Journal of Structural Geology 29 (2007) 1022–1033

JOURNAL OF STRUCTURAL GEOLOGY

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Relationship between non-cylindrical fold geometry and the shear direction in monoclinic and triclinic shear zones

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Received 2 June 2006; received in revised form 11 January 2007; accepted 30 January 2007
Available online 9 February 2007

Abstract

We investigate the relationship between non-cylindrical fold geometry and the shear direction of the hosting high-strain zone by numerical modeling, and show that apical axes of non-cylindrical folds may develop into directions highly oblique to the shear direction if the zone has a pure shear component. The common practice of using well-developed sheath folds as indicators for the shear direction is not reliable and the use of immature non-cylindrical or sheath folds appears more reliable. Hinge lines of mature sheath folds approach parallelism with the fabric attractor (to which all material lines rotate), which can have variable angles with respect to the shear direction. In thinning zones, the fabric attractor is the direction of the maximum principal strain rate of the pure shear component and is parallel to the shear zone boundary. In thickening zones, it lies somewhere in the quadrant between the direction of the maximum principal strain rate of the pure shear component (perpendicular to the shear zone boundary) and the simple shear direction, and is generally oblique to the shear zone boundary. The exact location depends on the flow geometry of the shear zone.

Keywords: Sheath fold; Shear direction; Numerical modeling; High-strain zone; Transpression; Fabric

1. Introduction

Non-cylindrical folds developed in a shear zone are generally accepted as indicators for shear direction (e.g. Hansen, 1971; Lacassin and Mattauer, 1985; Azcárraga et al., 2002; shear-related late folds of Carreras et al., 2005) based on the simple shear model. The relationship between the direction of non-cylindrical folds and the shear direction is expected to be more complex in triclinic zones, but has not been investigated systematically. Jiang and Williams (1999) investigated the development or not into sheath folds from initial drag folds. This paper investigates the geometrical relationship of non-cylindrical folds with the shear direction in general shear zones, using numerical modeling.

It has previously been demonstrated that stretching lineations may have varying geometrical relationships with the shear direction. For monoclinic shear zones, there are two possibilities: the lineation may lie within the vorticity-normal section (VNS; Jiang and Williams, 1998; Lin et al., 1998; cf. Lister and Williams, 1983; cf. Fig. 1b) and rotate toward parallelism with the shear direction (Lin and Williams, 1992a), or it may be parallel to the vorticity vector (Tikoff and Fossen, 1999, cf. Jiang and Williams, 1998, and Lin et al., 1998). For triclinic shear zones, the stretching lineation rotation paths are oblique to the VNS and the vorticity axis (Jiang and Williams, 1998; Lin et al., 1998).

Similar to lineations, fold hinge lines rotate towards the shear direction during monoclinic progressive simple shear (Bryant and Reed, 1969; Sanderson, 1973; Bell, 1978) and

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doi:10.1016/j.jsg.2007.01.009

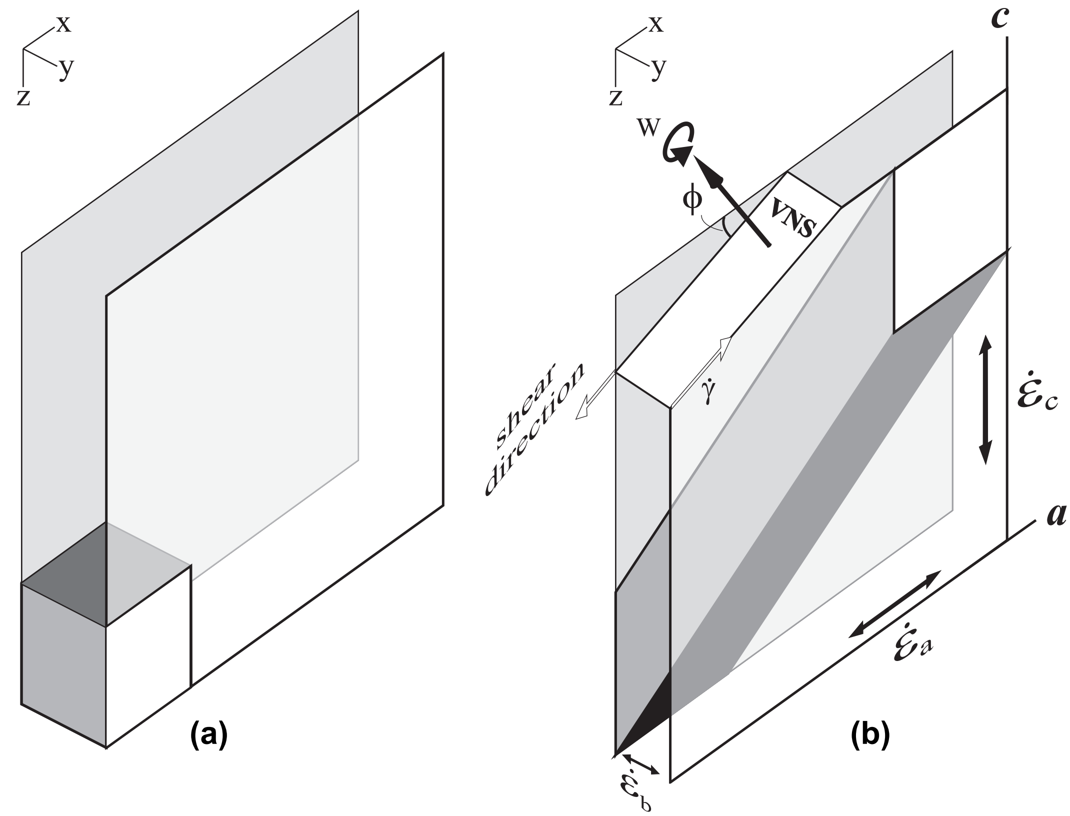

Fig. 1. A cube in a shear zone in the undeformed state (a) and after triclinic deformation (b). General progressive deformation is a combination of pure shear and simple shear components, and is characterized by five parameters: the principal rates-of-stretch ($\dot{\varepsilon}_a$, $\dot{\varepsilon}_b$ and $\dot{\varepsilon}_c$), the shear strain rate ($\dot{\gamma}$) and the shear direction (ϕ, the angle between the shear direction and the a-direction) (Jiang and Williams, 1998). The letter W indicates vorticity and VNS indicates the vorticity-normal section. The flow is described relative to the reference frame *xyz*. Modified after Jiang and Williams (1999).

non-cylindrical (including sheath or tubular) folds may result (Escher and Watterson, 1974; Carreras et al., 1977; Rhodes and Gayer, 1977; Williams and Zwart, 1977; Quinquis et al., 1978; Cobbold and Quinquis, 1980; Henderson, 1981; Skjernaa, 1989; Alsop and Holdsworth, 2004). A sheath fold is a highly non-cylindrical fold, with a hinge angle (Fig. 2a) less than 90° (Skjernaa, 1989); the hinge angle is measured between the parts of the hinge line that have rotated most. If the hinge angle is less than 20°, the sheath fold may be called a tubular fold (Skjernaa, 1989). In this paper, we use the term 'immature non-cylindrical fold' for folds with hinge angles greater than 90°. The effect and importance of the pure shear component in the formation of sheath folds was recognized by Henderson (1981) and Fletcher and Bartley (1994), but the hinge lines were still thought to rotate towards the shear direction.

To date, non-cylindrical folds have been used to determine the shear direction in various regions, such as the Swiss Alps (e.g. Lacassin and Mattauer, 1985), the Cabo Ortegal complex in NW Spain (e.g. Azcárraga et al., 2002) and the Newfoundland Appalachians in Canada (e.g. Brem et al., 2007). The shear direction is thought to be parallel to the 'cone axis' (Fowler and Kalioubi, 2002) or 'apical axis' (Azcárraga et al., 2002) which is the direction towards which the non-cylindrical fold convexes (Fowler and Kalioubi, 2002) (Fig. 2a). Where the apical axis is not directly measurable, Hansen (1971) developed a method (the Hansen method) to determine the shear direction from non-cylindrical folds. When sections of non-cylindrical folds are exposed (Figs. 2a, 3) hinge lines of folds of opposite asymmetry can be plotted in a stereogram (lower hemisphere projection; Fig. 2b). These hinge lines plot approximately along a great circle and a separation line or angle exists between hinge lines of folds of opposite asymmetry (Fig. 2b). If a separation angle exists, the separation line (Fig. 2b) is often taken as the line bisecting the separation angle. It has roughly the same direction as the apical axis. The shear direction is then taken to be parallel to the separation line.

