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Fabric stability in oblique convergence and divergence

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Abstract

Forward modeling of transpression–transtension, assuming homogeneous strain and a direct relationship between finite strain axes and foliation–lineation in tectonites, investigates fields of stability of foliation and lineation orientations in oblique convergence and divergence. Vertical foliation–horizontal lineation (VF–HL) develop for angles of convergence–divergence between 0 and 20°. With increasing finite strain, this narrow window of stability is further reduced; lineation switches to vertical in transpression and foliation switches to horizontal in transtension. If a shear zone contains VF–HL, it either developed as a zone very close to pure wrenching, or recorded low finite strain. The stability of VF–HL at high strain and higher angles of convergence is enhanced by lateral extrusion of material along transpression zones. VF–HL may be stabilized in magmatic bodies that progressively intrude transtension zones, if the wrench component of deformation partitions within them. Alternatively, if these bodies are dike-like, cool fast, and do not record large deformation, they take up the extension component of transtension through anisotropic volume addition, leaving a larger component of wrench deformation in the country rocks; this effect stabilizes VF–HL effectively at low strain, but only marginally so at high strain.

1. Introduction

Most published models of geologic deformation examine two-dimensional flow fields, primarily because of the limitations of numerical modeling of three-dimensional deformation. However, within the last five years, three-dimensional kinematic modeling has become available, enabling structural geologists to take into account the complex boundary conditions (Robin and Cruden, 1994; Dutton, 1997) and progressive, non steady-state flow (Fossen and Tikoff, 1997) that typically characterize the deformation of Earth's materials. The results of three-dimensional analyses are often unexpected, and can overturn interpretations commonly made about the orientation of fabrics in rocks (Tikoff and Greene, 1997; Treagus and Lisle, 1997). The difficulty, as always, is applying these models successfully to naturally deformed rocks.

This paper introduces the concept of stability fields of foliation and lineation orientations. The abbreviations used throughout this paper are: VF vertical foliation; HF horizontal foliation; VL vertical lineation; and HL horizontal lineation. This is not to say that dipping foliation and plunging lineation are not important; rather we use a set of simplifying assumptions that constrain these fabrics to be either vertical or horizontal for the purpose of illustration. Fabric stability is related to the fabric attractor concept of Passchier (1997). The maximum finite strain axis and material lines are always 'attracted' to the extensional flow apophysis (or maximum extensional flow direction) (e.g. Fossen et al., 1994; Passchier, 1997). Consequently, a relation exists between the *orientation* of strain/fabric and the principal movement directions. To characterize the *shape* of the finite strain ellipsoid, and the stability of the fabric, one must investigate how the fabric evolves with increasing strain or displacement. If the deformation is considered as consisting

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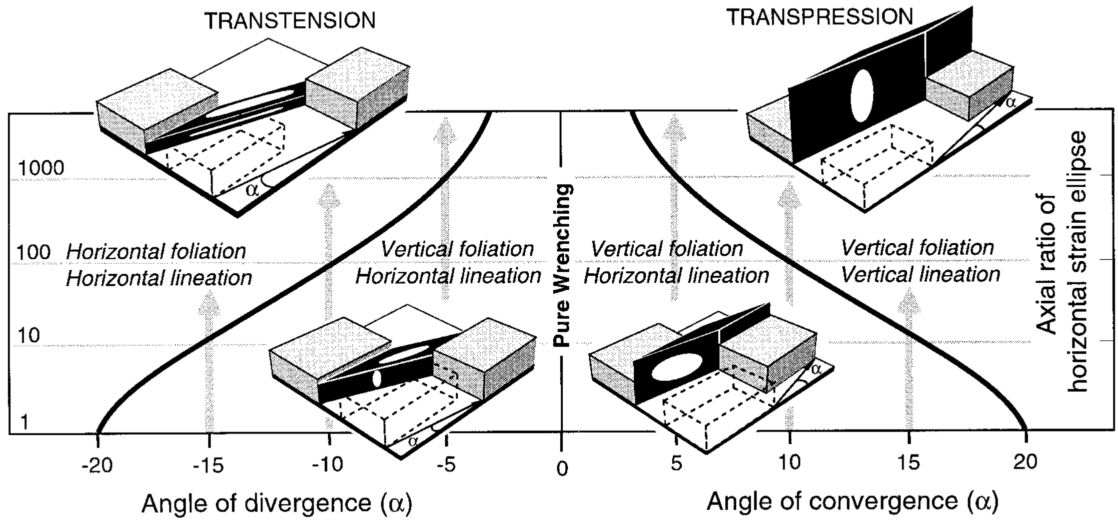

