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Stretching lineations in transpressional shear zones: an example from the Sierra Nevada Batholith, California

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Abstract—Ductile shear zones and associated stretching lineations are generally considered to be the result of two-dimensional, simple shear deformations, with stretching lineations interpreted to rotate into parallelism with the direction of tectonic transport with increasing deformation. However, stretching lineations perpendicular to the inferred tectonic transport direction are displayed by some shear zones. Field studies in the Sierra Nevada batholith have revealed a single shear zone (the Rosy Finch–Gem Lake shear zone) that contains both steeply-plunging stretching lineations in older metamorphosed sedimentary and granitic rocks, and shallowly-plunging stretching lineations in syntectonic granitoids. Dextral sense-of-shear indicators are found in all these units and deformation occurred simultaneously along the length of the shear zone.

Theoretical strain modeling indicates that stretching lineations can be either horizontal or vertical within transpressional shear zones. To investigate the kinematics of three-dimensional deformation, we examine the role of stretching lineations which form as a result of finite strain, including the possibility of partitioning a component of the strike-slip movement onto shear bands. Comparing the field data with the strain modeling, we interpret the along-strike variation in lineation behavior within the Rosy Finch–Gem Lake shear zone to be a result of the differences in finite strain recorded by different units. The older units, showing steeply-plunging lineation, have recorded more finite strain across a narrower shear zone than the syntectonic granites which record shallowly-plunging lineations. We conclude that the orientation of the lineation within transpressional shear zones does not necessarily correlate with the transport direction, but may reflect along-strike variations in finite strain and/or strain partitioning.

INTRODUCTION

Lineations provide important information concerning movement and deformation of geological materials, from the micro- to plate scale (Cloos, 1946). Lineations are routinely used in structural analysis to evaluate strain and determine the direction of movement within ductile shear zones (Berthé *et al.*, 1979; Simpson and Schmid, 1983). Regional studies commonly use lineations to constrain the direction of tectonic movement and attempts have been made to relate regionally consistent lineations to plate motion (Shackleton and Ries, 1984; Burg *et al.*, 1987; Ellis and Watkinson, 1987; Fossen *et al.*, 1994).

Kinematic interpretations of shear zones and lineations generally assume simple shear deformation because of strain compatibility restrictions (Ramsay and Graham, 1970). This assumption was reinforced by the application of sense-of-shear indicators (Berthé *et al.*, 1979; Simpson and Schmid, 1983; Hanmer and Passchier, 1991), which assume that the stretching lineation forms in the direction of tectonic movement in simple shear. However, Sander (1930, 1970) noted that lineations can be parallel ('a'-type lineation) or perpendicular ('b'-type lineation) to the inferred movement direction. The occurrence of 'b'-type lineations in some shear zones suggests that either the dominant lineation formed is not a stretching lineation or shear zones record a three-dimensional deformation that is not just simple shear.

Vertical stretching lineations within a vertically-oriented shear zone, perpendicular to the simple shear component of deformation and the direction of tectonic movement, were first interpreted to be the result of transpressional deformation by Hudleston *et al.* (1988). Subsequently, several other transpressional shear zones have been recognized which also contain vertical stretching lineations (Robin and Cruden, 1994; Greene and Schweickert, 1995). These interpretations were based on strain modeling of transpression, which indicate that the long axis of the finite strain ellipsoid is vertical for some transpressional deformations (Sanderson and Marchini, 1984; Fossen and Tikoff, 1993). Transpression, a combination of simple shearing and an orthogonal pure shearing (Fig. 1), results in a distinctly non-plane strain deformation (Fossen *et al.*, 1994). The assumptions inherent in a transpressional model, such as a free upper surface, have been noted by many authors (Sanderson and Marchini, 1984; Robin and Cruden, 1994). Transpression is often invoked as an important style of deformation in regions of oblique convergence (Oldow *et al.*, 1989; Teyssier *et al.*, 1995).

The role of lineations in transpressional shear zones

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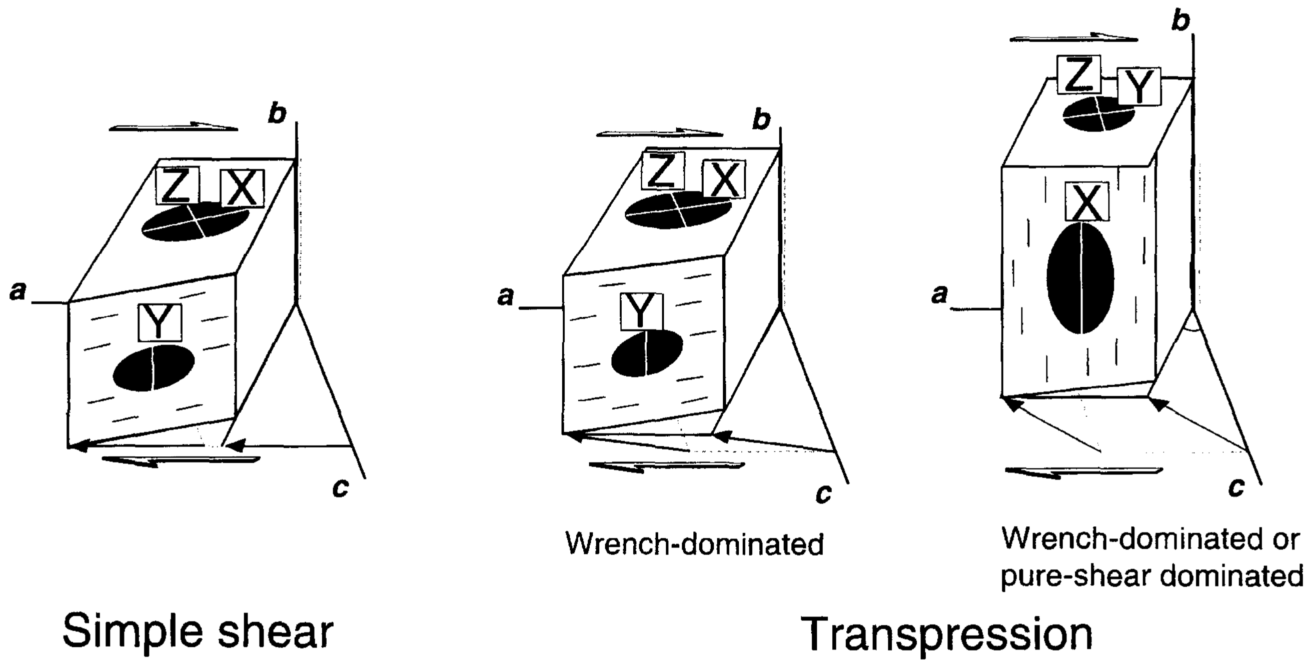


Fig. 1. Stretching lineations, assumed to form parallel to the long axis of the finite strain ellipsoid, within simple shear and transpressional shear zones. Lineations in simple shear parallel the direction of tectonic movement, whereas in transpression, the lineations can be parallel or orthogonal to the simple shear component of movement. The dotted lines represent the undeformed shape of the box, large arrows indicate the dextral simple shear component, and small black arrows show movement direction. *X*, *Y*, and *Z* are the long, intermediate, and short axes of the finite strain ellipsoid.

has specifically been addressed for homogenous transpression by Fossen *et al.* (1994) and in 'ductile transpression' by Robin and Cruden (1994). In the latter example, a sophisticated model of flow with triclinic symmetry was developed that accommodates the boundary conditions of transpression but maintains strain compatibility with the bounding rocks. The model reproduced much of the complexity of particle motion in naturally deformed shear zones, but the complexity of the model did not allow generalization concerning finite strain (Robin and Cruden, 1994). In our opinion, fabrics in naturally deformed rocks, including foliation and lineation, are primarily the result of finite strain, and it is these effects that we explicitly address herein.

