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STRAIN ACCOMMODATION IN THE FOOTWALL OF THE RUBYS INN THRUST FAULT, HILLSDALE CANYON, SOUTHERN UTAH

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ABSTRACT

The Rubys Inn thrust fault in southern Utah has produced several styles of deformation in its footwall. This project describes four exceptionally well exposed examples of strain accommodation, including a mountain-scale, ductile footwall drag fold, cataclastic flexural slip between bedding surfaces of differing competencies, plastically deformed petrified wood within the zone of flexural slip, and cataclastic shear expressed as deformation bands. Such examples show how various lithologies can be deformed into a wide array of structures during a single deformation event. Furthermore, some of these structures result in changes in permeability, which are important for those interested in subsurface fluid flow.

KEY WORDS: Marysvale volcanic field; Wahweap Formation; Claron Formation; Bryce Canyon National Park; Paunsaugunt fault; Sevier fault; Basin and Range Province; Colorado Plateau; Trishear Model

INTRODUCTION

Southern Utah's Rubys Inn thrust fault in Bryce Canyon National Park and Hillsdale Canyon (Fig. 1) occurred due to the gravitational collapse of the late Oligocene and early Miocene Marysvale volcanic field (Davis and Krantz, 1986; Lundin, 1987; Lundin, 1989; Merle, *et al.*, 1993; Davis, 1997; Pollock and Davis, 2004; Davis and Pollock, 2010). The south-directed thrust fault placed Cretaceous Wahweap Formation sandstone and conglomerate beds over Paleocene and Eocene Claron Formation paleosol, fluvial, and lacustrine deposits. Younger extensional faults crosscut the Rubys Inn thrust fault near the eastern boundary of Bryce Canyon National Park and on the western boundary of Hillsdale Canyon (Fig. 1). The Paunsaugunt and Sevier faults are both westward dipping normal faults active in the late Neogene (Pliocene) and Quaternary periods (Lund, *et al.*, 2007; Anderson and Barnhard, 1992; Biek, *et al.*, 2012). They are the easternmost extensional faults in the transition zone between the Basin and Range Province and the Colorado

Plateau. Our study area lies between these normal faults and directly south of the Rubys Inn thrust fault in Hillsdale Canyon. MacLean (2014) showed that some structures associated with the Rubys Inn thrust fault in the Badger Creek area close to Bryce Canyon National Park were reactivated during Neogene and Quaternary extension, but such extensional features have not been observed in Hillsdale Canyon. Thus, this paper focuses on contractile structures. May, *et al.* (2012) gave a general summary of the area's geologic setting and Biek, *et al.* (2012) described the pertinent stratigraphic units in great detail. Figure 1 and 2 summarizes the spatial relationships of major structures of the Wahweap and Claron formations, respectively.

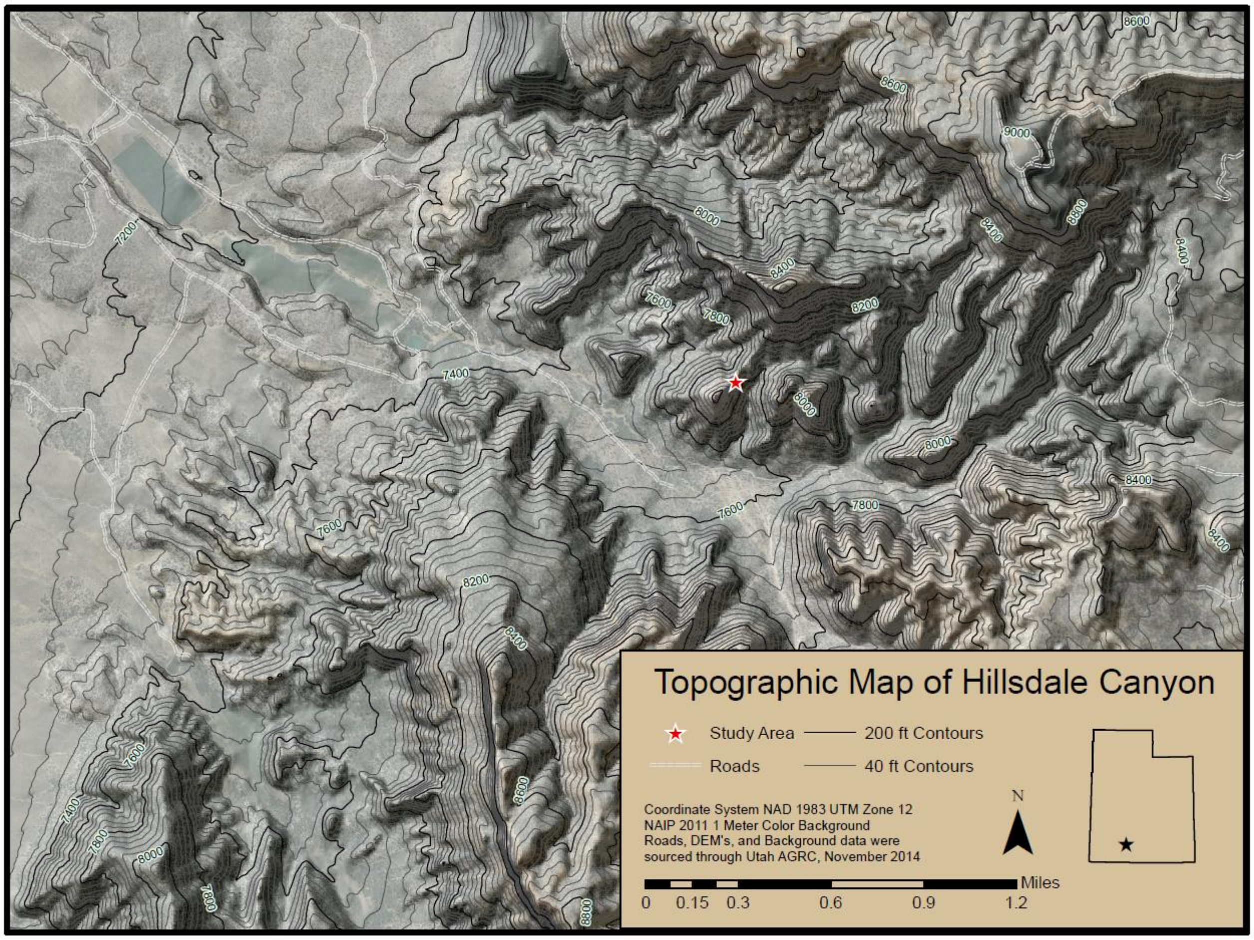


Figure 1. Topographic map and hillshade of the field area in Hillsdale Canyon in southern Utah.

