Extended models of transpression and transtension, and application to tectonic settings

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Abstract: We introduce a spectrum of transpressional and transtensional deformations that potentially result from oblique plate interaction. Five separate types of deformation are designated, in which a simple shear deformation is combined with an orthogonal coaxial deformation. The types vary in the amount of extension v. contraction, both parallel to the margin and vertically. The interaction between the angle of convergence, kinematic vorticity, infinitesimal strain axes, finite strain, and rotation of material lines and planes is investigated. Quantification of the finite strain indicates that the orientation, magnitude, and geometry (flattening, constriction, etc.) change continually during steady-state transpression.

These results are then applied to the cases of transpression, particularly resulting from oblique plate convergence of terranes. The obliquity of plate motion and the geometry of the plate margin determine which of the types of transpression or transtension is favoured. A component of margin-parallel stretching also potentially causes terrane motion to locally exceed oblique plate motion, or move opposite to the general direction of movement between the converging plate boundaries. The kinematic models also suggest that the boundaries between converging terranes are likely to exhibit vertical foliation, but either vertical or horizontal lineation. Finally, narrow transpressional zones between colliding blocks may have very high uplift rates, resulting in exhumation of high-grade metamorphic fabrics.

Transpression and transtension are broadly defined as steep strike-slip influenced deformation zones that deviate from simple shear by a component of shortening (transpression) or extension (transtension) across the zone (Fig. 1). The result is a spectrum of three-dimensional deformation which involves complex histories of fabrics, strain, and rotation. Even for homogeneous models for transpression, such as a perpendicular combination of a pure shear and a simple shear (Sanderson & Marchini 1984), the resulting deformation path is much more complex than for a simple shear zone.

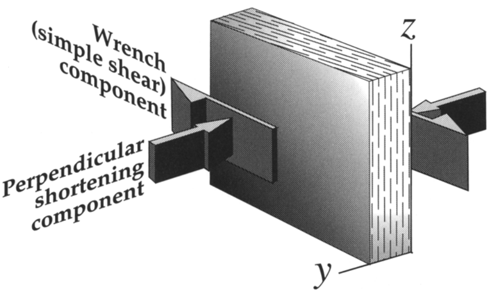

Fig. 1. Definition of transpression as a combination of a simple shear (wrench) component and a simultaneous coaxial shortening component perpendicular to the vertical shear plane. For volume-conserving deformations, the latter component must be accommodated by vertical and/or horizontal extension or contraction, and variations of these variables give rise to the spectrum of transpressional deformations illustrated in Fig. 2.

In this paper we discuss different models for transpression and transtension, and explore some of the deformation patterns and strains that can emerge. We then apply these models to simple tectonic analyses involving oblique convergence and divergence of terranes.

Approach

The deformation within a steep deformation zone in the crust is primarily governed by external or boundary conditions. On the scale of plate tectonics, the boundary conditions include the relative movements of the plates involved and whether the deformation zone extends (lengthens) vertically and/or horizontally. Vertical extension is, for example, possible if the zone reaches the surface of the crust, in which case tectonic and erosional processes allow the zone to grow upwards. Vertical contraction is feasible

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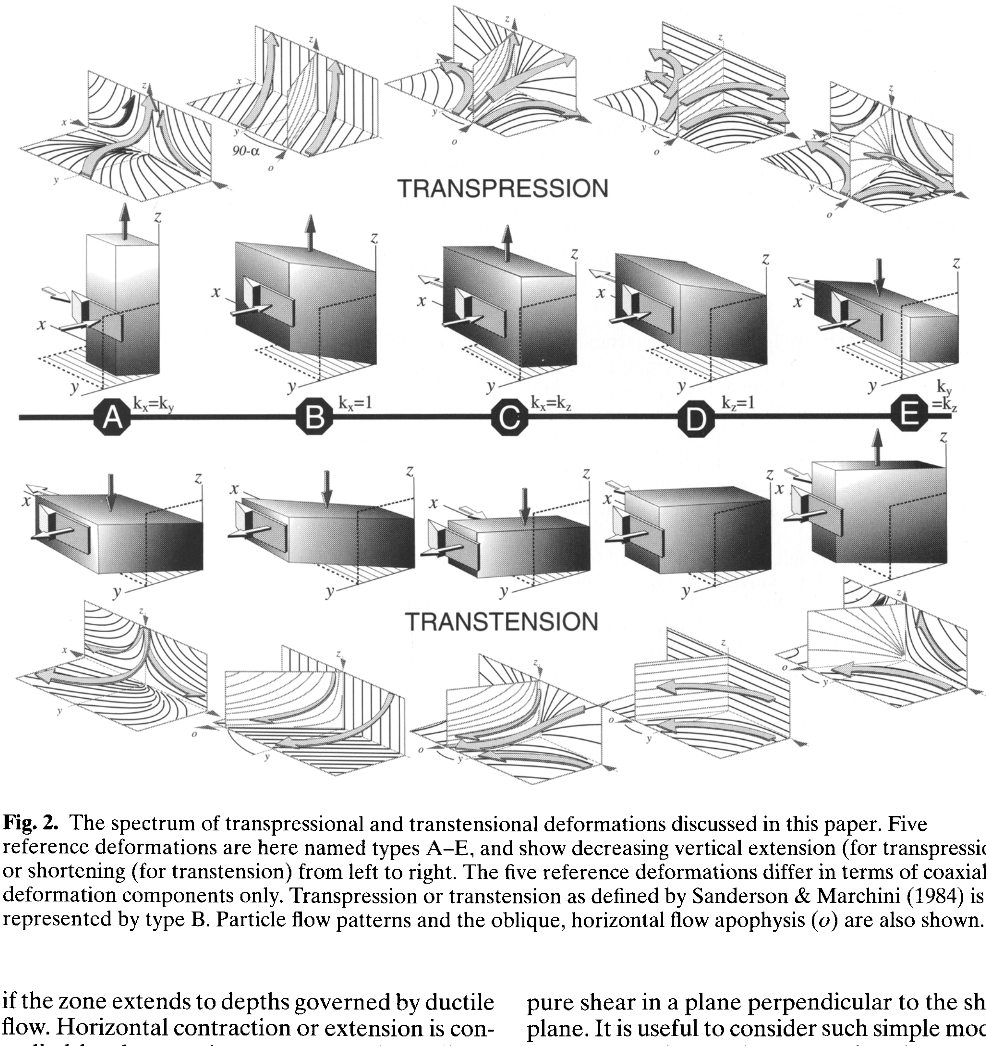

Fig. 2. The spectrum of transpressional and transtensional deformations discussed in this paper. Five reference deformations are here named types A–E, and show decreasing vertical extension (for transpression) or shortening (for transtension) from left to right. The five reference deformations differ in terms of coaxial deformation components only. Transpression or transtension as defined by Sanderson & Marchini (1984) is represented by type B. Particle flow patterns and the oblique, horizontal flow apophysis (*o*) are also shown.

if the zone extends to depths governed by ductile flow. Horizontal contraction or extension is controlled by the margin geometry and the divergence of plate motion (e.g. McCaffrey 1992). In this work we will assume that the zone is able to grow or shrink vertically, and locally also horizontally along strike. For simplicity, we will consider two rigid blocks with different relative velocities, and an intermediate zone of deformation. The deformation is homogeneous and determined by the relative motions of the rigid blocks.

Modelling

The definition of a transpressional or transtensional zone outlined above is similar to, but more general than that of Sanderson & Marchini (1984). Sanderson & Marchini discussed the case where a vertical shear zone with horizontal displacement was modified by an additional pure shear in a plane perpendicular to the shear plane. It is useful to consider such simple models of transpression and transtension for general reference, and then modify these if more complex models are needed. However, Sanderson & Marchini's model is only one of several related models. In this work we define five such reference deformations for transpression, and five corresponding ones for transtension. They all contain a shear system and a shortening (extension) perpendicular to the shear plane (Fig. 1), and thus fulfil the above definition of transpression (transtension). It is emphasized that slip is allowed along the margins of the transpression zone, as in the model by Sanderson & Marchini (1984). This condition is a simplification of actual boundary conditions in many transpression zones, although less so if one considers basal boundary conditions (Teyssier & Tikoff, this volume). The results of the simple models of transpression and transtension are easily applicable in a qualitative, if not quantitative, way to geological examples.

