Journal of Structural Geology 102 (2017) 147–167

Contents lists available at ScienceDirect

Journal of Structural Geology

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

How do horizontal, frictional discontinuities affect reverse fault-propagation folding?

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ARTICLE INFO

Article history:
Received 7 April 2017
Received in revised form
29 July 2017
Accepted 3 August 2017
Available online 4 August 2017

Keywords:
Reverse faults
Fault-propagation fold
Mechanical discontinuities
Analog modeling

ABSTRACT

The development of new reverse faults and related folds is strongly controlled by the mechanical characteristics of the host rocks. In this study we analyze the impact of a specific kind of anisotropy, i.e. thin mechanical and frictional discontinuities, in affecting the development of reverse faults and of the associated folds using physical scaled models. We perform analog modeling introducing one or two initially horizontal, thin discontinuities above an initially blind fault dipping at 30° in one case, and 45° in another, and then compare the results with those obtained from a fully isotropic model. The experimental results show that the occurrence of thin discontinuities affects both the development and the propagation of new faults and the shape of the associated folds. New faults 1) accelerate or decelerate their propagation depending on the location of the tips with respect to the discontinuities, 2) cross the discontinuities at a characteristic angle (~90°), and 3) produce folds with different shapes, resulting not only from the dip of the new faults but also from their non-linear propagation history. Our results may have direct impact on future kinematic models, especially those aimed to reconstruct the tectonic history of faults that developed in layered rocks or in regions affected by pre-existing faults.

1. Introduction

Shortening in the brittle crust is mostly accommodated by folding, fracturing, and faulting. These processes are intimately associated with one another and understanding their evolution through time is of paramount importance. Several kinematic models have been proposed to explain the relationships between faulting and folding (for a recent summary see McClay, 2011; and Brandes and Tanner, 2014). It is generally accepted that fault-related folding can be described by three end-member geometries: detachment folds, fault-bend folds, and fault-propagation folds (e.g. De Sitter, 1956; Dahlstrom, 1969; Suppe, 1983; Suppe and Medwedeff, 1984, 1990; Jamison, 1987; Chester and Chester, 1990; Mitra, 1990, 1992, 2003; Erslev, 1991; Fisher et al., 1992; Epard and Groshong, 1995; Poblet and McClay, 1996; Storti and Salvini, 1996; Hardy and Ford, 1997; Allmendinger, 1998; Suppe et al., 2004; Tavani et al., 2006; Hardy and Finch, 2007; Albertz and Lingrey, 2012). Such three end-members, however, often represent different stages in the evolution of the same structure (e.g., Tavani and Storti, 2006; Storti et al., 1997). For instance, a contractional structure may form as a detachment fold, then propagate upward forming a ramp as a fault-propagation fold, and finally be deflected along a weak layer to operate as a fault-bend fold.

Although the evolution of detachment folds and fault-bend folds is mainly related to the friction of the surface where they propagate and to the intrinsic mechanical properties of the rocks involved, the propagation of a ramping fault is a more complex mechanism, mainly because a new slipping surface must be created. The development of new faults in an isotropic medium occurs through three successive phases (e.g., Anderson, 1942; Brace et al., 1966; Segall and Pollard, 1983; Cartwright et al., 1995; Mansfield and Cartwright, 2001; Scholz, 2002; Faulkner et al., 2006; Bonini et al., 2015): 1) a "nucleation" phase, during which small cracks form as a consequence of the applied stress, usually with an *en echelon* arrangement; 2) a "creation" phase, when new

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http://dx.doi.org/10.1016/j.jsg.2017.08.001
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fault planes form through the coalescence of previously formed cracks; and 3) a “propagation” phase, when a single fault grows through the connection of small cracks located at its outer tips. Note that during the propagation phase, both nucleation and creation phases continue to occur at fault tips, and that the general evolution of a fault is seldom a linear process. In an ideal isotropic case, however, the linear propagation of a new fault is often an accepted assumption. Different factors may affect this linearity in nature, including the different strength of the rocks involved in the faulting process, the non-uniformity of the stress field, the presence of fluids, the occurrence of background inherited fractures - which may not be homogeneously distributed in the faulted sequence - and pressure and/or heat flow variations. As a result, any deviation from the linearity of fault propagation impacts also on the associated folding.

Understanding the deviations from linearity in the propagation of a ramping fault is fundamental in many applications which use the activity (slip) of the fault as a basic parameter. In regions of active tectonics or in the external portion of orogenic belts, reverse faults or thrust-fault ramps are often blind or buried below piles of sediments, thus preventing any direct observation of the faults. Several kinematic models have been developed to relate the observations of deformation features (e.g. folded horizons, secondary brittle structures, uplifted and warped terraces, growth strata) to their causative fault and to investigate the evolution of the whole system through time (e.g., Suppe, 1983; Suppe and Medwedeff, 1990; Erslev, 1991; Epard and Groshong, 1995; Hardy and Ford, 1997; Allmendinger, 1998; Mitra, 2002, 2003; Allmendinger et al., 2004; Suppe et al., 2004; Vannoli et al., 2004; Jin and Groshong, 2006; Tavani et al., 2006; Storti and Salvini, 1996; Cardozo and Aanonsen, 2009; Cardozo et al., 2011; Maesano et al., 2013, 2015; Grothe et al., 2014; Bergen et al., 2017). Other studies used different approaches based on mechanical modeling, such as boundary element methods (BEM; e.g. Roering et al., 1997), finite element methods (FEM; e.g. Albertz and Lingrey, 2012), and discrete element methods (DEM; Hughes and Shaw, 2015).

