



Conjugate Riedel deformation band shear zones

George H. Davis, Alexander P. Bump, Pilar E. García, Stephen G. Ahlgren

The Department of Geosciences, The University of Arizona, Tucson, Arizona 85721, USA

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Abstract

Our investigations have disclosed that individual Riedel shear zones may organize themselves into broadly distributed though rigorously oriented intraformational *conjugate* systems which may form without relationship to, or dependence upon, an underlying basement fault zone. The Riedel shear zones we mapped are zones of deformation bands, which developed as the preferred deformation mechanism in porous Navajo Sandstone (Jurassic). In the Cottonwood area, located at the northern end of the Kaibab Uplift, a conjugate normal Riedel deformation band shear system developed during the Laramide in the uppermost Navajo Sandstone on the outer arc of the upper hinge zone of the East Kaibab monocline. In the Sheets Gulch area, located at the northern end of the Waterpocket Fold, a conjugate strike-slip Riedel deformation band shear system developed during the Laramide in upper Navajo Sandstone within an imperfect transfer zone between the northeast-vergent Circle Cliffs Uplift and the southwest-vergent Miners Mountain Uplift. Within both the Cottonwood and Sheets Gulch areas there are tens to hundreds of Riedel shear zones, the largest of which are up to hundreds of meters in trace length.

In classic Riedel fashion, the synthetic R-shears within each Riedel shear zone depart by $\sim 15^\circ$ from the zone as a whole and are arranged in an en échelon, overstepping geometry. The antithetic R'-shears depart by $\sim 75^\circ$ from the Riedel shear zones of which they are a part, and are especially abundant in transfer zones where they create hard linkages between overstepping R-shears. At both localities the Riedel shear zones occur in two sets that intersect at $\sim 60^\circ$. The Riedel shear geometry is self-similar from the scale of hand samples (and thin sections) where offsets are measured in centimeters (or millimeters), to the map scale where displacements are measured in meters. Because of the small amount of deformation which had to be accommodated in each of the two study areas, and the limits imposed by the strain-hardening nature of deformation banding, we may be seeing a rare snapshot that records an image of early, arrested fault-system development in relatively homogeneous, porous sandstone.

The literature on classic Riedel shear zones postulates that displacement and shear along Riedel shears brings about a localized reorientation of stress. This interpretation can be tested and confirmed, using the geometry and kinematics of conjugate Riedel systems. Detailed understanding of the total nested geometric characteristics of the conjugate Riedel deformation band shear zone systems also provides insight regarding controls on reservoir-scale fluid flow. The low permeability of the deformation band shear zones tends to compartmentalize the Navajo Sandstone into chambers along which fluid flow is channeled. The geometry and spacing of the deformation band patterns controls shapes and sizes of the compartments, which in these examples tend to be long, polyhedral, porous chambers marked by either diamond- or rhombic-shaped cross-sections. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Riedel shear zones are typically interpreted in relation to deformation in cover rocks above a single discrete strike-slip fault zone. The properties of Riedel shearing were first observed and documented by Cloos

(1928) and Riedel (1929) in clay-cake deformation experiments featuring an underlying 'basement' block cut longitudinally by a single principal displacement zone (PDZ), which is forced to accommodate strike-slip movement. Two adjoining boards overlain by a moist clay cake simulated sedimentary cover over a basement fault, i.e. the PDZ. A quasi-tabular, vertical Riedel shear zone forms directly above the master fault in the overlying clay cake 'cover', into which the strike-slip

E-mail address: geodavis@geo.arizona.edu (G.H. Davis).

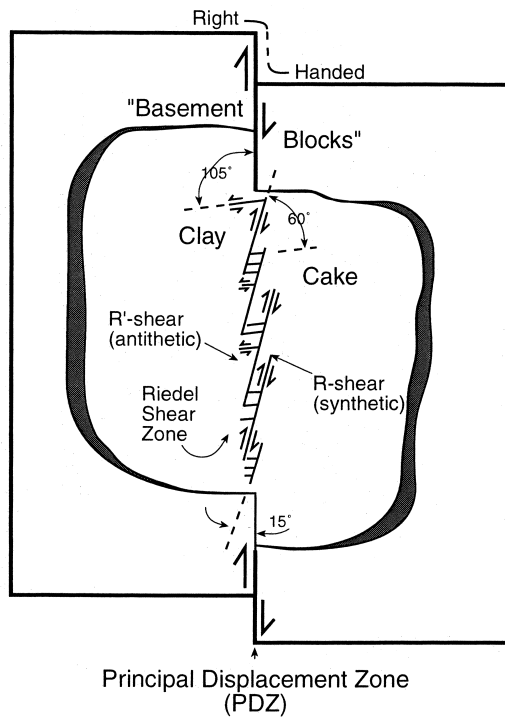


Fig. 1. Birds-eye view of a Riedel shear zone formed in a clay cake lying atop a rigid basement cut by a principal displacement zone (PDZ). Right-handed slip along the PDZ imposes a shear strain upon the overlying clay-cake cover, which deforms through Riedel shearing. Two integral elements of a Riedel shear zone are R-shears and R'-shears, the former a synthetic shear, the latter an antithetic shear. See text for description of angular relationships.

shear strain is imposed. It was in this zone that the Riedel shearing was noted (Fig. 1).

More recently, strike-slip clay-cake deformation experiments by Tchalenko (1970) and Wilcox et al. (1973) have demonstrated that Riedel shear zones evolve as a sequence of linked displacement surfaces. The complete pattern may consist of as many as five elements (Fig. 2). One of the chief characteristics of a Riedel shear system is an overstepping, en échelon array of synthetic shears (called 'R-shears') oriented $\sim +15^\circ$ (i.e. 15° clockwise) from the trace of right-handed strike-slip shear zones (see Fig. 2), or $\sim -15^\circ$ (i.e. 15° counterclockwise) to the trace of left-handed strike-slip shear zones. Across transfer zones these may be connected by an en échelon array of antithetic shears (called 'R'-shears') which strike at $\sim +75^\circ$ to the trace of right-handed strike-slip shear zones (see Fig. 2), or $\sim -75^\circ$ to the trace of left-handed strike-slip shear zones. Progressive development of Riedel systems may result in the formation of a second en échelon array of synthetic shears (called 'P-shears') which strike $\sim -15^\circ$ to the trace of right-handed strike-slip shear zones (see Fig. 2), or $\sim +15^\circ$ to the trace of left-handed strike-slip shear zones (see Fig. 2). Furthermore, some shears may form roughly parallel to the trace of the shear zone, and these are termed 'Y-shears' (Woodcock and Schubert, 1994). Finally, an array of extensional, mode I fractures (called 'T-fractures') may form at $\sim +45^\circ$ to the trace of right-handed shears, or $\sim -45^\circ$ to the trace of left-handed shears (see Fig. 2). The geologic literature now contains abundant descriptions of field examples of Riedel

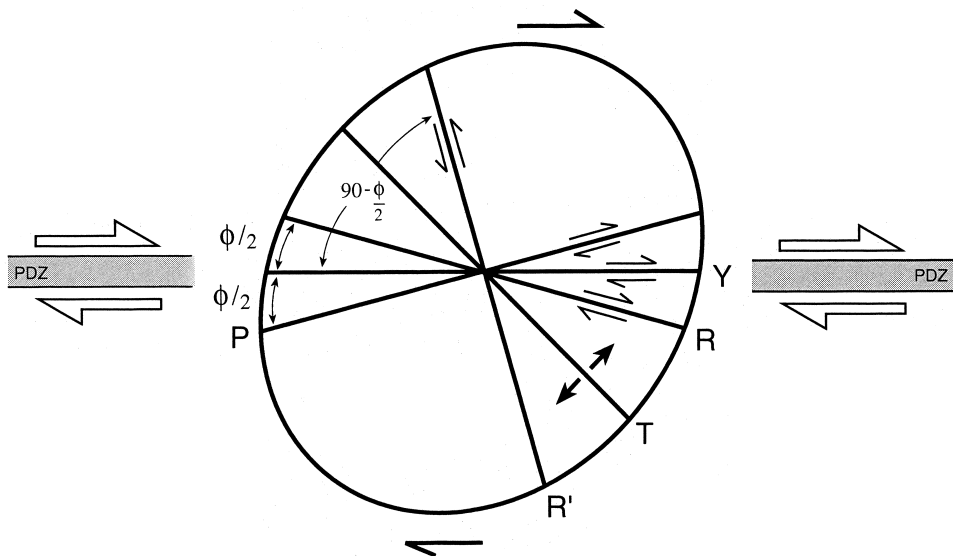


Fig. 2. Drawing of the common elements within a Riedel shear system, though not all will be present in any given zone. The presence of R-shears is the only mandatory requirement for a shear zone to be considered to be a Riedel shear zone, and R'-shears are almost always present. In this example, the angle of internal friction (ϕ) is 30° . For right-handed Riedel shear zones, a P-shear (which is synthetic in sense-of-shear) makes an angle of -15° to the principal displacement zone (PDZ). A Y-shear (also synthetic) forms parallel to the trace of the PDZ. T-fractures (tension fractures) would form at $+45^\circ$ to a right-handed PDZ. After Bartlett et al. (1981) and Woodcock and Schubert (1994).

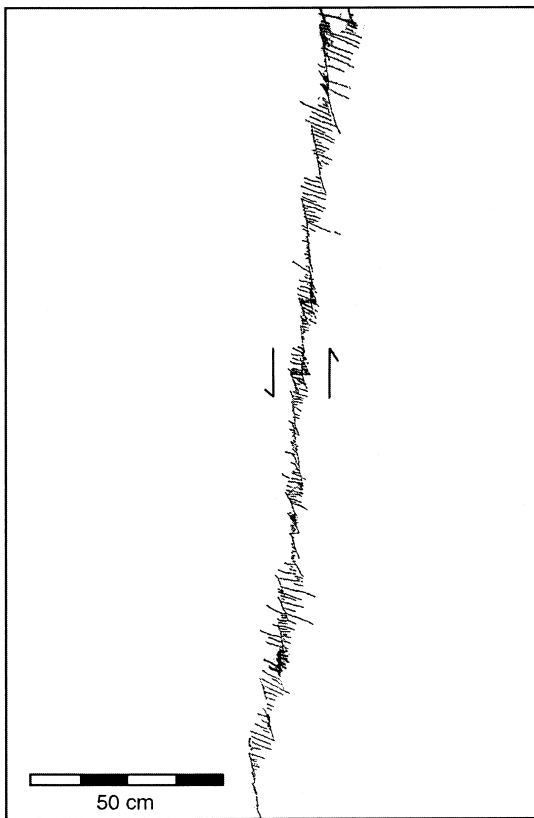


Fig. 3. Riedel shear zone in the Sheets Gulch area. The Riedel pattern shown is an accurate tracing of ~16 photographs, each of which was taken downward to the outcrop from waist-level. The composite drawing was scanned and then rendered by computer into a perspective view. The left-handed sense-of-shear for the zone as a whole was determined from offsets of cross-bedding. Note the R-shears oriented at $\sim -15^\circ$ to the principal shear zone (PSZ). The R'-shears are mainly developed where the R-shear overstep one another.

shear zones (e.g. Tchalenko and Ambraseys, 1970; Schandelmeier and Richter, 1991; Cunningham, 1993; Arboleya and Engelder, 1995). Most are descriptions of single, discrete, *strike-slip* Riedel shear zones which are interpreted to be linked at depth to a master fault zone that was responsible for the formation of the Riedel shear zone in cover rocks.

While carrying out a regional structural analysis of deformation band shear zones in southern Utah, Davis (1994, 1996) discovered well-developed outcrop- and map-scale Riedel shear zones in outcrops of Navajo Sandstone (Jurassic). These Riedel shear zones (Fig. 3) are marked by classic R-shears and R'-shears. Some of the best examples were found to occur in two areas associated with Laramide Colorado Plateau uplifts: the Cottonwood area on the north end of the Kaibab Uplift (Fig. 4A), and the Sheets Gulch area at a transfer zone between the Circle Cliffs and Miners Mountain Uplifts (Fig. 4B). Reconnaissance examination of the structures at each of these two localities revealed that the outcrop-scale Riedel shear zones

occurred in more than one set. Thus detailed structural geologic mapping was initiated to better understand the nature, cause, and significance of this deformation.