The five reference models of oblique convergence

We consider constant-volume transpression (transtension) where the deformation is separated into a single *simple shear component* with vertical shear plane and a *coaxial component* with axes oriented perpendicular and parallel to that shear plane (Fig. 1). We keep the nature of the shear component the same for all deformations and allow for variations in the relative magnitudes of the infinitesimal stretching axes of the coaxial components. In this scheme, a spectrum of volume-conserving deformations emerges, in which we sample five transpressional and transtensional reference deformations, labelled from A to E (Fig. 2). Each of these classes of transpression implies shortening perpendicular to the shear plane (along the y-axis), and they differ only in the coaxial components in the other two directions (x- and z-axes). Type A transpression involves an equal amount of shortening along the x- and y-axes and stretching along the z-axis, type B also has vertical extension, but no stretching along the shear direction (x-axis), type C involves flattening of the shear plane (equal stretching in x and z directions), type D has constant vertical height, and in type E, the coaxial component causes a vertical shortening of equal magnitude to the shear-zone normal shortening, compensated by stretching in the x direction.

Transtensional deformations involve a component of extension perpendicular to the shear plane (in the y direction). The transtensional reference deformations correspond directly to the transpressional deformations, except that the directions of the coaxial components of deformations are simply reversed. This simple relationship allows us to use the same labels (A–E) for the transtensional reference deformations.

Two of the deformations (B and D) are special in that they are combinations of two plane strain deformations (a simple shear and a pure shear), and D is the only plane strain deformation in this spectrum of transpressional and transtensional deformations. Type B is identical to the model studied by Sanderson & Marchini (1984), and type D has been referred to as sub-simple shear by Simpson & De Paor (1993) (also Weijermars 1991). Furthermore, type E transpression was discussed in terms of finite strain by Dias & Ribeiro (1994).

The difference between the different types of transpression (transtension) lies in how the shear zone perpendicular shortening is accommodated along the shear plane. For example, in the Sanderson & Marchini model (B), the shear zone perpendicular shortening is accommodated by vertical extension (shortening). The more general cases include additional components of horizontal shortening or extension. However, all of the classes of transpression or transtension (Fig. 2) have a vertical simple shear plane and component of horizontal shortening perpendicular to the simple shear component of deformation.

Having defined the deformations (Fig. 2), we investigate the related movement, kinematic vorticity, finite strain, and material line and plane rotation patterns. The mathematical relations have been outlined by Tikoff & Fossen (1993, 1995) and may be visualized for two-dimensional sections using available computer programs (Tikoff & Fossen 1996).

Flow apophyses and angle of convergence

If we fix a coordinate system to one of the two margins of a transpressional zone, then the observed movement direction of the opposite margin will define the direction of convergence. The angle between this direction and the strike of the transpression zone is defined as the angle of convergence, and governs the degree of non-coaxiality in the horizontal plane. An important observation is the parallelism between the convergence vector and one of the three axes called flow apophyses (or flow asymptotes). The flow apophyses are directions of maximum, intermediate and minimum rate of particle movement of the flow. In transpression and transtension, the one flow apophysis which is horizontal and (in general) oblique to the x-axis marks the convergence direction.

For transpressional and transtensional deformations, the flow apophyses are described by the vectors

$$(1, 0, 0), \{\gamma/[\ln(k_x/k_y)], 1, 0\}, (0, 0, 1) \quad (1)$$

where γ is the simple shear component (shear strain), and k_x and k_y are the pure shear components in the x and y directions, respectively (for derivation, see Tikoff & Fossen (1993)). The expressions show that one of the flow apophyses is always vertical (z-axis), one is always horizontal and parallel to the shear direction (x-axis), and the third is also horizontal but generally oblique to the shear direction. Particle paths are always straight along the oblique apophysis for all types of transpression and transtension (Fig. 2). The convergence angle, α, is the angle between the oblique flow apophysis and the x-axis, and is described by the formula

$$\alpha = \tan^{-1} [\ln(k_x/k_y)/\gamma] \quad (2)$$

Thus, the relative components of pure and simple shear deformation are described by the convergence angle (α) of the system. If the coaxial component is missing, the deformation zone is a simple shear wrench zone with $\alpha = 0°$. If the simple shear component is zero, we have a pure contractional zone ($\alpha = 90°$).

As discussed by Tikoff & Fossen (1993), equation (2) is not applicable if $k_x = k_y$. This case, which is found for perfect type A transpression or transtension, is mathematically degenerate as two flow apopohyses are parallel to the x direction (e.g. Simpson & DePaor 1993).

In this case, the coaxial deformation in the xy-plane leads to area loss, compensated by flow in the z direction. Any change in relative magnitude of the finite strain axes in the xy-plane is caused by the simple shear component. Thus, we need a more general way to describe the ratio between the coaxial and simple shear components of any type of transpression or transtension.

Kinematic vorticity

The kinematic vorticity number (*Wk*; Truesdell 1953) quantifies the relative rate of stretching to rotation for any three-dimensional flow. Thus, *Wk* can be considered a non-linear ratio between simple shear and coaxial components of deformation (Tikoff & Fossen 1995). *Wk* can vary between zero and one for any of the deformation types in Fig. 2. Consequently, we choose to investigate the differences of the types of transpression and transtension with respect to *Wk*, rather than orientation of the flow apophyses. However, for types B–E, there is a direct correlation between these two quantities (Fig. 3): $\alpha = 90°$ corresponds to $Wk = 0$ and $\alpha = 0°$ corresponds to $Wk = 1$.

Infinitesimal stretching axes

During deformation, there are three directions called infinitesimal stretching (or strain) axes (ISAs). These orientations represent the directions of maximum, intermediate, and minimum elongation of material lines for an infinitesimal deformation, and are mutually perpendicular. Both the magnitude and orientation of these axes depend on the type of flow during deformation. They vary within the spectrum of deformations discussed in this paper (also within each of types A–E in Fig. 2), but by definition do not change during steady-state deformation.

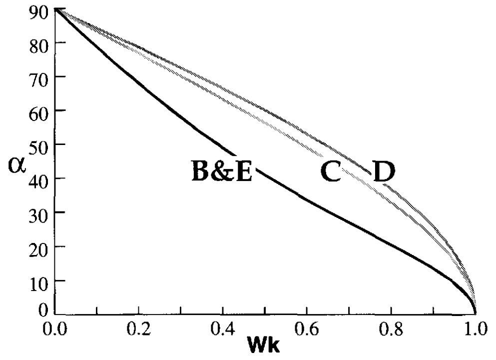

Fig. 3. Relation between angle of convergence and the kinematic vorticity number (*Wk*). It should be noted that equation (2), from which the curves are calculated, is not applicable if $k_x = k_y$ (type A transpression or transtension). This case is mathematically degenerate, as both horizontal flow apophyses are parallel to the x direction (no convergence direction defined).

Both boundary conditions (Fig. 2) and kinematic vorticity number (*Wk*) control the orientations of the ISAs. Because *Wk* can vary within any of the deformation types in Fig. 2, so can the orientations of the ISAs. One of the ISAs is always vertical (parallel to x-axis), implying that the other two always lie in the horizontal (xy) plane. The two horizontal ISAs are oblique to the coordinate axes (x and z), as a result of the simple shear component. They are parallel to the coordinate axes only if deformation is perfectly coaxial. If the deformation is perfect simple shear in the horizontal plane, the largest horizontal ISA is inclined at a 45° angle to the shear direction (x-axis). For intermediate cases ($0<Wk<1$) the largest horizontal ISA is oriented between 0 and 45° (transpression) or 45 and 90° (transtension). This result has been explored in detail for type D (Passchier 1988; Simpson & DePaor 1993; Weijermars 1993) and type B (Fossen & Tikoff 1993) transpression and transtension.

Figure 4 shows how the vertical ISA may change within and between the deformation types, depending on *Wk*. For type A transpression, the largest stretching axis (ISA_1) is vertical if deformation is dominated by the coaxial deformation component. If $Wk = 0.87$, ISA_1 and ISA_2 are of equal magnitude, and for $Wk > 0.87$

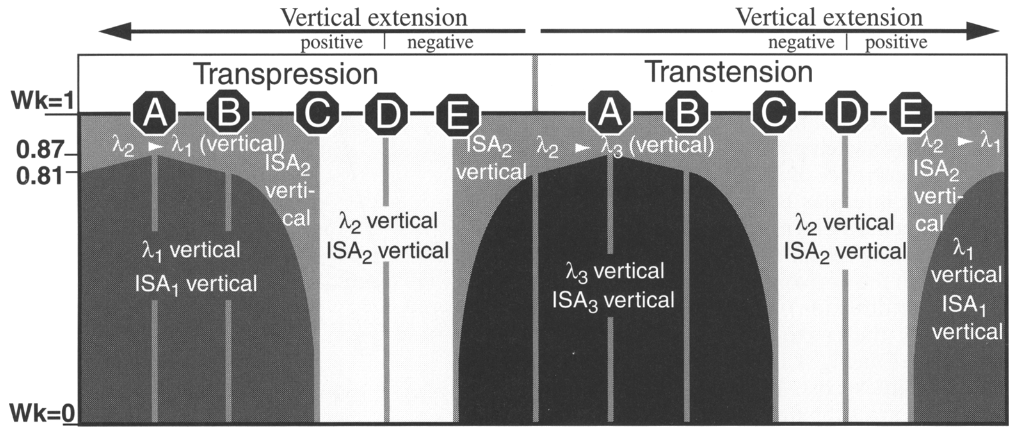

Fig. 4. Orientation of infinitesimal strain axes (ISAs) and finite strain axes (λ) for the spectrum of transpressional or transtensional deformations discussed in the text. ISA_1, largest infinitesimal stretching direction; λ_1, maximum finite stretch direction. It should be noted that the ISAs have a constant orientation during steady-state deformations, whereas the finite strain axes rotate (for $Wk>0$) and may exchange positions. $Wk = 1$: simple shear (top). $Wk = 0$: coaxial deformation (bottom).

