THE NUCLEATION AND EVOLUTION OF RIEDEL SHEAR ZONES AS
DEFORMATION BANDS IN POROUS SANDSTONE

by

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A Prepublication Manuscript Submitted to the Faculty of the
DEPARTMENT OF GEOSCIENCES

In Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

1999
STATEMENT BY AUTHOR

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ACKNOWLEDGEMENTS

Deformation bands first invaded my life thanks to George Davis, to whom I owe a great deal. His unrivaled field skills and enthusiasm for structural geology, teaching and everything in between are an inspiration. I especially thank him for providing the unique opportunity to explore and enjoy the lesser-known reaches of southern Utah under the guise of science. I am also exceptionally grateful to have spent the last two years surrounded by a close knit, eclectic group of classmates, and thank them all for friendship, general silliness and shoulders to lean on. George will never be the same. I would like to thank David Woody for help and goofiness in the field, as well as Dave Streeter of the Mining and Geological Engineering department for assistance with sample preparation. Last, but not least, I am grateful to my family for unending love and support.

This study was supported in part by grants from (in alphabetical order) Amoco, Arco, Midland Valley Services, and Sigma Xi GIAR.
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ABSTRACT

Riedel shear zones are geometric fault patterns commonly associated with strike-slip fault systems. The progressive evolution of natural Riedel shear zones within the Navajo Sandstone of southern Utah is interpreted from the spatial evolution of small-scale, incipient Proto-Riedel Zones (PRZs) to better-developed Riedel shear zones using field mapping and three-dimensional digital modeling. PRZs nucleate as a tabular zone of localized shearing marked by en échelon deformation bands, each of which is no more than a few mm wide and tens of cm long, and oriented at 55° – 85° to the trend of the zone. With increasing strain, deformation bands and sedimentary markers are sheared ductily through granular flow and assume a sigmoidal form. The temporal and spatial evolution of bands comprising a Riedel shear zone suggests that PRZs nucleate as transitional-compactional deformation bands under localized, supra-lithostatic fluid pressure. Subsequent bands develop under modified regional stresses as conjugate shear fractures within the strain-hardened axis of the PRZ. These antithetic driven systems are not compatible with traditional synthetic driven models of Riedel shear zones. Unlike most synthetic driven examples, these antithetic driven systems are not controlled by pre-existing “basement” structures, thus their geometries reflect a primary propagation or secondary passive deformation mechanism.
INTRODUCTION

The purpose of this contribution is to explore and document the sequential development of Riedel shear zones in porous sandstone from field examples, with emphasis on the spatial and temporal evolution of the developing Riedel shear zone and the individual shear surfaces comprising the zone. These systems are most commonly recognized in natural wrench fault environments and are easily created in analog systems, but their systematic structural evolution in natural systems is thus far poorly documented. Although many of the fundamental concepts explored in this paper are not new, the synthesis of these ideas in the context of interpreting naturally deformed structural systems and the application of advanced visualization techniques may shed light on this particularly complex and interesting fault pattern.

BACKGROUND

The term “Riedel Shears” (Hills 1963) refers to a specific geometric fault pattern first demonstrated in clay-cake models (Riedel 1929). The pattern includes relatively short, en échelon fault segments that may link to form a through-going Principal Shear Zone (PSZ) (Skempton 1966). Numerous workers have subsequently generated the Riedel pattern through clay cake experiments (e.g. Cloos 1955, Morgenstern & Tchalenko 1967, Tchalenko 1968, Hildebrand-Mittlefehldt 1979, Gamond 1983, Maltman 1987), direct shear experiments (e.g. Mandl et al. 1977, Bartlett et al. 1981, Schreurs 1994), triaxial experiments (e.g. Marone & Scholz 1989, Morrow & Byerlee 1989), and through computer simulations (Dresan 1991, Braun 1994, McKinnon &
Garrido de la Barra 1998). Many workers document Riedel shear zones in natural systems ranging in scale from regional-scale (e.g. Tchalenko & Ambraseys 1970, Moore 1979, Moore & Byerlee 1992) to outcrop-scale (e.g. Dengo & Logan 1979, Davis 1996, Garcia & Davis 1997) to thin section-scale (e.g. Morgenstern & Tchalenko 1967, Tchalenko 1968, Maltman 1987). Riedel shear zones are found in dip-slip fault regimes (Dengo & Logan 1979, Garcia & Davis 1997) although the pattern is generally assumed to form in the cover sequence overlying some planar "basement" wrench-fault system (as in the wrench-fault block models of Tanner 1962, Wilcox et al. 1973, Moore 1979). Thus, laboratory and computer experiments are typically designed to simulate this situation and are composed of a single basement ‘fault’ (such as a longitudinally split board) overlain by a simulated cover sequence (e.g. Cloos 1955, Braun 1994). Smaller-scale Riedel shear zones are generally associated with a larger-scale Riedel shear zone system (e.g. Davis 1996) or found within fault zones (as in gouge experiments by Moore & Byerlee 1991).

Geometrically, the idealized Riedel pattern is defined by a series of shear fractures oriented at specific angles to the trend of the PSZ (Figure 1). The idealized system includes conjugate R and R’ shears, inclined at $\pi/4 \pm \phi/2$ ($\phi$ is the internal friction angle of the host rock), a P shear, inclined at $-\pi/4 + \phi/2$, and a T fracture, inclined at $\pi/4$ (e.g. Bartlett et al. 1981, Fig. 3). Some workers report X shears, oriented at $-\pi/4 - \phi/2$ (Bartlett et al. 1981), but these shears are not considered in this study. The R and P shears exhibit a synthetic sense of shear with respect to the PSZ, R’ shears exhibit an antithetic (terminology after Wilcox et al. 1973) sense of shear with respect to the PSZ,
Figure 1: Idealized Riedel shear zone geometry. $\phi$ is the angle of internal friction of the host rock. Principal Displacement Shears (PDS or Y shears) form sub-parallel to the trend of the zone.
and $T$ fractures are considered purely tensional fractures (e.g. Skempton 1966, Bartlett et al. 1981). Some shear fractures may be sub-parallel to the trend of the PSZ and are alternatively termed “Principal Displacement Shears” (PDS) (Skempton 1966), “D” shears (Tchalenko 1968) or “Y” shears (Bartlett et al. 1981). This study uses ‘$R$’ to describe a synthetic shear, ‘$R$’ to describe an antithetic shear, and ‘PDS’ to describe a shear oriented sub-parallel to the trend of the Riedel shear zone.