2. Background: deformation band shear zones

Most Riedel shear zones described in the literature are composed of fault and fracture elements marked by the standard physical properties of *brittle* shear zones, e.g. slickenlined, slickensided surfaces; abundant fracturing; and gouge and/or breccia. However, the outcrop-scale Riedel shear zones that are so extensively developed at Cottonwood and Sheets Gulch are expressed physically as *deformation bands* and *zones of deformation bands* (Aydin, 1978; Aydin and Johnson, 1978, 1983; Jamison, 1979; Jamison and Stearns, 1982). Deformation bands of tectonic origin form in highly porous sandstones ($\sim 15\text{--}25\%$ porosity), such as the Navajo Sandstone. They are fault-like features in that they accommodate shear displacement and thus cause offset of markers, such as cross-bedding. However, the physical properties of deformation bands are generally *not* fault-like, for the mechanism is not one of stick-slip deformation (Byerlee and Brace, 1968). Instead, the shear is accomplished through a mechanism that involves stress-induced collapse of porosity, grain-scale fracturing, grain-size reduction, and cataclastic flow (Aydin, 1978; Aydin and Johnson, 1978; Antonellini et al., 1994a,b), without development of a discrete fracture surface. The volume loss is so radical that at the site of a zone of deformation bands a host rock porosity of $>20\%$ may be reduced to $<1\%$ (Antonellini and Aydin, 1995). Deformation bands, therefore, do not look like faults. Instead, they are very thin (mm-scale) to thick (cm- to m-scale) shear zones that resemble quartz veins or quartz lodes, which are resistant to weathering and erosion (Fig. 5A), commonly projecting as blades or fins from outcrops or the landscape (Fig. 5B). Where deformation bands are large and pervasive, the physiographic expression may take the form of a 'fault-fin landscape' (Davis, 1998), especially at locations where there has been adequate time for differential weathering and erosion of Navajo Sandstone to reveal that contrasts between relatively weak porous sandstone host rock and strongly resistant deformation band shear zones.

Aydin (1978) and Aydin and Johnson (1978, 1983) concluded that individual deformation bands of tectonic origin most commonly form as a result of a transpressional shearing involving the shear-induced collapse of pore spaces; translation and rotation of quartz grains into direct contact; grain-contact stress build-up that causes grain-scale microfracturing; and grain-size reduction through continued shear-induced cataclastic flow. After just a few millimeters of shear,

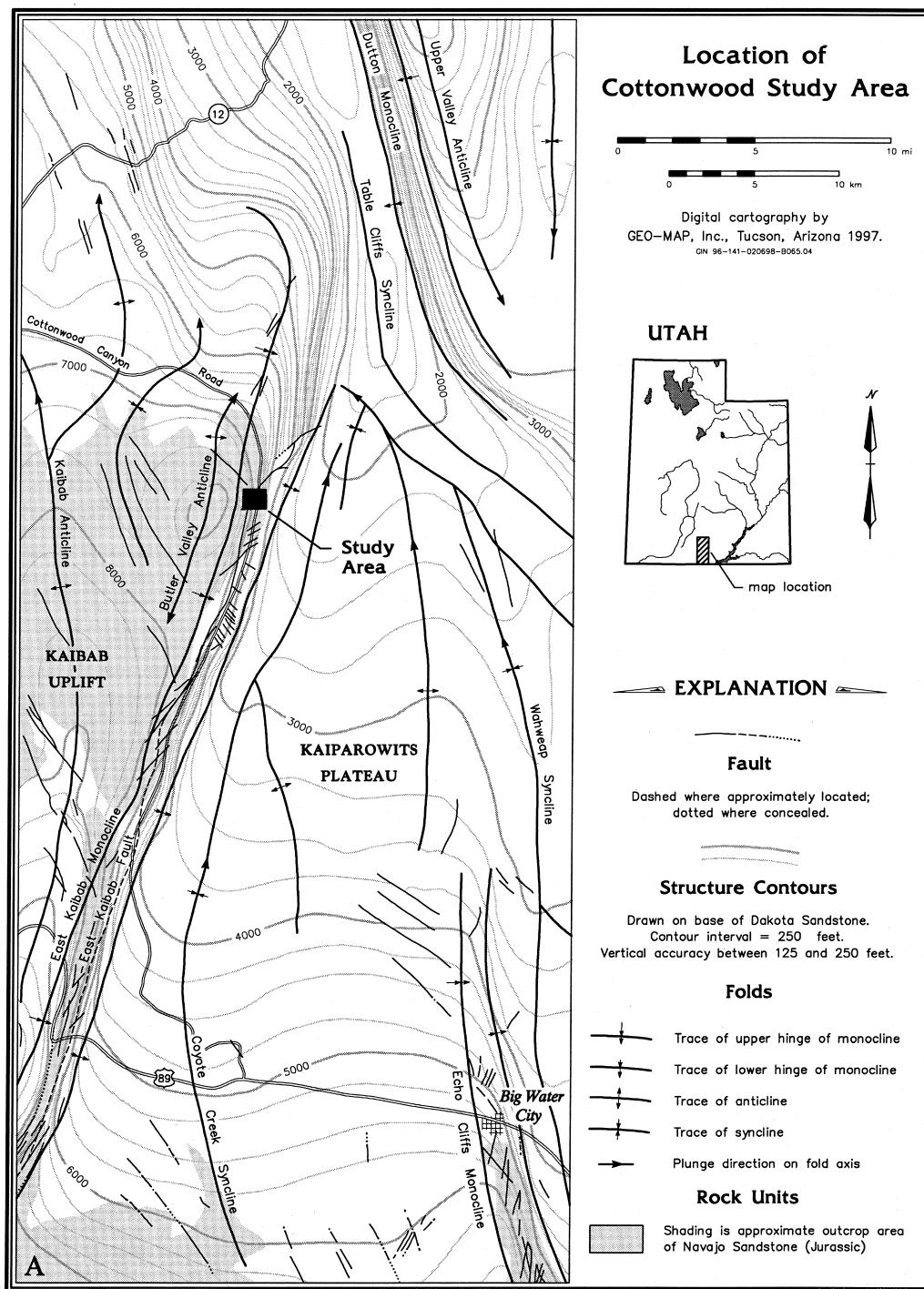


Fig. 4. (A) Structure-contour map showing the location of the Cottonwood study area in relation to the East Kaibab monocline and other structures at the north end of the Kaibab uplift. To the east of the East Kaibab monocline is the Kaiparowits Plateau, the western part of which is shown. (B) Structure-contour map showing the location of the Sheets Gulch area in relation to the Waterpocket Fold, the Circle Cliffs uplift, and the Miners Mountain uplift.

internal friction builds to the point that the deformation band 'locks up'. If the conditions required for failure by this mechanism persist, a new deformation band will begin to form immediately adjacent to the first. In this way, zones of deformation bands form,

and they may accrue to thicknesses of centimeters or meters. Zones of deformation bands of cm- or m-thickness are commonly slickensided and slickenlined on their outer margins (Fig. 6), revealing that a stage may be reached where wholesale faulting can take

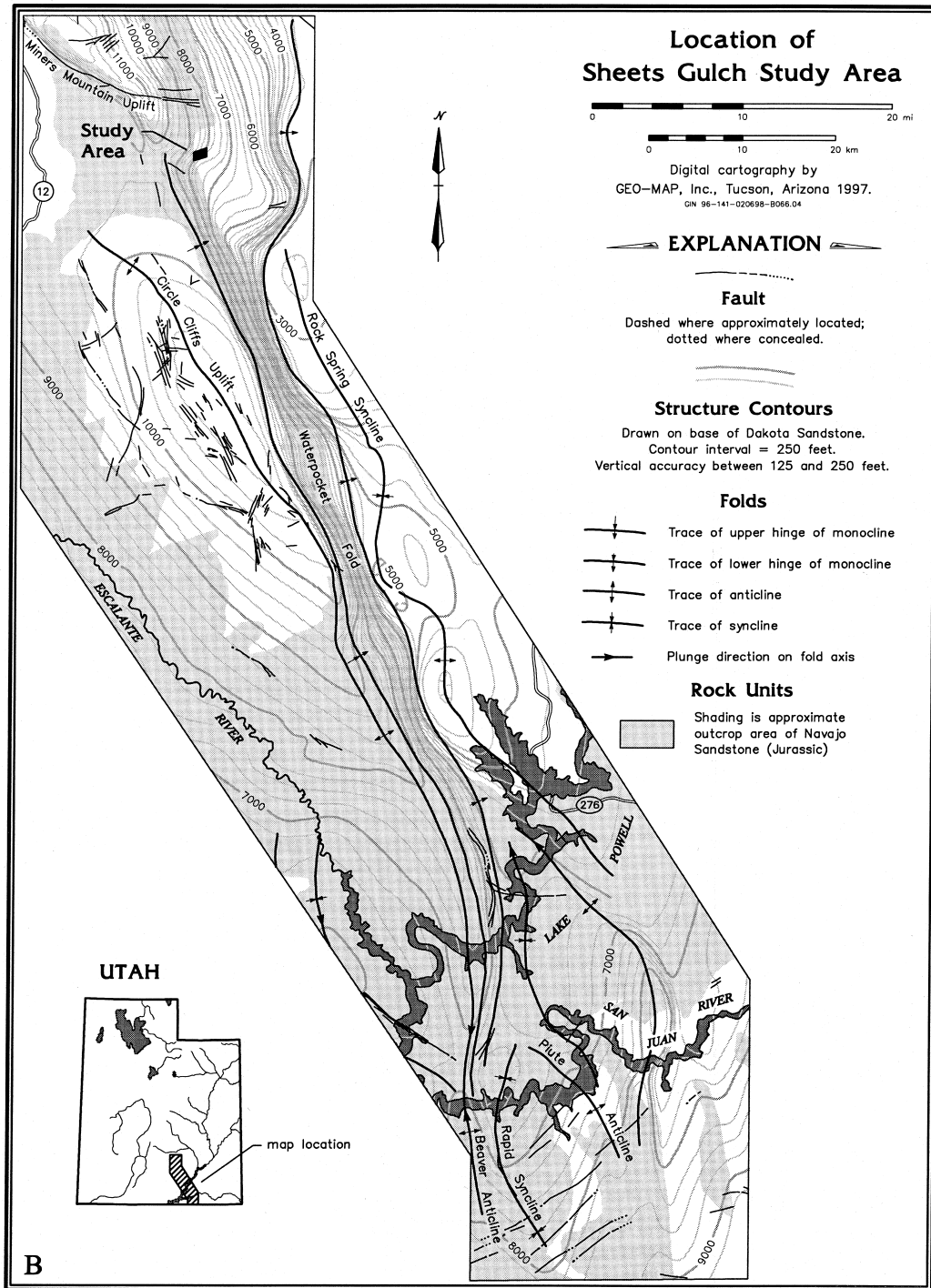
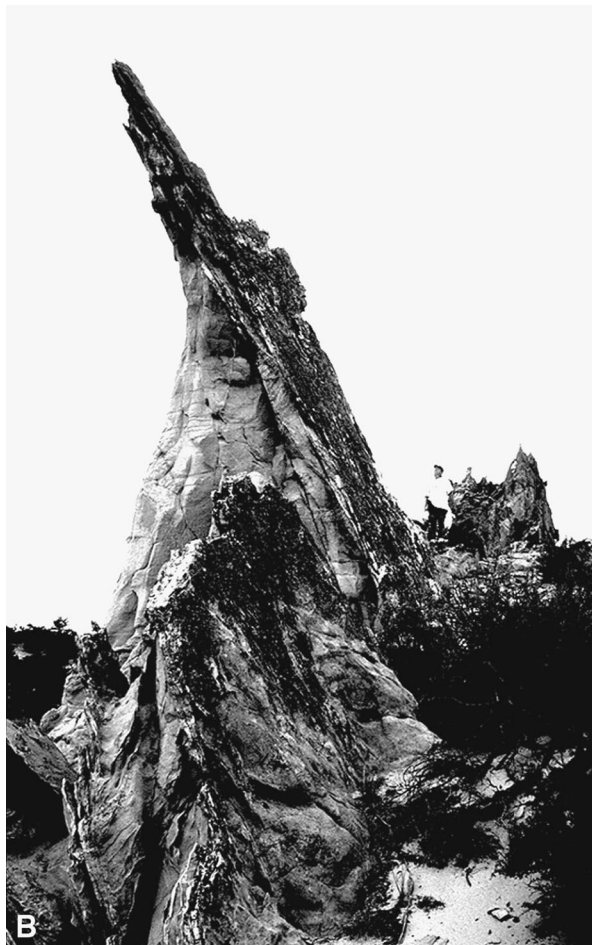
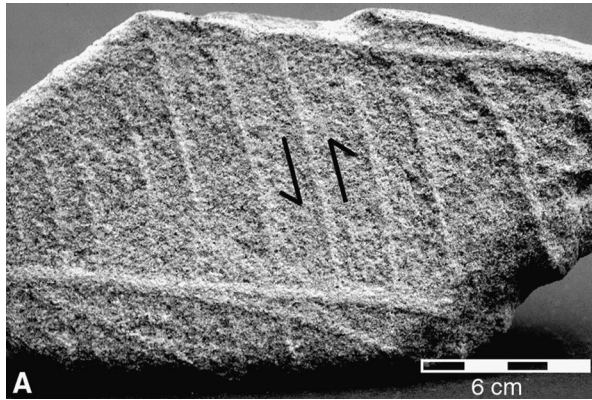


Fig. 4 (continued)

place (Aydin, 1978; Aydin and Johnson, 1978). The overprinting of faulting on deformation banding reflects a change in deformation mechanism, insight for which can be found in Byerlee and Brace (1968). They have shown that highly porous rocks, such as certain tuffs and sandstones, are incapable of deform-

ing by stick-slip behavior. Byerlee and Brace (1968) regard these as 'type 2' rocks, to be distinguished from 'type 1' rocks such as limestones, well cemented sandstone, granites, etc., which deform by stick-slip behavior. In our studies, we see that the development of zones of deformation bands in highly porous Navajo



Sandstone (a 'type 2' rock) can transform the sandstone locally, within the zones of deformation bands, into a 'type 1' rock fully capable of stick-slip behavior. Hence, deformation banding prepares the way for faulting and frictional sliding to take place in such rocks. Thus polished, slickenlined surfaces commonly mark the outer margins of zones of deformation band shear zones.

