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Insights into the damage zones in fault-bend folds from geomechanical models and field data

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A B S T R A C T

Understanding the rock mass deformation and stress states, the fracture development and distribution are critical to a range of endeavors including oil and gas exploration and development, and geothermal reservoir characterization and management. Geomechanical modeling can be used to simulate the forming processes of faults and folds, and predict the onset of failure and the type and abundance of deformation features along with the orientations and magnitudes of stresses. This approach enables the development of forward models that incorporate realistic mechanical stratigraphy (e.g., the bed thickness, bedding planes and competence contrasts), include faults and bedding-slip surfaces as frictional sliding interfaces, reproduce the geometry of the fold structures, and allow tracking strain and stress through the whole deformation process. In this present study, we combine field observations and finite element models to calibrate the development and distribution of fractures in the fault-bend folds, and discuss the mechanical controls (e.g., the slip displacement, ramp cutoff angle, frictional coefficient of interlayers and faults) that are able to influence the development and distribution of fractures during fault-bend folding. A linear relationship between the slip displacement and the fracture damage zone, the ramp cutoff angle and the fracture damage zone, and the frictional coefficient of interlayers and faults and the fracture damage zone was established respectively based on the geomechanical modeling results. These mechanical controls mentioned above altogether contribute to influence and control the development and distribution of fractures in the fault-bend folds.

1. Introduction

Fractures occur at different scales in a hierarchical fashion, and they strongly influence the permeability architecture of most geologic formations (Florez-Nino et al., 2005; Smart et al., 2012). Therefore, the ability to predict rock mass deformation, and the development and distribution of fractures within a geologic structure along with their orientation and intensity is of great importance during the oil and gas exploration and development (Aydin, 2000; Manzocchi et al., 2010), geothermal energy production (Moeck et al., 2009), groundwater resource analysis (Ferrill et al., 2004), and CO_2 injection and storage (Annunziatellis et al., 2008; Vidal-Gilbert et al., 2010; Viete and Ranjith, 2006).

Controls on fracture development and distribution include lithology, layer thickness, proximity to faults, ramp cutoff angle, and position on folds (Ackermann et al., 2001; Ju et al., 2011; Lin et al., 2010; Smart et al., 2009; Wennberg et al., 2006; Wu and Pollard, 1995). Several studies have found that fracture spacing is positively correlated with layer thickness (e.g., Ackermann et al., 2001; McQuillan, 1973; Narr and Suppe, 1991), whereas other workers suggest that mechanical stratigraphy may be more important than simply layer thickness (Hanks et al., 1997; Underwood et al., 2003; Wennberg et al., 2006). Smart et al. (2009) studied the impact of interlayer slip on fracture prediction based on geomechanical models. The presence or absence of interlayer slip controlled the development and distribution of fractures (Smart et al., 2009). The development and distribution of fractures around a fault are mainly controlled by this fault (e.g., Gudmundsson et al., 2010), and an exponential relationship between fracture density and its distance to the fault is established (Ju et al., 2011). Natural fracture systems tend to be heterogeneous, with fractures clustered in swarms that separate areas with relatively few fractures (Odling et al., 1999).

A common approach to deformation and strain prediction related to folding and fault-related folding is by geometric and kinematic modeling (e.g., Mitra, 1990; Smart et al., 2010; Suppe, 1983; Suppe and Medwedeff, 1990). However, these models were typically constrained by simplifying assumptions such as constancy of geometric parameters (e.g., bed thickness, area or volume, bed length). This approach is useful as it relates deformation to structural position, while it is limited because it is specifically tied to geometric models or assumptions that may not completely represent the deformation behaviors and mechanical properties of rocks (Smart et al., 2009, 2012). Field observation on thrust belts has demonstrated that the deformation types are strongly controlled by structural position and mechanical properties of the deformed rocks during deformation (Evans and Dunne, 1991; Hickman et al., 2009). As to the geomechanical modeling,

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it incorporates important characteristics such as the mechanical properties of the rocks involved, both the geometry and kinematics of geologic structures in all tectonic regimes, and small scale deformations governed by these material properties and stress history rather than geometric assumptions (Ackermann and Schlische, 1997; Ackermann et al., 2001; Ferrill and Morris, 2008; Yin, 1989).

Tong and Yin (2011) presented a theory for predicting the evolution of preexisting weakness under uniform stress state, and this weakness might be a start for the fracture forming (Tong and Yin, 2011). As practiced in the petroleum geology, fracture prediction is commonly based on geometric and kinematic models such as analysis of fold curvature (Bergbauer and Pollard, 2004; Fischer and Wilkerson, 2000; Hennings et al., 2000; Lin et al., 2010) or seismic-based techniques (Gray et al., 2002; Hall et al., 2002; Masaferro et al., 2003), but far less with geomechanical modeling. However, numerical geomechanical modeling such as finite element, boundary element and discrete element can provide powerful tools for simulating the spatial and temporal development of geological structures (Erickson, 1995, 1996; Erickson and Jamison, 1995; Gudmundsson et al., 2010; He et al., 2011, 2013; Hou et al., 2006, 2010a,b; Ju et al., 2013a; Smart et al., 2011, 2012; Wyrick and Smart, 2009; Yin, 1989, 1991, 1994). Finite element modeling allows complex geometries (e.g., faults and mechanical stratigraphy) to be combined with realistic material models to produce physically realistic and mechanically rigorous forward models. The geometric and kinematic history is captured with this approach and further permits tracking the spatial and temporal evolution of stress and strain in the deformed rocks or beddings (Smart et al., 2012; Yin, 1991, 1994).