In natural systems, the angular relationships between individual shear surfaces and the PSZ is variable and dependent on a number of factors such as the strain rate (Lucas & Moore 1986) and the stress state at the time of faulting. Localized elevated fluid pressure within a faulting region may result in reorientation of the principal stresses (e.g. Byerlee 1990, Byerlee 1992) causing synthetic and antithetic shears to be inclined more steeply with respect to the trend of the PSZ (e.g. Gamond 1983, Naylor et al. 1986). Propagation of shears with the Riedel shear zone may also induce local stress field rotations, the local stress field, further influencing the orientations and types of shear fractures that develop (e.g. Naylor et al. 1986, Mandl 1988).

The sequential development of shear surfaces within a natural Riedel system is difficult to ascertain, and to the best of my knowledge is incompletely documented. In models and computer simulations, however, the sequential progression of shearing within Riedel shear zones is well defined but dependent on modeling conditions. Generally speaking, the most widely accepted model for Riedel shear zone development is synthetic driven in the sense that lower-angle synthetic R and P shears generally pre-date higher-angle antithetic R’ shears (Figure 2). Most workers agree that synthetic R shears are the
Figure 2: The sequential development of a sinistral synthetic driven Riedel shear zone. a) Zone initiates as en échelon R shears and in most systems, b) antithetic R' shears develop, although in some systems, c) P shears may develop.
first or one of the first shears to form (e.g. Morgenstern & Tchalenko 1967, Tchalenko 1970, Bartlett et al. 1981), although P shears may also form first, especially in dilational systems (Moore & Byerlee 1992). R and P shears may develop synonymously (Bartlett et al. 1981) or P shears may also develop later as links between R shears (Tchalenko 1968, Moore & Byerlee 1992). R’ shears may develop concurrently with or postdate R shears (e.g. Tchalenko 1968, Moore 1979) and they are typically confined to the overlap zones between overstepping R segments (e.g. Tchalenko 1968). Most workers agree that Y shears (PDSs) are the last to develop (e.g. Tchalenko 1968, Bartlett et al. 1981), although some computer modeling predicts that these shears actually form first (Braun 1994). It is important to note that individual shears generally remain active after other types develop, thus strain within a Riedel shear zone will be accommodated by synchronous movement on all surfaces comprising the zone (e.g. McKinnon & Garrido de la Barra 1998).

**LOCATION OF STUDY AREA AND STUDY METHODOLOGY**

The study examines Riedel shear zones in the Jurassic Navajo Sandstone of southern Utah, a relatively homogenous aeolian sandstone exposed throughout Utah (e.g. Hintze 1988). The primary study area (hereafter referred to as Sheets Gulch) is located near Sheets Gulch, a two square km region along the eastern edge of the Waterpocket Fold in Capitol Reef National Park (Figure 3). Structural data from Sheets Gulch are compiled from previous field maps (Davis et al. 1997) and from 1:600 and finer-scale mapping on aerial photographic base maps. Supporting data were also collected within
Figure 3: Map of Utah showing location of Sheets Gulch and simplified structural geology of the study area (after Billingsley et al. 1987).
the Navajo Sandstone exposed along the eastern edges of the San Rafael Swell and the East Kaibab Monocline.

**STRUCTURAL GEOMETRY**

*Regional Scale Structure*

Sheets Gulch is located geographically between two Laramide uplifts, the Circle Cliffs uplift to the southwest and the Miners Mountain uplift to the northwest (Bump *et al.* 1997) (Figure 3). Structurally, this region may represent a transfer zone between basement structure(s) controlling each of the uplifts, although the exact geometry of these basement structures is unknown. Striking geometrical differences between the two uplifts suggest that the Circle Cliffs uplift is cored by an east-vergent reverse fault and the Miners Mountain uplift is cored by a west-vergent reverse fault with left-oblique slip, which may be a backthrust subordinate to a dominant east-vergent reverse fault (Bump *et al.* 1997). Incomplete hard linking (terminology after Walsh & Watterson 1991) between the basement structures results in strain “leaking” from the basement into the cover sequence, which is manifested as penetrative deformation within the cover rocks at Sheets Gulch. The exposed supracrustal sequence comprises the Jurassic Navajo Sandstone underlain by the shales and sandstones of the lower members of the Jurassic Glen Canyon Group, and overlain by shales and sandstones of the Jurassic San Rafael Group (Hintze 1988). Of the exposed units, the Navajo Sandstone is the most mechanically competent unit, thus minor strain within the transfer zone, although
presumably distributed throughout the exposed supracrustal sequence, is visibly recorded in the Navajo Sandstone.

The Navajo Sandstone within Sheets Gulch is penetratively deformed by a system of conjugate strike-slip deformation band shear zones (DBSZs) (Davis et al. 1997). Although DBSZs may extend the breadth of the study area, measurable offset on individual bands is no more than 4 m and total regional strain may not exceed 2%. DBSZs typically outcrop as resistant, light-colored bands, up to a few tens of cm wide, composed of tens to hundreds of anastomosing individual deformation bands (Davis et al. 1997). Dextral and sinistral DBSZs are mutually offsetting and there is no clear temporal relationship between DBSZs in the two orientations, thus they may have formed contemporaneously (Davis et al. in press, Davis et al. 1997). Slickenlines on DBSZs are generally oriented sub-parallel to bedding within the Navajo Sandstone and bands dip more shallowly to the north with increasing southerly dips of bedding, suggesting that band formation preceded local bedding rotation, and thus the formation of the Waterpocket Fold (Davis pers. commun. 1997). As seen in other Riedel systems (e.g. Morgenstern & Tchalenko 1967) the system at Sheets Gulch displays a remarkable scale-invariance and self-similarity over at least three orders of magnitude (Davis 1996, Ahlgren 1999) (Figure 4). For example, regional-scale DBSZs may be interpreted as large-scale Riedel shear zones, sub-bands within the DBSZs often exhibit a Riedel geometry, and these bands, in turn, may be Riedel shear zones.
Outcrop Scale Structure

This study examines the sequential development of outcrop-scale Riedel shear zones composed of deformation bands (Davis 1996) marked by grain-scale cataclasis and compaction of the Navajo Sandstone (e.g. Aydin 1978). Deformation bands are typically less than one millimeter wide and crop out as positive weathering, light-colored planar to slightly curviplanar shear bands. Riedel array deformation bands may form as subsidiary shears associated with a regional-scale DBSZ, as a PSZ contained within a regional-scale DBSZ, or within otherwise undisturbed host rock (Figure 4). Tipping PSZs are common, and often form as subsidiary shears terminating on one end in undisturbed rock and on the other end at a PSZ or DBSZ. Tip-to-tip examples, with both ends of the zone terminating in undisturbed Navajo Sandstone, are also present although uncommon.