The literature reveals that there are other varieties of deformation bands and deformation band mechanisms than those described above (e.g. see Antonellini et al., 1994a; Davis, 1999). Some deformation bands may form during primary deposition, compaction, and gravitational loading of aeolian sands through mechanisms dominated by granular flow and the development of conjugate normal shear zones lacking signs of cataclastic flow and tectonic deformation (Davis, 1999). Some deformation bands are analogous to cleavage, forming perpendicular to the direction of greatest contraction and reflecting volume loss but no shear (Mollema and Antonellini, 1996). Some deformation bands are preserved at an early stage of their development, recording an initial positive dilatation which normally is reversed by eventual porosity collapse, grain-scale fracturing, grain-size reduction, and cataclastic flow (Antonellini et al., 1992). Notwithstanding the several types of deformation bands, each with its own nuance of interpretation, we believe that the original descriptions and interpretations of the tectonic variety of deformation bands described by Aydin (1978) and Aydin and Johnson (1978) apply to the systems of deformation band shear zones in the Cottonwood and Sheets Gulch areas.

Fig. 5. (A) Photograph of hand sample of deformation bands in Navajo Sandstone, Sheets Gulch area. The steeply inclined deformation bands are R'-shears which are transferring displacement from one R-shear to another. One R-shear in this photograph is the thicker deformation band that 'caps' the top of the specimen. A second R-shear is nearly horizontal as well, and occurs near the base of this specimen. Sense-of-shear is right-handed. (B) South-directed photograph of outcrop expression of thick zone of deformation bands in Navajo Sandstone, Cottonwood area. Geologist for scale at right base. The deformation band shear zone dips to the right (west). Its resistance is due to the lack of porosity, grain crushing, and silica precipitation. Its thickness is of the order-of-magnitude of the uppermost projection of the fin. Note that host Navajo Sandstone can be seen in the footwall of the zone of deformation bands (light colored and cross-lamination evident). The dark-weathering appearance of the deformation band is due to manganese staining. Reproduced from Davis (1999) with permission from the Geological Society of America.

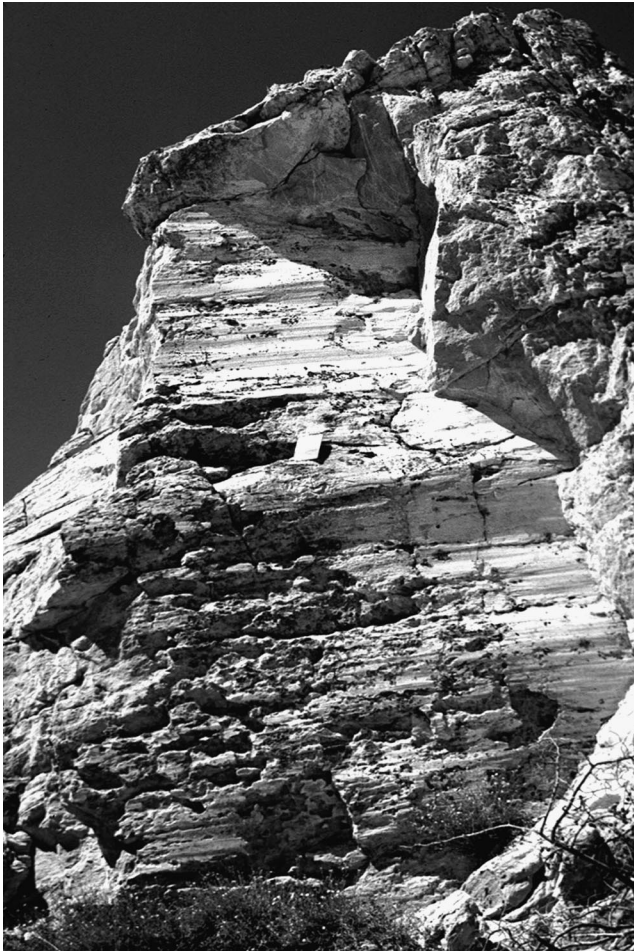


Fig. 6. Photograph of slickenlines, grooves, and high polish along the margin of a strike-slip deformation band shear zone in the Sheets Gulch area. Notebook for scale may be seen halfway up the polished face (light-colored, rectangular). Reproduced from Davis (1999) with permission from the Geological Society of America.

3. The shear zones at Cottonwood

3.1. Structural description of the patterns

In the Cottonwood area at the northern end of the Kaibab Uplift (see Fig. 4A), the upper hinge region of the East Kaibab monocline is marked by an extremely well-developed system of map-scale deformation band shear zones in the Navajo Sandstone, which we refer to as principal shear zones (PSZs). Using 1:600 scale aerial photographs and identically scaled topographic maps with 3-m contours, we mapped nearly all of the PSZs within the 1000 m × 900 m Cottonwood study area (Fig. 7). The PSZs were found to range up to hundreds of meters in length, striking consistently ~N50°E, and dipping moderately steeply both northwest and southeast throughout most of the area. The spacing of the traces of the major PSZs was found to be quite regular, ranging from ~5 to ~25 m. In the easternmost part of the area, the average strike of the

PSZs bends from a N50°E trend to a N25°E trend (see Fig. 7), as a result of rotation by folding along the N20°E-trending, east-southeast-verging East Kaibab monocline. This rotation causes a change in dip orientation of the shear zones as well, such that the northwest-dipping PSZs assume shallower dips, and the southeast-dipping PSZs assume steeper dips.

During mapping we recognized that each PSZ is itself the expression of a linked set of overstepping deformation band shear zones, which we interpret to be R-shears (Fig. 7) (Davis, 1996). The orientations of the R-shears are *not* strictly parallel to the orientations of the PSZs of which they are a part. The R-shears are expressed in the form of relatively thin (3–50 cm), massive, continuous deformation band shear zones. They commonly resemble quartzite layers of either uniform thickness or uniformly changing thickness (Fig. 8). Offsets (i.e. separations) along almost all of the R-shears in the area are normal, except along the easternmost margin of the map area, where steeply west-dipping R-shears may show reverse offset.

Outer surfaces of many of the R-shears are commonly polished and slickenlined. The ~70–85°S rake of the slickenlines discloses that the movement accommodated by the R-shears is mainly dip-slip, but with a modest, consistent strike-slip component. Where mapped in detail, the R-shears are found to be oriented slightly oblique to the overall attitude of the PSZs. This is evident in the structure maps (see Fig. 7), and is represented schematically in Fig. 9. For a northwest-dipping R-shear of dominantly normal displacement, the strike-slip component is left-handed. Yet, for a southeast-dipping R-shear of dominantly normal displacement, the strike-slip component is right-handed. The strike directions for the northwest-dipping vs. southeast-dipping R-shears are not the same at a given location, nor are they parallel to the strike of the PSZ of which they are a part. The northwest-dipping R-shears are left-handed normal and right-stepping, and the southeast-dipping R-shears are right-handed normal and left-stepping (see Fig. 9).

Transfer zones occur where the R-shears overstep one another, and they are marked by well-developed sets of antithetic deformation band shear zones which we interpret as R'-shears (Fig. 10). These are oriented at a relatively high angle with respect to the R-shears which they connect. Seen in a cross-sectional view, almost every transfer zone is bounded by well-defined R-shears, and each is typically expressed by a winnowed, weathered 'boxwork' composed of two sets of deformation band shear zones, one an R-shear set, the other an R'-shear set (see Fig. 11). The R'-shears typically make angles of ~50–80° to the R-shears and have the opposite sense of shear. Slickenlines on the R-shears are oriented perpendicular to the intersection of the R-shear and R'-shear deformation band shear

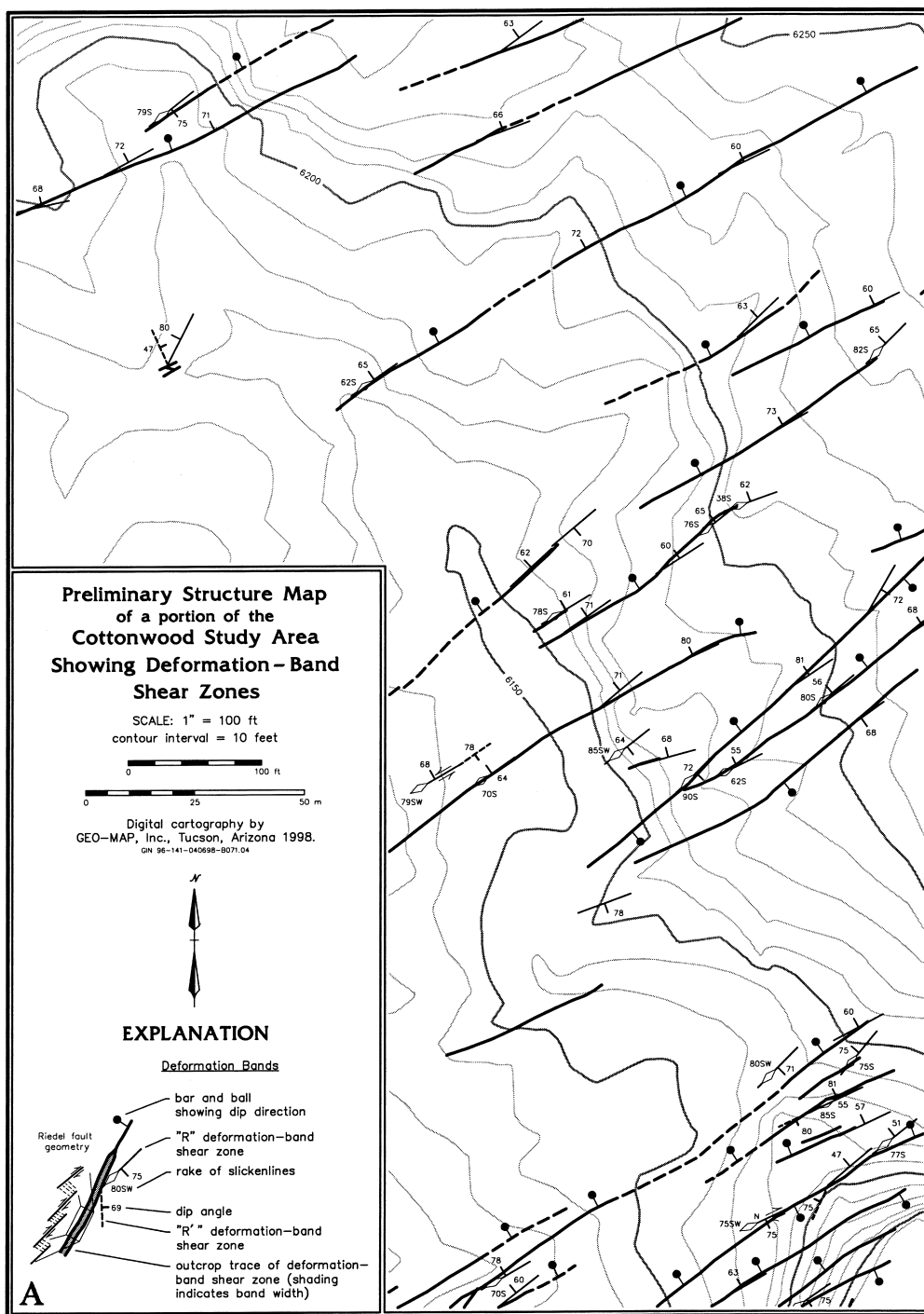


Fig. 7. Structure map of a representative part of the system of deformation bands in the the Cottonwood area showing details of PSZs in terms of R shears, R' shears, and slickenlines. (A) western half, (B) eastern half of map area. Reproduced from Davis (1999) with permission from the Geological Society of America.

zones. Sense of offset for a given PSZ, which is a linked array of R-shears, is disclosed by the polarity of the acute angle between the R- and R'-shears.

