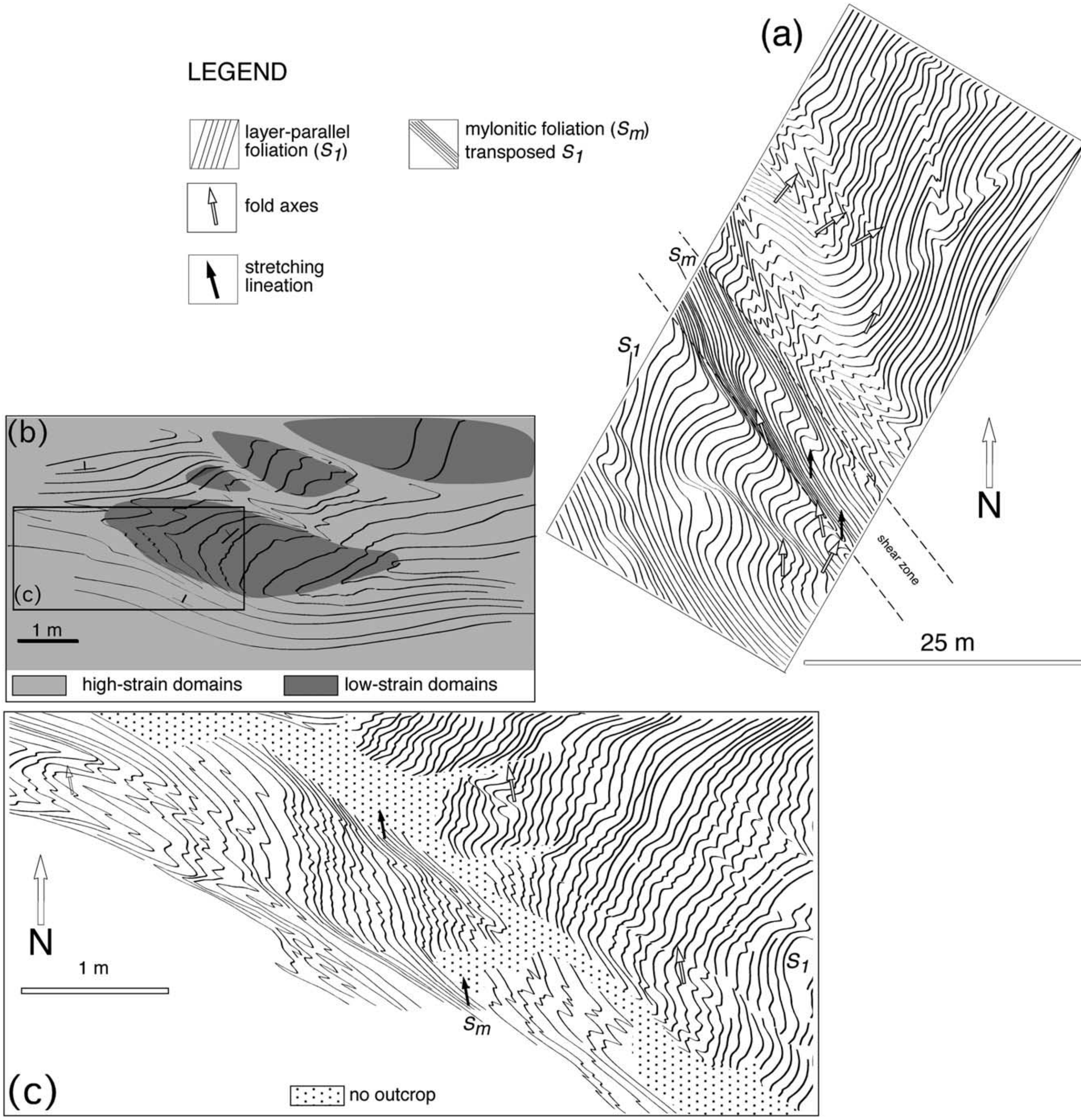

Fig. 9. Maps showing examples of folds developed on a sheared pre-existing foliation, in the Cap de Creus shear belt. (a) Folds show rotation of hinges from NE (at the margin of a shear zone) to N (at the shear zone interior). (b) Structure of a schistose lozenge. (c) Enlargement of part of (b) showing the folds at the tail of the lozenge. In this case there is little rotation of fold axes, due to the initial orientation of the pre-existing foliation relative to the shear framework, in a similar way to what is sketched in Fig. 6b.

controls the growth rate of fold instabilities and therefore the efficiency of the buckling process. Moreover, the dynamic rate of limb rotation is directly related to the growth rate. For high competence contrast, the rate of limb rotation is much larger than the bulk angular shear component and, thus, fold development is nearly independent of the shear components. Asymmetries due to difference in velocity of limbs related to differences in flow angular velocities are negligible, and M-shaped folds will form. Folds can gain asymmetry due to strain partitioning during flattening at mature stages of fold development (Fig. 10a), in a similar way to that proposed by Treagus (1997).

For low competence contrast, the difference between dynamic and kinematic rates is smaller, and differences in the rotation and stretching rate of fold limbs are plausible. This will generate a progressive increase in fold asymmetry, increased by shear induced flattening.

Mechanical anisotropy also has an important effect on the early geometry of folds (Cobbold et al., 1971; Hoeppener et al., 1983). In highly anisotropic materials, buckling onsets quickly and kink-like structures develop with large short-limb rotations. In materials with low mechanical anisotropy, layer parallel shortening prior to folding will be significant and, furthermore, limb rotation will be attenuated. Additionally, in anisotropic materials, initial orientation of fold axial planes is generally oblique to the finite stretching direction, and conjugate sets of folds can form at particular orientations.

The complexity of fold asymmetry increases when different vorticity numbers ($0 \leq Wk \leq 1$) are considered. This is illustrated in a two-dimensional experimental analysis by Hoeppener et al. (1983), who showed that fold asymmetry depends on both the initial orientation of the layer and the degree of monoclinic character of strain (defined by the angle between planes without internal rotation). For sub-simple shear, due to differences in angular velocity and stretching rate of each limb, which depend on the particular orientation of each limb with respect to the flow eigenvectors, folds can evolve towards opposite asymmetries (Hoeppener et al., 1983; Carreras and Ortuño, 1990; Fig. 10b). Thus, for a given original foliation orientation and shear sense, a general rule cannot be used to predict the final shape (tight or sigmoidal) or sense of asymmetry. However, in two dimensions and simple shear, a dextral shearing will lead to S-asymmetries, which is contrary to what one would expect for most shear-related late folds, as discussed in Section 4.

3.2.2. Fold rotation

In a three-dimensional analysis, shear-related early folds will develop on a pre-existing surface as it is deflected while sheared. In such a situation, folds nucleate with axes parallel to the maximum finite strain axis X of the sectional ellipse (Flinn, 1962, 1978; Ghosh, 1966, his fig. 1b; Ramberg, 1976; Ramsay, 1980; Skjernaa, 1980; Treagus and Treagus, 1981). As stated by Treagus and Treagus (1981), James and Watkinson (1994) and Tikoff and Peterson (1998), it is likely that at initial stages the fold axis follows the X direction in the deforming plane as a non-material line. However, in mature stages of fold development, when the inner arc of the hinge is pinched, fold hinge migration towards the X axis would no longer be an efficient process to accommodate layer parallel shortening. Then, the fold axis will behave nearly as a material line subjected to passive rotation. In fact, at these late stages, when the fold axis is close to the bulk X axis, the difference in angular velocity between the sectional finite strain axis and a material line initially parallel to this axis is very small. Nevertheless, the fold axis always lies close to parallel to the maximum extension in that plane (i.e. the associated stretching lineation in the deflecting plane), and rotates towards parallelism with the shear direction (i.e. the stretching lineation in the highest shear domains) (Bell, 1978; Carreras, 1997; Fig. 10). Examples of oblique crenulations with orientations consistent with this are commonly observed at Cap de Creus at the margins of shear zones cutting across schists.