We present here an example of a transpressional shear zone in the Sierra Nevada Batholith, California, which displays *both* shallowly-plunging and steeply-plunging lineations, along strike, within the same shear zone. This behavior is explained using three-dimensional kinematic modeling, in which we determine the conditions of formation for vertical and horizontal stretching lineations within transpressional shear zones. Additionally, because finite strain is commonly partitioned onto shear bands in ductile shear zones, the possibility of strike-slip partitioning or heterogeneous transpression on an outcrop scale is addressed, as well as the ramifications for stretching lineation development. Using the field study and the strain modeling, we suggest that: (1) different orientations of stretching lineation can potentially form concurrently in ductile shear zones, such as occurs in the Rosy Finch–Gem Lake shear zone; and (2) the stretching lineation direction does not necessarily correlate with the direction of the simple shear component of deformation (e.g. tectonic transport direction), as often assumed in tectonic studies.

ROSY FINCH–GEM LAKE SHEAR ZONE, SIERRA NEVADA

The Sierra Crest shear zone system in the eastern Sierra Nevada (U.S.A.) (Fig. 2) consists of at least three sections that are continuous from south to north: the Rosy Finch (Tikoff and Teyssier, 1992; Tikoff, 1994), Gem Lake (Greene and Schweickert, 1995), and Cascade Lake shear zones (Hutton and Miller, 1994; Tikoff and Greene, 1994; Davis *et al.*, 1995; Davis, 1996). The Rosy Finch shear zone (Tikoff and Teyssier, 1992) is exposed in the granitic rocks of the John Muir Intrusive Suite, including the syntectonic Mono Creek Granite (Tikoff, 1994). The Gem Lake shear zone (Greene and Schweickert, 1995), in northward structural continuity with the Rosy Finch shear zone, deforms Paleozoic metasedimentary rocks and Upper Triassic to Lower Jurassic metavolcanic rocks in the Ritter Range and Northern Ritter Range pendants. Along the western edge of the Northern Ritter Range pendant, the Gem Lake shear zone also deforms the Late Cretaceous granodiorite of Kuna Crest (Hutton and Miller, 1994; Tikoff and Greene, 1994; Greene and Schweickert, 1995). The northern segment of the Gem Lake shear zone is in structural continuity with the Cascade Lake shear zone (Davis *et al.*, 1995; Davis, 1996), which records dextral shearing in the eastern Cathedral Peak and Half Dome plutons (Tikoff, 1994). The last movement on this shear zone occurred at ~85–80 Ma, as constrained by Ar/Ar dating (Sharp *et*

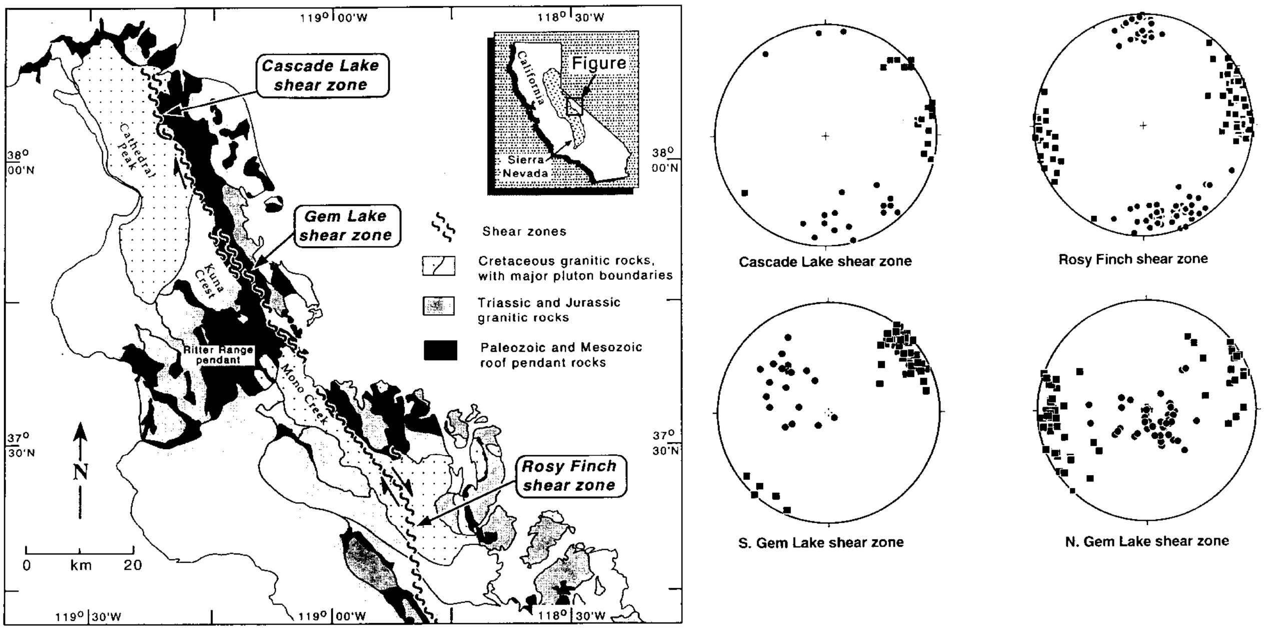


Fig. 2. Generalized map of east central Sierra Nevada, U.S.A., showing the Rosy Finch, Gem Lake, and Cascade Lake shear zones. Equal-area stereonets indicate lineation orientation (circles) and poles to foliation (squares). Structural and isotopic dating relations suggest movement occurred concurrently, although lineation orientations are shallowly plunging in the Rosy Finch and Cascade Lake shear zones and steeply plunging in Gem Lake shear zone.

al., 1993; Tobisch *et al.*, 1995) and the syntectonic nature of the Mono Creek and Cathedral Peak plutons (Tikoff, 1994) combined with their isotopic ages (U/Pb on zircon; Stern *et al.*, 1981).

