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

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A B S T R A C T

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 σ3 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 contractual steps along strike-slip fault segments (Fig. 1). Contractual or restraining steps occur along transform boundaries, intraplate and intracontinental strike-slip faults and transpressional settings. In these settings, transpression zones develop in contractual 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 contractual 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

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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., 2016, 2017a, 2017c). Strain partitioning (with both spatial and temporal end members) (Curts, 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; Mukherjee et al., 2016; Nabavi et al., 2017a, 2017c; Philippon and Corti, 2016). The angle of oblique convergence (depending on the kinematic vorticity number, Wk) quantifies the relative plate motion of a system (Fossen and Tikoff, 1993; Fossen, 2016) (Fig. 2). A convergence angle perpendicular (α = 90°, Wk = 0) (Fig. 2a: i–iii) or parallel (α = 0°, Wk = 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° < α < 90°) (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 (Vitaletti and Mazzoli, 2010, 2015; Fossen and Cavallarante, 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; Vitaletti and Mazzoli, 2015; Mukherjee et al., 2016; Nabavi et al., 2017c; Fossen and Cavallarante, 2017). The angle between the infinitesimal contraction and the convergence vectors are 0° and 45° for orthogonal contraction and simple shears, 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 tension zones have been introduced based on the kinematic vorticity number (Wk) 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 > Wk > 0.81, α < 20°); (ii) pure-shear-dominated (Wk < 0.81, α > 20°).

Obliquely convergent orogens such as the Zagros Mountains Range (Mohajel 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 contractual 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 Masesano, 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 contractual 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)
convergence angle, (ii) step geometries, and (iii) overlap-to-separation ratio. In this study, we extend our previous study (Nabavi et al., 2017a) into the three-dimensional displacement-based, non-linear finite-element (FE)-models using the commercial FE-package ABAQUS™ to study the role of fault interactions in the evolution of transpression zones, an approach that also includes two dimensional problems.

Three-dimensional numerical modelling decodes fault interactions and their influence on complexities that arise from non-linear evolution of transpression zones. The main sources of non-linearities in the model are frictional sliding on the fault segments (e.g., Vernant and Chéry, 2006a, 2006b; Maerten, 2010; Soliva et al., 2010; Maerten et al., 2016; Zeumann and Hampel, 2016), and inelastic material behaviour or, large deformation beyond the linear elastic regime, changing strains and boundary conditions, or any combination of these factors during the modelling of deformation. These parameters might work coevally during deformation. Early numerical analysis of transpression between contractional fault steps (e.g., Nabavi et al., 2016, 2017a) as two-dimensional discontinuities in an isotropic, linear elastic medium gave first-order insights into the evolution of stress and strain distribution, accumulation of displacements and interaction between adjacent fault/fracture segments. We apply here various factors, such as overlapping fault step, oblique convergence angle, fault slip, and thickness that control the evolution of 3D stress, strain, traction vectors, and displacement paths within transpression zones. We monitor the evolution with time of oblique convergence together with increasing displacement on the fault segments. Another novelty in our analysis is that (i) we remove the ‘confined transpression’ boundary restriction, and (ii) use non-rigid deformation zone boundaries that differ from all previous transpression models.

We mainly address: 1) How do the displacements, stresses and strains evolve in the step between adjacent fault segments and how do these differ from the deformation outside the transpression zones?, 2) How do the total inelastic strains (i.e., permanent deformation) and coefficient of sliding friction on the fault segments influence the evolution of transpression zones?, 3) How does the displacement field vary with structural position in the transpression zones?, 4) How do the implications of our 3D FE-models improve understanding of the development of hard linkage between adjacent fault steps. The outcome of this study is compared to earlier analogue and mechanical modelling studies and a natural example.

2. Model setup

2.1. Geometric configuration

The model (Fig. 3) comprises two rectangular blocks with their edges parallel to the axes of a Cartesian coordinate system. The XZ plane is horizontal, with the X axis parallel to the strike of the fault segments, and the Y axis is vertical (Fig. 3a and b). The blocks frictionally slide along fault segments. In brief, these blocks are collectively
called ‘active’ blocks (Fig. 3a). The dimensions of the model are scaled to natural examples of continental oblique-slip systems (70 × 70 × 15 km$^3$) (Fig. 3c). The model block has two pre-defined fault segments or slip surfaces, where displacement is allowed parallel to the fault planes in both horizontal and vertical directions and can act as oblique-slip faults in the analysis (Fig. 3b). The pre-defined fault segments have a length along strike of 50 km. The fault segments, also known as principal displacement zones (e.g., Dooley and Schreurs, 2012), are vertical (i.e. 90° dip) in cross-section and their ends are defined by rectangular tip lines (YZ section in Fig. 2). In the present study we model two fault segments with an overlap of 30 km and a separation of 10 km (Fig. 3c). Incorporating fault segments with rectangular tip lines, as in the models discussed here, offers some critical insights into the variations in the three dimensional stress and strain verified in the transpression zone.

2.2. Material properties

Elasto-plastic rheology (a solid-like, Prandtl material) describes the behaviour of material that involves both elastic and plastic deformation components. Stress and elastic strain increase until a critical stress reached, called the yield strength, beyond which the deformation is plastic (Mohammadi, 2003). The rheology of the upper crust is elastoplastic, which means that stresses increase with strain up to a certain limit, where failure occurs and plastic deformation starts. Plastic models can predict the initiation and development of fractures or faults that can be readily implemented in different numerical models (Ramsay and Lisle, 2000; Mohammadi, 2008, 2012).

