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Applying a general triclinic transpression model to highly partitioned brittle-ductile shear zones: A case study from the Torcal de Antequera massif, external Betics, southern Spain

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ABSTRACT

Oblique convergence and subsequent transpression kinematics can be considered as the general situation in most convergent and strike-slip tectonic boundaries. To better understand such settings, progressively more complex kinematic models have been proposed, which need to be tested against natural shear zones using standardized procedures that minimise subjectivism. In this work, a protocol to test a general triclinic transpression model is applied to the Torcal de Antequera massif (TAM), an essentially brittle shear zone. Our results, given as kinematic parameters of the transpressive flow (transpression obliquity, ϕ; extrusion obliquity, υ; and kinematic vorticity number, W_k), suggest that the bulk triclinic transpressive flow imposed on the TAM was partitioned into two different flow fields, following a general partitioning type. As such, one flow field produced narrow structural domains located at the limits of the TAM, where mainly dextral strike-slip simple-shear-dominated transpression took place (Outer domains, ODs). In contrast, the remaining part of the bulk flow produced pure-shear-dominated dextral triclinic transpression at the inner part of the TAM (Inner domain, ID). A graphical method relating internal (ϕ, W_k) to far-field (dip of the shear zone boundary, δ; angle of oblique convergence, α) transpression parameters is proposed to obtain the theoretical horizontal velocity vector ($\overrightarrow{V}$), which in the case of the TAM, ranges between 099 and 118. These results support the applicability of kinematic models of triclinic transpression to brittle-ductile shear zones and the potential utility of the proposed protocol.

1. Introduction

In plate tectonics, the relative displacements of lithospheric plates over a sub-spherical surface are necessarily rotational. The inevitable consequence of this fact is that linear velocity vectors describing such displacements are normally oblique to boundaries between plates (e.g., Harland, 1971; Dewey, 1975; Dewey et al., 1998), which is particularly expected in lateral branches of orogens (Teyssier et al., 1995) or restraining bends of strike-slip systems (Cunningham and Mann, 2007). The general situation in such oblique convergence settings is that the velocity vector responsible for the deformation affecting plates is oblique to the boundaries of the resulting deformation zones, which are normally subparallel with the main plate boundary (e.g., Jiang et al., 2001). Such obliquity generates shear zones with transpressional kinematics (first defined by Sanderson and Marchini, 1984), which is characterized by the simultaneous activity of simple shearing parallel with the shear zone boundaries and coaxial flow producing shortening orthogonal with the shear zone and stretching parallel with it (e.g., Fossen and Tikoff, 1998; Jiang and Williams, 1998; Fernández and Díaz Azpiroz, 2009).

Since the pioneering mathematical description of transpressional shear zones, progressively more complex kinematic models have been proposed in an attempt to better describe natural transpressional cases. The first models (Sanderson and Marchini, 1984; Fossen and Tikoff, 1993) simulated monoclinic vertical shear zones with the simple shear direction restricted to the horizontal plane. More recent and complex models simulate triclinic symmetries (Robin and Cruden, 1994; Lin et al., 1998; Jiang and Williams, 1998; Jones et al., 2004). Other features of natural triclinic shear zones, such as opposing plunge senses of the stretching lineation have only been explained by even more

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complex models considering either migrating boundaries (Jiang, 2007) or oblique extrusion of the coaxial component (Fernández and Díaz Azpiroz, 2009). However, discrepancies with nature are still apparent, in part due to the unavoidable simplifications assumed by mathematical models, where only a limited number of variables are considered. Further complexity can arise when considering non-isochoric deformation (e.g., Ebner and Grasemann, 2006; Horsman and Tikoff, 2007), non-steady strain rate (Horsman and Tikoff, 2007) or heterogeneous partitioning of the simple shear and coaxial components (Jiang, 2007; Iacopini et al., 2009). Combinations of these kinematic models will progressively yield a better fit to nature but in return they will result in highly complex models, only resolvable by rather cumbersome mathematical processes, which would produce an enormously large number of results according to numerous possible combinations of variables. Before undertaking this task, it is appropriate to test available models against nature to ensure they reproduce natural transpression zone features accurately and to constrain the range of relevant variables. Such tests require an objective and standardized testing procedure that minimizes subjectivism.

In the last decade, few proposals have been made of a standardized procedure to compare transpression (Czeck and Hudleston, 2003; Fernández et al., 2013) or more general deformation models (Davis and Titus, 2011) with ductile natural cases. Ductile deformation is preferable because (1) strain partitioning occurs at the micro-scale and thus bulk finite strain usually distributes in few, albeit complex, shear zones; and (2) structures observed in ductile shear zones (mylonitic foliation, stretching lineation, etc.) can be directly compared with results produced by the models (orientation and shape of the finite strain ellipsoid, Instantaneous Stretching Axes, etc.). In contrast, in the upper crust, shear zones are highly heterogeneous and display a strong strain partitioning (e.g., Jones et al., 2005). In such cases, a unique imposed deformational event does not produce a map-scale single transpressive structure (a ductile shear zone), but a set of discrete structures, spatially distributed in heterogeneous deformational domains, each of them accommodating part of the imposed bulk strain (e.g., Jones et al., 2004). Comparison of these structural patterns with the finite strain ellipsoids produced by kinematic models is particularly difficult. Nevertheless, it is obvious that general conditions leading to transpressional kinematics also take