This study is most concerned with the geometry and kinematics of Riedel shear zone development in both the tip regions of evolving PSZs and regions between adjacent, en échelon PSZs (Figure 4). These regions tend to be geometrically simple and, kinematically, they capture the zone at a primitive developmental stage. Deformation within the tip regions of a PSZ are interpreted as the lateral propagation mechanism of the PSZ as well as the original nucleation mechanism (thus the earliest stage of sequential development) of the PSZ. These regions of incipient Riedel array development are termed Proto Riedel Zones (hereafter referred to as PRZs).

The following section describes the geometry of PRZs and PSZs and incorporates a nomenclature similar to Morgenstern (1967) by which individual deformation band types are labeled \( Z_1 \ldots Z_4 \).
Figure 4: Geometry and scale invariance of Riedel shear zones composed of deformation bands and systems of deformation bands. Zones are shown with long axis oriented horizontally. a) Regional-scale Deformation Band Shear Zones (DBSZs) with overstep regions between adjacent DBSZs. b) Outcrop-scale Principal Shear Zones (PSZ) with overstep regions between other smaller-scale PSZs. c) Tip region of PSZ composed of individual deformation bands. PSZ tips as a Proto Riedel Zone (PRZ).
Geometry of a Riedel Shear Zone

Some Riedel arrays exhibit a systematic along-strike geometric change from a tip with zero displacement to a Proto Riedel Zone (PRZ) to a well developed Principal Shear Zone (PSZ) with the greatest displacement (Figure 5). These smaller-scale zones are oriented similarly to regional-scale Deformation Band Shear Zones (DBSZs) and may tip into DBSZs or evolve into DBSZs along strike.

A PRZ is defined by a tabular zone of en échelon, planar to curviplanar, unconnected deformation bands (Z₁ bands) (Figure 6). Spacing of the bands along strike of the PRZ is semi-regular, and on the order of a few cm. Z₁ bands are oriented at 50° to 88° (average 67° ± 11°) with respect to the strike of the PRZ, are roughly symmetric about the PRZ axis and extend laterally a few cm to tens of cm. Some PRZs are composed solely of spaced, en échelon Z₁ bands, which may or may not exhibit a sigmoidal geometry in plan view (Figure 6a).

Moving up-gradient along the PRZ (e.g. Figure 5), Z₁ bands typically assume a gently curved, sigmoidal geometry in plan view, and a single Z₁ band may exhibit a 13° - 43° angular discordance between the strike of one of its free tips and the strike of its interior region. Similarly, there may be a change in dip magnitude and/or direction from tip to tip along a single Z₁ band, suggesting that the band is helicoidal in three dimensions. Z₂ bands may be present in regions between adjacent Z₁ bands. If present, Z₂ bands are centered on the axis of the PRZ, typically sigmoidal in plan view and oriented sub-parallel to Z₁ bands, at least near the axis of the PRZ (Figure 6b).
Figure 5: Plan view of the tip region of an idealized sinistral PSZ showing systematic up-gradient evolution from a PRZ to a PSZ to a more complex fault zone.
**Figure 6:** Geometry of PRZs from Sheets Gulch. a) Plan view of a sinistral PRZ composed entirely of en échelon $Z_1$ bands oriented at a high angle to the zone boundary ($\delta = 75^\circ$). Note semi-regular spacing, linearity of $Z_1$ bands and the lack of lower-angle bands. b) Plan view of a sinistral PRZ composed primarily of $Z_1$ and $Z_2$ bands. Displacement grows toward the left side of the image and the PRZ evolves into a PSZ along strike. Note the regular $Z_1$ band spacing, in filling by $Z_2$ bands, sigmoidal form of $Z_1$ and $Z_2$ bands, and minor $Z_3$ band development.
Continuing up-gradient along the PRZ, lower-angle $Z_3$ deformation bands are typically present at $5^\circ$ to $35^\circ$ (average $19^\circ \pm 8^\circ$) with respect to the strike of the PRZ. $Z_3$ bands may offset both $Z_1$ and $Z_2$ bands with a sense of shear synthetic to displacement on the PRZ. In some examples, $Z_3$ bands link the tips of $Z_2$ bands, although there may be incomplete along-strike linking of the $Z_1$ and $Z_2$ bands comprising the PRZ (Figure 7a). The tip-linking $Z_3$ bands may overstep and overlap in plan view, and within regions between adjacent, overlapping $Z_3$ segments, additional laterally discontinuous $Z_4$ deformation bands oriented at $40^\circ$ to $114^\circ$ (average $78^\circ \pm 14^\circ$) with respect to the PRZ may be present. In plan view, $Z_4$ bands tend to be linear and they are generally oriented sub parallel to $Z_1$ and $Z_2$ bands in the interior of the PRZ.

Further up-gradient, the system is typically too geometrically complex for detailed geometric interpretation although through-going deformation bands oriented sub-parallel to the trend of the PRZ are easily interpreted. $Z_1$, $Z_2$, $Z_3$ and $Z_4$ bands are often thicker with polished or slickenlined sides, suggesting that each band is now (spatially along strike of the PSZ) a brittle fault. The sense of slip on $Z_2$ bands is synthetic to sense of slip on the zone as a whole and the sense of slip on $Z_1$, $Z_2$ and $Z_4$ bands is antithetic with respect to the sense of slip on the zone as a whole. At this point (at least spatially), the PRZ may be considered a PSZ. Figure 8 provides a graphical summary of the variable orientations of $Z_1...Z_4$ bands.
Figure 7: Overstep region geometry. a) Photograph of an open overstep region between two dextral Z3 bands. Note incomplete linking of sigmoidal Z2 bands by lower-angle Z3 bands. b) Photograph and tracing of closed overstep region between PSZs tipping as PRZs. Note the regularly spaced Z1 bands within the overstep region and the lack of lower-angle bands within the overstep.
**Figure 8**: Summary of the orientations of observed $Z_1$, $Z_2$, $Z_3$ and $Z_4$ bands. Angles are measured from the axis of the Riedel shear zone; anticlockwise is positive. Average $Z_1/Z_2$ inclination is $67^\circ \pm 11^\circ$ ($n = 139$), average $Z_3$ band inclination is $16^\circ \pm 9^\circ$ ($n = 92$), and average $Z_4$ band inclination is $78^\circ \pm 15^\circ$ ($n = 26$).
Geometry of Overstep Regions

Overstep regions are defined as discrete, roughly orthorhombic regions where there is spatial overlap between pairs of deformation bands (commonly Z3 bands) or band systems (PRZs or PSZs) (Davis 1996). The overstep zone is closed if the segments overlap and are connected by other bands or band systems (for example, Z3 bands connected by Z4 bands) and open otherwise (Figure 7). All observed examples are contractional oversteps; dextral bands and band systems step to the left and sinistral bands and band systems step to the right across an overstep zone, (Segall & Pollard 1980). In large-scale systems, spacing between PSZs or DBSZs may be tens of cm to a few m, but in more poorly developed overstep systems between pairs of Z3 bands or PRZs, spacing of the approaching segments is a few cm to twenty cm. Commonly, stepping Z3 bands do not overlap spatially, and sigmoidal Z2 bands are present within the overstepping region (Figure 7a). It is important to note, however, that the Z2 bands do not necessarily physically connect with the overstepping Z3 bands, thus the Z2 bands form part of the “soft” link (terminology after Walsh & Watterson 1991) between the Z3 bands. In situations where Z3 bands do overlap spatially, however, Z4 bands are present and act as hard links between the Z3 bands.