According to Flinn (1962, p. 424) the initial attitude of the axial plane in a newly developed fold cannot be predicted, as this will depend on the initial fold shape and on the rheological properties of the rocks during the shearing event. For weakly anisotropic materials, the most likely initial orientation of axial planes is normal to the envelope of the layering/foliation, although this subsequently rotates towards the bulk XY plane of the finite deformation ellipsoid.

Assuming that shear zones in foliated materials deviate from the simple shear model, the three-dimensional analysis of fold nucleation and evolution becomes a complex matter. The path of rotation of maximum stretch in the plane (i.e. the fold hinge line) towards the shear direction depends on the vorticity of the flow (Fig. 11; Carreras and Ortuño, 1990). In natural shear zones, the use of hinge rotation paths could be considered as a complementary method to the one suggested by Lin et al. (1998) to infer the deviation from simple shear. Progressive deformation will lead to the simultaneous rotation of fold axis and axial plane, respectively, towards the shear direction and the shear plane. In analogy to the deformation of pre-existing folds, this process is accompanied either by tightening or unfolding, generally associated in both cases with the development of asymmetry in fold or sigmoid profiles.

3.2.3. Extensional structures

In the preceding sections, the development of folds has been considered in cases in which the sectional ellipsoid involves shortening. However, at some stage of shear zone development, the pre-existing foliation or layering generally undergoes extension. This can occur simultaneously with or subsequently to folding. For the case of simultaneous folding and extension, fold growth is also controlled by the sectional strain dilatancy of the layer. Values near to plane strain and/or discontinuous flow along the layer will be required for active fold amplification (Fletcher, 1991; Grujic and Mancktelow, 1995; Druguet et al., 2000). Folds can be associated with extensional structures, such as in previously foliated rocks, where extensional and normal crenulations often coexist. Two sets of shear bands can simultaneously form when the instantaneous stretching direction is at a high angle to the foliation (fig. 22 in Carreras, 2001). A common setting in nature is the development of a shear zone sub-parallel to a pre-existing foliation, in which case extensional structures will prevail. However, this does not exclude the development of folds due to back rotation between shear bands (Ghosh and Sengupta, 1987; Harris, 2003). This case will be further discussed in the next section.

