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Joint spacing and distribution in deformation band shear zones

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Abstract – Tectonic joints localized within deformation band shear zones on the Kaibab uplift in Utah, USA, show the same spacing and distribution characteristics as joints controlled by primary lithological mechanical stratigraphy, despite the fact that deformation band shear zones are secondary structural features oblique to primary sedimentary layers. The spacing and distribution of joints that traverse deformation band shear zones are important factors in the permeability and connectivity of sandstone reservoirs compartmentalized by deformation band shear zones.

Keywords: joints, planar deformation features, sandstone, permeability.

1. Background

Deformation band shear zones are tectonically generated planar structures, 1 mm to several metres wide, that form as the preferred deformation mechanism in porous granular materials, particularly porous sandstones. Deformation band shear zones accommodate volume reduction and shear offset, accomplished through porosity collapse and cataclasis. As a result, the porosity of a deformation band shear zone is about an order of magnitude less than the host rock, and permeability across the zone is reduced by up to three orders of magnitude (Antonellini & Aydin, 1994). Deformation band shear zones display increased material strength and resistance to erosion, as evidenced by their 'fin-like' protrusion from hand samples and outcrops (Fig. 1). The sequential growth, microscopic characteristics and material properties of these zones have been studied by Aydin (1978), Aydin & Johnson (1978, 1983) and Mair, Main & Elphick (2000), among others.

Individual deformation band shear zones form a barrier to fluid flow perpendicular to zone boundaries, and may create preferential pathways parallel to zone boundaries (Antonellini & Aydin, 1994; Antonellini, Aydin & Pollard, 1994). To complicate matters, deformation band shear zones do not form alone; they develop as three-dimensional networks of closely spaced, intersecting planes throughout porous sandstone bodies (e.g. Ahlgren, 1999; Davis, 1999; Davis *et al*. 2000). A deformation band shear zone network creates small, isolated pockets of porous sandstone bordered by impermeable deformation band zones, effectively destroying connectivity between compartments; therefore, deformation band shear zones are an important consideration in groundwater and hydrocarbon reservoir quality (Nelson, 1985; Edwards, Becker & Howell, 1993; Knott, 1993; Antonellini, Aydin & Pollard, 1994; Antonellini & Aydin, 1994, 1995).

In some areas, however, pervasive joints traverse and are confined within deformation band shear zones. Studies by Cruikshank, Zhao & Johnson (1991*a*,*b*) and Roznovsky & Aydin (2001) address a spatial association between deformation band shear zones and joints, but do not examine joints localized within deformation bands. The significance of deformation band shear zone-confined joints has not been examined from a structural, tectonic or reservoir characterization standpoint. In fact, joints are often ignored as a factor in petroleum reservoir permeability because larger features like faults and persistent fractures provide the primary pathways for fluid flow (Gross & Eyal, 1999). In porous sandstones, however, development of deformation band shear zones is often favoured over formation of through-going faults or fractures. As a result, joints that traverse impermeable deformation band shear zones may provide the primary pathways for fluid flow in sandstones compartmentalized by these zones.

In the present study we examine the spacing and distribution characteristics of sets of joints that are confined within deformation band shear zones, and we compare these with existing models of joint spacing in mechanically layered sedimentary sequences. We also consider attitudes of joints with respect to deformation band shear zone orientation and tectonic context of the field area, the Kaibab uplift in southern Utah. We identify simple relationships between deformation band shear zone characteristics and joint attitudes and spacing, and discuss avenues for further study. The results of this research will be useful in evaluating the contribution of joints to reservoir connectivity in

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Figure 1. Fin-like expression of a deformation band shear zone in Jurassic Navajo Sandstone on the Colorado Plateau. The serrated edge of the protrusion is controlled by closely spaced joints confined within the cataclastic shear zone.

porous sandstones compartmentalized by deformation band shear zones.