Visualizing Riedel Shear Zones in Three Dimensions

To better understand the internal geometry of a Riedel array, I reconstructed a Riedel array in three-dimensional digital space (Ahlgren 1999), which, to the best of my knowledge, has been previously documented only for analog models. Previous workers
effectively apply methods such as tomographic imaging to visualize the three-dimensional structure of complex fault structures such as Riedel shear zones (e.g. Schreurs 1994). Destructive methods, such as sequential sample dissection, lead to complete annihilation of the original sample, but are inexpensive and more accessible compared to methods such as tomography. In this study, the dissected sample is a field sample of a representative PSZ.

The destructive modeling procedure includes sectioning, imaging and reconstruction of a PSZ (Figure 9). The sample was cast into a 35 cm x 25 cm x 25 cm block of gypsum cement and sliced sequentially at 5 mm intervals with a standard rock saw. Each freshly exposed rock surface was photographed with tripod-mounted digital and film cameras from an orthogonal distance of 65 cm. After digitally trimming and scaling the photographs, deformation band traces were digitized in a two-dimensional structural cross section balancing computer program, and these sequential cross sections and plan-view sections were imported into a three-dimensional structural restoration computer program\(^1\). Much like interpreting gridded seismic data, deformation band traces were correlated across adjacent vertical sections and verified by plan view sections (Figure 10a). The final model is composed of approximately forty vertical cross sections and three plan-view sections, and unlike the original sample, the three-dimensional model facilitates full virtual tours through the heart of the PSZ (Figure 10b). It is important to

\(^1\) Two-dimensional cross sections and three-dimensional models created with 2DMove\textsuperscript{TM} and 3DMove\textsuperscript{TM}, respectively, courtesy of Midland Valley Exploration, Glasgow, UK.
Figure 9: Method for three-dimensional reconstruction of a PSZ. a) Field sample is cast in block of gypsum cement prior to b) sequential dissection with a rock saw. c) Digital photographs from each slice are traced as cross-sections in two dimensions. d) Two-dimensional sections are used to construct a three-dimensional digital model. See text for details.
Figure 10: Three-dimensional digital reconstruction of a sinistral PSZ. Note: scale bars are approximate due to perspective views. a) Two dimensional map and cross section views of the dissected field sample mapped into three dimensions. Light-colored lines are traces of deformation bands in the dissection planes. b) Plan view of three-dimensional reconstruction of the PSZ. Surfaces are shaded by relative depth within the model.
emphasize that the digital model is a reconstruction of the dissected field sample, not an interpretation of the dissected field sample.

The digital model supports and clarifies relationships gleaned from field observations. Since this particular field sample is not from the exact tip region of a PSZ (e.g. the sample is not a PRZ), all four types of deformation bands (Z₁, Z₂, Z₃, and Z₄) are present and each is geometrically similar to field examples. Z₁ bands are sigmoidal in plan view and they are clearly helicoidal in three dimensions, with along-strike variability in dip magnitude and direction. In plan view, Z₂ bands are sigmoidal and sub-parallel to Z₁ bands, although they are not as laterally extensive as Z₁ bands. In cross-section, Z₂ bands do not extend as deeply into the sample as Z₁ bands, and they exhibit a more subtle three-dimensional helicoidal geometry. Z₃ bands are relatively planar, oriented at smaller angles with respect to the PRZ, and clearly offset both Z₁ and Z₂ bands although these mm-scale offsets are not honored in the digital representation. Similarly, Z₄ bands are present in overlap zones between stepping Z₃ bands, but are not incorporated in the digital reconstruction due to their small-scale and geometric complexity.

DISCUSSION OF STRUCTURE

As described, PSZs vary geometrically along-strike from a PRZ composed of spaced Z₁ deformation bands, to a geometrically simple Riedel shear zone, to more complex fault zones (e.g. Figure 5). The apparent along-strike spatial continuum between a PRZ and a PSZ and the kinematic compatibility between components of the PRZ and the PSZ suggests that the PRZ evolves continuously into a PSZ (Figure 11).
Figure 11: The sequential development of an antithetic driven Riedel shear zone. a) Zone initiates PRZ composed of spaced $Z_1$ bands with $\delta = 70^\circ$ (arbitrary). b) Simple shear sigmoidally deforms $Z_1$ bands; $Z_2$ bands form. c) $Z_3$ (R) and $Z_4$ (R') bands form; shear on $Z_1$ and $Z_2$ bands (R'). d) Most slip occurs on through going PDS bands sub-parallel to zone axis.
This variation in structural style is consistent with the along-strike displacement gradient observed in numerous field examples, with zero displacement at the tip of the zone and some maximum displacement near the center of the zone (for tip-to-tip examples) or at a junction with another zone.

The PRZ nucleates as a tabular array of $Z_1$ bands and, if additional strain is necessary, the zone propagates laterally as a tabular zone of $Z_1$ bands, while more complex structures evolve toward the center of the zone (along strike) where strain is greatest. The initiation of PSZs as tabular zones of high-angle $Z_1$ deformation bands is incompatible with the traditional synthetic driven model of Riedel array development documented in the literature. Rather, the preferred mode of array development is antithetic driven in which $Z_1$ and $Z_2$ bands (which evolve into R' bands) initiate the brittle deformation process and are subsequently overprinted by a pair of conjugate $Z_3$ and $Z_4$ bands (which evolve into R and R' bands, respectively).

The along-strike geometrical evolution of a Riedel shear zone from a PSZ to a PRZ, and in some examples, to zones of sigmoidally deformed cross beds projecting along strike from the PSZ tip, is analogous to other documented examples of shear fractures tipping in subsidiary structures. For example, brittle faults may terminate as kink-bands projecting along strike away from the fault tip (e.g. Peacock 1991, fig. 3), and, under higher-temperature conditions, a mylonitic ductile shear zone may project from the tip of a strike-slip fault (Burgmann & Pollard 1994, fig. 3d). Similarly, a tensile fracture may evolve into an en échelon tensile crack array oriented along the strike projection of the parent tensile fracture (e.g. Pollard et al. 1982).
In each of these analog examples, the changing structural morphology of the primary strain feature (e.g. the fault zone) reflects the along-strike change in strain magnitude. Thus, the region along strike of the primary strain feature with the lowest strain records the lowest-strain mechanism. In a natural system the earliest physical strain mechanism(s) may not be clear due to overprinting by higher-strain features. As discussed, however, within Sheets Gulch these initial features are visible as isolated PRZs and within the tip regions of propagating PSZs (e.g. Figure 6), suggesting that the strain mechanism responsible for nucleation of PSZs is the same mechanism responsible for lateral propagation of PSZs.

