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Inclined transpression

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Abstract

Inclined transpression can be defined in terms of simultaneous contraction and strike-slip and dip-slip shearing, and is illustrated here using a strain triangle in which the apices represent the three strain components. Strain matrix modelling shows that all three axes of the finite strain ellipsoid are non-parallel to the Cartesian reference frame, and that they experience complex non-planar rotations during ongoing deformation. As there is a component of vorticity about each axis of the strain ellipsoid, strains have triclinic symmetry. Providing structural fabric at least partially tracks the orientation of the finite strain ellipsoid, then both strike and dip of foliation will be oblique to zone boundaries. Pitches of stretching lineations within the fabric plane are very variable, and can change during progressive deformation.

An example of an upper-crustal inclined transpression zone is exposed at Eyemouth, SE Scotland. As with most natural transpression zones, deformation at Eyemouth is highly heterogeneous, and widespread kinematic strain partitioning has given rise to an irregular distribution of strain components and resulting structures. A wide range of coeval structures are visible in outcrop and allow four different types of deformational domain to be defined. Domains are characterised by the presence or absence of dip-slip, strike-slip, oblique-slip, contractional, and hybrid structures at outcrop and map scales. Localisation of one or more types of structure occurs within deformational domains, and delineation of these can help interpretation of complex transpression zones.

Keywords: Deformational domains; Strain partitioning; Transpression; Triclinic strain symmetry

1. Introduction

Non-coaxial, non-plane strain deformation is an inevitable consequence of the motion of lithospheric plates on the surface of a sphere (Dewey, 1975; Dewey et al., 1998). Transpression and transtension are concepts that can help us understand the three-dimensional nature of deformation and are often used when analysing deformed regions of the Earth's crust (e.g. Holdsworth et al., 1998 and references therein). Sanderson and Marchini (1984) provided a mathematical framework for analysing transpression. Although they assumed highly idealised and simplified deformation, their model was nevertheless a useful first-order description of deformation zones in which the bulk strain is determined by deformation zone boundaries (or pre-existing structural anisotropy) oriented oblique to the direction of tectonic contraction/extension. This was an important step in increasing our understanding of the way in which deformation arising from plate movements is accommodated in the heterogeneous anisotropic crust.

There have subsequently been many modifications and further developments of the Sanderson and Marchini model. Various boundary conditions inherent in the original model have been changed in order to analyse the effects of simultaneous pure and simple shearing (Fossen and Tikoff, 1993; Tikoff and Fossen, 1993), strain partitioning (Tikoff and Teyssier, 1994; Jones and Tanner, 1995; Teyssier et al., 1995), heterogeneous variation in strain intensity (Robin and Cruden, 1994; Dutton, 1997), volume change (Fossen and Tikoff, 1993), basal and lateral stretch (Jones et al., 1997; Fossen and Tikoff, 1998), and vertical displacement of one bounding block relative to the other (Robin and Cruden, 1994; Jones and Holdsworth, 1998; Lin et al.,

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1998). More detailed mathematical analyses have been developed by Soto (1997) and Ghosh (2001).

A common feature of most transpressional models is that they have used a basic geometry of an upright zone deformed between vertical zone boundaries. Non-vertical zones were considered briefly by Dutton (1997), who termed such deformation 'inclined transpression'. Inclined transpressional models are applicable to most natural collisional plate margins and many other shear zones in the crust, which are often non-vertical. This paper develops a mathematical description of inclined transpression, and then discusses the applicability and limitations of the model in relation to naturally occurring zones of inclined transpression.

2. Theory

2.1. Inclined transpression

We can develop a mathematical description of inclined transpression by extending the model of Sanderson and Marchini (1984) to consider non-vertical dipping deformation zones (Fig. 1). All other assumptions involving idealised boundary conditions remain as defined by Sanderson and Marchini: deformation is homogeneous, constant volume, laterally and basally confined, and occurs between parallel zone boundaries. We can consider inclined transpression in which the undeformed zone bounding blocks approach one another along displacement vectors that remain in the horizontal plane (Fig. 1b), or we can relax the boundary conditions and also allow vertical movement of one zone bounding block with respect to the other (Fig. 1c).

Because the orientation of transpressional shortening across an inclined zone is oblique to all three principal planes of the reference coordinate system (i.e. the X_cY_c, X_cZ_c and Y_cZ_c planes), the component of simple shear acting in the plane of the zone boundary will be oblique to both the X_c and Z_c axes. This simple shear component in the X_cZ_c plane can therefore be further factorised into two simple shears, one acting parallel to the X_c axis, the other parallel to Z_c, and the inclined transpressional deformation can be described by the strain matrix for oblique simple shear in transpression

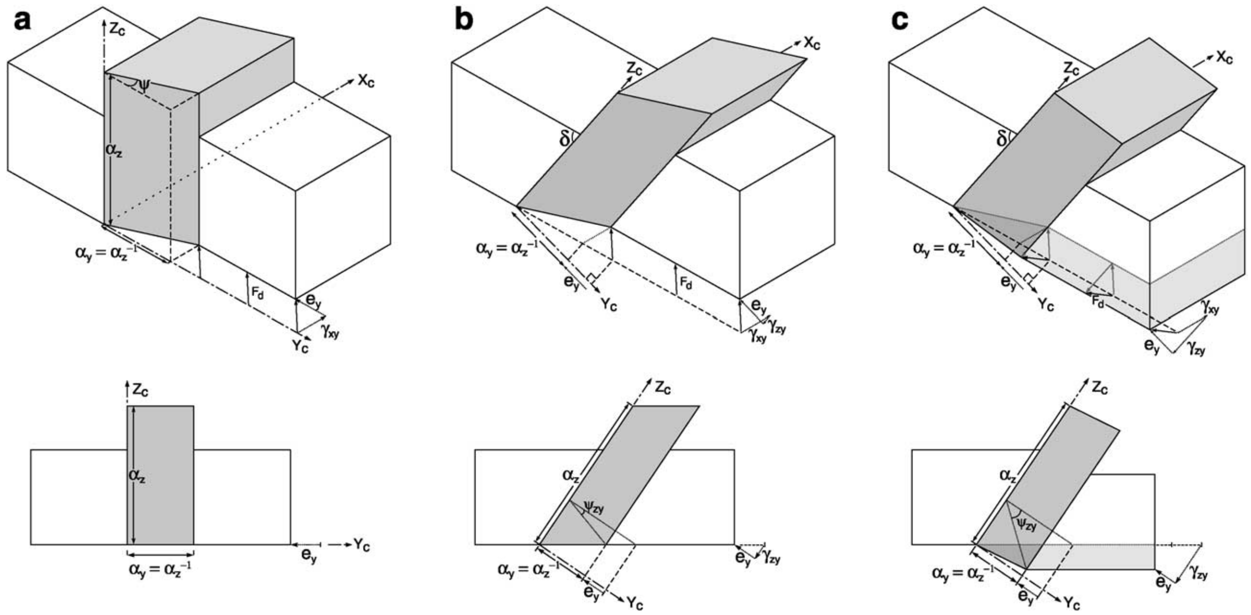

Fig. 1. Vertical and inclined transpression viewed in 3D (top) and in cross-section normal to X_c (bottom). The original width of the zone orthogonal to the zone boundary is unity. Deformation is constant volume. (a) Vertical transpression zone, from Sanderson and Marchini (1984). The Cartesian coordinate axes X_c and Y_c are horizontal, and Z_c is vertical. The zone boundary displacement vector lies in the X_cY_c plane. (b) Inclined transpression zone; dip of the zone = δ. Displacement of the undeformed zone bounding blocks with respect to one another occurs entirely in the horizontal plane. (c) Inclined transpression in which the zone bounding blocks experience a component of relative vertical displacement. The frontal block (i.e. the footwall) is downthrown with respect to the rear block, so that part of it (light shading) lies below the horizontal reference frame. In both (b) and (c) the vector of finite zone boundary displacement lies oblique to all three principal planes of the Cartesian coordinate system. Mathematical description is simplified by rotating the Cartesian coordinate system (about the X_c axis which remains horizontal), so that Z_c lies in the plane of the zone boundary (i.e. Z_c lies along the true dip of the zone), and therefore Y_c remains perpendicular to the zone boundary. α_y is the stretch parallel to the Y_c axis, so that α_z^{-1} is the ratio of the deformed to original zone width (measured along the Y_c axis). e_y is the extension/contraction of the zone parallel to Y_c, and therefore $e_y = (1 - \alpha_y)$. γ_{xy} and γ_{zy} are the shear strains acting in the plane of the zone boundary parallel to X_c and Z_c, respectively. *Fd* is finite displacement of one zone-bounding block relative to the other (note that the incremental displacement path need not necessarily be straight).

given by Jones and Holdsworth (1998):

$$\mathrm{D} = \underbrace{\begin{pmatrix} 1 & \gamma_{XY} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{simple shear in } X_c Y_c \\ \text{(strike-slip)}}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & \gamma_{ZY} & 1 \end{pmatrix}}_{\substack{\text{simple shear in } Y_c Z_c \\ \text{(dip-slip)}}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \alpha_z^{-1} & 0 \\ 0 & 0 & \alpha_z \end{pmatrix}}_{\substack{\text{pure shear in } Y_c Z_c \\ \text{(contraction)}}}$$

$$= \underbrace{\begin{pmatrix} 1 & \gamma_{XY}\alpha_z^{-1} & 0 \\ 0 & \alpha_z^{-1} & 0 \\ 0 & \gamma_{ZY}\alpha_z^{-1} & \alpha_z \end{pmatrix}}_{\text{inclined transpression}} \tag{1}$$

In terms of the deformation matrix, inclined transpression in a dipping zone is directly comparable with oblique transpression in a vertical zone, the only difference being the orientation of the reference coordinate system.