The depth to which oblique convergence extends is typically restricted to the brittle-ductile thickness of the crust. Linear elastic material properties have been used to model deformation at shallow crustal level (e.g., Crider and Pollard, 1998). The choice of elastic rheology, however, ignores the permanent deformations observed in rocks (e.g., fractures, faults, and folds). In this study, the model block is assigned an isotropic, elasto-plastic rheology (upper part of the crust) assuming the average material properties of sandstone. Young’s modulus (E), Poisson’s ratio ($\nu$) and density ($\rho$) are taken as 55 GPa, 0.25, and 2600 kg/m$^3$ (based on Carmicheal, 1982; Pollard and Fletcher, 2005; Mukherjee and Mulchrone, 2012; Goteti et al., 2013), respectively for the elastic component, whereas for the plastic component, a yield strength of 890 MPa is used (based on Carmicheal, 1982). The pre-defined fault segments are assigned a constant coefficient of sliding friction of 0.51 (Pollard and Fletcher, 2005).

2.3. Displacement-based boundary conditions

Oblique convergence is modeled by imposing a given displacement (Fig. 3a) at the boundaries. A total oblique convergence of 20% (14 km shortening) with a convergence angle of 45° is imposed onto the model block. Imposing displacements, instead of traction, allows formulating a model that is consistent with field observations and obviates the need to infer stresses. This boundary condition is consistent with the common
observation that the central parts of fault segments evolve in an overall plane strain deformation. However, this constraint does not include the transpression zone between contractional fault steps, which evolve in general three dimensional displacement fields. In addition to the displacement boundary condition, a body force corresponding to the acceleration due to gravity (9.81 m/s²) acts on the model block throughout the deformation. For the FE-analysis, the model block is discretized into 222,000 continuous, three-dimensional, linear, hexahedral finite elements (i.e., C3D8R) (Fig. 3d). These elements are recommended for simulations involving deforming contacts in FE-analysis. Upon imposing the far-field displacement boundary conditions and gravity, the stiffness of each finite element is calculated using 8-node Gaussian integration during each increment of the deformation (Bathe, 1996; Mohammadi, 2003, 2008, 2012). We use the 3D FE-modelling software package ABAQUS™ (ABAQUS/CAE; FE-commercial program ABAQUS™ tutorial version 6.14–2, 2014; www.simulia.com/) to simulate stress and strain features recorded in the transpression zone. Due to the continuum nature of the FE-analysis, the model presented here cannot precisely simulate the brittle failure of rocks characteristic of shallow crustal levels. However, by using the orientation of the principal stresses and strains that develop in the model transpression zone, it is possible to show and predict the most probable orientation of brittle structures that could develop during deformation.

3. Results and discussion

We propose a transpression model configuration with two right-stepping, en-échelon fault segments interacting under oblique convergence (α = 45°) to produce a transpression zone within the contractional fault configuration. In this Lagrangian model, meshes deform along with the crustal block. During oblique convergence, material trapped between the two fault segments deforms in a ductile fashion, and the deformation preferentially localizes in the model within the contractional fault step between blocks separated by en-échelon fault segments. Deforming material is allowed to shorten (or lengthen), and shear vertically and horizontally, while slip is possible along the deformation zone boundaries (i.e., both fault segments). Given the chosen obliquity angle, the model develops a pure-shear-dominated transpression zone. The deformed model geometry reproduces many of the first-order geometric features of natural transpression zones and pop-up structures such as the regional doubly plunging anticline, reverse and high-angle sinistral-oblique-reverse faults, flower (or Y-shaped) structure, uplift and exhumation, local folding, and basins associated with oblique convergence and frictional slip on the fault segments. This overall conformity of the results of the models in this work with the analogue studies and natural transpression zone examples, gives insights into predicting and analyzing the evolution of three-dimensional deformation and displacement fields in transpression zones. Upon imposing the total oblique convergence (20%) in an incremental manner, the model block evolves under a combination of slip (discrete deformation) on the fault segments and distributed deformation within the ‘active’ block. The ‘active’ block overall undergoes oblique contraction, shortens, and thickens in both the horizontal and vertical directions, respectively, with rotation around horizontal and vertical axes. It is important to note that uplift and subsidence develop in the models as a result of the amount of the oblique convergence, and that processes such as sedimentation, and isostatic response (as in Mukherjee, 2017) do not contribute. This is a simplification, as these processes are known to affect uplift and subsidence.

3.1. Modeled stress fields

Changes observed in the slip behaviour of each modeled fault are caused by transient changes in the crustal stress field related to the growth and shrinkage of the surface load (Hampel and Hetzel, 2006; Turpeinen et al., 2008). The results show that the mean and maximum principal stresses increase (compression increases) inside the step between the fault segments compared to the region outside the step (Fig. 4a and b). In other words, the contractional quadrants of the inner fault segment tips are located inside the step, resulting in local high stresses and strains in this part. Under simple shear conditions (fracture mode II or III), strike-slip faulting can propagate through the specified process zone. In contrast, the complex stress and strain trajectories associated with an oblique-slip setting such as transpression zones prevent it from extending through the specified and single process zone.

The orientation and magnitude of the minimum compressive stress (σ3) can be used to understand the overall evolution of the three dimensional stress field in the transpression zone, and we compare the spatial variation of stresses within (Fig. 5a) and outside (Fig. 5b) the relay zone. Note that σ3 represents the stress at the end of each increment of deformation. Within the transpression zone, the interaction of the stress fields near the tip lines of the fault segments results in a complex three dimensional stress field. The σ1 and σ3 axes within the transpression zone are initially parallel and normal to the imposed oblique convergence direction, respectively. With progressive deformation of the model block, the σ3 axis rotates within the transpression zone forming an oblique angle (~9°–10°) to the regional transport direction and the transpression zone boundaries. Therefore, the orientations of the σ3 axis are strongly dependent on the structural position within the transpression zone. Outside the transpression zone, the σ3 tensor is sub-normal to the regional transport direction (with only slight deviation of ~4° with respect to sub-normal state, Fig. 5b); it is also sub-parallel to the maximum extensional finite strain (S1). Alternatively, the σ1, the minimum extensional finite strain (S3), and the convergence direction sub-parallel each other outside the transpression zone. The sub-parallelism between incremental and finite strain axes and also their negligible deviation outside the transpression zone suggests coaxial flattening, and not necessarily plane strain deformation. The magnitude of stress generally increases as deformation intensifies (Fig. 5).

