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Using fault displacement and slip tendency to estimate stress states

Alan P. Morris*, David A. Ferrill, Ronald N. McGinnis

Department of Earth, Material, and Planetary Sciences, Southwest Research Institute®, 6220 Culebra Road, San Antonio, TX 78238, USA

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ABSTRACT

We suggest that faults in high slip tendency orientations tend to develop larger displacements than other faults. Consequently, faults that accumulate larger displacements are more likely to be reliable indicators of the longer term stress field and should be weighted accordingly in paleostress estimation. Application of a stress inversion technique that uses slip tendency analyses and fault displacements to interpret populations of coherent normal faults within the Balcones Fault System of south-central Texas provides stress estimates that are consistent with established regional stress analyses. Although the method does not require measurement of slip directions, these data, where available, and sensitivity analyses of the angular mismatch between measured slip directions and those predicted by inverted stress states provide high confidence in the stress estimates generated using slip tendency analyses. Close inspection of the fault orientation and displacement data further indicates that subpopulations of faults with orientations different from the regional pattern have formed in response to stress perturbations generated by displacement gradients on an adjacent seismic scale fault.

1. Introduction

Slip tendency (T_s) is the dimensionless ratio of maximum resolved shear stress to normal stress (τ/σ) acting on a surface and is therefore a function of the orientation of the surface of interest and the form of the stress tensor (Morris et al., 1996). Slip tendency analysis provides useful insights into the distribution of past slip on faults and fractures and the ability to predict behavior of these structures (Morris et al., 1996; Lisle and Srivastava, 2004; Streit and Hillis, 2004; Collettini and Trippetta, 2007). Analysis of slip tendency is predicated on:

(1) Calculation of the state of normal and shear stress for a fault or fracture of any orientation within a stress tensor (e.g., Ramsay, 1967; Ramsay and Lisle, 2000).
(2) The assumption that the resolved shear and normal stresses on a surface are strong predictors of both the likelihood and direction of slip (assumed to be equivalent to the direction of the maximum resolved shear stress) on that surface (Wallace, 1951; Bott, 1959; Lisle and Srivastava, 2004).

Although slip tendency is not a direct measure of slip on surfaces, it represents the potential for slip in an applied stress state. Patterns of slip tendency are sensitive to the stress ratio ($\Phi = \frac{(\sigma_2-\sigma_3)}{(\sigma_1-\sigma_3)}$; Angelier, 1975; Morris et al., 1996; Morris and Ferrill, 2009), and a technique exists that uses this property to invert stress states using slip tendency analyses without reference to slip directions (McFarland et al., 2012).

In this paper we explore the relationships among (i) fault orientations, (ii) fault displacements, and (iii) computed slip tendencies for populations of small-displacement faults in mechanically layered limestone to understand the interrelationships between these three parameters. Results of the analysis support the premise that faults that are well oriented for slip in a given stress field tend to develop larger displacements. Consequently, displacement can be considered a key parameter for fault-based stress inversion and should be weighted heavily when inferring paleo-stress conditions from fault populations.

2. Background on study area

The Balcones Fault System is a network of normal faults (Fig. 1) that forms the southern and eastern edge of the Edwards Plateau in central Texas (Cope, 1880; Hill, 1889, 1890; Foley, 1926; Weeks, 1945). The fault system cuts Cretaceous strata at the surface and is curved, generally following the subsurface trend of the Late Paleozoic Ouachita Orogen that the Cretaceous strata

* Corresponding author.
E-mail addresses: amorris@swri.org (A.P. Morris), dferrill@swri.org (D.A. Ferrill), rmcginnis@swri.org (R.N. McGinnis).

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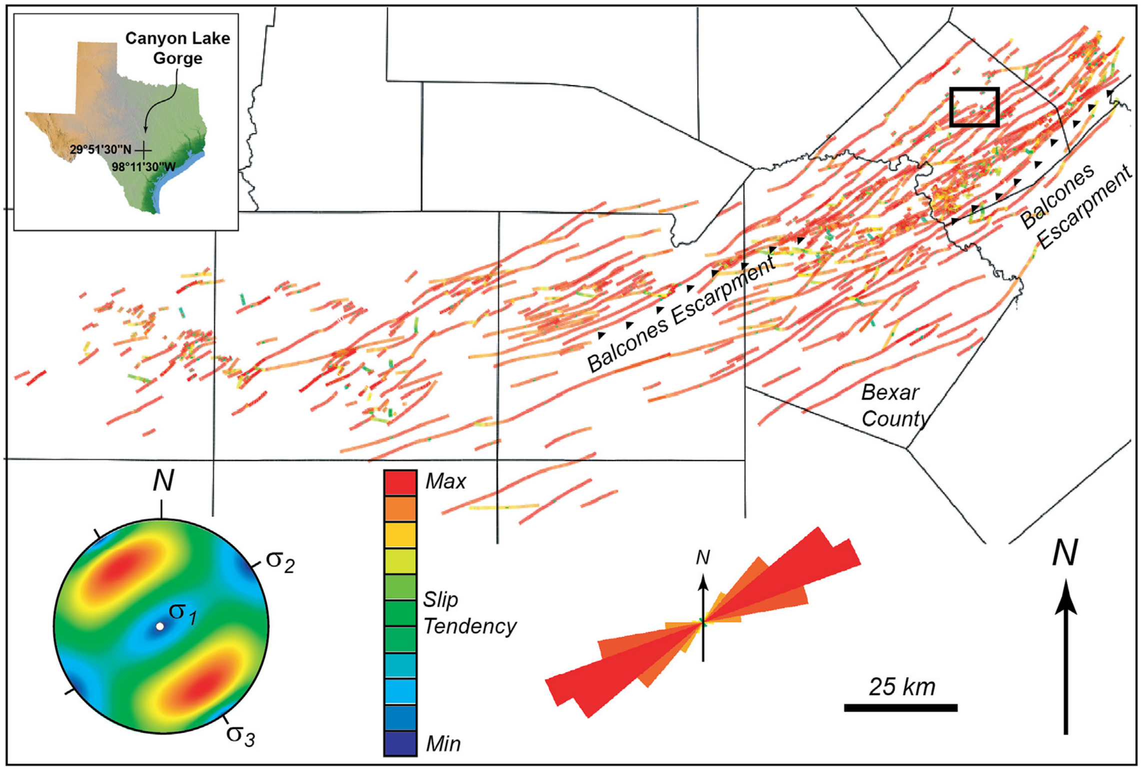