ISA_2 becomes vertical (e.g. simple shear dominated). Similarly, for Sanderson & Marachini's model of transpression (type B), the orientation of ISA_1 is in the horizontal plane only for $1>Wk>0.81$ (simple shear dominated), and vertical for $Wk<0.81$ (pure shear dominated). If a stretch is added to the horizontal shear direction (x), the shift between ISA_1 and ISA_2 occurs at lower Wk values, and when the stretching along the x-axis matches or is greater than that along the z-axis (type C transpression), ISA_2 is always vertical for any Wk. ISA_2 is also vertical for type D to E transpression. The orientations of the ISAs depend on Wk and the boundary conditions for transtensional deformations in a similar way, as mapped in Fig. 4 (right-hand half). The distinction is that for type A and B transtension, ISA_3 (rather than ISA_1) is oriented parallel to the z-axis for coaxially dominated deformation.

Change in the orientation of ISAs during a single deformation history implies that deformation is non-steady state. Hence, Wk, the angle of convergence or divergence, and the orientation and magnitude of ISAs remain constant throughout steady-state deformations.

Finite strain

As opposed to the ISAs, the orientation, magnitude and shape (flattening, constriction, etc.) of the finite strain ellipsoid change continually during steady-state transpression. The change in orientation is a result of the simple shear component of deformation, and the change in geometry reflects the interaction of the simple shear and coaxial components of deformation. The initial orientations of the finite strain axes are identical to those of the ISAs (Fig. 4). Hence, for all of the transpression and transtension classes in Fig. 2, one of the finite strain axes will always be vertical, parallel to one of the flow apophyses. The other two finite strain axes lie in the horizontal xy-plane, with the larger horizontal strain axis (λ_1 or λ_2) rotating towards the shear (x) direction (also a flow apophysis) during progressive deformation. The long and intermediate finite strain axes rotate into parallelism with the flow apophyses, which act as attractors of the finite strain axes (Passchier 1997). Thus, for transpression, the horizontal finite strain axes rotate towards the coordinate axes. For transtension, the horizontal finite strain axes may be oblique to coordinate axes with one axis parallel to the oblique flow apophysis. The orientation of the strain ellipsoid at any point during deformation depends on deformation type (A–E), angle of convergence, and the non-coaxiality of deformation (Wk). In terms of the pure shear components in the horizontal plane and the simple shear component, the angle ϕ between the larger horizontal strain axis (λ_1 or λ_2) and the x-axis is given by the formula

$$\phi = \arccos \{[-k_y\Gamma/(\Gamma^2 + k_x^2 - \lambda)]\} \quad (3)$$

where $\Gamma = \gamma(k_x - k_y)/[\ln(k_x/k_y)]$ (Tikoff & Fossen 1993). Equation (3) holds for the entire spectrum of deformations discussed in this work.

For the subspectrum of deformations between types C, D, and E, the intermediate principal strain axis (λ_2) is vertical for any *Wk* (this applies to both transpression and transtension). For the other deformations, the axes of the finite strain ellipsoid may switch positions for high values of *Wk*. The occurrence of such switches depends on *Wk* and the interplay between the simple shear and the coaxial deformation components. The simple shearing component produces maximum stretching in the horizontal plane (initially at 45° to the shear direction). If the vertical extension imposed by the coaxial deformation is strong (left of type C in Fig. 4, including types A and B), two possibilities exist. The first is that the finite strain axes are subparallel to the coaxial components throughout deformation. Alternatively, for high-*Wk* (simple shear-dominated) transpression, λ_1 still may initiate with a horizontal orientation, but does not grow as quickly as the vertical principal strain axis (λ_2). Thus, if deformation proceeds long enough, the result is that λ_1 and λ_2 switch positions.

In steady-state type A and B transpressions, the switch may only occur if $Wk > 0.87$ (type A) or 0.81 (type B; Fig. 4). Similarly, λ_2 changes to λ_3 for the corresponding transtensional reference deformations (types A and B). The reason for such switches is that coaxial deformations accumulate strain faster than simple shear (Tikoff & Fossen 1995). Consequently, stretching caused by the simple shear component may dominate the strain in the early history, but eventually is overcome by the increasingly effective coaxial deformation at a later stage.

Switches in strain axes were first described for type B transpression by Sanderson & Marchini (1984), and occur as the strain exhibits a perfect flattening (transpression) or constriction (transtension) geometry. This coincides with the strain path touching the horizontal axis of the Flinn diagram (see A and B transpression in Fig. 5). Furthermore, the boundaries between deformations where finite strain axes do and do not switch positions during progressive steady-state deformation trace deformations where the first strain increment produces a perfect flattening geometry (constrictional geometry for transtension). In general, transpressional (transtensional) deformations in the vicinity of these lines develop strains very close to pure flattening (constriction).

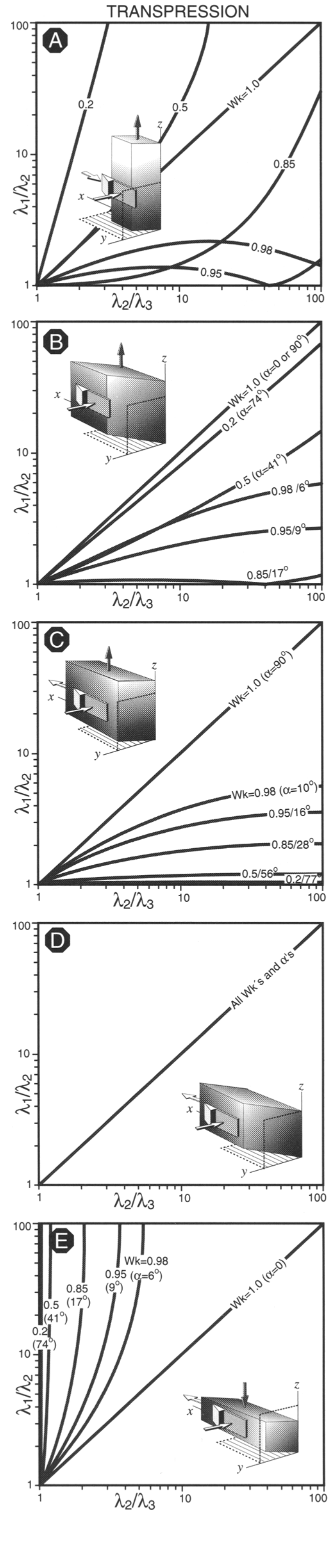

Fig. 5. Steady-state (constant *Wk* and α) strain path in Flinn space for the five reference transpressional deformations A–E. (Note the large variations in paths and strain geometry. See text for discussion.)

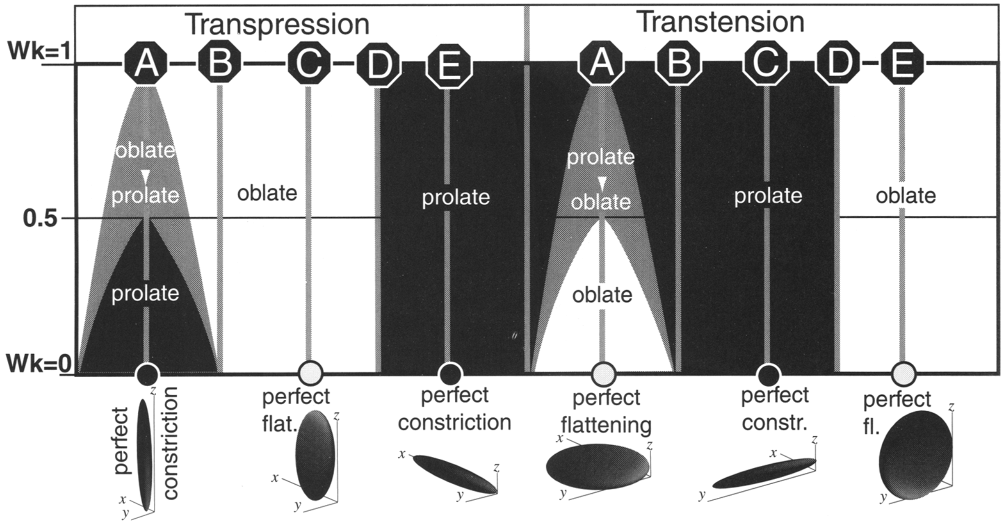

Fig. 6. Variation in shape of strain ellipsoid for transpression or transtension. Perfect coaxial strains along bottom ($Wk = 0$) line. Simple shear along upper, horizontal boundary. The strain ellipsoids at the bottom apply for $Wk = 0$ and illustrate the shape and orientation of the coaxial components of three of the reference deformations (A, C, and E) of transpression and transtension.

