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Physical experiments of vertical transpression with localized nonvertical extrusion

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Abstract

Previously proposed models of vertical-walled transpression implicitly assume that material extrudes upwards during deformation. This assumption is not necessarily valid at all scales given that: (a) in areas of diverse lithologies, local zones of relatively rigid materials may cause extruding material to deflect around those zones, and (b) ductile strain often forms anastomosing geometries of shear zones. Therefore, it is possible that a local extension direction in otherwise classic transpression may be nonvertical for rocks deforming at depth. Using an analogue experiment, we have modeled a transpression zone with localized nonvertical extrusion. This extrusion is accomplished by the addition of a side 'leak' that allows sideways extrusion in addition to vertical extrusion. The net extension direction depends on the material's position within the deforming zone, resulting in a significant range of lineation orientations with deformation. The strain patterns produced by transpression with localized nonvertical extrusion may explain the wide array of lineation orientations found in some natural ductile transpression zones.

Keywords: Vertical transpression; Nonvertical extrusion; Sideways extrusion

1. Introduction

Ductile transpression is a form of deformation (Fig. 1a) in which simple shearing is parallel to the zone boundary and pure shearing is perpendicular to the zone boundary (Sanderson and Marchini, 1984). It results in shortening across the zone accompanied by extension parallel to the zone boundaries. The fabrics that form in an idealized ductile transpression zone (e.g. Sanderson and Marchini, 1984; Fossen and Tikoff, 1993; Simpson and De Paor, 1993; Tikoff and Fossen, 1993) result from finite strain. Fossen and Tikoff (1993) determined fabrics in an idealized ductile transpression zone and predicted that in all cases, ductile transpression creates stretching lineations that are only vertical or horizontal. Despite the theoretical predictions for fabrics in ductile transpression, many field examples of rocks that appear to have otherwise deformed with idealized transpressional kinematics, exhibit a range of nonvertical and nonhorizontal (obliquely plunging) lineations (e.g. Hudleston et al., 1988; Schultz-Ela and Hudleston, 1991; Holdsworth, 1994; Robin and Cruden, 1994; Goodwin and Williams, 1996; Dutton, 1997; Lin et al., 1998; Czeck, 2001; Czeck and Hudleston, 2003).

The model proposed by Robin and Cruden (1994) predicts some obliquely plunging lineations in transpression. In the transpression model described by Sanderson and Marchini (1984), strain compatibility is not maintained at the discrete boundary between the deformation zone and the wall rocks. To resolve this problem, Robin and Cruden (1994) proposed a transpression model with no-slip boundaries (Fig. 1b). They calculated the variation in strain rate and inferred the systematic variations in instantaneous foliation and lineation fabrics that occur vertically and horizontally across such a model. Dutton (1997) further developed this approach by calculating the finite strains and corresponding structural fabrics, foliation and lineation, created during transpression with no-slip boundary conditions. With the no-slip condition and orthogonal simple shearing and pure shearing, the foliation and lineation fabrics vary together systematically within the deformation zone.

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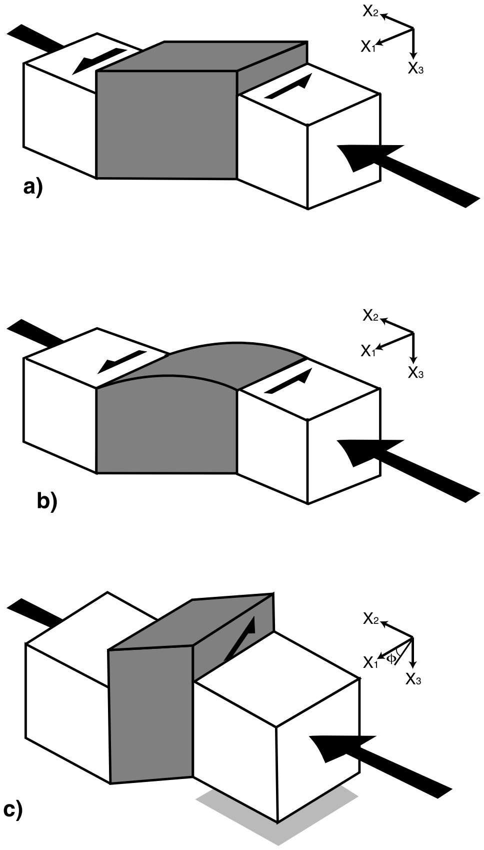

Fig. 1. Transpression models: (a) after Sanderson and Marchini (1984), (b) after Robin and Cruden (1994), (c) after Lin et al. (1998).