2. Study area

Joint spacing and orientation data were gathered in Jurassic Navajo Sandstone near the northern end of the Kaibab uplift in southern Utah (Fig. 2). The Kaibab uplift is a Laramide-age (~ 80–50 Ma) basement-cored uplift expressed at the Earth's surface by a 30–40 km wide, generally N–S-trending anticline in Palaeozoic and Mesozoic shelf sediments, with an abrupt, E-dipping monoclinal flexure on its eastern margin. The monocline roots into a W-dipping fault in Precambrian basement that developed initially during Proterozoic tectonic events (Reches, 1978; S. Stern, unpub. M.S. thesis, Univ. North Carolina, Chapel Hill, 1992; Huntoon *et al*. 1996; T. A. Roznovsky, unpub. M.S. thesis, Stanford Univ., 1998; Tindall & Davis, 1999). The basement fault was reactivated as an oblique-reverse fault during Laramide, ENE-directed horizontal shortening (Walcott, 1890; Huntoon, 1981, 1993; Tindall & Davis, 1999). Fault-accommodated offset in basement changes progressively to fold-accommodated offset within the Palaeozoic and Mesozoic sedimentary cover, so that at the structural and stratigraphic level of Jurassic Navajo Sandstone in the study area, only small, discontinuous oblique-reverse faults have propagated through the steep limb of the monocline (Tindall & Davis, 1999; Tindall, 2000). The structural relief between anticlinal crest and synclinal trough in the study area is approximately 1600 m, accomplished in the Navajo Sandstone almost entirely by folding.

Navajo Sandstone is a porous, fine- to medium-grained, nearly pure quartz sandstone deposited as eolian dunes across the Colorado Plateau region during latest Triassic or Jurassic times. The Navajo and its equivalents (Nugget Sandstone and Aztec Sandstone) are exposed in many areas on the Colorado Plateau and in surrounding parts of the Rocky Mountain and Basin and Range provinces, and these porous sandstones have developed deformation bands in the vicinity of major regional structures (Davis, 1999). In the study area, the stripped upper surface of Navajo Sandstone is exposed

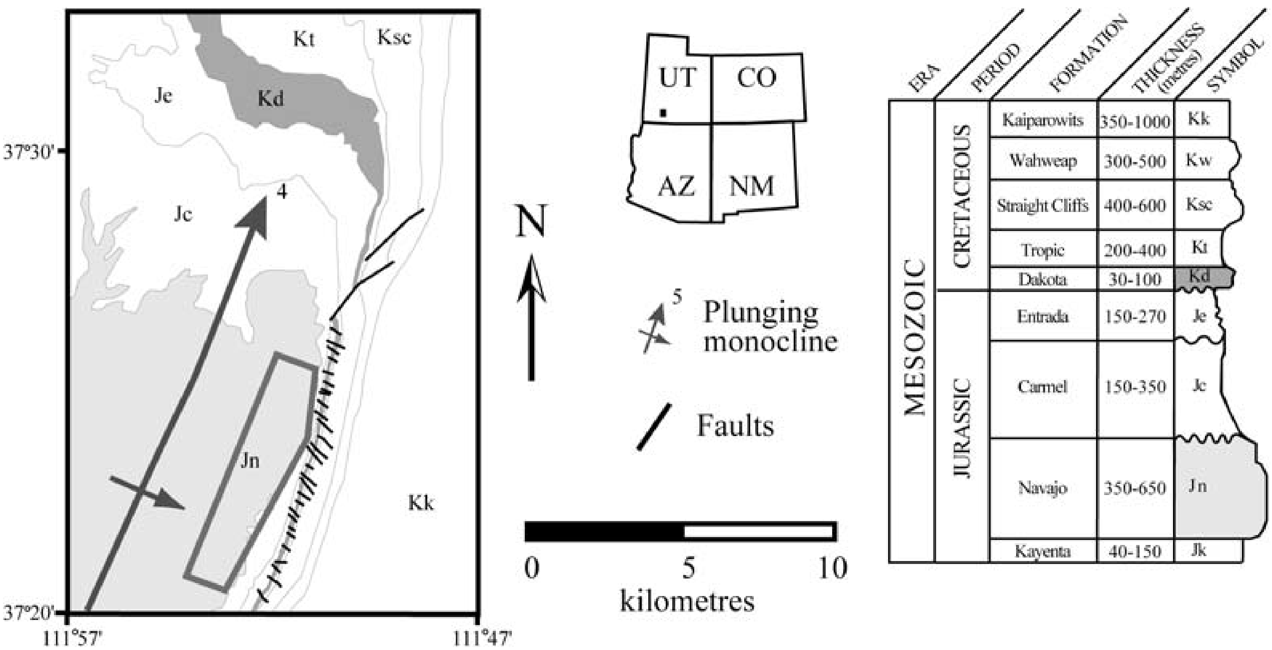

Figure 2. Location, stratigraphy and geological setting of the study area, near the northern end of the Kaibab uplift in southern Utah. Deformation band shear zone data and joint data were gathered in Navajo Sandstone near the crest and in the steep, E-dipping limb of the uplift.

