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Characterization of strike-slip fault–splay relationships in sandstone

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Abstract

We document the length and angular relationships between strike-slip faults and their splays. The data indicate that the maximum splay length is correlated to the fault length by a power law but shows little correlation with the fault slip magnitude. The kink angle between faults and their splays is small for isolated faults (average ∼20°) and systematically larger for mechanically interacting faults (average ∼50°). Analytical models predict that splay length decreases with increasing confinement under biaxial compression. 2D numerical models of isolated faults show that small kink angles correspond to small values of the angle between the fault and the maximum compression (β) whereas large kink angles require greater β values. Similar models of interacting faults confirm the critical role of β on the kink angles and suggest that fault overlap and fault separation can also induce important variations in the kink angles. Our results provide a basis for a better understanding of fault segment linkage via splaying process and for a better assessment of the maximum thickness of fault damage zones. The results may also help to predict the length and orientation of secondary faults formed by splaying associated with first order faults with resolvable slip magnitude in the subsurface.

Keywords: Splays; Strike-slip faults; Splay length; Kink angle; Cohesive end zone

1. Introduction

Splays, also called wing, tail, kink, horsetail and branch cracks, are dominantly opening-mode fractures formed in response to slip across shear fractures in brittle rocks such as sandstone (Cruikshank et al., 1991; Myers and Aydin, 2004), limestone (Rispoli, 1981; Fletcher and Pollard, 1981; Petit and Mattauer, 1995) and granite (Segall and Pollard, 1983; Granier, 1985), and in other natural materials such as ice (Wilson, 1960; Schulson, 2002; Kattenhorn and Marshall, 2006). They form due to tensile stress concentration at fault tips (Pollard and Segall, 1987; Martel et al., 1988), at fault plane irregularities such as bends, steps, or relay zones and at points of variable frictional properties along the fault surface (Cooke, 1997).

Splays may form a dense and well connected damage zone around strike-slip faults (Martel et al., 1988; Kim et al., 2003, 2004; Myers and Aydin, 2004; Flodin and Aydin, 2004b) and may enhance fault zone permeability with a large impact on fluid flow in the subsurface. They also play a critical role in the process of fault growth by segment linkage (Martel, 1990; Bürgmann et al., 1994; Peacock and Sanderson, 1995; Martel and Boger, 1998; de Joussineau and Aydin, in press) and have a strong influence on the formation and evolution of normal faults (McGrath and Davison, 1995; Davatzes and Aydin, 2003; Davatzes et al., 2003a,b) and strike-slip faults (Martel et al., 1988; Kelly et al., 1998; Myers and Aydin, 2004; Flodin and Aydin, 2004a; Kim et al., 2004). Accordingly, splays were the subject of many studies over the past few decades. In particular, the angular relationships between faults and their splays have been intensively studied experimentally and theoretically. In experiments, the kink angle between a fault and its splays was found to be influenced by the frictional properties of the faults, the remote stress field, the angle of the faults

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to the maximum compressive stress or the stress perturbations induced by fault interaction (Brace and Bombolakis, 1963; Bombolakis, 1973; Nemat-Nasser and Horii, 1982; Horii and Nemat-Nasser, 1985; Barquins et al., 1991; Barquins and Petit, 1992; Du and Aydin, 1995; Chaker and Barquins, 1996). From a theoretical point of view, Linear Elastic Fracture Mechanics (LEFM) theory predicts a kink angle equal to 70.5° between a pure mode II (shearing) crack and its splays based on the maximum circumferential stress criterion (Erdogan and Sih, 1963; Ingraffea, 1987). However, kink angles much smaller than 70.5° are reported along natural faults with a shear offset and no evidence of opening perpendicular to the faults (Rispoli, 1981; Liu, 1983; Petit and Barquins, 1988; Martel, 1997). This discrepancy between theory and nature has been attributed to the fact that the LEFM theory implies a point of infinite stress concentration and infinite displacement gradient at the fault tips, which is unrealistic because natural materials cannot bear infinite stress. To overcome this stress singularity at fault tips, some authors introduced a zone of higher friction or cohesion near the tips of the fault models, named the cohesive end zone (Dugdale, 1960; Barenblatt, 1962). This modeling procedure reproduced the kink angles observed in nature (Martel, 1997; Willemse and Pollard, 1998; Davatzes and Aydin, 2003) and helped to explain the formation of a set of splays behind the fault tip which are often observed in outcrop (Cooke, 1997).