For the following analysis we use the more rigorous matrix, based on the approach used by Fossen and Tikoff (1993) and Tikoff and Fossen (1993), which allows transpressional deformation to be considered in terms of simultaneous pure and simple shearing:

$$\mathrm{D} = \begin{pmatrix} 1 & {}_{\mathrm{FT}}\gamma_{XY}(1-\alpha_z^{-1})\ln(\alpha_z) & 0 \\ 0 & \alpha_z^{-1} & 0 \\ 0 & {}_{\mathrm{FT}}\gamma_{ZY}(1-\alpha_z^{-1})\ln(\alpha_z) & \alpha_z \end{pmatrix} \tag{2}$$

2.2. Shape and orientation of the finite strain ellipsoid during inclined transpression

Inclined transpression gives rise to non-coaxial, non-plane strain geometries. Finite strains lie in the flattening field of the Flinn plot for transpression (as shown in fig. 3 of Jones and Holdsworth, 1998), and in the constrictional field in transtension. The exact shape of the finite strain ellipsoid ('FSE') after deformation depends upon the interplay of all three strain components γ_{XY}, γ_{ZY} and γ_z (Eqs. (1) and (2)). Of these, the dip-slip simple shear component γ_{ZY} will have relatively little influence on FSE shape unless the dip of the transpression zone (δ) is shallow, and/or there is significant vertical movement of one zone bounding block relative to the other.

Because the direction of regional (far-field) shortening is oblique to all three principal planes of our coordinate system, all three axes of the FSE will continuously change orientation during progressive inclined transpression (cf. fig. 4 of Jones and Holdsworth, 1998). Each axis does not remain within a single plane during ongoing deformation (so that when the rotation path is plotted on a stereonet it does not lie on a great circle). Thus, the vorticity vector for finite strain changes orientation progressively and remains non-parallel to the three principal finite strain axes (when $0 < \delta < 90$ and $0 < \beta < 180$). Because there is a component of vorticity acting on all three axes of the FSE the resultant strain geometries have triclinic symmetry (Paterson and Weiss, 1961; Robin and Cruden, 1994; Jones and Holdsworth, 1998; Lin et al., 1998; Jiang, 1999).

2.3. Simple inclined transpression

Eqs. (1) or (2) can be used to predict bulk finite strains arising from any sequence of combinations of infinitesimal pure and simple shear, representing an infinite range of possible deformation paths. In situations where the relative displacement of zone boundaries is known (e.g. from plate motion vectors) or where field data contain adequate strain markers to allow the deformation path to be well understood, appropriate incremental strain values can be carefully chosen to allow specific deformation zones to be modelled in detail. In order to be able to analyse transpression models that are more generically applicable, we can add a further boundary condition and consider inclined transpression in which zone boundaries approach one another along straight horizontal displacement vectors (i.e. constant zone boundary displacement). Following the terminology of Harland (1971) and Sanderson and Marchini (1984), we call this '*simple* inclined transpression' (Fig. 2). The advantage of this approach with respect to modelling is that it makes it possible to express the amounts of pure and simple shear (α_y, γ_{xy}, γ_{zy}), and hence the shape and orientation of the strain ellipsoid, entirely in terms of zone geometry (β, δ) and amount of shortening (S):

$$\alpha_y = \alpha_z^{-1} = (1 - S) \tag{3}$$

$$\gamma_{xy} = \tan\psi_{xy} = S\cot\beta((1-S)\sin\delta)^{-1} \tag{4}$$

$$\gamma_{zy} = \tan\psi_{zy} = S\cot\delta(1-S)^{-1} \tag{5}$$

For an inclined transpression zone of given dip (δ) and strike (β), we can model progressive deformation by substituting Eqs. (3)–(5) into Eq. (2), for successive increments of S. The progressive change in shape of the finite strain ellipsoid can then be plotted on Flinn diagrams, and the progressive rotation of the ellipsoid axes can be plotted on stereonets. Previous work has shown that variations in the angle β generally have a marked effect on both the shape of the finite strain ellipsoid (e.g. fig. 7 of Sanderson and Marchini, 1984) and its orientation (e.g. fig. 5 of Jones and Tanner, 1995). Fig. 3 shows the predicted influence of zone dip, δ, on the shape of the finite strain ellipsoid. A range of values of δ is shown, for four fixed values of β, during progressive simple inclined transpression. As expected for transpressional deformation, the strain paths fall in the flattening field of the Flinn diagram. The plots show that for a given value of β, the angle of inclination of the zone δ has relatively little effect on the strain path unless zone dip is shallow (typically less than 30–40°).

The stereonets in Fig. 4 confirm that during progressive zone shortening all three axes of the FSE continuously change orientation along non-planar arcs, and always remain oriented oblique to all three Cartesian coordinate axes (until 100% shortening is reached). This is most

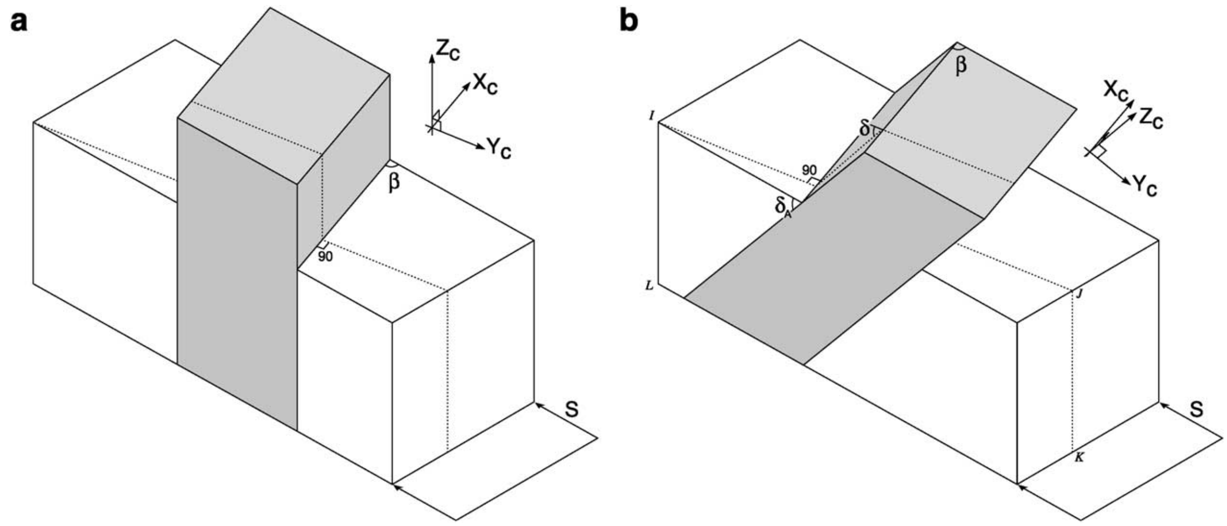

Fig. 2. Simple transpression. *S* is the amount of horizontal shortening across the zone measured parallel to the far-field displacement vector. β is the angle in the horizontal plane between the zone boundary and the direction of overall shortening. (a) Simple transpression in a vertical transpression zone, after Sanderson and Marchini (1984). (b) Simple inclined transpression. δ is true dip of the zone (δ_A is an apparent dip). The vertical plane *IJKL* is normal to the X_c axis, and contains the angle δ, and the Z_c and Y_c axes.

noticeable when deformation is markedly transpressional (i.e. both '*trans*' and '*press*' components are significant; see Fig. 4b and c). For zone geometries where β is low (Fig. 4a) or high (Fig. 4d) deformation tends towards end-member strains (strike-slip and overthrusting, respectively), and the orientation of the intermediate axis of the FSE does not change significantly with progressive deformation (until zone shortening exceeds 90%), so that resultant strain symmetries can effectively appear monoclinic (cf. Lin et al., 1998).

Because γ_{xy} and γ_{zy} both have a non-linear relationship with *S* (see Eqs. (4) and (5)), the orientation of the vorticity vector and the rate of vorticity will both vary as deformation progresses. Although we can characterise deformation in terms of finite vorticity relative to our Cartesian reference frame (Fig. 4), it is even more useful to consider the orientation of the vorticity vector relative to the FSE. With regard to observable geological structures it is this relationship between vorticity and foliation that gives rise to the development of asymmetrical shear-sense indicators (see later). One way of illustrating this is to show the change in orientation of the long axis of the FSE, X_s, measured within the X_sY_s plane. For some deformation paths X_s remains almost strike-parallel or down-dip during large amounts of transpressional shortening, but for most paths the angle of pitch of X_s will change significantly during ongoing deformation (Fig. 5).

3. Geological implications

Natural deformation of rocks rarely conforms with the inherent assumptions used in mathematical models The boundary conditions we have chosen are idealised and simplistic in comparison with deformation in real shear zones. Nevertheless, modelling does provide a basic framework for understanding finite strains in real transpression zones, and helps us to make general predictions concerning the nature and orientation of structures which should be broadly applicable (at least qualitatively) to zones of inclined transpression.

3.1. Fabric orientation in inclined transpression zones

Unless finite strain has been completely partitioned into separate deformational domains, the tectonic foliation that develops during transpressional deformation will generally have a strike and dip that is non-parallel to the zone boundaries (Fig. 6). The strike obliquity of the foliation will reflect the strike-slip component of deformation, γ_{xy}. The dip of the foliation will generally be steeper than dip of the zone boundary due to the non-coaxial component of overthrusting, γ_{zy} (though for some finite strains the direction of dip of foliation can be opposite to that of the zone boundary, as shown in Fig. 6b).

