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Three-dimensional reference deformations and strain facies

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Abstract

In an attempt to categorize three-dimensional deformations, the concepts of kinematic axes, three-dimensional reference deformations, and strain facies are utilized. We have chosen 12 reference deformations, each being an idealized end-member of deformation involving a simultaneous combination of a three-dimensional coaxial component (constriction, flattening, or pure shear) and an orthogonal simple shear component. Velocity and displacement fields, infinitesimal deformation parameters, and finite deformation parameters can be calculated for each reference deformation, assuming steady-state deformation. There are three possibilities for the orientation of foliation and three possibilities for the orientation of lineation, depending on the relative contributions of the coaxial and non-coaxial components. The six emerging combinations of foliation and lineation orientations each give rise to a characteristic strain facies. Each of the strain facies is correlated to the reference deformations, and thus deformation parameters, which caused its formation. However, since the coaxial deformation component accumulates more effectively than the non-coaxial component, a change from one strain facies to another (i.e. a change in the orientation of lineation or foliation) is possible during steady-state deformation. The strain facies emphasize the boundary conditions of deformation and, together with the reference deformations, provide a framework for three-dimensional deformations.

1. Introduction

Three-dimensional analyses of both individual shear zones and tectonic settings are becoming more common in the geological literature (e.g. Schultz-Ela and Hudleston, 1991; Jones et al., 1997; Tikoff and Greene, 1997). Although three-dimensional deformation may be quantified with a continuum mechanics approach, a useful framework for three-dimensional deformation analysis is still lacking. We have revived two old ideas from the structural geology literature in order to bridge this gap: *kinematic axes* (Sander, 1930) and *strain facies* (e.g. Hansen, 1971). Kinematic axes define the symmetry orientation of geological deformation. For a simple shear deformation, the *a*-axis is parallel to the movement direction, the *b*-axis lies in the shear plane and is the axis of rotation, and the *c*-axis is normal of the shear plane (Fig. 1; Sander, 1930; Ramsay, 1967). Kinematic axes were used as descriptive terms, and often invoked to describe the existence of *b*-axis-oriented lineations in shear zones.

The more general, and predominantly three-dimensional, concept reintroduced in this paper is strain facies. Hansen (1971), for example, utilized this concept to distinguish between fold geometries resulting from different types of flow. He was able to determine slip-line orientations (movement directions), and thus make a correlation between structures and their mode of formation. In analogy to metamorphic or sedimentary facies, these strain states were not considered end-members of deformation, but part of a continuum of deformation styles. The application of strain facies has been limited by the predominantly two-dimensional quantification of deformation. This manuscript is an attempt to reinvigorate this useful concept within a continuum mechanics framework, emphasizing the

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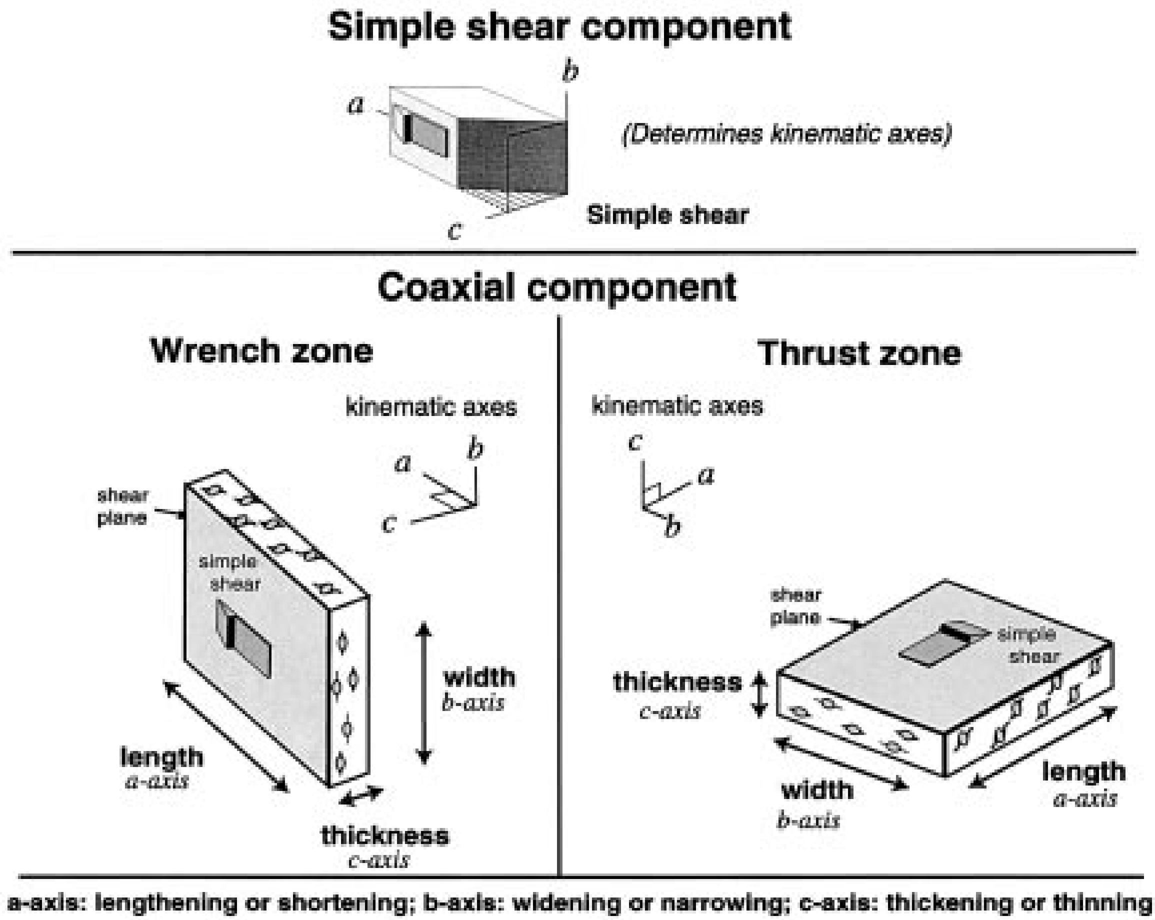

Fig. 1. Simple shear and coaxial (pure shear, flattening, constriction) components that make up the three-dimensional reference deformation. The kinematic axes for all deformations is from the simple shear component, which acts in the *ac*-plane (shear plane) in the *a*-direction (transport direction). The coaxial component is given in terms of the orientation of the shear zone: length (*a*-axis), width (*b*-axis), and thickness (*c*-axis). Material can lengthen or shorten along the *a*-axis, widen or narrow along the *b*-axis, and thicken or thin along the *c*-axis.

boundary conditions of three-dimensional deformations.

The present manuscript presents the concept of three-dimensional reference deformations. These are idealized three-dimensional boundary conditions and are similar to simple shear and pure shear in two dimensions. Twelve reference deformations are defined: five involve thinning of the shear zone, five involve thickening of the shear zone, and two do not affect the shear zone thickness. In each of the deformations, a simple shear component acts simultaneously with an orthogonal three-dimensional coaxial component of deformation. Thus, unlike the two-dimensional example, a coaxial end-member and a simple shear end-member are both part of the same reference deformation. The kinematic axes are defined on the basis of the simple shear component, and the reference deformations are defined by the orientation and type of the coaxial component. The flow apophyses, infinitesimal strain axes, flow lines of deformation, rotation of material lines, rotation of planes, and accumulation of finite strain may be described for each reference deformation (e.g. Fossen and Tikoff, 1998). Calculation of the finite strain, in particular, leads to the recognition of six distinct patterns of lineation and foliation, referred to as strain facies. These reference deformations are described only by the internal geometry of the flow and thus are applicable to any tectonic regime.

2. Three-dimensional reference deformation and kinematic axes

In two dimensions, pure shear, simple shear, and pure rotations are the end-members of non-spinning and spinning plane strain deformations (e.g. Ramberg, 1975; Lister and Williams, 1983). Spinning deformations involve external rotation of the shear zone (e.g. Ramberg, 1975) and will not be discussed here. Adding anisotropic volume change gives rise to additional spectra of plane strain deformations (e.g.