Other authors have proposed transpression zones with nonvertical walls (e.g. Dewey et al., 1998). The boundary condition of nonvertical walls leads to generally dipping foliations and lineations, but the pattern can be produced by tilting an equivalent vertical transpression zone.

Contrary to what one might expect from vertical-walled transpression with no-slip boundaries (Robin and Cruden, 1994; Dutton, 1997) or transpression with nonvertical walls (e.g. Dewey et al., 1998), there are many natural examples in which a range of obliquely plunging lineations occur without significant corresponding deviations from vertical orientations by the foliations (e.g. Hudleston et al., 1988; Schultz-Ela and Hudleston, 1991; Goodwin and Williams, 1996; Czeck, 2001; Czeck and Hudleston, 2003). Additional kinematic models are needed to reconcile this discrepancy between natural structures and existing models.

Several authors have proposed ideas to account for obliquely plunging lineation orientations within a bulk transpressional regime without the no-slip boundary condition by altering the orientation of the *simple shear* component of deformation with respect to the shear zone boundaries (Jiang and Williams, 1998; Jones and Holdsworth, 1998; Lin et al., 1998) (Fig. 1c). In these models, although differing in detail, the simple shearing is parallel to the shear zone boundary, but inclined at some angle (ϕ) from horizontal. The plunges of the resultant lineations vary depending on ϕ and increase with increasing strain. The foliation orientations also vary depending on ϕ and steepen with increasing strain. However, for transpression modeled without a no-slip boundary condition, foliations can be shown to be essentially subvertical for a wide range of deformations, especially those with relatively low ϕ (Lin et al., 1998). In particular, this type of triclinic transpression model (e.g. Lin et al., 1998) is effective at predicting obliquely plunging lineations for early stages of strongly simple shear influenced deformation. The validity of this type of model, as applied to a particular field area, can be assessed using a combination of field evidence, including foliation and lineation orientation, the orientation of the vorticity normal section, and strain magnitude (Czeck and Hudleston, 2003).

One similarity among all of the models previously discussed, is the implicit assumption that material extrudes upwards. This assumption is logical because, in general, one would expect the direction towards the earth's surface to be that of least resistance for material to move. Some authors have also included a horizontal extrusion component with vertical extrusion in transpression models (Jones et al., 1997; Teyssier and Tikoff, 1999). This changes the strain ellipsoid shape, but not the orientation, and consequently not the structural fabric orientations.

Recent work (Czeck and Hudleston, 2003) has documented oblique structural fabrics in a transpressional setting that could not be explained by transpression with an oblique simple shear component. Obliquely plunging lineations, in this case, were attributed to nonvertical extension directions due to the *pure shear* component of deformation. It is possible that these nonvertical extension directions were accommodated by patterns of localized nonvertical extrusion during deformation.

Rocks at depth may be subjected to other boundary conditions that cause local pressure gradients to deviate from the first-order assumption of vertical and horizontal extrusion. For example, in areas of diverse lithologies, local zones of relatively rigid materials may cause extruding material to be deflected around those zones. Also, ductile strain often develops in anastomosing geometries of shear zones associated with local deviations in the pressure gradient, producing similar effects.

In lithologically diverse areas, marked rheological contrasts can cause local pressure variations. Deformed conglomerates provide a useful example of this variation at a small scale. Structural fabrics in the surrounding matrix can be seen to wrap around clasts that behave more rigidly during deformation (Fig. 2) due to the flow of matrix around the clasts. On a larger scale, many examples of complex terranes that contain such diverse rocks exist in nature. For example, in deformed granite–greenstone terranes, the granitic units may have behaved as relatively stiff units surrounded by the much weaker greenstones. As these rock units have significantly different competencies, flow of material in the greenstones may be diverted around the

