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2D finite-element elastic models of transtensional pull-apart basins

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ABSTRACT

A set of two-dimensional finite-element elastic models are presented to provide insights on the evolution of transtensional pull-apart basins between two right-stepping, right-lateral fault segments. Three representative fault segment interaction geometries are modelled, showing underlapping, neutral and overlapping segments. Despite the simplifications of the 2D model, overall results are obtained that might help understanding the formation of pull-apart basins. Firstly, the orientations of the local σ_1 and σ_3 tensional stress directions markedly depend on the segment's position. Secondly, the mean normal stress is extensional in a transtensional basin between segments, while the region outside the step is characterized by more compressive mean normal stresses. Thirdly, the angle of offset between the fault segments is one of the most important parameters controlling the geometries of the transtensional pull-apart basins: connected depocenters with basin high and lozenge shape in the case of underlapping steps, spindle shape or lazy S or Z shape in the case of neutral steps, and broadly elongate rhomboidal to sigmoidal basins in the case of overlapping steps. Generally, *en-échelon* basin margin system, dual opposing asymmetric depocenter, intrabasin relative structural high, and wide basin width can be used as indicators that a pull-apart basin is developing in transtension zones.

1. Introduction

On geological maps, strike-slip fault systems are often apparently linear and relatively continuous. However, in nature, they are typically discontinuous and segmented on various scales (Mann, 2007). Such sub-parallel discontinuous fault segments often exhibit *en-échelon*, non-coplanar geometries and include steps and bends in the master fault (Peacock et al., 2016, 2017b). The individual fault segments are separated from each other and interact through their stress/strain fields (Peacock et al., 2017a, 2018). The stepovers between two fault segments represent the locations of extensional or contractional heterogeneous deformations depending on the sense of the fault step with respect to the sense of slip along the main strike-slip fault system (Woodcock and Schubert, 1994) (Fig. Sm1 in supplementary material). The sense of step is described as left- and right-stepping. Releasing or extensional stepovers result where the sense of step is the same as the sense of the overall slip (e.g., a left-step along a left-lateral/sinistral fault) (Cunningham and Mann, 2007; Fossen, 2016;

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Sylvester, 1988; Woodcock and Schubert, 1994). Extensional and contractional steps between two sub-parallel coeval faults were defined as "linking damage zones" (Kim et al., 2004).

Transtensional basins form under strike-slip conditions in an extensional environment (Fig. Sm1 in supplementary material), while transpressional basins form under strike-slip conditions in a compressional environment; both types are categorized as strike-slip or stepover basins (Ingersoll, 2012; Misra and Mukherjee, 2016; Nilsen and Sylvester, 1999; Ramsay and Huber, 1987; Sylvester, 1988; Talbot et al., 2009). Extensional settings can be categorized into orthogonal or oblique extension groups, based on the intersection angle between the pre-existing basement fault and the tensional stress direction. An oblique extensional basin forms when the strike directions of the reactivated basement faults cross the regional extensional direction at an oblique angle, and the boundary faults behave as normal faults with strike-slip features (Fossen et al., 2013; Manighetti et al., 2001a; Misra and Mukherjee, 2016). Different fault segments accommodate oblique faulting (strike-slip and normal displacements) within the transtensional pull-apart basin, which results in complex fault zone geometry, formation of valleys, and rotations along the fault systems (e.g., Chemenda et al., 2016 Manighetti et al., 2001a; Mart and Vachtman, 2015). Many continental rift margins undergo strike-slip controlled deformation associated with transtension and/or transpression basins (Dasgupta and Mukherjee, 2016; Misra and Mukherjee, 2016; Nemčok, 2016).