The practice of regarding the apical axis, as the shear direction and the Hansen method are generally valid for cases of monoclinic progressive deformation where the fabric attractor (Passchier, 1997) lies on the VNS and where the maximum principal strain rate of the pure shear component (the c-direction, defined below) is parallel to the shear direction. The practice is unjustified for any other progressive deformation. The complexity of non-cylindrical fold development in triclinic shear has previously been recognized; Howard (1968) and Jiang and Williams (1999) demonstrated that apical axes of sheath folds are oblique to stretching lineations and hinge lines of newly developed drag folds. We use numerical modeling (Jiang and Williams, 1998; Jiang, 2007) to study the development of initial folds into immature non-cylindrical

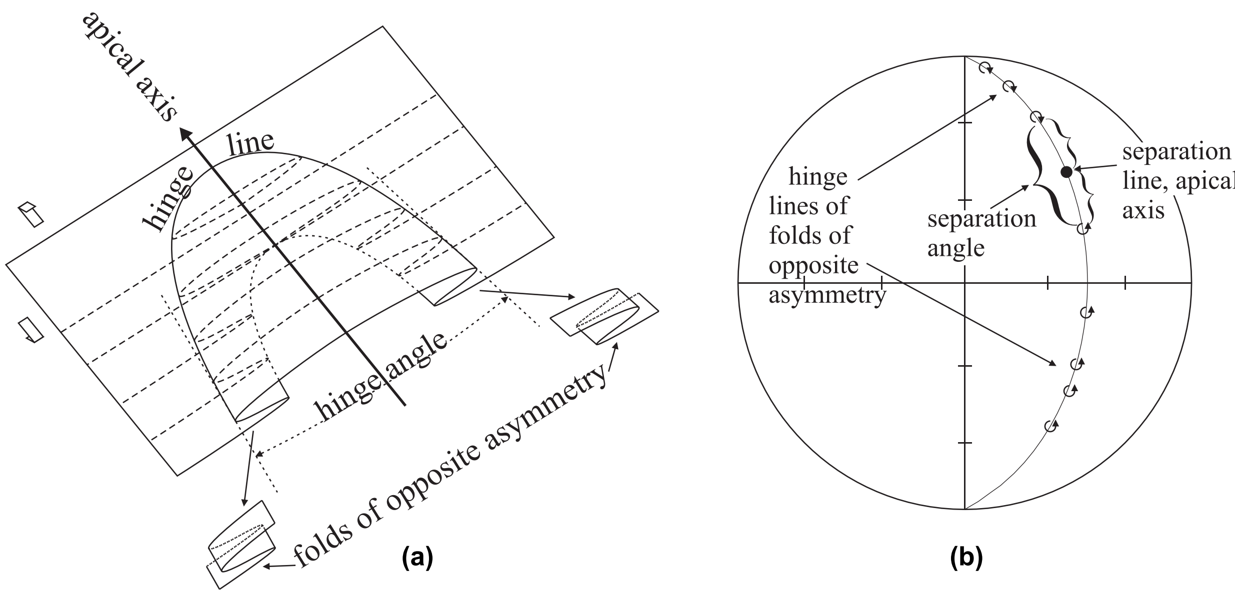

Fig. 2. (a) Sheath fold geometry indicating terms used in the text for all non-cylindrical folds. The shear zone boundary is parallel to the undeformed part of the plane that contains the sheath fold. The dashed lines indicate what exposures would look like if the fold was eroded perpendicular to the apical axis at those levels. (b) Stereogram explaining Hansen method and terms used in the text. The orientation of the shear zone (dipping 45° to the east) and the shear direction are taken arbitrarily. See text for discussion. All stereograms are lower hemisphere equal-angle projections.

folds, sheath folds and eventually tubular folds, as a result of various types of progressive deformation including triclinic shear. The progressive deformation within the zone is based on the unified model of Jiang and Williams (1998); the fold hinge lines are treated as material lines. The rotation of rigid ellipsoidal objects in viscous flows is described by Jeffery's (1922) theory. Since a material line can be treated as a rigid prolate object with an aspect ratio of infinity, we use the method and program of Jiang (2007) to model the rotation of fold hinge lines in this paper. The initial folds can be drag folds or pre-existing folds, and the hinge lines need to have a perturbation. These initial folds do not always develop into sheath folds. This issue has been addressed by Jiang and Williams (1999). In this paper, we address the question under what circumstances the shear direction can be estimated from non-cylindrical folds that developed during shearing and, therefore, only cases where sheath folds do develop are considered. We investigate various types of monoclinic and triclinic shear. We show that, in certain types of progressive deformation, the shear direction is not parallel to the apical axis and, at higher strains, it may not even lie within the separation angle.

In this paper, it is assumed that folds form in layers that are approximately parallel to the shear zone boundary. Development of shear-related folds in layers that are oblique to the shear zone boundary is discussed by Carreras et al. (2005).

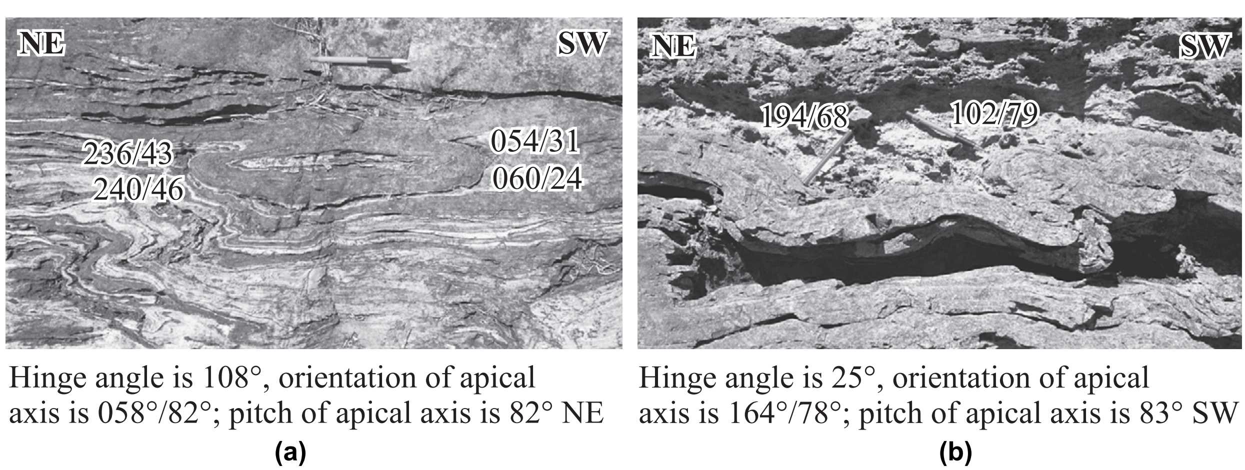

Fig. 3. Exposed sections of natural sheath folds (compare to dashed lines in Fig. 2). Trends and plunges of fold hinge lines are indicated. (a) Sheath fold from which the approximate shear direction may be estimated (assuming that the section is not close to the fold closure). The hinge angle is high enough, and the line bisecting the two exposed hinge lines is probably close to the shear direction. The fold closure is below the surface. (b) Sheath fold from which the shear direction may not be estimated. The hinge angle is too low and hinge lines may have rotated towards the direction of the maximum principal strain rate of the pure shear component, which may be different from the shear direction. See Section 4.2 for discussion.