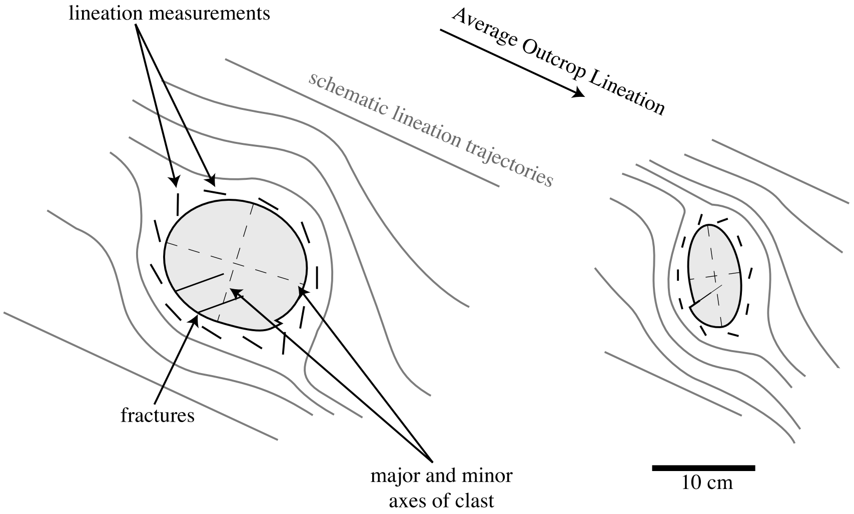

Fig. 2. Diagram of lineation variations around two rigid granitoid clasts, as viewed on the foliation plane. This figure was sketched at an outcrop of Seine River conglomerates within the Archean Superior Province near Mine Centre, Ontario. Clast shape and fractures are drawn schematically. Dashed lines indicate major and minor axes of clasts; long axes of clasts are not parallel to each other or the lineation, most likely because they behaved as rigid markers during deformation. Measured mineral lineations are shown in black. Gray lines indicate schematic lineation trajectories.

plutons. This flow pattern will result in different strain magnitudes within the two regions, but more importantly for this discussion, it will also result in localized deflection in extrusion directions resulting in variability of local structural fabric orientations.

Three-dimensional, anastomosing networks of shear zones may have similar effects on structural fabric geometries. Anastomosing shear zone networks have been described in field settings by many authors (e.g. Mitra, 1979; Ramsay and Allison, 1979; Choukroune and Gapais, 1983). It seems that, more often than not, at some scale, many shear zones can be described as such an anastomosing network surrounding less deformed lozenges. Bell (1981) and Hudleston (1999) have shown that such networks can cause quite complex local structural fabrics and strain patterns (Fig. 3). Within these networks, local extension directions may differ from the bulk extrusion direction. These local changes allow material to maintain continuity during deformation. As a result of the imposed geometrical constraints on deformation, anastomosing shear zones may produce a pattern of strain and structural fabric very similar to that produced by lithologically diverse regions in which there are bodies of varying lithologies and thus mechanical properties.

These examples indicate that local inclined extrusion directions may be commonplace in vertical deforming zones, and that the consequences for structural fabrics are marked. Thus, vertical transpressional zones with localized nonvertical extrusion are considered here in order to understand the influence of localized nonvertical extrusion on structural fabrics, stretching lineations in particular. In the present study, a physical analogue model was made to simulate a vertical-walled pure shear dominated transpression zone with localized nonvertical extrusion. Some comment about terminology is in order. In classical transpression, material is extruded vertically from between the converging plates or blocks. The maximum extension direction is also vertical in pure-shear dominated transpression. In the experiments we describe here, in addition to vertical extrusion, we have added lateral or oblique extrusion from the edge of the deforming zone—physically a 'leak' from the deformation box. Maximum stretch in the experiment is deflected from vertical in the vicinity of the

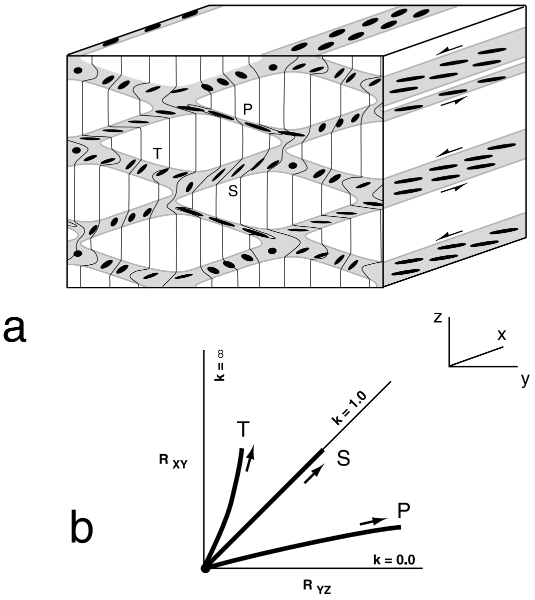

Fig. 3. From Hudleston (1999). (a) Network of shear zones after deformation. Simple shear parallel to *X*, with no bulk strain in the *YZ* plane. Along individual lozenge boundaries occur transpression (P), transtension (T), and simple shearing (S). Overall strain compatibility is maintained with this geometry. (b) Deformation paths on the Flinn plot are highly variable corresponding to different positions around the lozenges. Most paths will be close to simple shearing. Note that the shape of the block in (a) does not imply shortening in *Z* or extension in *Y*.

leak and is variable in inclination. In this case, we cannot equate extrusion direction with extension direction. It is the maximum stretch or extension direction we are really concerned with here, expressed in rocks through linear fabric elements and the state of strain.