More important than switching strain axes is perhaps the *geometry* of finite strain and the strain path in general for the different types of transpression. Figure 5 shows a selection of steady-state (constant Wk) transpression strain paths (Wk = 0.98, 0.95, 0.85, 0.5, and 0.2) (the corresponding paths for transtension are found by reflecting the transpression paths about the $Wk = 1$ line). The simplest pattern is developed during type D deformations, which is a plane strain sub-simple shearing. It is well known that plane strain deformations develop along the line with slope of one (Flinn k value of one), regardless of the degree of non-coaxiality of the deformation.

Type C deformations develop a spectrum of strain paths between simple shear (plane strain; $Wk = 1$) and perfect flattening ($Wk = 0$). However, strain becomes increasingly oblate during deformation, and strong flattening fabrics are characteristic even for relatively low strains (unless deformation is very close to simple shear). Type E deformations behave identically to type C, except that strains are constrictional instead of flattening.

Type B transpression develops flattening strains, particularly for Wk values between *c.* 0.6 and 0.95. Type A transpression is different because (1) any strain geometry (oblate or prolate) can be achieved (depends only on Wk), and (2) steady-state paths with $Wk>0.5$ may cross the diagonal $Wk = 1$ line. If so, strain develops from a flattening fabric to a constrictional one for transpression (but never from constriction to flattening) and vice versa for transtension.

The geometry of the strain ellipsoid is qualitatively shown in Fig. 6 for the spectrum of deformations discussed in this work. It should be noted how type D transpression and transtension separate deformations that produce oblate and prolate strain shapes, and how perfect constriction and flattening throughout deformation only occur along the base of the diagram ($Wk = 0$).

Finite strain has implications for fabric development in deformed rocks. It is generally true that constrictional strain leads to strongly lineated rocks (L-fabrics) whereas flattening strain results in strongly foliated rocks without a lineation (S-fabrics). Intermediate cases give rise to LS- and SL-fabrics. Although it is shown above that the geometry of finite strain changes during deformation in most cases, it is possible to predict the finite fabric in rocks deformed by the various types of transpression and transtension discussed in this work. Such fabric variations are shown in Fig. 7 for reasonable amounts of finite strain. In this figure, which is based on Figs 4–6, type D transpression and transtension separate fields of S- and L-dominated fabrics, and the upper Wk=1 (simple shear) boundary

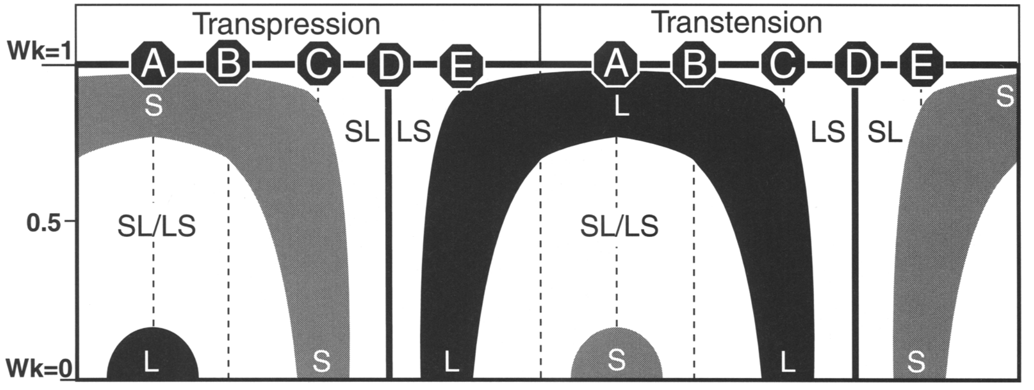

Fig. 7. Variation in type of fabric for the different types of transpression and transtension discussed in the text.

marks fabrics where planar and linear fabrics are equally well represented in the ideal case.

Rotation of lines

Analytical work has revealed that lines and planes rotate away from a certain direction (usually a line orientation, less commonly a plane), commonly referred to as the source, fabric repellor or repulsor. Lines and planes rotate towards a different direction (or plane) known as the sink or fabric attractor (Passchier 1997). These directions are governed by the orientations of *flow apophyses* (see above), which are directions of maximum, intermediate and minimum rate of particle movement of the flow.

Passive rotation of linear and planar markers can be modelled mathematically by use of the deformation matrix, as described by Flinn (1979) and explored for type B transpression or transtension by Fossen *et al.* (1994). The result of such modelling (Fig. 8) shows a range of patterns that characterize the different classes of transpression. For type A transpression, a rotational movement of line markers towards vertical is characteristic. This 'down-the-drain' pattern is only perfectly developed if the two coaxial components along the shear plane are of equal magnitude. If not, an oblique flow apophysis emerges and modifies this pattern somewhat. However, for all transpressional deformations between types A and C (Fig. 8), lines will always rotate towards the vertical direction. This pattern changes across type C transpression, where the two coaxial components along the shear plane are of equal magnitude. Here material lines rotate from an oblique, horizontal orientation along great circles until they meet the vertical shear plane and essentially stop rotating (fly-paper effect). Hence, line orientations are expected to be distributed along the shear plane for high strains. However, if the vertical stretching is reduced or reversed in magnitude (including types D and E transpression), lines are finally parallel to the horizontal shear direction. Type E transpression is peculiar insofar as lines rotate away from an oblique plane defined by two of the flow apophyses (planar source).

In general, lines are finally vertical in transpression if the vertical stretch is significant, but rotate towards the horizontal shear direction if the vertical stretch is small or negative. For transtension, on the other hand, lines tend to rotate towards a horizontal direction which is governed by the oblique flow apophysis. The exception to this general rule occurs in the case when an additional vertical component of stretching occurs (type E in Fig. 8). In this case lines are attracted to, and eventually distributed along, a plane containing the oblique flow apophysis and the z-axis (fly-paper effect).

An important difference between transpression and transtension is that whereas lines rotate towards parallelism with the x- or z-axis in transpression, lines generally rotate towards a horizontal direction oblique to the shear direction (x) in transtension (compare type B, C and D transpression with transtension in Fig. 8). In both cases a large angle is expected between rotated linear structures and the shear direction.

Rotation of planes

Rotation patterns for passive planar markers (poles to planes) in transpression are also shown in Fig. 8. The shortening perpendicular to the shear zone generally causes planes to rotate towards a vertical position, eventually parallel to