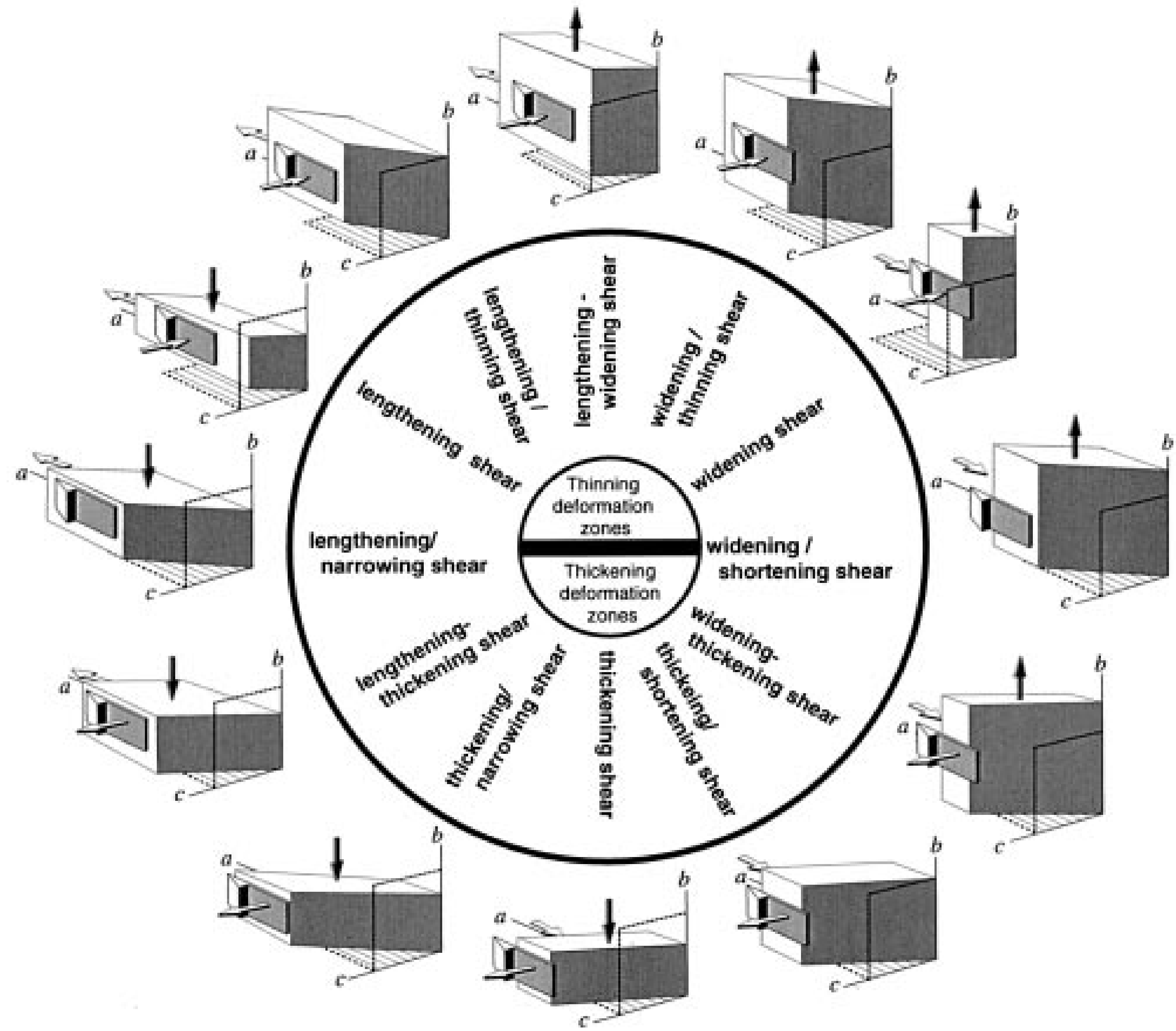

Fig. 2. Three-dimensional reference deformations. Each case involves a simultaneous combination of a three-dimensional coaxial deformation (constriction, flattening, or pure shear) with an orthogonal simple shear in the *ac*-plane.

Fossen and Tikoff, 1993), but the possible deformations are still easy to visualize. Isotropic volume loss does not affect the relative behavior of material lines (e.g. shortening or extension relative to other lines; Passchier, 1992), and is not considered in the analysis.

When the third dimension is considered, the kinematics of deformation become far more complex. In terms of non-spinning deformations, one can have any combination of three simple shears and a general non-coaxial deformation (Tikoff and Fossen, 1993). Simplification into certain three-dimensional reference deformations is necessary for three-dimensional deformations. These reference deformation types are simple enough to model mathematically, easy to envision, and describe a wide variety of deformations expected in common tectonic settings.

We restrict the following analysis to cases where one simple shear system (shear zone) acts simultaneously with an orthogonal two- or three-dimensional coaxial component, without any volume loss. This is sometimes considered as 'monoclinic' deformation, since the resulting flow pattern never displays a geometry that cannot be described by monoclinic symmetry (e.g. Robin and Cruden, 1994).

To describe orientation, we have returned to the use of kinematic axes, defined with respect to the simple shear component of the deformation (e.g. Sander, 1930, 1970; Ramsay, 1967). Our way of describing the coaxial component of deformation is based on the geometry of naturally deformed shear zones, by defining three orientations of a shear zone—length, width, and thickness (Fig. 1). None of these terms has a predefined meaning with respect to map coordinate systems (e.g. horizontal and vertical), but depends on the orientation of the shear zone (Fig. 1). The length of the shear zone lies along the *a*-axis, the width along the *b*-axis, and the thickness along the *c*-axis. Thus, if there is a coaxial component parallel to the *a*-axis, it either lengthens or shortens the shear zone. A coaxial component parallel to the *b*-axis widens or narrows, and a coaxial component parallel to the *c*-axis thickens or thins. Again, these terms relate only to the kinematic axes of the shear zone.

These coaxial components may be considered in the context of constriction, flattening, and pure shear. Notice that we reserve pure shear as a two-dimensional, plane strain deformation, following the usage of Ramsay (1967) and Ramberg (1975). For constrictional deformations, one can consider lengthening (*a*-axis parallel constriction), widening (*b*-axis parallel constriction), or thickening (*c*-axis parallel constriction). The combination of lengthening (*a*-axis extension) with a simple shear, lengthening shear, implicitly requires both narrowing (*b*-axis contraction) and thinning (*c*-axis contraction). For flattening deformations, there is extension along two of the axes, caused by the coaxial component of deformation. As a flattening component is added to a simple shear component, there is lengthening–widening (*a*–*b*) shear, lengthening–thickening (*a*–*c*) shear, and widening–thickening (*b*–*c*) shear. These deformations are designated by a dash (–). Again, extension in two directions implies contraction in the third. For example, lengthening–widening shear implies thinning (*c*-axis contraction).

A combination of pure shear and simple shear (subsimple shear; Simpson and De Paor, 1993) requires extension along one axis and contraction along another. The orientation is designated by the description of extension in one direction (lengthening, widening, or thickening) or contraction in another (shortening, narrowing, or thinning). If the extension component is listed first, the emerging six types are: lengthening/thinning (*a*-axis extension/*c*-axis contraction), thickening/shortening (*c*/*a*), widening/thinning (*b*/*c*), thickening/narrowing (*c*/*b*), lengthening/thickening (*a*/*b*), and widening/shortening (*b*/*a*) shear. These deformations are designated by a slash (/). Implied in all of these deformations is the lack of contraction or extension in the third direction. For example, lengthening/thinning does not affect movement with respect to the *b*-axis or shear zone width. In this context, it is useful to note that most previous analyses have considered either the plane strain case (lengthening/thinning shear and thickening/shortening shear; e.g. Bobyarchick, 1986; Weijermars, 1991; Simpson and De Paor, 1993), or the case of transpression/transtension (widening/thinning and thickening/narrowing shear; Sanderson and Marchini, 1984; Fossen and Tikoff, 1993; Krantz, 1995).

