Journal of Structural Geology 106 (2018) 19–40

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Mechanical evolution of transpression zones affected by fault interactions: Insights from 3D elasto-plastic finite element models

Seyed Tohid Nabavi[a,*], Seyed Ahmad Alavi[a], Soheil Mohammadi[b], Mohammad Reza Ghassemi[c]

[a] Faculty of Earth Sciences, Department of Geology, Shahid Beheshti University, Tehran, Iran
[b] High Performance Computing Laboratory, School of Civil Engineering, University of Tehran, Tehran, Iran
[c] Research Institute for Earth Sciences, Geological Survey of Iran, Tehran, Iran

ARTICLE INFO

Keywords:
Fault interaction
Pure-shear-dominated
Triclinic transpression
Vertical and lateral extrusion
Discontinuous heterogeneous flow
Finite-element method

ABSTRACT

The mechanical evolution of transpression zones affected by fault interactions is investigated by a 3D elasto-plastic mechanical model solved with the finite-element method. Ductile transpression between non-rigid walls implies an upward and lateral extrusion. The model results demonstrate that a, transpression zone evolves in a 3D strain field along non-coaxial strain paths. Distributed plastic strain, slip transfer, and maximum plastic strain occur within the transpression zone. Outside the transpression zone, fault slip is reduced because deformation is accommodated by distributed plastic shear. With progressive deformation, the σ_3 axis (the minimum compressive stress) rotates within the transpression zone to form an oblique angle to the regional transport direction (~9°–10°). The magnitude of displacement increases faster within the transpression zone than outside it. Rotation of the displacement vectors of oblique convergence with time suggests that transpression zone evolves toward an overall non-plane strain deformation. The slip decreases along fault segments and with increasing depth. This can be attributed to the accommodation of bulk shortening over adjacent fault segments. The model result shows an almost symmetrical domal uplift due to off-fault deformation, generating a doubly plunging fold and a 'positive flower' structure. Outside the overlap zone, expanding asymmetric basins subside to 'negative flower' structures on both sides of the transpression zone and are called 'transpressional basins'. Deflection at fault segments causes the fault dip fall to less than 90° (~86–89°) near the surface (~1.5 km). This results in a pure-shear-dominated, triclinic, and discontinuous heterogeneous flow of the transpression zone.

1. Introduction

Fault steps or stepovers are sites of localized deformation where a straight planar fault surface is interrupted by discontinuities. This definition refers to geometric segmentation (Fossen and Rotevatn, 2016). In this sense, fault steps are zones of slip transfer between discontinuous sub-parallel fault segments in which segments interact through their associated stress field and any hard-linkages. Various non-planar fractures and fault geometries observed in nature and studied both theoretically and numerically (e.g., Rodgers, 1980; Segall and Pollard, 1980; Aydin and Schultz, 1990) are segmented/stepping, ramped, intersecting/branching, splayed, and curved (Ritz et al., 2012, 2015; Ritz, 2013). Fault steps localize either contraction or extension as a function of their manual geometries (right- or left-stepping) and fault kinematics (left- or right-lateral) (Christie-Blick and Biddle, 1985; Woodcock and Fischer, 1986; Ramsay and Huber, 1987; Reches, 1987; Crider, 2001; Storti et al., 2003; Cunningham and Mann, 2007; Mann, 2007). Strike-slip systems (e.g., Misra et al., 2014; Misra and Mukherjee, 2015; Mukherjee, 2015a,b; Dasgupta and Mukherjee, 2017) can also produce important vertical displacements. Pop-up structures and transpressional deformation are local zones of uplift at contractional steps along strike-slip fault segments (Fig. 1). Contractional or restraining steps occur along transform boundaries, intraplate and intracontinental strike-slip faults and transpressional settings. In these settings, transpression zones develop in contractional sectors between overlapping en-échelon fault segments (Biddle and Christie-Blick, 1985; Woodcock and Schubert, 1994; Richard et al., 1995; Storti et al., 2003; Crider, 2015).