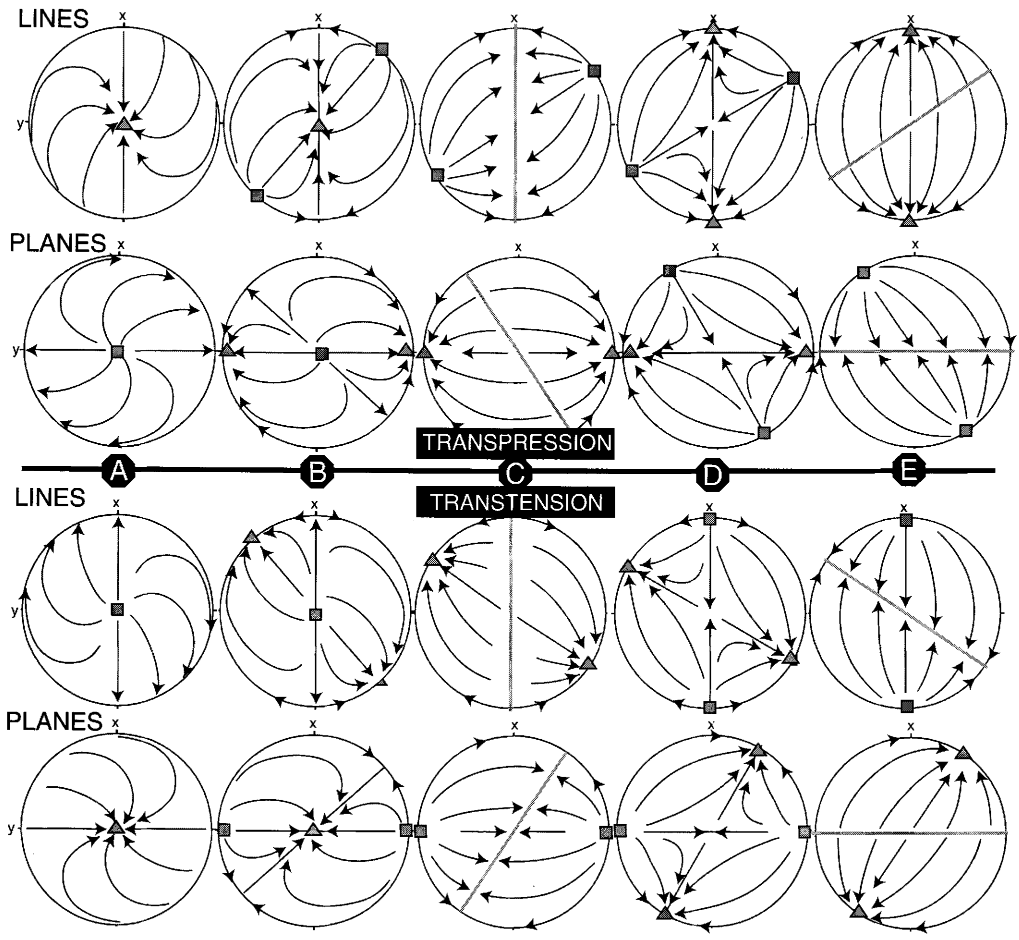

Fig. 8. Rotation patterns of lines and poles to planes for Wk = 0.75. Squares are sources; triangles are sinks or attractors. Planar sources and sinks are shown by stippled lines. (See text for discussion.)

the shear zone. An exception to this is (rare) type E transpressional zones, which shorten vertically and extend in the shear direction. In this case planes end up with a common strike direction (parallel to the shear direction) but with any amount of dip.

In transtension (Fig. 8, lower part), planes rotate towards a horizontal position if the shear zone perpendicular extension is mainly compensated by vertical shortening (left of type C). If shortening in the shear direction is significant (right of type C), planes rather rotate into a vertical orientation which is oblique to the shear plane.

Complicating factors

The characteristics explored above for various types of transpression (and transtension), such as finite strain, rotation patterns and fabrics, are not unique to a certain type of deformation. However, a combination of several characteristics may help to constrain the boundary conditions and kinematic vorticity. Table 1 shows the characteristic features for type A–E transpression. Although natural deformation zones may have additional complications that may restrict the usage of this table, it is useful for a general classification of the deformation in question.

Common complications include heterogeneous deformation, non-steady-state deformation, and strain partitioning (see below).

Strain is not likely to be homogeneous throughout the zone, but rather: (1) increases in intensity towards the central part of the zone, and/or (2) preferentially partitions a component of the simple shear deformation into a high

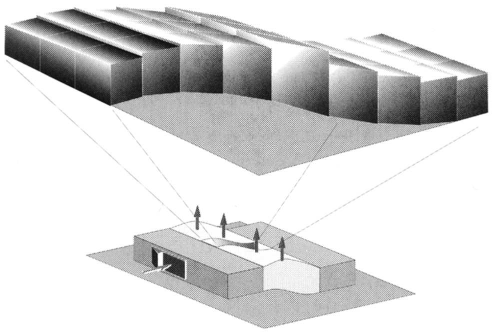

Fig. 9. Heterogeneous strain across a transpression zone can be modelled by use of several deformation boxes with different finite strain. The example shown models heterogeneous, steady-state type B transpression with maximum strain in the central part of the zone.

strain zone. In the first case, the kinematic vorticity number and boundary conditions may be constant. The deformation zone can be modelled by using multiple deforming elements instead of just one (Fig. 9), and Table 1 is still applicable. However, the shape and the orientation of the finite strain ellipsoid generally change during deformation, even if *Wk* and the angle of convergence do not. Of particular interest are the cases where λ_2 and λ_1 switch positions during progressive deformation (e.g. type A and B transpression; see Fig. 4). In the extreme case (type A transpression with *Wk* around 0.6), oblate marginal strain ellipsoids may change to prolate ellipsoids towards the centre. Similarly, low-strain parts of the deformation zone may show horizontal lineations whereas more intensely deformed parts exhibit vertical lineations (switch of λ_2 and λ_1) (Fig. 4). For transtension, low-strain zones may have vertical foliation and high-strain zones have horizontal foliation (switch of λ_2 and λ_3). Any partitioning of the simple shear component will tend to accentuate such effects (Tikoff & Teyssier 1994; Tikoff & Greene 1997).

Non-steady-state transpressional deformations are easily modelled as a number of incremental deformations with different kinematic vorticity number and/or different boundary conditions (e.g. a change from type B to type C transpression). However, the problem requires knowledge of the change in external boundary conditions, which is difficult or impossible in most cases (see, however, Fossen & Tikoff 1997). A change in convergence angle along an obliquely convergent plate margin is the simplest case that could be modelled very easily (as sequential deformations).

Evidence of strain partitioning is easily observed in the field as domains of low kinematic vorticity numbers (strong component of shortening across the shear zone) between strike-slip dominated faults or narrow shear zones of high shear strain (e.g. Tikoff & Teyssier 1994; Jones & Tanner 1995; Kirkwood 1995; Goodwin & Williams 1996; Northrup & Burchfiel 1996).

Tectonic application of transpression and transtension

Obliquely convergent plate boundaries are generally characterized by a contractional orogenic wedge tens to hundreds of kilometres wide (e.g. Vauchez & Nicolas 1991). Relative plate motion and the plate boundary are proposed to provide the primarily boundary conditions for continental deformation (e.g. McKenzie & Jackson 1983; Molnar 1992; Teyssier *et al.* 1995). Proof of this relation is the generally good correlation between neotectonic strain rates from geodetic surveys and relative plate motions. This relation is relatively straightforward in continental interiors and orthogonal collisional belts,

Table 1. *Characteristics for the five transpressional reference deformations in Fig. 2; a similar scheme can be made for transtension, using the results presented in the other figures and in the text*

Type	Strain	λ_1 (lineation)	Fabric	ISA_1	Linear markers	Planar markers
A transpr.	any	vertical (horizontal)	L, S	vertical, horizontal	→vertical	→vertical (any strike)
B transpr.	oblate	vertical (horizontal)	LS, S	vertical, horizontal	→vertical	→vertical (‖shear plane)
C transpr.	oblate	horizontal	S, SL	horizontal	→*yz*-plane	→vertical (‖shear plane)
D transpr.	plane	horizontal	S = L	horizontal	→horizontal	→vertical (‖shear plane)
E transpr.	prolate	horizontal	SL, L	horizontal	→horizontal	any dip, strike normal to oblique flow apophysis

but also applies in more complex areas of oblique convergence (e.g. the San Andreas fault system; see Teyssier & Tikoff, this volume). Thus, we investigate the effect of the boundaries of obliquely convergent systems on the style of transpression.

Movement and slip rates

Deformation within an obliquely collisional zone depends primarily on the direction of the plate motion relative to the plate margin orientation. Plate motion is commonly decomposed into a normal and tangential component (e.g. Engebretson *et al.* 1985). However, the relation between the plate motion and the deformation is complex, except for the case where the movement is perfectly orthogonal to the plate boundary. In regions of oblique convergence or divergence, the motion, the infinitesimal strain axes (ISAs), and the finite strain axes are not parallel (Fig. 10b). In all models of transpression (types A–E) with any wrench component, there is an angular difference between the plate motion (oblique flow apophysis) and the fastest horizontal shortening direction (ISA_{Hmin}, equal to ISA_3 if ISA_3 is horizontal or ISA_2 if ISA_3 is vertical). The finite strain long axis is originally parallel to the fastest horizontal stretching direction (ISA_{Hmax}, equal to ISA_1 or ISA_2), but rotates toward a margin-parallel orientation. Progressive simple shearing (wrenching) is a good end-member example of this behaviour. Experimental deformation, even applied to fracturing, for example, by Withjack & Jamison (1986), corroborates the numerical modelling. In their transtensional model (type B), normal faults form slip parallel to the ISA_{Hmax}, not the plate motion.