Stretching lineations lying almost strike-parallel, or significantly oblique, or approximately down-dip are all feasible in inclined transpression zones, so that the angle of pitch of the lineation within the foliation plane can vary from almost 0° to nearly 90°. When the elongation direction remains roughly down-dip (e.g. Fig. 6b) or strike-parallel (e.g. Fig. 6c) the strain symmetry can appear almost monoclinic (Lin et al., 1998; Jiang et al., 2001), whereas intermediate values of pitch are associated with strains that are more recognisably triclinic (e.g. Fig. 6a). In any case, interpretation of the finite strain is most reliable when the deformation zone boundaries are well exposed and well defined, so that the orientation of the foliation and stretching

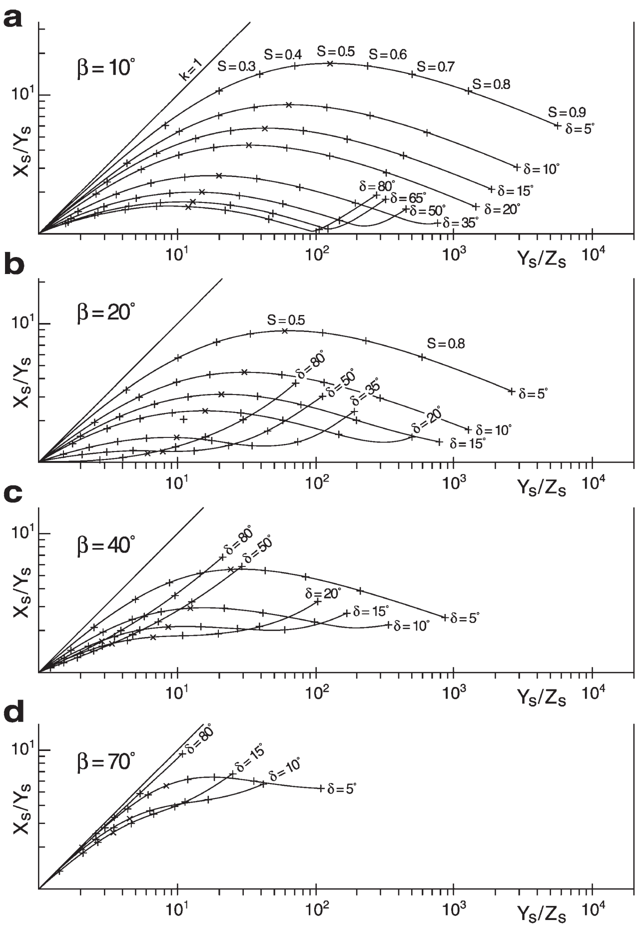

Fig. 3. Flinn plots showing strain paths for simple inclined transpression, for four different convergence angles β. Each plot shows a set of strain paths for a range of different angles of dip of the deformation zone, δ. The plots represent zone shortening from zero to 90% (i.e. from $S=0$ to $S=0.9$). All plots show that unless the dip of the zone is shallow (e.g. less than 40°), the progressive change in shape of the three-dimensional finite strain ellipsoid is not heavily dependent upon zone dip.

lineation can be compared with the orientation of the zone boundaries. Whether or not the stretching direction is roughly strike-parallel, oblique or nearly down-dip, strain symmetry can be recognised as triclinic when the angle measured in the plane of foliation between stretching lineation and the intersection of foliation and zone boundary is not zero or 90° (Fig. 6). Providing the zone boundary can be delineated, this relationship is a useful diagnostic, as it applies even if the whole zone has experienced post-deformational tilting or reworking.

3.2. Progressive changes in orientation during ongoing deformation

During inclined transpression there is a general tendency for the orientation of the X_s axis and X_sY_s plane of the FSE to change progressively in 3D space (Figs. 4 and 5). If we assume that the tectonic fabric at least partially tracks the orientation of the X_sY_s plane, then both strike and dip of foliation will gradually change so that foliation rotates towards parallelism with the zone boundaries (Fig. 4). In many mid- and lower-crustal deformation zones, the lithological and environmental controls (e.g. P, T, strain rate, mineralogy, grain size, etc.) give rise to rheologies in which fabric can re-orientate progressively, at least for moderate strain levels. As deformation increases, it is less likely that foliation will remain parallel to the X_sY_s plane of the FSE, as secondary fabrics develop and strain heterogeneity increases (Lister and Williams, 1983; Goodwin and Tikoff, 2002).

Even for a deformation that is relatively homogeneous, the progressive change in the orientation of stretching lineations can be highly variable, and depends heavily upon the actual strain path experienced by the deforming zone (cf. Fig. 5). For some deformation paths the lineation can remain almost strike-parallel or down-dip during large amounts of transpressional shortening, but for most paths the angle of pitch of the lineation will change significantly during ongoing deformation, even after only small amounts of zone shortening.

The constant re-alignment of foliation, and stretching lineation within it, gives rise to complex structural histories, and the accommodation of complicated rotational strains can lead to the development of enigmatic field structures. Although structural evidence for earlier fabric orientations is often removed as deformation progresses, an indication of 3D rotation of the FSE can sometimes be gained by analysing the nature of structural overprinting, fabric crenulation, growth of secondary fabrics, complex patterns of porphyroblast rotations, patterns of vein growth, difference in lineation orientation between high and low strain zones, convoluted fold evolution (including hinge rotation and migration, and development of curvilinear folds), polymodal mesofracture arrays, fault-slip data showing multiple phases of movement, etc. (e.g. Holdsworth, 1994; Dewey et al., 1998).

3.3. Shear-sense criteria

Because of the non-coaxiality of both strike-slip and dip-slip strain components in inclined transpression, sections that are cut parallel to X_sZ_s or Y_sZ_s may both contain asymmetrical structures that can be used as shear-sense indicators (Llana-Fúnez, 2002; Bailey et al., 2004). Even within the plane of foliation, X_sY_s there may be evidence of non-coaxiality, as a consequence of the progressive re-alignment of the elongation lineation during deformation (Figs. 5 and 7). The extent to which asymmetric structures are likely to be well developed on different orientations of surface is very dependent on the actual deformation path that the rock experiences; some paths for inclined transpression involve only small amounts of rotation around the X_s axis, whilst others can give rise to complex rotations about all FSE axes in which the sense of vorticity can

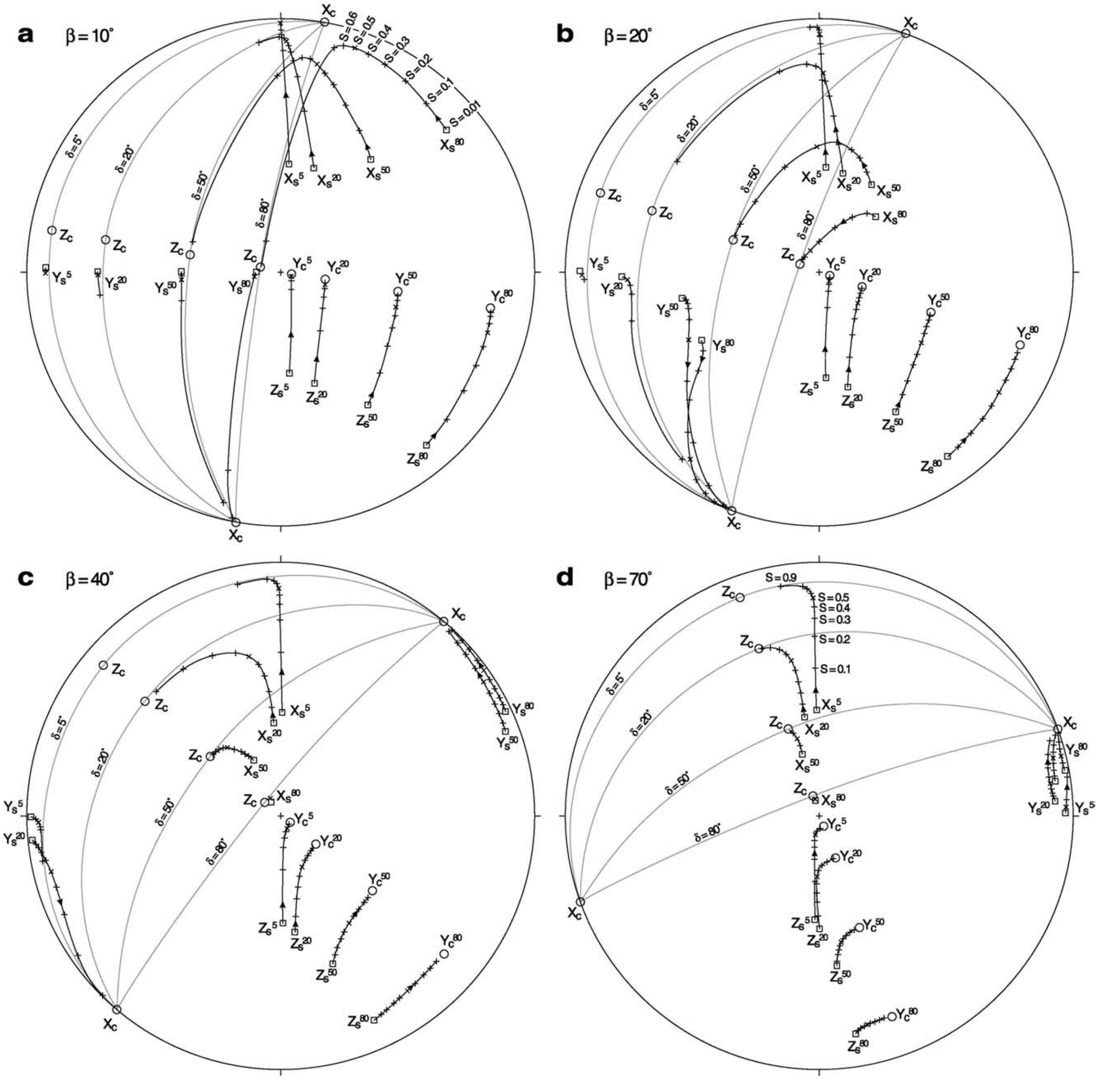

Fig. 4. Equal angle lower hemisphere stereonets showing the changes in orientation of the finite strain ellipsoid during progressive homogeneous simple inclined transpression. Four plots are shown, for varying angles of zone convergence, β. The zone geometry is comparable with that shown in Fig. 2b. Zone boundary (far-field) displacement is orientated N–S. The shear zone is sinistral and broadly NW dipping (i.e. WNW for low β angles, NNW for high β angles), and hence transpressional shortening gives rise to a top-to-SE component of overthrusting. Each plot shows ellipsoid orientations for a range of values of zone dip, δ (5°, 20°, 50° and 80°). In all cases, the short axis of the strain ellipsoid, Z_s, is oblique to all three Cartesian reference axes at the onset of zone shortening, but rotates towards parallelism with the Y_c axis during progressive deformation. Similarly, the long axis of the strain ellipsoid, X_s, rotates towards the down-dip Z_c direction, although this does not necessarily happen until high amounts of shortening. Rotation paths for the X_s axis can be complex. For some deformation paths the X_s axis becomes steeper as strain accumulates, whilst for others the opposite occurs. In some cases (e.g. $\beta = 10°$, $\delta = 50°$) the long axis of the strain ellipsoid plunges quite steeply at first, then becomes gradually shallower as deformation progresses, then steepens again as the X_s axis rotates towards the Z_c axis (see also Fig. 5b and c).

change during deformation. Whether or not the vorticity leads to the development of asymmetrical structures is also dependant upon the rheological properties of the rock and the deformation processes acting upon it. In some situations the constant realignment of the finite vorticity vector and the FSE, and their misalignment with respect to the instantaneous strain ellipsoid may be a factor that increases the likelihood of strain partitioning (cf. Tikoff and Teyssier, 1994).