Fig. 1. Angle of divergence–convergence plotted against horizontal finite strain ellipse ratio, for wrench-dominated transtension and transpression. The line of pure constriction separates stability fields of vertical foliation and horizontal foliation for transtension. The line of pure flattening separates stability fields of vertical and horizontal lineations. A single steady-state deformation (i.e. constant values of α), shown with upward arrows for 5°, 10°, and 15° convergence–divergence, can move from one stability field to another with progressive deformation.

of coaxial and non-coaxial components (Ramberg, 1975), the coaxial component has an increasingly large effect on fabric stability with increasing strain (Tikoff and Teyssier, 1994; Fossen and Tikoff, 1998). Heterogeneous and non-steady state flows are difficult to characterize (Fossen and Tikoff, 1997), but again the fabrics are always dominated by the coaxial component of deformation.

In this paper, we focus on shear zones with VF–HL that transect most continents, probably extend into the lithospheric mantle, and are commonly exposed in the exhumed high-grade core of orogens (e.g. Nicolas et al., 1977; Vauchez and Nicolas, 1991). These zones are typically interpreted as wrench zones (Berthé et al., 1979; Burg et al., 1981) or general shear zones (Lacassin et al., 1993; Simpson and De Paor, 1993). However, structural analyses, combined with metamorphic and thermochronological data suggest that many deformation zones containing VF–HL developed with a component of contraction or extension across them (e.g. Leloup et al., 1993; Tommasi et al., 1995). These components of contraction or extension play a destabilizing role on VF–HL. Therefore, we investigate analytically the factors that enhance the stability of VF–HL. We use the models of transpression and transtension, two simple models of three-dimensional flow appropriate to describe oblique convergence and divergence (Sanderson and Marchini, 1984) and determine that VF–HL occur in a narrow window of angles of convergence–divergence. Then we relax this definition of transpression (Harland, 1971) and introduce an additional coaxial component of extension in the horizontal direction (e.g. Avé Lallemant and Guth, 1990; Jones et al., 1997) that allows for lateral extrusion of the deformation zone. This component enhances the stability of VF–HL in transpression, placing constraints on the relationship between the stability field of this fabric and finite strain. Finally, we investigate the role of magmatic volume addition as a stabilizing factor of VF–HL in transtension.

2. Transpression and transtension

Among the kinematic models appropriate to describe oblique convergence–divergence, transpression and transtension are the simplest. Consider the steady flows (upward paths in Fig. 1) of transpression and transtension spanning the spectrum of oblique motion represented by the angle of convergence–divergence α. For cases of pure shear dominated transtension with $\alpha < -20°$ and pure shear dominated transpression with $\alpha > 20°$, stable HF–HL and VF–VL develop, respectively (Fossen and Tikoff, 1993; Tikoff and Teyssier, 1994). For cases where $-20° < \alpha < 20°$, i.e. wrench-dominated transpression and transtension, VF–HL remains stable near pure wrenching ($\alpha = 0$). However, as α increases to $\pm 20°$, VF–HL becomes increasingly unstable with accumulated finite strain. In transpression, accumulated strain leads to pure flattening at which point a switch in S_1–S_2 occurs ($S_1 \geq S_2 \geq S_3$ finite strain axes) and the lineation becomes vertical (VF–VL) (Tikoff and Greene, 1997). In transtension, accumulated strain leads to a constrictional fabric ($S_2 = S_3$) and the foliation switches from vertical to horizontal (HF–HL) with increasing strain. Therefore, VF–HL is generally an unstable orientation in oblique convergence–divergence, unless the boundary con-

