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# Evolution of fault efficiency at restraining bends within wet kaolin analog experiments

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A B S T R A C T

Restraining bends are regions of mechanical inefficiency along strike-slip faults where faults evolve to improve efficiency. Analog experiments using wet kaolin examine the evolution of a variety of restraining bends. Restraining bends with 15° bends continue to slip while systems with greater bends develop new faults. The new faults, which flank the uplifted region, accommodate right-lateral slip when parallel to the plate movement and oblique-slip motion when parallel to the restraining segment. Within the wet kaolin, strain is partitioned into fault slip and off-fault deformation, such as distributed shear and uplift. The wet kaolin produces restraining bend deformation patterns, fault sequence and mechanical efficiency similar to dry sand experiments and natural restraining bends. The propagation of new faults in the wet kaolin improves the mechanical efficiency of the fault system by increasing the ratio of fault slip to off-fault deformation. Local inefficiencies, such as linkage of faults via a sharp kink, do not affect the overall increase in efficiency of the linked fault system. Furthermore, wider restraining bend stepovers have lower mechanical efficiency than close stepovers, but the difference in mechanical efficiency decreases as faults grow and link up around the restraining bends. This study demonstrates that restraining bend fault systems evolve toward greater mechanical efficiency.

## 1. Introduction

One of the fundamental topics in structural geology is the evolution of active fault systems, which both generate devastating earthquakes and produce orogenic belts. Restraining bends along strike-slip fault systems exhibit complex fault evolution including both the abandonment and formation of new fault strands (e.g. Marshall et al., 1991; Morton and Matti, 1993; Matti and Morton, 1993; Wakabayashi et al., 2004; Mann, 2007). Local transpression within restraining bends produces pronounced uplift that is associated with flanking reverse or oblique-slip faults along an otherwise strike-slip system. Such patterns have been observed along many crustal strike-slip fault systems (e.g. Anderson, 1990; Schwartz et al., 1990; Campagna and Aydin, 1991; Marshall et al., 1991; Matti and Morton, 1993; Yule and Sieh, 2003; Wakabayashi et al., 2004; Gomez et al., 2007; Mann, 2007; Carne and Little, 2012; Bemis et al., 2012) and within analog experiments of restraining bends (McClay and Bonora, 2001). The observation of decreased rates of strike-slip motion within restraining bends (e.g. Cooke and Dair, 2011 and references therein) reveals that these structures do not efficiently accommodate the regional transcurrent shear of the fault system. However, the locally inefficient restraining bend may not be locked in its geometry. The evolution of active faulting at restraining bends, including the abandonment and the development of new fault strands, may allow the fault system to more efficiency accommodate strike-slip strain. This idea extends from the principle of work minimization, which posits that that fault systems evolve to minimize work on the system (e.g. Mitra and Boyer, 1986; Masek and Duncan, 1998; Maillot and Leroy, 2003; Cooke and Murphy, 2004). Consequently, new fault segments grow if they reduce the work of deforming the system (e.g. Cooke and Murphy, 2004; Del Castello and Cooke, 2007). For example, analog experiments have directly measured the decrease in work associated with new fault growth (Cruz et al., 2010; Souloumiac et al., 2012). The work minimization approach has been successful in predicting fault evolution within accretionary systems (e.g. Del Castello and Cooke, 2007; Cubas et al., 2008; Souloumiac et al., 2012) and extensional systems (Dempsey et al., 2012) but has not yet been applied to restraining bends.

To investigate the evolving mechanical efficiency of restraining bends, we simulate their evolution using analog experiments with wet kaolin. The analog experiments utilize a range of initial restraining bend geometries. We analyze the evolution of fault slip

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throughout the experiments and document the details of fault abandonment, growth and reactivation in these regions of complexity. We also use data from the experiments to quantify the evolving mechanical efficiency as the ratio of fault slip to the total displacement applied to the experiment. Along the most efficient fault system this ratio is one; all of the applied displacement is accommodated by fault slip and off-fault deformation is negligible. Our results indicate that the long-term stability of restraining bends depends on their ability to develop new fault strands that improve the efficiency of the fault system.