Another important aspect of inclined transpression is that whilst one of the zone boundaries has a strong thrust component the other is a normal fault or shear zone. In this

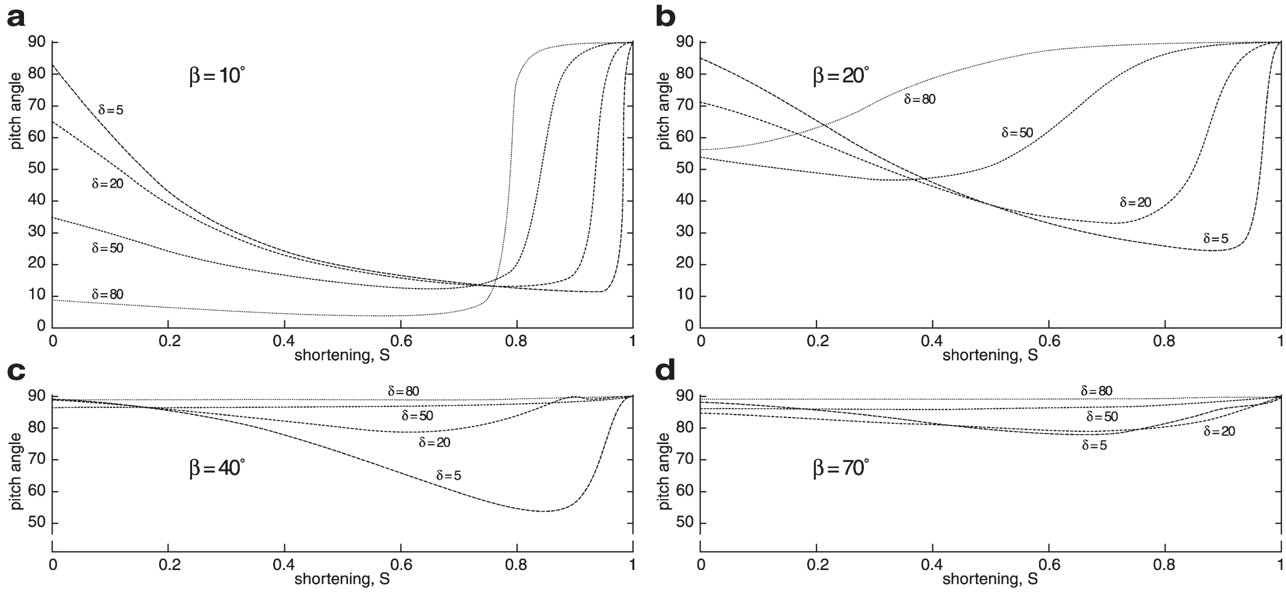

Fig. 5. Examples of deformation paths showing how the pitch of the long axis of the finite strain ellipsoid, X_s (measured in the X_sY_s plane) can vary during simple inclined transpression. For some deformation paths the X_s axis remains nearly strike- or dip-parallel throughout large amounts of transpressional shortening, but for many paths the pitch of X_s changes considerably, even during the first 20 or 30% of shortening.

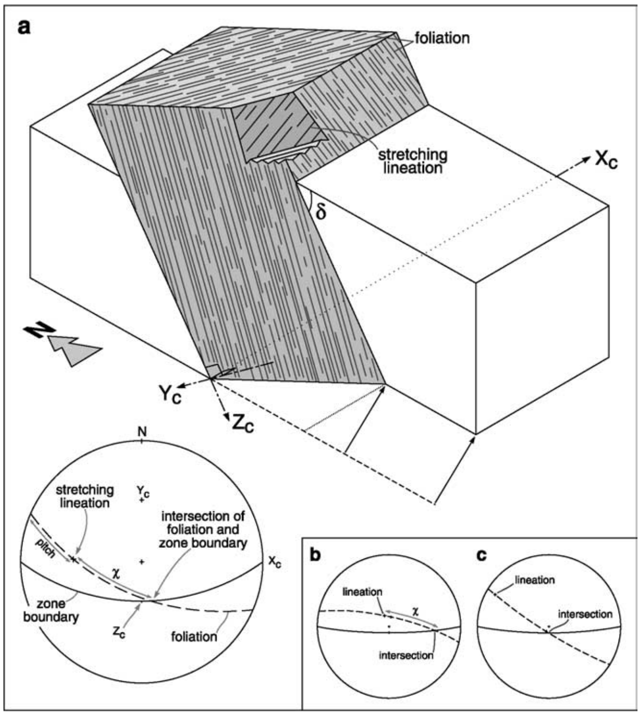

Fig. 6. Typical orientation of foliation and stretching lineation in inclined transpression (after Bailey et al., 2004). Foliation strikes obliquely to the deformation zone; foliation shown here lies clockwise of the zone boundary because the strike-slip component is sinistral. Foliation generally dips more steeply than the zone boundaries due to the non-coaxiality of the γ_{zy} component, shown in (a) as top-to-N overthrusting. When the zone is steeply dipping the foliation can have opposing direction of dip, as shown in inset (b). The pitch of stretching lineations within the plane of foliation can be steep (b), moderate (a), or shallow (c) depending on the state of finite strain. χ is the angle between the stretching lineation and the intersection of the foliation and zone boundary, measured in the plane of the foliation, and for triclinic strains $0° < \chi < 90°$.

way normal faulting can be intimately associated with the crustal shortening process, and the presence of normal faults does not necessarily imply crustal extension. Low angle normal detachments are recognised at the rear of the Himalayas (Searle and Brewer, 1998; Beaumont et al., 2001; Grujic et al., 2002).

4. Heterogeneity of strain

Deformation in the earth's crust is characteristically heterogeneous rather than homogeneous. Strain is usually heterogeneous at most scales of observation, and usually only approximates to homogeneity for a conveniently chosen scale and arbitrarily limited volume of rock. In many deformation zones there is an overall increase in the magnitude of strain towards the centre of the zone (Ramsay and Graham, 1970; Robin and Cruden, 1994), and often superimposed on this is a pattern of strain fluctuation in which strain intensity varies between low strain regions and anastomosing zones of localised high strain (e.g. Ramsay, 1967; Girard, 1993). Another very widespread expression of strain heterogeneity is the kinematic partitioning of strain into distinct deformational domains (see below).

Prevalent deformation mechanisms affecting most rock types tend to impart structural anisotropy in the rock during early phases of deformation, which subsequently influences rheology during progressive deformation (e.g. Lister and Williams, 1983; Jiang and White, 1995; Goodwin and Tikoff, 2002). Therefore, even when initial boundary conditions permit early deformation to be relatively homogeneous, it is nevertheless likely that strain heterogeneity will increase as deformation progresses.

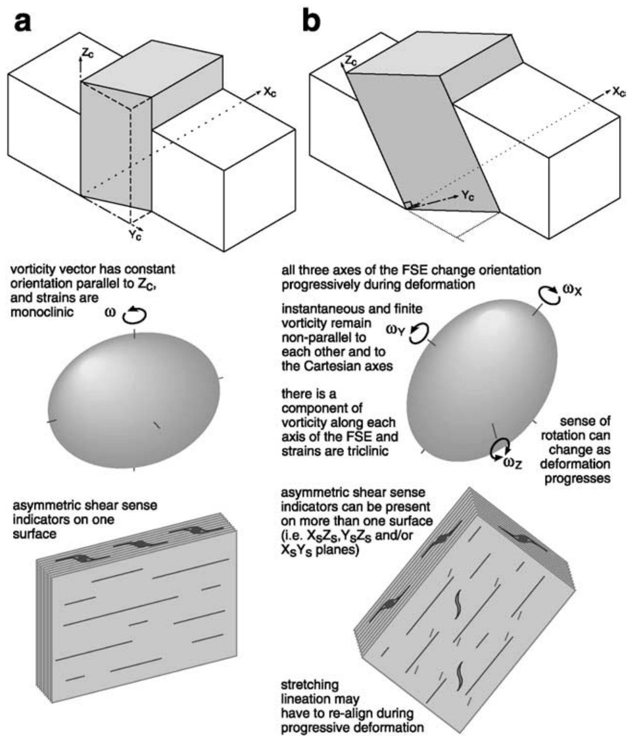

Fig. 7. Shear-sense indicators, vorticity and strain symmetry. (a) Vertical, idealised transpression. Rotation occurs around a vertical axis, which does not change orientation as deformation progresses. Therefore the instantaneous vorticity vector is always parallel to the axis of finite vorticity and one of the axes of the FSE. Strains have monoclinic symmetry, and asymmetric shear-sense indicators are visible on only one surface. (b) Inclined transpression. There is a component of vorticity acting along all three axes of the FSE, so that each axis will generally change orientation during progressive deformation, and the orientation of instantaneous vorticity and finite rotation are not aligned. Strains are triclinic, and for some strain paths asymmetric shear-sense indicators can appear on sections cut both parallel and perpendicular to the maximum elongation direction, and even within the plane of foliation.

5. Strain partitioning in inclined transpression

Deformation in transpression zones is often compartmentalised so that individual constituents of bulk strain are segregated and localised into separate deformational domains (e g. Cobbold et al., 1991; Cashman et al., 1992; Molnar, 1992; Tikoff and Teyssier, 1994; Jones and Tanner, 1995). This kind of spatial segregation of strain components allows adjacent domains to display very different contrasting structural geometries. Kinematic partitioning of strain can occur from grain-scale to plate-scale, and often represents a much greater cause of heterogeneity than gradual variations in strain intensity. Strain partitioning develops in response to initial (and/or deformation induced) structural anisotropies in the deforming material (e.g. Jones and Tanner, 1995; Curtis, 1998; Goodwin and Tikoff, 2002), and because of the mechanical difficulty of superimposing successive strain increments onto structures that are not suitably aligned; i.e. the misalignment of the principal axes of the instantaneous and finite strain ellipses during non-coaxial deformation (Tikoff and Teyssier, 1994).