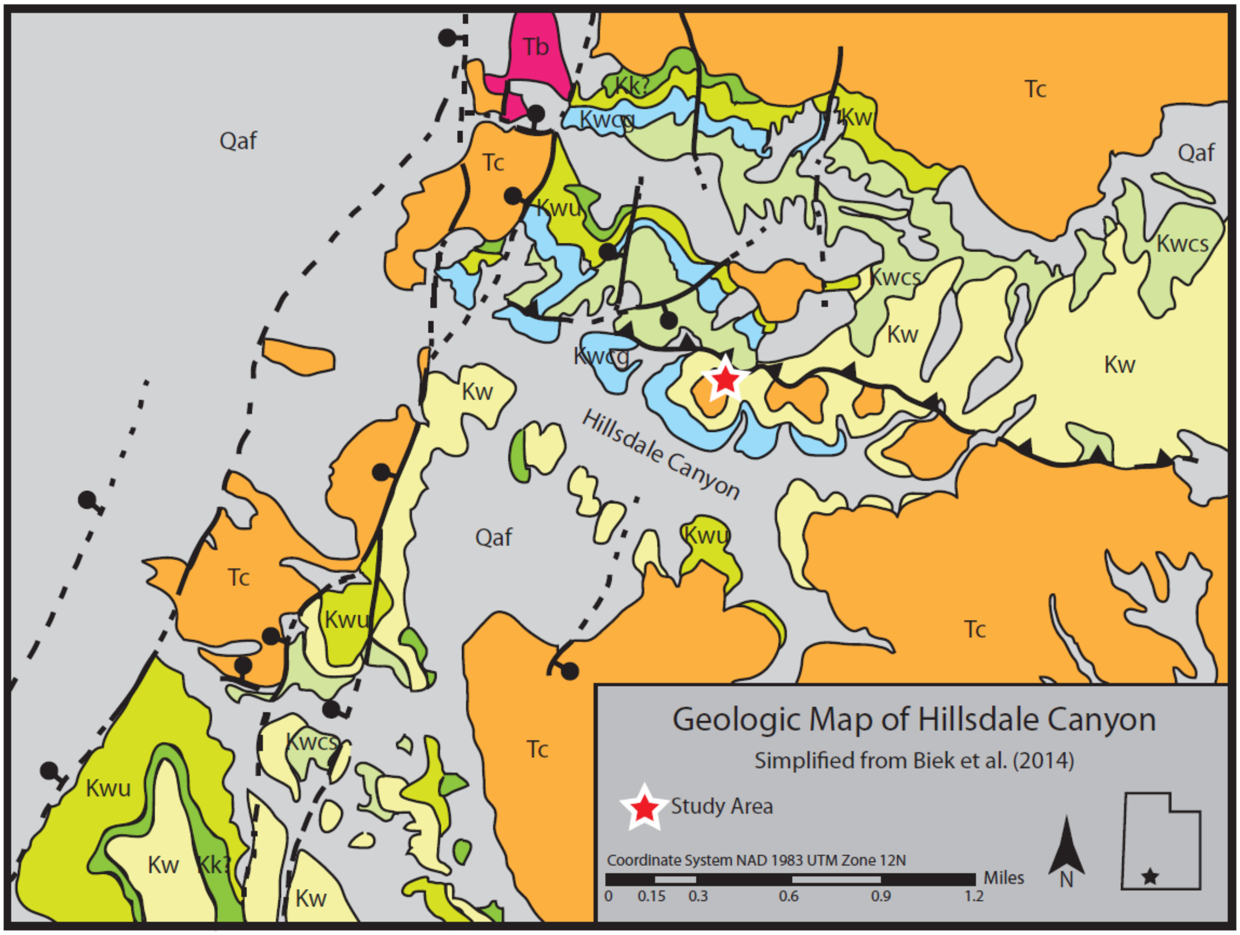


Figure 2. Geologic map of the field area in Hillsdale Canyon in southern Utah. The Rubys Inn thrust fault is represented by the NW-SE trace with barbs on the hanging wall. All other faults are extensional faults related to the Sevier fault zone. Kw = Wahweap Formation, undivided; Kwu = upper unit of Wahweap Formation; Kwcg = pebbly sandstone unit of Wahweap Formation; Kwcs = capping sandstone member of Wahweap Formation; Kk? = Kaiparowits Formation; Tc = Claron Formation; Qaf = Quaternary alluvial fill. Geologic map is modified from Biek, *et al.* (2014).

Several structures exposed in Hillsdale Canyon occur in the footwall of the Rubys Inn thrust fault, including: 1) a mountain-scale synclinal drag fold involving both the Wahweap and the Claron Formations, 2) flexural slip along thin shale layers between more competent Wahweap sandstone and conglomerate beds, 3) plastically strained petrified wood fragments deposited in one such shale layer, and 4) an abundance of deformation bands crosscutting Wahweap sandstone and conglomerate beds. In this article we investigate how each of these structures contributed to the total accommodation of strain during displacement of the Rubys Inn thrust fault. We include thorough descriptions of each structure, and provide kinematic and dynamic structural analyses where appropriate.

FOOTWALL SYNCLINAL DRAG FOLD

The Rubys Inn thrust fault and its accompanying Pine Hills thrust fault have an east-west trace across the Paunsaugunt plateau between the Paunsaugunt fault and the Sevier fault (fig. 1). The Rubys Inn thrust fault dips to the north at approximately 30° and places Cretaceous strata of the Wahweap Formation over younger Eocene strata of the Claron Formation (Davis and Bump, 1999). Southeast of Wilson Peak, the northern branch bends slightly to the northwest before terminating into a gentle monocline. The southern branch, which is the main branch, traces to the west until it is truncated by the Sevier Fault (Merle, *et al.*, 1993). The western footwall of the Rubys Inn thrust fault has the best exposed structures, particularly in the Hillsdale Canyon area.

In Hillsdale Canyon, one structure we examined was a synclinal drag fold. Drag folds result as fault blocks slide past each other during faulting. In our study area, the Wahweap Formation in the footwall was folded into a syncline beneath the overriding Claron Formation in the hanging wall (fig. 3).