Five of the combinations of simple shear and coaxial deformation components shown in Fig. 1, require that the zone of shear decreases in thickness during deformation (Types A–E transpression of Fossen and Tikoff, 1998), five require an increase in thickness (Types A–E transtension of Fossen and Tikoff, 1998), and two have no effect on the thickness of the shear zone. Since this only affects the *c*-axis direction, or thickness of the shear zone, we designate these as thinning, thickening, and constant-thickness shear zones, respectively (Fig. 2). The five thinning deformation types are: (1) lengthening shear; (2) lengthening/thinning shear; (3) lengthening–widening shear; (4) widening/thinning shear; and (5) widening shear. In the order presented, they exhibit a decreasing coaxial component of elongation in the *a*-direction and an increasing coaxial component of elongation along the *b*-axis (Fig. 2). The corresponding thickening deformation types are: (1) widening–thickening shear; (2) thickening/shortening shear; (3) thickening shear; (4) thickening/narrowing shear; and (5) lengthening–thickening shear. These deformations exhibit a decreasing coaxial component of elongation along the *b*-axis and an increasing coaxial component of elongation along the *a*-axis, moving clockwise in Fig. 2. The two types of constant-thickness shear zones are lengthening/narrowing and widening/shortening shear. The constant thickness occurs because neither the pure shear component nor the simple shear component affects the thickness, regardless of the amount of deformation. These constant thickness shear zones form the connection between the thinning and thickening shear zones: lengthening/narrowing shear is just an intermediate case between lengthening–thickening shear and lengthening shear, while widening/shortening shear lies between widening shear and widening–thickening shear.

For generality, we utilized the self-descriptive naming system explained above (Fig. 2) instead of names related to tectonic settings. For instance, consider the case of widening/thinning shear, of which transpression is an example (Fig. 2, Sanderson and Marchini, 1984, Fossen and Tikoff, 1993). This type of deformation could also occur in a thrusting system which was simultaneously undergoing thrust-perpendicular stretching (e.g. Nadeau and Hanmer, 1992), and ‘transpression’ is not an appropriate term in this circumstance.

The organization of the coaxial components of the reference deformations follows the approach of earlier workers (e.g. Harland and Bayly, 1958; Hsu, 1966;

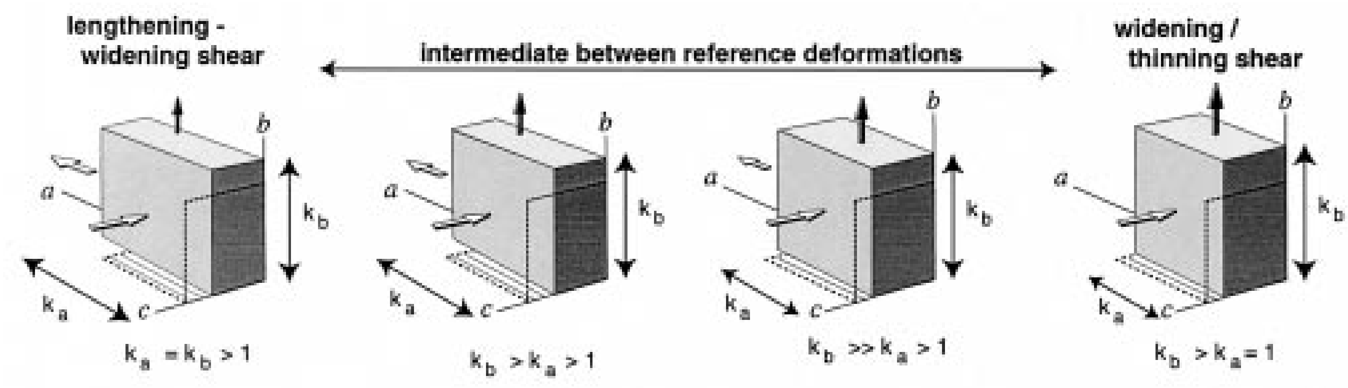

Fig. 3. Intermediate deformations between lengthening–widening shear and widening/thinning shear, involving variation of the coaxial component. Intermediate deformations occur between all adjoining reference deformations.

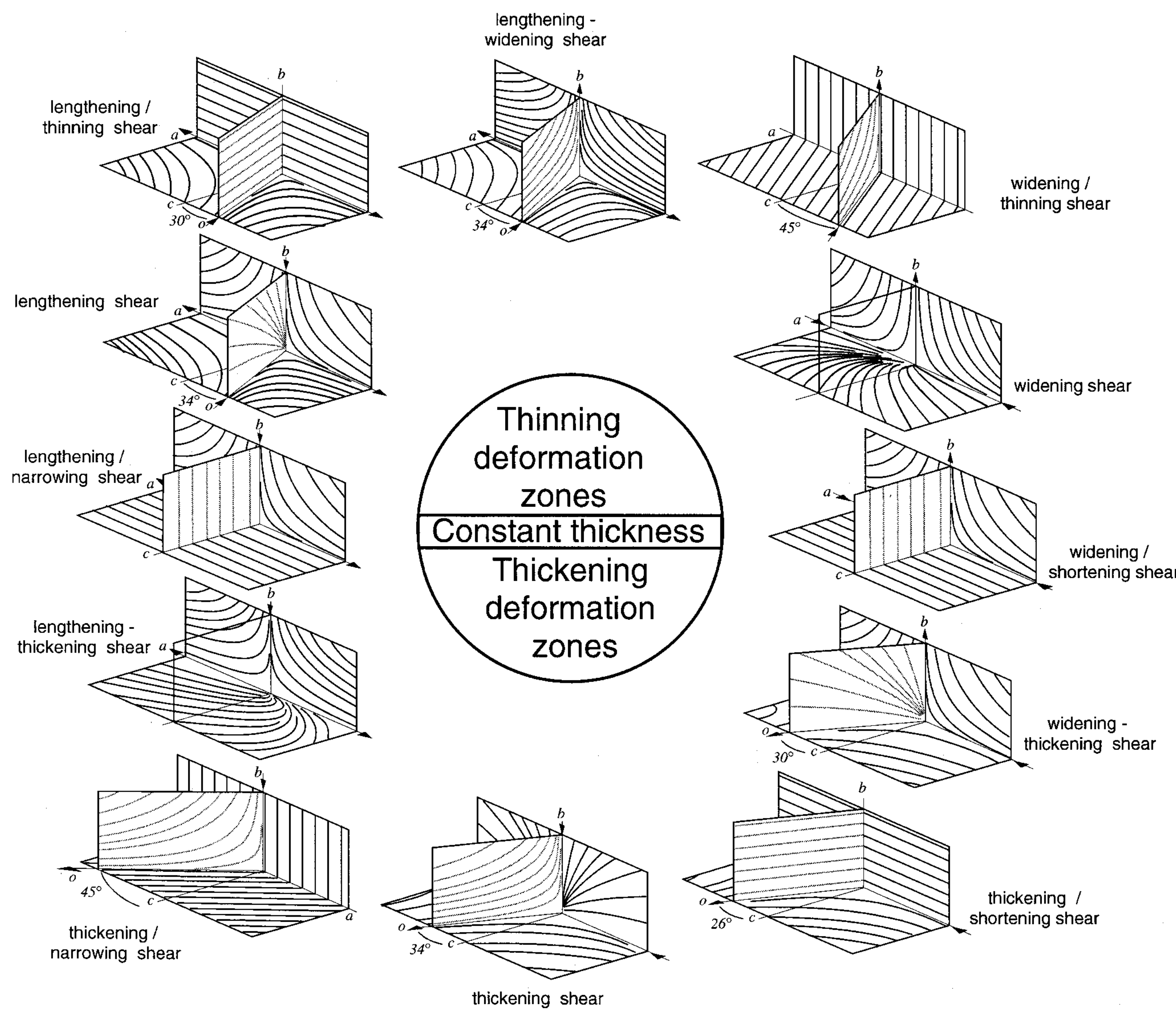

Fig. 4. Three-dimensional flow fields for the reference deformations.