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on the crest of the Kaibab uplift and in the steep, E-dipping limb of the East Kaibab monocline. The Navajo is approximately 400 m thick in the study area.

3. Data and observations

3.a. Deformation band shear zones

Deformation band shear zone orientation and joint spacing data were gathered near the crest and in the E-dipping monoclinal limb of the Kaibab uplift, where bedding strikes ~ N 20–30° E and dips 4° E to 50° E. Jointed deformation band shear zones in the study area strike northeast, dip both east and west, and represent conjugate normal faults that accommodated outer-arc stretching near the upper hinge of the East Kaibab monocline (Davis, 1999). In accordance with this interpretation, the deformation band shear zones do not extend through the entire 400 m thickness of Navajo; rather, they are localized in the uppermost part (within tens of metres of the structural surface) where outer-arc extension was greatest. Bands and zones of bands range in thickness from ~ 1 mm to ~ 1 m measured perpendicular to the plane of the shear zone, and display millimetres to several metres of shear offset. The architecture of deformation band shear zones in the study area is complex, consisting of Riedel relays, networks of antithetic and synthetic bands, and laterally thickening or thinning deformation bands; a comprehensive description can be found in Davis (1999). Figure 3 contains representative photographs of jointed deformation band shear zones.

In order to isolate the relationship between joint spacing and deformation band shear zone width, we gathered data only from deformation band shear zones with relatively planar traces, and we avoided segments of deformation band shear zones with complex, centimetre- to metre-scale Riedel shear geometry. Figure 4a is a lower-hemisphere, equal-area plot of 26 deformation band shear zones along which joint spacing and orientation were measured. The bands strike northeast and dip both northwest and southeast. The wide range of dip values reflects the original E- and W-dipping orientations of the conjugate faults and modifications of original dips as the bands progressively rotated with the steep monoclinal fold limb (Davis, 1999).