It is a relatively common misconception in the geological and geophysical literature that the slip direction on faults (representing the infinitesimal contraction direction or ISA) is parallel to the plate motion vector (e.g. Mount & Suppe 1992; Yu *et al.* 1993) (Fig. 10a). This idea of 'uniaxial' deformation is not applicable to obliquely convergent boundaries, because it fails to account for the wrench component of deformation. Parallelism of the plate motion and the slip vectors only applies if (1) the deforming zone is orthogonal to the motion ($\alpha = 90°$) or (2) the deforming zone is offset along a strike-slip fault so that the margin locally is orthogonal to the motion vector (Fig. 10c). Typically, the orientation of the slip vectors is at a higher angle to the plate boundary than the plate motion vector (e.g. Yu *et al.* 1993) (Fig. 10b), similar to

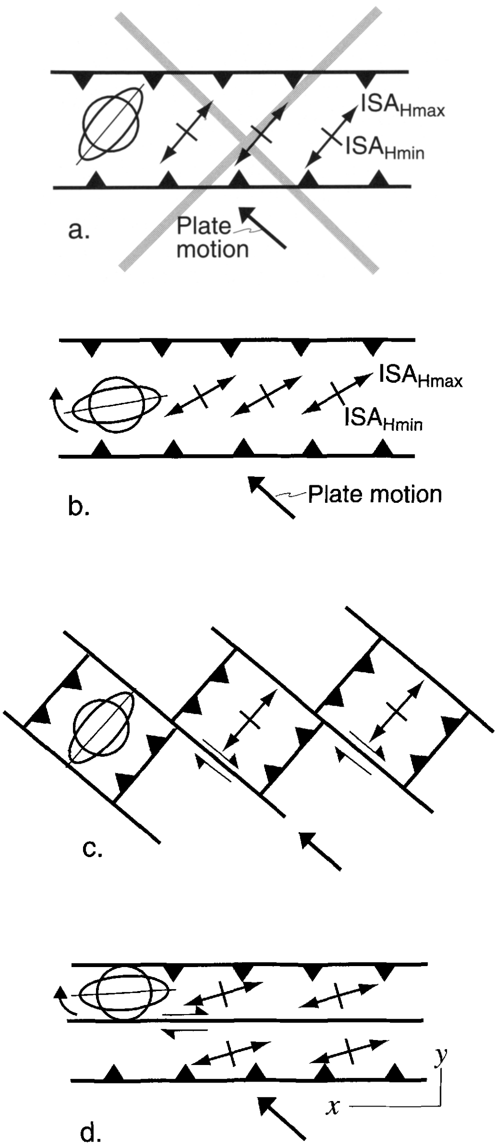

Fig. 10. The relationship between plate motion (convergence vector), plate boundary orientation, infinitesimal strain axes (ISA_{Hmax} and ISA_{Hmin}), and finite strain axes in the horizontal section for a transpressional system. (**a**) The common misconception is that the plate motion vector is parallel to the infinitesimal contraction direction (ISA_{Hmin}) or the finite contraction direction, a geometry that cannot accommodate the wrench component. In general, the plate motion, ISAs, and finite strain axes are all differently oriented (**b**) except for special cases where the margin is locally orthogonal to the motion vector (**c**). (**d**) Strike-slip partitioning increases the misfit between the plate motion and the ISA_{Hmin}.

numerical predictions for transpression. For example, on the South Island of New Zealand, an obliquely convergent setting which does not exhibit strike-slip partitioning, the slip on increasingly recent faults is oriented at a systematically higher angle than that predicted from the plate motion direction (Norris *et al.* 1990; Teyssier *et al.* 1995). If strike-slip partitioning occurs, the angle of contractional slip vectors should be oriented at an even higher angle to the plate margin (Fig. 10d).

Conditions leading to type B transpression or transtension

The orientation of the relative plate motion, its along-strike variation, and the geometry of the plate margin will have major effects on the resultant deformation (e.g. Beck 1991; McCaffrey 1992). In a straight plate margin with a constant angle of plate convergence, type B transpression is the most likely deformation. The reasoning is based on the nature of the flow apophyses and particle paths discussed above. The map-view flow lines created in such a tectonic setting must move directly toward each other, as no gradient of deformation will occur along the collisional boundary. Rather, deformation will accumulate by vertical movement of material. In type B transpression, flow lines are straight when viewed in the horizontal plane (Fig. 2). However, vertical movement is accommodated by a pure-shear component of deformation. It should be noted that, at high crustal levels, this 'bulk' pure shear component of deformation is attained along opposite dipping thrust faults and related folds, such as in a flower structure.

Conditions leading to type A, C, D and E transpression or transtension

A component of arc parallel stretching (Fig. 11) occurs if: (1) the plate margin has a *convex* orientation or (2) the angle of relative plate motion changes along strike, such that the tangential component of the relative plate motion increases along the plate margin. This situation results if the oceanic plate has a nearby pole of rotation, located within the oceanic plate (Avé Lallemant & Guth 1990; Beck 1991; McCaffrey 1992, 1996). In these cases, the material is forced to stretch parallel to the margin, to maintain compatibility. The resulting types of deformation are, with an increasing component of arc-parallel stretching, types C, D, and E. The amount of divergence and curvature will ultimately determine which deformation occurs. In terms of movement in the horizontal plane, curved particle paths are necessary to move material away from the colliding unit. An extreme case of margin-parallel extension occurs as a collision, either of a crustal salient or a triple-junction.

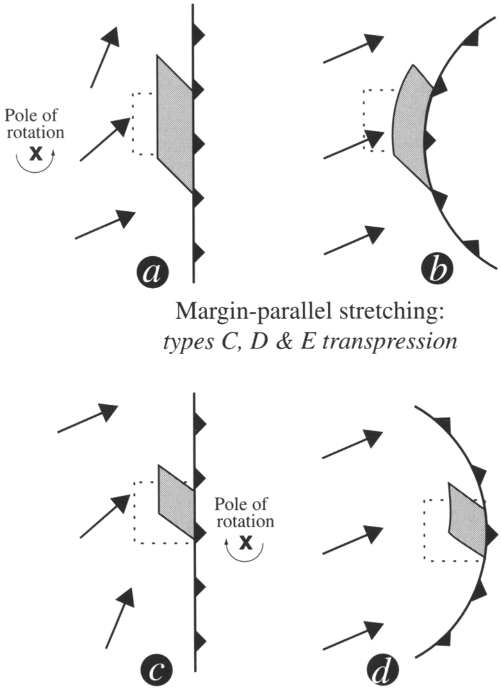

Fig. 11. The effect of divergent or convergent displacement fields and non-planar boundaries (margins) of transpression zones on the resulting type of transpression. Type B transpression would be expected from a setting with straight margins and a homogeneous displacement field (not shown). Based on McCaffrey (1992).

The effects of such a plate margin will probably be most extreme in the fore-arc region, in which the stretching will be maximum (Avé Lallemant & Guth 1990). Very prominent, margin-perpendicular normal faults are expected and may involve structures similar to core-complexes. Rapid uplift of deep-seated material, such as blueschists, has been proposed, as a result of such kinematics (Avé Lallement & Guth 1990). If type D transpression is suggested, the plane-strain aspect of this deformation is easily accommodated by conjugate strike-slip faults (Weijermars 1993).

The reverse case, involving a component of arc-parallel stretching, occurs if (1) the plate margin has a *concave* orientation, such as a large-scale salient or (2) the tangential component of the relative plate motion decreases along the plate margin, caused by a nearby pole of rotation within the adjacent continental plate (Fig. 11; Beck 1991; McCaffrey 1992, 1996). In these cases, a transition from type B to type A transpression is expected, and all of the normal component of oblique plate motion and a percentage of the transcurrent motion (resulting in orogen-parallel shortening) is accommodated by vertical uplift. Thus, this type of plate interaction is extremely efficient at uplifting rocks quickly. In the brittle regime, the margin-parallel and margin-normal shortening will both result in contractional structures. Thus, dome and basin structures may result from folding, or two separate, sub-perpendicular orientations of thrust faulting may occur.

Strike-slip partitioning transpression

Fitch (1972) originally observed that the oblique plate motion is commonly accommodated by a large strike-slip fault (e.g. Great Sumatra fault) and regions undergoing primarily contractional deformation. However, as was routinely noted (e.g. Oldow *et al.* 1989), regions on both sides of these major structures commonly contain a large component of wrench deformation. In particular, Jamison (1991) demonstrated that a significant percentage of wrench motion is accommodated within the structures adjacent to major strike-slip faults. This process of strike-slip partitioning has been kinematically modelled for type B transpression (Fossen *et al.* 1994; Tikoff & Teyssier 1994; Jones & Tanner 1995; Krantz 1995) and type B transtension (Fossen *et al.* 1994; Teyssier *et al.* 1995).