2. Progressive deformation in shear zones

Flow in a general shear zone requires five variables to characterize it (Fig. 1; Jiang and Williams, 1998, 1999): the shear strain rate ($\dot{\gamma}$), three principal strain rates for the pure shear component ($\dot{\varepsilon}_a, \dot{\varepsilon}_b$ and $\dot{\varepsilon}_c$) and the angle (ϕ) between the shear direction and the a-direction ($\dot{\varepsilon}_a$). In this paper, $\dot{\varepsilon}_a = 0$ and $\dot{\varepsilon}_b = -\dot{\varepsilon}_c$, such that there is no strain along the strike of the shear zone boundary and the volume is constant (as in Lin et al., 1998). Because $\dot{\varepsilon}_b$ and $\dot{\varepsilon}_c$ are equal in magnitude, we use the same symbol $\dot{\varepsilon}$ for the absolute value of both. In a thinning or transpression zone $\dot{\varepsilon}_b$ is negative and $\dot{\varepsilon}_c$ positive, and in a thickening or transtension zone $\dot{\varepsilon}_b$ is positive and $\dot{\varepsilon}_c$ negative. Constant-thickness (simple shear) zones are not considered separately in this paper, but they are approached by the cases where $\dot{\gamma}/\dot{\varepsilon}$ is high. We use a right-handed coordinate system, *xyz* (Fig. 1), such that the *x*-axis is parallel to the a-direction, the *y*-axis is normal to the shear zone boundary (parallel to the b-direction), and the *z*-axis is normal to the *xy*-plane. In Fig. 1, the *xy*-plane is shown to be horizontal and the shear zone boundary (*xz*-plane) is vertical. However, it should be clear that the geometries described in this paper are independent of the actual orientation of the shear zone with respect to the geographic coordinates.

We subject initial drag fold hinge lines, which are subparallel to the vorticity axis of the deformation, to various types of progressive deformation (and one example of a pre-existing fold to monoclinic thinning flow) by applying the velocity gradient tensor **L** (Eq. 3 of Lin et al., 1998; cf. Ramberg, 1975, and Jiang and Williams, 1998), which can be expressed as:

$$\mathbf{L} = \begin{pmatrix} 0 & \dot{\gamma}\cos\phi & 0 \\ 0 & -\dot{\varepsilon} & 0 \\ 0 & \dot{\gamma}\sin\phi & \dot{\varepsilon} \end{pmatrix} \text{ (for thinning zones)} \quad (1a)$$

$$\mathbf{L} = \begin{pmatrix} 0 & \dot{\gamma}\cos\phi & 0 \\ 0 & \dot{\varepsilon} & 0 \\ 0 & \dot{\gamma}\sin\phi & -\dot{\varepsilon} \end{pmatrix} \text{ (for thickenning zones)} \quad (1b)$$

The rotations of hinge lines with time, or increasing shear strain, can be modeled using the program of Jiang (2007). The longitudinal strains (stretches) of the hinge lines at certain shear strains are calculated using the position gradient tensor $\mathbf{F}(t)$ (Eq. 6 of Lin et al., 1998; cf. Ramberg, 1975, and Jiang and Williams, 1998):

$$\mathbf{F}(t) = \begin{pmatrix} 1 & \frac{\dot{\gamma}}{\dot{\varepsilon}}\cos\phi[1-\exp(-\dot{\varepsilon}t)] & 0 \\ 0 & \exp(-\dot{\varepsilon}t) & 0 \\ 0 & \frac{\dot{\gamma}}{\dot{\varepsilon}}\sin\phi\sinh(\dot{\varepsilon}t) & \exp(\dot{\varepsilon}t) \end{pmatrix} \text{ (for thinning zones)} \quad (2a)$$

$$\mathbf{F}(t) = \begin{pmatrix} 1 & \frac{\dot{\gamma}}{\dot{\varepsilon}}\cos\phi[\exp(\dot{\varepsilon}t)-1] & 0 \\ 0 & \exp(\dot{\varepsilon}t) & 0 \\ 0 & \frac{\dot{\gamma}}{\dot{\varepsilon}}\sin\phi\sinh(\dot{\varepsilon}t) & \exp(-\dot{\varepsilon}t) \end{pmatrix} \text{ (for thickening zones)} \quad (2b)$$

The orientations and stretches of hinge lines of opposite asymmetry (which are actually segments of one hinge line; Fig. 2), and therefore the geometry of non-cylindrical folds, at certain shear strains during progressive deformation can thus be modeled.

We model the rotation paths of fold hinge lines for various types of progressive deformation by varying ϕ and $\dot{\gamma}/\dot{\varepsilon}$ in Eqs. (1) and (2). In monoclinic shear, the shear direction is parallel to one of the pure shear principal strain rate directions (ϕ = 0° or 90°). In triclinic shear, 0° < ϕ < 90°. In monoclinic thinning zones, drag folds do not develop into sheath folds when the shear direction is parallel to the a-direction (Jiang and Williams, 1999). In all other types of monoclinic shear, drag folds do develop into sheath folds (Jiang and Williams, 1999). In triclinic thinning zones, drag folds may or may not develop into sheath folds, depending on ϕ and $\dot{\gamma}/\dot{\varepsilon}$, and the initial curvature of the drag fold hinge line (cf. Jiang and Williams, 1999). In triclinic thickening, drag folds develop into sheath folds.

3. Relationship between non-cylindrical fold geometry and the shear direction

The discussion in this section mostly concerns drag folds developed during shearing (Sections 3.1–3.4). However, the conclusions are mostly applicable to pre-existing folds as well (see Section 3.5). We use $\dot{\gamma}\cdot t$ as a measure for progressive strain accumulation (as in Jiang and Williams, 2004). It should be noted that $\dot{\gamma}\cdot t$ is not the shear strain, γ, parallel to the zone boundary unless the flow is simple shear only because the pure shear component of flow also contributes to the shear strain accumulation. The higher the $\dot{\gamma}/\dot{\varepsilon}$ ratio is, the closer is $\dot{\gamma}\cdot t$ to the actual shear strain parallel to the shear zone boundary, γ.

3.1. Monoclinic thinning flow

In thinning shear zones, extension occurs along the c-direction and shortening along the b-direction (Fig. 1). In monoclinic thinning zones, drag folds develop into sheath folds only when the shear direction is parallel to the c-direction. The c-direction is the fabric attractor and both hinge lines rotate towards it (Fig. 4). Therefore, the apical axis of the non-cylindrical fold indicates the shear direction.

Fold hinge lines rotate and stretch faster, and sheath folds develop faster (i.e. at lower finite shear strains) at a lower $\dot{\gamma}/\dot{\varepsilon}$ ratio (compare Fig. 4a and b). For example, when $\dot{\gamma}\cdot t$ = 5, the hinge angle is 83° and the stretch of the hinge lines is 1.46 for $\dot{\gamma}/\dot{\varepsilon} = 20$ whereas the hinge angle is 26° and the stretch is 4.30 for $\dot{\gamma}/\dot{\varepsilon} = 2$. Extension in the direction of shear enhances sheath fold development. However, in the centre of a shear zone, a $\dot{\gamma}/\dot{\varepsilon}$ ratio of 2 is probably too low to maintain,