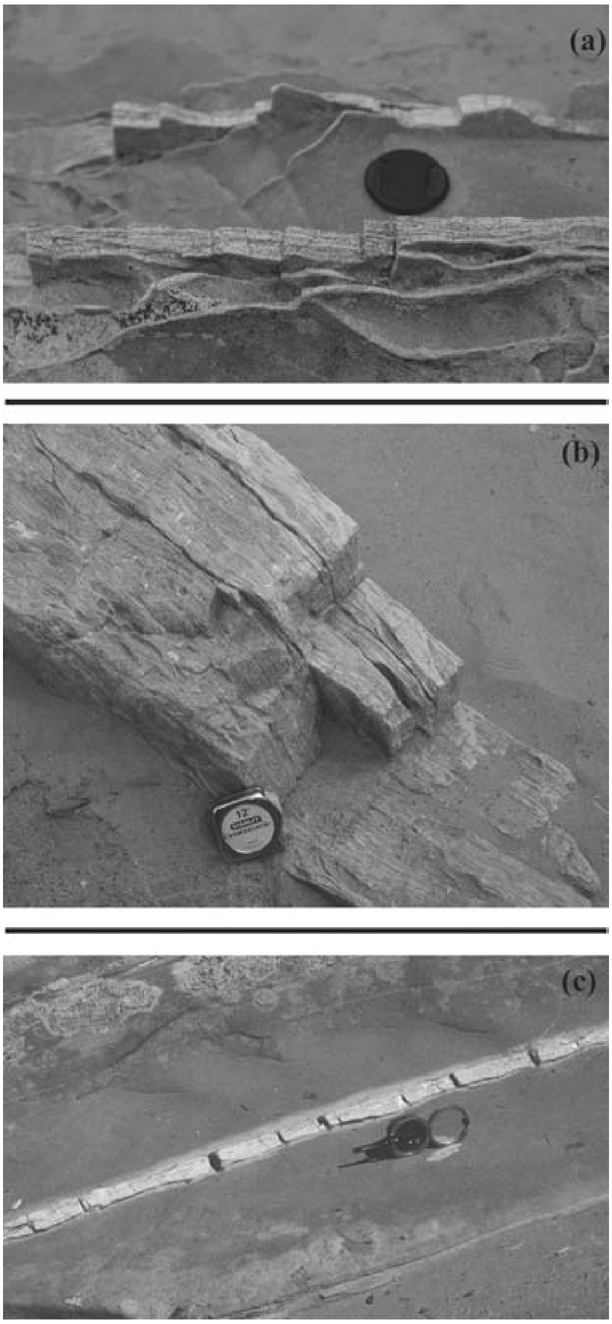

Figure 3. Joints confined within deformation band shear zones. In (a) and (b) the general relationship between joint spacing and shear zone thickness is evident. Diameter of lens cap = 5.5 cm. Tape box = 5 cm. In (c), iron-stained Navajo Sandstone displays a reduction zone on both sides of a jointed deformation band shear zone, indicating that the feature acts as a conduit rather than a barrier to fluid flow. Compass diameter = 8 cm.

3.b. Joint orientation

We measured the orientations of 427 joints within the 26 deformation band shear zones represented in Figure 4a. Joints were recognized as planar, opening-mode fractures that crossed the entire width of a deformation band shear zone and terminated at the contact between the shear zone and relatively undeformed Navajo Sandstone (Fig. 3). In the study area joints within deformation band shear zones dip steeply and strike N 45° W, perpendicular to the deformation band shear zones they occupy (Fig. 4b).

Figure 4c depicts the orientations of large joint surfaces that traverse multiple cross-bed sets within relatively undeformed Navajo Sandstone. The small number of joints plotted in Figure 4c reflects the sparse distribution of large, laterally and/or vertically

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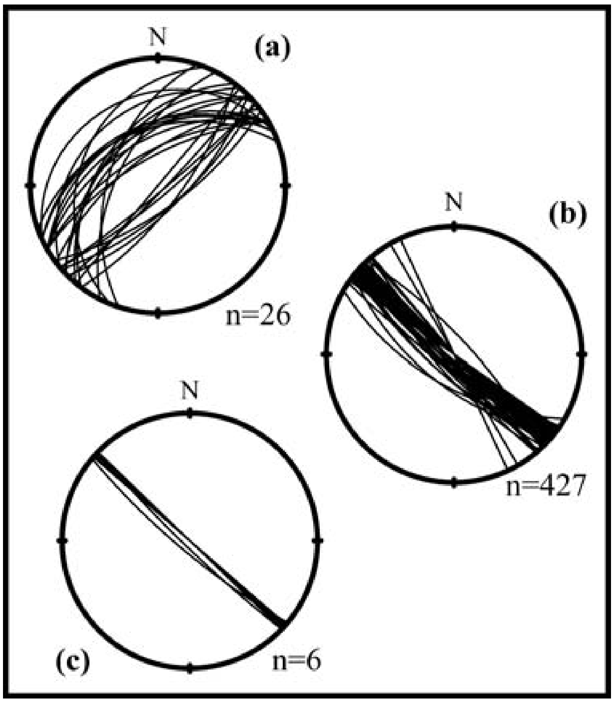

Figure 4. (a) Equal-area projection of deformation band shear zone orientations within the study area. (b) Orientations of 427 joints confined within deformation band shear zones. Joints are perpendicular to shear zone boundaries and to inferred, NE-directed post-Laramide extension. (c) Attitudes of persistent joints that traverse deformation band shear zones and multiple cross-bed sets in Navajo Sandstone.

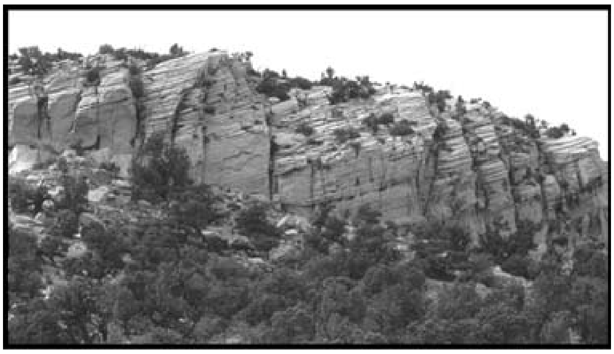

Figure 5. Photograph of persistent joints in Navajo Sandstone. Width of view is approximately 125 metres. Representative orientations are plotted in Figure 4c.

