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Analogue modelling of inclined, brittle–ductile transpression: Testing analytical models through natural shear zones (external Betics)

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ABSTRACT

The combination of analytical and analogue models gives new opportunities to better understand the kinematic parameters controlling the evolution of transpression zones. In this work, we carried out a set of analogue models using the kinematic parameters of transpressional deformation obtained by applying a general triclinic transpression analytical model to a tabular-shaped shear zone in the external Betic Chain (Torcal de Antequera massif). According to the results of the analytical model, we used two oblique convergence angles to reproduce the main structural and kinematic features of structural domains observed within the Torcal de Antequera massif ($\alpha = 15°$ for the outer domains and $\alpha = 30°$ for the inner domain). Two parallel inclined backstops (one fixed and the other mobile) reproduce the geometry of the shear zone walls of the natural case. Additionally, we applied digital particle image velocimetry (PIV) method to calculate the velocity field of the incremental deformation. Our results suggest that the spatial distribution of the main structures observed in the Torcal de Antequera massif reflects different modes of strain partitioning and strain localization between two domain types, which are related to the variation in the oblique convergence angle and the presence of steep planar velocity – and rheological – discontinuities (the shear zone walls in the natural case). In the 15° model, strain partitioning is simple and strain localization is high: a single narrow shear zone is developed close and parallel to the fixed backstop, bounded by strike-slip faults and internally deformed by R and P shears. In the 30° model, strain partitioning is strong, generating regularly spaced oblique-to-the backstops thrusts and strike-slip faults. At final stages of the 30° experiment, deformation affects the entire model box. Our results show that the application of analytical modelling to natural transpressive zones related to upper crustal deformation facilitates to constrain the geometrical parameters of analogue models.

1. Introduction

Transpression kinematics (Sanderson and Marchini, 1984) is a direct consequence of oblique convergence where velocity vectors are oblique to boundaries between deforming crustal blocks (e.g., Dewey, 1975; Dewey et al., 1998). Transpressional shear zones form from simultaneous simple shearing parallel with the shear zone boundaries and coaxial flow producing shortening orthogonal to the shear zone and stretching parallel with it (e.g., Fossen and Tikoff, 1998; Jiang and Williams, 1998; Fernández and Díaz-Azpiroz, 2009). Depending on the characteristics of the affected medium and other boundary conditions different mechanisms are commonly active during deformation. Accordingly, transpression kinematics may produce essentially ductile, brittle shear zones or a combination of both. In essentially ductile shear zones both simple shear and coaxial deformation are commonly present along the entire shear zone and produce complex finite deformation geometries (Tikoff and Teyssier, 1994; Fernández and Díaz-Azpiroz, 2009; Davis and Titus, 2011). In contrast, brittle–ductile shear zones usually show strain partitioning, with narrow discrete simple shear-dominated zones separating wider domains dominated by coaxial deformation (e.g., Tikoff and Teyssier, 1994; Teyssier et al., 1995; Schulmann et al., 2003; Jones et al., 2005; Fossen, 2010; Díaz-Azpiroz et al., 2014).

Both analytical and analogue models have been used to better understand transpressional shear zones. Most analytical models are based on a steady kinematic flow that is integrated with time to obtain finite deformation geometries (Fossen and Tikoff, 1993; Tikoff and Fossen, 1993; Lin et al., 1998; Jiang and Williams, 1998; Jones and Holdsworth, 1998; Jones et al., 2004; Fernández and Díaz-Azpiroz, 2009), which are compared with finite strains deduced from natural cases. This methodology has been widely applied to ductile shear zones where deformation can be considered approximately homogeneous and structures can be directly compared with model outputs (Czeck and Hudleston, 2003; Fernández et al., 2013). In contrast, rarely have these models been used to explain highly-partitioned shear zones where obtaining bulk finite strains from approximately homogeneous domains is a major obstacle (Jones et al., 2004; Titus et al., 2007;

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Díaz-Azpiroz et al., 2014). In addition, analytical kinematic models are unable to reproduce the highly heterogeneous structural pattern that characterise these shear zones. On the other hand, analogue modelling has been mainly focused on highly-partitioned transpressional shear zones (Schreurs and Colletta, 1998; Casas et al., 2001; Coke et al., 2003; Schreurs et al., 2010; Leever et al., 2011a,b) whereas few attempts on transpressional folding (Tikoff and Peterson, 1998) or ductile transpression (Czeck and Hudleston, 2004) have been carried out.