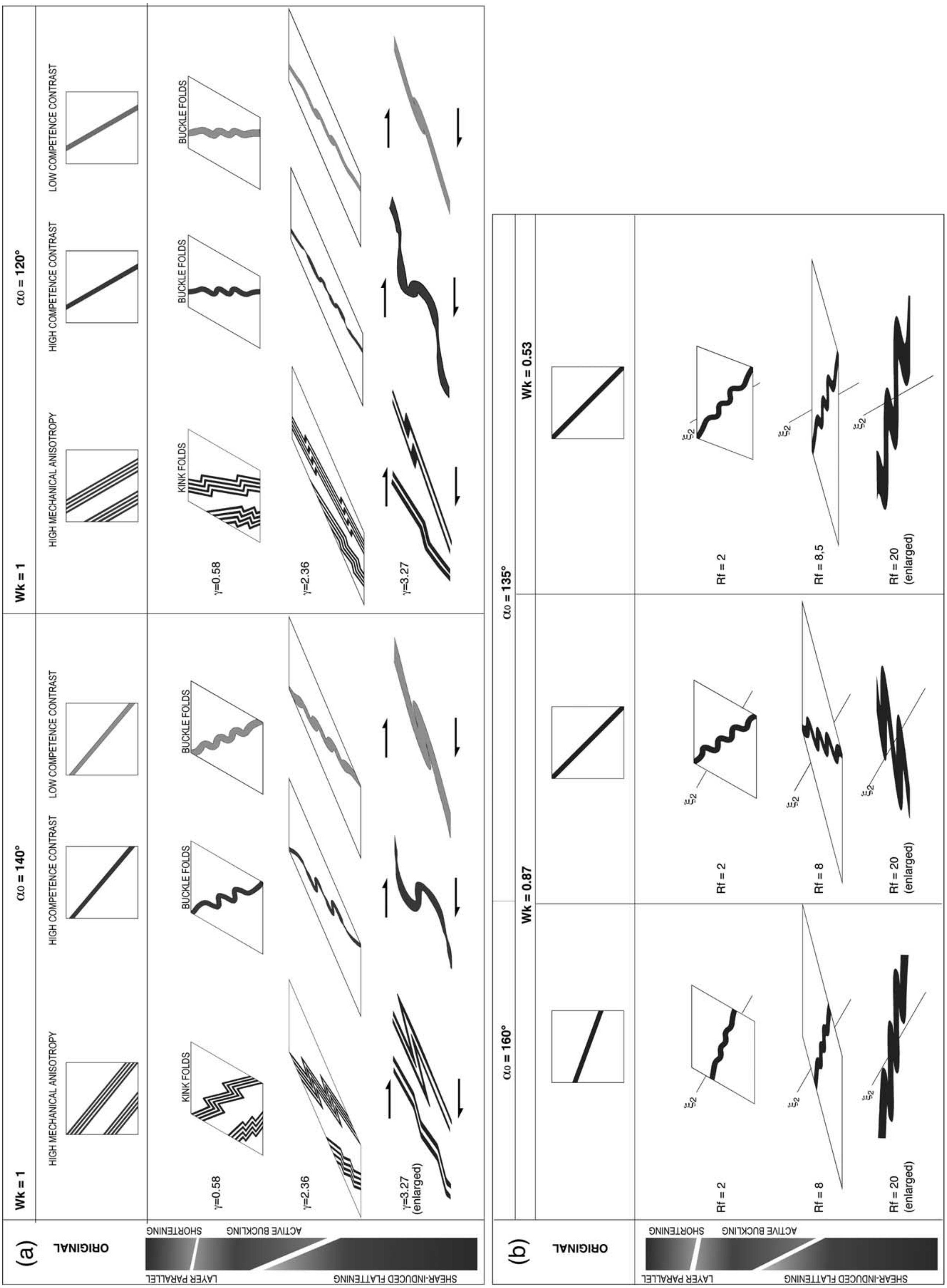

Fig. 10. Caption opposite

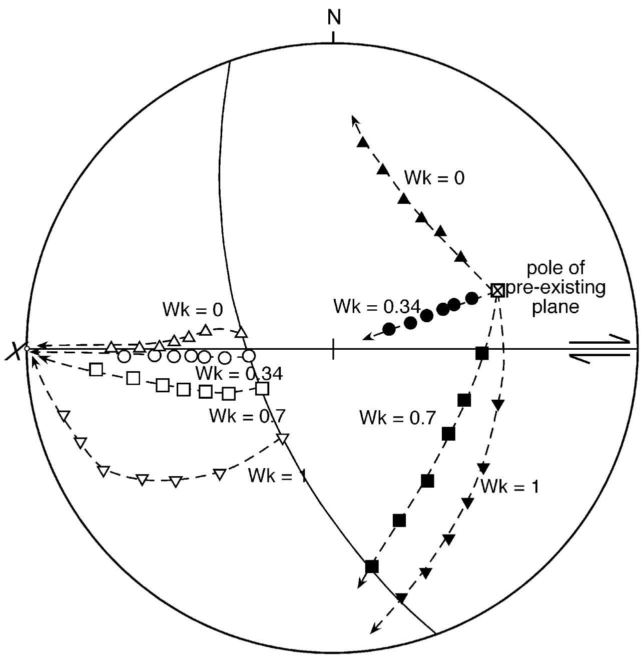

Fig. 11. Stereoplot showing paths of fold hinges developed on a surface being sheared under different vorticities. Open and solid symbols refer to fold axes and to poles to planes, respectively. The fold axes are always drawn parallel to the finite maximum stretch on the sheared plane. Locating the folds parallel to the instantaneous stretching at each stage or alternatively rotating these as material lines after they have amplified, would produce slightly different paths. However, these differences are much less than those produced by changing vorticity.

4. Shear-related late folds

Among shear zone-related folds, those that develop late are the most described in the literature (Howard, 1968; Bryant and Reed, 1969; Carreras et al., 1977; Rhodes and Gayer, 1977; Quinquis et al., 1978; Minnigh, 1979; Platt, 1983; Hanmer and Passchier, 1991; Jiang and Williams, 1999; Mandal et al., 2004). In contrast to the other types (Fig. 12a), late folds nucleate on surfaces closely parallel to the shear zone boundary, which consist of newly formed shear-related foliations or banding (Fig. 12b). This category can easily be identified in the field when bodies of non-foliated rocks (e.g. an igneous dyke) in the wall rock, become penetratively foliated inside the shear zone. Then, the shear-related late folds may affect this newly formed foliation. Another common feature is the folding of the stretching lineation associated with the shearing event (Ghosh and Sengupta, 1984, 1987). Origin and evolution are the key points to understanding shear-related late folds. Although evolution is a consequence of origin, it will be treated first as it can be more easily understood by field examination.

4.1. Geometry and orientation of folds

Geometric analysis of folds with regard to the shear zone geometry and kinematics provides a clue to understanding their evolution. This is done in this section mostly using examples from Cap de Creus. These folds are predominantly asymmetric. Regarding the relationship between fold asymmetry and shear sense, two broad categories of shear-related late folds can be established (Fig. 13): synthetic (folds verging consistent with the shear sense) and antithetic (folds verging opposite to the shear sense, i.e. back-rotating folds).

Synthetic folds are the most common in Cap de Creus and most other areas (Bryant and Reed, 1969; Ghosh and Sengupta, 1987; Alsop, 1992). A striking field observation is the common variability in orientation of fold axes (between 0 and 90°) with respect to the overall stretching lineation, with a predominance of stretching-parallel fold axes. The variability in fold orientation and the link between mylonitic folds and the shear direction was first reported by Howard (1968). The prevalence of a shear-related asymmetry can be used as a shear sense indicator. This can be done using populations of coeval folds with variable axis orientations, by applying the separation angle method of Hansen (1971) (Fig. 14a and b). The application of this method at Cap de Creus enables us to confirm the relation between shear direction, stretching lineation and fold orientation (Carreras and Santanach, 1973). In spite of the variability in axis orientation, the coherence of the data indicates that these folds are all associated with a single shearing event (Fig. 14c). When using a population of asymmetric folds, it is crucial to note whether more than one order of folds is present, as folds with apparent contradictory asymmetry often appear on the short limbs of lower order folds (Fig. 12b).

The variation in the geometry of folds is directly related to fold axis orientation with respect to the shear direction (Carreras et al., 1977; Fig. 15a). A whole spectrum of orientations and styles ranging between class 1B and 2 geometries is observed in competent quartz bands at Cap de Creus (Fig. 15b). Folds at a high angle to the shear direction display a rather open shape with axial planes forming a

Fig. 10. Two-dimensional profiles of folds formed by non-passive shearing of pre-existing surfaces. (a) Simple shear models. Structures depend on the rheology of the pre-existing layers. Three cases are considered: a mechanical anisotropy, a single layer with high competence contrast and a single layer with low competence contrast. For the sake of simplicity, for structures arising from mechanical anisotropy and low competence contrast, fold evolution has been drawn on the basis of passive shearing. In the case of high competence contrast, flattening partitioning is accommodated by homogeneous and discontinuous flow (e.g. boudinage of long limbs). Simple shear components are essentially accommodated by shearing along the limbs and by rigid body rotation (spinning) of the hinges. (b) Models of single layer buckling folds with variable vorticity and initial orientations. In these cases, the effect of competence contrast has not been considered during shear-induced flattening. Note, in all cases, the gradual development of asymmetry of the structures during shearing. $\alpha 0$ is the initial angle of the surface to the shear plane, γ is the shear stain and other symbols are as in Fig. 4.