Even though the angular relationships between faults and splays have been widely studied, few investigations have dealt with the length relationships between shear fractures and their splays (Nemat-Nasser and Horii, 1982, 1984; Horii and Nemat-Nasser, 1985, 1986). These studies showed that the propagation and length of splays were influenced by the loading conditions (uniaxial/biaxial compression or tension–compression) and the magnitude of the maximum compressive stress. In particular, they demonstrated that splays could have a greater length that their parent shear fractures under favorable stress conditions. They also suggested a possible relationship between shear fracture length and splay length such that the longest shear fracture produced the longest splays in samples tested under the same loading conditions (Horii and Nemat-Nasser, 1986). However, to the best of our knowledge, no geological field data concerning the length relationships between faults and splays are available to compare with these results.

In this paper, we document the fault slip and length and the angular relationships between small faults (length < 100 m) and their splays in strike-slip fault networks exposed in the Valley of Fire State Park (SE Nevada, USA). We establish that the length of the longest splay produced by a fault is correlated to the fault length by a power law, but shows very little correlation to the fault slip magnitude. Also, we use analytical models to investigate the impact of boundary conditions on finite splay length. We identify two distinct fault configurations leading to different kink angle distributions, and use mechanical models of faults with a cohesive end zone to constrain the range of variation in the kink angles. The results obtained provide a means of estimating the maximum thickness of fault damage zones and the orientation and length of splay fractures around subsurface faults with detectable slip magnitude.

2. Geologic setting

The study area is the Valley of Fire State Park located in southeast Nevada, where the Jurassic Aztec Sandstone has spectacular exposures and forms the southwestern extremity of the Colorado Plateau Mesozoic sandstone deposits (Fig. 1). This aeolian sandstone is a fine to medium-grained quartz arenite with porosities around 25% and permeabilities up to several Darcys (Flodin et al., 2003). The Aztec Sandstone is divided into three sub-units based on rock color and related diagenetic history: the lower (red) unit, the middle (buff) unit and the upper (orange) unit (Carpenter and Carpenter, 1994; Eichhulb et al., 2004). The total thickness of the Aztec Sandstone in the study area ranges from 800 m to 1400 m. It is estimated that the Aztec Sandstone was buried at approximately 1500–2000 m at the beginning of the formation of the strike-slip faults, based on the stratigraphic column in the study area (Bohannon et al., 1993; Çakir et al., 1998).

Deformation occurred in several stages in the Valley of Fire. The first stage was an episode of compaction and shear deformation banding (Hill, 1989; Taylor et al., 1999; Myers and Aydin, 2004; Sternlof et al., 2005) associated with the Cretaceous Sevier orogeny (Bohannon, 1983). Joints overprinted the bands and, finally, a network of strike-slip faults formed during the Miocene Basin and Range extension (Myers, 1999; Fig. 1). The relative temporal relationship between normal faults accommodating extension and the predominantly strike-slip faults in Fig. 1 is controversial.

Regarding the formation of the apparent conjugate strike-slip fault patterns in Fig. 1, Flodin and Aydin (2004a) proposed that this system of left- and right- lateral strike-slip faults owes its existence to the sequential shearing of an initial joint zone, formation of splays, and subsequent shearing of the splays (Fig. 2). Flodin et al. (2005) studied the distribution of cataclastic fault rock along these strike-slip faults as a function of fault slip and measured their petrophysical properties in the laboratory. They concluded that the fault rock thickness generally increases with fault slip. Ahmadov et al. (2007) focused on the geometry and petrophysical properties of multiple slip surfaces commonly observed within the fault zones and evaluated their impact on fault permeability. They concluded that slip surfaces should be treated as partially filled planar features rather than open features. The present authors also have a separate work in progress (de Joussineau and Aydin, in press) dealing with the evolution of damage zone associated with the strike-slip faults in the same locality. Fig. 3, simplified from this manuscript, illustrates fault growth and damage zone evolution by segment linkage.

3. Methodology

Measurements were taken throughout the three units of the Aztec Sandstone of the Valley of Fire to establish a