3.2. Variation of slip along fault segments

The distribution of the deformation is determined by the rate of decrease of slip toward the end of the fault segments (i.e., towards the vertical tip line) (Fig. 6). The slip along the fault segment creates an offset between ‘active’ blocks. Due to the gradual decrease of slip along the sliding surfaces, the transpression zone between the two faults is expected to gradually increase its height (vertical displacement) towards the overlying zone. This means that the compression component of the transpression zone is concentrated in the central area of the fault step. The slip decrease along fault segments can be attributed to the accommodation of bulk shortening across adjacent fault segments. Furthermore, the slip along the fault segments decreases with increasing depth, so that distinct slip offsets are visible at depths of 0–5 km and 5–15 km (Fig. 6). Fig. 6 illustrates these results with a view of the fault surface after deformation. Results show about 5% (depth 12 km) to 19% (near surface) of imposed displacement and deformation accommodated by fault slip on pre-existing faults (Fig. 6). The results also show that fault slip distributions in the elasto-plastic model are quite asymmetric. The lower portion of the fault can lock with increasing depth, while its upper portion slips at the plate displacement condition. The maximum slip occurs near the center of the fault surface near the surface of the model.

3.3. Displacement and strain patterns within and outside the transpression zone

Another feature resulting from the interaction between the modeled fault segments is the almost symmetrical rectangular pop-up structure or domal uplift (up-dip extrusion in Fernández and Díaz-Azpiroz, 2009; Díaz-Azpiroz et al., 2014; Barcos et al., 2016) along and across the
transpression zone bounded by the overlapping faults (Figs. 7 and 8). Following an initially circular antiform/domal area, this uplift or vertical extrusion (material particles displace upwards) becomes progressively better defined with increased displacement. This typically generates doubly plunging arrangements of folds that produce four-way dip closure (a periclinal structure) (e.g., Woodcock and Rickards, 2003) or synclastic antiform (terminology from Lisle and Toimil, 2007), of limited strike extent. This doubly plunging fold structure grows in all three dimensions and its long axis rotates with the oblique convergence in time. The obliquity of the hinge line of the antiform with respect to the fault strike decreases with increasing fault overlap so that its trends sub-parallel the fault for the largest overlaps. On the other hand, the uplift, which is evident as vertical separation or fold amplification (Frehner, 2014, 2016a) in Fig. 7, is one source of off-fault deformation that is more prevalent in transpression zones with large slip gradients (e.g., Cooke et al., 2013; Herbert et al., 2014).

For transpression, the resulting fold axis deviate from being perpendicular to the convergence direction and the orientation of the fold...
axis in map view is a function of the convergence angle (e.g., Titus et al., 2007; Fossen et al., 2013; Frehner, 2016) (Fig. 8). The angle between the fold axis and the X reference-axis increases from pure shear (0°) to simple shear. Fold axes are commonly curved in transpression zones. Fold amplitude and wavelength increase and decrease, respectively, with strain (i.e., the fold tightens), such that the transpression zone within the contractional step suffers convex upward heterogeneous thickening (Fig. 8a). The directions of maximum compressive stress and fold axes are nearly perpendicular to each other. Additionally, the transpression zone stretches along the X-axis (lateral extrusion) (e.g., Dias and Ribeiro, 1994; Jones et al., 1997; Fernández and Díaz-Azpiroz, 2009; Massey and Moecher, 2013; Massey et al., 2017) in addition to uplift along the Y-axis (vertical extrusion as topographic relief), and it also rotates about the Y-axis ca. 30° (Fig. 8b).

Although the geometry of both fault segments is symmetric, the resulting plastic strain is not. The results (Fig. 9) show that the region of the model experiencing the largest plastic strain (damage) is located in three parts within the transpression zone, one in the central part of the transpression zone, and the other two coinciding with the tips of the fault segments (Fig. 9a). These plastic zones are the preferred sites for the nucleation and growth of early reverse and sinistral-oblique-reverse faults (as conjugate step-up shears) similar those observed in experimental studies of oblique convergence and contractual steps/bends of strike-slip systems (e.g., McClay and Bonora, 2001; Cooke et al., 2013). With continued convergence, the plastically deformed volume thickens and rapidly widens along the X-, Y-, and Z-axes (Fig. 9b). Strain localization (that can generate shear bands, Barnichon and Charlier, 1996; Barnichon, 1998) takes place within the transpression zone at the bottom of the model. The plastic strain is distributed throughout the step, with its greatest values in the center of the transpression zone that decreases outward from the step. A sharp transition occurs between the significant plastic strains within the step to very low plastic strains immediately outside the contractional fault step. Hence, slip transfer is greater across the transpression zone and contractual fault step than in transtensional zones and releasing fault steps, this is due to the stress state and plasticity in this zone (e.g., Nevitt and Pollard, 2017).
According to the spatial variation of plastic strain through the transpression zone, two pairs of high-angle sinistral-oblique-reverse faults, that is called “sidewall faults” (e.g., Sylvester, 1988; Mann, 2007), can be identified bounding the transpression zone. Indeed, the orientation of stress and strain principal axes are compatible with the activity along the oblique-reverse fault systems that fan outward from the overlapping step. This result is approximately coincident with the results of scaled analogue modelling (e.g., McClay and Bonora, 2001; Dooley and Schreurs, 2012; Cooke et al., 2013). At the final stages of the 45° oblique convergence, deformation and plastic strain affects the entire model. Distributed plastic strain beyond each fault segment effectively lengthens the faults, allowing slip magnitudes to increase toward the transpression zone.