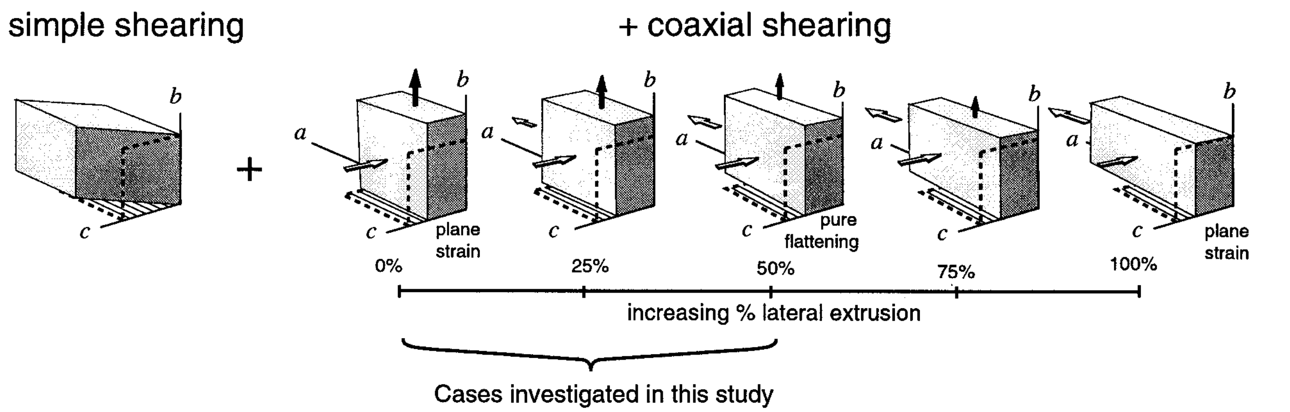

Fig. 2. Cartoon showing simple shear component and coaxial components of deformation for obliquely convergent deformation. The amount of lateral extrusion is 0% for transpression, 50% for simultaneous flattening + simple shearing, and 100% for sub-simple shearing deformation. These three end-members can accommodate any angle of convergence between 0 and 90°. Vertical lineations can only occur for < 50% lateral extrusion, shown on graphs in Fig. 3.

ditions are very close to pure wrenching. In the following sections, we explore factors that may stabilize VF–HL in oblique convergence–divergence. These results provide general guides for the kinematic interpretation of regions displaying VF–HL.

3. Transpression with lateral extrusion

The model of transpression has the distinct advantage, like simple shear, of creating no space problem along the deformation zone (Sanderson and Marchini, 1984): contraction across the zone is taken up by vertical extension, i.e. vertical motion of the Earth's free surface. However, a number of studies have shown that a component of horizontal stretch, associated with lateral extrusion of the deformation zone, may be geologically realistic (Fig. 2) (Harland, 1971; Avé Lallemant and Guth, 1990; Means, 1990; Jones et al., 1997). For example, shear zones accommodating the lateral escape of large lithospheric fragments in SE Asia (Tapponnier et al., 1990) may undergo some component of lateral extrusion. If rigid blocks can escape, material in ductile shear belts of some finite width could extrude laterally as well, the difference being one of scale. This component of lateral extrusion is important in controlling the attitude of foliation and lineation in transpression zones; in particular, it stabilizes VF–HL.

We model this effect by adding a component of pure shear that elongates the material in a horizontal direction, parallel to the transpression zone (see Appendix A). If this added horizontal coaxial extension is equal to the vertical coaxial extension of transpression (50% extrusion, Fig. 2), S_1 is always horizontal, whatever the angle of convergence and the amount of strain. Because the combined horizontal and vertical stretches result in pure flattening strain, the development of lineation is solely due to the simple shear component which produces a HL. Fig. 3 demonstrates the effect of lateral extrusion on the stability of VF–HL. The 0% lateral extrusion case is represented by the curve shown in Fig. 1 for classical transpression. Each curve delimits the stability field of VF–HL and represents the limit where the switch occurs (finite strain is pure flattening). For example, in a zone of transpression with lateral extrusion of 25% and an oblique convergence angle of 40°, S_1 begins horizontal and switches to vertical when the axial ratio of the horizontal strain ellipsoid reaches 11 (Fig. 3). If the lateral extrusion is now 30% instead of 25%, the switch of S_1 from horizontal to vertical will not occur before the horizontal

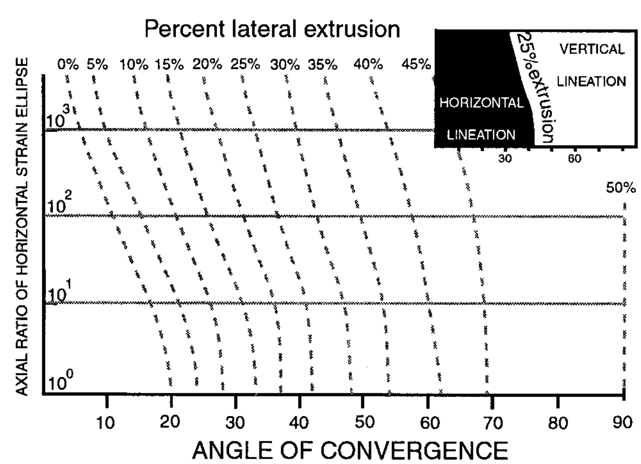

Fig. 3. Angle of convergence plotted against horizontal finite strain ellipse ratio for oblique convergence. Each line represents pure flattening, for a particular percentage of lateral extrusion, separating stability fields of vertical lineation and horizontal lineation. Inset shows example for 25% lateral extrusion. All deformations show some variation with finite strain, but this effect decreases for higher proportions of lateral extrusion.

