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Evaluation of transtension and transpression within contractional fault steps: Comparing kinematic and mechanical models to field data

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ABSTRACT

Rock deformation often is investigated using kinematic and/or mechanical models. Here we provide a direct comparison of these modeling techniques in the context of a deformed dike within a meter-scale contractional fault step. The kinematic models consider two possible shear plane orientations and various modes of deformation (simple shear, transtension, transpression), while the mechanical model uses the finite element method and assumes elastoplastic constitutive behavior. The results for the kinematic and mechanical models are directly compared using the modeled maximum and minimum principal stretches. The kinematic analysis indicates that the contractional step may be classified as either transtensional or transpressional depending on the modeled shear plane orientation, suggesting that these terms may be inappropriate descriptors of step-related deformation. While the kinematic models do an acceptable job of depicting the change in dike shape and orientation, they are restricted to a prescribed homogeneous deformation. In contrast, the mechanical model allows for heterogeneous deformation within the step to accurately represent the deformation. The ability to characterize heterogeneous deformation and include fault slip – not as a prescription, but as a solution to the governing equations of motion – represents a significant advantage of the mechanical model over the kinematic models.

1. Introduction

Faults can be discontinuous at many scales and often exhibit en echelon geometries, characterized by sub-parallel fault segments that are either left- or right-stepping (Segall and Pollard, 1980, 1983b; Wesnousky, 1988; Aydin and Schultz, 1990). Deformation within fault steps plays a significant role in both long- and short-term fault processes, including fault coalescence and lengthening, and earthquake rupture nucleation and termination (King and Nabelek, 1985; Sibson, 1985; Harris et al., 1991; Zhang et al., 1991; Harris and Day, 1993; Kase and Kuge, 1998; Harris and Day, 1999; Harris et al., 2002; Cowgill et al., 2004; Wakabayashi et al., 2004; Oglesby, 2005; Wesnousky, 2006). Thus, an improved understanding of deformation within fault steps will shed light on how fault structures evolve through time, with consequent benefits for seismic hazard analysis.

Deformation within steps is heterogeneous and depends on the relationship between the step geometry and the sense of slip (Fig. 1a). A step with the same sense as that of the fault slip (e.g., left step along a left-lateral fault) results in extensional deformation, such as open cracks at the meter scale (Fig. 1b) (Segall and Pollard, 1980, 1983b; Martel et al., 1988; Kim et al., 2000; Kim et al., 2003; Flodin and Aydin, 2004; Kim et al., 2004) and the development of a pull-apart basin at the kilometer scale (Fig. 1c) (Mann et al., 1983; Aydin and Nur, 1985; Westaway, 1995). In contrast, a step with an opposite sense to that of the fault slip (e.g., right step along a left-lateral fault) results in contractional deformation structures, including mylonitic foliation (Fig. 1d) or pressure solution seams at the meter scale (Bürgmann and Pollard, 1992, 1994; Peacock and Sanderson, 1995) and push-up ranges at the kilometer scale (Fig. 1e) (Aydin and Nur, 1985; Westaway, 1995). For the examples given in Fig. 1, differences in secondary structures for the small- and large-scale steps are likely related to the confinement during deformation. Because it is active at the earth's surface, the kilometer-scale contractional step (Fig. 1e) is unconfined in the vertical direction, which facilitates the development of the push-up range. For the meter-scale fault step (Fig. 1d) that formed at depth, however, the three-dimensional confinement discouraged preferential extension in the vertical direction; thus, deformation was accommodated through the development of mylonitic foliation. In each of these cases, the steps are characterized by secondary

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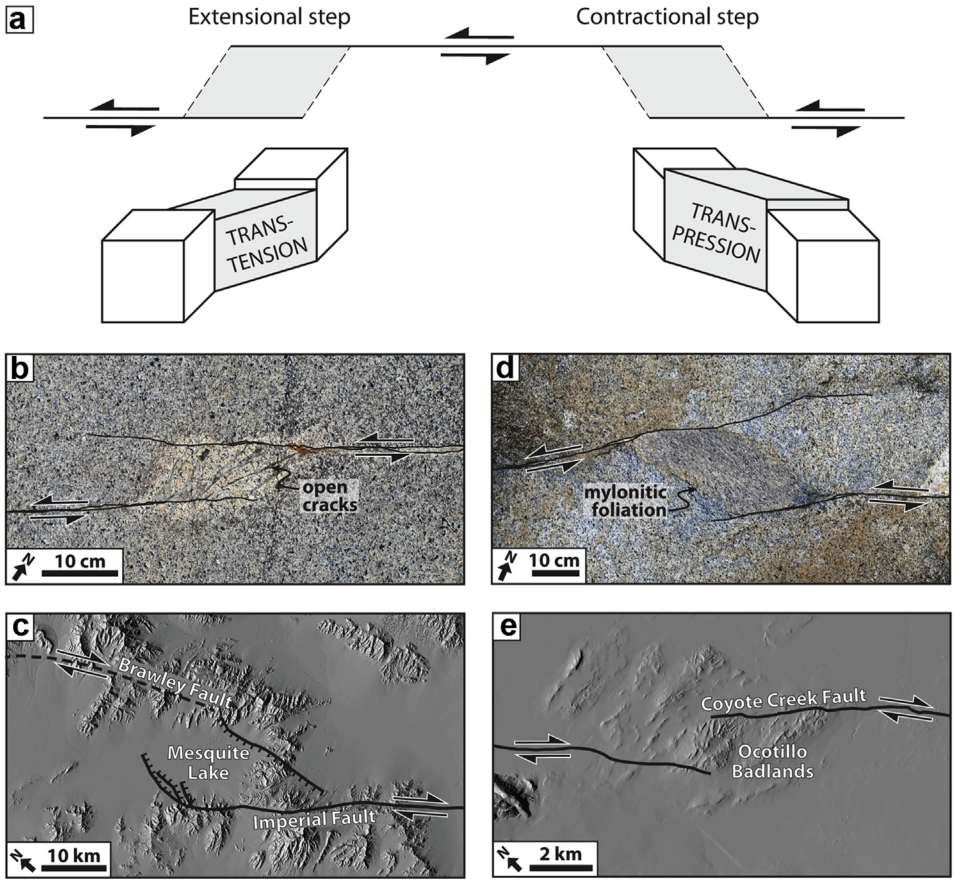