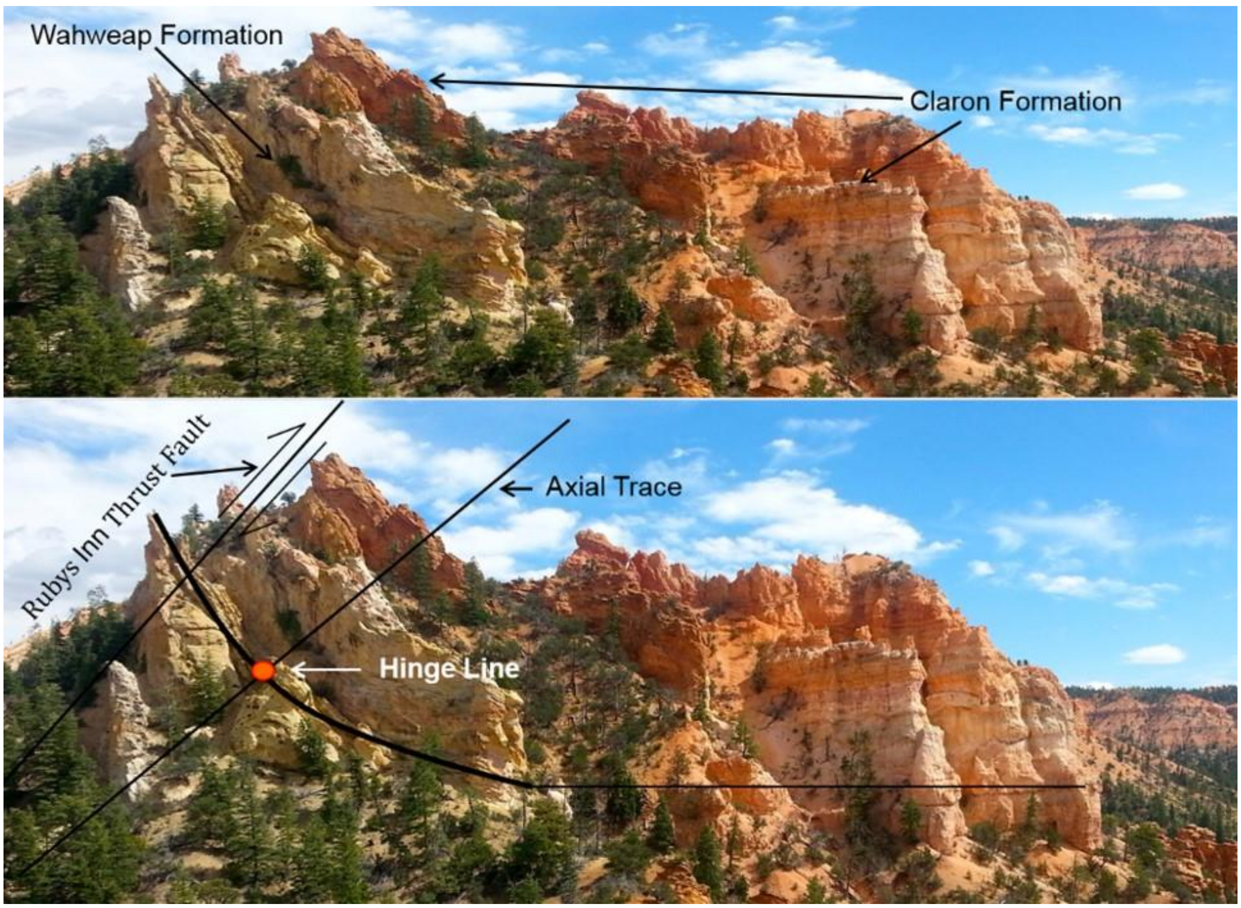


Figure 3. Photograph of a footwall drag fold beneath the Rubys Inn thrust fault in Hillsdale Canyon. View is to the east.

We can use the Trishear Model (Erslev, 1991) to better explain how drag folds occur. In the trishear model, the slip discontinuity on a fault becomes distributed into a triangular zone of shear in front of the fault with an apex at the propagating fault tip (Twiss and Moores, 2007). The footwall stays fixed while the hanging wall moves at a constant velocity. The triangle is symmetric with the fault while the velocity vectors are constant and identical for any point originating at the fault tip (fig. 4) (Fossen, 2010b). In a brittle environment, a damage zone occurs in the trishear zone. This damage zone consists of rocks that have been damaged by shear fracturing. In a ductile environment, the shear zone develops by ductile flow (Twiss and Moores, 2007). In Hillsdale Canyon, we examined folds that appear to have formed in the trishear zone. These folds were subsequently cut by the propagating fault tip, creating drag in the footwall block.

We can describe our fold as an open, concentric, inclined fold with a shape category of B, and an amplitude of 4 (fig. 5) (Fossen, 2010b). We were also able to estimate the strike and dip of the folded limb, fault plane, and axial plane. The folded limb is oriented N43W, 66SW. The fault plane is oriented N77W, 33NE, and the axial plane is oriented N70W, 43NE. The orientations are estimates because of the large scale of the outcrop, the poor accessibility, and the fact that both the fault plane and axial plane have been eroded. Folding was accommodated through a cataclastic flow mechanism during flexural slip, described below.

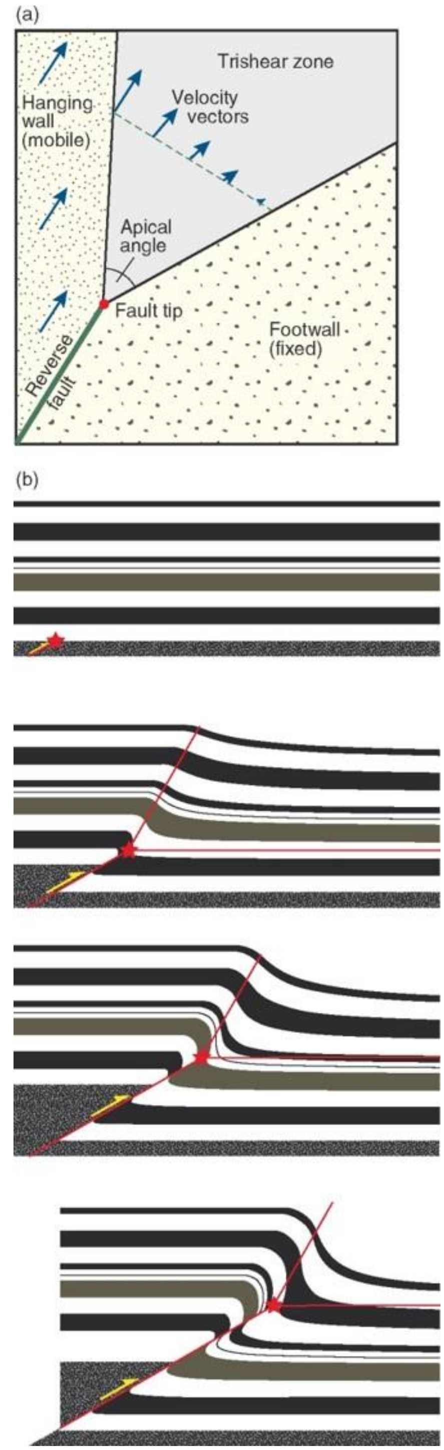


Figure 4. Trishear model of a reverse fault similar to the deformation seen in Hillsdale Canyon (from Fossen, 2010b).