Transpressional deformation in contractional steps is commonly accommodated by doubly plunging and highly curvilinear folds, shear indicators, boudinage, flanking reverse or oblique-slip faults (flanking structures reviewed in Mukherjee and Koyi, 2009; Mukherjee, 2013, 2014a, 2014b, 2015a,b), uplift, block rotation, subsidiary extensional structures, extrusion, and exhumation (e.g., Upton and Craw, 2014) (Fig. 1). Such deformation patterns and features have been observed in many field studies (e.g., Sanderson et al., 1991; Alsop et al., 1998; Holdsworth and Pinheiro, 2000; Tavarnelli et al., 2004; Wakabayashi

* Corresponding author.
E-mail addresses: Tohidnabavi@gmail.com, T_nabavi@sbu.ac.ir (S.T. Nabavi).

https://doi.org/10.1016/j.jsg.2017.11.003
Received 16 August 2017; Received in revised form 2 November 2017; Accepted 5 November 2017

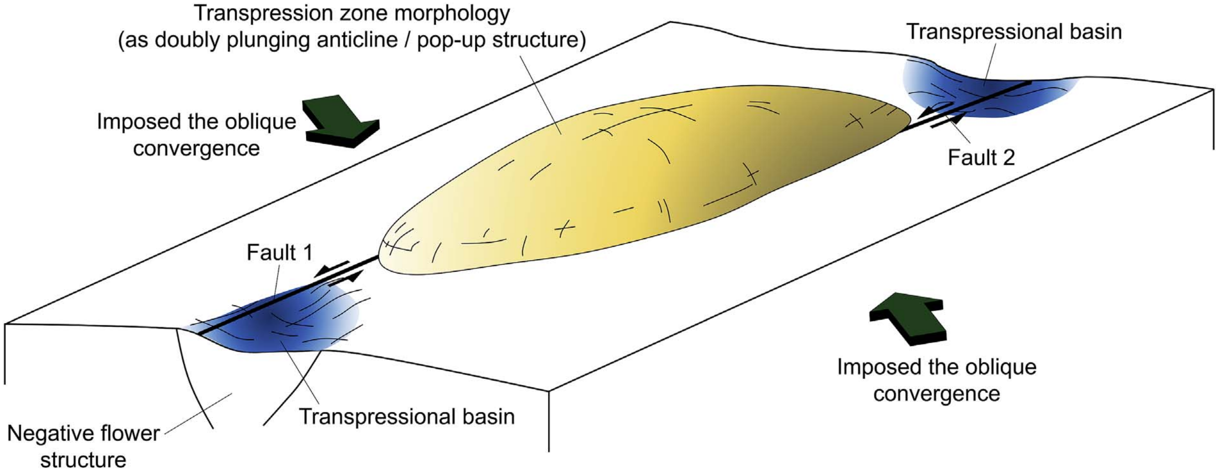

Fig. 1. 3D sketch of the transpressional basins, which is consistent with the results obtained in the present study.

et al., 2004; Carosi et al., 2005; Wakabayashi, 2007; Waldron et al., 2007, 2010; Crispini et al., 2009; Mukherjee and Koyi, 2010; Sylvester, 2012; Massey and Moecher, 2013; Talbot, 2014a, 2014b; Nabavi et al., 2017b, 2017c; Zanchi et al., 2016; Massey et al., 2017; Zhang et al., 2017), scaled analogue (Richard et al., 1995; Schreurs and Colletta, 1998, 2002; McClay and Bonora, 2001; Czeck and Hudleston, 2004; McClay et al., 2004; Leever et al., 2011; Mitra and Paul, 2011; Dooley and Schreurs, 2012; González et al., 2012; Ghosh et al., 2014; Barcos et al., 2016; Frehner and Schreurs, 2016) and numerical (Willemse et al., 1996; Ramsay and Lisle, 2000; Duan and Oglesby, 2005; Davis and Titus, 2011; Davis et al., 2013; Landgraf et al., 2013; Strijker et al., 2013; Dasgupta et al., 2015; Lozos et al., 2015; Frehner, 2016a, 2016b; Nabavi et al., 2016, 2017a, 2017e) studies of strike-slip and oblique convergence systems.