2. Analogue experiments

2.1. Experimental setup

The purpose of our experiments is to illustrate the principle of modifying transpression by the addition of localized nonvertical extrusion. Therefore, the experiments described here are not scaled and do not lead to quantitative assessment of strain or a precise deformation history that could be correlated to a field setting. Rather, the experiments demonstrate a qualitative model illustrating how fabrics might be affected by localized nonvertical extrusion during transpression that should be considered when interpreting structural fabrics in the field.

An experimental apparatus based on the design of Tikoff and Peterson (1998) was constructed to simulate bulk transpression (Fig. 4). The two metal plates were cut at an angle $\alpha = 30°$ from one another to simulate pure shear dominated transpression with vertical stretching lineations (Tikoff and Teyssier, 1994). Added to the design were vertical clear plastic walls that were attached to the metal strips that anchor the rubber sheet. Two adjoining clear plastic walls were attached with hinges, which allowed these walls to swing as deformation progressed. Thus, a three-dimensional homogeneous transpression box was created with tall confining walls to contain transparent polydimethyl siloxane (PDMS) of the variety RG20 manufactured by Rhône-Poulenc. PDMS may be approximated as a Newtonian material (Weijermars, 1986).

The experiments began by stretching the rubber sheet to its maximum length (approximately 8 cm parallel to convergence direction). Vegetable shortening (cooking grease) was applied to the plastic box edges in order to minimize friction along the boundaries, and the box was filled with PDMS and allowed to equilibrate. Most air bubbles escaped from the PDMS at this time. Colored blobs of PDMS, with no ductility contrast to the matrix, were used as markers to document strain in each of the two experiments. As these strain markers are not originally spherical, their deformed shapes cannot be interpreted as strain ellipsoids. However, because the colored markers were moderately non-spherical and approximately randomly oriented before deformation, their overall shape and orientation after deformation should roughly correlate to finite strain fabric. Moreover, by tracking each marker during the experiment, we can determine the strain responsible for the change in marker shape.

The experiments proceeded by slowly moving the metal plates together at a convergence rate of 0.04–0.06 mm/s. Two experiments were conducted. In the first experiment, the vertical walls were left intact as deformation progressed and material extruded only upward. In the second experiment, a horizontal slit was cut into one of the swinging walls to allow material to extrude laterally as well as upward. This effectively created a ‘leak’ where material could move out of the deforming box.

2.2. Experimental results: transpression with no leak

The first experiment, with intact walls and no leak, was performed in order to simulate ductile transpression with

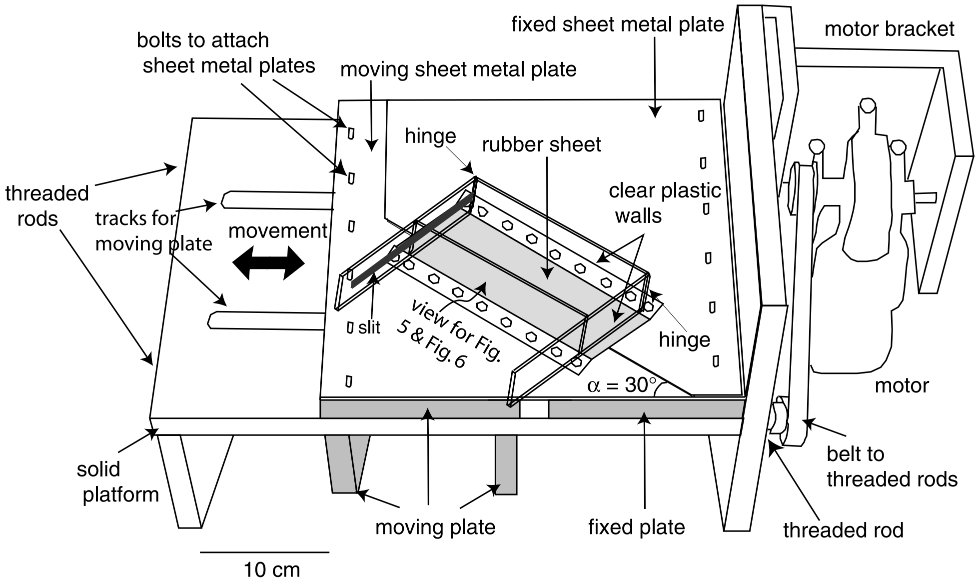

Fig. 4. Diagram of transpression machine used in experiments. After Tikoff and Peterson (1998).

orthogonal pure shear and simple shear, as defined by Sanderson and Marchini (1984).