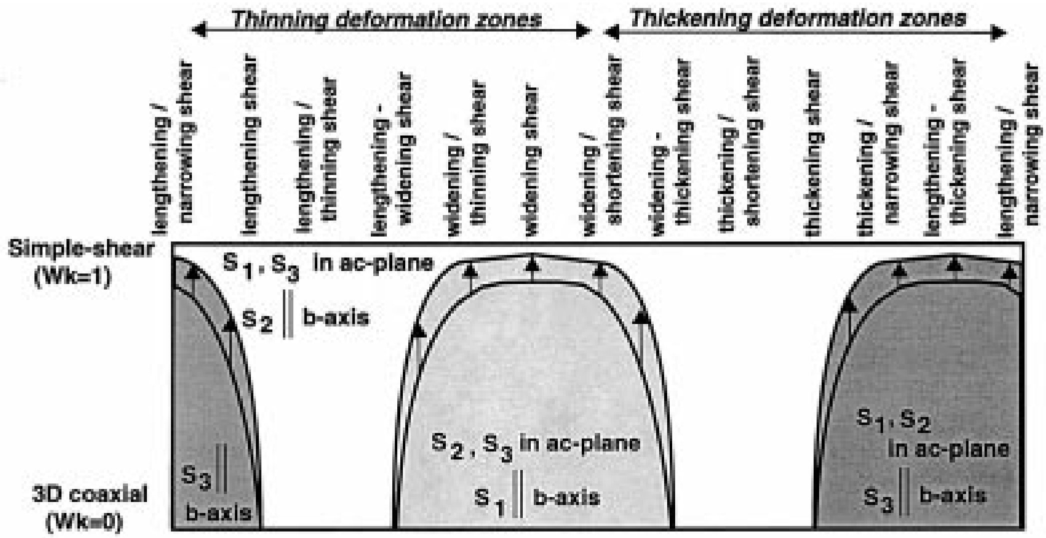

Fig. 5. The orientation of the finite strain axes, given in terms of Wk and the three-dimensional reference deformations. The curve changes with time, as denoted by the arrows. The inside curve is for the infinitesimal strain axes and the outside curve represents some point during the deformation. The orientation of the finite strain axes changes during material steady-state deformation (constant Wk), as the coaxial component increasingly affects the finite strain pattern.

Owens, 1974). It is critical to understand that a continuum of deformation lies between each of the three-dimensional reference deformations. For example, between lengthening–widening shear and widening/thinning shear are a series of deformations (Fig. 3), which involve a decreasing amount of stretching parallel to the *a*-axis. These intermediate deformations will, of course, have characteristics of deformation that are intermediate between the two reference deformations. In our approach, the categorization of the boundary conditions according to the kinematic axes (of the simple shear component) provides the basis for the three-dimensional reference deformations. Consequently, any reference deformation varies between a coaxial end-member and a simple shear end-member.

3. Deformation patterns in the three-dimensional reference types

Deformation within a sheared zone is characterized by a series of physical parameters, of which finite strain is the best known, which relate directly to the boundary conditions that produced them. These parameters are invariably linked with mathematical quantities and are discussed in more detail in Fossen and Tikoff (1997). For our purposes, it is critical to know only two components—the displacement field and the finite strain—which are both the result of the deformation matrix **D** (also known as the position gradient tensor) for steady-state deformations. The results are summarized in Fig. 4 for the flow fields and in Fig. 5 for the finite strain. More detail about the displacement field and the finite strain for the reference deformations is given in Appendix A.

4. Strain facies

The three-dimensional reference deformations describe a wide range of flow fields and are useful to prescribe a potential range of geological structures that can form in a ductiley deformed rock. Further, they have specific geometrical and mathematical properties. However, deformation in naturally deformed rocks will deviate from these end-members, and it is therefore useful to note the similarities between the reference deformation in terms of the produced structures. Therefore, we will categorize the patterns of lineation and foliation into strain facies. Although the concept of a 'strain' facies has been in the structural geology literature for some time (e.g. Harland, 1956; Dunbar and Rodgers, 1957; Arthaud and Mattauer, 1969; Hansen, 1971), it is not currently utilized. Hansen (1971) describes the motivation for the concept of strain facies as:

> The physical distinctiveness of each assemblage and the corresponding distinctiveness of the genesis of each assemblage, understood here in terms of simple flow environments, lead us to the concept of strain facies: *Physical properties of a structural assemblage express the conditions of its formation*. Practically anywhere a given assemblage occurs in Trollheimen, it looks the same and exhibits the same relative orientations of fabric and kinematic axes. The integrity of the assemblage further indicates that the

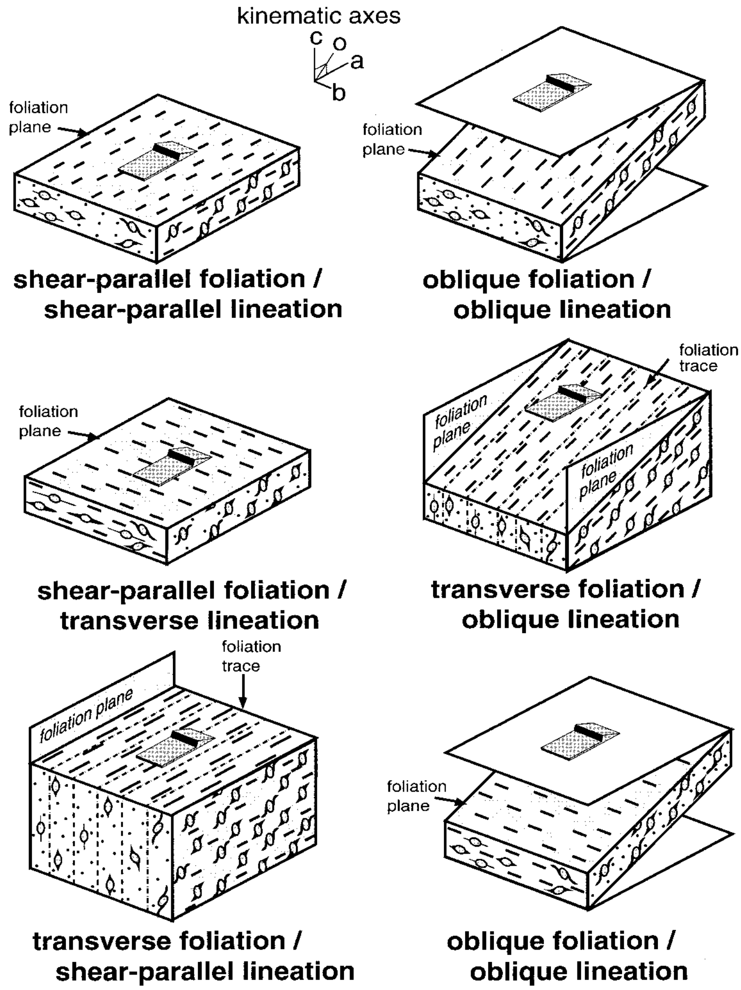

Fig. 6. The six strain facies—six patterns of foliation and lineation—that are possible for the reference deformations are shown in Fig. 2. Gray represents foliation plane and short bold lines indicate lineation. The sense of shear indicated by the porphyroclasts results from the simple shear component of deformation. There are three possibilities for foliation orientations—shear-parallel (*ab*-plane), transverse (*ac*-plane), and oblique (*bo*-plane)—and three possibilities for lineation orientation (shear-parallel or *a*-axis, transverse or *b*-axis, oblique or *o*-apophysis).

facies concept is appropriate as a classification scheme for strain features.

The concept of strain facies provides a useful way of determining the formation of structures in the field. The strain facies acts to facilitate, rather than limit, more quantitative analysis of deformation. At its most basic, the strain facies is a way of describing the three-dimensional geometry of structures and their relationship to the deformation (flow) that caused it.

The strain facies are delineated by the orientation of the lineation and the foliation within a deforming zone. The lineation and foliation in three-dimensional shear zones are relatively straight-forward to investigate, since they can be related directly to finite strain. We will investigate a ‘stretching’ lineation which is assumed to be parallel to the finite strain maximum axis (S_1). Likewise, we will consider a ‘flattening’ foliation which forms in the plane of the maximum and intermediate finite strain axes (S_1–S_2), although it is more convenient to think of it as the pole to the minimum finite strain axis (S_3). The discussion will focus on the orientations and magnitudes of the finite strain axes in the three-dimensional reference deformations, interpreted in terms of lineations and foliations.