## 2. Models of fault evolution at restraining bends

The evolution of restraining bends along strike-slip faults has previously been studied using numerical models (Li et al., 2009) and sandbox analog models (McClay and Bonora, 2001). The two studies predict different fault evolution around restraining bends because they employ both different loading of the system and different material rheology (Fig. 1). Li et al. (2009) use numerical models with remote loading of the restraining bends where new faults grow by strain weakening of the host rock. The model predicts new faults that grow outward from the restraining bend and turn to parallel the strike-slip fault segments outside of the restraining bend (Fig. 1a). In those models, all of the initial faults segments are abandoned in favor of a new releasing bend fault configuration. This evolution has been likened to the development of the San Jacinto fault and Eastern California shear zone at the Big Bend along the southern San Andreas fault in southern California (Li et al., 2009). In contrast, many other crustal-scale restraining bends, such as the Dead Sea (e.g. Gomez et al., 2007) and the Santa Cruz Mountains (e.g. Anderson, 1990) maintain activity along restraining bends rather than develop into releasing bends. This suggests that either these crustal faults do not grow by the modeled strain weakening process or, more likely, that the tectonic loading of crust in these areas does not correspond to the far-field loading of the numerical model. An alternative to remote loading is to apply basal displacements beneath the crust that create a dislocation below the restraining bend. Analog models that simulate crustal deformation within several hours on a table-top device utilize basal loading of restraining bends. Scaled analog experiments provide the benefits of having well constrained boundary and material conditions so that we can test the effects of specific factors on fault evolution (e.g. Hubbert, 1951; Davis et al., 1983). Furthermore, recent analog models use techniques that permit quantification of deformation. These techniques are revolutionizing our understanding of fault evolution and facilitate investigation of increasingly complex systems (e.g. Adam et al., 2005; Mourgues and Cobbold, 2006; Haq and Davis, 2009; Cruz et al., 2010; Souloumiac et al., 2012; Leever et al., 2011).

The dry sand experiments of McClay and Bonora (2001) use basal plates configured with an open rhombochasm that closed upon deformation so that the zone of active transpression decreases in width during the experiment (Fig. 1). Consequently, the first faults form on the outer flanks of the restraining bend and later faults form within the uplifted region. Unlike the FEM experiments of Li et al. (2009) the strike-slip segments outside of the restraining bend remain active in the dry sand experiments. However, the inward sequence of faulting is unlike that observed within restraining bends where active reverse faulting occurs along the flanks of the uplifting region (e.g. Schwartz et al., 1990; Yule and Sieh, 2003; Gomez et al., 2007). The inward sequence of faulting also differs from the observed evolution of faulting within sandbox experiments of oblique convergence that employ stable basal conditions (Leever et al., 2011).

Our study utilizes wet kaolin over basal plates where one plate slides over the other. This approach produces an outward sequence of thrust faults and the active strike-slip fault geometry outside of the restraining bend remains stable. The wet kaolin material was chosen rather than the more commonly used dry sand (e.g. Emmons, 1969) for two reasons. One benefit of wet kaolin is that it fails via localized faults that are more distinct than faults in sand, which facilitates analysis of fault characteristics (e.g. Spyropoulos et al., 1999; Clifton et al., 2000; Henza et al., 2010). The second benefit is that, the wet kaolin reactivates existing faults more readily than sand (e.g. Henza et al., 2010). Geologic evidence suggests that many faults are long-lived despite having inefficient geometry, such as the >2 million year old restraining bend of the southern San Andreas fault (e.g. Matti and Morton, 1993; Spotila and Sieh, 2000). For investigations of fault evolution that involve abandonment of active fault segments, a material that permits long-lived faults, such as wet kaolin, provides a more conservative evolution than a material that forms new faults readily (i.e. dry sand). The experiments of this study also expand upon the McClay and Bonora (2001) restraining bend models by utilizing 3D laser scanning technology to provide quantitative measurement of slip that facilitate assessment of mechanical efficiency.

## 3. Experimental methods

### 3.1. Properties of wet kaolin

The computer-controlled claybox analog model experiments were carried out using a wet kaolinite clay, which well-replicates a wide range of deformation mechanisms observed in the crust

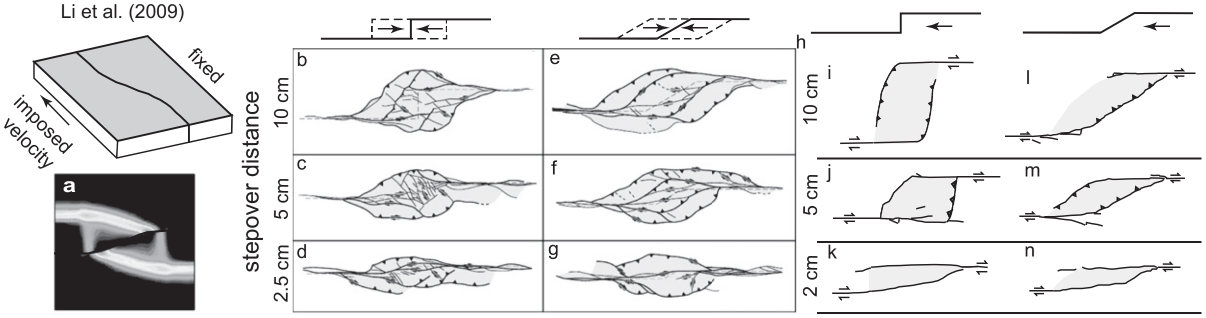

**Fig. 1.** Setup of various restraining bend models and experiments shown in top row with resulting fault maps (a–n). Numerical models of restraining bend evolution (b) predict abandonment of the initial restraining bend and development of a releasing stepover. The basal plates of the dry sand experiment move toward one another to close an initial rhombohedral gap. For the wet kaolin experiments, one plate slides over the other stationary plate. The wet kaolin shows less dense secondary fracturing and more pronounced strain partitioning between reverse and strike-slip faulting within the 90° restraining bend experiments. This reflects the greater cohesive strength of the wet kaolin compared to dry sand.