During deformation, the PDMS bulged somewhat on the top of the experiment as predicted by Robin and Cruden (1994) for transpression with frictional boundaries. The boundaries of the box displayed a fabric similar to that described by Robin and Cruden (1994), with frictional contact with the plastic walls. The main difference between their model and our experiment is that rather than two vertical no-slip boundaries along the length of the deforming zone, our experiment has four vertical no-slip boundaries corresponding with the four walls of the plastic box.

The resultant fabric for this first experiment is shown in Fig. 5. This figure was drawn from photographs taken on the front side of the box, which is coincident with the foliation plane at the final stage of deformation. This view was selected because it shows the maximum stretching direction of the finite strain. The strain markers behaved as expected with predominantly vertical stretching during ordinary progressive transpression. The center of the experiment showed primarily vertically stretched markers; however, the stretching directions of the markers near the top were skewed due to the bulge of extruding material. The fabrics directly near the walls are slightly skewed due to frictional boundary effects.

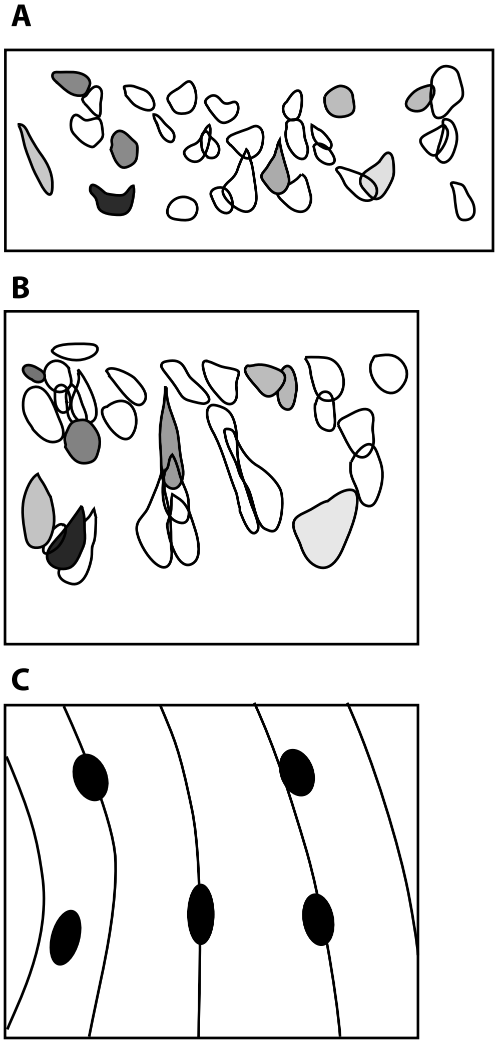

Fig. 5. Analogue experiment showing deformation: transpression. Diagrams are drawn from photographs taken through the front of the moving box created by the clear plastic walls shown in Fig. 4. This is a view of the foliation plane at the final state of deformation. (A) Randomly oriented blobs of colored PDMS before deformation. (B) The same blobs after deformation (8 cm convergence). (C) Schematic lineation trajectories and strain ellipses drawn for the final deformation.

2.3. Experimental results: transpression with leak

The second experiment was similar to the first except that it included a horizontal slit, or leak, in one of the swinging plastic walls on the side of the box. This experiment was performed in order to simulate ductile transpression with orthogonal pure shear and simple shear as defined by Sanderson and Marchini (1984) with the added component of localized nonvertical extrusion. The slit allowed small amounts of material to extrude laterally in addition to the material extruding upwards in general transpression. For material at the top of the box, the extrusion direction was roughly vertical. For material directly adjacent to the leak, the extrusion direction was roughly horizontal. For material at other points in the box, the net result of allowing bulk vertical extrusion and a localized horizontal extrusion through the slit resulted in a net inclined extrusion direction. For clarity of presentation, an experiment with only one leak is shown here. Additional leaks in other portions of the box have the effect of creating similar fabric patterns about each leak.