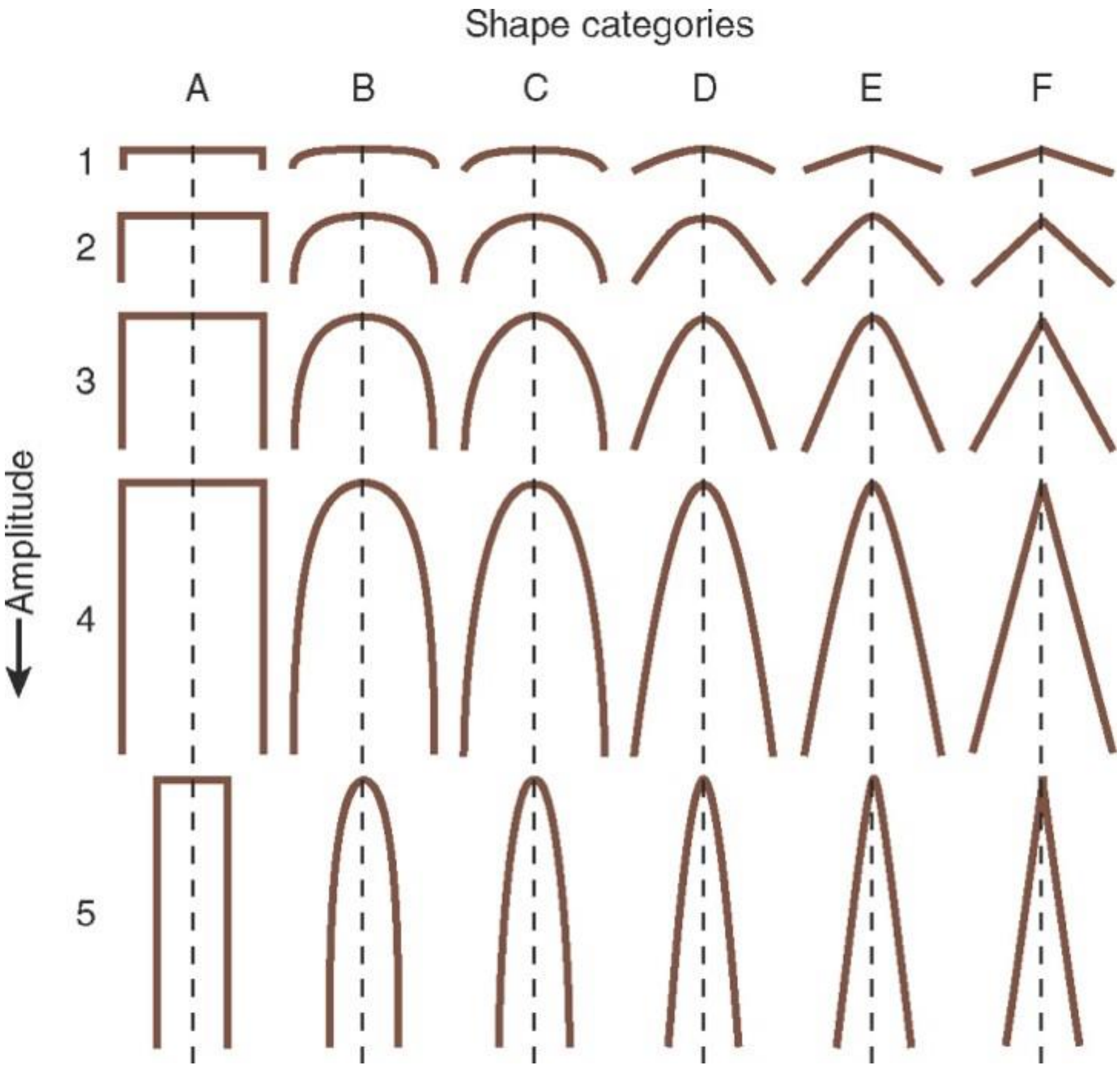


Figure 5. Fold classification based on shape (Fossen, 2010b).

FLEXURAL SLIP

Cataclasis occurs through brittle crushing of grains accomplished by frictional sliding and rotation between rocks, which can cause the formation of a fault gouge. Cataclasis is commonly found in brittle environments where flexural slip occurs along bedding interfaces during the folding of rock layers. Less competent material such as mica, clay, and evaporites at bedding interfaces allows slip to occur more easily compared with the more competent rock layers. As the rock folds, layers will slip past each other with slip displacement increasing away from the hinge line. Strain accommodation, therefore, is concentrated cataclastically at the weak layers. In such environments, competent layers retain their original thicknesses, and incompetent layers exhibit internal deformation. A good analogy is shown in Figure 6 (Fossen, 2010b) where competent layers are represented by playing cards, and incompetent layers are represented by the boundaries between the playing cards.

Our study area contained competent, well sorted, fine quartz sandstone layers above and below an incompetent siltstone layer. The incompetent layer is characterized by cataclasized white, pink, and purple clay minerals with angular, poorly sorted quartz grains (fig. 7). The individual competent layers observed were not internally deformed. The siltstone layer was fractured cataclastically and was cohesive and non-foliated.

The flexural slip structure found at Hillsdale Canyon has created other indicators for paleostress and strain. The siltstone layer is rich with petrified wood, which now displays deformation from the flexural slip. The deformed petrified wood is described in the following section.

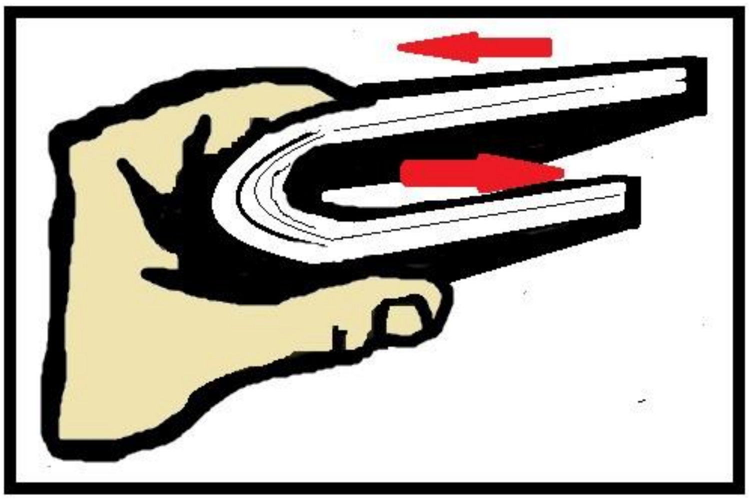


Figure 6. Model of flexural slip. Pages of a rolled paperback magazine slide past each other. In Hillsdale Canyon, flexural slip occurred along incompetent, fine-grained beds as more competent sandstone layers were folded in the footwall beneath the Rubys Inn thrust fault.