Z₁ Band Nucleation

The presence of PRZs comprising only Z₁ bands and the geometrical symmetry of deformational styles about the center of tip-to-tip PSZs suggests that Z₁ band formation is the earliest stage in the progressive development of PSZs. After exploring a number of possibilities to explain the formation mechanism(s) of these deformation bands, I conclude that they most likely nucleate as shear fractures. Although it is unlikely that Z₁ bands initiate as purely tensional features, the following discussion of Z₁ bands possibly nucleating as tension fractures is included due to the geometric similarly of PRZs and tension fracture arrays composed of sigmoidal gash fractures (e.g. Shainin 1950, Plates 1-2). Please note that the alternative interpretation may also apply to Z₂ bands.

There is debate about the kinematic significance and development of sigmoidal, en échelon tensional fractures (e.g. see Rickard & Rixon 1983, Olson & Pollard 1991).
but ideally, fractures within an array nucleate as planar tensile fractures at $\delta = 45^\circ$, where $\delta$ is the angle from the crack tip to the zone (e.g. Hancock 1972) and are subsequently sigmoidally deformed by simple shear (e.g. Roering 1968). The angle $\delta$ is variable and dependent on a number of factors including the relative volume change of the shearing zone during fracture propagation. For example, if the shear zone positively dilates, $\delta$ will be greater than $45^\circ$, and if the zone negatively dilates, $\delta$ will be less than $45^\circ$ (e.g. Ramsay & Huber 1983, fig. 3.21) (Figure 12). It is also possible that sigmoidal, en échelon tension fracture arrays may develop without a component of simple shear (Type II fractures of Beach 1975). In this situation, fractures propagate under a localized stress field influenced by interaction between neighboring fractures (Latjai 1969). This idea is supported by field evidence (e.g. Nicholson & Pollard 1985) and more recently by numerical modeling (Olson & Pollard 1991) which uses a randomly seeded fracture population to demonstrate how some fracture orientations in favorable orientations with respect to the far-field stresses evolve into en échelon arrays of sigmoidal fractures. This digital crack interaction model may be successfully applied to numerous field examples (see Olson & Pollard 1991) but the model fails to predict fracture arrays with large $\delta$ values ($\delta > 50^\circ$). As $Z_1$ and $Z_2$ bands typically exhibit $50^\circ \leq \delta \leq 90^\circ$, the model probably does not apply to Sheets Gulch. As discussed, there is also ample field evidence suggesting that heterogeneous simple shear is an important component in PRZ development.

It is most likely that incipient $Z_1$ and $Z_2$ deformation bands nucleate as shear fractures, which is consistent with the generally accepted theory that deformation bands
Figure 12: The development of tensile fractures within a sinistral shear zone. 

a) Constant volume deformation ($\Delta v = 0$); $\delta = 45^\circ$, $e_1 = 45^\circ$. 

b) Net negative dilation of the shear zone ($\Delta v > 0$) (simple shear + pure shear); $\delta > 45^\circ$, $e_1 < 45^\circ$. Modified after Ramsay and Huber (1983), fig. 3.21.
form as shear fractures (faults) (e.g. Aydin 1978). In thin section, $Z_1$ bands are texturally identical to other deformation bands from Sheets Gulch and documented examples from the literature (for detailed microstructure of typical deformation bands see Aydin 1978, Antonellini et al. 1994). $Z_1$ bands are composed predominantly of crushed, angular quartz grain fragments localized in discrete bands one-two grains wide, suggesting that these bands form through localized compaction and cataclastic flow (e.g. Borradaile 1981) imposed during shearing. Direct evidence for shear offset across $Z_1$ bands is difficult to identify in thin section, although in all observed examples, the sense of displacement of individually offset quartz grains is consistent with the “expected” direction of slip along the $Z_1$ band gleaned from mesoscale shear zone relationships.

Thus, although these incipient $Z_1$ bands appear to be shear fractures, their relatively high angle (55° – 85°) with respect to the strike of the shear zone is challenging to interpret kinematically, as is their apparent antithetic affinity. Kinematically, these bands are most convincingly interpreted as “transitional-compactional” shear fractures nucleating within a region of localized high fluid pressure and low differential stress such that failure takes place within the parabolic portion of the Mohr-Coulomb envelope of failure. This failure mechanism is consistent with those proposed by other workers for similar structures in porous sandstone (Davis pers. commun. 1998, Rickard & Rixon 1983).
Interpretation of Structure