Analogue models have only simulated monoclinic transpression (Tikoff and Fossen, 1995; Casas et al., 2001). In such models, the angle of oblique convergence α (Fitch, 1972; Teyssier et al., 1995; Schulmann et al., 2003) is the only kinematic variable taken into account. Nevertheless, there are several examples suggesting that transpression with triclinic symmetry is a common situation in nature (e.g., Lin et al., 1998; Czeck and Hudleston, 2003; Jones et al., 2004; Díaz-Azpiroz and Fernández, 2005; Sarkarinejad and Azizi, 2008). Analytical models have simulated triclinic symmetries by heterogeneous strain within the shear zone (Robin and Cruden, 1994; Dutton, 1997), migrating boundaries (Jiang, 2007), oblique simple shearing (Jones and Holdsworth, 1998; Lin et al., 1998; Jiang and Williams, 1998; Jones et al., 2004), oblique coaxial extrusion direction or a combination of the latter two (Fernández and Díaz-Azpiroz, 2009). Triclinic transpression due to oblique simple shearing can be simulated in analogue models following the geometrical inclined transpression approach of Jones et al. (2004). According to this, transpression obliquity (ϕ) (the angle ϕ between the simple shearing direction and the azimuth of the shear zone boundaries is ≠0°) is produced by a horizontal velocity vector ($\vec{V}$) acting on an inclined shear zone. Accordingly, the dip angle δ of the shear zone should be introduced to model triclinic transpression.

This work presents the first analogue model of oblique convergence made up by two inclined-parallel backstops that simulates triclinic inclined transpression. The natural case study modelled is a highly-partitioned brittle–ductile shear zone in the External Betic Chain. Geometrical boundary conditions of the analogue model are: i) the dip angle δ directly measured from the natural shear zone; and ii) angle α previously constrained by applying a general triclinic transpression analytical model (Fernández and Díaz-Azpiroz, 2009) to the natural case (Díaz-Azpiroz et al., 2014). The main objectives of this study are (1) to analyse the influence of the angle of oblique convergence in the strain partitioning patterns of triclinic transpression developed in upper crustal conditions with rheological profiles characterised by plastic material covered by frictional layers and (2) to test the reliability of combined analytical and analogue models to simulate highly-partitioned brittle–ductile transpressional shear zones.

2. Geological setting

The Gibraltar orogenic arc, composed of the Betic and Rif mountain chains, is located at the western end of the Mediterranean Alpine belt (Fig. 1a). This arc resulted from the Neogene collision between the Internal Zones (the Alboran Domain) and two foreland domains (the South Iberian in the Betics and the Maghrebian margin in the Rif) (e.g., Balanyá et al., 1997; Booth-Rea et al., 2005; Platt et al., 2013).

The External Betic Chain consists of non-metamorphic Mesozoic and Cenozoic cover units (Fig. 1a, c): i) the Subbetic and Prebetic units, detached Triassic to Miocene sequences derived from the South Iberian paleomargin (Vera, 2004); and ii) the Flysch Trough units, detached covers Cretaceous to Lower Miocene in age, derived from a deep through (Durand-Delga et al., 2000). The External Zones were deformed during the Neogene as a thin-skinned fold-and-thrust belt (Crespo-Blanc, 2008; Expósito et al., 2012).