continuous joint planes in Navajo (Fig. 5). We speculate that the sparse distribution and wide spacing of large joints is proportional to mechanical layer thickness (that is, the 400 m thickness of Navajo Sandstone, or the thickness of packages of mechanically coupled cross-bed sets). By measuring joints that are laterally and vertically extensive we intended to obtain orientations of structures that developed in response to far-field tectonic stress rather than structures influenced by small mechanical boundaries or interlayer slip within the Navajo (e.g. Cooke *et al*. 2000). As shown in Figure 4c, persistent joints in Navajo Sandstone strike N 45° W and dip vertically; they are generally parallel to joints that are confined within deformation band shear zones. The similarity in orientation between joints in deformation band shear zones and those in relatively undeformed Navajo implies similar timing and a tectonic cause. Because both sets are approximately perpendicular to NE-directed Laramide horizontal shortening, we follow Kelley & Clinton (1960) in interpreting both groups of joints as a response to termination of Laramide, ENE-directed horizontal shortening of the Colorado Plateau.

3.c. Joint spacing

Figure 6 contains graphs of deformation band shear zone thickness versus joint spacing for 427 joints confined within deformation bands. Spacing was measured as the perpendicular distance between two adjacent joints that traverse a deformation band shear zone, and each spacing measurement was paired with a measurement of the shear zone thickness halfway between the two joints. Data are plotted on a linear scale in Figure 6a; as band thickness increases joint spacing tends to increase, but the relationship is difficult to distinguish because of the large cluster of data near the origin. Figure 6b presents the same data plotted on a log–log scale in order to stretch and disperse points at small values of deformation band thickness and joint spacing. On the log–log plot the linear relationship between joint spacing and deformation band shear zone width is evident, despite the wide degree of variation. The cause of variation in the relationship between joint spacing and mechanical layer thickness has been explored by Narr & Suppe (1991), who suggested that it stems from the influence of randomly distributed irregularities that nucleate joints. Imperfections (weaknesses) within or at the boundaries of a mechanical layer may cause a joint to form closer or farther from neighbouring joints than it would in an ideally homogeneous material, so that within a particular jointing layer, individual joint spacing values differ considerably from the average value (Narr & Suppe, 1991).

The relationship between joint spacing and deformation band shear zone width is clarified by considering plots of median joint spacing versus median deformation band thickness in order to remove outlying values (e.g. Narr & Suppe, 1991). Median spacing and thickness were calculated and plotted for subsets of data in which at least ten joints were measured in a single deformation band shear zone. Figure 6c presents a log–log plot of median joint spacing versus median deformation band thickness for the 16 data subsets. The linear relationship on the log–log plot is strong; the slope of the best-fit linear regression line is 0.96, with a coefficient of determination (R^2) of 0.86.

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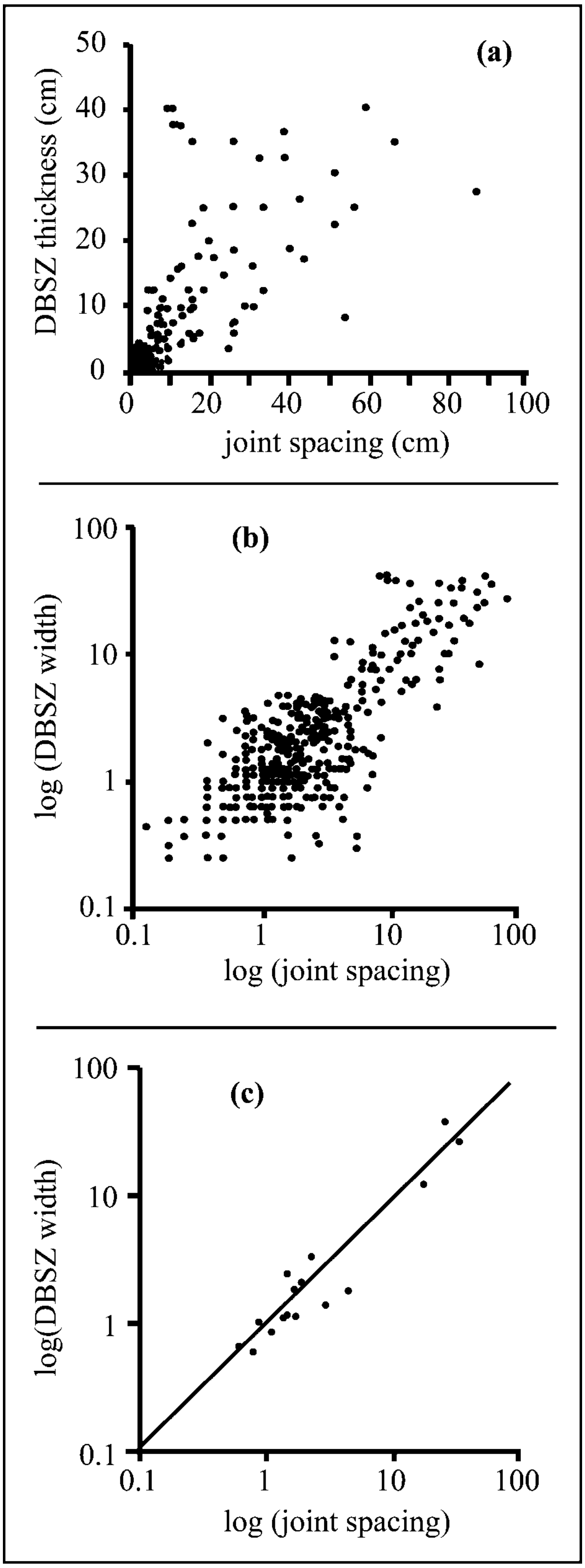