Fig. 1. Map of the Balcones Fault System in south-central Texas with fault traces colored according to their slip tendencies. Slip tendency analysis was performed using 3DStress™ v. 1.3.3 (see Ferrill et al., 2004) based on mapped faults of Collins and Hovorka (1997). Black outline represents the Canyon Lake Gorge area. Modified from Fig. 5 of Ferrill et al. (2004).

unconformably overlie (Murray, 1956, 1961; Flawn et al., 1961; Young, 1972). Although the overall Balcones Fault System makes a major bend through central Texas, faults within the system have a narrow range of strikes and are compatible with having formed in a relatively uniform normal faulting stress regime, controlled by vertical maximum principal compressive stress and horizontal minimum principal compressive stress in the direction 150° (Ferrill et al., 2004, 2012). The Hidden Valley Fault is a typical example of a normal fault within the Balcones Fault System (Ferrill et al., 2011, Fig. 1). It has a mapped trace length of approximately 45 km, with a strike of 044°–065°, a dip of 60°–80°, and a maximum normal, down to the southeast displacement of approximately 60 m. Because of the generally poor exposure in the Texas Hill Country, this trace length may not be a single, continuous, fully linked fault and may include segments linked by relay ramps. Where exposed, the fault displaces rocks of the Lower Cretaceous carbonate section (George, 1952; Abbott, 1966; Ferrill et al., 2004, 2011; Ferrill and Morris, 2008), and likely loses displacement with depth (Ferrill et al., 2011) possibly tipping before penetrating rocks of the Late Paleozoic Ouachita Orogen.

A unique exposure of part of the Hidden Valley Fault Zone was formed in July 2002 when flood waters eroded a gorge into the Glen Rose Formation through the emergency spillway of Canyon Lake (Ward and Ward, 2007; Ferrill et al., 2008, 2011; Ferrill and Morris, 2008; Lamb and Fonstad, 2010). In addition to the fault zone itself, several subhorizontal bedding-parallel pavements were exposed by erosion, and these pavements are cut by networks of small-displacement (<1 m) normal faults (Fig. 2; Ferrill et al., 2011; McGinnis et al., 2015).

The surfaces of these faults are clearly visible and are commonly decorated with slickenlines (slip direction indicators) in the form of grooves, striations, ridges and swales, or fibrous calcite. Detailed stratigraphic mapping (Ferrill et al., 2011) and close inspection of faulted strata permit precise measurements of displacement parallel to slickenlines on every exposed fault surface within Canyon Lake Gorge. Fault measurements (strike, dip, and rake using the right-hand rule, and displacement measured along the fault plane and parallel to the slip indicators) were made at 609 locations on four bedding pavements – three pavements (stratigraphic heights = 19.7, 22.8, and 23.5 m) in the footwall (329 locations) and one pavement (stratigraphic height = 86.6 m) in the hanging wall (280 locations) of the Hidden Valley fault; pavement names are taken from the stratigraphic numbering scheme outlined in Ward and Ward (2007) and Ferrill et al. (2011). Measurement locations were surveyed and recorded using a real-time kinematic global positioning system (Fig. 3A).

3. Fieldwork

3.1. Hidden Valley fault

For a distance of approximately 160 m, the Hidden Valley fault separates the footwall and hanging wall bedding pavements from which detailed fault measurements were made in this study (pavements 19.7, 22.8 and 23.5, and 86.6; see Supplemental data). At the Waterfall location (west-southwest end of traverse), total normal throw is 59.2 m with 4.02 m accommodated by bed tilting (synthetic dip), 4.28 m accommodated by synthetic faulting, and the balance (50.90 m) being carried on a narrow (<0.05 m thick) fault core (Ferrill et al., 2011). The Hidden Valley fault strike is 060° and the dip is 65° (to the south-southeast) measured from the fault core. Mapped locations from the footwall and hanging wall