The Rosy Finch shear zone in the Mono Creek Granite is a foliated and lineated zone of deformation striking NS–N40W, characterized as an orthogneiss (Tikoff, 1994). Throughout the shear zone, the foliation is subvertical and the lineation is generally shallowly plunging (Fig. 3). *S–C* relationships, imbricated porphyroclasts (Tikoff and Teyssier, 1994a), folded aplite dikes, σ and δ-porphyroclasts (Passchier and Simpson, 1986), and 'bookshelf' displacement on feldspar cleavages all indicate dextral shear. The style of deformation varies along strike, but in general, foliation is defined by the orientation of deformed quartz grains and by mica folia wrapping around well-preserved feldspar porphyroclasts. The streaky lineation in the Rosy Finch shear zone resembles a slickenside that develops on mica folia consisting of biotite (generally altered to chlorite) and quartz (Fig. 3). The lineation develops preferentially on the shear planes (interpreted as C' planes), which commonly nucleate along the edges of the K-feldspar porphyroclasts. Aggregates of quartz grains within the granite also show elongation parallel to the streaky lineation, consistent with interpretation as a stretching lineation. The Cascade Lake shear zone, which deforms the eastern edge of the Cathedral Peak Granodiorite, is very similar in deformation style to the Rosy Finch shear zone in the Mono Creek Granite (Tikoff, 1994; Davis *et al.*, 1995). Foliation in this zone strikes N30–45W, the lineations plunge shallowly ($<30°$), and dextral shear indicators are found throughout (Fig. 2).

The Gem Lake shear zone is a $\sim$1 km wide, anastomosing zone of mylonitic foliation striking N30–60W and dipping steeply to the SW. Throughout these metavolcanic rocks (S. Gem Lake shear zone, Fig. 2), the Gem Lake shear zone has a moderately- to steeply-plunging lineation which is visible on steeply-dipping foliation surfaces (Fig. 4). This lineation is defined by elongate aggregates of phyllosilicates, extended lithic clasts, and extended quartz and feldspar porphyroclasts. Lithic clasts are fractured and extended in the lineation direction, with no sense of asymmetry, and the extensional fractures are filled by calcite (Fig. 4). Lineation-parallel thin sections show boudinaged and brittley extended porphyroclasts, which generally have symmetric pressure shadows containing calcite, sericite, and quartz. This lineation records steeply-oriented extension and is also interpreted as a stretching lineation. Dextral shear indicators are best developed in metavolcanic rocks, where *S–C* fabrics on horizontal exposures occur in fine- to medium-grained tuffs. Asymmetric pressure shadows and winged porphyroclasts are observed in medium- to coarse-grained lapilli tuffs and tuff breccias (Fig. 4). Quartz veins are commonly deformed, rotated, and boudinaged with asymmetric pressure shadows around individual boudins consistent with dextral shearing.

The Gem Lake shear zone also deforms the granodiorite of Kuna Crest (91 Ma), which is 5 m.y. older than the syntectonic Cathedral Peak Granodiorite (86 Ma; U/Pb zircon ages, Stern *et al.*, 1981). Foliation, striking N10E–N20W, and lineation are generally well developed (N. Gem Lake shear zone, Fig. 2, Greene, 1995). Lineation in this zone is sub-vertical and is formed by elongate aggregates of phyllosilicates and segregations of quartz and feldspar. Vertically boudinaged felsic dikes and the vertical elongation of quartz phenocrysts indicate a stretching lineation. Dextral shearing is recorded by rotated tension gashes, locally developed *S–C* fabrics, and rare asymmetric folds (Greene and Schweickert, 1995).

VERTICAL STRETCHING LINEATIONS AND TRANSPRESSION

The co-existence of vertical lineations and horizontal sense-of-shear indicators have been reported from a variety of transpressional shear zones, particularly in the Canadian shield. The Vermillion District, northern Minnesota, was one of the earliest recognized transpressional shear zones (Hudleston *et al.*, 1988; Bauer and Bidwell, 1990). This zone displays a well-developed vertical foliation and sub-vertical lineation. However, sigmoidal foliation patterns, shear bands, asymmetric pressure shadows, and predominantly Z-shaped folds on sub-horizontal surfaces all indicate dextral, transcurrent motion. Finite strain analyses from this zone indicates flattening fabrics (Schultz-Ela and Hudleston, 1991), consistent with strain models of transpression.

The Larder Lake-Cadillac break, Ontario, is an approximately 1 km wide zone of well-developed fabric that has also been interpreted as a transpressional shear zone (Robin and Cruden, 1994). This zone also contains sub-vertical foliation and predominantly steeply-plunging lineation. Dextral shear sense indicators are well developed on sub-horizontal faces, and no shear indicators are developed parallel to lineation (Robin and Cruden, 1994). For both the Vermillion District and Larder Lake-Cadillac break, the vertical lineation is interpreted as a stretching lineation, consistent with observed finite strain patterns, in an overall transpressional deformation.

However, the unique observation within the northern Sierra Crest shear zone system, compared to transpressional shear zones within the Canadian Shield, is the domainal existence of *both* shallowly- and steeply-plunging lineations along strike in a structurally continuous shear zone. This observation requires a more in-depth investigation into the behavior of stretching lineations in transpressional shear zones.

STRAIN MODELING APPLIED TO LINEATION DEVELOPMENT

Theoretical modeling of homogeneous transpressional shear zones indicates that the orientation of the long axis of the finite strain ellipsoid, and thus the stretching lineation (Fig. 1), can be either horizontal or vertical (Sanderson and Marchini, 1984; Fossen and Tikoff, 1993; Fossen *et al.*, 1994; Tikoff and Teyssier, 1994b). In the case of pure shear-dominated transpression, which corresponds to cases where the angle of convergence $(\alpha) > 20°$, the long axis of the finite strain ellipsoid is always vertical (Fig. 5). In the case of wrench-dominated transpression, $\alpha < 20°$, the long axis of the finite strain ellipsoid initially lies in the horizontal plane, but becomes vertical with increasing deformation (Fossen and Tikoff, 1993; Tikoff and Teyssier, 1994b). When this switch in orientation of the finite strain axes occurs depends on: (1) the kinematics, and (2) the amount of deformation. Therefore, the orientation of the stretching lineation in wrench-dominated transpression depends on the amount of deformation for a given set of boundary conditions (such as a constant α).

The exact nature of this switch in orientation of the finite strain ellipsoid long axis in wrench-dominated transpression is shown graphically in Fig. 5, where the angle of convergence α (kinematics) is plotted against the axial ratio of the horizontal finite strain ellipse (amount of deformation). This graph was produced by simply plotting the axial ratio of the horizontal strain ellipse, for a given α, which created a perfectly oblate shape (or perfect flattening; $k = 0$). However, for any angle of convergence, the orientation of the infinitesimal strain (or stretching) axes remains fixed throughout the deformation (Tikoff and Teyssier, 1994b).

Applying this analysis to stretching lineations, it is clear that a fixed α in wrench-dominated transpression could result in either horizontal or vertical lineations, depending on the magnitude of finite strain recorded in the shear zone (Fossen *et al.*, 1994). For instance, if $\alpha = 17°$, then shear zones with a horizontal finite strain ellipse ratio greater than ~ 10 will record vertical lineations, while those recording less deformation will record horizontal lineations (Fig. 5). This result is shown in Fig. 6, where a constant angle of convergence leads to sequence of horizontal lineation, pure flattening, and vertical lineation with progressive deformation. A more general consequence of the strain modeling is that for any *high strain* transpression zone that deviates more than slightly from simple shear ($\alpha > 5$–$10°$), the long axis of the finite strain ellipsoid, and consequently the stretching lineation, will be vertical.