The state of stress before and during PRZ development is shown on a series of dimensionless Mohr circles with an arbitrary Coulomb failure envelope (Figure 13). Under low differential stress, the system is stable (Figure 13a). Compaction of the deforming region induces locally elevated fluid pressure (Byerlee 1990) resulting in transitional-compactional shear failure (Figure 13b). Data from Sheets Gulch suggest that the angle between $\sigma_1$ and rupturing $Z_1$ bands is 4° to 40° (average of 22° ± 9°, n = 59) (discussion of methodology follows). Failure within the parabolic portion of the failure envelope normally implies a combination of opening-mode failure, net positive dilation and shear. $Z_1$ bands may exhibit initial positive dilation at peak stress, as demonstrated by other workers for other types of shear fractures (e.g. Edmond & Paterson 1972), but post-rupture compaction and cataclasis results in net negative dilation along the bands, thus these bands may be termed “transitional anticracks” in contrast to transitional tensile fractures (Davis pers. commun. 1998). It is important to note that this stress interpretation, which is consistent with the construction used by others (e.g. Rickard & Rixon 1983) and with the synthetic driven Riedel array model, predicts a pair of conjugate shear fractures inclined at ± $\theta$ with respect to $\sigma_1$ (where $\theta$ is approximately 30°). In the antithetic driven system at Sheets Gulch, however, the synthetic shear fracture oriented at –$\theta$ to $\sigma_1$ is not observed. The lack of the lower-angle synthetic shear fracture is likely due to increased normal stress on that potential failure plane resulting from a component of pure shear orthogonal to the zone; this pure shear component is reflected in negative dilation of the deforming zone.
It is apparent that the initiation and evolution of a PRZ includes both non-destructive reorganization of the host sandstone within the boundaries of the PRZ and localized grain-scale cataclasis of the host sandstone within deformation bands. As described, compaction of the host sandstone within the nucleating PRZ provides the elevated pore fluid pressure essential to Z1 band rupture, and passive deformation of these Z1 bands and sedimentary horizons suggests that the subsequent evolution of a PRZ includes heterogeneous simple shear. The interpretation of this particular deformation path including elevated fluid pressure, distributed shearing, incipient cataclasis, and subsequent shear localization is consistent with published interpretations of deformation within overpressured porous sediments obtained from deep sea cores (Lucas & Moore 1986) (Figure 14). Increased fluid pressure within a deforming porous medium facilitates non-destructive reorganization and compaction, and in systems where differential stress is low, deformation may be distributed across a broad region (Borradaile 1981, Lucas & Moore 1986). Experimental and theoretical evidence from similar porous media suggests that shearing and compaction of the Navajo Sandstone may be facilitated by distributed shear across the breadth of the PRZ through “independent particulate flow” (Borradaile 1981). This forms a continuous feedback loop; distributed granular shearing within some pre-determined tabular region (where the PRZ nucleates) causes locally increased fluid pressure, which, in turn, facilitates further distributed shearing. This cycle of fluid pressure buildup and subsequent stress release allows for Z1 and Z2 band formation under constant differential stress.
Eventually, distributed shearing becomes localized toward the center of the deforming zone (e.g. Mandl et al. 1977, Cundall 1989), and different strain mechanisms evolve including localized cataclasis (e.g. Griggs & Handin 1960). The changing strain mechanisms reflect the changing mechanical characteristic of the host medium. Within a PRZ nucleating in the Navajo Sandstone, shearing and compaction reduces porosity within the PRZ (see Antonellini & Aydin 1994, for representative porosity values) and the region becomes work-hardened (Edmond & Paterson 1972), with a fundamental change in the mechanical character of the host sandstone such as increased cohesion (Vernik et al. 1993) or a larger angle of internal friction (Underhill & Woodcock 1987). Thus, initial strain softening facilitates granular flow resulting in strain hardening and subsequent shear band localization toward the axis of the PRZ (e.g. Lucas & Moore 1986, Underhill & Woodcock 1987, Menéndez et al. 1996). The strain-hardened PRZ then serves as a guide for further localized deformation first as Riedel-array deformation bands, and, with increasing strain, as a through-going fault zone.

After formation of the incipient $Z_1$ deformation bands, the state of stress becomes sub-critical (Figure 13c), although minor $Z_2$ bands continue to form near the axis of the PRZ due to continued cyclical fluid pressure buildup and release. Compaction of the host sandstone eventually reaches some critical level and cannot deform through granular flow or compaction and fluids dissipate resulting in sub-lithostatic fluid pressure. At this point, due to passive rotation, $Z_1$ and $Z_2$ bands may no longer be kinematically favorable as strain paths thus differential stress builds (although the magnitudes of $\sigma_2$ and $\sigma_3$ may remain fixed). If the stress buildup is sufficient to cause failure, $Z_3$ and $Z_4$ deformation
bands will develop within the strain-hardened axis of the PRZ (Figure 13d). These conjugate deformation bands are geometrically and kinematically consistent with R and R’ shears in the traditional Riedel framework (e.g. Figure 1). In addition, field evidence indicates that at this point in the evolution of a PRZ to a PSZ, \( Z_1 \) and \( Z_2 \) bands are polished and/or slickenlined with a shear sense antithetic to the sense of shear along the PSZ, and they may be interpreted as R’ shears. These incipient deformation bands, which initially accommodate negligible offset, become “recycled” as shear fractures when strain along the developing PSZ reaches some critical level.

As deformation along the PSZ continues, additional shears (PDSs) oriented sub-parallel with respect to the trend of the PSZ may develop, and a the PSZ may evolve into a through-going fault system marked by a dense mass of coalescing deformation bands. Previously formed deformation bands may become rotated within the fault zone due to passive rotation accommodated by minor distributed shear and by mechanical rotation. The suggestion that the orientation of Riedel shears, especially high-angle R’ shear, changes significantly through the progressive evolution of the fault zone is not revolutionary (e.g. Morgenstern & Tchalenko 1967, Tchalenko 1970, Wilcox et al. 1973, Moore 1979, Bartlett et al. 1981, Dresan 1991). Similarly, rotation across a PSZ is illustrated by deformed passive markers (e.g. Tchalenko & Ambraseys 1970). Most attribute the change in orientation to progressive block rotation on linked shears such as documented in larger-scale wrench fault systems like the San Andreas (Nur et al. 1986).
Figure 13: Conceptual Mohr circles illustrating the evolution of a Riedel shear zone. a) System is stable at low differential stress until b) elevated fluid pressure results in failure on transitional-compactional shear fracture. c) System is temporarily stable with cyclical pressure buildup/release; strain-hardening may lead to an increase in the angle of internal friction. d) Failure within the strengthened zone occurs under elevated differential stress on conjugate deformation bands. See text for details.
Figure 14: Sequential development of a Riedel shear zone in porous sandstone.

a) Undeformed, fluid-saturated sandstone is subjected to dextral shearing.

b) Elevated pore fluid pressure results in dilation and non-destructive particulate flow accompanied by angular shear $\psi$. 

c) Continued shearing results in compaction and incipient cataclasis. Zone becomes work-hardened.

d) Cataclastic deformation on localized shear bands 1-2 grains wide. In Riedel shear zones, initial deformation is on high-angle, antithetic deformation bands ($Z_1$ bands). See text for details. Modified after Lucas & Moore (1986), fig. 17.
Strain Analysis

It is possible to approximate the amount of shear strain accommodated within a PRZ using the following equation relating the shear strain, area change of the shear zone and the change in orientation of a linear marker crossing the zone (Ramsay & Huber 1987, eq. 26.4):

\[
\cot \alpha' = \frac{\cot \alpha - \gamma}{1 + \Delta_A}
\]

(1)

\(\alpha\) and \(\alpha'\) are the angles a linear feature makes with the shear zone walls outside and inside of the zone, respectively, \(\gamma\) is the shear strain along the shear zone, and \(\Delta_A\) is the area dilation of the shear zone. Simplifying for \(\gamma\), the equation becomes:

\[
\gamma = \cot \alpha - (\cot \alpha')(1 + \Delta_A)
\]

(2)

The amount of angular shear (\(\psi\)) is then calculated from \(\gamma\) using the simple relationship (Ramsay & Huber 1983, p. 3):

\[
\gamma = \tan(\psi)
\]

(3)