4.1. Lineation and foliation orientation

As with the maximum finite strain axis (S_1), three orientations are possible for the stretching lineation: shear-parallel (*a*-lineation), transverse (*b*-lineation), or oblique (*o*-lineation, but lying in the *ac*-plane) (Fig. 6). Thinning shear zones can show any of these three orientations, as can thickening or constant-thickness shear zones. As with the finite strain axes, the three-dimensional reference deformation, *Wk*, and amount of deformation determine the orientation of the stretching lineation. *Wk*, or the kinematic vorticity

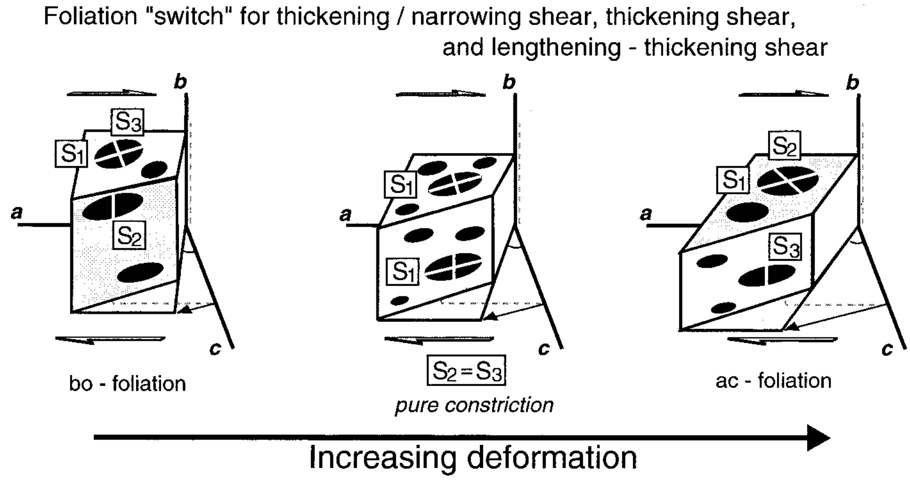

Fig. 7. Examples of a 'switch' of foliation during a steady-state deformation. The 'switch' represents the coaxial component accumulating more effectively than the simple shear component, and dominating the finite strain axes. Gray represents foliation plane.

number, measures the amount of stretching to spin at any instant in a flow. For a steady-state, non-spinning deformation, Wk measures the relative ratio of simple shear to coaxial shear components (Tikoff and Fossen, 1995). For any reference deformation, the coaxial component has no rotation ($Wk = 0$), the simple shear component records an equal rate of rotation and spin ($Wk = 1$), and most deformations lie between these two end-members ($0 < Wk < 1$).

For many deformations—such as lengthening–thickening shear, lengthening/narrowing, lengthening, lengthening/thinning, and lengthening–widening shear—the orientation of the stretching lineations remains in the same plane during deformation. The maximum finite strain axis does rotate, due to the non-coaxial nature of the simple shear component (Lin and Williams, 1992). In these cases, the rotation of stretching lineation is into parallelism with the shear direction, such as occurs in simple shear. The lineation orientation may remain in the same plane during deformation and is also oblique to all kinematic axes, in the direction of the oblique flow apophyses. This type of structure can occur in thickening/narrowing shear, thickening shear, thickening/shortening shear, widening–thickening shear, and widening/shortening shear.

For the other deformations, the relative magnitudes of the maximum and intermediate finite strain axes can switch during the course of a steady-state deformation. This effect is very well documented for transpressional (widening/thinning shear) deformations (Sanderson and Marchini, 1984; Fossen and Tikoff, 1993; Tikoff and Teyssier, 1994; Tikoff and Greene, 1997). This switch results if the simple shear component is acting to elongate material in a direction different from the elongation caused by the coaxial component. Whether or not this shift in strain axes occurs for a given three-dimensional reference deformation depends on both the relative ratio of coaxial to non-coaxial components of deformation and the amount of deformation (e.g. Tikoff and Greene, 1997). The switch in lineation orientation is accompanied by the finite strain ellipsoid going through a stage of pure flattening (Fossen and Tikoff, 1993). Since natural deformation commonly contains a large simple shear component, the same situation which favors the switch in lineation orientation, this effect may be applicable to a variety of structural settings.

Since we are assuming that lineation is parallel to the long axis of finite strain, the rock could eventually lose the first lineation as a flattening fabric develops, and acquire the second lineation as the deformation moves away from pure flattening. However, two more complicated situations could exist for naturally deformed rock, if this assumption does not hold. First, the first-formed lineation may be overprinted by the second-formed lineation. This pattern would look like the result of polyphase deformation, although it can result from a single, steady-steady deformation. Second, a gradual reorientation of the lineation, from the orientation of first-formed lineation to that of the second-formed lineation, may exist.

Foliations for the three-dimensional reference deformation can also be easily predicted by following the orientation of the S_1–S_2 plane. There are three possibilities for the foliation orientation: (1) rotating towards the *ab*-plane (shear-parallel); (2) parallel to the *ca*-plane (transverse); or (3) rotating towards the *b*-axis/*o*-apophysis plane (oblique). Shear-parallel and oblique foliations involve a component of simple shear deformation and therefore rotate toward parallelism during deformation. Transverse (*ca*-plane) foliation is controlled by the coaxial component and no rotation of foliation is involved.

Thickening and constant-thickness shear zones exhi-

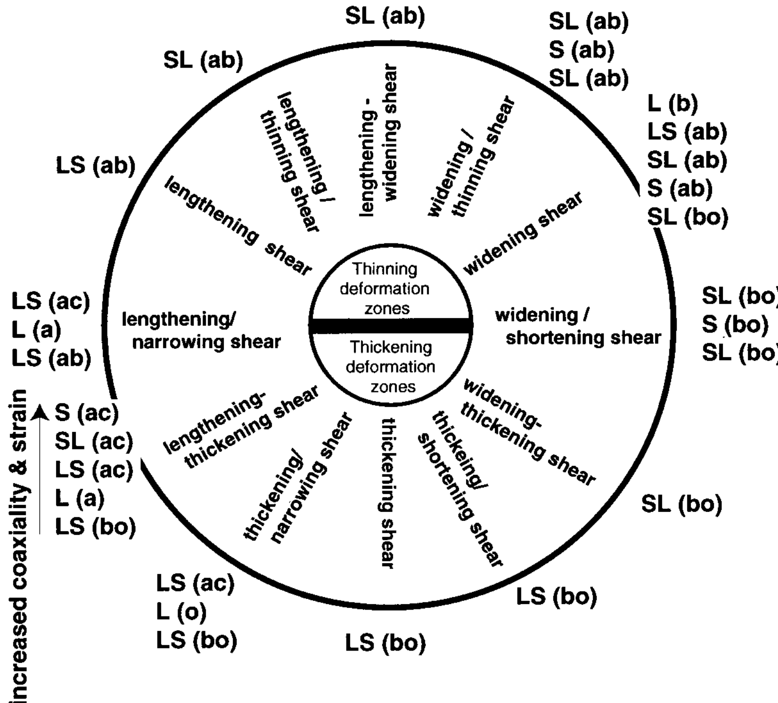

Fig. 8. Relative strength of fabric for the reference deformations given in terms of *L*-, *LS*- (prolate field), *SL*- (oblate field), and *S*-tectonites. For complex patterns, deformations resulting from the largest coaxial component are listed at the top.

bit complex foliation behavior. For deformations that vary from widening/shortening shear to thickening shear, an oblique foliation is developed. For deformations from lengthening/thickening shear to thickening/narrowing shear, there is contraction along the *b*-axis, and thus either shear-parallel or transverse foliation is possible. The transition between these two foliation patterns occurs between thickening shear and thickening/narrowing shear. Consequently, thickening shear zones can have foliation in any of the three possible orientations.