Following the method used by Jones et al. (1997) and Jones and Holdsworth (1998) we can depict inclined transpression in terms of a 'strain triangle' (Fig. 8), in which the apices of the triangle represent the individual end-member strain components that comprise the strain matrix of Eq. (1). The area inside the triangle represents inclined and/or oblique transpressional strains. When partitioning occurs, bulk deformation that would plot inside the strain triangle is distributed between separate domains that are situated closer to the apices and edges of the triangle (Fig. 9).

Individual sets of structures each have a particular kinematic significance in relation to bulk transpressional deformation. Some examples of structures typically found in transpression zones are shown in Fig. 10. Interpretation should rarely, if ever, rely upon structural geometry alone, and kinematic evidence should be used as much as possible. Because the incremental strain history for some structures (e.g. folds with highly curvi-linear hinge lines), can be more difficult to interpret than for others, plotting on a strain triangle can involve varying degrees of subjectivity. Nevertheless, evaluating the kinematic effect of each type of structure with respect to domain and zone boundaries can be a helpful approach when analysing structurally complex transpression zones. Here we use this approach to interpret transpressional deformation in the coastal section at Eyemouth, SE Scotland.

6. Inclined transpression at Eyemouth, SE Scotland

The Eyemouth coastal section in SE Scotland displays a well exposed sequence of Silurian sediments (Dearman et al., 1962), part of the Southern Uplands terrane that deformed during late Silurian Caledonide orogenesis (McKerrow et al., 1977). The sedimentary sequence, consisting predominantly of turbiditic greywackes, is variously believed to represent an accretionary prism (Leggett et al., 1979; Needham and Knipe, 1986), or other type of subduction-related basin (Hutton and Murphy, 1987; Stone et al., 1987) associated with the sinistral transpressional closure of the Iapetus Ocean (Soper and Hutton, 1984; Soper et al., 1992).

6.1. Structural description

The structure of the Eyemouth section is described in detail by Mackenzie (1956), Dearman et al. (1962), Greig (1988) and Holdsworth et al. (2002a). Much of the section consists of several kilometres of NW-dipping homoclinal bedding, in places folded by SW-plunging, SE-verging folds. However, in the northern part of the section structural heterogeneity is much greater, with a broad range of fold and fault structures of varying structural geometry and style.

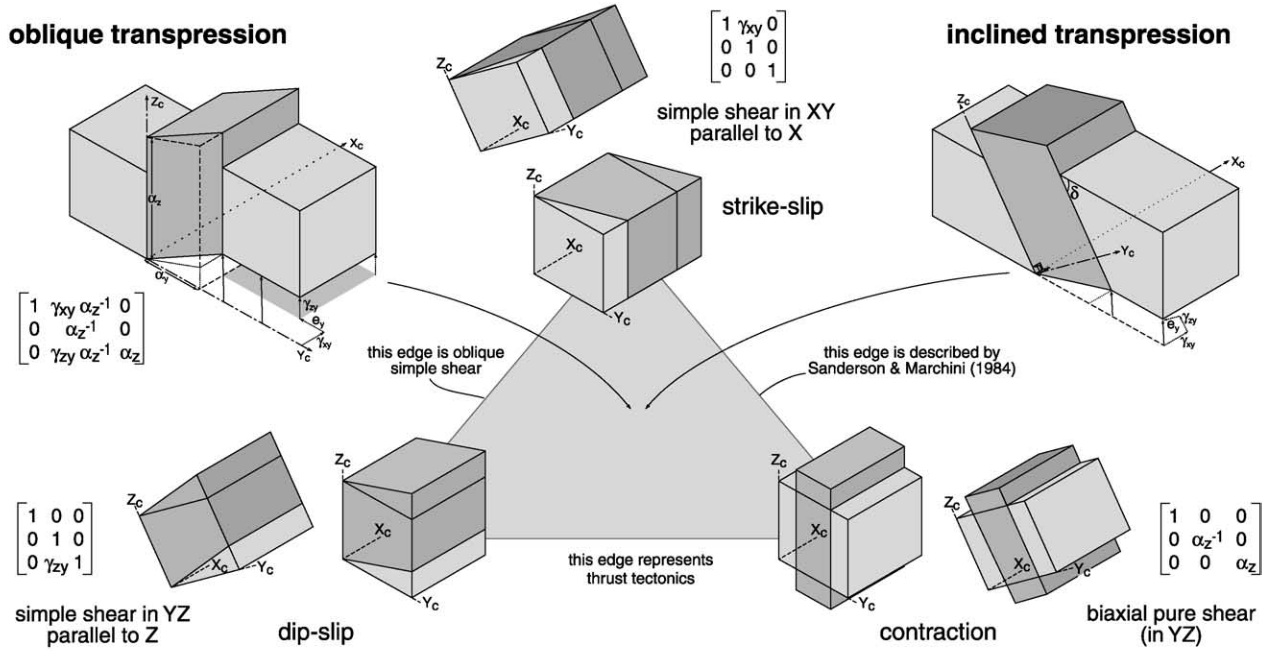

Fig. 8. Strain triangle showing how bulk oblique and inclined transpressional strains, which in general are non-coaxial and non-plane flattening strains, can be visualised in terms of three plane strain end-member components. In naturally occurring transpression zones there is often a marked tendency for bulk strains (which plot inside the triangle) to partition into separate deformational domains situated towards the edges or apices of the triangle.

Prevalent fold structures include upright, SW- and NE-plunging folds, sideways-closing 'S' folds, and locally, a series of enigmatic folds with highly curvilinear hinges (Dearman et al., 1962; Treagus, 1992). Reliable way-up evidence shows that significant numbers of folds are downward facing. Fold geometry, and prolific layer-parallel slickenfibre growths, suggest that most folding has involved flexural slip; cleavage development is generally weak, and visible mainly in more pelitic layers. Cleavage locally transects fold hinges. The sequence is pervasively fractured and veined with carbonate and lesser amounts of quartz.

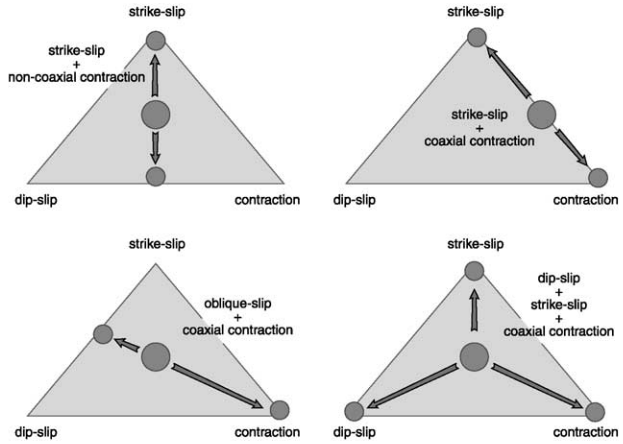

Fig. 9. Some ways of partitioning bulk transpressional strain into separate deformational domains, applicable to both oblique and inclined transpressions. Partitioning of bulk inclined transpression into strike-slip plus non-coaxial contraction is common, and is probably more favourable than partitioning into oblique-slip and coaxial contraction (Molnar, 1992; Dewey et al., 1999).

Arrays of dip-slip and strike-slip faults are widespread, and individual sinistral oblique-slip faults are also present. The majority of dip-slip faults are contractional, mostly top-to-SE thrusts and outcrop-scale imbricate arrays, with occasional top-to-NW back-thrusting. Some cross-cutting thrust detachments trace downwards into antiformal hinges and link into flexural-slip surfaces of fold limbs. Sinistral faults, which are much more numerous than dextral, include bedding-parallel detachments, extensional and contractional faults (analogous to Riedel and P shears), and vein-filled tension gashes. All the structures summarised here are described in more detail in Holdsworth et al. (2002a).

Sets of structures with different kinematic significance are believed to be inter-related. Contractional, dip-slip, oblique and strike-slip structures are mutually cross-cutting and kinematically linked, and there is little evidence to suggest that any of the types of structure are related to later overprinting (a minor set of late faults which post-date all structures described here are not included in further discussion). The inter-linking of contrasting structures is best observed on an outcrop scale at Dulse Craig in the northern part of the section (Fig. 11), where strike-slip and oblique-slip faults form duplexes that are closely associated with contractional folds and subordinate dip-slip faults (Tavarnelli et al., 2004).

Interpreting the kinematic significance of each set of outcrop-scale structures is best done with respect to the regional boundaries of the deformation zone. We infer from regional geology that deformation was bounded and controlled by the tract bounding faults of the Southern Uplands terrane (Fig. 11 inset). Outcrop-scale structures