The PSZs in the Cottonwood study area, therefore, are normal-slip *Riedel* shear zones (RSZs). They comprise two sets, which together constitute an extensional

conjugate system (see Fig. 9). Each northwest-dipping RSZ is the locus of synthetic northwest-dipping R-shears which dip more steeply (by $\sim 15^\circ$) than the RSZ. Because there is a slight left-handed strike-slip component of offset along the northwest-dipping RSZs in the Cottonwood area, each northwest-dipping R-

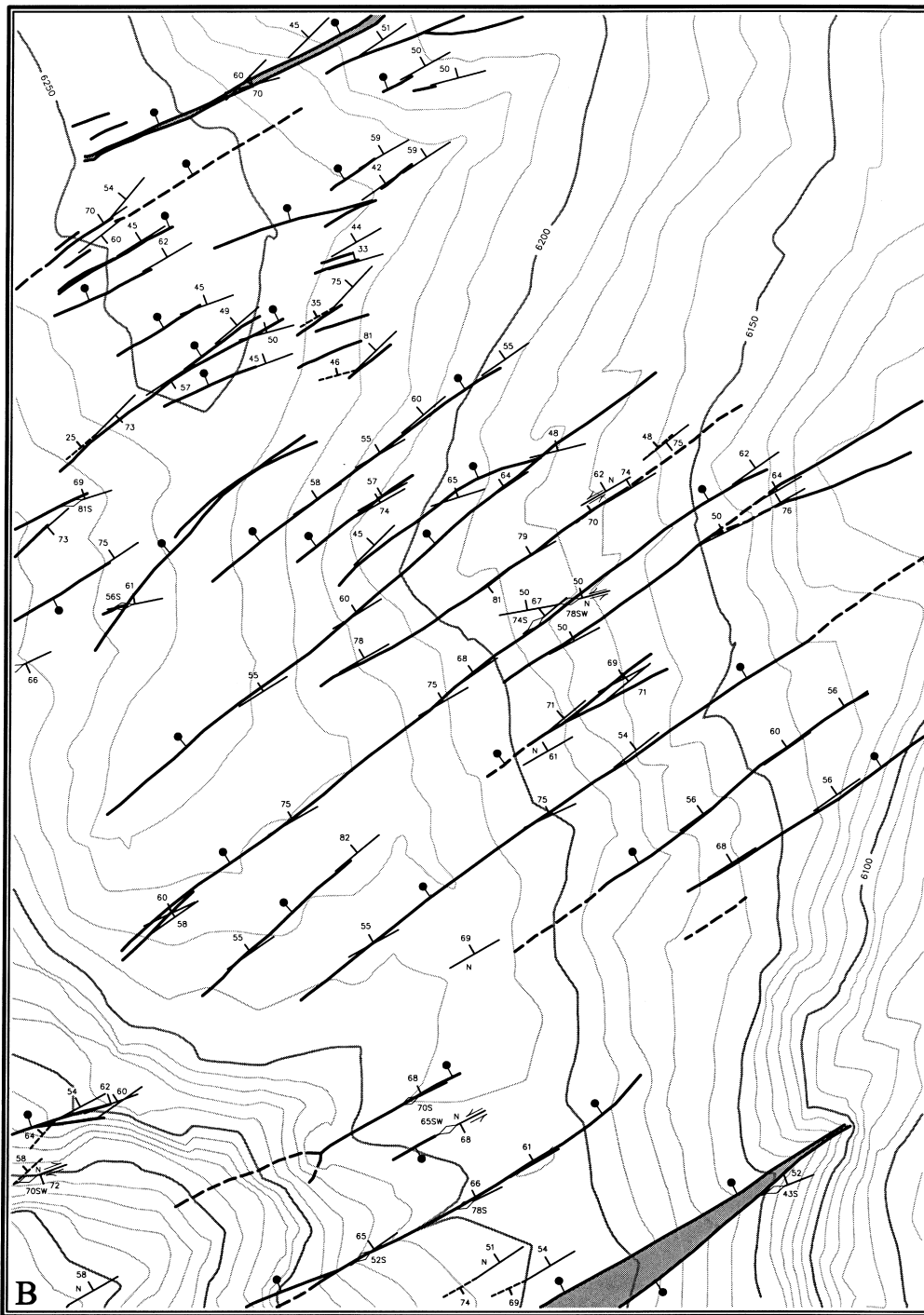


Fig. 7 (continued)

shear strikes more westerly (by less than $\sim 15^\circ$) than the RSZ. Each southeast-dipping RSZ is the locus of synthetic southeast-dipping R-shears which dip more steeply (by $\sim 15^\circ$) than the RSZ of which it is a part (see Fig. 9). Because there is a slight right-handed strike-slip component of offset along the southeast-dipping RSZs in the Cottonwood area, each southeast-

dipping R-shear strikes more easterly (by less than 15°) than the RSZ as a whole.

We separated measurements of R-shears, R'-shears, and slickenlines taken in the Cottonwood area into two domains (Fig. 12): Domain C1, where bedding is essentially horizontal; and domain C2, where bedding is inclined east-southeasterly (as much as $\sim 20^\circ$) along

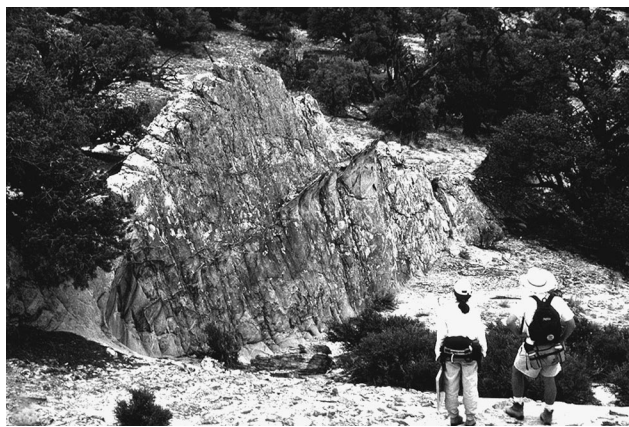


Fig. 8. Photograph of outcrop expression of massive, continuous R shear in the Cottonwood area. Reproduced from Davis (1999) with permission from the Geological Society of America.

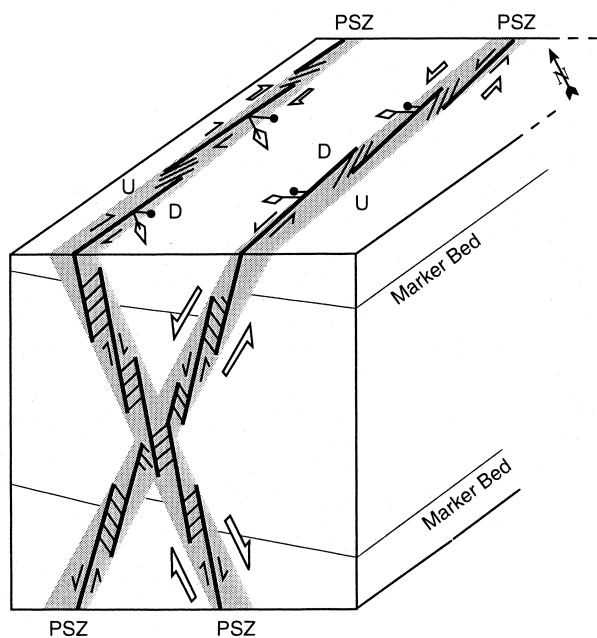


Fig. 9. Block diagram showing the fundamental geometric relations in the Cottonwood area. Drawing includes a depiction of the left-handed and right-stepping nature of the northwest-dipping, predominantly normal-slip Riedel systems, and the right-handed and left-stepping nature of the southeast-dipping, predominantly normal-slip Riedel systems.

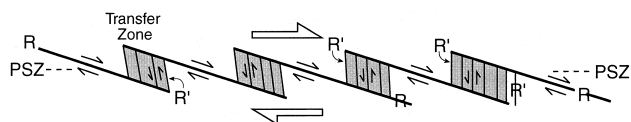


Fig. 10. Line drawing showing a Riedel shear zone composed of R-shears linked by transfer zones containing R'-shears.

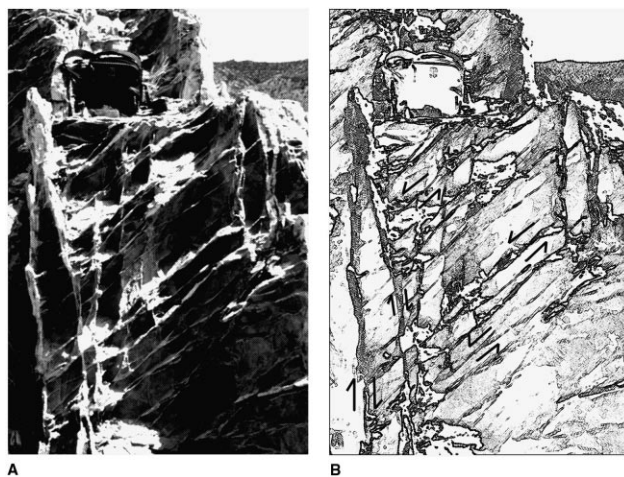


Fig. 11. Photograph and drawing, looking northeast, of a transfer zone in the Cottonwood area. (Note camera bag for scale.) The near vertical sidewalls are synthetic R-shears which accommodated upward movement of the northwest wall (left) relative to the southeast wall (right). The northwest (left)-dipping shears are antithetic R' shears which accommodated normal displacement.

the East Kaibab monocline. We note that when data of domain C2 are stereographically rotated by an amount that corresponds to an unfolding of the monocline, the resulting stereographic plot essentially matches that of domain C1 (see Fig. 12A and C). This is consistent with the inference that in both domains the RSZs formed as a response to layer-parallel stretching, for in both domains the sets of RSZs are layer-parallel extensional, symmetrically disposed about the trace of bedding. The geometric relationships are such that as bedding steepens within domain C2, west-dipping RSZs assume progressively gentler dips, whereas originally east-dipping RSZs assume progressively steeper dips, even to the point of going beyond vertical and becoming west-dipping. In domain C1, where bedding dips gently, the layer-parallel extensional relationships are clearest (Fig. 13A). West-northwest-dipping, predominantly normal-slip RSZs are composed of yet more steeply west-northwest-dipping R-shears; while east-southeast-dipping, predominantly normal-slip zones are composed of yet more steeply east-southeast-dipping R-shears. In each case, the Riedel shears are overstepped and connected by relays within which R'-shears are abundantly developed.

In domain C2, by virtue of the steepened dips of the Navajo Sandstone, the layer-parallel extensional geometry is more obscure (Fig. 13B). Where bedding is inclined, e.g. 20° E, west-northwest dipping RSZs and associated R-shears dip $\sim 20^\circ$ more gently than dips in domain C1. In contrast, the east-southeast-dipping RSZs and associated R-shears become steeper by $\sim 20^\circ$. The most challenging arrangements to interpret occur where the inclination of bedding is such that

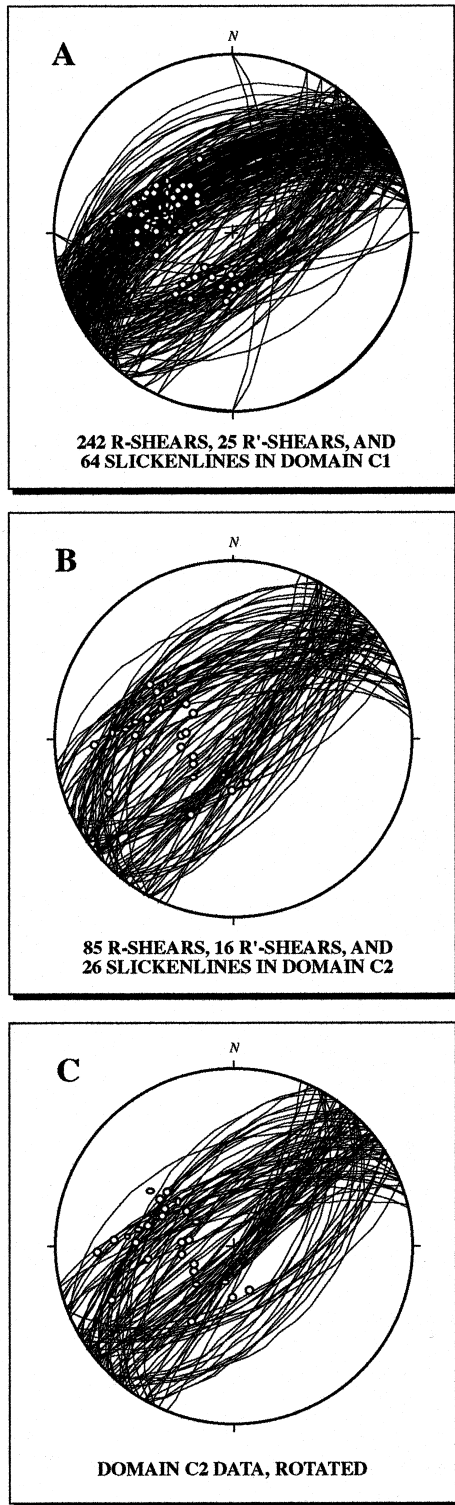


Fig. 12. Lower-hemisphere equal-area projections of orientations of R shears, R' shears, and slickenlines measured in the Cottonwood area. (A) Domain C1 contains measurements where Navajo Sandstone dips less than 5° east-southeast. (B) Domain C2 contains measurements where Navajo Sandstone dips between 5° and 20°. (C) Domain C2 measurements rotated by an amount that unfolds the Navajo Sandstone to horizontal.