During deformation, like in the first experiment, the PDMS bulged somewhat on the top of the experiment, as predicted by Robin and Cruden (1994) for transpression with frictional boundaries. The material extruded vertically within the box and laterally (both horizontally and in an inclined direction) through the leak. The final amount of material extruded through the slit was minor, significantly less than 1% of total PDMS.

The resultant fabric for this second experiment is shown in Fig. 6. Again, this figure was drawn from photographs taken on the front side of the box, which is coincident with the foliation plane at the final stage of deformation. Like the first experiment, the majority of the markers are oriented vertically, and some of the marker orientations are skewed near the top due to effects of the bulge. The fabrics directly near the walls are slightly skewed due to frictional boundary effects. The difference in the fabrics, compared with the first experiment, is also significant. As may be expected, the orientations of the markers near the leak have been substantially skewed. Directly near the slit, the long axes of the markers are horizontal, and they gradually plunge more steeply away from the slit. Many marker orientations, plunging both towards and away from the slit, were generated in this experiment.

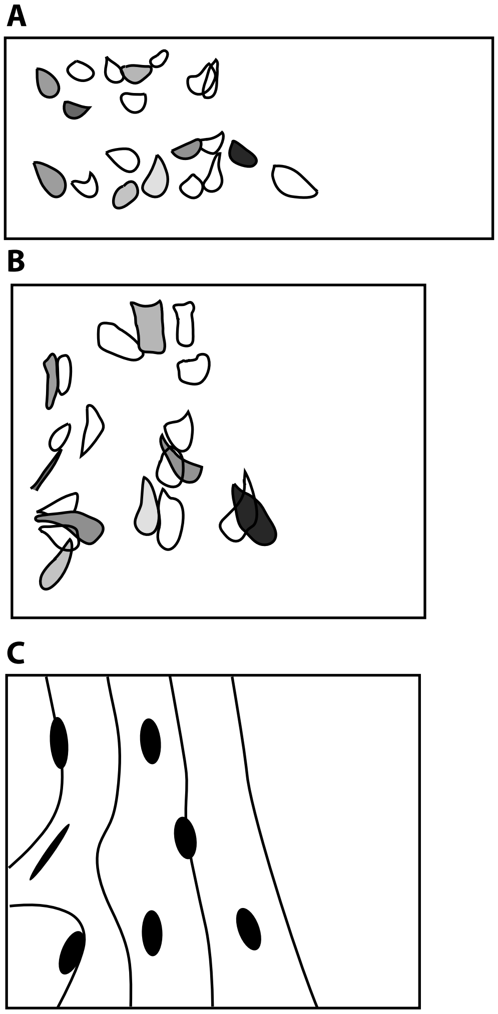

Fig. 6. Analogue experiment showing deformation: transpression with nonvertical extrusion. Diagrams are drawn from photographs taken through the front of the moving box created by the clear plastic walls shown in Fig. 4. This is a view of the foliation plane at the final state of deformation. The 'leak' is made by the slit on the left side of the diagram. (A) Randomly oriented blobs of colored PDMS before deformation. (B) The same blobs after deformation (8 cm convergence). (C) Schematic lineation trajectories and strain ellipses drawn for the final deformation.

2.4. Discussion of deformation in the experiments

Using the changes in blob shapes to infer the strain ellipsoid, we have determined the foliation (*XY* orientation of the strain ellipsoid) and lineation (*X* orientation of the strain ellipsoid) within our experiments. To do this, we used a graphical software program to superimpose circles onto our undeformed photo of strain markers. We then 'deformed' the photo with the circles until it resembled most closely the deformed result from the experiment. The circles, now ellipses, were inferred to reflect the two-dimensional strain ellipses on the vertical photographed plane, which is roughly coincident with the foliation plane at the final stage of the experiment.

In both experiments, throughout most of the experimental deformation zone, the fabric inferred from the markers includes vertical foliation planes and vertical lineation orientations. In both experiments, the fabrics directly near the walls are skewed due to frictional boundary effects. In the experiment with the leak, the lineation orientations are similar to those in the first experiment, except that they differ significantly near the leak. They plunge horizontally adjacent to the slit and gradually plunge most steeply away from the slit. Above and below the slit, the lineations plunge in opposite directions. The plane of foliation is consistently parallel throughout the volume of the experiment, and is not shown.

3. Applying the nonvertical extrusion model to the field

While nonvertical extrusion is relatively easy to create in the physical model, it is less obvious to relate to natural transpression zones. Experimental observations suggest that the nonvertical extrusion needed to significantly change local lineation orientations need not be large ($<1\%$ of the total material). It follows that local perturbations in nature need not be large to create obliquely plunging lineations.