In this context, Robin and Cruden (1994) have developed a sophisticated model of deformation that accommodates the boundary conditions of transpression, but by a complex flow. The edges of this flow retain strain compatibility with the rigid boundary walls, and maximum extrusion occurs in the middle of the zone. Because of the complexity of the model, finite strain was not calculated for this model of ductile transpression, but patterns of particle trajectories were interpreted in terms of lineation. Their modeling also suggested that lineation direction could be either horizontal or vertical, or vary continuously between the two, in a ductile transpression shear zone. In our interpretation, however, the movement direction, as indicated by particle trajectories, is not necessarily indicated by the lineation direction. Rather, it is the finite strain that is reflected by the orientation of lineation.

Shear zones rarely act in a completely homogeneous manner and partitioning of deformation commonly occurs in shear zones on a variety of scales. *S–C* structures are a particularly common form of strain partitioning that tend to concentrate a larger portion of the simple shear component of deformation into discrete

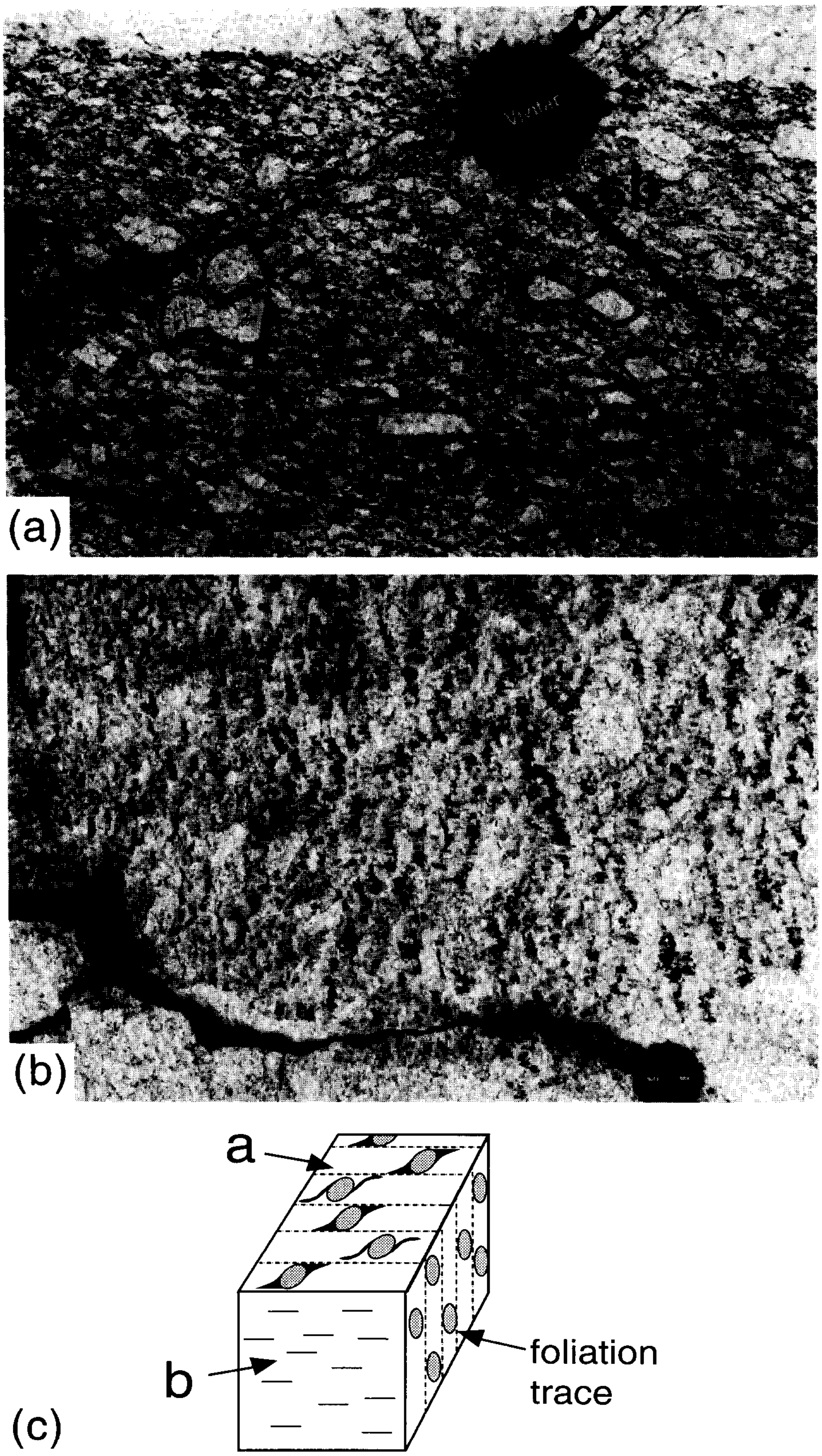


Fig. 3. Deformation from orthogneiss, Rosy Finch shear zone. Photo (a) shows imbricated feldspars and *S–C* relationships, indicating dextral shear. *S* designates foliation and *sb* parallels a shear band. Photo (b) showing the face of the shear plane, shows the streaky lineation consisting of biotite, altered to chlorite, and quartz. Quartz grains also show elongation parallel to the lineation, consistent with the interpretation of a stretching lineation. Cartoon (c) demonstrates the position of photos (a) and (b) on the outcrop.