For thinning shear zones, the foliation typically rotates into parallelism with the *ab*-plane. However, there are two exceptions to this rule. For strain histories intermediate between widening/shortening shear and widening shear, foliation can lie in the *b*-/*o*-apophysis plane if the deformation deviates significantly from simple shear. Likewise, for strain histories intermediate between lengthening/thickening shear and lengthening shear, foliation can lie in the *ac*-plane. Thus, all three orientations of foliation are possible for thinning shear zones, although *ab*-foliation is most likely.

Similar to lineation, the foliation orientation can actually switch during steady-state deformation (Fig. 7), after going through a stage of pure constriction. This switch in the orientation of foliation has been noted for thickening/narrowing shear (transtension; Fossen et al., 1994). As noted earlier, this occurs when the coaxial shortening direction, although infinitesimally smaller than the simple shear shortening direction, dominates the contractional finite strain axis. Foliation can rotate from the *ab*-plane to either the *ac*-plane (e.g. thickening/narrowing shear) or *b*-/*o*-apophysis plane (e.g. widening–thickening shear).

As with the case of a switch in lineation direction, a switch in the foliation direction could occur in several ways, depending on the rock rheology, temperature during deformation, and amount of deformation. If the foliation exactly tracks the S_1–S_2 plane, the rock would simply lack a good foliation, and become lineated (*L*-tectonite). Alternatively, one could find either: (i) the formation of two orthogonal foliation planes; or (ii) a gradual reorientation of foliation planes. In either of the latter cases, the final rock fabric would resemble a polyphase deformation, although it accumulated in a single, steady-state deformation.

4.2. S vs L tectonites

Each of the three-dimensional reference deformations causes a predictable orientation and magnitude of foliation and lineation, which can ultimately be related to the strain facies (Fig. 8). These patterns are labeled *S*-, *SL*-, *LS*-, and *L*-tectonites, in order of decreasing strength of foliation and increasing strength of lineation.

The orientation and type of fabric for each three-

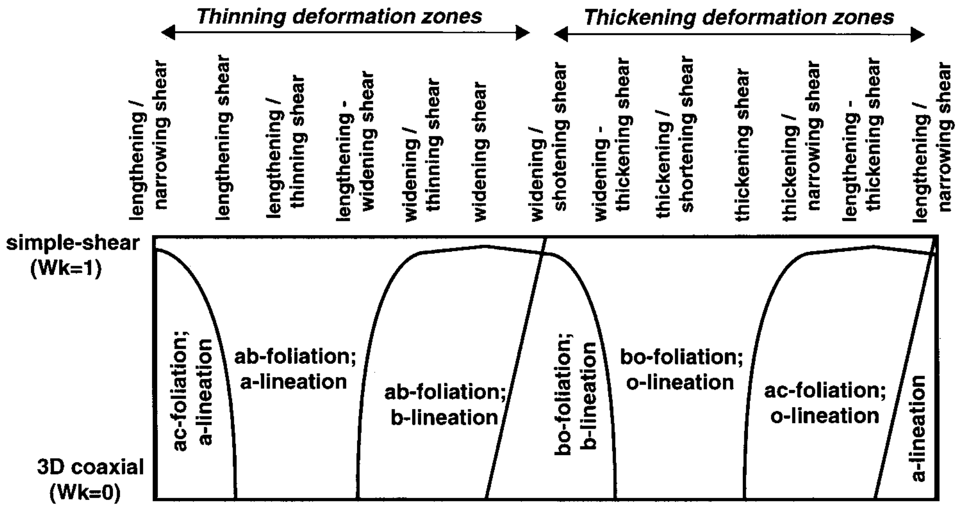

Fig. 9. Relationship between the strain facies and the reference deformations. The exact boundaries are approximate, since they require knowledge of finite strain. The curved boundaries represent fields of perfect constriction or flattening strain, and indicate a switch of foliation or lineation, respectively.

dimensional reference deformation is given on Fig. 8. As discussed above, the foliation often rotates into a final position, because of the effect of the non-coaxial component of deformation. Therefore, the 'final' position, such as the *ab*-plane, of the fabric is given for each deformation. Notice that the fabrics are symmetrical across the three-dimensional reference deformation circle (Fig. 2): *S*-tectonites typically form across the circle from *L*-tectonites. Further, the fabric caused by the coaxial end-member is listed above that caused by the non-coaxial end-member in Fig. 2, as this component of deformation will dominate for large finite strains.

Some of the three-dimensional reference deformations, such as lengthening/thinning and thickening/shortening shear, only cause one pattern of foliation and lineation (i.e. strain facies). Most of the reference deformations are capable of forming different fabrics, based on the relative magnitudes of the non-coaxial vs coaxial component of deformation. The only predictable pattern that results from Fig. 2 is the foliation resulting from simple-shear dominated deformations. This foliation in the thinning shear zones is typically in the *ab*-plane (although not always—see below), as caused by the simple shear component of deformation. The foliation produced by a large simple shear component in thickening shear zones typically lies in the *bo*- or *ac*-planes.

4.3. Description of strain facies

Based on the above discussions, there are six basic possibilities for the orientation of lineation and foliation, which form the strain facies (Figs. 6 and 9). As with the reference deformations, the strain facies are written in terms of the kinematic axes, in order to be self-descriptive and not specify a certain type of tectonic setting. They are:

1. shear-parallel foliation/shear-parallel lineation (*ab*-foliation/*a*-lineation);
2. shear-parallel foliation/transverse lineation (*ab*-foliation/*b*-lineation);
3. transverse foliation/shear-parallel lineation (*ac*-foliation/*a*-lineation);
4. oblique foliation/oblique lineation (*bo*-foliation/*o*-lineation);
5. transverse foliation/oblique lineation (*ac*-foliation/*o*-lineation); and
6. oblique foliation/transverse lineation (*bo*-foliation/*b*-lineation).

The thinning deformations result in one of the upper three strain facies, while the thickening deformations result in one of the lower three strain facies. The borders between these two types are quite distinct. The reason that the simple shear end-members of the thinning and thickening deformation zones fall into different facies results from simple shear being a degenerate case where two flow apophyses (*a* and *o*) are parallel. However, any small component of coaxial deformation causes a shear parallel (*a*-axis) lineation for thinning zones and an oblique (*o*-apophysis) lineation for thickening zones.

The simple shear component of deformation implies some rotation of foliation and lineation throughout deformation (e.g. Lin and Williams, 1992). Thus, the shear-parallel and oblique foliations/lineations are really stable directions towards which the finite strain axes rotate (fabric attractor concept of Passchier, 1997; also Fossen et al., 1994). Thus, for low strains, certain strain facies may look similar, such as shear-parallel foliation/shear-parallel lineation and oblique foliation/oblique lineation. However, the use of strain gradients or moderate to highly strained rocks will alleviate these problems.

Notice that there is a relationship (Fig. 9), but not a one-to-one correspondence, between the strain facies and reference deformations. Some reference deformations always result in one facies (e.g. lengthening/thinning shear), while other deformations result in either of two strain facies (e.g. widening/thinning shear).

Except for the thinning/thickening transition, the boundaries between the other strain facies are mapped by fabrics which represent either pure constriction or pure flattening fabrics. For instance, widening/thinning shear deformation which causes a switch from *ab*-foliation/*a*-lineation facies to *ab*-foliation/*b*-lineation facies goes through a pure flattening fabric. A steady-state thickening/narrowing shear deformation switching strain facies—from *bo*-foliation/*o*-lineation to *ac*-foliation/*o*-lineation—goes through a pure constrictional fabric.

According to some authors (e.g. Ramsay and Graham, 1970) simple shear is expected as a major component in most ductiley deformed rocks. Thus, the *ab*-foliation/*a*-lineation facies may be rather common in naturally deformed rocks. However, small amounts of coaxial component added to primarily a simple shear deformation, if the deformation zone is thickening, will result in *bo*-foliation/*o*-lineation. The other facies are possible, particularly for high strain deformations where they only require very small deviations from simple shear (Tikoff and Greene, 1997).