Anastomosing shear zone networks and rheological contrasts can be seen at many scales in deforming zones. Therefore, localized nonvertical extrusion, and subsequent deflection of structural fabrics, may happen at a variety of scales.

4. Discussion

4.1. Nonvertical extrusion

Previously proposed models have assumed that the stretch from the coaxial strain component of transpression is accommodated by either vertical or horizontal extrusion parallel to the zone boundary (Sanderson and Marchini, 1984; Fossen and Tikoff, 1993; Simpson and De Paor, 1993; Tikoff and Fossen, 1993; Robin and Cruden, 1994; Dutton, 1997; Jones et al., 1997; Jiang and Williams, 1998; Jones and Holdsworth, 1998; Lin et al., 1998; Teyssier and Tikoff, 1999). Perhaps, most commonly, deforming rocks will preferentially flow upward because the pressure gradient is greatest in this direction. However, this may not always be the situation, particularly at depth. During ductile deformation, the extrusion direction is controlled by the distribution of pressure. It may be the case that local pressure gradients form, caused by distinct rheological boundaries or anastomosing shear zone geometries. In such a situation, local directions of shear and extrusion will vary and lead to non-vertical, non-horizontal lineations. This phenomenon may occur at many scales.

In our model, nonvertical, nonhorizontal extrusion is included to simulate the various ways in which the extrusion direction can be deflected from the vertical. While the direction of the maximum contraction due to pure shear remains the same, the free boundary that helps define the maximum extension direction is locally changed by the nonvertical extrusion. In our experiment, the local maximum extension direction is determined by the strain components and a combination of the free boundary at the top of the transpression zone and the free boundary of the slit. The fundamental feature of this model is that the simple shear component remains fixed compared with the general transpression model (Fig. 1a), whereas the orientation of the extension due to the pure shear component changes with position in the deformation zone.

A model of transpression accompanied by nonvertical extrusion (Czeck and Hudleston, 2003) is similar to the model discussed by Lin et al. (1998) and Jones and Holdsworth (1998) in that it has triclinic symmetry. However, in contrast, this triclinic symmetry is achieved by a deviation in the pure shear component from traditional transpression (e.g. Sanderson and Marchini, 1984) rather than by deviation of the simple shear component with respect to the deformation zone boundaries. It is also local rather than regional.

4.2. Variation in lineation plunge

The models that alter the orientation of the simple shear component of deformation with no-slip boundaries (Jiang and Williams, 1998; Jones and Holdsworth, 1998; Lin et al., 1998) only predict one specific lineation orientation for a given bulk homogeneous strain. To create multiple lineation orientations across a deforming zone, one could call upon no-slip boundaries (Robin and Cruden, 1994; Dutton, 1997) in which case the foliations and lineations would vary together systematically across the zone. Alternatively, without the no-slip condition, one could also call upon heterogeneous deformation including various types of strain partitioning (Jones and Tanner, 1995). Even with partitioning of strain or gradations in strain magnitude, these models can only predict lineations that plunge within a 90° span without a reversal in shear sense.

As in the models that alter the orientation of the simple shear component of deformation without a no-slip condition (Jiang and Williams, 1998; Jones and Holdsworth, 1998; Lin et al., 1998), in its simplest, homogeneous form (Fig. 7a), the nonvertical extrusion model produces only a single lineation orientation for a given set of boundary conditions (Czeck and Hudleston, 2003). There must be a variation in the direction of stretch associated with the pure shear in order to produce multiple lineation orientations across a zone. Such variation will inherently occur with either a contrasting rigid rheological zone or with an anastomosing shear zone network, producing variation in extrusion directions, and thus fabric orientations, even if the overall extrusion direction remains vertical (e.g. Fig. 7b). Similar to the experiment that allows for local pressure variation, the wide variation in extrusion direction about the vertical in either direction is likely to occur in nature if one considers natural rheological contrasts and geometrical complexities. The nonvertical extrusion model predicts lineations that plunge within a 180° span for bulk homogeneous strain, without requiring strains of opposing shear sense.