Any of the models of transpression or transtension (A–E) could exhibit strike-slip partitioning behaviours if the partitioning is caused by a tendency to localize deformation. However, in a dynamic explanation of the process, Tikoff & Teyssier (1994) suggested that strike-slip partitioning is caused by a major misorientation of infinitesimal strain and finite strain axes. If this reasoning is correct, strike-slip partitioning is limited to types A and B transpression (e.g. Tikoff & Teyssier 1994).

Transpressional terrane tectonics

A common observation in orogenic belts is the accumulation of small fragments of oceanic or continental material, or tectonic terranes, within areas of oblique convergence (e.g. Coney *et al.* 1980). The western edge of North America, for instance, is a well-known example of terrane accretion. Because these terranes collide obliquely with the irregular margin of North America, the kinematic models of transpression are relevant in describing their deformation. This analysis follows the concept of transpressional terranes proposed by Oldow *et al.* (1989).

Terrane bounding faults and shear zones

It is commonly considered that major transcurrent motion only occurs on vertical faults or shear zones with sub-horizontal lineations. It has been repeatedly pointed out (Fossen & Tikoff 1993; Fossen *et al.* 1994; Robin & Cruden 1994; Tikoff & Teyssier 1994) and documented in geological field examples (Hudleston *et al.* 1988; Tikoff & Greene 1997) that the lineation direction in transpressional shear zones does not reflect the tectonic movement direction of the simple shear component of deformation. Strain modelling indicates that it takes a relatively low angle of convergence ($\alpha<20°$) to cause a vertical lineation within a type B transpressional shear zone. If the transpressional deformation is intermediate between type B and type A transpression, the angle of convergence is even lower for vertical lineations to form.

These observations are particularly appropriate for terrane boundaries, which typically involve components of both contraction and strike-slip motion. Alternatively stated, terrane boundaries are generally transpressional. Finite strain patterns for the types of transpressional deformations are (1) vertical foliation with horizontal lineation or (2) vertical foliation with vertical lineation. Hence, the orientation of the foliation is a more appropriate guide for recognizing transpressional shear zones than is the lineation. In fact, models of transpressional deformation which include compatibility restrictions (Robin & Cruden 1994) suggest an even more complicated pattern of lineation development but a comparatively straightforward pattern of foliation development. Therefore, the rotation of the foliation associated with a strain gradient may be the most useful guide to the vorticity. A problem is that vertical lineations may also result from high-angle reverse faulting. However, the existence of vertical to steeply oriented shear zones commonly found near terrane collisions is not consistent with thrust tectonics. Relative movement on a vertical dip-slip fault does not achieve crustal contraction, it merely juxtaposes different crustal levels. In short, no tectonic effect is accomplished on vertical dip-slip faults except local accommodation.

Case example: coast shear zone and Baja–BC

The terrane movement of the Baja–British Columbia (Baja–BC) terrane against North America serves as a useful example for the significance of lineations in tectonic interpretation (Fig. 12). A major debate in the evolution of the North American Cordillera involves differences in geological-based small-scale versus palaeomagnetic-based large-scale estimates of margin-parallel terrane transport. Palaeomagnetic constraints on the Baja–BC terrane require 3000 km of dextral movement of the Baja–BC terrane relative to North America, and 2000 km with respect to the intermediate Intermontane terrane, in the 40 Ma interval between 90 and 50 Ma (e.g. Irving *et al.* 1995; Wynne *et al.* 1995). Geologically derived estimates on observed strike-slip faults are of the order of 500–1100 km (e.g. Gabrielse 1985; Struik 1993). The Late Cretaceous–early Tertiary Coast shear zone is the best candidate for accommodation of large-scale motion of the Baja–BC terrane. Extending over 1000 km along the western flank of the Coast Mountains in southeastern Alaska and coastal British Columbia, the Coast shear zone must record 2000 km of strike-slip motion if the palaeomagnetic data are correct (Cowan 1994). This interpretation is supported by plate motion reconstructions that suggest a strong oblique component to subduction along the northeast Pacific margin from *c.* 85 to 50 Ma (Engebretson *et al.* 1985).

The Coast shear zone is a 5–15 km wide, steeply oriented shear zone with sub-vertical foliation and steep, down-dip lineations (Crawford & Crawford 1991; McClelland *et al.* 1992). The Coast shear zone displays ambiguous sense-of-shear indicators parallel to the lineation direction, although the movement is interpreted as an east-side-up thrust fault derived from the sense-of-shear indicators parallel to the lineation (Ingram & Hutton 1994). This interpretation is at odds locally with the metamorphic geology, which exposes deeper rocks on the west side of the fault compared with the east side (e.g. McClelland *et al.* 1992). In contrast, sense-of-shear indicators *perpendicular* to the lineation are dextral, although domainal (e.g. Stowell & Hooper 1990). The existence of only steeply oriented lineations has been used to rule out the possibility of large-scale horizontal movement (e.g. Ingram & Hutton 1994). This evaluation is in direct contrast to strain modelling of transpressional shear zones, which suggests vertical lineations particularly in high-strain zones. Although the Coast shear zone records some component of east-side-up movement (Ingram & Hutton 1994), it may have accommodated much larger amounts of strike-slip motion. The existence of steeply oriented, down-dip lineations does not rule out the possibility of major (hundreds to thousands of kilometres) strike-slip motion on the Coast shear zone.

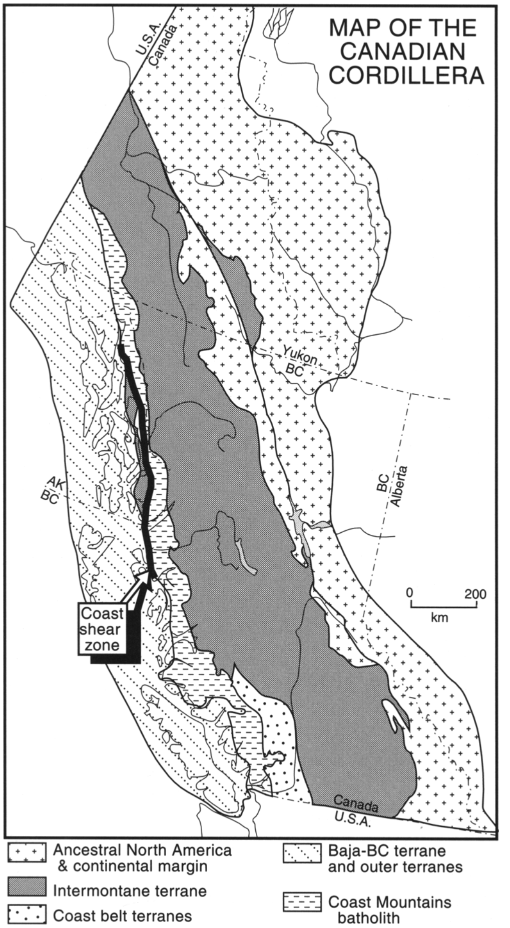

Fig. 12. Geological map of the Canadian Cordillera, indicating the location of the Coast shear zone and the Baja–BC terrane discussed in the text.

Faster than plate motion? Opposite to plate motion?

The nature of margin-parallel movement of terranes depends on (1) the kinematic model of oblique convergence and (2) the amount of strike-slip partitioning between the terrane and the adjacent continent. For transpressional deformations that involve a component of margin-parallel extension, an interesting effect occurs (Fig. 13). In this case, the motion of the terrane results in a combination of the transcurrent motion and the extrusion caused by the coaxial component of deformation. Parts of the terrane actually move *faster* than the relative plate motion, where these two effects are combined. Other sections of the terrane move much slower than, or even in an *antithetical* direction to (opposite to the tangential component of) plate motion. The latter case occurs if the coaxial deformation is larger than the transcurrent component. This effect could occur for either homogeneous or partitioned transpression (Fig. 13). Strike-slip partitioning enhances the effect of the coaxial component of deformation because the transcurrent component is localized. Thus, a larger percentage of the terrane moves faster or opposite to plate motion. The upper-crustal structural manifestation of margin-parallel extension is a conjugate set of strike-slip faults or margin-perpendicular normal faults (e.g. McCaffrey 1992). However, these same structures may also result from type B transpression or transtension (Withjack & Jamison 1986; Jamison 1991), with no margin-parallel extension, as a result of horizontal elongation caused by wrenching.