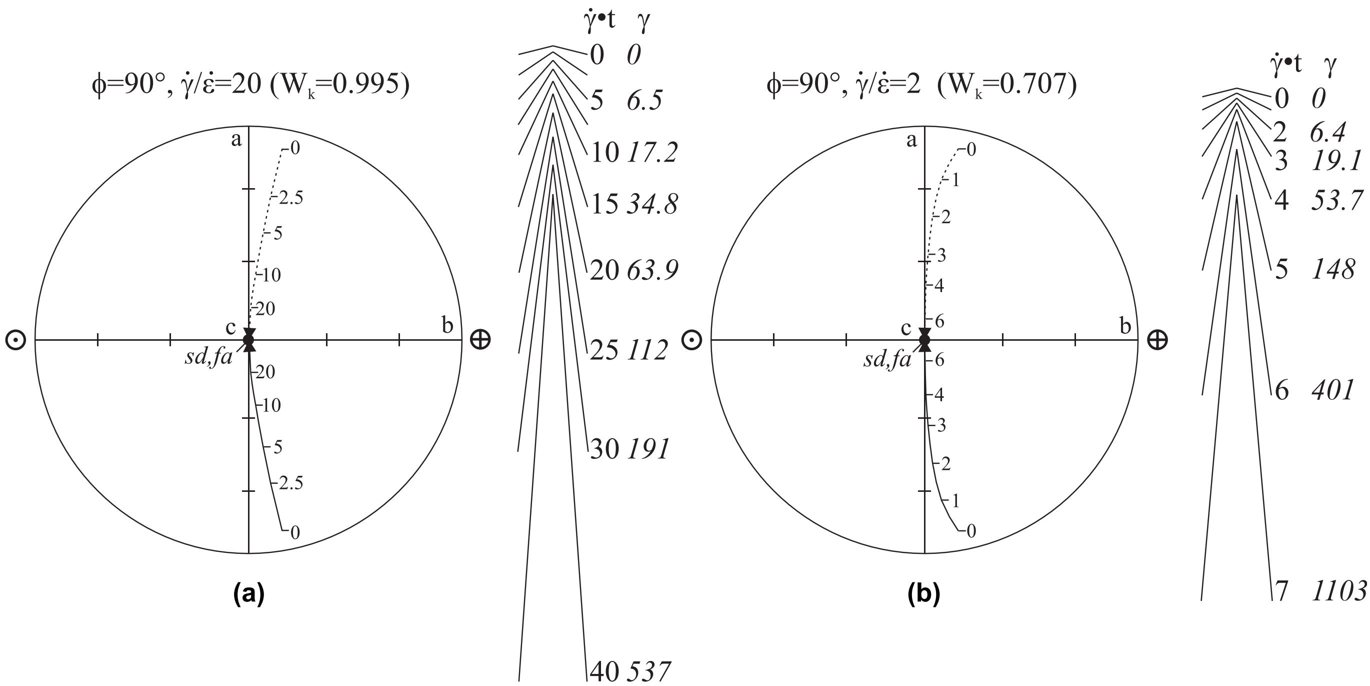

Fig. 4. Evolution of non-cylindrical fold geometries from drag folds in monoclinic thinning flow. The shear direction is parallel to the direction of the maximum principal strain rate of the pure shear component, or the c-direction, and shortening occurs along the b-direction, perpendicular to the shear zone boundary. Geometries for $\dot{\gamma}/\dot{\varepsilon} = 20$ (a) and $\dot{\gamma}/\dot{\varepsilon} = 2$ (b). W_k is the kinematic vorticity number of Truesdell (1953). $\dot{\gamma}$ is 1 and $\dot{\varepsilon}$ is varied in all figures. Solid arrows represent the rotation path of S-fold hinge lines and dashed arrows the path of Z-fold hinge lines. The hinge lines lie approximately within the foliation plane, and rotate towards the fabric attractor (fa). Solid circles represent the shear direction (sd). Non-cylindrical fold geometries to the right of the stereograms are as seen looking towards the left in the stereograms, perpendicular to the plane that contains both hinge lines. The orientations and stretches of the hinge lines are shown with increasing shear strain ($\dot{\gamma}\cdot$t and γ are indicated). The stretches of the hinge lines are indicated by the lengths of the lines. See text for further discussion.

because simple shear is a softening process and pure shear is a hardening one (Williams and Price, 1990; Lin et al., 1998, 2007; Williams and Vernon, 2001; Williams et al., 2006). For example, in Fig. 4b, at $\dot{\gamma}\cdot t = 2$, the stretch along the c-direction is 2.7, and the stretch along the b-direction is 0.37. The shear zone has thus thinned by 63% as a result of the pure shear component, and in nature the pure shear strain rate is likely to have lowered at this stage due to strain hardening. Therefore, a low $\dot{\gamma}/\dot{\varepsilon}$ ratio, if present at the early stage of deformation, is expected to become higher with increasing strain. A $\dot{\gamma}/\dot{\varepsilon}$ ratio of 20 is probably much more sustainable in the centre of a shear zone (cf. Williams et al., 2006). Near the margin of a shear zone, the $\dot{\gamma}/\dot{\varepsilon}$ ratio is usually low (Lin et al., 1998, 2007), but the accumulated strain is generally not high enough for sheath fold development.

3.2. Triclinic thinning flow

Sheath folds develop from drag folds in triclinic thinning in an asymmetric manner (Fig. 5). One hinge line becomes steeper, rotates initially past the c-direction towards the shear direction and then back to the c-direction. The other hinge line rotates through horizontal and passes the shear direction towards the c-direction. The apical axis rotates towards parallelism with the c-direction, which is at a 45° angle with the shear direction in Fig. 5a, c ($\phi = 45°$). At low strain, the shear direction lies within the separation angle (strictly the hinge angle in the modeling, because there is only one fold; cf. Fig. 2), but is not parallel to the apical axis (Fig. 5c). At high strain, the shear direction does not lie within the separation angle (Fig. 5c; cf. Fig. 5a). Thus, the angle between the apical axis and the shear direction increases with increasing strain, in triclinic thinning. At low strain values in triclinic thinning, the apical axis of the non-cylindrical fold does approximately indicate the simple shear direction. If the $\dot{\gamma}/\dot{\varepsilon}$ were too low, then both hinge lines would rotate the same way and no sheath fold would develop (cf. Jiang and Williams, 1999).

With higher or lower values of ϕ, geometries are similar (Fig. 5b, d). However, a lower value of ϕ (i.e. a shallower shear direction, e.g. 35° in Fig. 5d) requires a higher amount of strain to produce a sheath fold. For example, at $\dot{\gamma}\cdot t = 20$, no sheath fold has developed yet with $\phi = 35°$, while at the same $\dot{\gamma}\cdot t$ a well-developed sheath fold formed if $\phi = 55°$. Sheath fold formation is therefore unlikely in thinning zones for very low values of ϕ unless the accumulated strain is very high and sheath folds do not develop when $\phi = 0°$ (see above).

Also, at lower values of ϕ, higher $\dot{\gamma}/\dot{\varepsilon}$ ratios are required for sheath fold development (Fig. 6). For example, at $\phi = 55°$ the minimum value of $\dot{\gamma}/\dot{\varepsilon}$ required for sheath fold development is 13.2, at $\phi = 45°$ it is 22.7 and at $\phi = 35°$ it is 41.7. In thinning zones with low values of ϕ sheath folds only develop if the $\dot{\gamma}/\dot{\varepsilon}$ ratio is very high (Fig. 6). As the $\dot{\gamma}/\dot{\varepsilon}$ ratio approaches infinity the deformation approaches simple shear (with monoclinic symmetry).