In this study, the "internal" strike of a \(Z_1\) band (proximal to the PRZ axis) and its "external" strike (distal from the PRZ axis) are used as \(\alpha'\) and \(\alpha\) values, respectively, and \(\gamma\) values are computed iteratively for a range of area changes. Strain analysis of 13 PRZs yields \(\gamma\) values ranging from 0 to 1.75 with an average \(\gamma\) of .31 ± .28. Corresponding \(\psi\) values range from 0° to 58° and average 22° ± 14° (\(n = 59\)) (Table 1). Although there is great variability in shear strains calculated from different PRZs, \(\gamma\) and \(\psi\) values computed from multiple \(Z_1\) bands within a single PRZ are reasonably consistent, and computed \(\psi\)
<table>
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<tr>
<th>Band</th>
<th>Offset Sense</th>
<th>$\gamma$ average</th>
<th>std. dev.</th>
<th>$\psi$ average</th>
<th>std. dev.</th>
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**Table 1:** Results from strain analysis of 13 PRZs. Note lack of consistency in computed $\gamma$ and $\psi$ values between different PRZs.
values are compatible with angular rotations of deformation bands and cross beds across PRZs. A more complete strain analysis is necessary, however, to fully understand and quantify the amount of shear accommodated on a PRZ prior to PSZ development.

Stress Analysis

The orientations of the principal paleostress axes may be interpreted from Riedel shear zones using a simple graphical construction based on the angle between conjugate R and R' bands, assuming that these two shears form conjugate deformation bands symmetric about the $\sigma_1$ axis. This graphical stress interpretation may only be applied to Riedel shear zones containing both R and R' bands, thus the method may not be entirely accurate when applied to PRZs lacking R and R' ($Z_3$ and $Z_4$) bands. Additionally, since the orientation of bands comprising one band type (e.g. R bands) may change along strike of the band, average band orientations compiled from field data are generally used to compute the stress orientation for a single PSZ. The computed inclination of $\sigma_1$ with respect to PRZs is $22^\circ$ to $61^\circ$ (average of $47^\circ \pm 13^\circ$, $n = 92$) (Figure 15a) (description of computation method follows), which is consistent with theoretical and experimental data suggesting that $\sigma_1$ is inclined at $45^\circ$ to a shearing zone (e.g. Mandl et al. 1977, Naylor et al. 1986). These $\sigma_1$ inclinations translate into N64E/S64W $\pm 13^\circ$ (std. dev.) for sinistral PSZs ($n = 76$) and S69E/N69W $\pm 13^\circ$ (std. dev.) for dextral PSZs ($n = 14$), with an angular discordance between the two orientations of approximately $40^\circ$ (Figure 15b).
Figure 15. Histograms of calculated $\sigma_1$ orientations. a) Average $\sigma_1$ inclination to PSZ axes computed from sinistral and dextral PSZs is $47^\circ \pm 13^\circ$ ($n = 92$). b) $\sigma_1$ azimuths computed from sinistral and dextral PSZs ($n = 90$). Average $\sigma_1$ azimuth compatible with sinistral PSZs is $65^\circ \pm 13^\circ$ ($n = 76$). Average $\sigma_1$ azimuth compatible with dextral PSZs is $102^\circ \pm 13^\circ$ ($n = 14$). Note relative symmetry of the two orientations about the regional $\sigma_1$ azimuth ($80^\circ$).
The NW and NE striking regional-scale DBSZs within Sheets Gulch are thought to have developed with a regional $\sigma_1$ orientation of approximately N80E/S80W (Davis et al. in press), an orientation that bisects the PSZs but is discordant with paleostress orientations interpreted from PSZs. The apparent discontinuity between stress fields compatible with DBSZs and mesoscale PSZs is likely due to localized changes in the orientation of the principle far-field stress axes during shearing. The potential discordance between local and far-field stress orientations is widely noted in the literature (e.g. Mandl et al. 1977, Naylor et al. 1986, Byerlee 1992, McKinnon & Garrido de la Barra 1998) although the exact mechanism for principal stress rotation is variably explained. Rotations may be induced dynamically by movement along slip discontinuities or statically by non-straining processes. For example, faults may exhibit local stress field perturbations, especially near their tips (e.g. Chinnery 1966, Segall & Pollard 1980, Gamond 1983), which has been reflected experimentally as changing deformational styles along fault and crack tips (e.g. Mandl et al. 1977, Olson & Pollard 1991). Local stress field rotations and interactions are also interpreted from field examples of brittle cracks and faults (e.g. Nicholson & Pollard 1985). These local stress perturbations may be caused by induced local fluid pressures (Byerlee 1990) or the result of some shear couple resulting from simple shear across a deforming region (e.g. Mandl et al. 1977, Braun 1994, McKinnon & Garrido de la Barra 1998). More recently, McKinnon & Garrido de la Barra (1998) document progressive stress rotations and counter-rotations in two-dimensional modeling of Riedel shear arrays. They observe up to 30° stress readjustments occurring during the shearing process and conclude that the
local orientation of the principal stress axes is at least partially controlled by the type of active shear fracture; e.g. if the currently shearing surface is an R shear or R’ shear. These stress rotations may be responsible for the geometric evolution of Riedel shear arrays including the development of new types of shear surfaces (e.g. Naylor et al. 1986).

Since PRZs and PSZs are in similar orientations as DBSZs and are structural precursors to DBSZs, it is likely that these structures formed in the same WSW-ENE regional stress field, although the discordance between interpreted $\sigma_1$ paleostress orientations would suggest otherwise. Davis et al. (in press) note a similar discordance between the regional $\sigma_1$ orientation and larger-scale Riedel geometries observed within DBSZs, and conclude that this discordance is strong evidence for localized stress field rotations within macroscale DBSZs. Data from small-scale structures at Sheets Gulch strongly suggest that the regional $\sigma_1$ orientation becomes reoriented before the inception of brittle faulting within conjugate Riedel shear arrays. Along sinistral PRZs, $\sigma_1$ must experience at least 15° of anticlockwise rotation, and along dextral PRZs. $\sigma_1$ must experience at least 15° of clockwise rotation in order to be compatible with structures that evolve within these PRZs (Figure 16). Although $\sigma_1$ rotations are well documented in the literature, rotations documented from analog modeling are not entirely consistent with stress rotations interpreted from Sheets Gulch. For example, analog modeling of sinistral shear zones in unconsolidated sand (Gamond 1983) suggests a clockwise $\sigma_1$ rotation, and computer modeling of dextral shear zones, suggests an anticlockwise $\sigma_1$ rotation (Dresan 1991, Braun 1994). Stress rotations interpreted from modeling are probably dependent on boundary conditions, e.g. the initial stress configuration preceding deformation and
Figure 16: Localized rotation of the regional $\sigma_1$ within PSZs. Computed $\sigma_1$ rotation is approximately $+15^\circ$ for dextral PSZs and $-15^\circ$ for sinistral PSZs (clockwise rotation is positive).
the direction of induced strain. Thus, confined models with loading orthogonal to the shear plane will exhibit stress rotation opposing the sense of shear (e.g. clockwise $\sigma_1$ rotation with sinistral shearing) and models with loading parallel to the direction of stress will exhibit rotation consistent with the sense of shear (anticlockwise rotation with sinistral shearing) (e.g. Naylor et al. 1986). Models with isotropic horizontal stresses (orthogonal to the strain plane) will assume an instantaneous $\sigma_1$ oriented at 45° to the shear zone upon the inception of shearing (e.g. Mandl et al. 1977). Stress rotations within Sheets Gulch are presumably strain-induced and are a response to localization and first increment of shear strain along a PRZ.