One advantage of the nonvertical extrusion model when considering natural lineations is the inherent range of stretching lineations produced around a local pressure gradient. The lineations formed in the analogue experiment span the entire possible range of lineation orientations within the foliation plane, including those plunging in opposite directions. In field settings where there is such a significant range in lineation orientation, it is perhaps more likely that the extrusion direction was significantly variable across the zone rather than the inclination and/or sense of simple shear, as would be required in the inclined simple shear models. The nonvertical extrusion model is useful because it can readily predict a large range of lineation orientations in transpressional zones, especially those in which lineations display opposite plunge directions, where other models do not apply (e.g. Hudleston et al., 1988; Schultz-Ela and Hudleston, 1991; Czeck, 2001; Czeck and Hudleston, 2003).

4.3. Wrench dominated vs. pure shear dominated

Strictly, the terminology of ‘pure shear dominated’ and ‘simple shear dominated’ (Fossen and Tikoff, 1993) does not apply to transpressions with triclinic symmetry because there is never an instantaneous switch in lineation orientation. However, a particular fabric can still be considered as having been primarily controlled by either the simple shear or the pure shear deformation component. In fact, the lineation orientation in previous triclinic models is still primarily controlled by the pure shear component of strain in many cases when the finite lineation is steeply oriented.

In most triclinic models (Jiang and Williams, 1998; Jones and Holdsworth, 1998; Lin et al., 1998), deviation of the simple shear component from the horizontal is the fundamental reason for the creation of obliquely plunging lineations. Therefore, such models only predict significantly obliquely plunging lineations when the transpression fabrics are primarily controlled by the simple shear component of strain. In deformations with relatively low W_k and with increasing strain in deformations with high W_k, the pure shear component of strain primarily controls the fabrics, and subvertical foliations and lineations will result. Obliquely plunging lineations in such models only occur in strongly simple shear-influenced deformations with relatively low strains. The precise division between deformations with fabrics influenced primarily by pure shear from those influenced primarily by simple shear depends on ϕ and the amount of strain (Czeck and Hudleston, 2003).

The nonvertical extrusion transpression model, as a mode to explain obliquely plunging lineations, is not limited to either simple shear- or pure shear-influenced

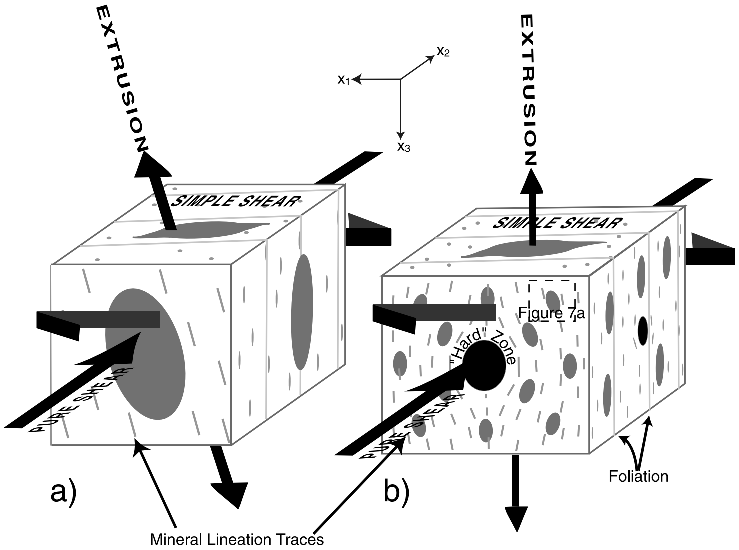

Fig. 7. From Czeck and Hudleston (2003). Schematic view of strain and deformation fabrics for transpression with nonvertical extrusion. Light colored ellipses represent schematic clast traces on each plane. (a) Transpression with nonvertical extrusion. (b) Schematic view of transpression with overall bulk vertical extrusion and localized zones of nonvertical extrusion. Dark colored ellipses represent schematic 'hard' zones that influence local extrusion directions. The relative location of (a) is indicated.

transpression. Because the obliquity of lineation is controlled primarily by the extrusion direction, obliquely plunging lineations can be formed regardless of strain magnitude or the relative influence of pure vs. simple shear. Therefore, it is a possible solution for obliquely plunging lineations in many generalized transpression zones, including those where the inclined simple shear models do not apply (Czeck and Hudleston, 2003).

The conclusion that the nonvertical extrusion model is more general is consistent with analysis that shows that, although the noncoaxial component of deformation influences strain orientation, the coaxial component of deformation primarily controls the strain shape and eventually dominates its orientation (Fossen and Tikoff, 1993; Passchier, 1997; Teyssier and Tikoff, 1999). Thus, a model that creates a range of fabric orientations by relying on the pure shear component of deformation rather than the simple shear component may be more significant.

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