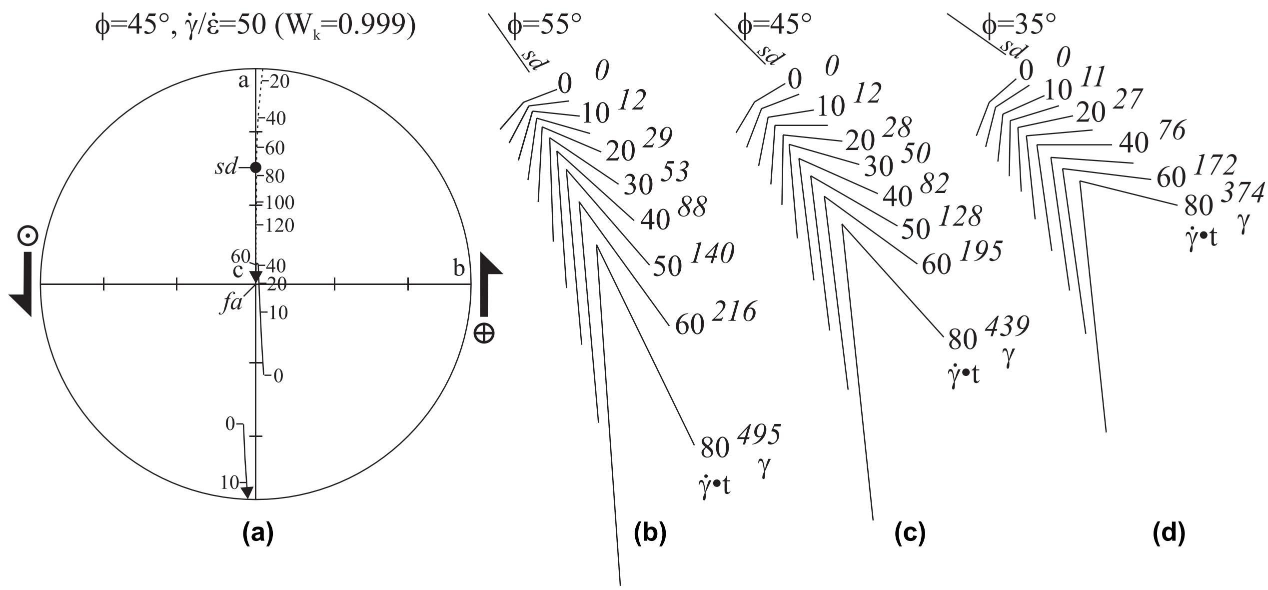

Fig. 5. Non-cylindrical folds developing from drag folds in triclinic thinning flow. (a) Stereogram showing the rotation paths of the hinge lines for $\dot{\gamma}/\dot{\varepsilon} = 50$ and $\phi = 45°$. To the right, non-cylindrical fold geometries (constructed as in Fig. 4) are shown for $\dot{\gamma}/\dot{\varepsilon} = 50$ and $\phi = 55°$ (b), $\dot{\gamma}/\dot{\varepsilon} = 50$ and $\phi = 45°$ (c), and $\dot{\gamma}/\dot{\varepsilon} = 50$ and $\phi = 35°$ (d). Other annotations as in Fig. 4.

In triclinic thinning zones with low values of ϕ (e.g. 35°; Fig. 5d), apical axes of sheath folds with hinge angles of ~80° or more approximately give the shear direction (e.g. at $\dot{\gamma} \cdot t = 40$, the hinge angle is 82° and the angle between the shear direction and the apical axis is 6°, which is low enough to be useful in the field). Thus, at lower values of ϕ, only the apical axes of immature non-cylindrical folds, and of (immature) sheath folds with greater hinge angles, indicate the shear direction. Therefore, immature non-cylindrical and sheath folds, which developed from drag folds, can be used to estimate the shear direction by the Hansen method. The apical axis may be taken as the line bisecting the hinge angle (or separation angle).

In summary, in triclinic thinning zones, the shear direction usually lies within the separation angle of immature non-cylindrical folds (cf. Fig. 5b–d). It commonly lies within the separation angle of sheath folds at low strain values, but at high strains it does not. The shear direction rarely lies

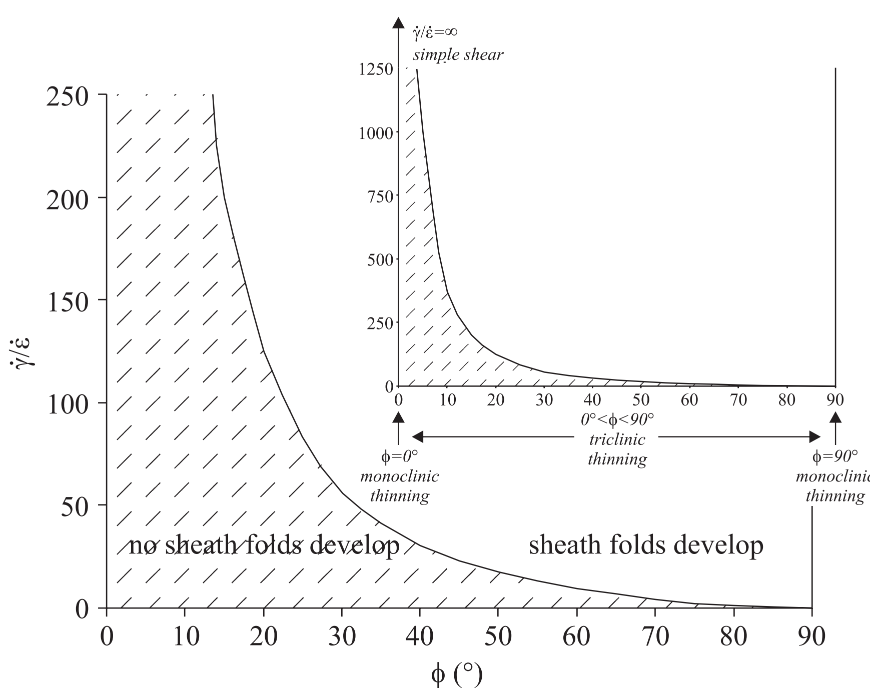

Fig. 6. Diagram showing the minimum $\dot{\gamma}/\dot{\varepsilon}$ ratio required for sheath fold development from drag folds in thinning zones for various values of ϕ. The scale of the y-axis is varied for clarification. For the lowest values of ϕ, the required $\dot{\gamma}/\dot{\varepsilon}$ is so high that the deformation approximates simple shear.

within the separation angle of tubular folds in triclinic thinning, unless the shear direction is close to the direction of the maximum principal strain rate of the pure shear component and the deformation approaches monoclinic symmetry.

3.3. Monoclinic thickening flow

In thickening zones, shortening occurs along the c-direction and extension along the b-direction. The sheath fold development shown in Fig. 7a is very similar to that shown in Fig. 4a by monoclinic thinning, because both models have a high $\dot{\gamma}/\dot{\varepsilon}$ ratio (20), meaning that the pure shear component is low, and therefore both models approximate simple shear.

Unlike in thinning zones, the fabric attractor for a thickening zone is not the direction of the maximum principal strain rate of the pure shear component. In monoclinic thickening, it lies between the direction of the maximum principal strain rate of the pure shear component (this is the b-direction in thickening zones) and the simple shear direction. When $\dot{\gamma}/\dot{\varepsilon}$ is low (e.g. 2, Fig. 7b), the fabric attractor lies closer to the b-direction than when $\dot{\gamma}/\dot{\varepsilon}$ is high (e.g. 20, Fig. 7a). The plane that contains both non-cylindrical fold hinge lines can be at a significant angle with the shear zone boundary. The fold hinge line geometries drawn to the right of the stereograms in Fig. 7, which are drawn within the plane that contains both hinge lines, are therefore seen at an angle to the shear zone boundary. The projection of the apical axis on the *a-c* plane indicates the shear direction. The shear direction can thus be estimated by such projection (similar to the estimation of the shear direction from stretching lineations by projecting them onto the shear zone boundary in simple shear, as explained by Lin and Williams, 1992a). This projection method should, strictly speaking, also be used in monoclinic thinning, but the angle between the apical axis and its projection on the shear zone boundary is so small (and probably not distinguishable in the field) that it can be ignored.

As in monoclinic thinning, hinge lines rotate and stretch faster, and sheath folds develop faster with a lower $\dot{\gamma}/\dot{\varepsilon}$ ratio (compare geometries for $\dot{\gamma}\cdot t = 5$ in Fig. 7a and b). A larger pure shear component therefore enhances sheath fold development.

In Fig. 8, sheath fold development as a result of monoclinic thickening is shown, with the a- and c-directions switched (compared to Fig. 7; $\phi = 0°$). It requires less finite strains to develop sheath folds when the shear direction is parallel to the a-direction ($\phi = 0°$, Fig. 8) than when it is parallel to the c-direction ($\phi = 90°$, Fig. 7). The hinge lines rotate faster, but experience less stretch. This is clear when, for example, the sheath fold geometries at $\dot{\gamma}\cdot t = 5$ between Figs. 7a and 8a ($\dot{\gamma}/\dot{\varepsilon} = 20$) are compared. The difference in geometries between Figs. 7b and 8b ($\dot{\gamma}/\dot{\varepsilon} = 2$) is even more striking. Thus, in monoclinic thickening, the best conditions for sheath fold development are when the $\dot{\gamma}/\dot{\varepsilon}$ ratio is low and the shear direction is parallel to the a-direction.