5. Discussion

5.1. Shear sense indicators

The evaluation of shear sense indictors, with respect to lineations and foliations, requires revision in light of the strain facies (see also Passchier, 1997). The lineation and foliation are a result of both the simple shear and the coaxial components of deformation, although the asymmetry generally results only from the simple shear component. Thus, the orientation of the lineation is not necessarily shear-parallel (*a*-axis) to the simple shear component, but could be parallel-transverse (*b*-axis) or oblique (oblique flow apophyses) if the coaxial component dominates the finite strain (Fig. 6). One interpretation of the effect on microstructures for the latter case, was given by Simpson and De Paor (1993) for thickening/shortening (c/a) shear. In this case, as well as all deformations that result in oblique foliation/oblique lineation, asymmetric structures lie in the *ac*-plane but the foliation is not parallel to the overall shear zone boundary (Fig. 6). Other thickening shear zones lie in the transverse foliation/shear-parallel lineation facies, in which the foliation and the shear sense indicators lie in the *ac*-plane (Fig. 6; Fossen et al., 1994). In these cases, the sense of shear indicators lie *within* the plane of foliation and parallel to the lineation. The case of the lineations forming in the *b*-axis (shear parallel foliation/transverse lineation facies) has been utilized to suggest transpressional tectonics, in zones of vertical lineation and vertical foliation (e.g. Hudleston et al., 1988; Fossen et al., 1994; Robin and Cruden, 1994). As stated above, several of the three-dimensional reference deformations exhibit this strain facies. In this case, the asymmetric structures will lie in the foliation, but the asymmetry indicators are perpendicular to the lineation (Fig. 6).

It is interesting, from a historical perspective, to realize that the concept of kinematic axes (Sander, 1930) was utilized primarily to explain the existence of *b*-axis-oriented lineations in strongly deformed rocks. Although favored in the later literature (e.g. Cloos, 1946; Anderson, 1948; Kvale, 1953), *a*-lineations are not the general rule for three-dimensional deformations and increased quantification requires a return to older ideas.

Other variations of foliation and lineation patterns are possible (Fig. 6). The transverse foliation/shear-parallel lineation facies is possible for intermediate deformations that lie between lengthening/narrowing shear and lengthening shear. In this case, the sense of shear indicators lie in the plane of foliation and the lineation is not parallel to the simple shear component of deformation. The shear-parallel foliation/transverse lineation facies is possible for deformations intermediate between lengthening/widening shear and widening/shortening shear. In this case, sense of shear indicators are perpendicular to the transverse lineations (Fig. 6).

There are additional complications that also deserve investigation. For example, deformations involving constrictional finite strains may not form the commonly used shear sense indicators, such as shear bands. In these cases, rotated porphyroclasts related to the simple shear component may still occur, but shear planes will not. Constrictional deformations which do not act parallel to the simple shear direction, such as widening shear or thickening shear, may form completely different structures. In contrast, in deformations which result in flattening fabrics, shear planes should be quite well developed, but other features (porphyroclast systems?) may be less well developed. Regardless, shear-sense indicators are still highly applicable to three-dimensional settings, but their application may require some re-evaluation in the context of three-dimensional deformation.

5.2. Assumptions of three-dimensional reference deformations and the strain facies

The three-dimensional reference deformations are one of the simplest sets for classification of three-dimensional deformation, in which the three-dimensional reference deformations form the end-members of a continuum of deformation. There are several assumptions and limitations of this approach. The three-dimensional reference deformations assume that the coaxial component acts perpendicular to the simple shear component of deformation. If this is not assumed, deformation becomes more complicated and generally has triclinic symmetry (e.g. Robin and Cruden, 1994; Dutton, 1997; Lin et al., 1998). The reference deformations also require that the shear zone does not have an external rotation (e.g. it is not a spinning shear zone) and that the translation caused by the deformation is treated independently. The three-dimensional reference deformation also assumes that there is no volume loss, either isotropic or anisotropic. For the finite strain results presented here, we assumed steady-state deformation: neither the three-dimensional reference deformation or *Wk* changed during deformation. However, the assumption of steady-state deformation is not required for either the concept of reference deformations or strain facies.

5.3. Lithospheric layers and boundary conditions

The motivation behind the description of the strain facies is ultimately to understand three-dimensional deformation in naturally deformed rocks. Some of the reference deformations may seem potentially less likely (e.g. thickening shear) than others (lengthening/thinning shear). This bias may be a result of our inherently upper-crustal perspective—fault zones are well-described as thin zones of simple shearing—and the notion that simple shear is the dominant kinematics of ductile shear zones. However, numerous studies of ductile shear zones indicate a significant departure from simple shear (e.g. Srivastava et al., 1995). Thus, the increased ductility with depth probably facilitates the coaxial component of deformation by relaxing the strain compatibility conditions. Large deviations from simple shear are also expected in areas around local heterogeneities, caused by either changes in rheology or boundary conditions. The difference in the rheological behavior of the crust, such as the cover–basement transition or the lower crust–upper mantle transition, may be a good example of the former. Extrusion tectonics—either outward (e.g. Ratschbacher et al., 1991) or upward (e.g. Robin and Cruden, 1994)—requires significant deviation from simple shearing.

The important aspect of the strain facies is the recognition that different fabrics potentially result from similar flow fields. Both shear-parallel foliation/shear-parallel lineation facies and shear-parallel foliation/transverse lineation facies are observed in structural continuity in thrust belts (e.g. Sander, 1930; Nadeau and Hanmer, 1991) and transpressional zones (e.g. Tikoff and Greene, 1997). The coexistence of these facies provides valuable information about the kinematics of deformation.

The physical experiments of Merle (1989) provide a good quantitative basis for application of the concept of strain facies. In these experiments, the gravitational movement of silicone was observed. The silicone was allowed to 'spread' (lengthen along the *a*-axis) down a tube. At the end of the tube, material was allowed to extrude radially (both *a*-axis extension and *b*-axis extension, or lengthening–widening), in an attempt to simulate a spreading nappe. Three of the strain facies existed in these experiments—*ab*-foliation/*a*-lineation, *bo*-foliation/*o*-lineation, and *ab*-foliation/*b*-lineation—all in structural continuity. Also, *ab*-foliation/*a*-lineation fabric was found in much of the experiment, particularly low in the material and against the rigid basement. *bo*-Foliation/*o*-lineation fabric was found in the higher levels, towards the tube. *ab*-Foliation/*b*-lineation fabric was found at the higher levels, but towards the toe of the extruding–spreading model.

These experiments are important for two reasons. First, they demonstrate the importance of the boundary conditions (walls vs no walls) on the development of fabrics. Secondly, they demonstrate that different structural styles occur at different structural levels. The strength of the strain facies approach is that it allows deciphering of the flow field from the available fabrics. The area of *bo*-foliation/*o*-lineation must be an area where the shear zone is thickening and an area of *ab*-foliation/*b*-lineations is a zone of thinning and widening. The zone of *ab*-foliation/*a*-lineation is a zone of predominantly simple shear, but with some thinning, because it is constrained by the compatibility with the base of the experiment. Yet, these fabrics are all kinematically related. Thus, the experiments of Merle (1989) allow us to check the validity of the strain facies approach: *Physical properties of a structural assemblage express the conditions of its formation.*

6. Conclusions

The three-dimensional reference deformations are idealized deformations that involve a simultaneous combination of a three-dimensional coaxial component (constriction, flattening, or pure shear) and an orthogonal simple shear component. These 12 deformations provide categorization for a continuum of volume-constant, three-dimensional deformations and may be distinguished by their velocity and displacement fields.

The kinematic vorticity, flow apophyses, and infinitesimal strain axes are defined for these deformations. If the assumption of steady-state deformation is made, the finite strain axes, movement of material particles, and rotation of material lines and planes can be calculated.

Characteristic patterns of foliation and lineation that emerge from general three-dimensional (or two-dimensional) deformations are considered as individual strain facies. Six strain facies are defined for the spectrum of three-dimensional deformations considered in this article. The concept of strain facies is a useful descriptive tool for three-dimensional deformation, in terms of the kinematic axes, and provides the connection between the reference deformations and the resultant geological structures. The ultimate purpose of the strain facies is to describe the flow of material in terms of the observable geological structures. The approach emphasizes the role of boundary conditions within naturally formed deformation zones.