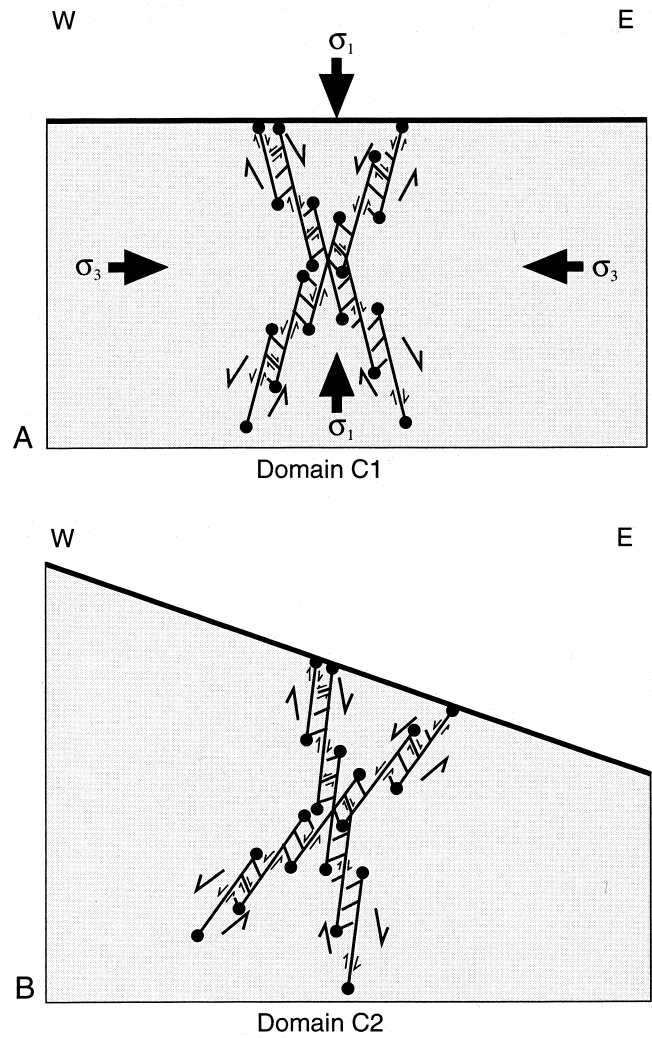


Fig. 13. Drawings showing that the acute bisector of the conjugate Riedel shear zones is always perpendicular to bedding, no matter whether bedding is (A) flat-lying or (B) inclined.

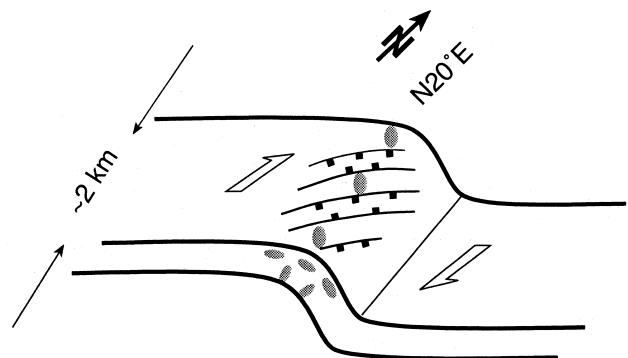


Fig. 14. Line drawing suggesting that the orientations of the PSZs along the northern part of the East Kaibab monocline in the Cottonwood area are consistent with folding during the reverse, right-handed transpressive shearing interpreted by Tindall and Davis (1999). Reproduced from Davis (1999) with permission from the Geological Society of America.

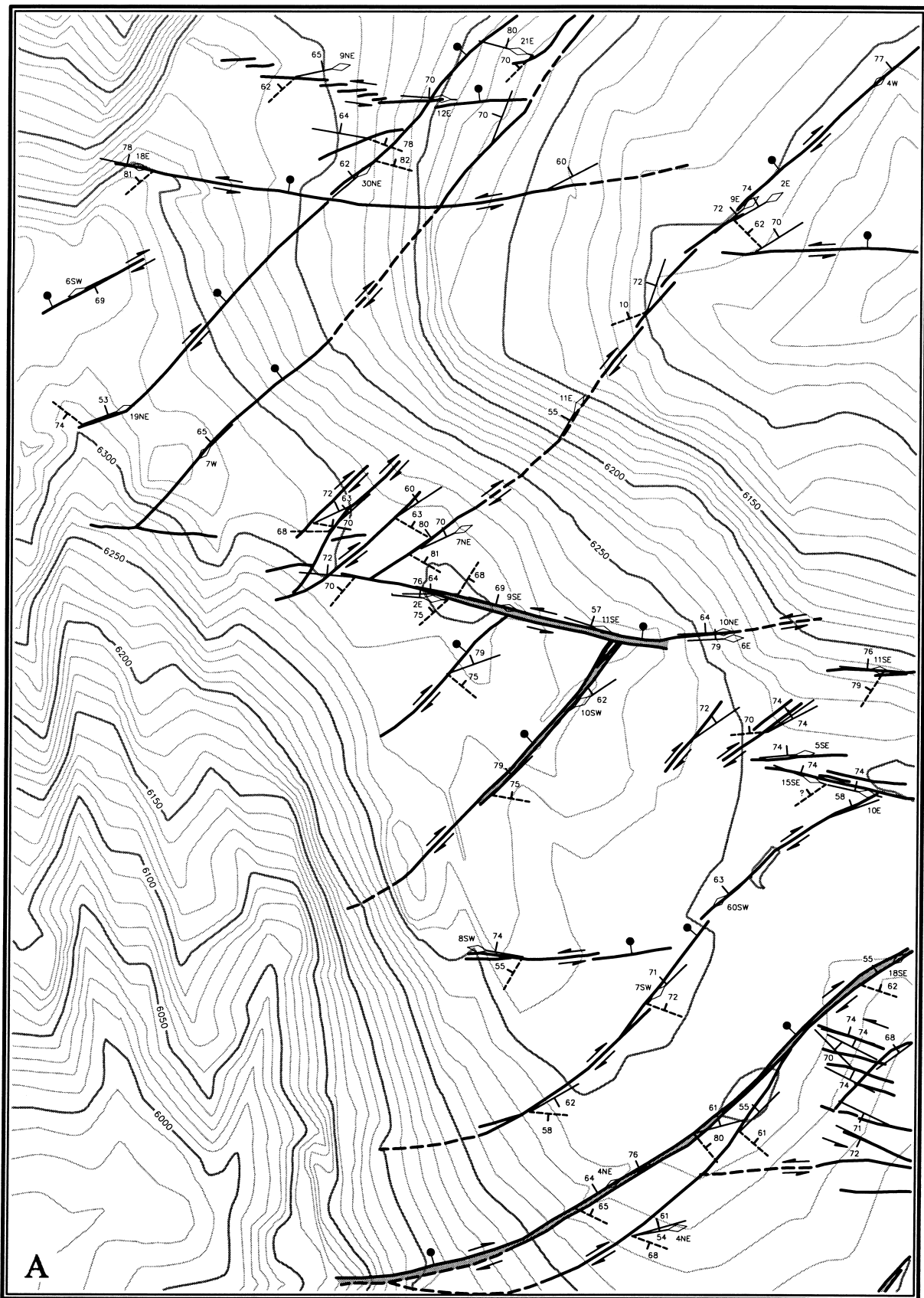


Fig. 15. Structure map of part of the Sheets Gulch area showing details of PSZs in terms of R shears, R' shears, and slickenlines. (A) western half, (B) eastern half of the map area. Reproduced from Davis (1999) with permission from the Geological Society of America.

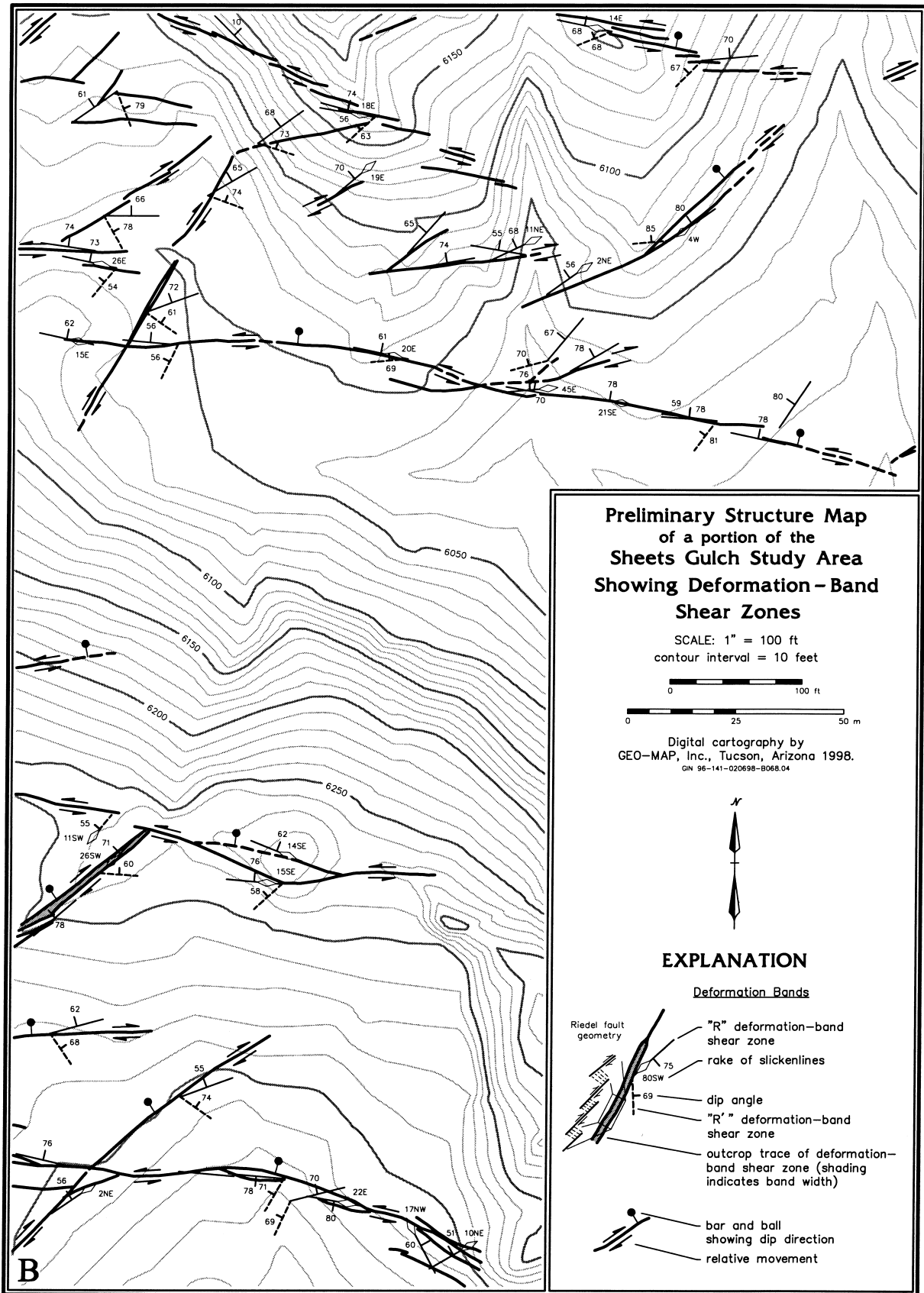


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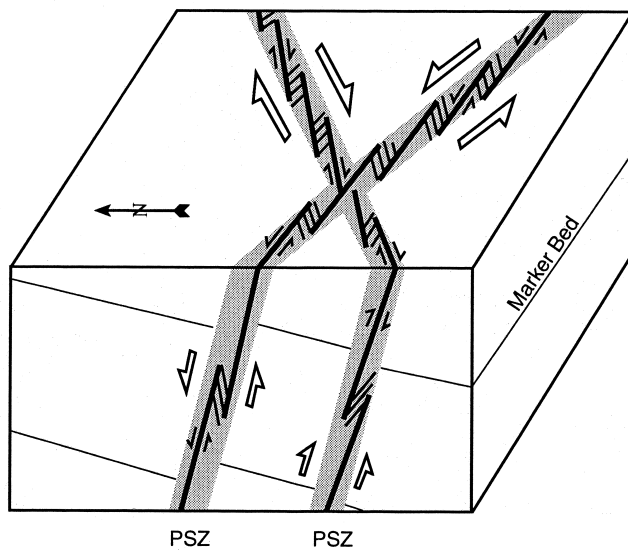


Fig. 16. Block diagram showing the fundamental geometric relations in the Sheets Gulch area.

east-southeast-dipping RSZs dip more steeply than $\sim 80^\circ\text{E}$, thus remaining normal-slip in offset, whereas the R-shears of this set are west-southwest dipping, thus high-angle reverse in nature.