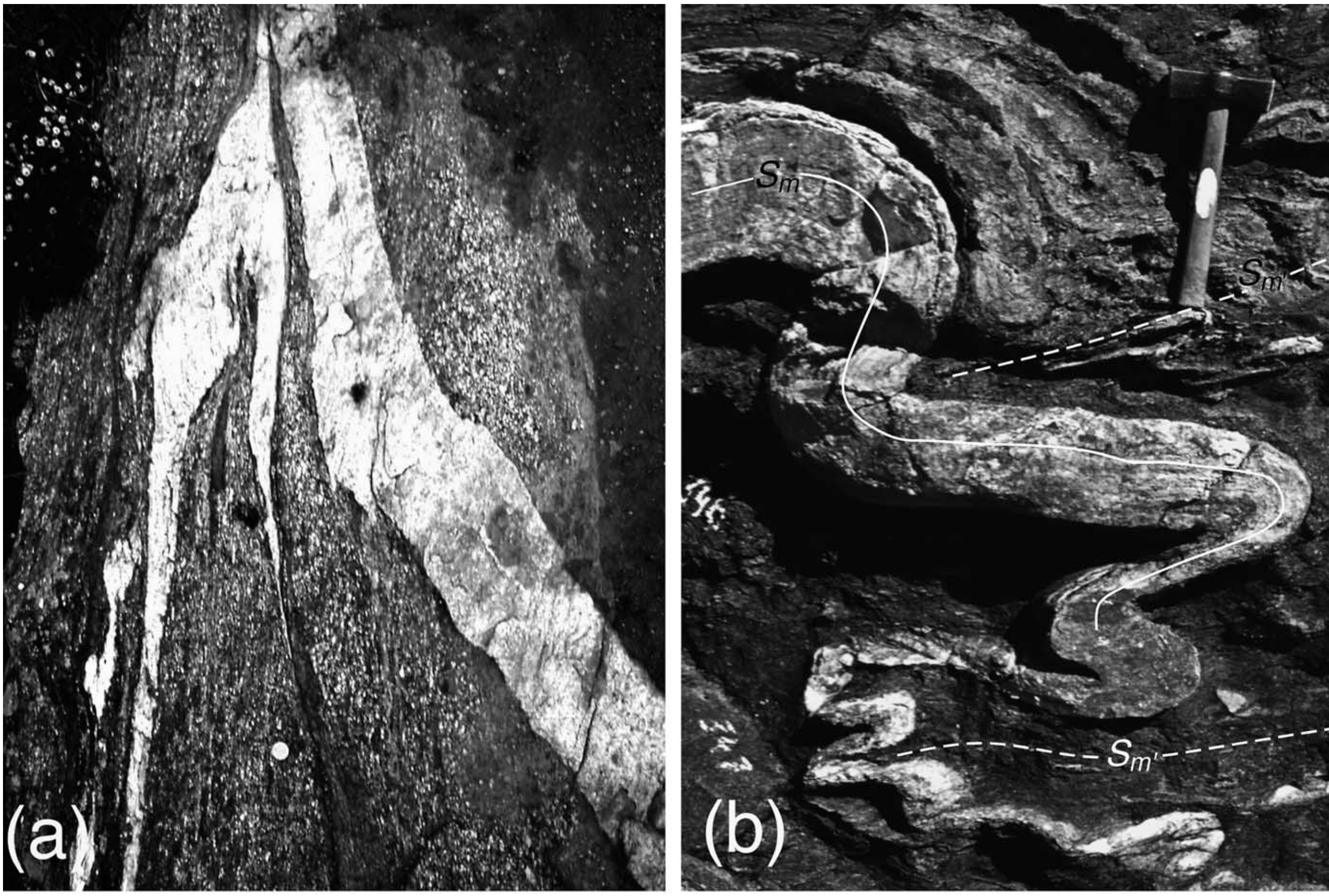

Fig. 12. Comparison of early and late shear-related folds from the Cap de Creus. (a) Early fold affecting an aplite–pegmatite dyke. (b) Late folds affecting a stretched and foliated pegmatite. Note the presence of minor synthetic folds in the long limb and an antithetic fold in the overturned short limb. Also note the difference between (a), where the mylonitic foliation is axial planar to the fold, and (b), where the mylonitic foliation (*Sm*) is folded, with a newly mylonitic axial planar foliation (*Sm'*) overprinting the earlier one. Width of view is 90 cm in both (a) and (b).

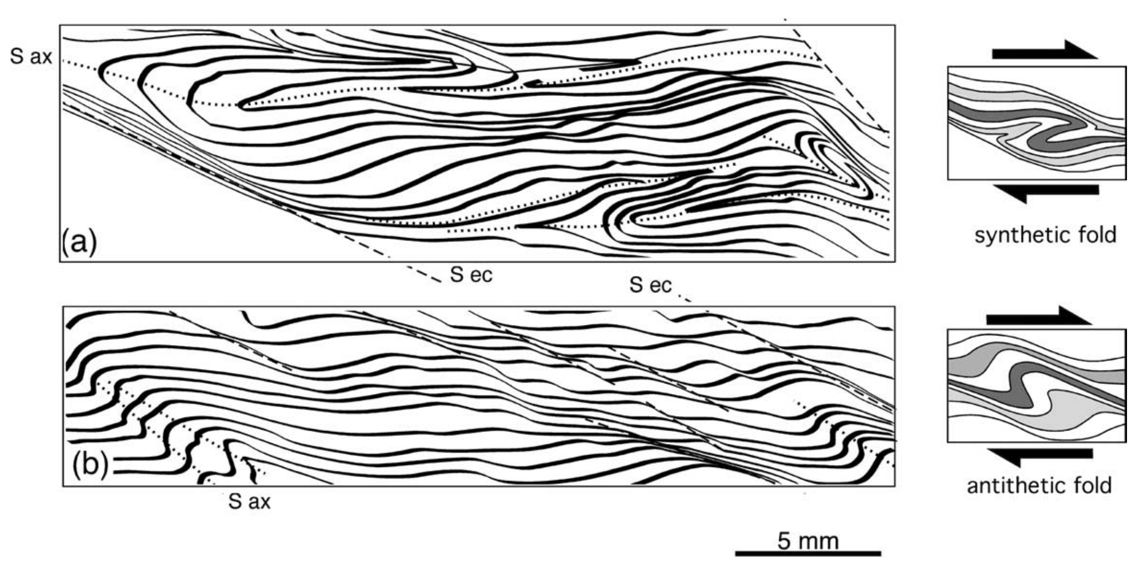

Fig. 13. (a) Synthetic (drag) shear-related late fold. (b) Antithetic (back-rotating) shear-related late fold. Both types of folds affect a mylonitic foliation and all involved structures formed during a single shearing event. Sec: extensional crenulation, Sax: axial planes. Cap de Creus shear zones.