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Appendix A

A.1. Displacement fields

The displacement field contains components of translation, rotation, and stretching (e.g. Means, 1990). Translation is not considered in strain analyses nor is it treated separately. Because we are considering non-spinning deformations, the only component of the rotation is the shear-induced rotation caused by the simple shear component of deformation (e.g. no rigid-body rotation). Further, because we are considering only material steady-state deformations (i.e. the kinematics of deformations do not change with time), the displacement field is simply the integration of the velocity field.

There are three directions of the displacement field which are of particular interest: the orientation of the flow apophyses, which define the maximum, intermediate, and minimum gradients of movement within the flow field. Movement of material particles in the direction of the flow apophyses is either directly towards the coordinate origin, directly away from the origin, or fixed. For the reference deformations, one flow apophysis is always parallel to the *a*-axis (*a*-apophysis) and one is always parallel to the *b*-axis (*b*-apophysis). The third flow apophysis, which is generally oblique to all the kinematic axes, represents the direction of relative particle movement between opposite sides of the deforming zone (*o*-apophysis). Its orientation depends on Wk or the kinematic vorticity number.

The displacement fields for the three-dimensional reference deformations are shown in Fig. 4, for a constant $Wk = 0.5$. Because of the difficulty in showing movement of material points in three dimensions, we have simplified the plots by showing movement in two orthogonal, two-dimensional planes.[1] These planes are defined as containing two of the flow apophyses, which generally act as barriers to particle movement (the *a*-apophysis/*o*-apophysis plane and the *b*-apophysis/*o*-apophysis plane). The orientations of the flow apophyses are given by the dark lines and the particle paths are given by the light lines (Fig. 4).

A.2. Thinning shear zones

For a given $Wk = 0.5$, two apophyses are parallel to the *a*- and *b*-axes for all thinning shear zones (Fig. 4). The orientation of the *o*-apophysis is generally different between the thinning reference deformations. For example, lengthening/thinning and widening/thinning shear have different coaxial components in the *ac*-plane and therefore different orientations of the *o*-apophysis for identical values of Wk. Lengthening shear or lengthening–widening shear have parallel *o*-apophyses, as they are only distinguished by whether material moves away from or toward the *b*-axis.

Lengthening shear, lengthening/thinning shear, and lengthening–widening shear all show curved or hyperbolic particle paths in the *ac*-plane (Fig. 4). For three-dimensional deformations, the occurrence of curved particle paths implies the existence of both a coaxial component of extension (or contraction) in one direction and a coaxial component of contraction (or extension) in the perpendicular direction, but the two do not need to be equal in magnitude. In other words, curved particle paths can result from cuts through flattened or constricted shear, and pure shear is not

[1] A computer program that simulates progressive deformation of the reference deformations is available. The program was presented at a GSA short course given in 1997 (Wojtal and Tikoff, 1997) and is freeware. The program requires NAG Explorer, which runs on either a SGI or PC computer, and is available from the authors (BT).

required as for the two-dimensional case (Ramberg, 1975).

Particle paths are distinctly different for these three deformations in the *b*-apophysis/*o*-apophysis plane. Lengthening shear has curved particle paths in this plane, with the extension direction parallel to the *o*-apophysis. Lengthening/thinning shear has straight flow lines in this plane, due to its plane strain behavior. Lengthening–widening shear shows outward radiating particle paths, described as an 'out-of-the-drain' path (Tikoff and Fossen, 1996; Passchier, 1997).

Widening/thinning shear has straight particle paths in the *ac*-plane because only the contraction part of the pure shear component of deformation is visible in the *ac*-plane. The corresponding extension in the *b*-direction is not visible on the diagram. Consequently, the flow lines for widening/thinning shear in the horizontal plane (only) are identical to those of anisotropic volume loss and simultaneous simple shear (Fossen and Tikoff, 1993; Tikoff and Fossen, 1996). Widening/thinning shear demonstrates curved particle paths in the *b*-apophysis/*o*-apophysis plane, with the extension direction toward the *b*-axis.

While widening/thinning shear represents anisotropic volume loss and simple shear in the *ac*-plane, widening shear is identical to isotropic volume loss and simple shear in the *ac*-plane. This results in inward-curving ('down-the-drain') particle paths in the *ac*-plane, in which the *b*-axis acts as a material line 'sink' (Passchier, 1987; Tikoff and Fossen, 1996) or attractor (Passchier, 1997). Unlike the other cases of thinning shear zones (e.g. lengthening/thinning shear), the constrictional coaxial component does not counteract the simple shear component to elongate material parallel to the *a*-axis, which would result in movement opposite to the simple shear component. Rather, all points are rotated by the simple shear component, while the coaxial component causes particle paths to become attracted to the *b*-axis. Widening shear, similar to widening/thinning shear, has curved particle paths in the *b*-apophysis/*o*-apophysis plane, with the extension direction parallel to the *b*-axis.

A.3. Thickening shear zones

Because of the inherent symmetry of the classification, the flow apophyses and particle paths of the thickening shear zones are just the inverse of their thinning counterparts across the circle (Fig. 2). The only distinction is that material moves away from the origin in the direction of the oblique flow apophysis for thickening shear zones, rather than vice versa.

For the constant $Wk = 0.5$, widening–thickening shear and thickening shear have identical flow apophyses, as do thinning shear zones lengthening shear or lengthening–widening shear (Fig. 4). Widening–thickening shear, thickening/shortening shear, and thickening shear all show curved or hyperbolic particle paths in the *ac*-plane. Thickening/narrowing shear has straight particle paths oriented parallel to the oblique flow apophysis, and lengthening–thickening shear shows 'out-of-the-drain' particle paths. In the *b*-apophysis/*o*-apophysis plane, widening–thickening shear, thickening/shortening shear, and thickening shear have curved particle paths, although the extension direction is toward the *b*-axis for the former case and toward the oblique flow apophysis for the latter cases. Thickening/shortening shear demonstrates straight particles paths, and lengthening–thickening shear shows 'out-of-the-drain' particle paths with the *b*-axis acting as the 'source' or 'repellor'.

A.4. Constant thickness shear zones

Lengthening/thickening shear and widening/shortening shear do not result in an increase or decrease in shear zone thickness, since neither the coaxial nor the simple shear component of deformation moves particles with respect to the *c*-axis. In the *ac*-plane, the deformation is a combination of simple shear and anisotropic area gain (lengthening/thickening shear) or loss parallel to the *a*-axis. Consequently, the particle paths in the *ac*-plane are always *a*-axis parallel, although movement can be away from (lengthening/thickening shear) or towards (widening/shortening shear) the oblique flow apophysis (Fig. 4). In the plane defined as the *b*-apophysis/*o*-apophysis plane, particle paths are hyperbolic. The only difference is that the extension direction is the *a*-axis for lengthening/thickening shear and the *b*-axis for widening/shortening shear.

A.5. Finite strain

The orientations and magnitudes of the finite strain axes are given by the deformation matrix, or position gradient tensor, **D**. For this discussion of the three-dimensional reference deformation, only steady-state deformation are described, although non steady-state histories for any of the reference deformations can be investigated (e.g. Fossen and Tikoff, 1997).

Finite strain is a result of the multiplicative addition of the infinitesimal strains (e.g. Elliott, 1972). That is, for very small deformations, the finite strain axes ($S_1 > S_2 > S_3$) are parallel to infinitesimal strain axes. From this point on, the flow apophyses and the displacement field play a major role in determining the orientation of the finite strain axes (Passchier, 1997). For all of the three-dimensional reference deformations, one of the finite strain axes will always lie parallel to the *b*-axis, parallel to the *b*-apophysis. The other two finite strain axes lie in the *ac*-plane and rotate with increasing deformation because of the simple shear component of deformation. The larger finite strain axis rotates into parallelism with the extensional flow apophysis. The other finite strain axis rotates into a perpendicular orientation to the extensional flow apophysis in the *ac*-plane, since the finite strain axes are mutually perpendicular. Notice that the extensional finite strain axes in the *ac*-plane rotate into parallelism with either the *a*-axes or the *o*-apophysis, depending on which is extensional. Only in the case of a coaxial deformation are all three of the finite strain axes parallel to both the flow apophyses and kinematic axes, since this is the only case when the flow apophyses are mutually orthogonal.

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