According to Sanderson and Marchini (1984), vertical stretching lineations should predominate in transpression zones. However, various field and analytical studies indicate that lineations can be either horizontal or vertical under monoclinic transpression, or even show intermediate plunges within triclinic transpression zones, depending on the angle of convergence. The results of this work show that the maximum tensile principal stress (Fig. 10) is well developed through the transpression zone. In addition, less well-marked lineations appear outside the transpression zone so that they may even remain unnoticed. On the other hand, the model show a progressive increase in the dip of planar fabrics (foliations) towards the transpression zone, and are approximately vertical along its central plane (Fig. 10). Hence, the strain ellipsoid varies in orientation throughout the step, depicting the heterogeneous nature of deformation (e.g., Goteti, 2009; Goteti et al., 2013). Generally, stretching lineation and the major principal strain axis are perpendicular to the shear direction and parallel to the transpression zone for pure shear-dominated transpression zones. Characteristic sub-horizontal to shallow plunging lineations and sub-vertical foliations agree with simple-shear-dominated deformation in central parts of the transpression zone (Fig. 10) with respect to the pure shear-dominated deformation in surrounding.

The early models of transpression zones described monoclinic flows, resulting in either strike- or dip-parallel lineations depending on the angle of convergence and magnitude of deformation (e.g., Sanderson and Marchini, 1984; Fossen and Tikoff, 1993). The oblique lineations

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**Fig. 6.** Slip distribution along the fault segment 1’s surface as the vertical section. This model is the middle part of whole model and its dimensions are 70 × 10 × 15 km.

**Fig. 7.** Model result showing vertical displacement (Uy) of the transpression zone.
recorded in many natural transpression zones cannot be explained by monoclinic models, and were modeled instead by transpression flow with triclinic symmetry (e.g., Jiang and Williams, 1998; Lin et al., 1998; Czeck and Hudleston, 2003, 2004; Jones et al., 2004; Iacopini et al., 2007, 2010; Jiang, 2007; Fernández and Díaz-Azpiroz, 2009). The results of this work indicate that the lineations are oblique in the transpression zone, both to the zone boundaries (i.e., fault segments) and to the horizontal plane. These results can provide a realistic test for natural cases. With time evolution of oblique convergence due to increasing displacement, opposing displacement on the adjacent fault segments results in a complex displacement field within the overlapping zone and around it, as shown in a fringe plot of displacement components along all three reference axes (Fig. 11). Contours on the deformed volume show how the strike of displacement vectors parallels the oblique convergence direction around the transpression zone, and those vectors are rotated within in the transpression zone. The steep displacement gradient at the tips of fault segments result is the strongest variation in the displacement pattern in the transpression zone (Fig. 11).

The same sense of slip along the fault segments warps and tilts the
overlapping contractional step by rotating vertical and horizontal axes. This superposition of distortion and rotational deformation results in a complex three-dimensional displacement field within the transpression zone. Fig. 11 illustrates modelling results of particle paths and the orientation of the oblique flow apophyses within the transpression zone. The rotational component increases along strike from the lateral limits of the model inwards towards the transpression zone. Rotation of the displacement vectors during increasing oblique convergence suggests that the transpression zone evolves under an overall non-plane strain deformation. Away from the lateral sides of the model, vertical displacement increases along-strike of the primary fault segments towards the transpression zone. Outside the transpression zone and away the fault segments, the displacement field is almost constant and the overall deformation conforms to plane strain. Near the fault segments and within the transpression zone, the displacement vector field is more variable with strong gradients in the orientation and magnitude of the displacement vectors, with distinct shapes of the deformation ellipsoids. Directional derivative azimuth (0°–360°) was plotted by measuring the angle between the displacement vectors and the transpression zone boundaries (Fig. 12). The area of slow displacement (oblique to the transpression zone, where displacement is attributed to sigmoid-I and –II transpressional faults or Y-shears; Mathieu and de Vries, 2011; Mathieu et al., 2011) rotates counterclockwise during the deformation. This rotation affects the extruded material within the transpression zone. The counterclockwise rotation resulting from the model for a right-stepping fault system is consistent with the rotations shown by analogue models (e.g., McClay and Bonora, 2001; Dooley and Schreurs, 2012). Unlike some other fault types (e.g., brittle rotational faults; Mukherjee and Khonsari, 2017), the fault segments do not rotate but instead accommodate the rotation of the material between them by slip gradients.

Fig. 12a shows the evolution of the finite displacements within the transpression zone at five selected increments of deformation corresponding to time steps 0.1, 0.25, 0.5, 0.75, and 1. At the onset of the imposed deformation, the displacement vectors are everywhere oblique to the transpression zone boundaries. The results of this work show how the overall transport direction outside the transpression zone is sub-parallel to the imposed regional oblique convergence (Fig. 12b). However, the displacement vectors within the transpression zone evolve along distinct paths. With the evolution of oblique convergence in time, the magnitude of displacement increases faster within the transpression zone than outside it. Moreover, the evolution of the finite displacements outside the transpression zone increases the deviation of displacement vectors (from 10° to 50°) to the transpression zone.
boundaries from time step 0.1 to 0.5. After that, the angle between the displacement vectors to the transpression zone boundaries decreases from time step 0.75 to 1 (from 47° to 35°) (Fig. 12b). Plots on Fig. 13b shows a curved path from time step 0.1 to 1 as upward convexity. This continuous reduction in deviation angle of displacement vectors could be due to the temporal evolution of oblique convergence and simple-shear-dominated deformation outside the transpression zone. Opposing displacement gradients on the adjacent fault segments define a counterclockwise vertical axis rotation of the model transpression zone. The counterclockwise rotation predicted by the model for a contractional right stepping is consistent with the rotations predicted by field and analogue studies (e.g., McClay and Bonora, 2001; Mitra and Paul, 2011; Dooley and Schreurs, 2012).

