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Extensional fault-propagation folds: mechanical models and observations from the Modoc Plateau, northeastern California

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Abstract

Extensional fault-propagation folds are produced by warping of material ahead of a growing normal fault. We use field observations of surface-breaking normal faults in the Modoc Plateau, California, in conjunction with three-dimensional linear elastic boundary element computer models, to address the mechanical controls on extensional fault propagation folds. Detailed topographic and structural maps of the near-tip regions of several kilometer-long faults reveal: throw decreases rapidly toward the tip, suggesting elliptical slip distributions; fault-parallel monoclinal folds are present beyond the tip, with axes offset into the hanging wall; and open fissures are common in the tip region. Parametric tests with the model show that the amplitude and form of folds at the fault terminations are influenced by slip distribution, fault dip, elastic properties of the rock, and the presence or absence of a blind portion of the fault. Models reproduce the form of observed folds to first order and suggest that the faults, both isolated and in relay zones, are probably blind for some lateral extent beyond the surface break.

Keywords: Extensional folding; Normal fault; Monocline; Boundary element model; Lateral propagation; Slip distribution

1. Introduction

Fault-propagation folds are produced by deformation of rock beyond the tip-line of lengthening faults. Research on the geometry, kinematics, and mechanics of fault-propagation folding has led to a better understanding of the growth of faults and fault systems, and to successful exploration for hydrocarbons near fault terminations (e.g. Mitra, 1990). The geometry and mechanics fault-propagation folds in contractional settings are well documented (e.g. Mitra and Wojtal, 1988; McClay, 1992). Of equal importance, but poorly documented, are fault-related folds produced in extensional tectonic environments. In the last decade, reviews of deformation around normal faults have illustrated the variety of folds possible in extensional environments (Schlische, 1995; Janecke et al., 1998). These include folds that occur around faults with irregular shapes (fault-bend folds), folds associated with variation in slip along faults (displacement-gradient folds), and fault-propagation folds.

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Normal-fault propagation is accompanied by warping of material beyond the tip-line, resulting in an extensional fault-propagation fold (Fig. 1; Gawthorpe et al., 1997; Corfield and Sharp, 2000; Sharp et al., 2000; Khalil and McClay, 2002; Willsey et al., 2002). In this contribution, we investigate the manner in which propagation direction (lateral vs. vertical) affects surface deformation at the termination of normal faults. We consider effects of slip distribution, material properties, and fault interaction. We address extensional fault-propagation folding by: (1) detailed mapping of surface deformation near the tips of small surface-breaking normal faults in the Modoc Plateau, northeastern California; and (2) assessing possible mechanical controls on near-tip folds with three-dimensional linear-elastic boundary element models.

1.1. Previous work

Two classes of fault-propagation folds can be recognized. *Vertical* fault-propagation folds form ahead of upward-propagating dip-slip faults and are the result of the relative motion of material on either side of the fault (a class of 'forced folds'). The concept of fault-propagation folding was originally applied to vertical fault propagation in contractional settings, where slip on a thrust fault decreases up dip until shortening is accommodated by folding rather than faulting. *Lateral* fault-propagation folds form ahead of horizontally-propagating

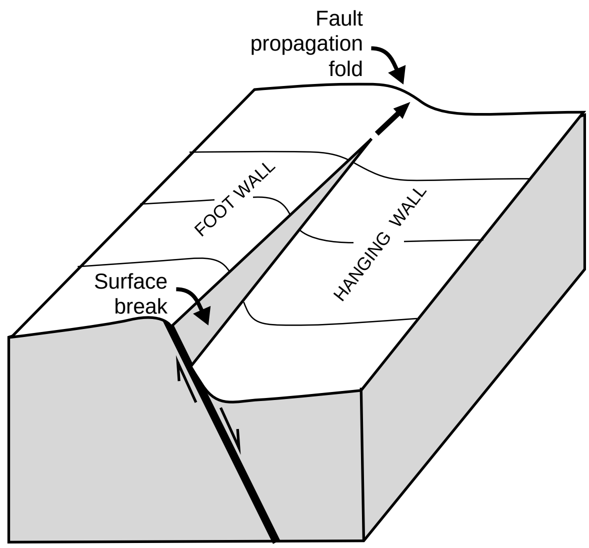

Fig. 1. Block diagram of warping beyond the tip-line (fault-propagation fold) produced by lateral and vertical propagation of a normal fault. A monocline forms above the blind, upwardly-propagating fault and/or ahead of the laterally-propagating fault. After Walsh and Watterson (1987), Schlische (1995) and Sharp et al. (2000).

dip-slip faults and are the result of warping of rock at the juncture of the footwall and hanging wall (Fig. 2). A lateral fault-propagation fold is not rooted in a blind fault, and its hinge is sub-perpendicular to the associated fault tip-line. Both classes of folds can change the local topography around near-surface faults, which, in turn, produces important controls on the pattern of erosion and deposition of sediments (Gawthorpe et al., 1997).