3.2. Tectonic significance of the patterns

The conjugate Riedel shear system in the Cottonwood study area occurs in Navajo Sandstone mainly along the upper hinge of the East Kaibab monocline, near the northernmost end of the Kaibab Uplift (see Fig. 4A). The Kaibab Uplift is a product of Laramide east-northeast to northeast contractional deformation that affected rocks of the Colorado Plateau. Strata as young as Paleocene are affected by this contractional deformation (Bowers, 1972). The Kaibab Uplift is a large asymmetrical anticline, with a long, gently dipping west limb and a moderately to steeply dipping east limb, which is the East Kaibab monocline (Sargent and Hansen, 1982). The crest line of the Kaibab Uplift is the trace of the Kaibab anticline, located just 5 km west of the upper hinge of the East Kaibab monocline (see Fig. 4A). The structural relief between the crest of the Kaibab anticline and the upper hinge of the East Kaibab monocline is approximately 1500 m. The conjugate Riedel shear system of the Cottonwood area lies along a part of the northernmost reach of the East Kaibab monocline, which trends $\sim \text{N}20^\circ\text{E}$, parallel to the trace of the Kaibab anticline. The monocline dies out to the north near the gently plunging termination of the Kaibab Uplift (Davis, 1999; Tindall et al., 1999).

The conjugate Riedel system of deformation band



Fig. 17. Photographs showing the elegant expressions of the Riedel shear systems and transfer zones in the Sheets Gulch area. (A) Small right-handed strike-slip PDZ composed of overstepping R shears. Antithetic R' shears fill in the transfer zones. (B) Hand sample collected in the Sheets Gulch area showing the details of transfer zones between overstepping R shears. These are right-handed examples. Part (B) reproduced from Davis (1999) with permission from the Geological Society of America.

shear zones formed during simple outer-arc bending and stretching of the Navajo Sandstone along the monocline during the folding, and this explains why the RSZs and R-shears reflect a layer-parallel stretching no matter whether the Navajo Sandstone is horizontal or inclined. Jamison and Stearns (1982) discussed the formation of deformation band shear

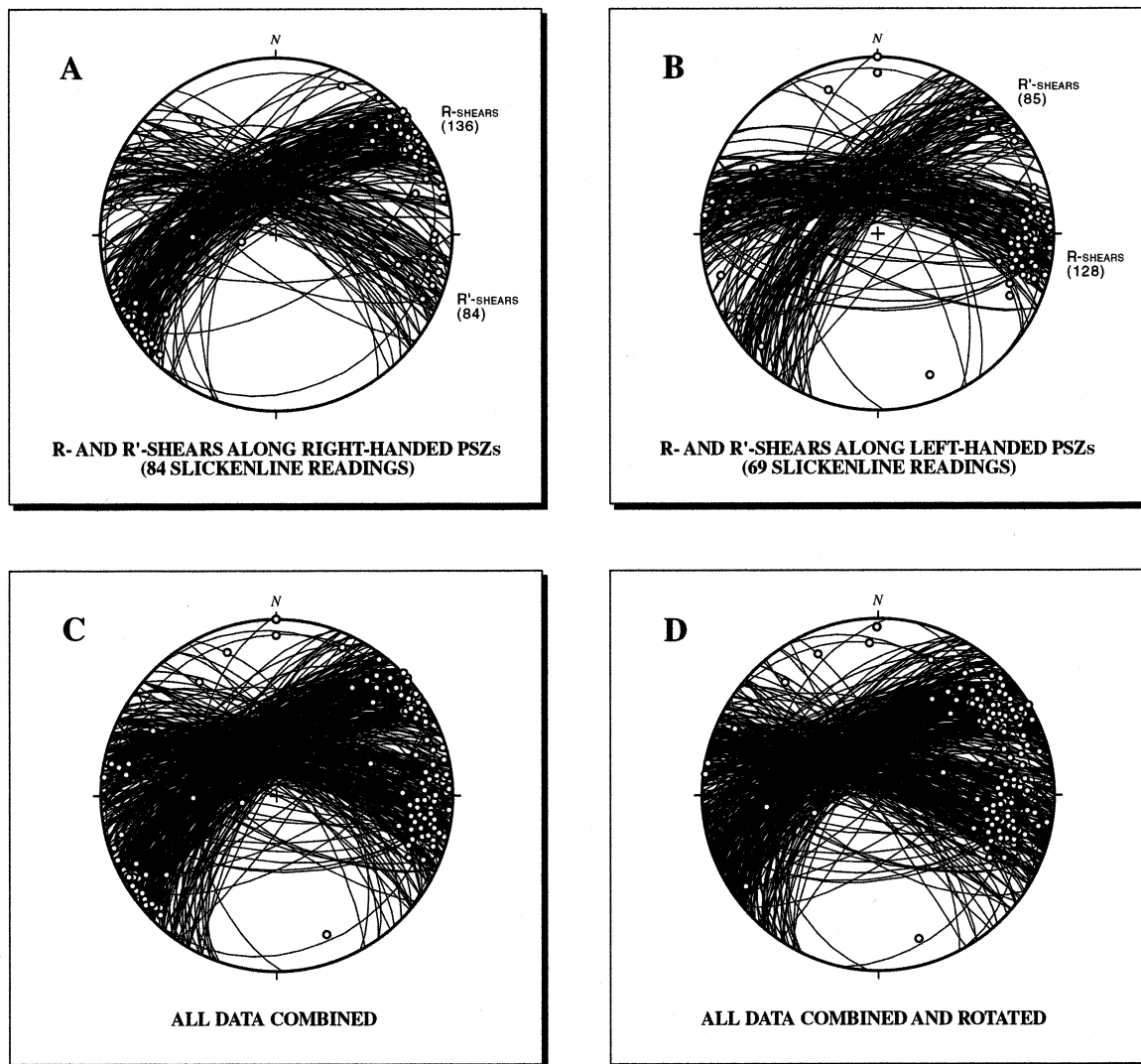


Fig. 18. Lower-hemisphere equal-area projections of the orientations of R shears, R' shears, and slickenlines in the Sheets Gulch area, for (A) northeast-striking right-handed zones, (B) west-northwest-striking left-handed zones, (C) both right-handed and left-handed systems, and (D) both right-handed and left-handed systems rotated by an amount that brings bedding to horizontal.

zones by this same mechanism at Colorado National Monument; and Antonellini and Aydin (1995) have described the formation of deformation band shear zones by outer-arc stretching in a rollover anticline in Entrada Sandstone in the Moab region of southeastern Utah. Interestingly, at Cottonwood, the strike direction of the deformation band shear zones (dominantly N50°E) does not match the trend of the monocline (N20°E) (compare Figs. 4A and 7), a discordance which would tend to weaken the argument that the shear zones resulted from simple bending along the outer arc of the fold hinge. As it turns out, the East Kaibab monocline formed in the Laramide in response to an oblique-slip reverse right-handed shearing (Davis and Tindall, 1996; Tindall and Davis, 1999). Thus, the actual stretching direction within the outer arc of the

upper hinge of the East Kaibab monocline in the Cottonwood area is obliquely oriented in a manner consistent with a right-handed shear component (Fig. 14). Tindall et al., (1999) have reproduced this obliquity in physical analogue experiments involving a forced folding and faulting in cover by right-handed reverse reactivation of a basement fault.

4. The shear zones at sheets gulch

4.1. Structural description of the patterns

The Sheets Gulch area (see Fig. 4B) occurs where the outcrop exposure of the Navajo Sandstone makes a jog to the east from the N20°W orientation that

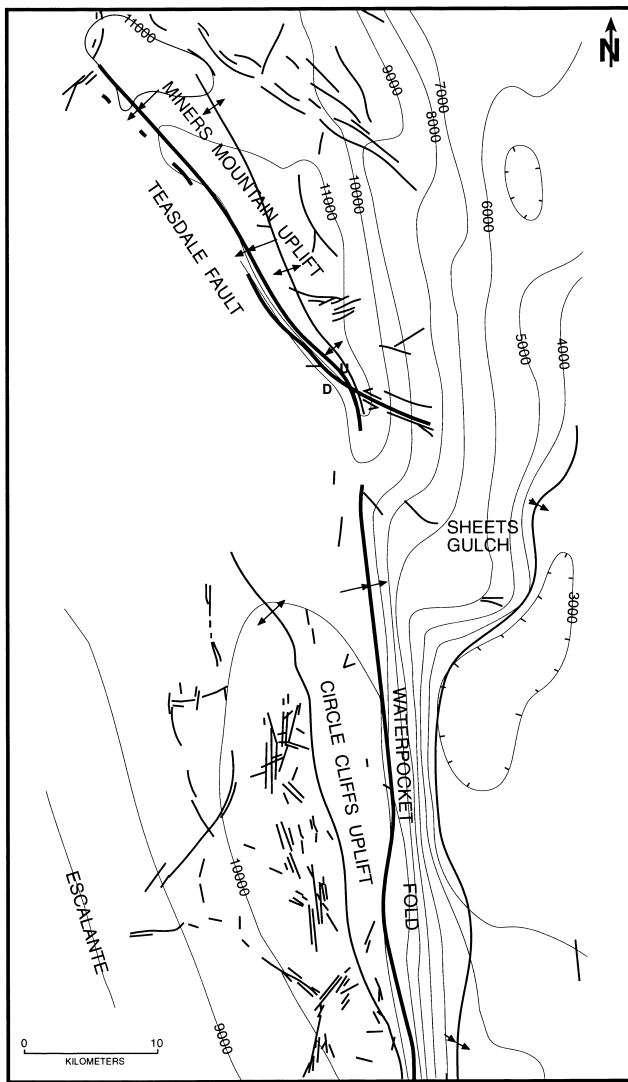


Fig. 19. Map showing the location of Sheets Gulch in relation to the Miners Mountain uplift and Teasdale fault to the northwest, and the Circle Cliffs uplift and Waterpocket Fold to the south. Sheets Gulch occupies a part of the transfer zone between the two uplifts. Reproduced from Davis (1999) with permission from the Geological Society of America.

marks its trend along the Waterpocket Fold to the south, creating the Sandy Ranch salient. Within the main stretch of the Sandy Ranch salient, bedding strikes east-northeast and dips just 15° S, much shallower than the $55\text{--}80^{\circ}$ dips evident further south along the northern stretch of the Waterpocket Fold. As at Cottonwood, the Sheets Gulch area is marked by deformation band shear zones which tend to project upward from the slickrock exposures of the Navajo Sandstone. Using 1:600 scale aerial photographs and topographic maps with 3-m contours, we mapped nearly all of the principal shear zones (PSZs) within the $1200\text{ m} \times 900\text{ m}$ Cottonwood study area (Fig. 15). We found that the PSZs occur in two conjugate sets: a

right-handed set striking $\sim N40\text{--}50^{\circ}E$ and dipping $\sim 75^{\circ}NW$, and a left-handed set striking $\sim N65\text{--}80^{\circ}W$ and dipping $\sim 75^{\circ}NE$. Spacing of the PSZs is quite regular, generally ranging from ~ 10 to $\sim 25\text{ m}$. Offset on map-scale PSZs is strike-slip and ranges from tens of centimeters to several meters or more. We also discovered that the PSZs are themselves composed of individual overstepping R-shears that are slightly discordant in trend to the PSZ as a whole. The R-shears associated with the northeast-striking PSZs are right-handed, striking $\sim N45^{\circ}$ to $65^{\circ}E$ and dipping from $\sim 65^{\circ}$ to $85^{\circ}NW$ (see Fig. 15). In contrast, the R-shears associated with the west-northwest-striking PSZs are left-handed, striking $\sim N60^{\circ}$ to $85^{\circ}W$ and dipping ~ 60 to $85^{\circ}NE$ (see Fig. 15). Fig. 16 shows the map geometry schematically. The PSZs are Riedel shear zones (RSZs).