The models explored in this work are based on the Sanderson and Marchini (1984) and Fossen and Tikoff (1993) models of transpression. However, those models assume homogeneous strain and produce a “flat topped” mountain range. Both the present work and natural cases of transpression zones, displacements, fault slips, and shortening are likely to partition across and along strike the deformation zone. This work shows that the particles move along curved paths (Fig. 14), an unlikely situation in some of the previous models of shear zones (e.g., Mukherjee...
Curved flow paths in shear zones are most likely in shear zones with curved boundaries (e.g., Mukherjee and Biswas, 2014; Zibra et al., 2014). These paths are almost parallel to the fault segments and their shear direction in the center of the model can be attributed to the effect of simple-shear-dominating the deformation or partitioning so that the paths are at distinct angles to the fault segments and shear direction. Hence, the displacement partitions into various amounts of extrusion (as doubly plunging folds) and heterogeneous strain throughout the transpressional system.

Our modelling results indicate that horizontal and vertical displacement of material within the transpression zone causes oblique frictional simple shear (Fig. 15) along the surfaces of fault segments, as seen by the asymmetric distribution of shear stress/strain, so that the simple shear direction is oblique to the strike of the transpression zone boundary (Fig. 15). The initial dip of the fault segments is 90° and we expect the result to be a monoclinic transpression zone, after the zone boundary has deformed and deflected the tips of fault segments (Fig. 16). Deflection at fault segments caused the fault dip to fall to less than 90° (~ 86–89°) near the surface (~ 1.5 km) (Fig. 16). Hence, none of the three-dimensional elastic and plastic stress and strain tensors within the transpression zone, are aligned with the axes of the coordinate system after the very beginning of deformation. The resulting transpression zone is only a few degrees (~ 1–4°) away from the monoclinic case. However, this results in a pure-shear-dominated triclinic transpression zone. According to these results, the model extrusion is symmetric although, the angle between the extrusion direction and the dip of the transpression zone (angle ν in Fernández and Díaz-Azpiroz, 2009) locally deviates from 0° (ν = 0°) at depths of 0–1.5 km and 0° (ν = 0°) at depths of 1.5–15 km. In addition, since the vertical extrusion varies in relative intensity from point to point along the transpression zone, the implication is that ν locally deviates from 0°. Therefore, there is an acute angle between the oblique simple shear and the vertical extrusion direction, i.e., 0° < ζ < 90°. The relative obliquity of the simple shear component creates obliquely plunging lineations. Transpression with an oblique simple shear direction is also described by Robin and Cruden (1994), Dutton (1997), Jones and Holdsworth (1998), Lin et al. (1998), and Czeck and Hudleston (2003) among others. The results of this work demonstrate that the transpression zones are highly sensitive to slight variations in their controlling parameters, a problem recently addressed on statistical grounds by Davis and Titus (2017).

Our results from modelling sinistral transpression indicate that the principal stress and strain axes will undergo a counterclockwise rotation of 20–45° with progressive deformation. In the modeled transpression zone, the principal stress axes rotate counterclockwise ahead of each fault segment. In addition, the magnitude of stress and strain components decreases outwards from the central part of the transpression zone. This shows that deformation distributes over several planes with different orientations. Hence, the rotation of the strain principal axes and the variation in their magnitudes reflects the heterogeneous nature of deformation, which ranges from approximately simple shear to non-coaxial flattening strain. Fig. 16 shows the architecture of the fault segments that illustrates the curved nature of the transpression zone.
primary sidewall oblique-slip faults and the change in their geometries along strike with upward convex positive flower or Y-shaped structure in cross-section as the width of the deformation zone decrease with depth and confining pressure (Figs. 17b and 18a–c). The angles defined by the curved faults, reflect the oblique convergence in en-échelon oblique-slip features and, are gentler compared to those shown by pop-up structures resulting from the steps in pure strike-slip faults (as has been observed in analogue modelling of Naylor et al., 1986; Richard and Cobbold, 1990; Richard et al., 1995; Dooley et al., 1999; McClay and Bonora, 2001; Cooke et al., 2013). Fig. 17 shows oblique shortening balanced by lateral and vertical extrusion at the transpression zone. In addition, the transpression zone is longer than the separation between

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Fig. 15. Shear stress along a) fault segment 1, and b) fault segment 2 (bottom). The model is the middle part of the whole model and its dimensions are $70 \times 10 \times 15$ km.

Fig. 16. The curved nature of the primary sidewall fault segments and the change in their geometries along strike after applying oblique convergence and deformation.

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the fault segments, so that zone located between the inward-approaching walls creates a discontinuous heterogeneous flow (Fig. 17).

According to the initial constraints of our modelling strategy, we expected the highest values of shear strain and dilation would occur along the fault segments and in the areas immediately around them. However, the maximum shear strain and slip correspond to the fault stepping area, creating a stress and strain peak (Fig. 18). Elements within the overlapping zone undergo large stresses and strains. Frictional shear strain and contact slip along elements of fault segments within overlap zone are basically higher than in the outer zone. In addition to these large shear strain values, low shear strain zones can be found far away from the fault stepping area, or in that area where the first stages of convergence occur (Fig. 18). These results show that most of the elastic and plastic energy is concentrated in the transpression zone (or the area limited by the two overlapping faults segments) and its adjacent regions, such as closer to the fault tips. The shear strain distribution along the fault segments, from surface to depth of the analyzed model, is illustrated in Fig. 18a–c, which shows a flower-shaped strain localization region oblique to the fault segment. Moreover, shear strain is not significant outside the transpression zone. In other words, the slip on the inner side of fault segments does not annihilate or disappear because the faults are linked to each other and slip is transferred from one fault segment to the other. Furthermore, distinct mesh elements along the fault segments and transpression zone have different responses. These complex responses are found due to step geometry, failures, and angle of convergence (or the orientation of fault segments with respect to the maximum principal stress). Furthermore, distributed shear strain within the transpression zone adjacent to the sliding surfaces is a sign of off-fault deformation. The mechanical models may fill the gap between the complexity of natural structures and our theoretical understanding of them. Although the models always simplify nature, they are realistic enough to uncover essential features of the natural processes. The results presented in this study are part of a broader spectrum of three-dimensional numerical models that we have developed to investigate the role of mechanical interaction between fault segments on the evolution of transpression zones. The mechanical studies of oblique convergence settings allow us to determine and discuss different deformation parameters such as three-dimensional geometry, stress and strain distribution, model restorations, slip intensities, etc.