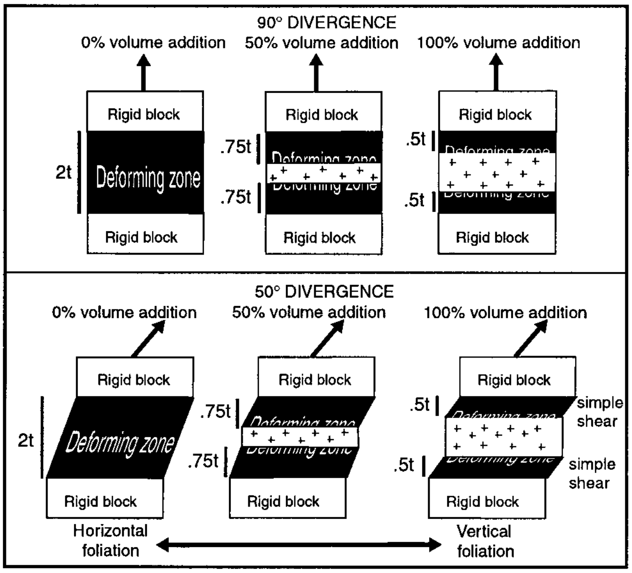

Fig. 4. Cartoon of transtensional deformation with anisotropic volume addition. In map view, for 90° divergence, deformation is shown for homogeneous extension, 50% volume addition, or 100% volume addition. In the latter case, no strain occurs in the zone, i.e. all the extension is accommodated by volume increase. In a case of 50° divergence, deformation is shown for homogeneous transtension, 50% volume addition, or 100% volume addition. In the latter case, only simple shear occurs in the non-intrusive units. Thus, for the same divergence angle (50°), either horizontal foliation or vertical foliation occurs, depending on the amount of volume addition. Volume addition tends to stabilize vertical foliation at low strain in transtension (Fig. 5).

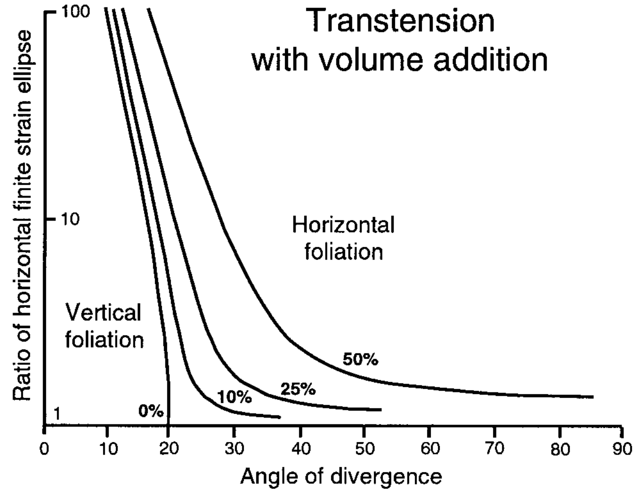

Fig. 5. Angle of divergence plotted against horizontal finite strain ellipse ratio for transtension and volume addition. Each line represents pure constriction, separating stability fields of vertical foliation (left) and horizontal foliation (right). With increasing volume addition, vertical foliation is stabilized at low strain, but only marginally so at high strain.

strain ellipse reaches a ratio of several hundred. This example demonstrates the large stabilizing effect lateral extrusion has on VF–HL. With increasing lateral extrusion, the slope of the curves increases slightly (Fig. 3), indicating that horizontal lineations are further stabilized.

4. Transtension with volume addition

Foliation switches from vertical to horizontal in transtension by increasing either the angle of divergence or the amount of finite strain (Fig. 1). Yet shear zones of supposed transtension origin, such as some of the large shear zones of northern Brazil, are typified by VF–HL (Tommasi et al., 1995). One possibility to explain this paradox is the common observation of vertical dikes and other igneous intrusions in regions of transtension and/or continental-scale shear zones (Nicolas et al., 1977; Tommasi et al., 1995). We envision two end-member scenarios of transtension deformation with simultaneous magmatic intrusion. One alternative is that the simple shear (non-coaxial) component of deformation may partition into the magmatic intrusions, as they are rheologically weaker (e.g. Lister and Williams, 1983). Consequently, the magmatic intrusions will record VF–HL. Sustained development of VF–HL is expected, as the locus of simple shear deformation will move progressively to younger, weaker intrusions. The other alternative is that magma injection and cooling are rapid relative to strain accumulation in the transtension zone, a condition favored by thin vertical dikes and upper crustal settings. In this case, the intrusions accommodate the pure shear component of oblique extension and the simple shear component is enhanced in the country rocks. Note that these two scenarios have the same effect—increased VF–HL stability. We quantify the latter scenario below.