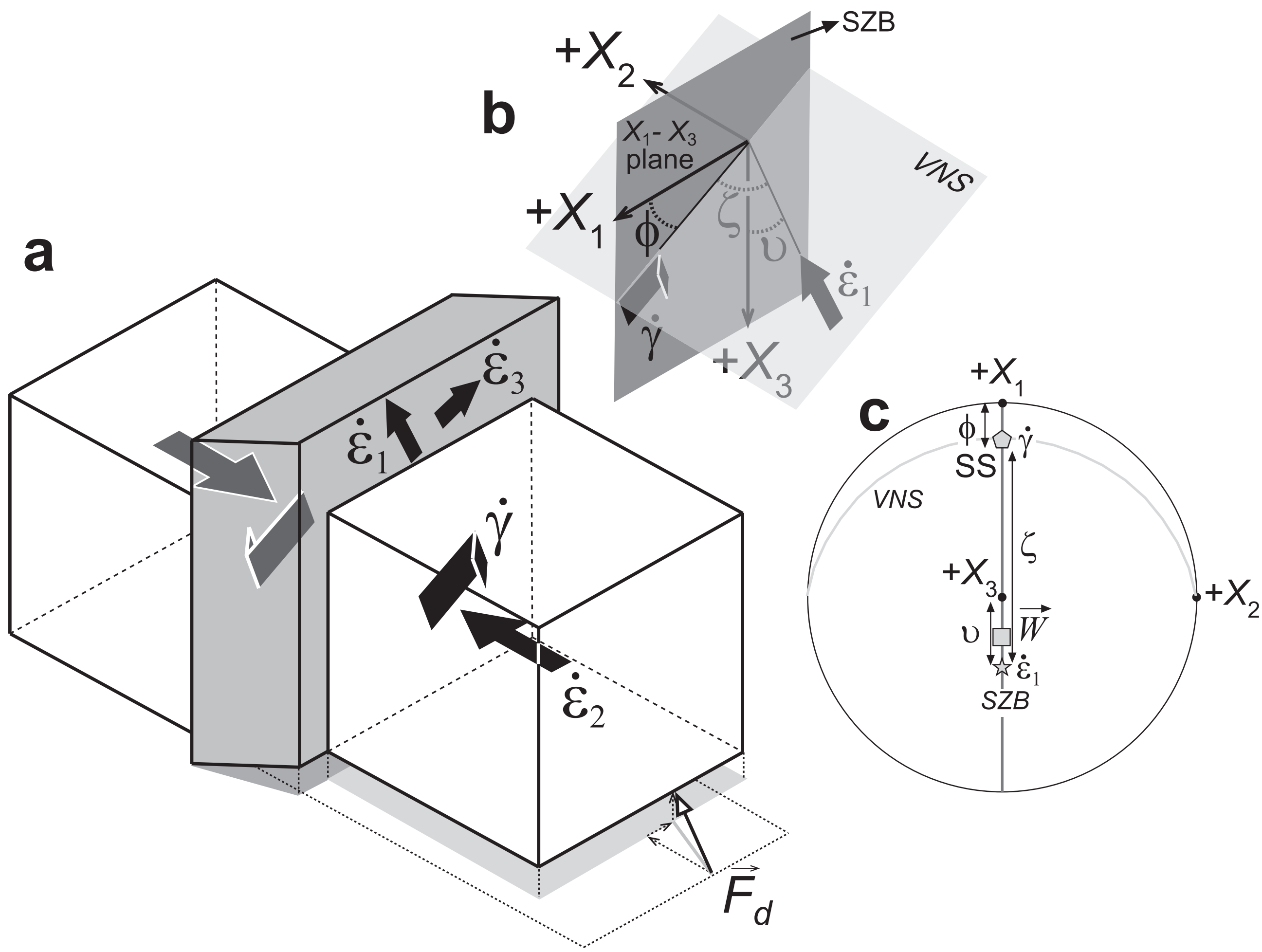

Fig. 1. Kinematic model of triclinic transpression with oblique extrusion (Fernández and Díaz Azpiroz, 2009). Reference frame: X_1 is parallel with the strike of the shear zone boundary (SZB), X_2 normal to the shear zone boundary and X_3 is parallel with the dip-direction. $\overrightarrow{F_d}$ is the convergence vector between one zone-bounding block and the other. The direction where simple shear strain rate ($\dot{\gamma}$) occurs is the simple shear direction (SS), and ϕ is the angle between the simple shear direction and the strike of the shear zone. υ is the angle between the extrusion direction ($\dot{\varepsilon}_1$) and the dip of the shear zone, whereas ξ is the acute angle between the simple shear direction and $\dot{\varepsilon}_1$. The vorticity vector ($\overrightarrow{W}$) is parallel with the shear zone boundary and normal to the simple shear direction, and it is the pole to the vorticity normal section (VNS). (a) Block diagram with the shear zone (shaded) and the direction of the main components of the flow. (b) and (c) Graphical definition of the reference frame, angles ϕ, υ and ξ, the VNS and $\overrightarrow{W}$. (c) Equal area, lower hemisphere projection.