Figure 6. (a) Linear scale plot of deformation band shear zone (DBSZ) thickness versus joint spacing for 427 joints confined within deformation band shear zones. (b) Log–log plot of deformation band shear zone thickness versus joint spacing for the 427 measurements plotted in (a). (c) Log–log plot of median deformation band shear zone thickness versus median joint spacing for 16 robust subsets of spacing and thickness data.

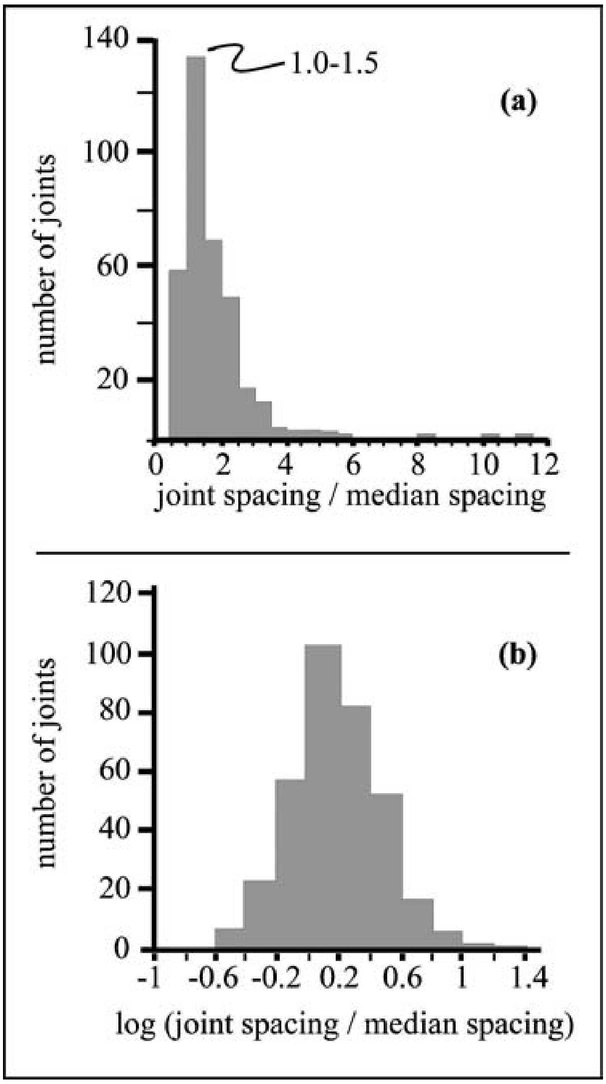

Figure 7. (a) Histogram of 350 normalized joint spacing measurements. (b) Histogram of log of 350 normalized joint spacing measurements.