Figure 7. Flexural-slip manifested in an incompetent folded siltstone between two competent sandstone layers. Such weak, thinly bedded siltstone layers are susceptible to cataclasis during flexural slip.

STRAINED PETRIFIED WOOD

In the zone of flexural slip in the White Sand Member, petrified wood is distributed within silty-sandstone beds including pebbly lenses indicative of a braided floodplain. The entrained wood specimens in less competent layers exhibit distinct evidence of plastic deformation through modification of transverse surfaces from round to elliptical forms (fig. 8). Numerous sections of wood ranging from less than 1 centimeter to greater than 0.4 meter in diameter are found with dominant orientations perpendicular to the exposed outcrop surface. Several of these samples lacked central masses yet did not show evidence of infilling (fig. 8). Coloration of the petrified wood is dull and limited, ranging from red-brown, indicative of a strongly oxidizing preservation environment, to a light buff color indicative of high silica content. Red-brown coloration is typically associated with fragmentation, dissolution of organic materials, and lack of structural definition, whereas in buff colored samples, structural preservation is high such that woody textures are easily observed. Through thin section analysis of the highly preserved specimen, possible plastic deformation also supports accommodation of strain during displacement of the Rubys Inn thrust.

Figure 8. The entrained wood specimens in less competent layers exhibit distinct evidence of plastic deformation through modification of transverse surfaces from round to elliptical forms. Red-brown coloration is typically associated with fragmentation, dissolution of organic materials, and lack of structural definition. This sample, as was common in others, also lacked a central mass.

Mesoscopic ellipticity data were collected from two regions along the zone of flexural slip, one along the eastern limb of the fold (fig. 9) and another within the nose of the fold (fig. 10). Each collection consisted of five specimens with longitudinal orientation nearly perpendicular to the outcrop surface selected to ensure observation of deformation along transverse cross-sections of the wood coincident with the predominant orientation of specimens within the zone of flexural slip. The orientation of each specimen as well as long and short axes dimensions were measured in the field. Two of these samples were then removed and returned to the lab for thin section analysis.

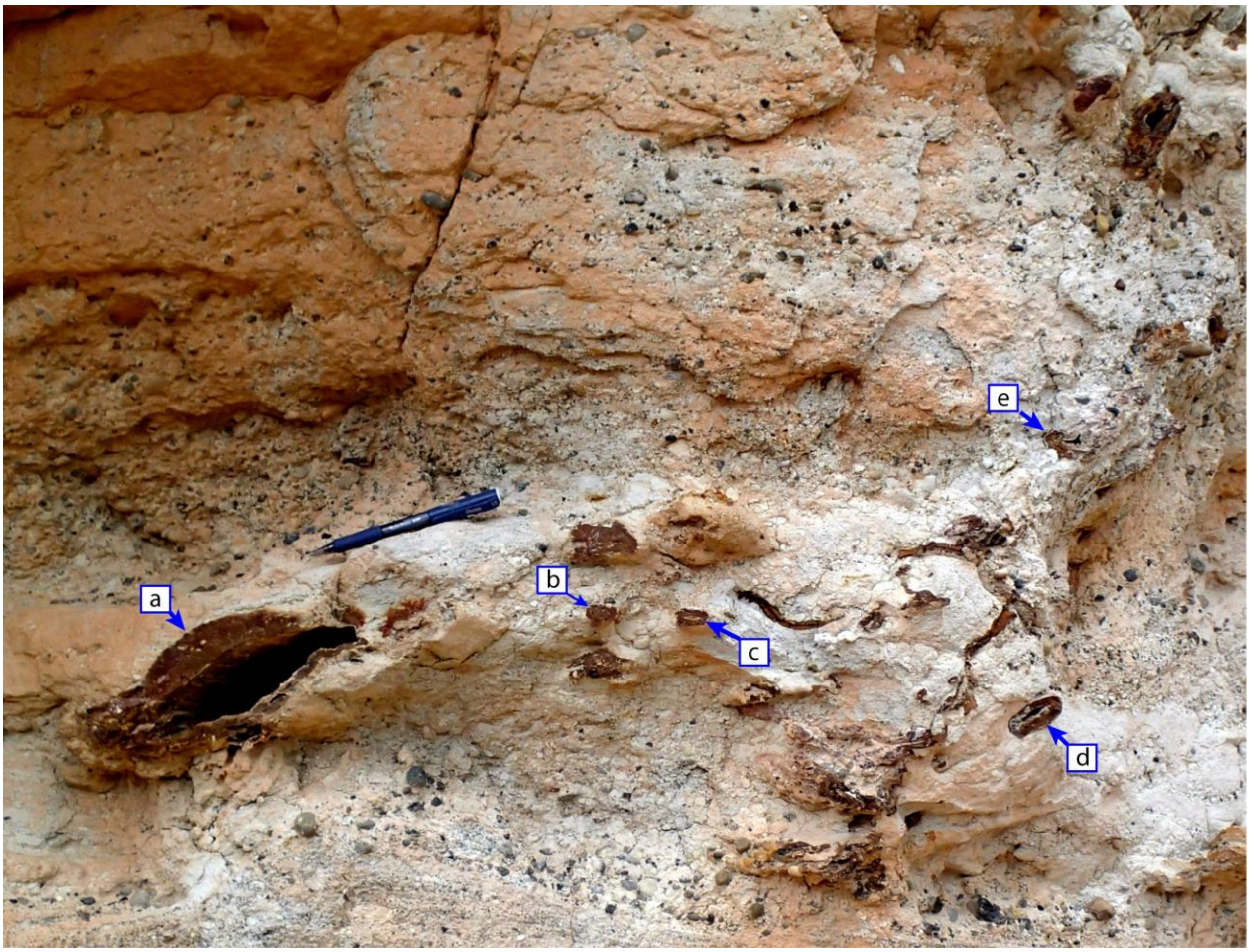


Figure 9. Five samples were collected along the eastern limb of the fold with longitudinal orientation nearly perpendicular to the outcrop surface and were selected to ensure observation of deformation along transverse cross-sections of the wood coincident with the predominant orientation of specimens within the zone of flexural slip.