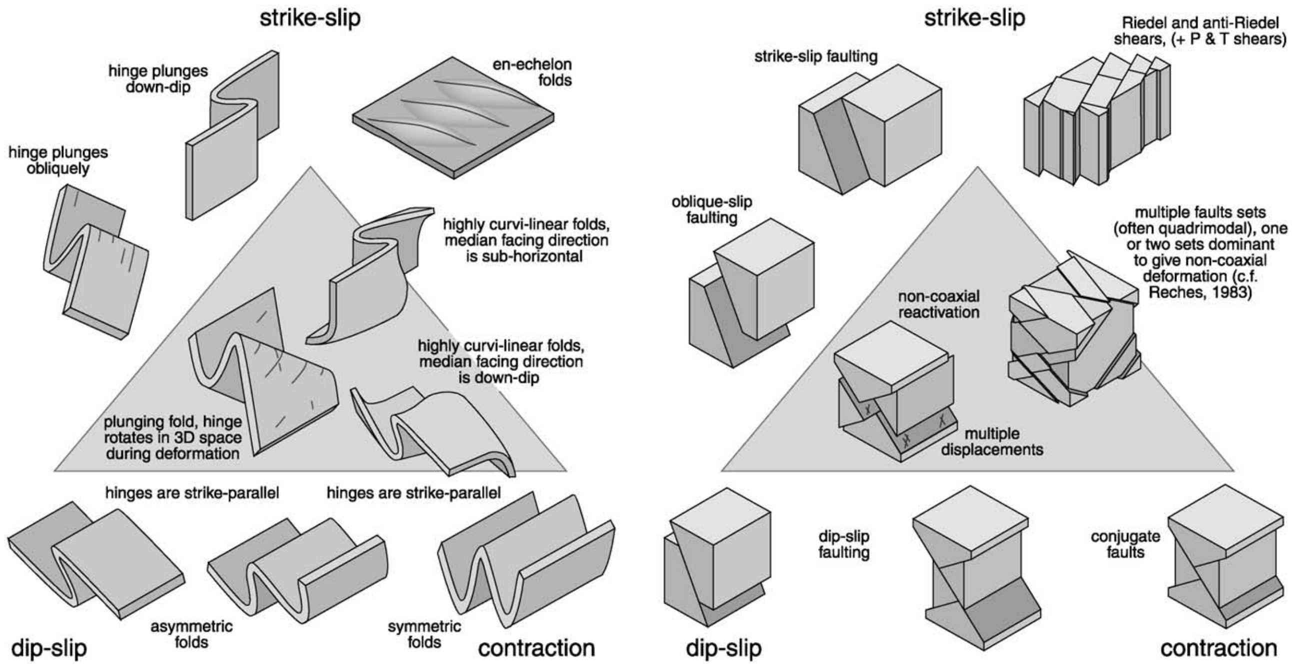

Fig. 10. Kinematic significance of individual structures typically found in inclined and oblique transpression zones. Note that when individual structures are analysed, care must be taken to understand not only their geometry but also their kinematic development, and that the kinematic effect must be defined in relation to the zone boundaries. For non-axial deformation in multiple fault sets see Reches (1983).

observed in the Eyemouth section form a wide range of broadly coeval structures that covers much of the area of the strain triangle, and this is strong evidence that deformation occurred in a zone of inclined transpression.

6.2. Deformational domains

The various types of observed outcrop-scale structure are not uniformly distributed across the Eyemouth section, and this allows a number of distinct, map-scale domains to be delineated (Fig. 11). The delineation of deformational domains is somewhat arbitrary. Changes in deformational style are in some places gradational, and domains defined at one scale of observation can often be further divided into localised sub-domains. Within sub-domains, adjacent structures often show a wide variety of geometries and kinematic patterns, typical of deformation of the brittle upper crust. As is typical of many transpression zones, it is common for different types of structure to be mutually cross-cutting, and for contrasting structures to be kinematically linked with one another. Although this can make it difficult to quantify finite strain even on the scale of a single outcrop, the localised predominance of some types of structures over others usually makes it possible to estimate in a qualitative way the approximate position of each domain and sub-domain on the strain triangle. Four main types of deformational domain are defined and described in detail by Holdsworth et al. (2002a), and these are depicted schematically in Fig. 12 and summarised briefly below.

6.3. Domain type 1

The deformation in this domain is dominated by NW-dipping homoclinal bedding with subordinate SW-plunging asymmetric folds that verge to the SE (figs. 4a, 5a and 6a of Holdsworth et al., 2002a). Steep NW-dipping detachment faults show predominantly sinistral oblique displacements. Slickenfibres related to flexural slip on the limbs of folds are non-orthogonal to fold hinges, suggesting that the direction of principal compression was oblique to hinge orientation during folding. Although we are not able to quantify the magnitude of strain or infer the exact orientation of the bulk FSE for the domain, field structures throughout the domain provide widespread evidence for the coexistence of contraction, sinistral strike-slip and top-to-SE dip-slip strain components. Hence, bulk finite strain for the domain plots well inside the strain triangle in Fig. 12.

6.4. Domain type 2

There are two separate domains displaying this type of deformation, cropping out to the north of Ramfaulds and at Elgy Rocks (Fig. 11). The most significant strain component is represented by folds that are nearly upright or slightly overturned towards the SE. Bedding is uninverted, so folds face consistently upwards. The majority of folds plunge shallowly to the SW. Slickenfibres related to flexural-slip on fold limbs are oriented anticlockwise of fold hinges, showing at least a minor sinistral component to the deformation. There are also minor amounts of localised

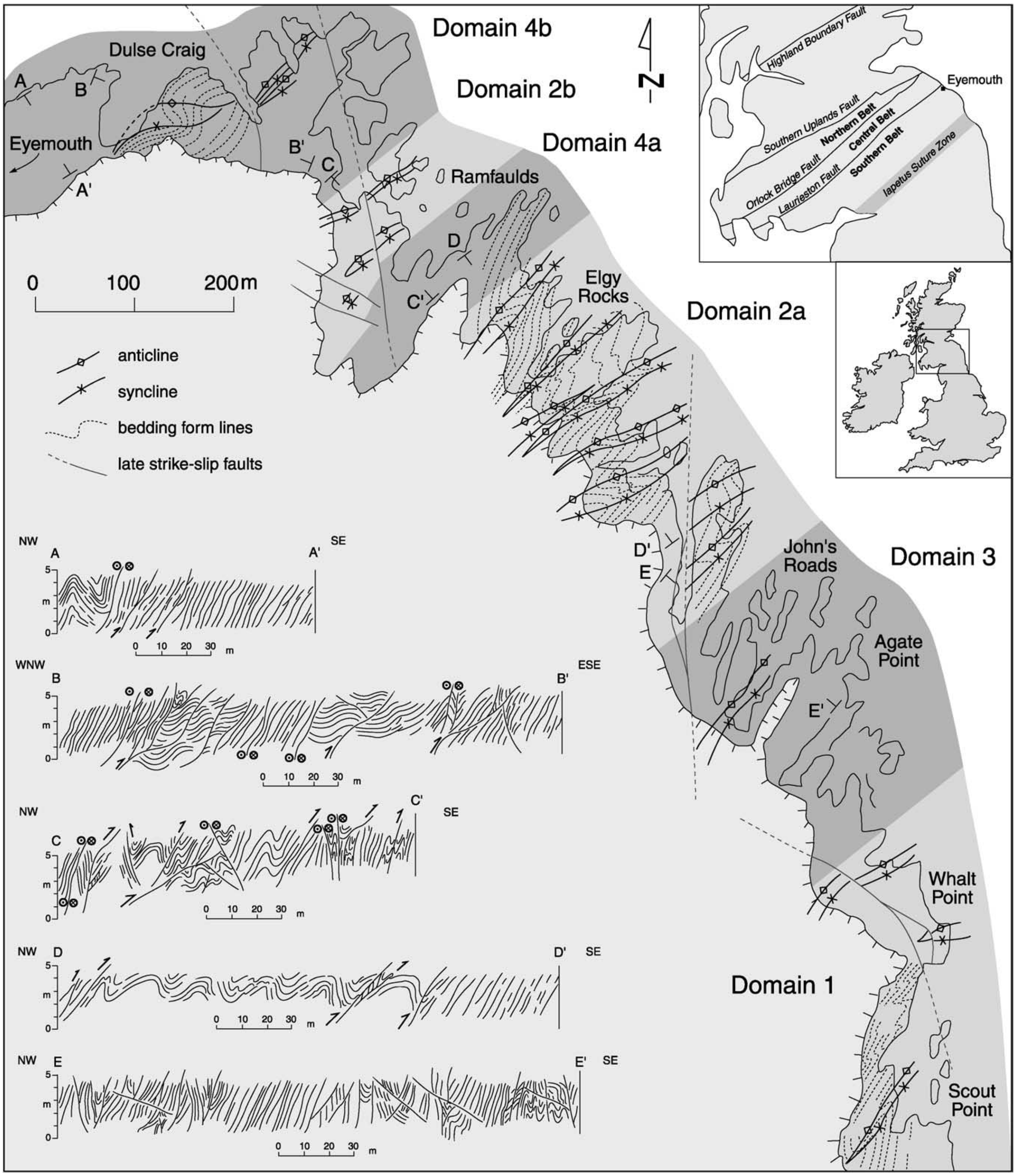

Fig. 11. Map and cross-sections showing main structural features of the coastal exposures SE of Eyemouth (after Holdsworth et al., 2002a). Four types of map-scale deformational domain are delineated. Inset maps show the location of Eyemouth with respect to regional faults and the Northern, Central and Southern tracts of the Southern Uplands terrane. Domain 1 continues 2 km south of the area shown.

sinistral and sinistral-oblique faulting. However, the bulk of the deformation in this type of domain consists of contraction and top-to-SE dip-slip, so type 2 domains plot towards the lower edge of the strain triangle in Fig. 12.

6.5. Domain type 3

This domain type is characterised by a steep NW-dipping homocline containing sinistral detachments and folds with

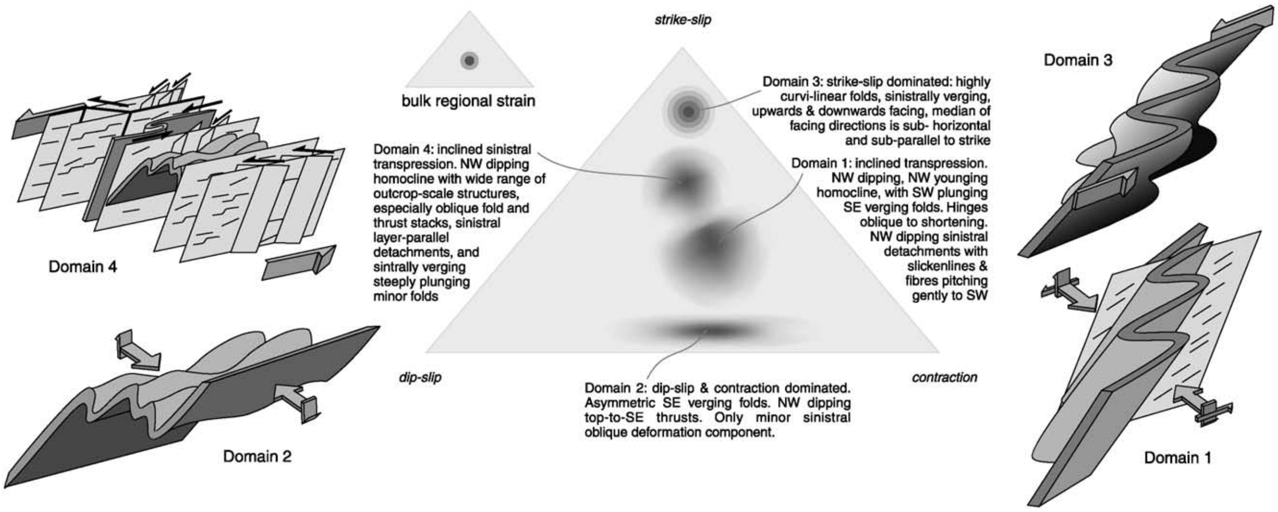

Fig. 12. Strain triangle showing estimated bulk strain for each of the four map-scale domain types from Eyemouth (see Fig. 11 for location of domains).

highly curvilinear hinges exposed at John's Roads and Agate Point (described by Dearman et al. (1962), Greig (1988) and Treagus (1992)). The folds are mostly very steeply plunging, sideways-closing, showing sinistral verging 'S' geometry in the profile plane. Locally, the angle of plunge of some fold axes varies by as much as 110° within a few metres (figs. 4c, 5e and f and 6c of Holdsworth et al., 2002a), with corresponding variation in the structural facing direction (in the sense of Shackelton (1957) and Holdsworth (1988)), between upward SW and downward SW facing. Importantly, the median value of the range of fold plunges is horizontal (see Fig. 10). Detachment faults show a dominance of sinistral and sinistral-oblique displacement. Although there are significant amounts of contraction and dip-slip across the domain, our interpretation is that the dominant strain component is sinistral strike-slip, and therefore the domain plots closest to the upper apex of the strain triangle in Fig. 12.