Most studies agree that one of the main elements controlling the evolution of a ramping fault is the mechanical stratigraphy. Deviations from a linear evolution are commonly observed in layered rocks that are often characterized by alternating weak and strong layers. However, such behavior can be also associated with other mechanical heterogeneities. For example, interlayer surfaces or pre-existing fault planes located along the propagating fault trajectories represent mechanical discontinuities within the hosting rocks. How do these thin, frictional, mechanical discontinuities impact on the propagation of a ramping fault? To answer this question we analyze a set of analog models. Our goal is to highlight how initially horizontal thin, mechanical discontinuities deviate a propagating fault from its linear development. We study how such discontinuities affect the evolution of fault-propagation folds, first by reproducing the development of initially blind, reverse faults dipping at different angles. We then introduce one or two horizontal discontinuities above the fault initial tip to quantitatively analyze their role in affecting the development of the whole structure. Finally, we use our results to discuss the potential impact of our findings in the investigation of natural cases.

2. Method

Among the various fault dips that can be adopted for a preliminary experimental analysis we chose to reproduce the dips that are most commonly observed in areas of active reverse faulting. A global compilation of active reverse faults (Sibson and Xie, 1998) indicates two prominent peaks in the 25°–35° and 45°–55° intervals. Accordingly, we designed two experimental boxes with the master fault, i.e. the inclined surface along which the two rigid blocks slip with reverse kinematics, dipping at 30° and 45° (Fig. 1): the corresponding sets of experiments are named DIP30 and DIP45, respectively (Table 1). The two boxes are composed by two rigid blocks: one is fixed and represents the footwall, the other is mobile and represents the hanging wall (Fig. 1). The analog material overlies these blocks and simulates the rock volume where the reverse fault is expected to propagate. In this setup the master fault is initially planar and blind.

As analog material we used wet kaolin (#CC31 China Clay), which is widely used to analyze faulting and folding processes in scaled experiments (e.g. Withjack et al., 1990; Miller and Mitra, 2011; Mitra and Miller, 2013; Cooke et al., 2013; Bonini et al., 2014a, 2016a). Several peculiarities make the kaolin especially suitable for our purpose: 1) its mechanical properties can be easily assessed by measuring the water content of the mixture and by imposing a specific strain rate; 2) thin mechanical discontinuities can be easily introduced by cutting the clay pack; 3) the small size of clay particles allows for a very high resolution of strain observations, especially those related with faulting and fracturing.

2.1. Scaling

A proper analog experiment is subject to specific scaling rules that must be representative of a natural setting (Hubbert, 1937, 1951; Ramberg, 1981). As recalled earlier, the mechanical behavior of wet kaolin depends mainly on its water content and strain rate (e.g., Eisenstadt and Sims, 2005; Cooke and van der Elst, 2012). In this study we used a mixture of clay with a 60% water content by mass, resulting in a density of 1.65 g/cm^3. It follows that we may assume a cohesion in the range 50–120 Pa (Eisenstadt and Sims, 2005) and a friction coefficient of 0.6 (Henza et al., 2010). To ensure a proper rheological behavior during the experiments we adopted a 0.02 mm/s hanging wall speed (Cooke and van der Elst, 2012). As a natural target we assumed a rock with a density of 2.5 g/cm^3 and a cohesion in the range 10–20 MPa. Hence, the scaling relationship can be calculated as:

$$\frac{c_m}{c_n} = \frac{\rho_m}{\rho_n}\frac{l_m}{l_n} \tag{1}$$

where c is the cohesion, ρ is the density and l is the length. The subscripts m and n denote the analog model and the natural target, respectively. Solving Eq. (1) for the length of the models gives

$$l_m = l_n\frac{\rho_n}{\rho_m}\frac{c_m}{c_n} \tag{2}$$

and using the maximum and minimum values of the kaolin cohesion we obtain that 10 mm in our model correspond to about 0.1–1.0 km in nature. Hence, the clay cake placed above the two rigid blocks was made 50 mm-thick, representing 0.5–5.0 km in nature.

2.2. Modeling strategy

To analyze the impact of the presence of thin, horizontal, mechanical discontinuities onto the development of reverse faults and related folds we introduced such discontinuities in our models by cutting the clay cake with an electrified probe before moving the hanging wall block. This technique allows us to precut the wet clay pack without modifying its mechanical properties (Cooke et al., 2013; Bonini et al., 2014a, 2015, 2016a). We thus assume that friction along the precut is the same as that of natural faults forming in the wet kaolin.