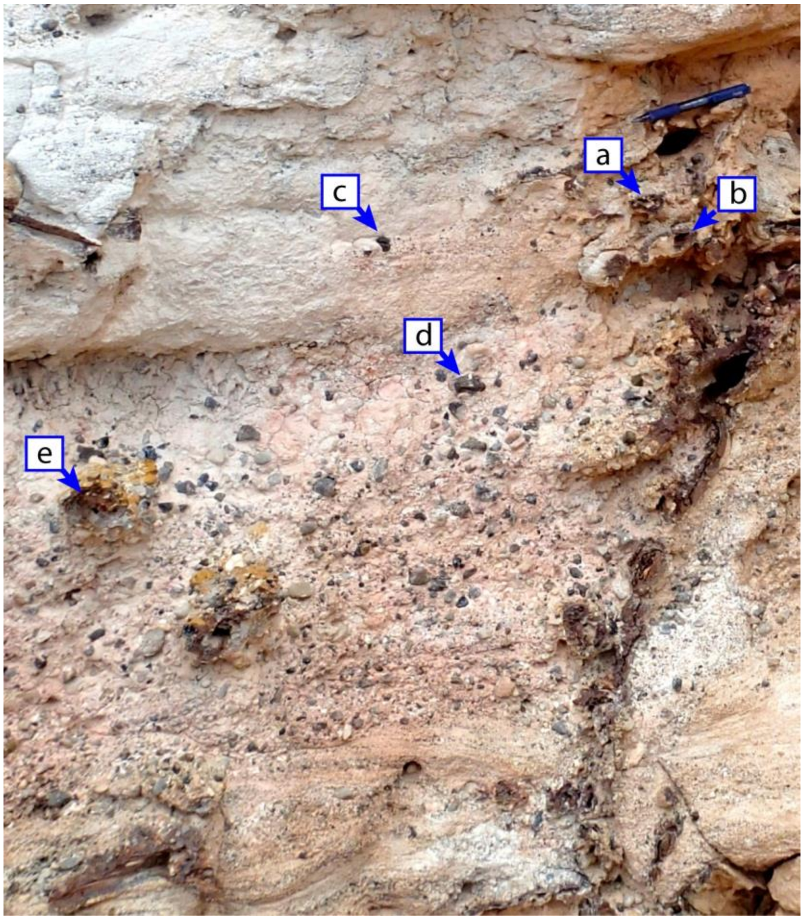
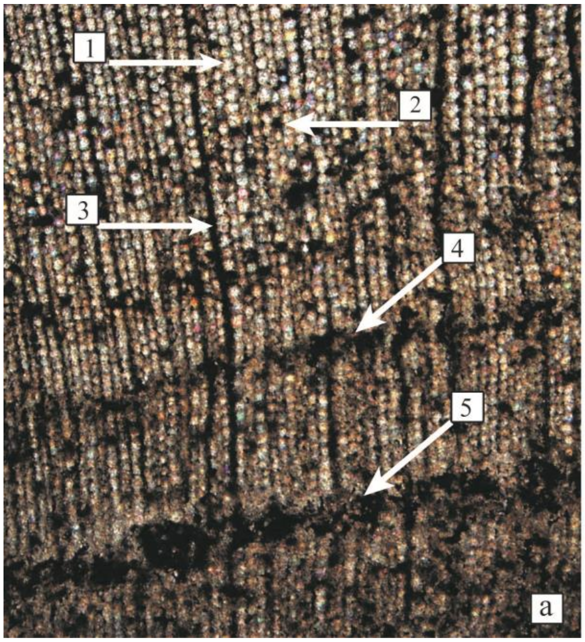


Figure 10. Similar to Figure 8, five samples were collected within the nose of the fold with longitudinal orientation nearly perpendicular to the outcrop surface and were selected to ensure observation of deformation along transverse cross-sections of the wood coincident with the predominant orientation of specimens within the zone of flexural slip.

Mean orientations of samples are N41W along the eastern limb and N81E in the nose. The orientations are consistent to within a standard deviation of 3° in each collection. Ellipticity is calculated by dividing the long axis of each sample by its short axis. It also should be noted that long and short axes are orthogonal in all cases. Results for the collection along the eastern limb (mean ellipticity = 2.0) are slightly stronger than for those within the nose (mean ellipticity = 1.9); however, Student's t-test indicates no statistical difference between the two collections ($p = 0.76$). Thin section analysis, only possible in the buff colored sample, did not show evidence of ellipticity; however, deformation of a right lateral nature was observed (fig. 11). Unfortunately, a different mode of preservation of the red-brown sample resulted in a silty, opaque thin section, precluding observable structure.

A ductile strain response is supported by mesoscopic deformation of petrified wood from cylindrical to elliptical form as well as by possible plastic microcscopic shear deformation within the zone of flexural slip. Interestingly, xylem structures in the sample are consistent in both pattern and size including random resinous tracheids indicative of a coniferous species at a time when angiosperms were achieving dominance within the terrestrial landscape. This is not surprising where *Taxodium* (cypress) was a common floral component of the area (Sadler, 2005). It may be possible to further constrain this species to *Taxodium distichum* (bald cypress) due to the lack of resin canals observed and through comparisons with thin sections found in the literature (e.g. Teachout, 1995). Although deformation in the fine-grained rock occurred cataclastically, the petrified wood deformed plastically. This evidence further supports accommodation of strain along the Rubys Inn thrust in these less competent layers.



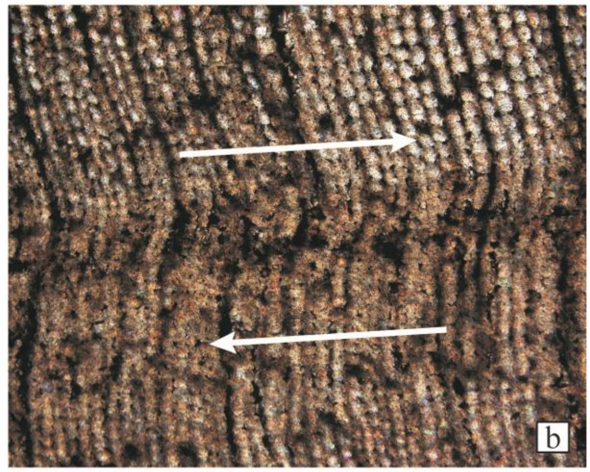


Figure 11. a. Xylem structures (1) in the sample are consistent in both pattern and size including random resinous tracheids (2) indicative of a coniferous species. Rays (3), possible drought wood (4), and late wood (5) also are observed. **b**. Thin section analysis did not show evidence of ellipticity; however, right lateral offset was observed.

DEFORMATION BANDS

Not all deformation associated with the Rubys Inn thrust fault system was accommodated in the incompetent layers in Hillsdale Canyon. Cataclastic deformation bands are present in the competent sandstone layers of the Cretaceous Wahweap Formation (fig. 12). Deformation bands commonly occur in thick deposits of highly porous, well sorted sandstone like those found in Mesozoic sedimentary basins such as the Wahweap Formation (Fossen, 2010a). They occur in the damage zone of faults (fig. 13) as millimeter- to centimeter-thick bands with lengths ranging from less than a meter to over 100 meters (Fossen, 2007; Schueller *et al.*, 2013). Cataclastic deformation bands are an important part of a fault system because of their potential to affect fluid flow and because they can be used as paleostress indicators.