3.4. Triclinic thickening flow

Sheath fold development in triclinic thickening zones is complex (Fig. 9). The fabric attractor lies somewhere in the

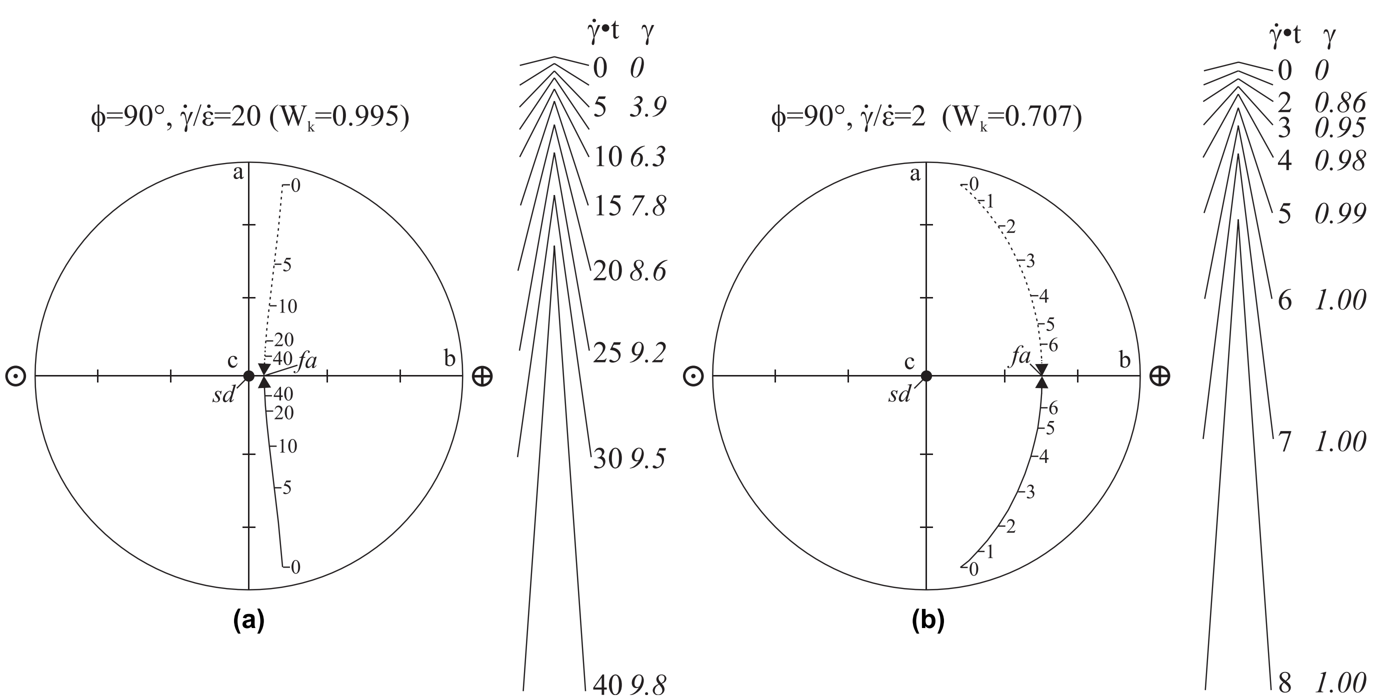

Fig. 7. Evolution of non-cylindrical fold geometries from drag folds in monoclinic thickening flow. The shear direction is parallel to the direction of the minimum principal strain rate of the pure shear component, or the c-direction, and extension occurs in the b-direction, perpendicular to the shear zone boundary. All other parameters are the same as in Fig. 4.

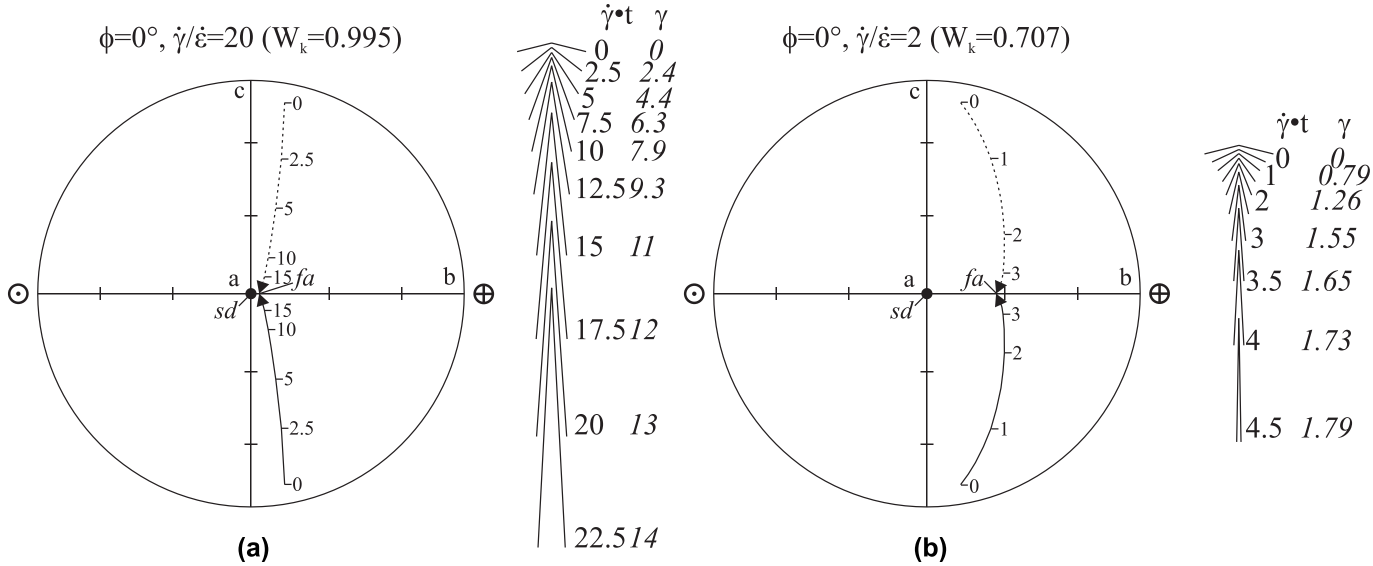

Fig. 8. Same as Fig. 7, but with shear direction parallel to the a-direction ($\phi = 0°$). The a- and the c-directions are reversed to avoid superposition of the two rotation paths in the diagram. Shortening occurs parallel to the shear zone boundary, but perpendicular to the shear direction.

quadrant between the b-direction and the simple shear direction, depending on the pure shear strain rates along the principal stretching directions and the simple shear strain rate (compare Fig. 9a and b). Neither the apical axis nor its projection on the shear zone boundary indicates the shear direction. For $\dot{\gamma}/\dot{\varepsilon} = 20$ (Fig. 9a), at high strain values, the shear direction does not lie within the 'separation angle' between the hinge lines of folds of opposite asymmetry. At low strain