Fig. 1. (a) Schematic diagram relating the geometry of extensional and contractional steps along left-lateral faults to block diagrams of transtension and transpression. (b) Photograph of a small-scale extensional step between left-lateral faults with opening-mode cracks surrounded by an alteration halo (pale yellow discoloration) in the Bear Creek field area. (c) Digital elevation model (DEM) of a large-scale extensional step between right-lateral faults in southern California (faults mapped after Johnson and Hadley, 1975). (d) Photograph of a small-scale contractional step containing mylonitic foliation between left-lateral faults in the Bear Creek field area. (e) DEM of a large-scale contractional step along the right-lateral Coyote Creek Fault, southern California, which resulted in the uplifted Ocotillo Badlands (faults mapped after Sharp and Clark, 1972).

structures (e.g., spatially variable foliation, fractures) that indicate the deformation was heterogeneous.

Extensional and contractional steps are sometimes referred to as being sites of "transtension" and "transpression," respectively (Miller, 1994; McClay and Bonora, 2001; De Paola et al., 2008; Elliott et al., 2009; Doğan and Karakaş, 2013). These terms were first introduced to describe deformation associated with oblique divergence and convergence of tectonic plates (Harland, 1971). In kinematic terms, transtension and transpression describe strike-slip deformations that differ from simple shear due to a component of extension or contraction orthogonal to the shear plane (Sanderson and Marchini, 1984; Dewey et al., 1998; Fossen and Tikoff, 1998). Thus, knowledge of the shear plane orientation is necessary to identify a region as transtensional or transpressional.

Previous kinematic studies of fault steps can be classified into two groups, based on two different models for shear plane orientation. The shear plane orientation in the first model, which we interpret to have been used by Cembrano et al. (2005) and De Paola et al. (2008), is equivalent to the orientation of the step-bounding faults. This may be the most intuitive orientation, since faults are generally modeled as parallel to the shear planes in kinematic analyses (e.g., Cladouhos, 1999). Furthermore, block diagrams of transtension and transpression (Fig. 1a) are visually consistent with a fault step in which the shear plane is defined by the orientation of the step-bounding faults. The shear plane orientation in the second model, proposed by Westaway (1995), is equal to that of an "internal fault," which connects and is oblique to the step-bounding faults. Fault steps, both at the meter scale (Fig. 2) and at the kilometer scale (Sieh et al., 1993; Westaway, 1995; Manaker et al., 2005; Madden and Pollard, 2012), may include a discrete internal fault, or set of faults, linking the bounding faults. In the absence of a well-developed or well-exposed internal fault, Westaway (1995) suggests using the plane connecting the fault tips in the deformed state as the shear plane orientation.

In addition to kinematic models, fault steps have been investigated using mechanics-based modeling techniques (Segall and Pollard, 1980, 1983b; Pollard and Segall, 1987; Reches, 1987; Bürgmann and Pollard, 1992; Harris and Day, 1993; Bürgmann et al., 1994; Parsons et al., 2003; Ando et al., 2004; Brankman and Aydin, 2004; Duan and Oglesby, 2006; Okubo and Schultz, 2006). In this study, we compare the value of kinematic and mechanical models in characterizing deformation features recorded in a meter-scale contractional fault step. We construct two kinematic models, based on the two models for shear plane orientation (step-bounding faults vs. internal fault). Each of these models tests the ability of simple shear and transtension/transpression to reproduce the step-related deformation. The mechanical model, on the other hand, uses the finite element method and assumes an elastoplastic constitutive law for rock behavior. The results of these models are compared with each other and to the outcrop measurements in