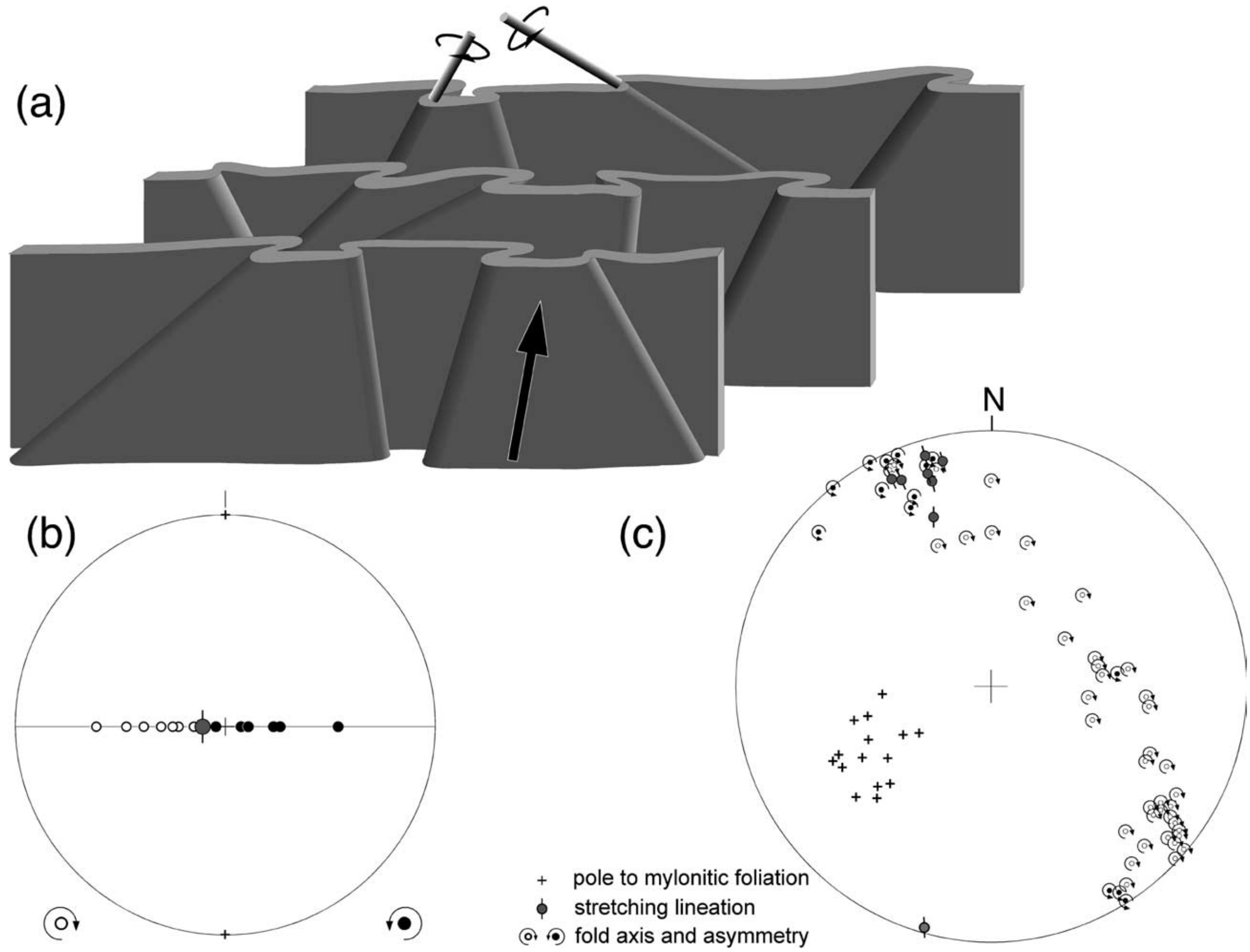

Fig. 14. (a) Shear-related late folds affecting a mylonitic foliation with variable axis orientation showing different asymmetry when observed in plane view section. The arrow indicates the sense and direction of shear compatible with the drawn asymmetry distribution. (b) Hansen's (1971) separation angle method based on fold asymmetry and fold axis orientation of the intrafolial folds, applied to the plot of fold axes drawn in the hypothetical situation shown in (a). (c) The separation angle method applied to a population of folds in the Cala Prona shear zone (Cap de Creus) shows a coincidence of stretching lineation and calculated direction of shear based on Hansen's method (after Carreras and Santanach, 1973).

moderate angle to the shear zone and they plot predominantly as type 1C, close to 1B, of Ramsay's classification. Folds trending parallel to the shear direction are isoclinal with axial planes parallel to the shear plane and they are of type 2 shape. Furthermore, folds with curved hinge lines (e.g. sheath folds) and fold superposition are common (Fig. 16).

The above descriptions indicate that these late folds form with their axial planes and axes oblique to the shear-related foliation and to the stretching lineation, respectively. Initially, they are close to being parallel in shape, and they gradually rotate towards parallelism with the foliation, becoming progressively tightened and approaching a similar fold geometry. Rotation is often associated with the development of folds with curved hinge lines as a result of amplification of initial slight curvatures or by inhomogeneity of flow (Howard, 1968; Carreras et al., 1977; Bell, 1978; Quinquis et al., 1978; Williams, 1978; Minnigh, 1979; Berthé and Brun, 1980; Mies, 1991; Alsop, 1992; Alsop and Holdsworth, 2002, 2004). However, folds do not always develop into sheath folds, as some folds nucleating oblique to the stretching lineation can rotate in the same sense along their hinges, passing through a stage of sigmoidal-shaped hinges. Jiang and Williams (1999) discuss the situations in which, depending on the type of strain involved in a particular shear zone, folds with initially slightly curved hinges evolve towards sheath shapes or not.

Folds accommodate shortening by active buckling until the inner arc of the hinge is pinched. Subsequently, the accommodation of shortening by shear-induced flattening leads to fold tightening. This can occur at any stage of fold rotation as evidenced by the variable geometry of folds with hinges at similar angles to the shear direction.

Although some folds display convergent dip isogons throughout, most show convergent isogons on the long part and nearly parallel dip isogons on the short part of the fold (Fig. 15a). In this case, the folds show a markedly thinned short limb (Fig. 17; fig. 19 in Hooper and Hatcher, 1988). This can be explained in the setting of a continuum of fold rotation and shear induced flattening. Folds being tightened

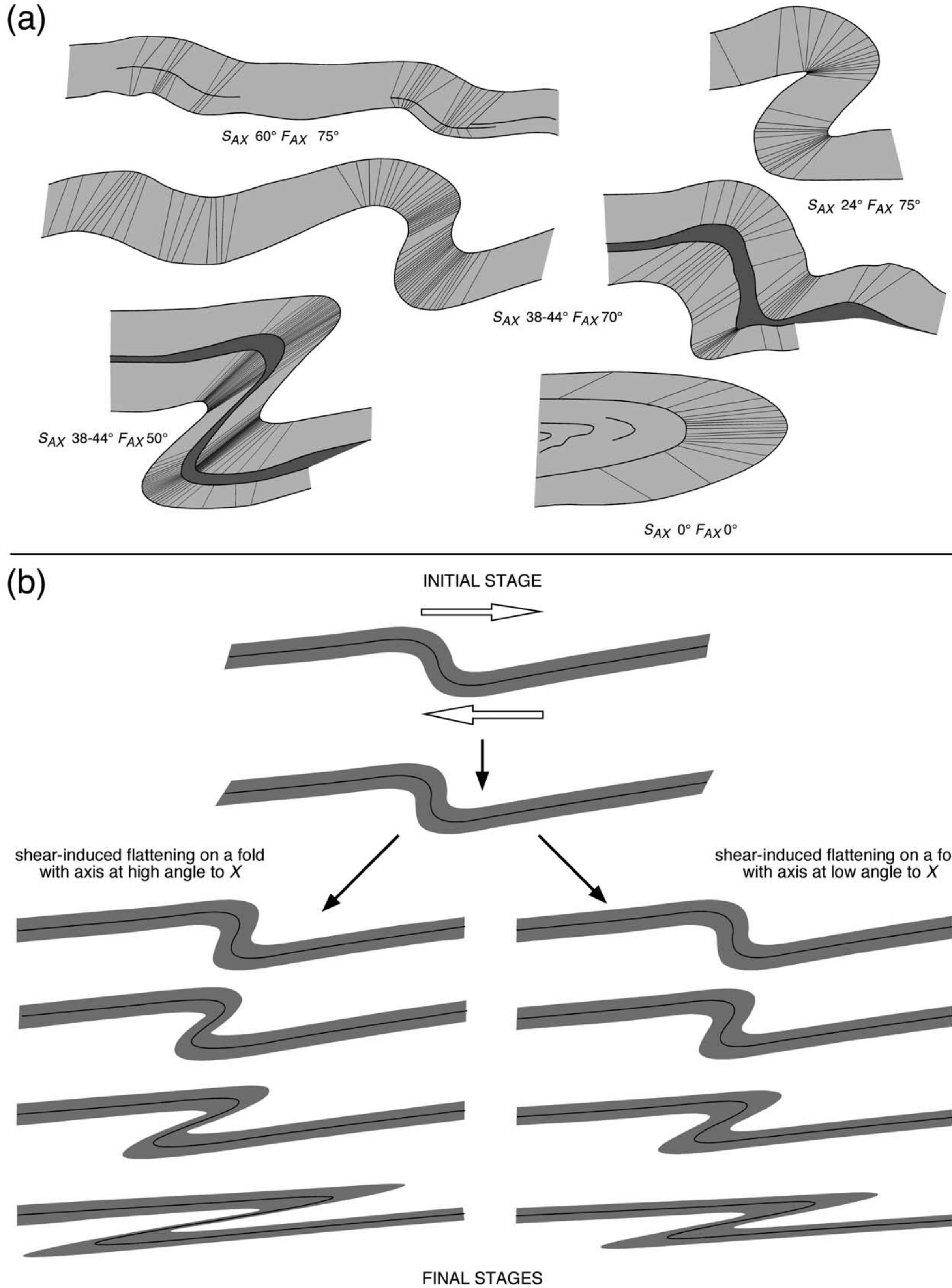

Fig. 15. (a) Fold profiles and associated dip isogons of folded mylonitic quartz bands at Cap de Creus. S_{AX}: angle between shear plane and axial plane. F_{AX}: angle between fold axis and shear direction. (b) Schematic evolution of the geometry of shear-related late folds based on observations as in (a). Folds that become flattened when their axes lie at a high angle to the shear direction are characterised by markedly thinned short limbs. For folds that become flattened when their axis lies at a small angle to the shear direction, there is a smaller contrast in limb thickness.