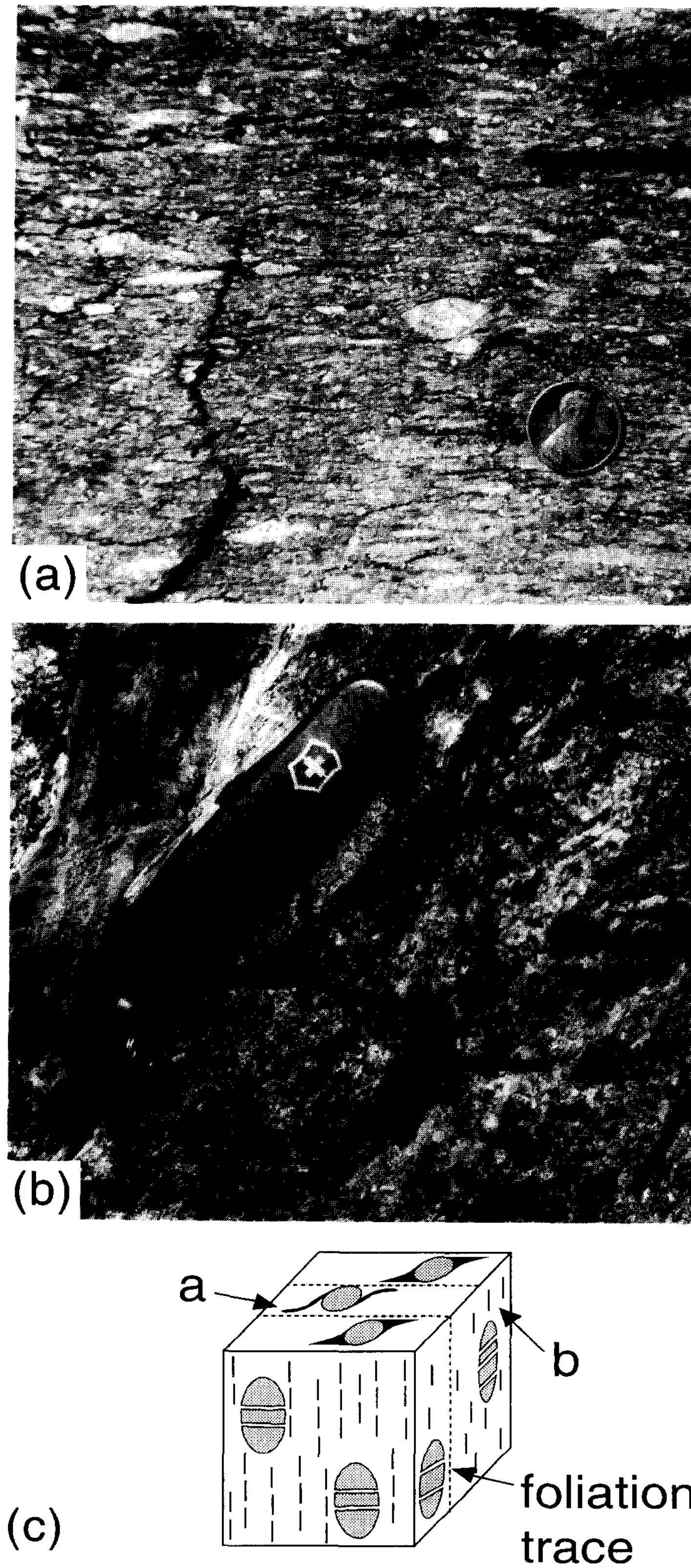


Fig. 4. Deformation features in crystal–lithic lapilli tuff, Gem Lake shear zone. Photo (a) is oriented horizontally and shows asymmetric pressure shadows and winged porphyroclasts indicating dextral shear. Photo (b) is oriented vertically, parallel with lineation and perpendicular to sub-vertical foliation, exhibiting boudinaged and brittlely-extended lithic clasts (arrows). The orientation of the foliation is denoted by the black line and labeled *S*. Cartoon (c) demonstrates the position of photos (a) and (b) on the outcrop.

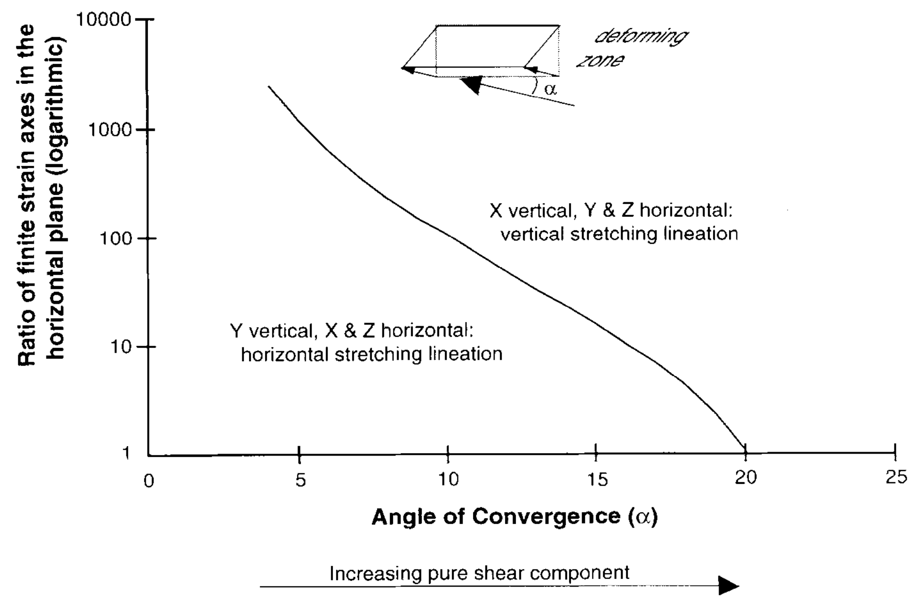


Fig. 5. Plot of the angle of convergence (α) versus horizontal finite strain ellipse ratio, for homogeneous wrench-dominated transpression, to determine if stretching lineations are vertical or horizontal. The line of pure flattening separates the field in which the long axis of the finite strain ellipoid is horizontal, producing horizontal stretching lineations, from the field in which the long axis of the finite strain ellipoid is vertical, producing vertical stretching lineations. For any $\alpha < 20°$, the stretching lineation is originally horizontal, but becomes vertical after some deformation.

zones (Lister and Williams, 1983). Because *S–C* structures form in transpressional shear zones, such as the Gem Lake (Greene and Schweickert, 1995) or Vermillion district (Schulz-Ela and Hudleston, 1991), it is appropriate to develop strain models of non-homogeneous transpression. Two ways of partitioning a transpression deformation are: (1) strike-slip partitioned transpression; and (2) heterogeneous transpression (Fig. 7).

One simplistic way of accounting for variations in simple shear across a shear zone is to consider a model of strike-slip partitioning for the transpressional deformation, in which the relative effects of distributed transpressional deformation and discrete slip are considered (Fig. 7, Teyssier *et al.*, 1995). The strike-slip partioned transpression model of Tikoff and Teyssier (1994b) was designed for brittle, upper crustal conditions and consequently a component of the simple shear motion was accommodated on discrete strike-slip faults. Because the material on either side of the strike-slip fault is extending in the vertical direction as a result of the pure shear