Field observations of extensional fault-propagation folds have come mainly from deformed pre- and syn-extensional strata associated with large normal fault systems in extended regions. Kilometer-scale fault-propagation folds have been recognized in the Gulf of California (Willsey et al., 2002), the Suez rift (Sharp et al., 2000), the Red Sea (Khalil and McClay, 2002), and from the Smørbukk area, mid-Norway based on 3-D seismic data (Corfield and Sharp, 2000).

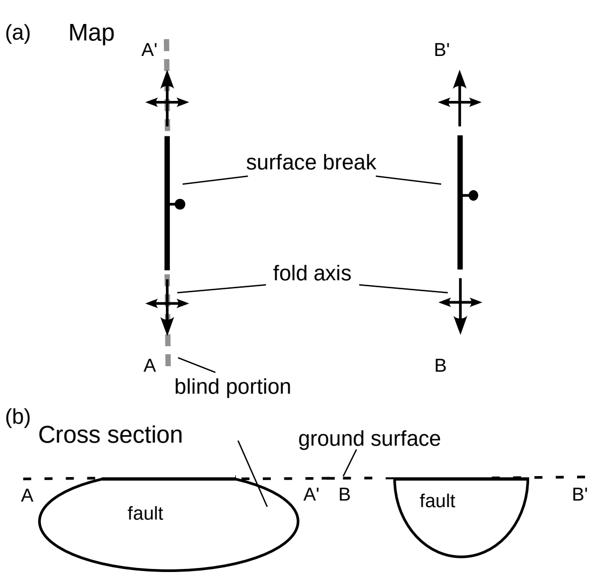

Fig. 2. Distinction between vertical and lateral fault-propagation folds at Earth's surface. (a) Vertical fault-propagation folds result from upward propagation of a blind fault, or a portion of a fault that is blind, toward the surface. (b) Lateral fault-propagation folds result from lateral propagation of a fault that breaks the surface completely along strike.

Study of young surface-breaking normal faults allows for detailed investigations of relatively simple structures. Peacock and Parfitt (2002) examined fault linkage structures on the south flank of Kilauea Volcano, Hawaii where the shield volcano is actively deforming to accommodate gravity driven extension. Grant and Kattenhorn (2004) document normal-fault-related monoclines in southwest Iceland. Both sets of researchers demonstrate the importance of folding in normal-fault growth; they differ in their interpretation of the initiation and role of accompanying fissures.

A small pool of research focuses on using experimental and kinematic models to study extensional fault-propagation folds. Horsfield (1977) describes sandbox models of deformation above dipping normal faults, resulting in subsidiary faulting. Withjack et al. (1990) used aluminum blocks with an overlying clay layer to simulate forced folding. They found that strain is distributed in an upward widening monocline above a discrete normal fault surface. Using a 2-D trishear kinematic model, Hardy and McClay (1999) were able to successfully reproduce the results of clay analogue modeling.

A number of studies in recent decades have explored the mechanics of forced folds. Haneberg (1992) examines forced folding of compressible elastic strata over rigid basement blocks. Patton and Fletcher (1995) present a 2-D mathematical model for deformation of an incompressible layer overlying a relatively rigid basement fault of arbitrary dip. Johnson and Johnson (2002b) show the influence of fault geometry and cover anisotropy with 2-D mathematical models of cover over a rigid basement fault. All three of these approaches are limited to cross-section views of an infinitely long fault, and thus address only the geometry of vertical fault propagation (or drape) folds. In this study, we sacrifice mechanical complexity for three dimensions, allowing us to explore folds produced above or beyond the lateral tip lines of normal faults.

1.2. Geology of the Modoc Plateau

The Modoc Plateau volcanic-upland region of northeastern California (Fig. 3) provides an excellent location to observe surface deformation associated with normal faults. Miocene and younger normal faults break the surface through basalt and are exceptionally well preserved. Volcanic terrain such as the Modoc Plateau preserves surface deformation relatively well and is thus a common substrate for mechanical studies of faulting (e.g. Dawers et al., 1993; Dawers and Anders, 1995; Crider and Pollard, 1998; Crider, 2001). Additionally, the Modoc Plateau is sparsely vegetated in many areas, providing easy access and good exposure.

The Modoc Plateau is situated between the Basin and Range Province and the Cascades Volcanic Arc. The plateau is the southernmost part of a region of Miocene-to-Quaternary, flat-lying basaltic lava flows that extend northward into Oregon