Transpression is characterized by simultaneous simple shearing parallel to the shear zone boundaries (i.e., strike-slip component) together with coaxial flow shortening orthogonal across the shear zone boundaries and stretching parallel to them (Harland, 1971; Sylvester and Smith, 1976; Sanderson and Marchini, 1984; Fossen et al., 1994; Braun and Beaumont, 1995; Dewey et al., 1998; Mukherjee and Koyi, 2010; Fernández et al., 2013; Díaz-Azpiroz et al., 2014, 2016; Frehner, 2016a, 2016b; Nabavi et al., 2017c). Strain partitioning (with both spatial and temporal end members) (Curtis, 1997) is common in these tectonic settings leading to oblique displacement that has important consequences in tectonic interpretation (Jones and Tanner, 1995; Curtis, 1997; Ellis and Beaumont, 1999; Tikoff and Teyssier, 1994; Teyssier et al., 1995; Druguet et al., 2009; Carreras et al., 2013; Philippon et al., 2015; Díaz-Azpiroz et al., 2016; Philippon and Corti, 2016). Transpression zones are common in such tectonic setting in strike-slip fault systems, orogenic belts, and plate boundaries; they result from oblique convergence where convergence motion vectors are oblique to the boundaries between deforming crustal plates (Díaz-Azpiroz et al., 2016; Frehner, 2016a; Mookherjee et al., 2016; Nabavi et al., 2017a, 2017c; Philippon and Corti, 2016). The angle of oblique convergence (depending on the kinematic vorticity number, W_k) quantifies the relative plate motion of a system (Fossen and Tikoff, 1993; Fossen, 2016) (Fig. 2). A convergence angle perpendicular ($\alpha = 90^\circ$, $W_k = 0$) (Fig. 2a: i–iii) or parallel ($\alpha = 0^\circ$, $W_k = 1$) (Fig. 2c: i–iii) to the deformation zone boundary fault results in coaxial pure-shear contraction (or orthogonal convergence) and non-coaxial simple-shear (i.e., an ideal shear zone) (Ramsay, 1980; Mukherjee, 2012; Talbot, 2014a), respectively. These end-member strain states lead to plane strain (2D) deformation. Transpression (convergent strike-slip) occurs when the far-field shortening vector is at an oblique angle α to the deformation zone boundary faults (i.e., $0^\circ < \alpha < 90^\circ$) (Fig. 2b: i–iii) (Harland, 1971; Sylvester and Smith, 1976; Sanderson and Marchini, 1984; Sylvester, 1988; Fossen and Tikoff, 1993; Ghosh, 2001), and non-coaxial 3D strain develops (Vitale and Mazzoli, 2010, 2015; Fossen and Cavalcante, 2017). In this case, the transpression strain ellipsoid is oblate and lies in the flattening field (Sanderson, 1984, 2014; Sanderson and Marchini, 1984; Tikoff and Fossen, 1993; Fossen et al., 1994; Dewey et al., 1998; Fossen and Tikoff, 1998; Díaz-Azpiroz et al., 2014; Vitale and Mazzoli, 2015; Mookherjee et al., 2016; Nabavi et al., 2017c; Fossen and Cavalcante, 2017). The angle between the infinitesimal contraction and the convergence vectors are 0° and 45° for orthogonal contraction and simple shear, respectively. Transpression can have either a monoclinic or a triclinic kinematic symmetry, depending on the orientation of the pure shear axes with respect to the simple shear axes. Two types of transpression and two types of transtension zones have been introduced based on the kinematic vorticity number (W_k) and the convergence angle (α) (Fossen and Tikoff, 1993; Fossen et al., 1994; Tikoff and Teyssier, 1994, 1999; Casas et al., 2001; Bailey et al., 2004, 2007; Mukherjee, 2012): (*i*) simple shear (wrench)-dominated ($1 > W_k > 0.81$, $\alpha < 20^\circ$); (*ii*) pure-shear-dominated ($W_k < 0.81$, $\alpha > 20^\circ$).

Obliquely convergent orogens such as the Zagros Mountains Range (Mohajjel and Fergusson, 2000; Sarkarinejad and Azizi, 2008; Sarkarinejad et al., 2013; Ruh et al., 2015) and Alborz Mountains Range (Allen et al., 2003; Landgraf et al., 2009; Ballato et al., 2013; Nabavi et al., 2017c) are typically modeled as transpressional systems. Some natural cases of transpression zones associated with contractional fault steps are the Mecca Hills region of the San Andreas fault system, southern California (Sylvester and Smith, 1976), the Cerro de la Mica, Atacama fault system, northern Chile (McClay and Bonora, 2001), the Gargano Promontory, southern Italy (e.g., Brankman and Aydin, 2004), the Monte Cornetto di Folgaria, Southern Alps, northeastern Italy (Zampieri et al., 2003), the Mount Diablo, San Andreas fault system, San Francisco Bay area (Wakabayashi et al., 2004), the Mt. Kumeta-Rocca Busambra, western Sicily, Italy (Barreca and Maesano, 2012), the Kolah-Ghazi Mountains, south of Isfahan (Nadimi and Konon, 2012), and the Kuh-e-Hori, SE Iran (Nabavi et al., 2016, 2017a).

Analytical, analogue, and numerical models have been used to better understand transpressional deformation zones. There also are many numerical studies of transtensional settings such as oblique rifts and pull-apart basins. In contrast, such models, especially those in 3D, have rarely been used to understand brittle-ductile transpression zones. Our previous numerical analysis of two dimensional transpression zones within contractional steps has given important insights into the evolution of the stress distribution and strain localization within transpression zones (Nabavi et al., 2017a). That analysis suggested that transpression zones generate heterogeneous and non-coaxial strains. In addition, important factors influencing the strain field are: (*i*)