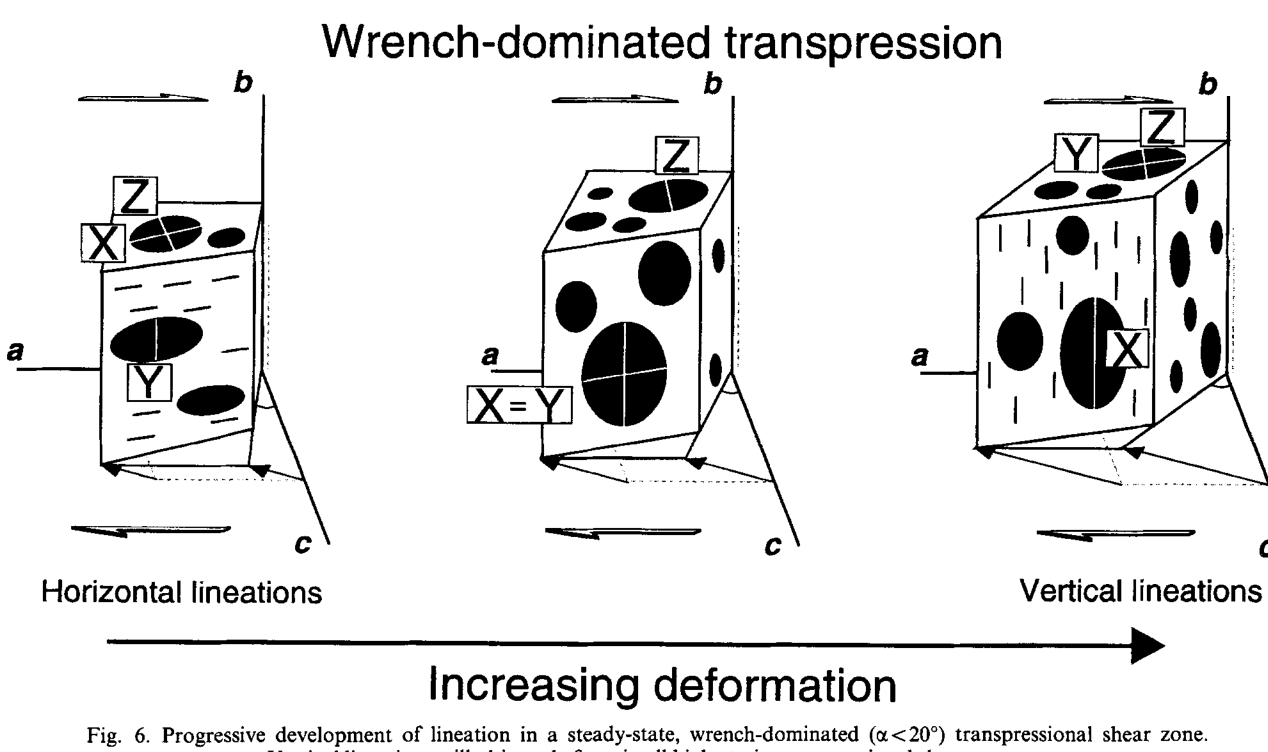
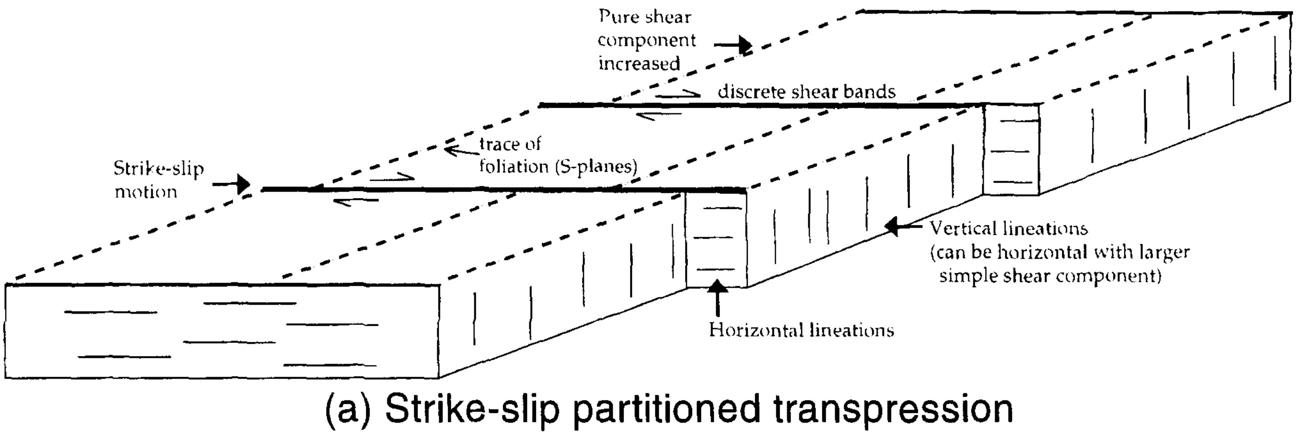


Fig. 6. Progressive development of lineation in a steady-state, wrench-dominated ($\alpha < 20°$) transpressional shear zone. Vertical lineations will ultimately form in all high-strain transpressional shear zones.



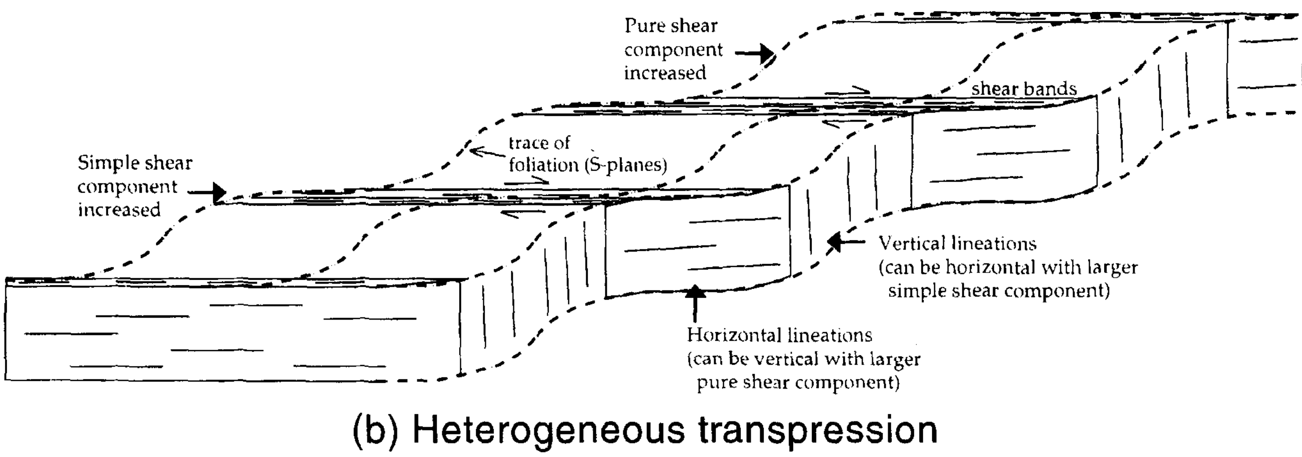


Fig. 7. Cartoon showing (a) strike-slip partitioning in transpression or (b) heterogeneous transpression, applied on the outcrop scale. For (a), a component of the bulk simple shear deformation is accommodated as strike-slip motion along the shear bands. The rest of the simple shear component and all of the pure shear component of deformation occurs as a transpressional deformation in the areas between shear bands. For (b), strain compatibility requirements are met and the pure shear component is constant across the entire zone. The simple shear varies throughout the zone and is maximum in the shear bands. Both figures show Option 2 development of stretching lineations.

component of deformation, the discrete strike-slip faults must 'stretch' in the vertical direction to maintain a bulk transpressional deformation (Fig. 8). This behavior is similar to the stretching faults of Means (1989), except that the stretching is perpendicular, rather than parallel, to the simple shear component of deformation. Notice that strain compatibility restrictions are not strictly applicable in this case because the material is not a continuum, a condition that is applicable to upper-crustal settings (Tikoff and Teyssier, 1994b)