There are hundreds of R-shears in the Sheets Gulch area, ranging in size from centimeters in trace length and several millimeters thick, to those that are tens of meters in trace length and tens of centimeters thick. Magnitude of offset ranges from centimeters to several meters. The strike-slip nature of the R-shears is quite obvious, for bedding and cross-bedding typically offset in right-handed or left-handed fashion along deformation bands whose outer surfaces are in places slickensided. Many of the slickensided surfaces are polished and marked by grooves and slickenlines (see Fig. 6). The slickenlines and grooves are only locally perfectly strike-slip in nature, but more typically rake at low angles, reflecting a small component of apparent normal displacement.

The RSZs, which can be traced by virtue of their resistance to erosion across the slickrock surfaces, have an outcrop width and a trend that is controlled by the tips of the overstepping R-shears (see Fig. 17A). The R-shears are connected by transfer zones within which there are abundant antithetic deformation band shear zones, which have the properties of R' -shears: (1) they are oriented at $\sim 75^{\circ}$ to the RSZs of which they are a part; (2) they are oriented $\sim 60^{\circ}$ to the R-shears; and (3) they are antithetical in sense-of-shear relative to the RSZs of which they are a part and to the R-shears that they link. The transfer zones at Sheets Gulch are relatively closely spaced in a plan view, and more widely spaced when viewed in vertical sections (see Fig. 16). The R' -shears form within the overlap zone of adjacent R-shears (see Fig. 16), and the antithetic strike-slip movement along them is a response to the compressional environments within relay zones stepped in this fashion (Segall and Pollard, 1980). Some bundles of R' -shears have clearly rotated into higher angles with respect to R-shear traces, and in the process of rotation, some R' -shears have taken on sigmoidal forms. Ahlgren (1999) has in fact determined that some of the features we refer to here as sigmoidal R'

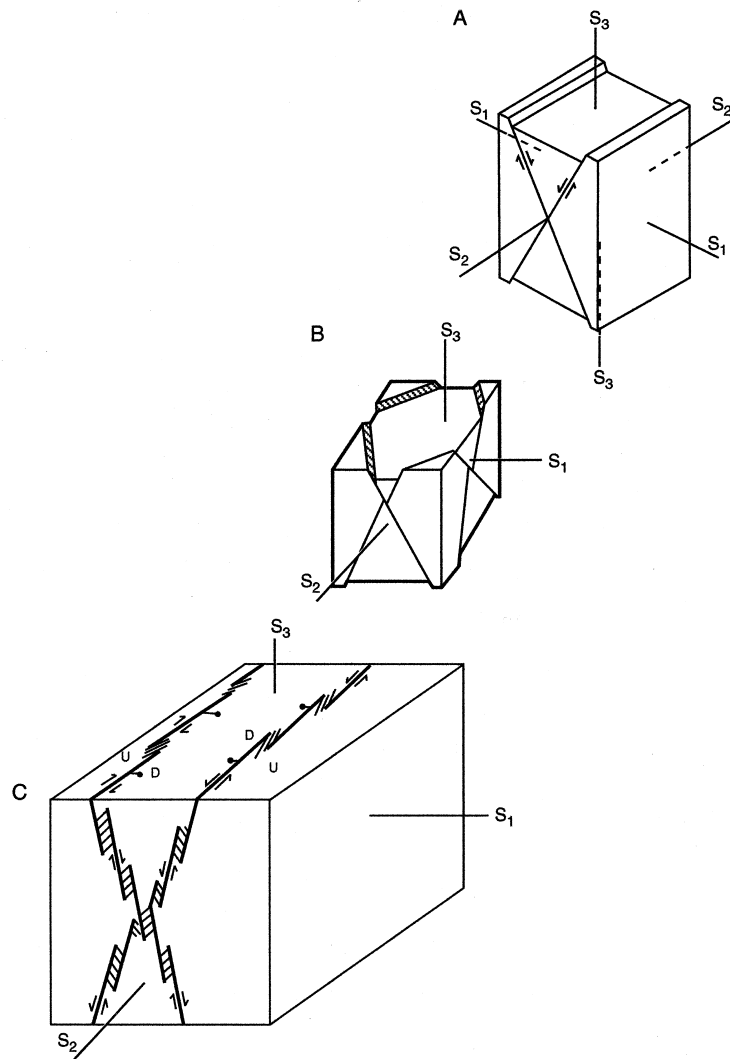


Fig. 20. Portrayals of three modes of faulting: (A) Coulomb conjugate faulting, (B) Reches conjugate faulting, and (C) Riedel conjugate faulting. See text for explanation.

shears may have been the earliest structures to have formed within the RSZs.

The orientations of the elements of the conjugate Riedel shear zone system in the Sheets Gulch area can be shown stereographically (Fig. 18). All of the shears are associated with nearly horizontal, but seldom perfectly horizontal, slickenlines. The direction of greatest shortening bisects the conjugate angle between the right-handed and left-handed RSZs. At the same time, this direction of greatest shortening is oriented $\sim 15^\circ$ to the left-handed and right-handed R-shear zones.

That the strike-slip deformation developed before tilting of the Navajo Sandstone can be shown stereographically. When the great circles and slickenlines representing R-shears and R'-shears in the Sheets Gulch map area are rotated by an amount consistent with removing the $\sim 15^\circ$ S bedding dip along the Sandy

Ranch salient (see Fig. 18), the R-shears and R'-shears tend to become vertical. Strike-slip deformation band shearing thus predates the tilting of beds, or accompanied the very early stages of tilting. This conclusion is further confirmed when noting that the trace of slickenlines is always subparallel to the trace of bedding (not cross bedding) on the fault surface, which indicates that at the time of faulting, the Navajo Sandstone was horizontal and the fault movements were horizontal. No amount of tilting could thus alter the parallelism.

4.2. Tectonic significance of the patterns

The Sheets Gulch area lies at the very northernmost end of the Waterpocket fold, where the Circle Cliffs Uplift gives way northward to the Miners Mountain

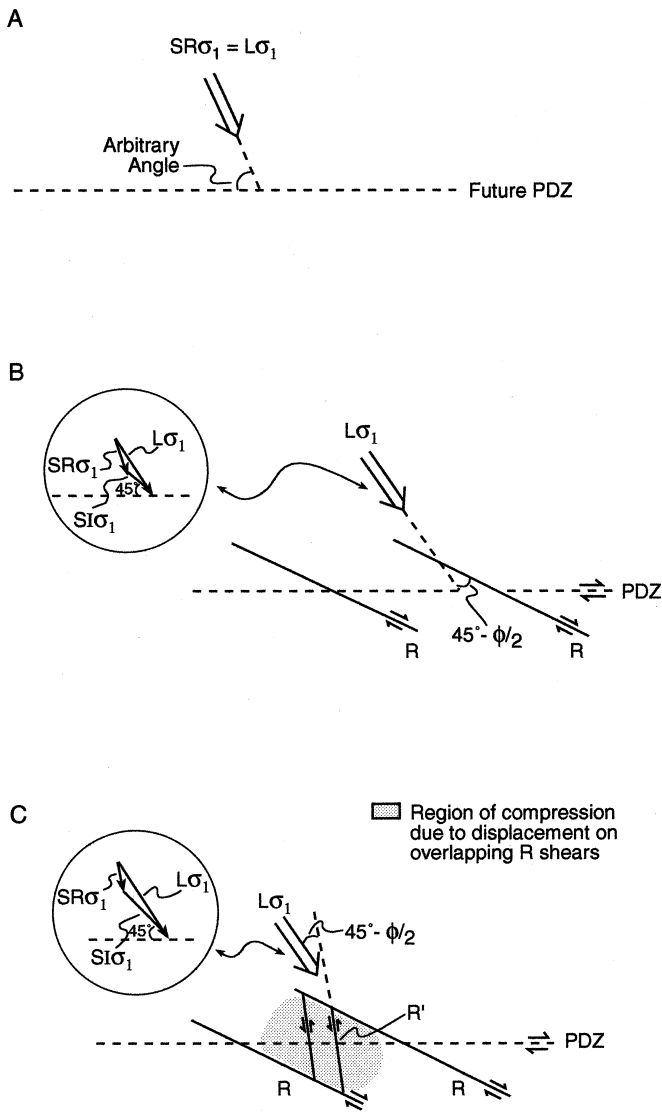


Fig. 21. (A) Prior to displacement on principal displacement zone (PDZ), the subregional direction of greatest principal stress ($SR\sigma_1$) is the same as the local direction of greatest principal stress ($L\sigma_1$). (B) Displacement on the PDZ introduces a shear-induced stress ($SI\sigma_1$), thereby altering $L\sigma_1$. The new $L\sigma_1$ is the vector sum of $SI\sigma_1$ and $SR\sigma_1$ (unchanged from A). (C) Increasing the displacement on the PDZ may increase the magnitude (though not the orientation) of $SI\sigma_1$, changing the orientation of $L\sigma_1$.

Uplift (see Fig. 19). Indeed, the Sheets Gulch area lies at the juncture between two Laramide uplifts, specifically at the northern termination of the east-vergent Circle Cliffs Uplift and the southern termination of the west-vergent Miners Mountain Uplift. The 140 km long circle cliffs uplift trends north-northwest and is 33 km at its widest (Davis, 1999). The gently dipping west limb ranges in strike from $\sim N35^\circ W$ to $N55^\circ W$, and dips $\sim 3\text{--}4^\circ SW$. The east limb is the spectacular Waterpocket Fold, a huge monocline which trends $N20^\circ W$ (Smith et al., 1963; Billingsley et al., 1987)

(see Fig. 19). It lies less than 8 km east of the crestal culmination of the Circle Cliffs anticline. Strata along the monocline dip eastward, with inclinations ranging from $\sim 15^\circ$ to 80° . The Circle Cliffs proper represent the culmination of the Uplift, in the form of a doubly plunging $N30^\circ W$ trending anticline. Plunge values of the Circle Cliffs anticline, both to the north and south, range up to $\sim 5^\circ$. Structural relief from the base of the western limb of the anticline to the crest is ~ 900 m. Structural relief from the crest of the uplift to the lower hinge of the Waterpocket monocline is ~ 1666 m. Lying immediately north of the Circle Cliffs Uplift, the Miners Mountain Uplift is a doubly plunging antinclinal uplift that trends $N55^\circ W$ (see Fig. 19). Its south-

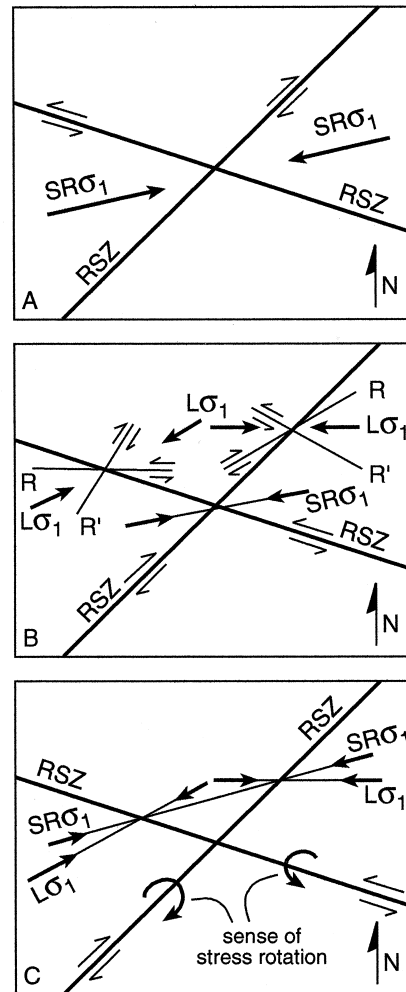


Fig. 22. Demonstration, using the Sheets Gulch relationships, that the obliquity of R and R' orientations to the trace of a Riedel shear zone is due to rotation of the subregional stress by the creation of shear-induced stresses. (A) Direction of the greatest principal subregional stress ($SR\sigma_1$) as inverted from the orientations of the RSZs. (B) Directions of the greatest principal local stresses ($L\sigma_1$) as inverted from the orientations of the conjugate sets of R and R' for each set of RSZs. (C) Sense of stress rotation, from subregional to local, for each set of RSZs.

easternmost end projects into the Sandy Ranch salient, where the Sheets Gulch area resides. Miners Mountain uplift is ~40 km in length and ~25 km in breadth. Previously mapped by others (Smith et al., 1963; Billingsley et al., 1987), the Miners Mountain uplift is bounded on the southwest by the N65°W-striking Teasdale fault and Teasdale monocline (Smith et al., 1963). The faulted fold is marked by structural relief of the order of ~1500 m (Bump et al., 1997). The monocline trends parallel to the fault and verges southwestward. The northeastern backslope of the Miners Mountain Uplift dips up to ~20°ENE, and it is within this backslope that the Visitors Center of Capitol Reef National Park resides (Bump et al., 1997). This backslope is commonly but erroneously referred to by many geologists as part of the Waterpocket Fold.