Pull-apart structures are depressions that form at releasing bends and steps in basement strike-slip fault systems. Pull-apart structures are generally inferred to occur as basins (Gürbüz, 2010; Misra and Mukherjee, 2016), although centimeter-scale veins (Peacock and Sanderson, 1995a, 1995b), region-scale plutons (Tikoff and Teyssier, 1992), and regional-scale blueschist massifs (Mann, 2007) are also inferred to fill these structural "holes" (Aydin and Nur, 1985). Traditional models of pull-apart basins usually show a rhombohedral (Talbot and Alavi, 1996) (e.g., Dead Sea basin) to spindle-shaped (e.g., Death Valley basin) depression between two parallel master vertical strike-slip fault segments (Mann, 2007; Mann et al., 1983; Ramsay and Huber, 1987). The basin is bounded longitudinally by a transverse system of oblique-extensional faults, termed "basin sidewall faults" (cf. Fig. Sm1 in supplementary material) that link with the bounding principal deformation zones (Dooley and Schreurs, 2012; Gürbüz, 2010; Waldron, 2005; Wu et al., 2009). Depending on the assumed fault plane orientation with respect to the oblique far-field stress, the extensional and contractional steps may be classified as either "transtension" or "transpression", respectively. Transtension (and transpression) zones result in a combination of simple- and lateral extensional pure-shear components with vertical depression (Dewey, 2002; De Paola et al., 2005; Fossen and Tikoff, 1998; Fossen et al., 1994; Sanderson and Marchini, 1984). Hence, transpression zones can be related to the boundary conditions and obliquity between the imposed compressive stress and plate boundaries (Díaz-Azpiroz et al., 2016; Frehner, 2016; Nabavi et al., 2017b, 2017c). Pull-apart basins that have developed with transtensional displacement are of significant economic importance and can contain zones of intense fracturing, giant hydrocarbon fields, mineralization, and geothermal fields (Dasgupta and Mukherjee, 2016; Dewey, 2002; Peacock and Anderson, 2012).

Numerical techniques, especially the finite-element (FE) method, are powerful to provide comprehensive insight beyond the direct observations, such as the stress state, strain and deformation patterns during and after the structural evolution. Mechanical modelling of a fault step avoids many common assumptions, for example homogeneous deformation, inherent to kinematic models (Nevitt et al., 2014). Mechanical analyses identified certain basic variables that influence the evolution of transtensional deformation in extensional fault steps, such as the fault overlap-to-separation ratio and the relative orientation of faults. The mechanical interaction between fault segments helps rationalize the overlap-to-separation ratio, to understand why some fractures/faults selectively terminate whereas, others propagate, and to understand why some faults deviate systematically from symmetric slip distributions (Lejri et al., 2015; Manighetti et al., 2001b; Strijker et al., 2013). The static sliding friction coefficient strongly affects the fault mechanical properties and local stress field (Maerten et al., 2016; Soliva et al., 2010).

Here, we use a series of 2D FE elastic models through ABAQUS™ software package to simulate stress and strain features recorded in a transtension zone within a straight and parallel extensional fault step. The strike-slip fault segments (also called master faults) can underlap, have a neutral configuration, or overlap. All of such step geometries form naturally and are found in nature (Cunningham and Mann, 2007). It is well known that fault step geometries affect the shape and structure of pull-apart basins between the fault segments, but the reasons are not fully understood. To approach them, we simulate the range of various divergence angles (30°, 45° and 60°) under different fault step geometries such as underlapping, neutral and overlapping releasing fault step geometry, and analyze the stress/strain fields by applying different sets of boundary conditions. The purposes of this study are:

- to understand the role of frictional strike-slip fault separation and amount of overlap on the development and evolution of transtension zones;
- to predict the possible fault pattern inside the transtension zone;
- to describe the stress distribution and strain localization patterns;
- and to predict the shape of the transtensional pull-apart basin.

We eventually compare our results to previous analogue (e.g., Dooley et al., 2004; Wu et al., 2009) and numerical models (e.g., Newitt et al., 2014; Strijker et al., 2013), which are complementary to the methods used here. Despite the limitations of our simple model (2D and elastic), we provide first-order insights that might be

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