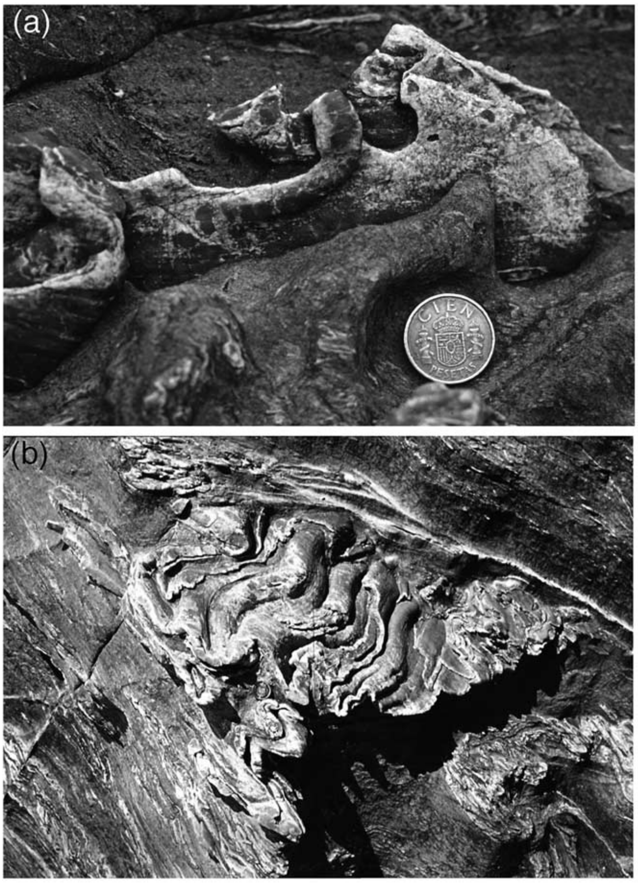

Fig. 16. Examples of shear-related late folds from the Cap de Creus. (a) Sheath fold. Width of view is 17 cm. (b) Superposition of three generations of folds affecting mylonitic quartz-bands. Two generations of folds have axes parallel to the shear direction, while the third generation consists of open folds at a high angle to the shear direction. The stretching lineation is at a high angle to the plane of the picture. Width of view is 90 cm.

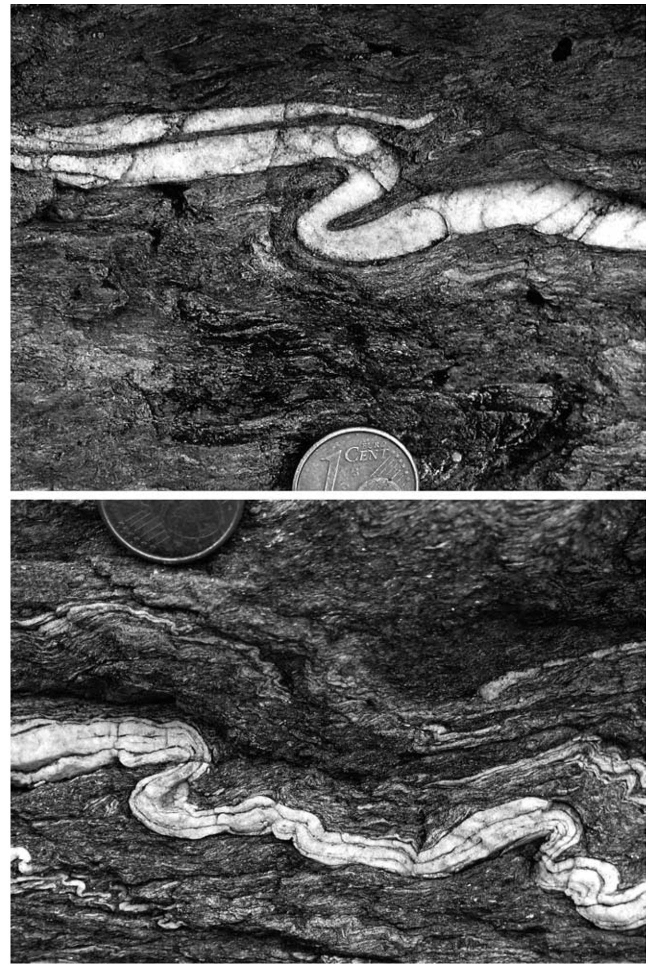

Fig. 17. Field photographs of shear-related late folds in mylonitic quartz bands (Cap de Creus). They show the typical geometry of synthetic folds characterised by a thinned short limb. The folds occur in dextral shear zones with the shear direction parallel to the plane of the picture. Fold axes are perpendicular to shear direction.

while their axes lie at a high angle to the shear direction exhibit a markedly thinned short limb. In contrast, folds being tightened while their axes lie in close parallelism to the shear direction show similar limb thicknesses (Fig. 15b).

In the process of combined buckling and shear-induced flattening, folds evolve towards becoming isoclinal and parallel to the plane of shear, setting the stage for nucleation of new buckling instabilities. Several generations of overprinting folds can often be observed (Ghosh and Sengupta, 1984, 1987; Fig. 16b).

4.2. Initiation of folds and evolution of symmetry

In ideal simple shear zones with a steady flow plane, a stretched surface (e.g. a shear-related foliation or layering) never enters the shortening field. Narrowing sub-simple shear zones (Simpson and De Paor, 1993) with constant vorticity in the range of $1 > Wk > 0$ also do not result in foliation formed during shear rotating into the shortening field. Consequently, deviations from these models are required for these surfaces to enter the shortening sector of the instantaneous flow field (Platt, 1983) and to allow for the nucleation of shear-related late folds (Fig. 18a). This can only be achieved by the onset of local or general perturbations of flow.

It has been suggested that a local flow perturbation can result from the presence of rigid objects (Cobbold and Quinquis, 1980; Bons and Jessell, 1998), from mechanically heterogeneous foliated rocks (Ghosh and Sengupta, 1984, 1987; Mandal et al., 2004) or from competence contrast between layers or variation in layer thickness (Lister and Williams, 1983; Platt, 1983). However, it is unlikely that all shear-related late folds arise solely from these above causes.