3.d. Joint spacing frequency distribution

The frequency distribution of joint spacing measurements has been employed by previous authors to describe joint spacing and joint development (e.g. Bridges, 1975; Huang & Angelier, 1989; Narr & Suppe, 1991), and its significance is discussed in Section 4.b. Frequency distribution can be characterized more accurately by large data sets than by small ones, so we calculated normalized joint spacing for data subsets in which at least ten joints were measured in a single deformation band shear zone. Spacing values were normalized by dividing each joint spacing in a data subset by the median joint spacing in that subset. Figure 7 shows the frequency distribution of 350 normalized joint spacing measurements; the distribution is approximately log-normal.

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4. Discussion

A considerable volume of literature has been published on the origin, spacing and distribution of joints within layered mechanical sequences, focusing on sedimentary sequences of varying lithology, or on physical and numerical models resembling mechanically contrasting sedimentary layers. Deformation band shear zones may be described as thin, tabular layers of strong material bounded by relatively weaker sandstone layers, and in this sense they present a layered mechanical sequence. However, deformation band shear zones on the Kaibab uplift are oblique to sedimentary layering and, in many cases, oblique to other deformation band shear zones, creating a situation notably different from stratigraphically controlled mechanical layering. In this section we compare the characteristics of deformation band-confined joints on the Kaibab uplift with characteristics of joints within mechanical stratigraphy.

4.a. Joint spacing

Joints in bedded sedimentary rocks typically develop in sets of pervasive parallel surfaces, with individual joint planes terminating at mechanical boundaries within the sedimentary sequence. A general correspondence between mechanical layer thickness and joint spacing often is noted: thicker layers of a given rock type develop joints at wider intervals than do thin layers of the same lithology. Stated concisely, the median spacing of joints of a given set is a linear function of the thickness of the mechanical layer containing the joints (Bogdanov, 1947; Price, 1966; Ladeira & Price, 1981; Narr & Suppe, 1991; Huang & Angelier, 1989; Bai & Pollard, 2000).

Several authors have defined parameters to describe relationships between joint spacing and mechanical layer thickness. Ladeira & Price (1981) and Ji & Saruwatari (1998) defined the coefficient of joint spacing, K, as the slope of the regression line on a plot of median spacing versus layer thickness for joint spacing data gathered in several mechanical layers of varying thickness. Narr & Suppe (1991) and Ruf, Rust & Engelder (1998) used fracture spacing index, FSI, the slope of the regression line on a plot of thickness versus spacing. In short, FSI is the inverse of K. Yet another parameter, fracture spacing ratio or FSR, is the ratio of bed thickness to median joint spacing for data from a single bed (Gross & Eyal, 1999; Eyal *et al.* 1999). Physical experiments, numerical models, and field observations of K range from < 0.1 up to 10.

The wide variation in FSI, FSR and 1/K values can be ascribed to the fact that strength and thickness of a jointed layer are not the only parameters affecting joint spacing. It is probable that joint development depends to some extent on the thickness and rheology of mechanical layers above and below the jointing layer, the shear strength of the boundary between layers in the sequence, and the presence of irregularities that nucleate joints (Harris, Taylor & Walper, 1960; Hobbs, 1967; Ladeira & Price, 1981; Gross *et al.* 1995). Mechanical models of Hobbs (1967), Pollard & Segall (1987), Ji & Saruwatari (1998) and others explore the significance of these parameters. Most models also emphasize that the degree of deformation is an extremely important factor in joint development and spacing. Intuitively, a layer that has undergone less extension should contain fewer joints than a layer of similar thickness and strength that has accommodated more deformation. Increased strain results in a progressively increasing number of joints, and decreasing joint spacing, up to the point of joint saturation. Based on mechanical principles, Bai & Pollard (2000) proposed that mechanical sequences with typical values of Young's modulus (E) and Poisson's ratio (ν) reach joint saturation when the fracture spacing to layer thickness ratio (K) reaches a value of approximately 1 (typically ranging from 0.8 to 1.2). The linear relationship between joint spacing and layer thickness is best developed in layers that have reached the saturation point. The K value for joints confined within deformation band shear zones on the Kaibab uplift is 1.04, implying that deformation band shear zones in the field area are joint-saturated.

4.b. Joint spacing frequency distribution

The frequency distribution of joint spacing measurements in individual mechanical layers within sedimentary rock sequences is often described as a log-normal distribution (Bridges, 1975; Narr & Suppe, 1991) or a gamma distribution (Huang & Angelier, 1989). A number of studies have focused on joint spacing frequency distribution as an indication of the processes involved in joint nucleation in interlayered mechanical sequences. Narr & Suppe (1991) produced a log-normal joint spacing distribution by adding flaws to a numerical simulation of the Hobbs (1967) model of joint development. Their results indicate that deviations from the median joint spacing in a given layer may result from initiation of joints at randomly distributed irregularities within the jointed layer or along its boundaries.