*Three-Dimensional PSZ Geometry*

Both the three-dimensional digital PSZ reconstruction and field observations document the helicoidal geometry of shears comprising a Riedel array, which has been noted either directly or indirectly by other workers (e.g. Emmons 1969, Wilcox et al. 1973, Moore 1979, Naylor et al. 1986, Braun 1994, Schreurs 1994). In these and other analog models, the synthetic shears exhibit a helicoidal morphology, not the antithetic shears, as documented in this study. Schreurs (1994) alludes to the helicoidal geometry of R' shears by suggesting that these shears exhibit along-strike changes in dip direction in analog models but does not elaborate (Schreurs 1994 fig. 3). R shears within the three-dimensional digital reconstruction created in this study are not helicoidal, which may be due a fundamental difference in their rupture mechanism as compared with other documented examples, or the relative difficulty in interpretation of these lower-angle
bands when constructing the model (they are inclined at a small angle to the dissection plane).

Physical analog models designed to create a Riedel array commonly consist of a deformable medium (e.g. clay cake or granular material) over a “rigid” basement with a single “fault,” a setup designed to reproduce a typical, natural wrench fault zones (e.g. Wilcox et al. 1973). For example, flower structures are commonly interpreted as rooting within a master fault zone at depth or within basement, and twist helicoidally and widen toward shallower depths (e.g. Harding 1985). In analog models, brittle deformation will nucleate at the break in the “rigid basement,” hence the model setup is predisposed to forming helicoidal Riedel shears. The shears nucleate from the basement “fault” and twist helicoidally upward through the cover sequence to the free surface at the top of the model, at which point they may be oriented at a significant angle to the basement structure. The twisted geometry may reflect the discontinuity in the stress state from the base of the model to the free surface of the model caused by shear stresses propagating upward from the “basement”, with the fault surface seeking some ideal orientation within the stress field (Naylor et al. 1986). For example, tensile fractures commonly evolve into en échelon crack arrays at their tips, which represents a localized stress perturbation at the tip of the master fault (Pollard et al. 1982). Similarly, recent computer modeling of wrench fault zones (Braun 1994) demonstrates that the helicoidal geometry of shears within a Riedel array may be related to far-field stresses around the Riedel array. As with physical analog models, Braun’s computer model generates a Riedel array above a single basement fault, and Riedel shears are sub-parallel to the basement fault at the
basement/cover interface and twist helicoidally upwards toward the free surface at the top of the model. Braun (1994) indicates that the shears are P shears, since they exhibit a sense of slip antithetic to the sense of slip on the PSZ. As with physical analog modeling, this digital model seems predisposed to forming helicoidal Riedel shears due to the non-linear failure criteria, in which stresses are depth dependent, used in the model (Braun 1994).

As previously mentioned, observable deformation within Sheets Gulch is confined to the relatively structurally competent Navajo Sandstone, which is sandwiched between more structurally incompetent mixed sand and shale units. Thus, it is reasonable to conclude that deformation within Sheets Gulch is not controlled by pre-existing basement-type structures in the underlying sedimentary and basement rocks, and that Riedel-array deformation banding occurs in free deformational space within the relatively mechanically homogenous sandstone host. It follows that the helicoidal geometry of antithetic deformation bands may be due to the state of stress during fracture propagation or due to secondary, post-rupture rotation. As discussed, there is strong evidence for localized regional σ1 reorientation along mesoscale PSZs and PRZs, and helicoidal antithetic deformation bands (Z₁ and Z₂ bands) suggests that there may be further modification of the regional stress field localized at the cm to mm-scale along propagating deformation bands. These stress field readjustments may be due to interaction between bands propagating close to each other spatially, as suggested to explain along-strike curvature of propagating tensile cracks (e.g. Latjai 1969), although in these documented examples, crack tips tend to propagate toward each other, not parallel
to each other as do \( Z_1 \) and \( Z_2 \) bands. It is also possible that these incipient, high-angle deformation bands propagate as planes and are subsequently sheared in three dimensions, resulting in a three dimensional helicoidal geometry. As discussed, there is strong evidence for distributed shearing in two dimensions, and it is reasonable to assume that shearing was not restricted to a plane orthogonal to the strike of a PSZ or PRZ.

**CONCLUSIONS**

*Antithetic driven* Riedel shear arrays nucleate as *Proto Riedel Zones (PRZs)* composed of spaced \( Z_1 \) deformation bands localized within a negatively dilating and shearing tabular zone of porous Navajo Sandstone. These initial shears develop as transitional-compactional shears induced by supra-lithostatic fluid pressures driven by fluid expulsion from the deforming region. The stress cycle of fluid pressure buildup with subsequent stress relaxation after band formation results in \( Z_1 \) and \( Z_2 \) band formation under constant differential stress, and continues until the host sandstone can no longer accommodate strain through compaction and granular flow. At this point, the PRZ is work-hardened and strain localizes toward the axis of the PRZ. Conjugate \( Z_3 \) and \( Z_4 \) deformation bands develop, transforming the PRZ into a *Principal Shear Zone (PSZ)*. These bands are consistent with R and R' bands in Riedel shear zones, and nucleate symmetrically about \( \sigma_1 \). With increasing strain, \( Z_1 \) and \( Z_2 \) deformation bands are “recycled” as antithetic R’ shears. Paleostress orientations consistent with PSZs are discordant with regional, far-field stress orientations, and strongly suggest that far-field stresses are rotated by \( \pm 15^\circ \) at the inception of deformation along PRZs. Helicoidal
deformation bands within PRZs and PSZs may also be indicative of localized stress reorientation.

The evolution of a single Riedel shear zone through these distinct developmental stages is apparent through along-strike transitions from simple, incipient geometries to more complex Riedel geometries. These geometries are visualized and clarified by three-dimensional digital reconstruction of a Riedel shear zone. The modeling technique utilized in this study may be applied effectively to other structural systems and may have far-ranging applications. For example, the models generated in this study are currently being used to assess three-dimensional fluid flow through the deformed Navajo Sandstone.
REFERENCES