The Sheets Gulch area is located precisely where the Circle Cliffs Uplift to the south is replaced by the Miners Mountain Uplift to the north (Bump et al., 1997) (see Fig. 19). The Waterpocket Fold, which marks the eastern margin of the Circle Cliffs Uplift, is presumed to be underlain by a blind west-dipping reverse or thrust fault, accommodating northeast/southwest horizontal Laramide contraction. The Miners Mountain monocline is associated with a range-bounding antithetic left-handed reverse fault, which accommodated the horizontal northeast/southwest Laramide contraction as well (Anderson and Barnhard, 1986; Bump et al., 1997). Davis et al. (1997) have suggested that the conjugate strike-slip system in the Sheets Gulch area is accommodating strain related to the imperfect transfer of displacement between northeast-vergent and southwest-vergent fault/fold zones. The transfer was not precise, and extra strain 'leaked' into the Sheets Gulch area in the form of a distributed strike-slip deformation. Part of the expression of the imperfect transfer of displacement from the Waterpocket Fold to the Miners Mountain fault/monocline is the Sandy Ranch salient. Part is the conjugate Riedel shear system. Laramide regional shortening was ~N65°E, essentially perpendicular to the trace of the Waterpocket Fold. The RSZs at Sheets Gulch intersect at ~60°, and the acute bisector of the RSZs is a line of shortening trending ~N60–75°E. Thus the Riedel shear pattern at Sheets Gulch is rational with respect to Laramide shortening.

5. Discussion

5.1. No basement fault needed

Both at Cottonwood and Sheets Gulch there are two equally developed sets of Riedel shear zones (RSZs) entirely contained and broadly distributed in

Navajo Sandstone. Moreover, there is no evidence at Cottonwood or Sheets Gulch that individual R-shears or the system as a whole roots into a single master fault. The deformation band shear zone systems exposed in the Cottonwood and Sheets Gulch areas thus demonstrate that Riedel shears can occur in conjugate Riedel systems, and that the formation of Riedel shears does *not* require a direct structural linkage downward to a discrete basement fault zone.

5.2. Conjugate Riedel shears as a separate geometric class of faulting

'Coulomb conjugate systems' (e.g. Anderson, 1951) are marked by two sets of faults that together have the effect of shortening a volume of rock in the direction of least stretch (S_3 , where $S = l_t/l_o$), extending the volume of rock in the direction of greatest stretch (S_1), and neither shortening nor stretching the volume of rock in the direction of intermediate stretch (S_2) (Fig. 20A). 'Reches conjugate systems' (Reches, 1978, 1983) are marked by four or more sets arranged in orthorhombic symmetry. The faulting by this means tends to conserve the volume of the rock body in which the faulting is distributed. Four or more fault sets are required because the deformation takes place within a three-dimensional strain field such that all three of the principal stretch directions (S_1 , S_2 , and S_3) are marked by a change in length, either shortening or stretching (Fig. 20B). Our work suggests that the 'Riedel conjugate system' is yet another geometric class of faulting for accommodating distributed strain within a volume of rock (Fig. 20C). Faulting is achieved by two sets of RSZs, each composed of Coulomb conjugate sets oriented obliquely to the RSZs. At Cottonwood and Sheets Gulch, the effect of the conjugate Riedel shearing is both distortion and volume loss. Volume loss is a consequence of collapse of porosity during the formation of the deformation band shear zones which comprise the Riedel systems.

5.3. Invariant nature of geometry of fault system

It is interesting that the shear zone deformation patterns in the Cottonwood and Sheets Gulch areas are so similar in terms of physical and geometric characteristics of the map-scale structures, spacing and geometry of the RSZs, and the order-of-magnitude of displacements along the RSZs. The basic similarity holds in spite of the fact that the shear zones in the Cottonwood area are normal-slip, and the shear zones in the Sheets Gulch area are strike-slip. The systems of structures in the two areas are essentially identical, except in absolute orientation, for the map-view characteristics of the Cottonwood system match the cross-sectional characteristics of the Sheets Gulch sys-

tem, and vice versa (compare Figs. 9 and 16). Examining these patterns we learn that the distance between transfer zones between overstepping R-shears is smallest when measured in the direction of slip within a RSZ, and greatest when measured perpendicular to the direction of slip within a RSZ. Specifically, the plan view distance between transfer zones in the normal-slip system at Cottonwood is greater than the plan view distance between transfer zones in the strike-slip system at Sheets Gulch. And, the cross-sectional distance between transfer zones in the normal-slip system at Cottonwood is less than that of the cross-sectional distance between transfer zones in the strike-slip system at Sheets Gulch (compare Figs. 9 and 16).

5.4. Factors favoring the formation of conjugate Riedel shears

There are three factors that favored the development of such highly systematic conjugate ‘fault’ patterns: homogeneity of the Navajo Sandstone host rock, a strain-hardening deformation mechanism, and very modest overall strain.

The Navajo Sandstone is thick and mechanically homogeneous. At Sheets Gulch, the thickness is ~250 m, and at Cottonwood ~400 m. The Navajo Sandstone is mineralogically homogeneous (greater than 95% quartz), and remarkably free of interbedded units of different lithologies. Although there is abundant cross-bedding throughout the Navajo Sandstone, the trace lengths of the cross-bedding and cross-lamination are extremely short compared to the scale of thickness and lateral extent of the Navajo Sandstone, and thus do not exert much of a mechanical anisotropy during deformation. Separation planes between cross-bedded units within the Navajo Sandstone are prominent and marked by significant continuity (up to hundreds of meters of trace length), but because they separate units above and below that are identical lithologically, the mechanical influence of separation planes on the deformation process is quite subtle as a rule. As a result, the Navajo Sandstone has responded to the Laramide deformation at Cottonwood and Sheets Gulch as if it were mechanically homogeneous.

Another factor favoring the exceptionally clear development of conjugate Riedel systems was the strain-hardening nature of the very process of formation of deformation bands. Strain-hardening tends to prevent individual, through-going ‘fault’ features from becoming physically and kinematically dominant. Instead, the strain hardening favors a broader distribution of strain within a given volume of rock.

The modest amount of strain needing to be accommodated is a deterrent to the development of major through-going faults. As a consequence, the conjugate

Riedel shear zone systems in the Cottonwood and Sheets Gulch area capture a glimpse of an early stage of development of a fault system in porous sandstones.

5.5. Insight regarding stress rotation

From the time of initial recognition of Riedel shear patterns, structural geologists have pondered the question of why the R-shears and R'-shears, which have a Coulomb relationship to one another, are oriented obliquely to the trace of the PDZ. Workers have concluded (e.g. Mandl, 1988) that displacement and shear along a PDZ generates a shear-induced stress ($SIS\sigma_1$) at ~45° to the PDZ which results in a rotation of the subregional direction of greatest principal stress ($SR\sigma_1$) into a local direction of greatest principal stress ($L\sigma_1$). Our findings can be used to demonstrate that the formation of Riedel shear zones (RSZs) creates a local reorientation of the principal stress directions. The presence of *conjugate* RSZs permits such stress rotation to be demonstrated.

The literature on classic Riedel shear zones addresses the question of stress rotation in the context of Riedel shears that are mechanically linked to single discrete master faults in the basement. Mandl (1988) provides an especially effective summary of the inferred stress relationships at work in the development of Riedel shears (Fig. 21). In the general case where the cover within which a RSZ is about to develop is marked by a subregional stress, $SR\sigma_1$ (Fig. 21A), the local stress, $L\sigma_1$, that will develop in the immediate vicinity of the RSZ will be the vector sum of shear-induced stress, $SIS\sigma_1$, and the subregional stress, $SR\sigma_1$ (Fig. 21B). If the $L\sigma_1$ is oriented at greater than 45° to the master zone, the initial R-shears will be oriented at greater than +15° to the trace of the PDZ (Fig. 21A). Because of this angular relationship, the R-shears will not be particularly effective in contributing significant shear displacement components parallel to the RSZ. The R-shears will tend to lock up quickly. With continued motion on the RSZ, there may be an increase in the magnitude of the $SIS\sigma_1$, resulting in rotation of $L\sigma_1$ toward the trace of the fault zone, thus creating R-shears that begin to approach the conventional +15° Riedel relationship. These R-shears will be more favorably oriented and thus will accommodate the shear along the basement fault more effectively. Regions of overlap between overstepping of R-shears become subjected to local compression. In essence, these areas become restraining bends (Fig. 21C) (Segall and Pollard, 1980).

In contrast, if the $L\sigma_1$ is oriented less than +45° to the master zone, the R-shears will be oriented less than +15° to the trace of the RSZ, oriented in a manner to more effectively contribute significant shear displacement components parallel to the RSZ. Rotation of

these R-shears even closer to the trace of the basement fault zone, and the development of P-shears creates a situation where the Riedel system quickly becomes an anastomosing network of shears, and ultimately becomes a through-going fault.

The interplay of $SIS\sigma_1$, $SR\sigma_1$, and $L\sigma_1$ can be examined using the geometry and kinematics of *conjugate* Riedel systems as a basis. Using Sheets Gulch as an example, the RSZs comprise two distinct sets which, in conformity with Coulomb failure, enclose an angle of $\sim 60^\circ$, intersect in the direction of intermediate principal stress (σ_2), and lie symmetrically disposed about the subregional greatest principal stress direction ($SR\sigma_1$), which by inversion is oriented $\sim N75^\circ E$ (Fig. 22A). When, stress inversion is carried out for each set of RSZs on the basis of R-shear and R'-shear orientations, the $L\sigma_1$ within each transfer zone is *discordant* by $\sim 15^\circ$ to the $SR\sigma_1$. For the right-handed RSZs, the inverted $L\sigma_1$ is $\sim EW$. For the left-handed RSZs, the inverted $L\sigma_1$ is $\sim N60^\circ E/S60^\circ W$ (Fig. 22B). The sense of rotation of σ_1 from $SR\sigma_1$ to $L\sigma_1$ is clockwise for the right-handed strike-slip set, and counter-clockwise for the left-handed set (Fig. 22C). Thus it would appear that shear-induced stress along each RSZ had the effect of rotating the subregional direction of greatest principal stress ($SR\sigma_1$). The actual incremental shifts in stress have been interpreted on the basis of outcrop- and hand-sample-scale analysis of deformation bands in the Sheets Gulch area by Ahlgren (1999).

5.6. Practical implications

Knowledge of the details of conjugate Riedel fault geometry will be helpful in modeling the influence of compartmentalization on fluid flow in sandstone reservoirs, especially where sandstones are highly porous and the favored mechanism of deformation is the development of deformation bands and zones of deformation bands. Deformation band shear zones are marked by significant reduction in porosity of the host lithology, and thus they form impermeable barriers to fluid flow within otherwise porous, permeable reservoir rock (Antonellini et al., 1992, 1994a,b; Antonellini and Aydin, 1994, 1995). Study of the Cottonwood and the Sheets Gulch areas have provided a better understanding of the three-dimensional geometry of the 'lattice-work' of deformation band shear zones, an important prerequisite to fluid flow modeling. We have documented these three-dimensional characteristics, and conclude that the conjugate Riedel shear system partitions the host rock into elongate polyhedra whose cross-sectional forms are dominantly rectangular (see Fig. 5A) and rhombic (see Fig. 11A). Sizes of compartments range from hand-specimen scale to map scale (see Figs. 7 and 15). Longest axes of these polyhedra are in the direction of intersection of the conjugate RSZs, which

is parallel to the direction of intersection of R-shears and R'-shears. The R-shears constitute the first-order compartment boundaries. Fluid flow *across* R-shear boundaries can take place where the R-shears are cut by joints, thus creating baffles for flow (see joints cutting deformation band in Fig. 8). Fluid flow *around* the tip lines of R-shears would occur, if at all, in the transfer zones, which are marked by boxworks of nearly equal development of R-shears and R'-shears.

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