The log-normal distribution of joint spacing measurements in deformation band shear zones conforms with frequency distributions observed in mechanical layers defined by stratigraphy. The similarity implies that joints in deformation band shear zones nucleate at irregularities along or within the brittle shear zones, and that the deformation band shear zones are joint-saturated. If joints indeed form in deformation bands by the same processes and physical principles as joints controlled by rheology of sedimentary layers, then existing mechanical models of joint formation can be adapted to predict joint spacing and distribution in porous sandstone reservoirs compartmentalized by deformation band shear zones.

4.c. The orientation coincidence

Joints confined within deformation band shear zones in the Kaibab study area appear to develop through processes comparable to those controlling joints in primary mechanical stratigraphy, despite the fact that the deformation band zones are not parallel to bedding or to cross-bedding in the study area. The angular relationships between deformation band shear zones and bedding, and in fact between different sets of deformation band shear zones, should present an opportunity to study systematic changes in deformation band shear zone-confined joint orientation and spacing as the orientation and spacing of the shear zones themselves vary. We note, however, that the strike of deformation band shear zones in the study area nearly parallels the ENE direction of post-Laramide extension or relaxation. Although the sets of deformation band shear zones are oblique to bedding, their strike orientations permit development of joints that are perpendicular both to the regional extension direction and to deformation band shear zone boundaries. It is therefore possible that the attitude, spacing, and the mere presence of joints within deformation band shear zones depend upon favourable deformation band shear zone orientation with respect to far-field extension directions. Because deformation band shear zones at the northern end of the Kaibab uplift strike northeast, we are unable to determine whether the orientation and spacing of deformation band-confined joints vary as deformation band orientation varies, or as the angle between the deformation band shear zones and the later extension direction, responsible for jointing, changes. The relationships between deformation band shear zone attitude, local or regional tectonic history, and resulting joint orientation, spacing, and distribution will be examined by including additional study locations.

5. Remaining questions

The presence of joints within deformation band shear zones offers the opportunity to identify systematic changes in joint orientation and spacing as the angular relationship between deformation band shear zones (stiff mechanical layers) and extension direction (causing joint development) varies. The development of intersecting sets of deformation bands in many areas also suggests a chance to quantify variations in joint spacing and distribution in relation to changes in thickness of jointing and bounding mechanical layers (that is, deformation bands and surrounding undeformed sandstone). The effect of layer thickness has been difficult to quantify through field studies of layered sedimentary sequences because individual strata are parallel and tend to maintain constant thickness over great distances. Deformation band shear zones frequently form in multiple sets with different orientations, so that they converge, cross and diverge in outcrop and in three dimensions. As a result, lenses of undeformed sandstone, the effective 'bounding layers', change thickness systematically. Furthermore, the thickness of an individual deformation band shear zone can change across a distance of several metres, allowing investigation of the effect of jointing layer thickness without relying on data from different layers. Additional studies of deformation band shear zones and associated joints in a variety of structural and tectonic settings will contribute to improvement of existing mechanical models of general joint development.

6. Summary

Our analysis shows that the spacing of joints within deformation band shear zones is proportional to band thickness, and that joint spacing distribution within bands is log-normal. The spacing and distribution are similar to observations of joint spacing in mechanical sequences of sedimentary beds of varying lithology that have undergone layer-parallel extension. We conclude that, when subjected to layer-parallel extension, deformation band shear zones behave as stiff mechanical layers bounded by relatively weaker porous sandstone, even when the shear zones are not parallel to primary (sedimentary) mechanical layering. Joints within and across deformation band shear zones may be a significant factor in permeability and connectivity of groundwater or hydrocarbon reservoirs in porous sandstones, causing deformation band shear zones to behave as conduits rather than as barriers to fluid flow. Future study will focus on (1) joint development in deformation band shear zones that are moderately to highly oblique to the regional extension responsible for joint development, (2) quantifying the effects of deformation band-confined joints on reservoir permeability and connectivity, and (3) improving existing mechanical models of joint development.

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