In this study, the Kezilenuer fault-bend fold within the Kuqa Depression is used as an example to analyze the fracture development and distribution in fault-bend folds and test whether the geomechanical finite element models we created are suitable to study the development and distribution of fractures in fault-bend folds. The ultimate goal is to develop several suites of geomechanical finite element models and experiments for analyzing how these important mechanical factors (e.g., the slip displacement, ramp cutoff angle, frictional coefficient of interlayers and faults) influence and control the development and distribution of these fractures in fault-bend folds.

2. Geologic setting and field observations

The Kuqa Depression (also known as the Kuche Depression) is located along the northern margin of the Tarim Basin between the South Tianshan Orogenic Belt and the Northern Tarim Uplift to the south (Fig. 1; Chen et al., 2005; Huang et al., 2006). The structures in the Kuqa Depression are dominated by thrust faults and related folds mainly developed during the Cenozoic time, and laterally, the Kuqa Depression can be divided into three structural belts and two sags, which are the northern monocline belt, Kelasu-Yiqikelike structural belt, Baicheng and Yangxia sags, and Qiulitage structural belt from north to south (Fig. 1; Allen and Vincent, 1999; Zeng et al., 2010).

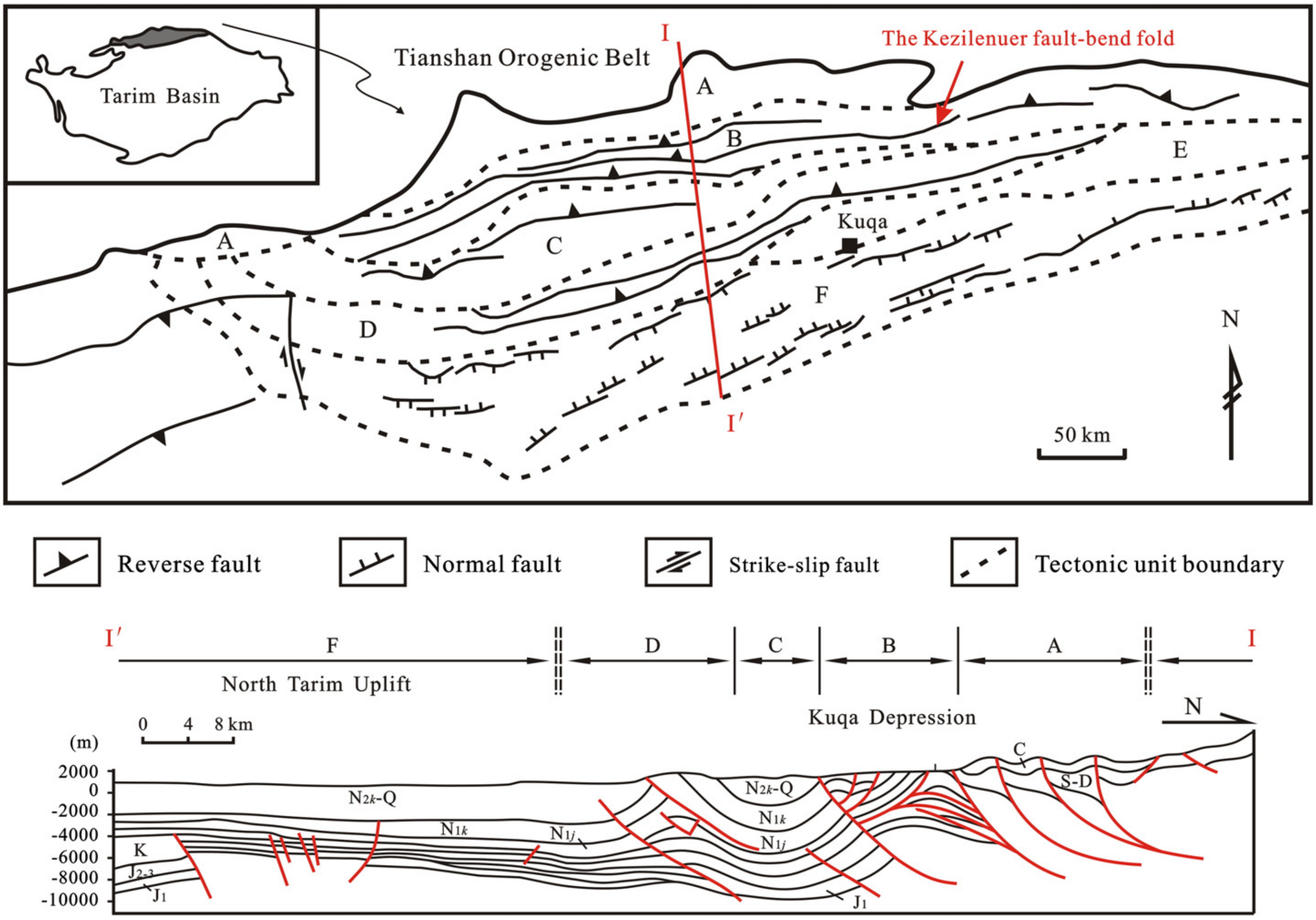

Fig. 1. Structural simplified map of the Kuqa Depression within the Tarim Basin, China. A—Northern monocline tectonic zone; B—Kelasu-Yiqikelike tectonic zone; C—Baicheng sag; D—Qiulitage tectonic zone; E—Yangxia sag; F—Northern Tarim Uplift; S–D: Silurian to Devonian; C: Carboniferous; J_1: Lower Jurassic; J_{2-3}: Middle to Upper Jurassic; K: Cretaceous; N_1j: Jidike Formation; N_1k: Kangcun Formation; N_2k–Q: Kuche Formation to Quaternary.
After Zeng et al., 2010.