An example of this behaviour is recorded by palaeomagnetic data from the Baja–BC terrane. Southern parts of the terrane indicate dextral transcurrent offsets of *c.* 2900 km (e.g. Mt Stuart; Irving *et al.* 1995; Wynne *et al.* 1995). Recent analysis of Cretaceous–Paleogene plate motions adjacent to North America (e.g. Kelley 1993; Kelley & Engebretson 1994) suggested less offset than previous reconstructions (Engebretson *et al.* 1985). Assuming that the Kula plate was adjacent to North America, 2900 km of offset is consistent with plate motion. However, palaeomagnetic data from the northern part of the terrane suggest *c.* 4000 km of dextral translation, which is approximately equal to or slightly higher than plate motion (Irving *et al.* 1996). The difference in offset between the southern and northern part of the terrane suggests margin-parallel stretching. Thus, we suggest that the observation of the northern part of the terrane moving faster than plate motion is geologically permissible, particularly given the evidence for strike-slip partitioning during northward movement of the Baja–BC terrane.

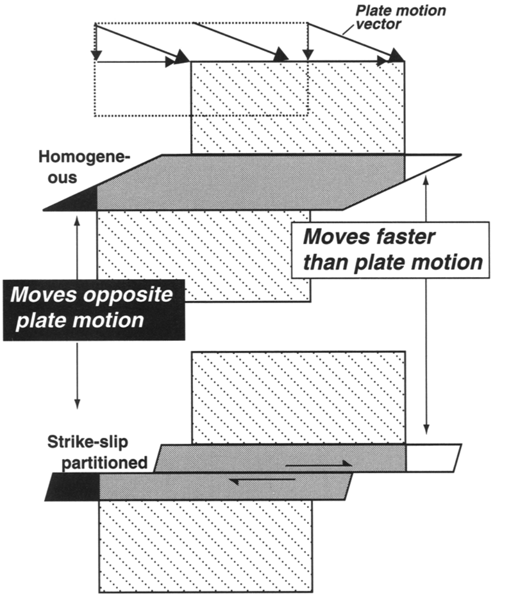

Fig. 13. The effect of margin-parallel extension on terrane motion. Modelling suggests that terrane motion faster than, or opposite to, the tangential component of plate motion is geologically acceptable.

Exhumation of deep crustal rocks

Strike-slip tectonism is commonly discounted as an effective mechanism for uplifting deep crustal rocks (e.g. Platt 1993). This idea overlooks the transpressional or three-dimensional nature of strike-slip zones, i.e. a component of wrench and normal convergence. The three-dimensional nature of transpression provides the two components needed to uplift deep crustal rocks: (1) a vertical conduit supplied by the wrench component; and (2) vertical flow from the contractional component. Transpressional systems are inferred to extend to deeper crustal levels as nearly vertical structures, a geometry that allows the wrench component of movement. Using this conduit, upward movement of lower-crustal rocks from deep to shallow settings is possible during a single deformation. If the lower-crustal rocks are able to flow, an analogy is possible to magma emplacement in transpressional or strike-slip settings. Similar to magmas, lower-crustal rocks may be 'emplaced' in structural voids in an overall transpressional environment, such as between en echelon P-shears (Tikoff & Teyssier 1992). If there are rheological contrasts and the flow field departs from homogeneity, pods of higher-pressure (and higher-density) rocks may be brought up by the flow in the transpressional zone, analogous to entrained xenoliths.

The contractional aspect is responsible for the rapid upward movement of lower-crustal rocks. In all of the transpressional models (types A–E), this upward movement is accommodated by the coaxial component which is more efficient than the wrench component (Tikoff & Teyssier 1994). Type C, D, and E transpression causes margin-parallel extension, which is capable of exhuming crustal rocks by causing extension *perpendicular* to the margin trend (Avé Lallement & Guth 1990). An equally effective mechanism of exhumation is type A and B transpression combined with erosion. In these cases, the normal component of plate movement is accommodated by vertical uplift of rocks. This vertical movement is visible in particle path movement and material line rotation (Fig. 8), and also indicated by a vertical axis of maximum finite strain. If the deformation zone has a relatively narrow width, erosion rates can keep pace with tectonic rates, leading to effective exhumation. As discussed above, type A and B deformation is favoured by straight to concave margins. Modern analogies of this setting are the 'bend' in the San Andreas system and in the Bolivian segment of the Andes, with attendant uplift of the Tranverse Ranges and Altiplano.

Exhumation of blueschist belts by terrane collision

A good example of the role of transpressional tectonics in the exhumation of deep crustal rocks involves the presence of high-pressure rocks (e.g. blueschists). Because of the density of these rocks, it is commonly recognized that buoyancy did not result in their upward movement (Hsü 1991). Many models have been developed for the exhumation of these assemblages to the surface of the Earth, most involving flow in subduction zones (e.g. Cloos 1982; Platt 1986). Whereas the blueschist mineralization clearly formed in a subduction-zone setting, this is not necessarily the cause of its exhumation.

The outboard existence of colliding terranes potentially explains the uplift of long, linear trends of blueschist commonly found in orogenic zones. Although linear, margin-parallel zones of high-pressure mineral assemblages presumably formed in subduction zone settings, they are commonly found in areas of collisional belts. Thus, the uplift of high-pressure rocks, and blueschists in particular, is broadly related to collision dynamics (Hsü 1991).

Terrane collision would effectively stop subduction and, if oblique, result in transpressional kinematics. As discussed above, transpression zones are effective at uplifting material because of the wrench-induced vertical conduit and the contraction-induced uplift. Further, in a terrane collision setting, the tectonic thickening is potentially accommodated in a narrow zone. A good example of this behaviour is thickening and extrusion in the form of flower structures, particularly along the San Andreas fault (e.g. Harding 1985). Because the zone is relatively narrow, erosion may be very efficient, leading to increased exhumation (e.g. Beaumont *et al.* 1992). In this way, metamorphic reactions from the subduction setting do not equilibrate, and high-grade mineral assemblages are preserved by rapid uplift (Thompson *et al.* 1997).

For example, a transpressional terrane collision may apply to the classic Franciscan complex of California, which is at present bounded on its west side by the Salinian block. $^{40}Ar/^{39}Ar$ and K/Ar ages indicate the last phase of blueshist metamorphism at *c.* 92 Ma (Cloos 1985), which corresponds generally to cessation of the Sierra Nevada magmatic arc (83 Ma; Stern *et al.* 1981). The uplift of the Franciscan complex is Late Cretaceous to early Paleogene, as indicated by pebbles of the Franciscan blueschists found in the Paleocene Great Valley sequence (Berkland 1973; Harms *et al.* 1992). This time also corresponds to proposed dextral strike-slip faulting of the Salinian block (proto San Andreas fault; Nilsen & Clarke 1975) and the inferred northward movement of Baja–British Columbia (Beck 1986). Thus, uplift of the Franciscan blueschists is hypothesized to be a result of terrane collision, rather than 'business-as-usual' subduction.

Conclusions

We have defined a spectrum of transpressional (and transtensional) deformations which have in common a simple shear (wrench) component and a perpendicular shortening component. Five reference deformations in this spectrum are named A–E, in which type B involves no extension or shortening along strike of the zone (transpression or transtension of Sanderson & Marchini (1984)). Type B is probably the most common type of transpression or transtension, but irregularities such as curved plate boundaries may give rise to other types.

Simple mathematical modelling shows that the orientation and geometry of the finite strain ellipsoid, fabric type (L, S, SL, etc.), fabric orientation, maximum infinitesimal stretching direction, kinematic vorticity, and/or rotation pattern of linear and planar features can together be used to distinguish between the different types of transpression (transtension) (Table 1), and to determine the angle of convergence. During heterogeneous deformation, several of the parameters listed in Table 1 will show large variations as *Wk* and finite strain vary across the zone (e.g. strain and fabrics for type A transpression). Also, partitioning of strain in transpression or transtension zones implies that observations within one part of the zone may not be representative for the entire system.

These models have implications for tectonic analysis in areas of oblique convergence and divergence. In areas of oblique convergence, the plate motion vector is *not* parallel to the infinitesimal contraction (stress) direction, as represented by the seismic slip vector. Furthermore, the finite strain features are not parallel to either the plate motion or the slip vectors. Evidence of exhumation or tectonic uplift of rocks within transpression zones, resulting from arc-normal extension, results from type C–E transpression. If erosion is active, type A and B transpression can lead to very rapid exhumation. Correspondingly, anomalous crustal thinning within the zone suggests type A–C transtension.

These results are also applicable to transpressional settings resulting from oblique plate convergence of terranes. The exact type of transpression (types A–E) is a result of the plate motion vectors and geometry of plate margins. The boundaries between converging terranes are likely to exhibit vertical foliation, but either vertical or horizontal lineation. Margin-parallel stretching may result in terrane motion which locally exceeds, or moves in an opposite direction to, the tangential component of plate motion. Finally, kinematics of transpression can cause rapid uplift in narrow, margin-parallel zones of deformation, which may result in the exhumation of high-pressure rocks.

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