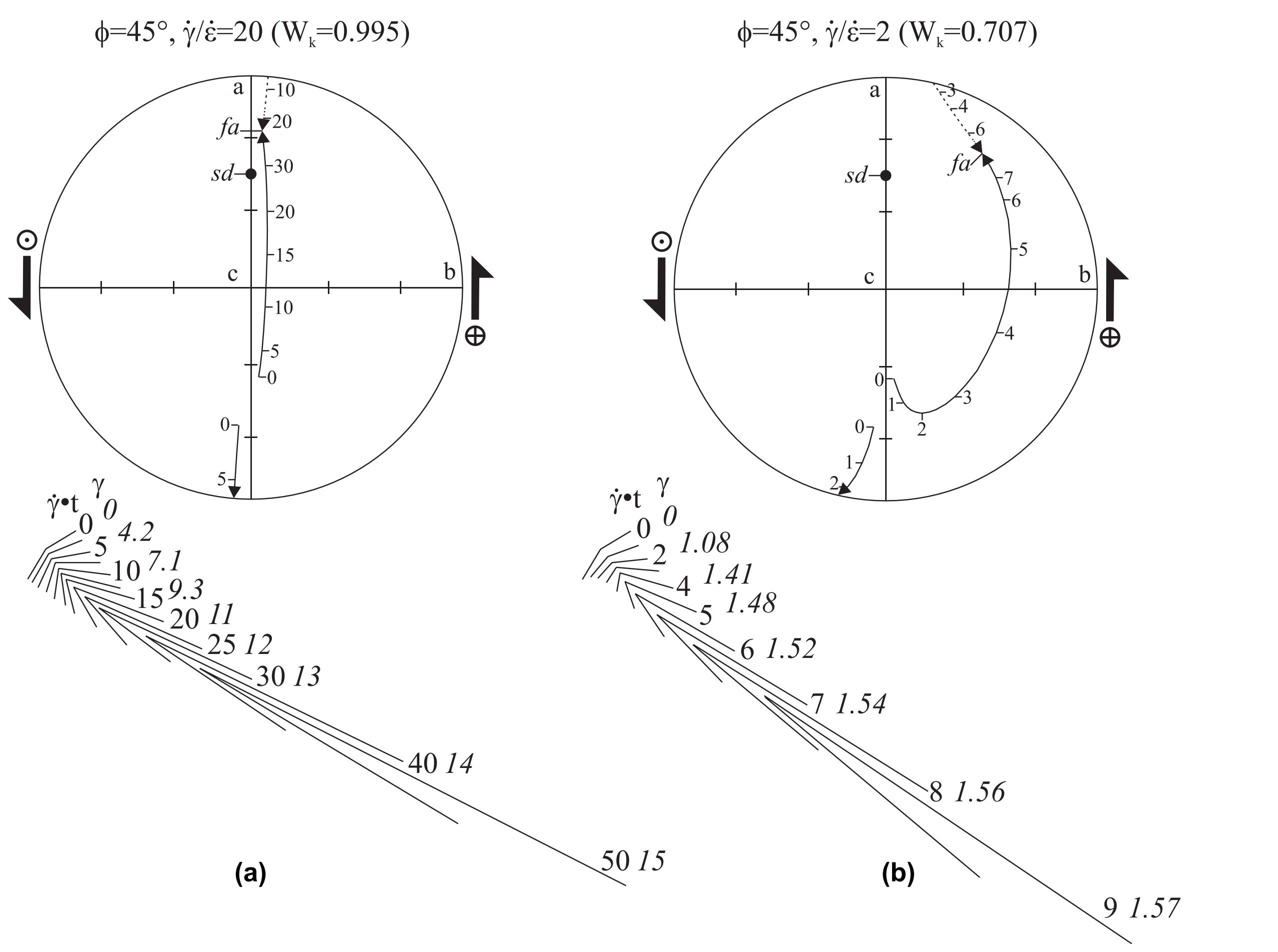

Fig. 9. Sheath folds developing from drag folds in triclinic thickening flow with $\phi = 45°$. (a) $\dot{\gamma}/\dot{\varepsilon} = 20$, (b) $\dot{\gamma}/\dot{\varepsilon} = 2$. The maximum and minimum principal strain rates of the pure shear component are parallel to the b- and c-directions respectively. Annotations as in Fig. 4.

values, the apical axis does approximately indicate the simple shear direction.

When $\dot{\gamma}/\dot{\varepsilon} = 2$ (Fig. 9b), the fabric attractor lies closer to the b-direction than when $\dot{\gamma}/\dot{\varepsilon} = 20$ (Fig. 9a). Furthermore, the plane that contains both hinge lines rotates in a complex manner with respect to the shear zone boundary.

3.5. Development of sheath/tubular folds from a pre-existing fold

In most cases, fold hinge lines of both pre-existing folds and drag folds rotate towards the fabric attractor, and where sheath folds develop, their apical axes rotate towards the fabric attractor. Therefore, in general, the conclusions drawn above for non-cylindrical folds developed from drag folds also apply to non-cylindrical folds developed from pre-existing folds. An exceptional example of a pre-existing fold developing into a sheath fold in monoclinic thinning with the shear direction parallel to the a-direction (Fig. 10) is described here in order to illustrate how large the angle between the shear direction and the apical axis of a sheath fold can be. This example is exceptional, because a drag fold that formed in this situation would not develop into a sheath fold. The initial hinge line is parallel to the shear direction, which is parallel to the a-direction. The initial hinge line is given a distortion (tail ends of the arrows in Fig. 10, where $\dot{\gamma} \cdot t = 0$) so that a sheath fold develops during deformation. The apical axis of the non-cylindrical fold first rotates toward the shear direction and subsequently towards the c-direction (the fabric attractor). At high strain values, the sheath or tubular fold direction is close to the c-direction, and at an angle (up to 90°) with the shear direction. One hinge line starts in a shortening field, but at higher strain values, the stretches of the two fold hinge lines are similar. Although this particular situation may not be likely, the existence of pre-existing folds is common and this example confirms that apparent shear direction indicated by the apical axis of the sheath fold may be misleading.

4. Summary and discussion

4.1. Summary

When sheath folds develop from drag folds in monoclinic thinning zones, fold hinge lines rotate towards the c-direction and the apical axes of the non-cylindrical folds indicate the simple shear direction. In monoclinic thinning zones, sheath folds only develop when the shear direction is parallel to the c-direction, not when it is parallel to the a-direction (Jiang and Williams, 1999).

In triclinic thinning zones, the apical axes of non-cylindrical folds that developed from drag folds are oblique to the simple shear direction. With increasing strain, hinge lines and apical axes (and any other linear structures) rotate towards the c-direction, not the shear direction. In other words, the apical axes of sheath folds and tubular folds are not parallel to the shear direction unless the shear direction is parallel to the c-direction (i.e. monoclinic thinning). However, even in triclinic thinning zones, at low strain values, the apical axes of immature non-cylindrical or sheath folds approximately indicate the simple shear direction. Estimating the shear direction from non-cylindrical folds, by taking the line bisecting the hinge angle (or separation angle of the Hansen method), is therefore reasonable as long as the non-cylindrical folds are immature (with hinge angles more than ~80°).

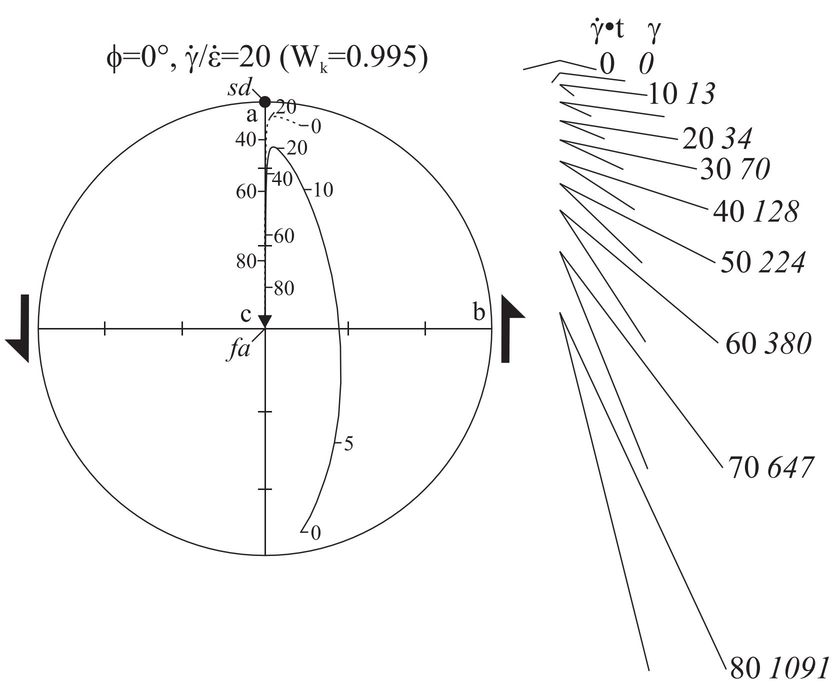

Fig. 10. Development of a non-cylindrical fold from a pre-existing fold in monoclinic thinning. The shear direction is parallel to the a-direction and the initial hinge line is parallel to the shear direction (and has a perturbation). Further explanation of projections as in Fig. 4.

Sheath fold development in thickening shear zones is more complex than in thinning shear zones, because the fabric attractor does not lie in the plane of the shear zone boundary. In monoclinic thickening, the fabric attractor lies between the direction of the maximum principal strain rate of the pure shear component (b-direction) and the simple shear direction. The projection of the apical axis onto the shear zone boundary indicates the shear direction. If the pure shear component is high, it lies close to the b-direction. If the simple shear component is high, then it lies closer to parallelism with the shear zone boundary. In triclinic thickening, the fabric attractor lies somewhere in the quadrant between the b-direction and the simple shear direction. As for monoclinic thickening, if the pure shear component is high, it lies closer to the b-direction, and if the simple shear component is high, then it lies closer to parallelism with the shear zone boundary. However, the projection of the apical axis onto the shear zone boundary does not indicate the shear direction.