6.6. Domain type 4

Two domains of this type crop out towards the northern end of the section, at Dulse Craig and Ramfaulds Deformation in this domain is pervasive, and is characterised by metre-scale fold and fault duplexes (Holdsworth et al., 2002a; Tavarnelli et al., 2004). Fold orientations, facing and vergence are variable, with top-to-SE and sinistral 'S' geometries most prevalent. Fracturing is widespread, with thrust faults and fold break-outs kinematically linked to sinistral oblique-slip and strike-slip duplexes and sinistral strike-slip detachments. Mesoscopic fault arrays include typical Riedel, anti-Riedel, *P* and *T* fracture geometries (Hancock, 1985). Thus, on the outcrop scale, deformation is highly partitioned into individual, interlinked meso-structures, and we are able to subdivide this domain using localised large-scale mapping (see Tavarnelli et al., 2004). However, on the regional scale at which the other domain types are defined, we can characterise the overall finite strain across domain type 4 as a bulk inclined transpression. This emphasises that the delineation of deformational domains is largely scale-dependant. As strain in domain type 4 involves significant sinistral strike-slip, together with coeval components of contraction and top-to-SE dip-slip, our interpretation is that the bulk strain plots above the centre of the strain triangle in Fig. 12.

6.7. Comparison of Eyemouth data with theoretical model

The complex nature of deformation in the Eyemouth section epitomises the inherent difficulty often encountered when interpreting upper crustal transpression zones. The mechanical anisotropy of the original sedimentary sequence at Eyemouth, combined with increasing structural heterogeneity during progressive deformation, has lead to the wide range of geological structures and their irregular distribution across the section. This typically gives rise to the situation in which individual outcrop-scale structures may be present that plot at any point across the whole strain triangle (cf. Fig. 10), irrespective of the overall regional bulk finite strain. (We can widen this statement to consider the whole strain *tetrahedron* presented in fig. 2 of Jones and Holdsworth (1998).) Obviously, unless we have reliable strain markers that allow finite strain and the deformation path to be quantified, it can be very difficult to make a precise evaluation of regional strain. In the absence of quantitative strain measurements, we have to estimate the relative kinematic significance of the various types of outcrop-scale structure within each domain. When bulk deformation estimated from each domain is plotted on the strain triangle (cf. Fig. 12), there is a much more restricted distribution than the outcrop-scale structures. Based on the geographic extent of the various domains, and an estimate of the magnitude of strain within each domain, it is then possible to make an estimate of the nature of the overall bulk regional finite strain (cf. inset triangle in Fig. 12).

As with many ancient orogenic belts there is considerable uncertainty concerning the nature of several of the boundary conditions existing at the time of deformation, and this precludes any chance of reaching a reliable unique *quantitative* interpretation. Nevertheless, it is possible to show that the structural data from the Eyemouth section conforms well to the general qualitative characteristics predicted by theoretical modelling, and comparing modelling with actual field data does help to reduce significantly the number of feasible interpretations that are internally consistent.

6.7.1. Overall assumptions

Because available data are incomplete, we have to make certain assumptions in order to define the geometry of the transpression zone and to infer the boundary conditions that we think best represent the zone at the time of deformation The most fundamental assumption inherent in our interpretation is that the datasets from Eyemouth, presented in Holdsworth et al. (2002a,b) and Clegg (2002), collectively comprise a valid representation of the finite strain within the deformation zone. Although this kind of assumption is implicit in any structural interpretation, we explicitly reiterate it here in order to emphasise that any bias in sampling (for example, due to preferential orientation of exposures, or limited vertical relief) can cause significant error in interpretation. This can often be a considerable problem in transpression zones, where strain distribution will typically vary significantly across the zone, along the length of the zone, and at different vertical levels in the zone. In particular, because components of simple shear strain are typically partitioned into narrow zone-parallel faults, they might be poorly exposed and easily overlooked. For the Eyemouth section, we believe that our raw dataset is representative of the finite strain, albeit at one discrete horizon in a zone of considerable vertical extent.

6.7.2. Zone geometry

1. The northern boundary to the zone is taken to be the tract-bounding fault between Central and Southern Belts of the Southern Uplands terrane (see Holdsworth et al., 2002b).
2. The southern boundary to the zone is more difficult to pinpoint, but is assumed to be a major regional fault that lay parallel to the other tract-bounding faults.
3. The strike of the zone is 040°. This is parallel (±5°) to the following: regional tract-bounding faults (Fig. 11 inset), the boundaries of the deformational domains at Eyemouth (Fig. 11), the overall bedding girdle (fig. 3a(i) of Holdsworth et al., 2002a), and the minor faults within the zone (fig. 3a(v) of Holdsworth et al., 2002a).
4. The dip of zone is difficult to constrain from regional data. Average dip of minor faults is 54–64° (fig. 3a(iv–v) of Holdsworth et al., 2002a), and we infer that the dip of the zone boundaries lies within this range.

6.7.3. Shape and orientation of FSE within the zone

1. We assume that the regional orientation of cleavage defines the X_sY_s plane of the bulk finite strain ellipsoid Average cleavage in the zone dips 72° and strikes 066° (fig. 3a(ii–iii) of Holdsworth et al., 2002a).
2. Measuring the orientation of the long axis of the FSE within the cleavage plane is hindered by the absence of stretching lineations. We can use the average orientation of facing directions and fold axes to estimate the approximate orientation of X_s and Y_s (cf. Fig. 10). Average pitch of the facing direction is approximately 50°, and is upwards to the SW (fig. 3b of Holdsworth et al., 2002a). On the lower hemisphere of a stereonet this corresponds to an X_s axis orientation of ca. 47° towards 045°. This coincides with the average orientation of fold axes and the intersection of average poles to axial planes and cleavage. Because the relationship between fold geometry and finite strain can be complex, this approach gives only a rough estimate, in this case with an estimated error margin of ±15°.
3. The exact shape of the bulk FSE is unknown, although interlinked structures that combine contraction with dip- and strike-slip show that bulk deformation is a flattening strain.

6.7.4. Qualitative comparison

1. The overall evidence of coeval strike-slip, oblique-slip, dip-slip and contraction within the zone is strongly indicative of inclined non-coaxial general flattening strain.
2. This is further supported by evidence of complex rotations during the formation of folds and development of brittle fault arrays.
3. All three axes of the inferred FSE are oblique to the boundaries of the deformation zone (cf. Fig. 7).
4. The average cleavage strikes clockwise of the zone boundary (cf. Fig. 6), consistent with a sinistral sense of shear.
5. The average dip of cleavage is steeper than the inferred dip of the zone boundaries. Although this itself is not a reliable argument (because the actual dip of the zone is not known with certainty), it is significant that the minor faults across the zone are oriented more shallowly than cleavage, such that their kinematic tendency is to rotate the FSE into a more shallow orientation. This is indicative of a top-to-SE sense of dip-slip shear.
6. The X_s axis of the inferred FSE plunges noticeably, and its pitch within the X_sY_s plane is probably between 35° and 65° (cf. Figs. 5 and 6).

6.7.5. Quantitative comparison

In order to test whether the field data are quantitatively consistent with the numerical modelling, further assumptions and inferences need to be made Those relating to general boundary conditions are as follows:

1. Zone boundaries are assumed to be parallel. Any wedge geometry is ignored (even though it is likely that the whole Southern Uplands terrane actually wedges downwards to the NW).
2. Zone boundaries are discrete and planar. This is probably a reasonable approximation, since deformation does appear to be controlled by large-scale faults.
3. Deformation is assumed to be constant-volume. This is a difficult boundary condition to assess. There is pervasive veining representing mobility of significant amounts of material at the time of deformation, and syn-deformational compaction could be considerable. However, we do not have data that allows us to quantify any volume change.
4. There is no evidence that suggests significant lateral extrusion, so it is assumed to be negligible.
5. Vertical thickening caused material to move upwards with respect to the level now exposed at the surface at Eyemouth (i.e. downward thickening may also have occurred, but the pin level is at a depth well below the current surface of the earth).
6. Bulk regional deformation can be considered to be homogenous. Obviously, deformation at Eyemouth is pervasively heterogeneous at outcrop and map-scales. However, we can aggregate strain heterogeneities at these scales by using the strain triangle in Fig. 12 to derive the bulk regional strain for the deformation zone as a whole.

6.7.6. Zone boundary displacement

As a starting point for modelling purposes we assume that deformation is a simple inclined transpression We do not know the exact orientation of the far-field displacement vector, although the abundance of sinistral kinematics within the zone allows us to infer that the vector must lie in the quadrant that is anti-clockwise of the zone boundary. We use the modelling to constrain the orientation of the vector more tightly. The amount of contraction across the zone is also not known, though the style of deformation and widespread preservation of primary sedimentary structures (see Greig, 1988; Holdsworth et al., 2002a) suggests that it is unlikely to exceed 50%. In practice, it is not necessary to know the amount of contraction as we consider whole deformation paths from 0 to 90% shortening, although had a reliable value been available it would provide a further consistency check.