3.4. Kuh-e-Hori transpression zone, SE Iran

Transpressed volumes are characterized by pop-ups or domes (e.g., Harding and Lowell, 1979; Harding, 1985; McClay and Bonora, 2001; Dooley and Schreurs, 2012; Pace and Calamita, 2014; Calzolari et al., 2015; Maia et al., 2016; Cheng et al., 2017). Several parameters have been invoked to explain them; examples are convergence angle, step geometry, pre-existing faults, and local variation in fault segment dip. Pop-up-boundary faults display concave-downward geometries (McClay and Bonora, 2001; Dooley and Schreurs, 2012), consistent with our modelling results (Fig. 1). Our model pop-up structure is broadly rectangular in plan form, almost symmetrical, with a doubly plunging fold, such as the Kuh-e-Hori transpression zone, SE Iran (Fig. 19a–d) (sections AA’–FF’ in Fig. 17e of Nabavi et al., 2017a), Torcal de Antequera massif in the external Betics of southern Spain (Fig. 3a–b of Díaz-Azpiroz et al., 2014), as well as the Cerro de la Mica, Atacama strike-slip fault system in the northern Chile (Fig. 21 of McClay and Bonora, 2001). Hence, model and natural pop-ups are non-cylindrical folds due to non-cylindrical vertical extrusions along the transpression zone. Note that doubly plunging folds can also be produced by superposed deformations. Non-cylindrical folds are one of a variety of fold geometries expected to develop in transpressional and transtensional settings (Fossen et al., 2013; Zulauf et al., 2017). In addition, pop-up structures are typically flanked by faults with oblique-reverse kinematics.

By contrast, asymmetric subsidence basins commonly expand on both sides outside the overlap of the transpression zone. These transpressional basins are generally long and narrow structural depressions, with oblique-slip faults and negative flower structures, and lie parallel to but outside the transpression zone and restraining bend/step (Figs. 1 and 19c–d) (Nilsen and Sylvester, 1999a, 1999b). Natural examples of these transpressional basins are the Sahl-abad and Nehbandan subsidence basins that have developed as a result of the evolution of the Kuh-e-Hori transpression zone in SE Iran (Fig. 19). The Kuh-e-Hori transpression zone is the result of interaction between the Esmaib-ad and the West Neh right-lateral strike-slip fault segments so that these two fault segments form a left-stepping geometry and create a contractual step (see Nabavi et al., 2017a for details). Depocentres typically form adjacent to uplifted structural blocks and subside either by flexure caused by the tectonic load, or in response to the local extension at the bend/step or intersection of strike-slip faults (Ingersoll, 2012). Similar to other basins in strike-slip zones, transpressional basins are generally smaller and more complex than other fault-related basins with linear or curvilinear map form. Transpressional basins are characterized by high subsidence rates, asymmetrical distribution of facies, and multiple and complex unconformities (Ingersoll, 2012).

Generally, in this study, the transpression zone undergoes vertical and lateral extrusion (e.g., the unconfined monoclinal transpression model of Jones et al., 1997; Fernández and Díaz-Azpiroz, 2009; Fernández et al., 2013; Díaz-Azpiroz et al., 2014). Transpression zones in which the base is not confined are also subject to downward material...
Fig. 18. a) Maximum principal strain distribution. This model is a section through the whole model. b) Minimum principal strain distribution. This model is a section through the whole model. c) Medium principal strain trajectories.
displacement at depth as we have seen in early boundary conditions of our model that the base of it was unconfined (not shown here). Jones et al. (1997) and Giorgis et al. (2009) presented an isostatically compensated model of transpression, where material is allowed to flow both upward and downward to form topographic relief and crustal roots, respectively. Extrusion (vertical or lateral) strongly depends on the convergence angle and the magnitude of shortening. For low convergence angles (simple-shear-dominated), lateral extrusion is always higher than vertical extrusion. By contrast, contraction-dominated high convergence angles always, drives more vertical extrusion than lateral extrusion. Moreover, the material in the transpression zones undergoes syn-shearing volume loss. Ramsay and Graham (1970) in their classic work dealt with the kinematics of shear zone flattening attributed to syn-shearing volume reduction in the shear zone. Syn-shearing volume reduction can be considered as an important parameter for transpression deformation (Le Pourhiet et al., 2014; Dasgupta et al., 2015).

For the model configuration and boundary conditions presented in this study, the Von Mises equivalent stress is highest within the overlapping fault step. For homogeneous transpression zones, the magnitude of rotation decreases with increasing angle of convergence. Away from the fault tips and out of the transpression zone, the strains are more homogenous across wide areas; this encourages new normal and

Fig. 19. a) Regional overview of Iran; b) Simplified geological map of the northern part of the Sistan Suture Zone (after Fotoohi-Rad et al., 2009; Brocker et al., 2013; Bayet-Goll et al., 2016). c) Google Earth™ image of the Kuh-e-Hori transpression zone from the map view. d) N-S topographic section of (Fig. 19c) that shows the Kuh-e-Hori transpression zone is surrounded by the Sahl-abad and Nehbandan transpressional subsidence basins on both sides of it.
reverse faults to form in extensional and contractional regions, respectively. However, these faults can be partitioned in terms of strain and slip. The strain distribution for oblique-slip system and deep in transpression zone is produced by the addition of pure strike-slip and dip-slip displacements, resulting in different and widely varying mechanisms.