In the Western Betics, the Internal Zones are mainly built up by two tectono-metamorphic elements, the Alpujárride and Maláguide complexes (Fig. 1a, b, c), composed of Paleozoic and Triassic rocks. Unlike the Malaguide complex, the Alpujarride complex is characterised by Alpine pervasive metamorphism (Goffé et al., 1989). On top of Alboran Domain, Lower to Middle Miocene marine deposits appear, including the La Joya olistostromic formation (Suades and Crespo-Blanc, 2013). Additionally, a set of non-metamorphic imbricates, the Dorsal complex, are located at the Alboran Domain mountain front (Balanyá, 1991; Fig. 1c).

Within the Betic branch of the Gibraltar arc the structural trend line pattern defines two main salients (Balanyá et al., 2007): the Western Gibraltar arc and the Prebetic arc (Fig. 1a). The NE ending zone of the Western Gibraltar arc is shaped by a deformation zone called the Torcal shear zone (Barcos et al., 2011, 2015; Díaz-Azpiroz et al., 2014). This high-strain zone is a roughly E–W-striking band, 70 km long and around 5–7 km wide formed by several uplifted Subbetic carbonate massifs (Fig. 1b). This shear zone results in a topographic lineament built up by a set of structural highs (ca. 1200 m) composed of Jurassic to Paleogene Subbetic rocks. The Torcal shear zone bounds to the north with other Subbetic Triassic and Upper Miocene formations, whose deformation structures could be related to this high-strain zone (Díaz-Azpiroz et al., 2014). The Torcal shear zone bounds to the south with the Alboran Domain and their Lower to Middle Miocene marine formations (Fig. 1b). Considered as a whole, the Torcal shear zone is a highly partitioned, brittle–ductile shear zone in which deformation, Late Miocene to Recent in age, evidence overall dextral transpressional kinematics (Barcos et al., 2011, 2012, 2015; Díaz-Azpiroz et al., 2014).

2.1. The Torcal de Antequera massif

The Torcal de Antequera massif is a nearly E–W, elongated (13 × 4 km) structural high located in the middle part of the Torcal shear zone (Fig. 1b). Its lithological sequence is typical of the Inner Subbetic being composed of three main rock units (Martín-Algarra, 1987). The lower unit is formed by Triassic gypsiferous-marls and dolostones, cropping out in neighbouring areas but not in the proper Torcal de Antequera massif. Structural relationships between Triassic evaporite-rich rocks and the rest of the Subbetic sequence north of Torcal de Antequera massif are not stratigraphic in nature. As well as in other parts of the external Betic Chain, complex structural relationships are probably due to diapiric processes occurred during the paleomargin Mesozoic extension (Nieto et al., 1992) and/or during the Neogene shortening (Berástegui et al., 1998). The second unit is 575–600 m thick and comprises mainly competent layers of Lower-Upper Jurassic dolostones and limestones. The upper unit of the Torcal de Antequera massif corresponds to a Cretaceous–Paleogene marly limestone formation (300–400 m thick; Fig. 1b, d). The mechanical stratigraphy controlled the structural style of the Torcal de Antequera massif, where the Triassic evaporite-rich rocks are completely detached from its Paleozoic basement. The depth of this basement beneath the Torcal shear zone is about 5–6 km estimated from gravimetry data (Torné et al., 1992; Fig. 1d).

On the basis of the heterogeneous spatial distribution of different structures and their kinematic meaning, two types of structural domains have been defined within the Torcal de Antequera massif (Barcos et al., 2011; Díaz-Azpiroz et al., 2014). Each domain is characterised by structures that appear spatially linked and are likely kinematically related (Fig. 2a). A first domain type corresponds to narrow zones at the northern and southern boundaries of the Torcal de Antequera massif (hereafter outer domains), and the second type comprises the inner part of the massif (inner domain).

The outer domains are characterised by (i) dextral strike-slip dominated fault zones approximately N80E-striking and steeply dipping to the North; (ii) NW–SE striking faults interpreted as synthetic Riedel shears; (iii) scarce upright open folds with axial traces parallel to the outer domains boundaries and (iv) a positive flower-like structure that uplifted the northern outer domains (Fig. 2a). The structures and kinematic criteria observed within these domains suggest the main displacement was dextral strike-slip shearing. Additionally, the