As evidenced from field observations at Cap de Creus, syn-shear late folds commonly affect the entire or large parts of some shear zones, while they are absent in others (Carreras, 2001). Furthermore, these folds do not form ubiquitously but preferentially along domains where a variation in attitude of the stretching lineation indicates variation in flow. Preferential settings are (i) domains where there is a coalescence of two flow systems (e.g. due to the

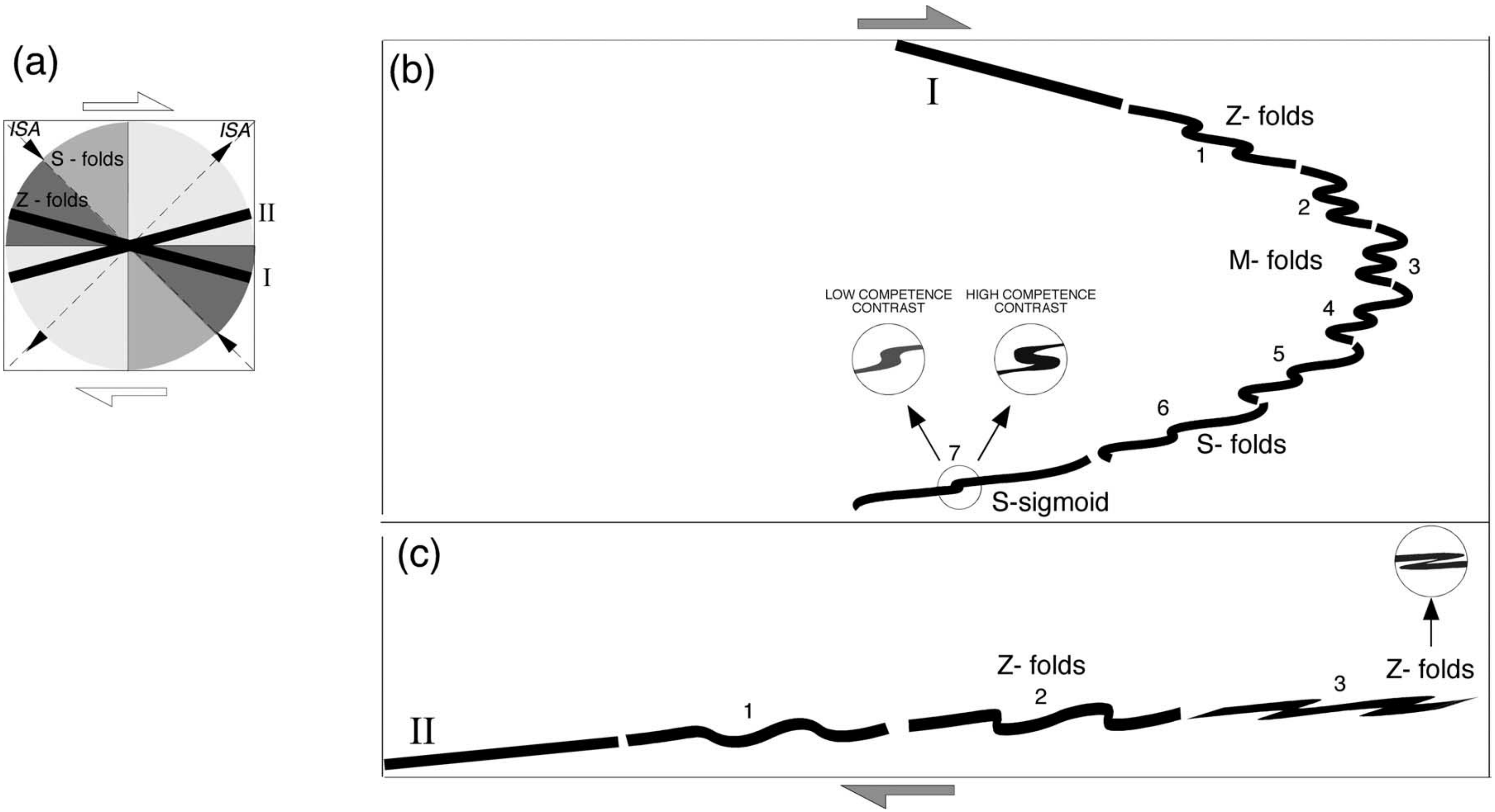

Fig. 18. Development of folds affecting a shear-related foliation. (a) Two-dimensional sketch showing the initial asymmetry of folds for differently oriented planes. The orientations of planes I and II, both at a low angle to the shear plane, are also shown. ISA are the instantaneous stretching axes. (b) Initiation (1) and evolution (2–7) of folds for the plane I, which enters completely the shortening field. The plane is orthogonal to the drawing surface and all lines in the plane initially have stretches $S \leq 1$. This situation implies a rotation of the fold enveloping surface of about 160° by stage 7. The final geometry is antithetic with respect to the sense of shear (see example in Fig. 12b). (c) Initiation (1) and evolution (2–3) of folds for plane II. Although in a 2-D section the line lies in the extensional field, this represents a section of a plane that in 3-D lies partially in the shortening field (the plane is oblique to the drawing surface and, regarding the instantaneous strain, it contains lines of $S \leq 1$ and $S \geqq 1$). This implies a small rotation of the enveloping surface, and the final geometry of folds is synthetic with respect to the sense of shear (see examples in Figs. 15a and 17).

anastomosing nature of shear zones) and (ii) domains where a shear zone reveals a change with time in the shear direction (Carreras and Druguet, 1994), while the shear plane itself remains rather stable. The resulting folds in a specific domain form with similar orientation, but individual competent layers develop folds of a particular wavelength. Frequently, in such folded domains shear bands are also abundant, suggesting that these two minor structures are associated with domains of complex kinematics.

It is proposed that, in addition to folds formed by rheologically associated local perturbations, most shear-related late folds develop as a result of changes in the kinematics of the shear zone, especially changes in the orientation of the flow plane and/or the shear direction. Change in the orientation of the flow plane or the shear direction can account for a stretched layer entering the shortening field (Fig. 18a). This statement is often understood, in a two-dimensional simplification, as that the angle of the layer must lie at less than 45° to the instantaneous shortening axis (e.g. Dennis and Secor, 1987; Mukhopadhyay et al., 1997). In this case, a layer would fold while its enveloping surface would rotate by up to 180°. Folds first tighten and later potentially unfold and reverse their asymmetry when rotating into the extension field. After a large shear strain the final structures will display a sigmoidal shape with reverse (antithetic) asymmetry (Fig. 18b).

In contrast to the above, most syn-shear late folds are synthetic and the enveloping surface stays in close parallelism to the shear zone, indicating that the layering and/or foliation was not as a whole in the shortening field.

A three-dimensional approach shows that planes can be in the bulk instantaneous extension field (all lines in the plane have a stretch $S \geqq 1$), in the bulk instantaneous shortening field (all lines in the plane have $S \leq 1$), but most probably are in such an orientation that some lines undergo extension while others simultaneously undergo shortening (Ramsay, 1980). In layers being simultaneously stretched and shortened, fold growth rates are smaller than in layers in the bulk instantaneous shortening field. However, after the onset of an instability and development of a low amplitude fold, one limb can reach the orientation of a high angular velocity plane, and thus amplify (Lister and Williams, 1983). The folds developed in these layers show a steady synthetic asymmetry (Fig. 18c).

In addition to the cases in which folds initiate as a result of rotation of the kinematic frame, other kinematic settings can be considered. Among them are, (i) change in Wk in such a way that the shortening flow eigenvectors become close to the layer (e.g. from a simple shear to a broadening sub-simple shear zone), and (ii) shear flow partitioning related to strain localisation, a suitable explanation for folding due to back-rotation (Harris, 2003). The diverse causes (kinematic and rheological) that can result in flow perturbations and subsequent development of folds can act solely or in combination.