Two zones can be identified in our model of strain distribution within transpression zones. Reverse fault mechanisms predominate in the footwall and directly ahead of the fault segment tips. In the hangingwall and the central part of the transpression zone, strike-slip mechanisms predominate. Furthermore, in this deformation system, strike-slip faulting is accompanied by oblique contraction driven by localized deep deformation resulting in positive flower/palm tree structures (Harding and Lowell, 1979; Stefanov and Bakeev, 2014, 2015), keystone structures (Sylvester and Smith, 1976) or pop-up relay structures, which involve multiple fault branches. In addition, localization of strike-slip shear produces an increase in the kinematic vorticity number within transpression zone relative to areas outside the zone. Therefore, a zone of normal faulting could develop in the subsidence regions behind the fault tips. Generally, contraction-dominated transpression was accommodated by a wider domain than simple-shear-dominated transpression; a process defined as “discrete partitioning” (Schulmann et al., 2003). Hence, slip partitioning results when the deformation is accommodated by two or more faults with different mechanisms (McCaflrey, 1992; Jiang and Williams, 2001; Bowman et al., 2003). In natural cases, however, slip partitioning can be more complex, with several domains of geological features contrasting in terms of strain distribution, location, scale, and time evolution.

In contraction convergence (α = 90°), the stress tensor is invariant (e.g., Upton and Craw, 2014, 2016). In transpression zones and oblique convergences zones, both stress and strain axes rotate. According to the present modelling, the temporal and spatial counterclockwise rotation of the principal axes of stress and strain can lead to contemporary strike-slip and dip-slip faulting. In the transpression zone, the structures accommodate the oblique motion with deformation propagating from surface to depth as has been observed in the development of the first plastic zones (Fig. 9). The transpression zone narrow with progressive deformation. The simple-shear component in the transpression zone can be accommodated by either individual slip planes or partitioned into pure-shear internal deformation as folding and strike-slip on numerous fault segments. The modelling results reveal that oblique convergence narrows contractual structures from wider transpression zones under oblique convergence settings, to either pure contraction settings or strike-slip dominated systems. Moreover, deformation partition in transpression zones under oblique convergence is stronger than that due to pure contraction and simple shear deformation. This means that regularly spaced oblique-reverse and strike-slip faults develop in the former case. Indeed, deformation partitioning is limited in pure-shear or simple-shear-dominated transpression zones (Barcos et al., 2016).

Our modelling results show that the degree of partitioning is controlled by the convergence angle and slip along the fault segments. This characteristic would result in oblique relationships between fold axial plane, as low angle counterclockwise rotation, and transpression zone boundaries (e.g., Sanderson et al., 1980; Sanderson and Marchini, 1984). The distribution of deformation depends upon the rate of decrease of slip towards the end of the fault segments, and with increasing depth, which is asymmetric (e.g., Duman et al., 2005; Khoshmanesh et al., 2015; Whipple et al., 2016; Nevitt and Pollard, 2017).

Determining the distribution of fault slip is important as it establishes which parts of a fault segment are locked. The model results (Fig. 6, and Section 3.2) imply that the lower portion of the fault can be locked with increasing depth, while its upper portion slips at the plate displacement condition. In dynamic models of crustal deformation (e.g., Aagaard et al., 2013), the locked, lower part of the fault accommodates slip as quasi-static viscoelastic deformation throughout the earthquake recurrence time and, keeps pace with the dynamic slip of the upper portion of the fault. This results in the cumulative slip being uniform across the fault surface over an earthquake cycle. The amount of fault slip is affected by the magnitudes of the normal and shear stresses along the fault segment. In turn, changes in slip behaviour within the contraction step can be attributed to increased mean compressive stress within the step. Any increase in mean compressive stress reduces fault slip. Therefore, high Von Mises equivalent stress within the transpression zone causes significant plastic shear strain to develop there (e.g., Nevitt, 2015; Nevitt et al., 2017). Most major earthquakes often take place in the seismogenic upper crust. Immediately below that level, the localizing mid-crust, layer decouple a region where weakening would generate relatively ductile shear zone and that may be associated with microseismicity (e.g., Gueydan et al., 2003, 2004). Micro-seismic clusters at depths ranging between 6 and 11 km below region of active extension (Rigo et al., 1996; Rietbrock et al., 1996) and less than 20 km (~10–20 km) in active contractual settings (Boese et al., 2012; Warren-Smith et al., 2017). It is possible to determine the stress transfer onto surrounding fault segments to detect parts of the fault system that are closer to failure, and to establish the relationships between fault geometry and surface geomorphology needed to understand fault segmentation (e.g., Calais et al., 2010; Raven et al., 2011; Elliot et al., 2016). Fault slip magnitude is mainly affected by the coefficient of sliding friction within the crust and along the fault segments as well as by the depth of the fault tips and dips of the faults (e.g., Kim and Sanderson, 2005; Aber, 2009; Hampel and Hetzel, 2012; Steffen et al., 2014a, 2014b, 2014c; Zeumann and Hampel, 2016).