We model an ideal transtension zone in which the material is added anisotropically, such that the added volume takes up a component of extension normal to the shear zone boundaries. Physically, this is the same as adding vertical tabular bodies, such as dikes, in an orientation that increases the width of the zone (Fig. 4). The result is an increase of the simple shear component relative to the pure shear component of transtension in the country rocks, which enhances the stability of VF–HL. Fig. 5 shows the curves that delimit the stability fields of VF–HL for various amounts of volume addition. Volume addition stabilizes horizontal foliation at low strain, but only marginally so at high strain. For higher angles of divergence, the stability field of VF–HL is much reduced. For example, for a zone steadily diverging at 30° in which 50% volume is added, the switch from vertical to horizontal foliation occurs before the horizontal finite strain ellipse reaches an axial ratio of 10. This result is explained by the overwhelming effect of the pure shear component of transtension, which accumulates strain very effectively, even if this component is substantially reduced by volume addition.

5. General application

The analysis presented in this paper has remained very simple for the purpose of drawing kinematic inferences based on the stability of macroscopic fabric orientation. The concept that there are fabric stablility fields in high strain rocks is related to fabric attractors (Passchier, 1997). If deformation combines coaxial and non-coaxial components, the fabric stability is dictated by the coaxial component of deformation, regardless of the orientation of the simple shear component (monoclinic transpression; e.g. Fossen and Tikoff, 1993; or triclinic transpression; e.g. Lin et al., 1998—see their fig. 9). This first-order approach establishes a simple relation between the kinematic framework and the boundary conditions through the 'stable' fabrics within a shear zone. For example, if the character of transpression, lateral extrusion, or volume change in a given region is estimated, then a possible range of angles of convergence or divergence can be determined, providing important tectonic constraints. Note that this approach should be used with caution because of the simplifying assumptions that were made (homogeneity of deformation and direct relationship between finite strain and rock fabrics).

6. Conclusions

Simple modeling of deformation in oblique convergence–divergence using three-dimensional strain theory provides quantitative constraints on the stability of orientations of foliation and lineation in tectonites. Because these assumptions are severe (homogeneous strain and direct relation between finite strain axes and foliation–lineation) results should be used only as a guide for tectonic interpretation. The *orientation* of stable fabrics is dictated by the flow apophyses (fabric attractors), while the *shape*, and hence stability, of a fabric orientation is dictated ultimately by the coaxial component of deformation. The modeling shows that vertical foliation–horizontal lineation typifies either transtensional or transpressional zones, but is unstable outside of a very narrow range of conditions. With increasing finite strain, lineation switches to vertical in transpression and foliation switches to horizontal in transtension. Lateral extrusion within transpression zones stabilizes horizontal lineation very effectively in oblique convergence, allowing horizontal lineations to develop even at high angles of convergence. Dike-like bodies intruded in transtension zones may partition the wrench component of strain, resulting in stabilized vertical foliation within the dikes. If these bodies take up mostly the extensional component through anisotropic volume addition, then vertical foliation is stabilized in the country rocks at low strain; at higher strain, this stabilizing effect is reduced due to the overwhelming effect of the pure shear component associated with extension.

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Appendix A

The mathematics used in the article are published in Tikoff and Fossen (1993) and Fossen and Tikoff (1997). The amount of lateral extrusion was calculated in an iterative fashion. The coaxial components k_a, k_b, and k_c, represent elements of the deformation matrix and the stretches parallel to the *a*, *b*, and *c* axes. The amount of lateral extrusion vs vertical extrusion depends on the relative values of k_a and k_b. The variable P is defined, such that

$$P = (k_a - 1)/(k_b - 1). \tag{A1}$$

P is 0 if $k_a = 1$ (transpression) and 1 if $k_a = k_b$ (flattening), which represent 0 and 50% lateral extrusion, respectively.

The solutions are found by choosing an angle of convergence (α) and calculating an incremental strain. Vertical principal elongations are stable throughout deformation. For angles of convergence in which the principal elongation was originally horizontal, the required strain to shift the principal elongation to vertical was found iteratively. For each k_a value (the iterative variable), k_b was given by the above relation and k_c is given by:

$$k_c = 1/(k_a k_b). \tag{A2}$$

The component of the simple shearing (γ) was given by the relation

$$\gamma = (\log(k_a) - \log(k_c))/\tan(\alpha). \tag{A3}$$

From these values, the components of the deformation matrix can be solved. The eigenvalues and eigenvectors of the Finger tensor are the magnitudes and orientations of the finite strain axes.

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