Applying strike-slip partitioning to *S–C* fabric requires that some of the simple-shear component of the bulk transpressional deformation occurs along discrete shear bands. The rest of the simple shear component, and all of the pure shear component, occurs within the areas adjacent to the shear bands (Fig. 7). Therefore, there are two distinct possibilities for stretching lineation development in strike-slip partitioned transpressional shear zones (Fig. 9): (1) horizontal lineations both within and outside of shear bands; and (2) vertical lineations outside of the shear bands and horizontal lineations within the shear bands. Option 1 describes the case of bulk wrench-dominated transpression (or simple shear) in which the

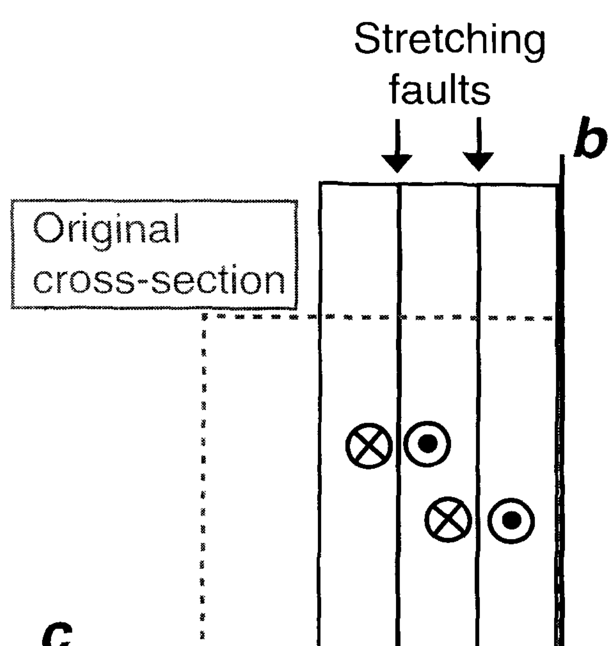


Fig. 8. Vertical, end-on view of a strike-slip partitioned transpressional system (see Fig. 1 for coordinate axes). Stretching faults (Means, 1989) form, but extend material in a perpendicular, rather than parallel, direction to the simple shear component of deformation.

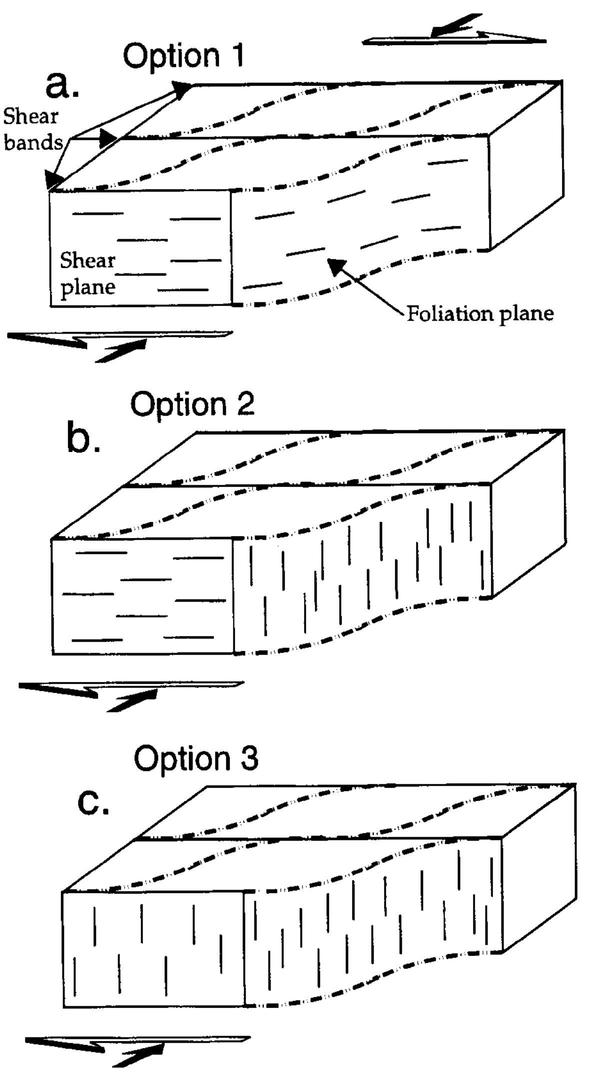


Fig. 9. Three possibilities for lineation orientation in transpressional shear zones, including the possibility of strike-slip partitioning. Option 1: horizontal lineations outside and within the shear bands, are the result of wrench-dominated transpression (or simple shear). Option 2: horizontal lineations within the shear bands and vertical lineations outside of the shear bands, are the result of either wrench or pure-shear dominated transpression. Option 3: vertical lineations outside and within the shear bands, are the result of pure-shear dominated or high-strain wrench-dominated transpression. Option 3 cannot occur in strike-slip partitioned transpression.

areas between shear bands record wrench-dominated transpression. This situation would occur with either very low angles of convergence ($\alpha < \sim 5$–$10°$) or associated with relatively low strain (but $\alpha < 20°$). Alternatively stated, the pure shear component in the areas between shear bands is not sufficient to cause vertical lineations even if a large portion of the overall strike-slip motion is taken up along the discrete shear bands. Option 2 describes some bulk wrench-dominated and all pure-shear dominated strike-slip partitioned transpression. Strike-slip movement and horizontal stretching lineations would characterize the areas within the shear bands. Pure shear-dominated transpression describes the deformation in the area outside of the shear bands and vertical lineations will form in these areas. This setting applies to some bulk wrench-dominated transpression, because in these cases the majority of the strike-slip component of motion occurs on the shear bands and therefore the pure-shear component is dominant in the areas between the shear bands.

An alternative model is heterogeneous transpression, in which strain compatibility requirements are maintained (Fig. 7). In this model, the pure shear component is distributed homogeneously across the shear zone, but with gradients in the simple shear component of deformation. This would result in a variation of the infinitesimal strain features-convergence angle, infinitesimal strain axes, and *Wk*-across the shear zone. This deformation is easy to model, but relies on *ad hoc* assumptions about the variation of deformation across the shear zone. However, since heterogeneous transpression is simply an intermediate case between homogeneous transpression and strike-slip partitioned transpression, it is easy to evaluate the results qualitatively. This type of strike-slip partitioning is probably the general rule for *S–C* fabrics, particularly in lower strain cases where through-going, discrete shear bands are not developed.