6.7.7. Results of modelling

In order to compare field data with theory, a wide range of different values for the various boundary parameters was applied to Eqs (3)–(5), which were then used to drive the strain matrix of Eq. (2). For each iteration the orientation of the resultant FSE was calculated (cf. Figs. 4 and 5) and tested to see whether it lay within the estimated margin of error for the bulk FSE inferred for the Eyemouth data. The following ranges of input values were used:

1. Values of zone dip, δ, were allowed to vary between 54° and 64°.
2. The strike of the zone boundaries used varied between 030° and 050°.
3. β values ranged from 5° to 80°.

The following values were used to define the range of realistic orientations for the observed bulk FSE for the Eyemouth section:

1. Strike of the X_sY_s plane = 066° ± 10°.
2. Dip of the X_sY_s plane = 72° ± 4°.
3. Pitch of the X_s axis within the X_sY_s plane = 50° NE ± 15°.

Deformation paths for over 200 different combinations of input parameters were studied. The results show that there is actually a very limited range of β values that are compatible with the reported field observations, even when the large error margin assigned to many of the parameters is taken into consideration (Fig. 13). Only deformation paths in which β lies within the range 14–23° will develop finite

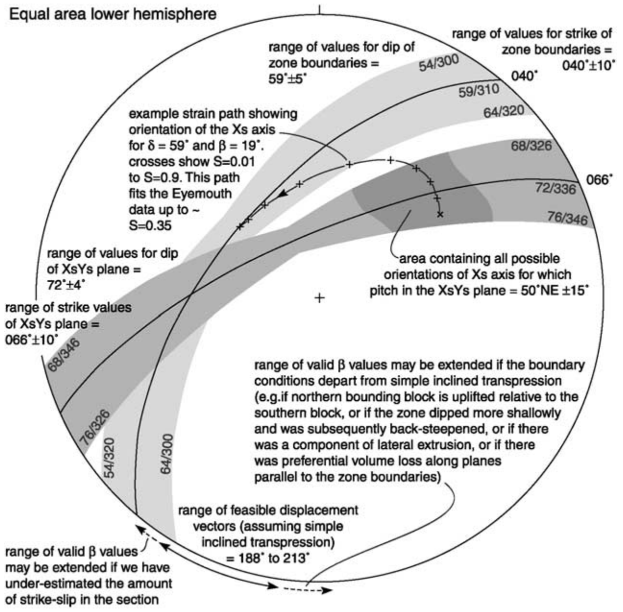

Fig. 13. Stereonet showing quantitative interpretation of the Eyemouth data. If a simple inclined transpression model is assumed, the direction of regional shortening must have been oriented between N/S and NNE/SSW. See text for details of the boundary conditions used and assumptions made.

strains in which the FSE is close to that inferred for the Eyemouth section. Values of zone shortening for these finite strains lie in the range 10–50%.

6.8. Discussion

Comparing field data from Eyemouth with theoretical transpression models helps to emphasise the inherent difficulties in analysing non-coaxial general flattening strains in real rocks. Despite hundreds of hours of fieldwork and thousands of data, we must still make several fundamental assumptions before attempting an interpretation. Consequently, this analysis cannot prove conclusively the validity of the theoretical model, or demonstrate beyond doubt the orientation of Caledonide plate motion vectors during Palaeozoic times. However, by describing explicitly the range of boundary conditions that can influence deformation, we hope that this study can act as a checklist for geologists working in areas of three-dimensional strain.

The basic geometry of existing transpression models is too simplistic to provide a rigorous *plate-scale* representation of deformation at collisional plate margins. Most orogenic belts have wedge-shaped zone geometries, non-planar zone boundaries, along-strike variations, and involve geological processes that can lead to significant volume change. Nevertheless, the concept of transpression is of major importance for the following reasons. Firstly, plate tectonics is not a plane strain process and cannot be approximated to simple shear. Transpression models are innately more applicable than 2D deformation models because they provide a preliminary framework for analysing non-coaxial, non-plane strains, which are the inevitable result of plate motion. Secondly, transpression models recognise the vital importance of the upper free surface of the earth in controlling crustal scale deformation. Provided that the rate of erosion is adequate, very large amounts of transpressional shortening can be accommodated without causing any strain incompatibilities at depth. Thirdly, deformation in the crust is not homogeneous, and is strongly influenced by pre-existing anisotropy. Transpression models are defined in terms of zone boundaries, which implicitly are structural anisotropies that control deformation. Therefore, transpression is a useful concept when considering fault and shear zone reactivation. Finally, even though transpression models are simplistic, they produce realistic, testable predictions about the complicated nature of progressive three-dimensional strain that can advance our understanding of complex zones of deformation in the Earth's crust.

7. Conclusions

The analysis of a strain matrix describing the simultaneous combination of pure shearing, strike-parallel simple shearing and dip-parallel simple shearing helps to make predictions that can form the basis for understanding natural zones of inclined transpression. The following conclusions are based on application of mathematical modelling to the interpretation of actual inclined transpression zones such as the coastal section near Eyemouth, SE Scotland:

(a) Inclined transpression is defined in terms of the simultaneous combination of contraction, and oblique-slip shearing. Oblique-slip shearing can be further factorised into strike-slip and dip-slip components.
(b) Inclined transpression gives rise to non-coaxial general flattening deformation, and can be represented in terms of a strain triangle in which the three end-member plane strain components form the apices of the triangle. The strain triangle is not a quantitative tool, but can be used to illustrate qualitatively the nature of overall bulk deformation and the degree and nature of strain partitioning.
(c) Strains that develop during inclined transpression lie in the flattening field of the Flinn plot. In idealised homogeneous deformation, the shape and orientation of the finite strain ellipsoid are influenced by both the strike and dip of the deformation zone with respect to the direction of regional shortening of the zone margins, and the exact deformation path experienced by the zone (i.e. deformation is dependant upon boundary conditions).
(d) In inclined transpression all three principal axes of the FSE will generally be orientated obliquely to all three axes of the Cartesian reference frame. Both the strike and dip of foliation will usually be oblique to the deformation zone margins. Within the foliation plane, stretching lineations can have nearly strike-parallel, intermediate or nearly dip-parallel angles of pitch, depending upon the exact strain state. For some strain paths the orientation of stretching direction can change significantly even during small amounts of shortening. For some other paths, the elongation direction remains nearly down-dip and strain symmetry effectively appears monoclinic.
(e) During progressive deformation, the orientation of all three axes of the FSE will change continuously in 3D space (i.e. each axis follows a path that does not lie in a plane), causing foliation to rotate towards parallelism with the inclined zone boundaries. Strains are triclinic. There is a component of vorticity acting along each of the axes of the FSE (although the amount of vorticity is not necessarily high), so that asymmetric shear-sense indicators can be prominent on two or even three orthogonal sections (i.e. the X_sZ_s, Y_sZ_s or X_sY_s surfaces) for some (though not all) deformation paths.
(f) Normal fault displacements are an inherent feature of inclined transpression models. Thus, normal faulting can be closely associated with crustal shortening, and therefore does not always indicate regional crustal extension.

(g) Most natural transpression zones are characterised by strain that is highly heterogeneous. Strain partitioning and variation in strain intensity are two ubiquitous manifestations of strain heterogeneity. Both can occur on a range of scales of observation from grain to plate scale, and often occur at several scales within the same shear zone.

(h) In upper crustal deformation zones strain heterogeneity at the outcrop-scale is typically displayed by the simultaneous development of a wide range of geological structures of apparently contrasting kinematic significance. When plotted on the strain triangle these structures can be widely separated, yet they can often be seen to be kinematically linked in the field. Identification of coeval interlinked sets of contractional, strike-slip and dip-slip structures can (with caution) be a valid way of recognising inclined transpressional deformation, even when zone boundary conditions cannot be fully elucidated.

(i) In many transpression zones kinematic partitioning of strain into separate deformational domains is particularly prevalent. Partitioning of strain is rarely perfect, so deformational domains will usually be defined in terms of a significant predominance of one or more types of structure over others. Plotting the bulk strain of each domain on the strain triangle can help to constrain estimates of overall regional strain. Partitioning generally has the effect that bulk strains which plot within the strain triangle will tend to be partitioned into separate domains that plot towards the edges or apices of the triangle. Partitioning of inclined transpression into strike-slip and contractional dip-slip end-members is common, and it is probably easier for triclinic strains to be accommodated in this way, instead of partitioning into oblique slip and coaxial contraction.

(j) The coastal section at Eyemouth, SE Scotland provides a well-exposed example of a Lower Palaeozoic inclined transpression zone. Throughout the section there are broadly coeval outcrop-scale structures that include contractional, sinistral strike-slip, dip-slip and sinistral oblique-slip kinematics.

(k) Four contrasting types of map-scale deformational domain can be delineated within the Eyemouth section. All four domain types display a wide range of outcrop-scale structures, but the domains can be defined in terms of the most predominant structures present. Domain type 1, the largest of the domains, displays non-coaxial general flattening deformation and may be quite representative of the overall (non-partitioned) regional strain. Towards the centre of the section domain type 3 contains a partitioned component of sinistral strike-slip, whilst domain type 2 is dominated by contractional dip-slip. The northern end of the section is characterised by domain type 4 in which deformation is highly partitioned on the outcrop scale. Bulk strain in this type of domain is a sinistral inclined transpression.

(l) Deformation at Eyemouth matches closely with the qualitative predictions derived from numerical modelling. Based on a number of specified assumptions, the field data is quantitatively consistent with a simple inclined transpression in which the orientation of far-field shortening was between N/S and NNE/SSW.

(m) Even though triclinic strains that can develop in some deformation zones may be theoretically complicated, in practice, qualitative and quantitative interpretation is possible by using careful field observations.

(n) Although boundary conditions used in simplistic transpression models are highly idealised (e.g. wedge-shaped zone geometries are ignored), the models can explain the development of rotational non-plane strains similar to those seen at destructive plate margins.

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