Fault overlap plays a prominent role in the evolution of displacement fields in transpression zone. The effects of fault overlap on the vertical deformation and rotation axes have been discussed by many researchers (e.g., Katzman et al., 1995; ten Brink et al., 1996). The fault separation has a considerable effect on the size and shape of transpression (or pop-up structures with uplift) and transtension zones (or pull-apart basins with subsidence) between two fault segments. When fault overlap exceeds the fault separation, a sigmoidal- or rectangular-shaped transpression zone forms (e.g., Mitra and Paul, 2011; Dooley and Schreurs, 2012). This zone is bounded by overlapping fault segments that experience localized oblique convergence. Unlike kinematic, geometric, and theoretical models, the three-dimensional FE-models allow us to monitor the finite rotations at different structural levels; it also tracks incremental rotations at various structural positions in the model transpression zone. In nature, the magnitude of rotation and deformation may vary in much more complex manners and depends on such parameters as mechanical stratigraphy, elliptical fault surface, inclined boundaries, and anisotropy (e.g., Nabavi et al., 2017d). Our model results suggest that even when the primary fault segments are subjected to a particular convergence angle (45° in this study), a transpression zone evolves in a complex three-dimensional strain field that is not consistent with the far-field strain. Our modelling results for overlapping fault segments imply that the magnitude of horizontal and vertical rotations are higher in the transpression zone than outside it. In addition, the magnitudes of rotations increases as the oblique convergence matures. Fault interactions in an overlapping step geometry can give rise to a broad variety of local structures that can be understood in terms of the variations in the stress and strain field predicted by the model. Block rotation, thrust emplacement, multiple faulting, and mylonitisation apparently occur in regions of high compressive stress and plastic strain (i.e., within contractual fault steps and transpression zones). The size and extent of the region with the largest stress changes in the contractual step is smaller than in frictionless fault step numerical models (e.g., Brankman and Aydin, 2004; Steffen et al., 2014; Lejri, 2015; Lejri et al., 2015; Bagge and Hampel, 2016). This is due to the effects of frictional faults, the magnitude of the increased mean stress (positive mean normal stress), and of shear stresses. These results are consistent with recent studies that point toward a complex deformation patterns within transpression zones (e.g. Zibra et al., 2014; Maia et al., 2016; Nabavi et al., 2017b, 2017c).
Our modelling results imply that plastic deformations and fracturing or faulting begins at the surface. Material strength increases with increasing depth due to the frictional component of the strength, which increases with lithospheric pressure or the mean stress. Hence, the material strength is lowest in the upper levels where plastic deformation occurs first. Since the tensile strength of any material is less than its compressive strength (Price, 1966; Price and Cosgrove, 1990), and since the presence of tensile or compressive mean normal stress has been observed in releasing and restraining steps, respectively (e.g., Nevitt et al., 2014; Nabavi et al., 2017a), plastic strain localization and generation of brittle fractures is predicted to be more marked in releasing steps and transtensional zone than in restraining steps and transpressional zones under similar conditions (e.g., Goteti et al., 2013; Ye et al., 2015). The rotational component is superposed on the deformation field generated in oblique structures that exist in a broad variety of orientations. Therefore, local structures develop oblique to the transpression zone boundaries and the primary fault segments. Such features are very common in oblique convergence settings and have been extensively documented in natural examples (e.g., Díaz-Azpiloz et al., 2014; Barcos et al., 2015). The model shows that deformation extends beyond the fault step, there is no oversimplified strain partitioning between pure- and simple-shear-domains, and strain gradients change smoothly. This problems was widely discussed by Carreras et al. (2013) and Jiang (2014).

4. Conclusions

Many oblique convergence settings are characterized by regional en-échelon oblique-slip fault segments that form a transpression zone. We have presented a three dimensional finite element model to analyse the role of fault interactions during the evolution of transpression zones between adjacent fault segments. Slip profiles, stress distributions, and strain localization patterns are described for the transpression zone affected by fault interaction as a function of the convergence angle between the far-field compression orientation and the strikes of fault segments. The results show the mean and maximum principal stress increase (i.e., the compression increases) inside the step between the fault segments relative to the region outside the step. With progressive deformation of the model block, the $\sigma_3$ axis rotates within the transpression zone to form an angle oblique to the regional transport direction ($\sim 9°$–$10°$) and the transpression zone boundaries. Outside the transpression zone, the $\sigma_3$ vectors are oriented sub-normal to the regional transport direction (with only slight deflection of $\sim 4°$) and are also sub-parallel to the maximum extensional finite strain.

Slip along the fault segment offsets ‘active’ blocks. As the slip along the sliding surfaces gradually decreases, the transpression zone between the two faults segments is expected to gradually increase its height (vertical extrudes) towards the overlapping zone. The slip decrease along fault segments can be attributed to the accommodation of bulk shortening along adjacent fault segments. Furthermore, the slip distribution along fault segments decreases with increasing depth, so that the slip decreases at distinct steps between depths from 0.5 km to 5–15 km. The fault slip distributions in the elasto-plastic model are quite asymmetric. The maximum slip occurs near the center of the fault surface. The superposition of distortion and rotational deformation results in a complex three-dimensional displacement field. With time evolution of oblique convergence, the magnitude of displacement increases faster within the transpression zone than outside it.

Rotation of the displacement vectors with time of oblique convergence suggests that the transpression zone evolves under an overall non-plane strain deformation. Another feature resulting from the interaction between the faults is the almost symmetrical domal uplift or vertical extrusion, that is one source of off-fault deformation, along the transpression zone as a doubly plunging fold and ‘positive flower’ structure. By contrast, commonly outside the overlap zone, expanding asymmetric subsidence basins develop on both sides of the transpression zone that are called ‘transpressional basins’ with ‘negative flower’ structures. Generally, the transpression zone undergoes lateral and vertical extrusion. After deformation the geometry of the zone boundary changed and deflected the tips of fault segments. Deflection at fault segments has caused the fault dip to decrease to less than 90° ($\sim 86–89°$) near the surface ($\sim 1.5$ km). Hence, none of the three-dimensional elastic and plastic stress and strain tensors are within the transpression zone, except at the beginning of deformation, are incompatible with the axes of the coordinate system. This results in a pure-shear-dominated, triclinic, and discontinuous heterogeneous flow model of transpression zone.

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