When the gravitational collapse of the Marysvale volcanic field introduced compression to the Wahweap Formation, the high porosity rock accommodated strain in localized bands at the granular level. The sand grains underwent translation and rotation within the available pore space (Fossen, 2007). Cataclasis, which is the microfracturing of grains in grain-to-grain contact (fig. 14), requires adequate confining pressure, but must be in the brittle regime. Therefore the Wahweap Formation must have been 2 to 3 kilometers below the surface when deformation was occurring (Fossen, 2007; 2010a). As the grains fracture into smaller and more angular fragments, they fill in the pore spaces and decrease permeability. Cataclasis flushes out weaker materials and causes an interlocking of small angular grains in the band's core (fig. 14). This process causes strain hardening as the deformation band strengthens the rock by increasing its resistance to shearing (Fossen, 2007). Strain hardening explains how millimeter-wide bands may grow to over 100 meters in length but typically have offsets of less than 2 centimeters. Strain is accommodated by several bands that form clusters of varying densities (Schueller *et al.*, 2013). After significant strain the interlocking grains will give way to small slip surfaces that link up to form a fault (Fossen, 2007). The overall result of this process is a selective reduction of pore space and permeability within the damage zone on either side of a fault surface (fig. 13).

The permeability reduction that results from cataclasis has the potential to interfere with fluid flow. Measurements indicate that deformation bands are up to six times less permeable than their host rock. However, individual bands are discontinuous features that can vary greatly in thickness and permeability along their length (Fossen, 2007). The presence of even trace amounts of clay minerals within a single band will be of greater importance than the degree of cataclasis. For deformation bands to have a serious effect on fluid flow, they must do so as a cluster. The tendency of clusters to form with preferred orientations allows them to influence the direction of fluid flow rather than trap fluid completely (Fossen, 2007). The bands can extend for over 100 meters beyond the tip of a fault, which gives them an area of influence wider than the fracture itself. The damage zone should not be overlooked by those attempting to interpret subsurface fluid flow at a fault.

Figure 12. Deformation bands in the Wahweap formation forming conjugate sets. The character of the bands changes rapidly between the fine grained sandstone and the pebble sized conglomerate. Despite the great thickness of the bands in the sandstone offset remains minimal. While in the conglomerate the same amount of stress it taken up by many small and thin bands. This is evidence for the importance of lithology in the formation of a damage zone. Pebbles will resist the micro-fracturing that readily occurs in fine grain sandstone.

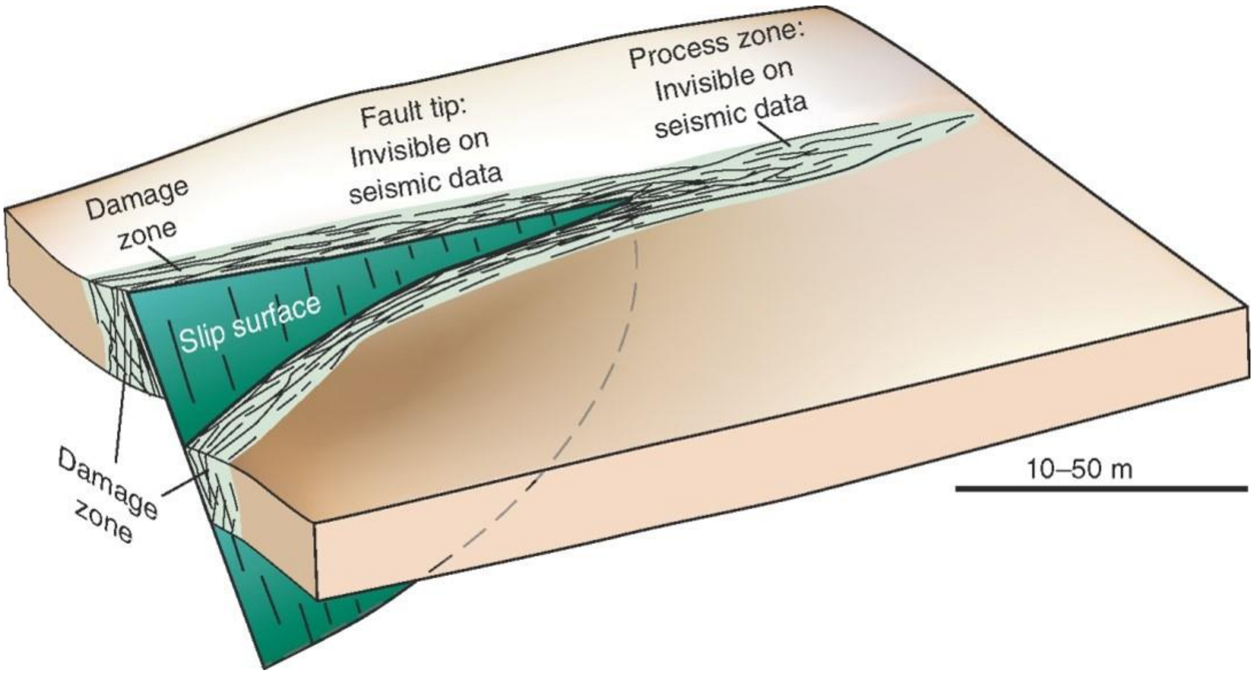


Figure 13. Deformation bands form in the damage zone surrounding a fault. As stress accumulates, single bands form clusters that may develop into a slip surface in the center of the zone. The width and density of the damage is generally constant except at fault irregularities such as fold or bends (Fossen, 2007).