The case of heterogeneous transpression leads to the three options of lineation development (Fig. 9). Option 1, horizontal lineations both within and outside of shear bands, can occur for bulk wrench-dominated transpression. As in the case of strike-slip partitioned transpression, this situation will preferentially occur for low finite strain and/or a small angle of convergence. Option 2, vertical lineations outside the shear band and horizontal lineations within the shear bands, can occur in either bulk wrench-dominated or pure-shear dominated transpression. However, to develop these features during heterogeneous transpression requires a high degree of partitioning of the simple shear component of deformation, tending toward strike-slip partitioned transpression. Because of the strain compatiblity constraints (i.e. some of pure shear component acts within the shear bands), non-simple shear ($\alpha > 0°$ or $Wk < 1$) characterizes the shear bands in this case. Option 3 describes pure-shear dominated transpression and high-strain wrench-dominated transpression. In this case, the areas between shear bands are dominated by the pure shear component of deformation and vertical lineations result. Although a large component of the overall strike-slip motion is accommodated along the shear bands, there is a large enough pure shear component that the stretching lineation is also vertical in the shear bands. Similar to the case of homogeneous transpression, all heterogenous transpressional shear zones will ultimately contain vertical lineations within and outside the shear bands if deformation is allowed to proceed to very high strain values.

The consequences for lineation development in transpressional shear zones are dramatic. If Option 2 occurred, one could potentially find two different orientations of stretching lineations at a single outcrop that formed simultaneous and are kinematically related. Further, if a large strain gradient existed across a transpressional shear zone, there could be vertical lineations in the center (Option 3), horizontal lineations on the edges (Option 1), and a transition fabric with both lineation orientations (Option 2) between the two.

DISCUSSION

We propose that the occurrence of both shallowly-plunging and steeply-plunging stretching lineations in the northern Sierra Crest shear zone system arises from an along-strike strain gradient. This results because the syntectonic granitoids only record the last increments of the strain history. The syntectonic Mono Creek and Cathedral Peak plutons record significantly less deformation, distributed over a larger area, than the older granodiorite of Kuna Crest and wallrocks. Within the Rosy Finch shear zone, Tikoff and Teyssier (1992, 1994a) estimate 8 km of dextral displacement over a 3.5 km width, resulting in relatively low shear strain ($\gamma <= 2.3$). This estimate has been subsequently corroborated by detailed AMS studies of the Mono Creek pluton, which demonstrate a rotation of magnetic lineation within the shear zone (Saint Blanquat and Tikoff in press). The deformed plutons record a horizontal stretching lineation similar to Option 1 (Fig. 9): both the streaky lineation within shear bands and the elongation of quartz aggregates in the areas between shear bands are horizontal. Deformation in the Rosy Finch shear zone is therefore consistent with a wrench-dominated transpressional setting and low values of accumulated finite strain.

In contrast, within the Gem Lake shear zone, Greene and Schweickert (1995) suggest a minimum of 20 km of dextral offset within a ~ 1 km-wide shear zone. The direction of the stretching lineation (and, therefore, the long axis of the finite strain ellipsoid) is steeply-plunging in this strongly deformed zone, although there is abundant evidence of dextral shear (Greene, 1995). Option 3 best describes deformation in the Gem Lake shear zone: stretching lineations are steeply-plunging throughout the zone, even on shear bands which indicate dextral shear. If the deformation is characterized by wrench-dominated transpression in the Gem Lake shear zone, as suggested by the kinematics of the Rosy Finch shear zone, the vertical lineations are the result of the high strain recorded within the zone, consistent with the strain modeling of transpressional zones that record large amounts of deformation (Fossen *et al.*, 1994).

Other explanations for the presence of vertical stretching lineations within the Gem Lake shear zone are possible. One possibility is that the difference in lineation orientation in different parts of the shear zone system is a result of rheological contrasts between granitic rock and metamorphic wall rock. However, the older granodiorite of Kuna Crest within the Gem Lake shear zone also contains steeply-plunging lineations, in contrast to the shallowly-plunging lineations in the granitic rock elsewhere in the shear zone. Since the deformation in the granodiorite is clearly solid-state and continuous with deformation in the wall-rocks, lithology does not appear to play a critical role in determining lineation orientation. Another possibility is that a set of vertical stretching lineations formed earlier and were overprinted by later transcurrent motion. In this scenario, the earlier-formed stretching lineations were not affected by the transcurrent motion, but the dextral asymmetry within the Gem Lake shear zone is a result of the later transcurrent movement. Supporting this hypothesis is the observation of steeply-dipping shear zones, with steeply-plunging lineations and asymmetric structures indicating contractional deformation, in the central Sierra Nevada (McNulty, 1995; Tobisch *et al.*, 1995). $^{40}Ar/^{39}Ar$ dating on these shear zones indicates that the contractional motion generally occurred before ~ 90 Ma (Tobisch *et al.*, 1995), and it is possible that portions of the Gem Lake shear zone (Northern Ritter Range Pendant and 92 Ma Kuna Crest pluton) could have been affected by this earlier contractional episode. However, regular overprinting of lineations is not observed in the Gem Lake shear zone (Greene and Schweickert, 1995). Further, the granodiorite of Kuna Crest, which records sub-vertical lineations, is only slightly older (5 m.y.) than the Cathedral Peak granodiorite, which records shallowly-plunging lineations (Fig. 2) and both are part of the same magmatic event (Tuolumne Intrusive Suite). Therefore, the relatively short time between intrusions does not support the idea of strong, pre-existing fabric in the Kuna Crest pluton prior to the activation of the Gem Lake shear zone.

CONCLUSIONS

Field studies in the Sierra Nevada batholith indicate that both steeply-plunging and shallowly-plunging stretching lineations formed within the transpressional Sierra Crest shear zone system. Steeply-plunging stretching lineations and large transcurrent movements occur in the highly deformed wall rocks (Gem Lake shear zone), whereas shallowly-plunging stretching lineations formed simultaneously within the syntectonic granitoids (Rosy Finch and Cascade Lake shear zones). The entire shear zone, regardless of the orientation of the stretching lineation, contains dextral shear-sense indicators on horizontal surfaces and the deformation is constrained to have occurred simultaneously along the extent of the shear zone.

These observations are consistent with strain modeling of transpression, which indicates that the orientation of the long axis of the finite strain ellipsoid, and hence the stretching lineation, can be either horizontal or vertical within transpressional shear zones. The orientation of the stretching lineations depends on both the kinematics (such as the angle of convergence α) and the amount of deformation within a shear zone. For pure shear dominated transpression, stretching lineations are always vertical. In contrast, stretching lineations within wrench-dominated transpression are either horizontal (low strain) or vertical (high-strain). Further, deformation is commonly partitioned onto shear bands, which can cause both vertical and horizontal stretching lineations within the same outcrop for either pure shear or wrench-dominated transpression.

Using the field study and the strain modeling, we conclude that stretching lineations do *not* necessarily record transport direction in a shear zone, particularly in high-strain zones. The assumption of lineation forming parallel to a movement direction stems from the application of sense-of-shear criteria (Berthé *et al.*, 1979; Simpson and Schmid, 1983) and is valid in cases where deformation approximates plane-strain, simple shear conditions. However, development of stretching lineations in three-dimensional deformation, such as transpression, can be quite complex and could potentially result in simultaneous formation of two orthogonal lineations that are kinematically related. In particular, the orientation of stretching lineation may vary either along strike or at a single outcrop, due to variations in accumulated finite strain and the amount of simple shear partitioned within shear bands. Three-dimensional aspects of deformation must be considered before any interpretation of lineation pattern, particularly transport direction, can be accomplished.

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