4.2. Application in the field

Sheath folds are most likely to be found in high-strain zones with high $\dot{\gamma}/\dot{\varepsilon}$ ratios, because, in triclinic thinning zones, with decreasing values of ϕ, increasing $\dot{\gamma}/\dot{\varepsilon}$ ratios are required for sheath fold development (Fig. 6). Because simple shear is commonly localized in the centre of a shear zone, whereas pure shear is widely distributed (Lin et al., 1998, 2007; cf. Tikoff and Teyssier, 1994, and Jones and Tanner, 1995), sheath folds are more likely to occur in the central domain of a thinning shear zone than in the marginal domain. For example, Lin et al. (2007) discussed the distribution, localization and partitioning of deformation across a thinning shear zone using an example with $\phi = 20°$. For $\phi = 20°$, the minimum value of $\dot{\gamma}/\dot{\varepsilon}$ for sheath fold development is 125 (Fig. 6), a value which only occurs near the centre of Lin et al.'s (2007) shear zone.

It is evident from above that tubular folds and mature sheath folds (with small hinge angles) are generally unreliable indicators of shear direction unless it is known that the kinematic framework of the deformation is of monoclinic symmetry. In thinning zones of unknown symmetry, immature non-cylindrical and sheath folds are more reliable for estimating the shear direction than tubular folds and mature sheath folds (Fig. 3). However, knowing the maturity of a non-cylindrical fold requires knowledge of the hinge angle. For use in the field this implies that both hinge lines need to be visible (Fig. 3) and the section of the fold that is exposed should not be too close to the 'nose' of the fold, where the hinge angle appears larger. In practice, it is useful to keep measurements from individual non-cylindrical folds separate from measurements from other shear zone-related folds, such that the shear direction can be estimated from individual non-cylindrical folds or groups of such folds. If the estimates from folds with various hinge angles are consistent, the shear direction is likely to be close to the c-direction (in thinning zones) or c- or a-direction (in thickening zones) and the estimated shear direction can be assumed to be reliable. If the orientations of the apical axes of various folds are inconsistent, then the shear direction cannot be estimated.

It is also useful to plot hinge lines of folds of opposite asymmetries in a stereogram, even when the exact geometries of the non-cylindrical folds are unknown. If these hinge lines lie within a plane that is parallel to the shear zone boundary, then the shear zone is a thinning or simple shear zone. If the hinge lines lie within a plane that is oblique to the shear zone boundary, or hinge lines seem to have rotated in a complex pattern, then the shear zone is probably a thickening zone. Non-cylindrical folds may be useful in determining whether a shear zone is thinning or thickening, when no other useful indicators, such as shear bands or kink bands (Williams and Price, 1990) are present.

4.3. Further considerations

In this paper, initial fold hinge lines of drag folds were assumed to develop at a high angle to the shear direction, within a plane parallel to the shear zone boundary. However, this may not always be the case, especially when the pure shear component is large and the initial fold hinge orientation is affected by the directions of the principal strain rate axes of the pure shear component. Therefore it may be appropriate to start our models with hinge lines that are oblique to the shear direction (within a plane parallel to the shear zone boundary). However, the exact angle between the initial fold hinge line and the shear direction in triclinic shear is not known at this time and would involve a separate study that is beyond the scope of this paper. Furthermore, the orientations of the initial hinge lines of drag folds are also dependent on the orientations of the compositional layers being folded; the latter may be at any angle with respect to the zone boundary at the time of fold initiation (cf. Carreras et al., 2005). In addition, inherited folds can have any initial orientation. There is an infinite number of possible situations. However, when the initial orientation of a fold is known, its subsequent development can be modeled following an approach similar to this investigation.

During deformation, a combination of simple shear and pure shear components determines the orientations of foliations and lineations (e.g. Sanderson and Marchini, 1984; Robin and Cruden, 1994; Jiang and Williams, 1998; Jones and Holdsworth, 1998, 2004; Lin et al., 1998; Teyssier and Tikoff, 1999; Tikoff and Fossen, 1999; Czeck and Hudleston, 2003) and of apical axes and hinge lines of non-cylindrical folds (this study). With increasing strain, the pure shear component becomes increasingly important for the orientations of fabrics and the simple shear component becomes less important. This is especially true for thinning zones. This implies that the orientation of other shear sense indicators, such as asymmetric clasts, shear bands, S–C fabric, mica fish, etc. are also influenced by the pure shear component (cf. Jiang and Williams, 1998, and Lin et al., 1998). These structures therefore may also not be reliable indicators for the shear direction. For example, the intersection between foliation (C-fabric) and shear bands (C′-fabric) may initially not be perpendicular to the shear direction and may rotate during progressive deformation.

The only structures that are thought to reliably indicate the shear direction, even in triclinic deformation, are well-developed ridge-in-groove type striations (Lin and Williams, 1992b; Lin et al., 1998, 2007). The presence of such striations indicates either monoclinic symmetry, or triclinic symmetry with a high $\dot{\gamma}/\dot{\varepsilon}$ ratio. The striations would not be well-developed in triclinic zones with a low $\dot{\gamma}/\dot{\varepsilon}$ ratio (Lin et al., 2007). Such striations are a product of ductile deformation. They occur on surfaces (ductile slickensides) exposed by parting along C-surfaces, reflecting the approximately curviplanar geometry of the C-surfaces. The reader is referred to Lin and Williams (1992b) and Lin et al. (2007) for a detailed description and discussion of such striations and their usage as a reliable indicator of the shear direction.

5. Conclusions

Our results show that the general practice of using well-developed sheath folds as indicators for the shear direction is often not reliable. In thinning zones, apical axes of non-cylindrical folds rotate towards the c-direction, not the shear direction. Therefore, the apical axes of mature sheath folds and tubular folds are not parallel to the shear direction unless the shear direction is parallel to the c-direction. Tubular folds and mature sheath folds are, thus, generally unreliable indicators of shear direction unless it is known that the shear zone is monoclinic. In general, in thinning zones, immature non-cylindrical and sheath folds are more reliable for estimating the shear direction than tubular folds and mature sheath folds.

The fact that apical axes of non-cylindrical folds may be oblique to the shear direction in triclinic shear zones, and in monoclinic shear zones if the non-cylindrical folds developed from pre-existing folds, has major structural and tectonic implications. Mature sheath folds and tubular folds are not reliable indicators for shear direction unless it is known that the kinematic framework of the shear zone is of monoclinic symmetry and non-cylindrical folds originated from drag folds. Since the apical axes of sheath folds are not generally parallel to the shear direction, shear zones where the sheath folds have been used to determine the shear direction in the past may need to be reviewed. If the interpreted shear direction appears to be incorrect or unreliable, the tectonic interpretations may need to be revised.

Two more practical applications of sheath folds in shear zones were found in this study. (1) When the orientations of the apical axes of individual non-cylindrical folds with various hinge angles are consistent, they are likely to be a reliable indicator of the shear direction. If they are inconsistent, the shear direction cannot be estimated. (2) If hinge lines of non-cylindrical folds, or of folds of opposite asymmetries, lie within a plane that is parallel to the shear zone boundary, the shear zone is a thinning or simple shear zone. If the hinge lines lie within a plane that is oblique to the shear zone boundary, or hinge lines seem to have rotated in a complex pattern, then the shear zone is probably a thickening zone. Therefore, non-cylindrical folds may help to determine whether a shear zone is thinning or thickening.

Acknowledgements

The research was conducted while YDK was a post-doctoral fellow at the University of Waterloo, supported by Natural Sciences and Engineering Research Council of Canada (NSERC) Collaborative Research and Development grant to SL. YDK and SL acknowledge support from Manitoba Geological Survey and Manitoba Hydro. DJ and SL acknowledge support from their respective NSERC discovery grants. Constructive journal reviews by Jean Crespi and Dyanna Czeck are greatly appreciated.

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