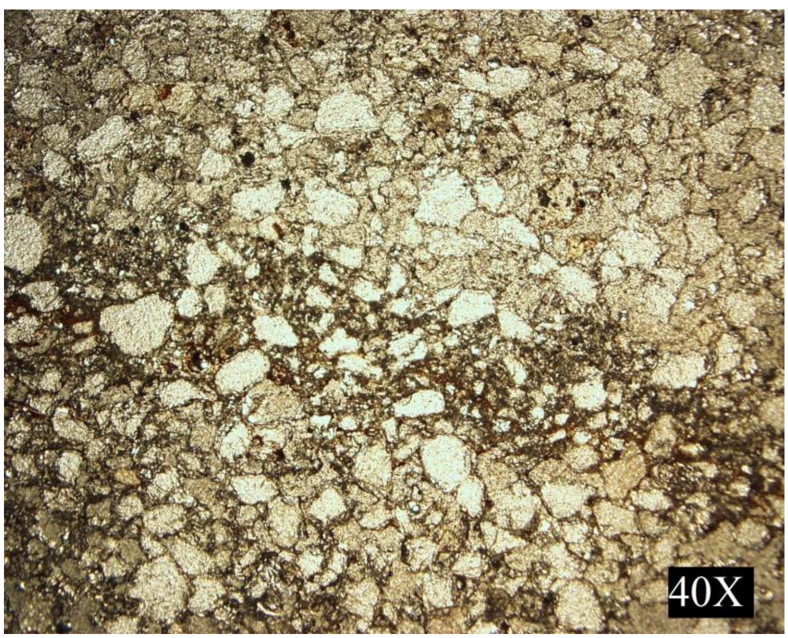


Figure 14. Thin section of a deformation band from Hillsdale canyon. The fine grained sandstone makes up the bulk of the slide but cataclasis is visible as noticeably finer grained band running through the center. The grains have reacted to shear stress from the Marysvale volcanic field via the Rubys Inn thrust fault. While all grains in the vicinity show evidence of compaction and increased angularity, cataclasis was concentrated into one area that now exhibits interlocking of angular grains and overall reduction of pore space. Photo from Skankey (2014).

Closer examination of deformation band orientations is also very telling on the development of the fault system. Cataclastic shear bands often form as conjugate sets (Fossen, 2007). According to Coulomb fracture criterion, shear strain is most likely to occur 20°-30° from the direction of maximum compressive stress. Therefore the line that bisects the acute angle of the conjugate sets is the orientation of maximum compressive stress after the angle of the bedding plane is taken into account.

Observations and measurements at Hillsdale Canyon in the footwall of the Rubys Inn thrust fault were made to determine the orientation of maximum compressive stress. The Wahweap Formation fines upwards. The longest and the thickest bands were found in the finer portion. Thickness varies from less than a 1 millimeter to 2 centimeters. Deformation bands also occur in conglomerate lenses, and they are much smaller and always less than 1 millimeter. However, clustering of bands increases in some areas. A few large bands in the fine sandstone commonly disaggregate to rows of 5-10 small bands in the conglomerate. The overall deformation band density was measured to be 13 bands per square meter. There is a clear crosscutting pattern with bands repeatedly facing one of two orientations. One orientation averaged N50W, 34SW; the other orientation averaged N70W, 24NE. The strike and dip of the bedding plane is N21E, 10NW. If we assume the deformation bands were created before the beds were tilted, we must rotate bedding back to horizontal (fig. 15). The resulting orientations of the deformation band sets are N25E, 32SE, and N49W, 26NE. The resulting orientation of maximum compression, which bisects the acute angle of the conjugate set, is approximately N20E. This orientation is consistent with the south-directed thrusting of the Rubys Inn thrust fault, which traces approximately 90° from N20E at approximately N70W (see fig. 1).

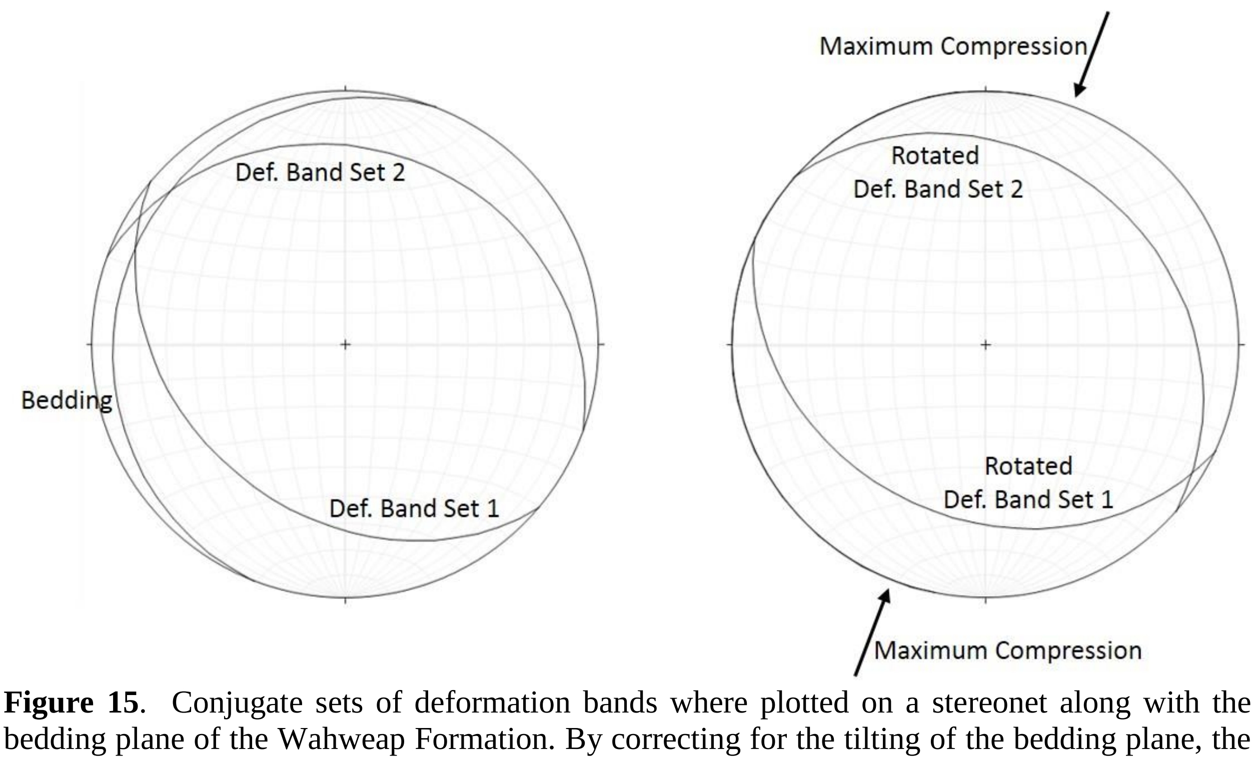


Figure 15. Conjugate sets of deformation bands where plotted on a stereonet along with the bedding plane of the Wahweap Formation. By correcting for the tilting of the bedding plane, the original inclination of the deformation bands could be plotted. The acute angle between the bands is the orientation of maximum paleostress. In this case the orientation of maximum paleostress is interpreted to be NE-SW.

CONCLUSION

Outcrops in Hillsdale Canyon expose several types of structures that were all created during the Rubys Inn thrusting event. Styles of deformation include brittle cataclasis, ductile folding accommodated through flexural slip, and plastic shear in wood fragments now preserved as petrified wood. The broad footwall synclinal drag fold, cataclastic flexural slip, deformed petrified wood, and cataclastic deformation bands allowed a thorough structural description and analysis in rocks that are important analogs for those studying fluid flow through porous sandstone reservoirs.

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