5. Other shear zone-related folds

Complex folds can also arise from superposition of any two or three of the categories described above. For instance, new folds can nucleate during deflection of folded layers if limbs are not behaving passively, leading to fold interference patterns. Also a stretched shear-related early fold can subsequently develop into a shear-related late fold.

Shear zone-related folds can also form in syn-tectonic veins (e.g. quartz, calcite) and igneous dykes or lensoid-shaped bodies that often fill tension or shear fractures associated with the shear zone, with orientations frequently lying in the instantaneous shortening field. Consequently, these discontinuities in the media will undergo shortening and, if they act as competent materials, they will buckle while rotating towards the shear plane (Hudleston, 1989). These discontinuities can develop at any stage of shear zone development, either cutting across a pre-existing foliation or a shear zone-related foliation. In addition to folding of the vein or dyke, accommodation structures can form in the adjacent host rocks (Gayer et al., 1978; Hudleston, 1989; Druguet et al., 1997) such as flanking folds (Grasemann and Stüwe, 2001; Passchier, 2001). In these settings involving shearing in foliated rocks and transecting bodies it is important to determine whether folds are delineated by pre-, by syn-shear surfaces or by both.

6. Concluding remarks

The analysis of folds associated with shear zones is a complex task, particularly because the origin and significance of folds are often unclear from field observation. Most folds observed in the interior of a shear zone look very similar to each other at a first glance, and geologists are often tempted to simplify and to make inferences directly from single observations. However, folds are complex structures that can have variable origins and, as argued above, the factors that influence their initiation and development are numerous. Moreover, as for most geological structures, the study of these folds requires a three-dimensional approach (Flinn, 1978; Skjernaa, 1980; Fletcher, 1991). Prior to any analysis, it is necessary to determine the relative timing of the involved structural elements.

6.1. Categorization of shear zone-related folds

Structures in the Cap de Creus shear zones have been used as a basis for categorization of shear zone-related folds into three situations that might be extended to any other setting involving shear zone-related folds:

1. Sheared pre-existing folds are folds of a previous deformation event that are involved in shear deformation. The final geometry of such folds is modified by

the effect of shearing, and largely depends on the degree of mechanical behaviour of the folded layers or foliations. The resulting folds will generally be non-cylindrical, although most sheath folds do not belong in this category.

2. Shear-related early folds are folds in planar fabrics (i.e. layering or foliation) of a previous deformational event that become deflected towards parallelism with a shear zone. The folding structures will vary for differently oriented pre-existing surfaces and also depend on the degree of non-passivity of the layers of foliation.
3. Shear-related late folds affect a newly formed shear zone-related foliation (e.g. a mylonitic foliation) or a stretched layer that becomes unstable during progressive shearing. Provided there is a flow perturbation, a large rotation of a continuous stretched surface is not required to nucleate folds. Instead, folds can nucleate and amplify in surfaces containing lines submitted to instantaneous shortening. There is a general tendency for these folds to nucleate at a high angle to the shear direction. During subsequent rotation towards the shear direction, they frequently become sheath folds.

There are also complex scenarios in which the final folding structures derive from superposition of any two or three of the above categories.

6.2. When and how can these three categories be distinguished?

Folds of these three categories can be distinguished when the shear zone forms a discrete band, and access to adjacent low strain domains is possible. There is no general rule, however, and discrimination among the situations is based on a variety of criteria. Sheared pre-existing folds (1) and shear zone-related early folds (2) can be especially difficult to distinguish, because in both cases folds are present in low strain domains. In order to discriminate between them, four main criteria may be used: (i) determining if there is a difference in distribution and frequency of folds between the shear zone and adjacent wall rock, (ii) establishing if there is strain compatibility between the shear zone and adjacent wall rock in terms of the folding, regardless of plausible variations in orientation of axial planes and/or fold axes, (iii) checking the relative temporal closeness of folding and shearing events or, on the other hand, if there is a clear division between the two events on the basis of additional relative timing criteria (e.g. a dyke crosscutting folds yet being affected by a shear zone), and (iv) checking the similarities or differences in deformation and metamorphic facies.

The basic criterion for discriminating between shear-related early folds (2) and shear-related late folds (3) is that in shear-related late folds the origin of the folded surface is exclusively within the zone of high strain. The folded surface is commonly a penetrative foliation (e.g. mylonitic foliation) or a stretched sheet (e.g. a flattened quartz vein that looks undeformed in low strain domains). By contrast, in case 2 the folded surface is present in the low strain domain.

6.3. Fold asymmetry and reliability as shear sense indicators

A characteristic shared by folds of all three categories is that, regardless of the original fold orientation, the fold axes always rotate towards parallelism with the shear direction. Thus, sections parallel to the shear direction generally show apparent fold profiles. In addition, rules governing the final asymmetry of the folds differ for each category. Characterisation of the category to which a certain type of shear-related folds belongs is the first requisite for kinematic interpretation:

1. Sheared pre-existing folds. The final asymmetry of folds is a result of a complex deformational history that depends on the original orientation of previous folds with regard to the kinematic frame. It is important to notice that for the same kinematic frame, both S and Z asymmetries are possible (Fig. 3). A thorough study of fold interference patterns of fold populations is required to make kinematic inferences. When these folds evolve into sheath folds, their asymmetry can furnish valuable information.
2. Shear-related early folds. There is no fixed relationship between geometric (i.e. fold and rotation axes) and kinematic axes, which can make an angle of between 0 and 90° with one another. For each case, the angle between the rotation axis and the shear direction remains constant, while the angle between the fold axis and the shear direction varies with increasing shear. The initial and final geometry and asymmetry of folds depend on many variables, such as the angular relationship between layering/foliation and the shear plane, the rheology and the vorticity of the flow. This fact makes kinematic interpretation of these folds complicated and any kinematic inference requires complementary criteria. Moreover, the assumption that an inferred local sense of shear reflects the sense of the regionally imposed shear (Hanmer and Passchier, 1991, p. 66) is not always applicable in complex shear zones with strong partitioning of strain (Druguet et al., 1997).
3. Shear-related late folds. These are potentially reliable shear sense markers as, a priori, the situation is less complicated than situations 1 and 2 due to the fact that the folds nucleate on similarly oriented surfaces, closely parallel to the shear plane. Thus, fold asymmetry largely depends on bulk kinematics. However, syn-shear late folds and shear bands are abundant in shear zones with complex kinematic histories and hence folds can only record the kinematics of late shearing stages. The key

point is to identify the synthetic or antithetic character of folds with respect to the sense of shear.

Synthetic folds develop with an associated small rotation of the fold enveloping surface (Fig. 18), have variable orientations with the shear direction and frequently develop into sheath folds (Fig. 16). They usually display thinned short limbs (Fig. 17) and, when associated with shear bands, folds and shear bands have opposite vergence (Fig. 13). Sheath folds, folds at high angle to the stretching lineation or populations of folds with variable axis orientations can be used for kinematic analysis.

Antithetic folds can be of two types: parasitic antithetic folds in the short limb of a larger synthetic fold, and back-rotating folds. Parasitic antithetic folds develop after large rotation of the fold enveloping surface, have opposite asymmetry compared to synthetic folds (Fig. 18b) and usually develop into thickened short limbs. Back-rotating folds are associated with shear bands and display small variability in degree of tightening and in fold axis orientation.

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