THE CORRELATION BETWEEN JOINT ORIENTATION AND TRANSPORT DIRECTION IN THE SAWTOOTH SALIENT, NORTHERN MONTANA.

A Thesis in
Geosciences
by
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Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

December 2008
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ABSTRACT

The Sawtooth Range in Montana is a Sevier orogenic event. Recent dating determined the main phase of thrusting to have occurred between 74-59Ma. The Northern Disturbed Belt is a section of the Sevier Orogenic Belt that contains the Sawtooth Range with its four major structural provinces; Flathead Range Complex, Sun River Valley, Sawtooth Range Complex, and the High Plains Complex. Situated in northern Montana, the 250 km Northern Disturbed Belt thrust front has a common transport of ENE. At Sawtooth Range, the 100 km Sawtooth Salient has three general transport directions; E, ENE, and NE. Seismic evidence, well control, and structural measurement suggests that the orocline bend is a manifestation of thin-skinned Sevier tectonics interacting with basement topography.

Jointing in the Sawtooth Range and High Plains Complex help determine paleostress trajectories. Andersonian stress regimes for thrust faulting favors extension fracturing on a horizontal plane during thrust faulting. At Sawtooth Salient, vertical jointing prevails. A stress regime that produces vertical extensional fractures and maintains a horizontal maximum stress is strike-slip faulting. In order to facilitate vertical extension fracturing in a thrust faulting regime, there must be strike parallel stretching to counteract the less horizontal stress and convert it to the least compressive stress ($\sigma_3$). During orocline development, significant strike parallel stretching occurs as an accommodation mechanism. In response to this transport with accommodating strike parallel stretching, joints will form parallel to localized transport. All locations contain a major set of ENE joints. Northern joint measurements contain both ENE and NE joints. Southern joint measurements contain both ENE and E joints. Abutment relationships in the field suggest that the ENE joint set was first to form and then both NE and the E set formed afterwards.
Additional field evidence of the ENE joint set occurs at Teton Anticline and Lesser Teton Anticline. Previously, jointing at Teton Anticline has been wholly attributed to folding stresses. Current field evidence shows that the ENE joint cuts through both Teton Anticline and Lesser Teton Anticline. Convincing evidence occurs at the nose of Lesser Teton Anticline. One hypothesis for jointing at an anticlinal nose is strike parallel stretching, creating an array of joints that follow dip direction. However, at Lesser Teton Anticline the ENE joint set dominates regardless of structural position. This evidence suggests the ENE joint set formed before the development of Teton Anticline and Lesser Teton Anticline.

Finally, a switch of stress regimes from thrust faulting to strike-slip faulting occurred. First introduced as bedding parallel strike slip faults, large conjugate wrench faults occur at Teton Anticline and thrust sheets toward the hinterland. Current measurement shows slip sub-normal to bedding, suggesting wrench faulting after bedding rotation has occurred in the thrust sheets and Teton Anticline.
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ACKNOWLEDGEMENTS

I would like to acknowledge the collaboration with my colleague Caroline Burberry (Ph.D. Candidate, Imperial College). Our professional relationship began in the summer of 2006 with our first field season in Montana and has continued since with more field sessions and collaborative presentations at GSA and Geological Society of London. Her topic of dissertation at Imperial College focuses upon the structural style of deformation at Teton Anticline and developing a deformational history for the entire Sawtooth Salient using seismic interpretation, well control, and structural field measurements and observations. Others I would like to acknowledge are Brett Carpenter (Ph.D. candidate, Penn State) for the helpful peer review of this thesis, Ryan Grimm (Ph.D. Candidate, Virginia Tech) for his constructive comments and review.
1 Introduction

Regional patterns of joints combined with cross-cutting relationships between joint sets record stress field orientation changes with time. The use of present day fracture orientations as a proxy for paleostress orientations is replete in the literature (Engelder and Geiser, 1980; Hancock et al., 1984; Olson and Pollard, 1989; Whitaker and Engelder, 2005). The elastic properties of the rock coupled with the stresses acting within the rock facilitate fracture mechanisms such as orogenic strike parallel extension, natural hydraulic fracturing and bending induced tension. Extensive mapping of structures, particularly fractures, assist with building a stress history of the Northern Disturbed Belt of Montana.

The Northern Disturbed Belt in Montana composes an arcuate zone of thrust faults and folds that verge to the east. A southern limit of the Northern Disturbed Belt is in the Little Belt Mountains and an arbitrary northern limit of the International Border between Canada and the United States (Fig. 1.1). The foreland fold-thrust belt is a small part of the larger North American Cordilleran Orogenic Belt running 10,000 kilometers from the Canadian Arctic and Alaska to southern Mexico. It also contains Teton Anticline, an anticline made famous by the seminal work of David Stearns in 1968, relating fracturing to fold development.

Building spatial patterns of stress from fracture measurement is one part of the geologic problem. Field measurement of fractures at specific locations will determine a spatial pattern. Comparison of shortening directions from thrust fault map data to the spatial pattern of joint measurements can elucidate the possible stress configurations of their formation. Fracture measurements from 5 separate localities along the Northern Disturbed Belt were utilized for this portion of the study; Swift Reservoir, Blackleaf Canyon, Teton River Canyon, Teton Anticline,
and Sun River. These locations represent the deformation front of the Northern Disturbed Belt (Fig. 1.1).

Use of cross-cutting relationships to see how stress orientations evolve over time is second. Verification of joint propagation timing can be found by observing the abutment relationships of the spatial patterns. Next, it will be useful to test mechanisms for the formation of vertical fractures within a thrust fault stress regime. Andersonian theory states that thrust fault stress regimes should facilitate the formation of horizontal extensional fractures. The field area observed and measured showcases vertical joints. Finding the mechanism for this formation of vertical joints is important for understanding the deformation history of the Northern Disturbed Belt.

Finally, the relationship between jointing observed in the field and those of the Stearns model will be compared. It will be useful to determine if modern fracture mechanics and modern approaches to fracture characterization can update this 40 year old model. Comparison of the joints at Teton Anticline and those found along the entire deformation front may lead to recognition of joint mechanisms at Teton Anticline.
Fig. 1.1: Showing the location of the NDB within the North American Cordillera. Map to the right delineates the extent of the NDB from the International Border south to Wolf Creek, Montana. (Source of left map: DeCelles, 2004)
1.1 Stratigraphy

Stratigraphic composition is important to the mechanism for fracturing. Properties such as Young’s Modulus and Poisson Ratio depend upon the composition of the rock. Knowing the stratigraphy of the field area is paramount to this structural study. The field area includes strata from Proterozoic Belt Supergroup metasediments to Mid-Cretaceous foreland basin clastics (Fig. 1.2). This study focuses on the sediments of the Paleozoic and Mesozoic. Shallow marine carbonates and deep marine, dark shales comprise the Paleozoic sediments. Mesozoic rocks vary from marine siliciclastics to terrestrial siliciclastics. Widespread unconformities separate some formations with parts of the Paleozoic and Mesozoic sedimentary record missing (Mudge and Earhart, 1978; Gardner and Achuff, 1992). At the field location several formations are key mechanical and stratigraphic markers in the study; the Madison Group, the Swift Formation, and the Morrison Formation. The next sections will briefly describe the sedimentary and stratigraphic properties of these three formations. Later discussion will comment on their mechanical importance.
**Fig 1.2:** Stratigraphic column of Paleozoic and Mesozoic rocks within the Northern Disturbed Belt. Proterozoic Belt Supergroup was not included in this stratigraphic column because Belt rock was typically not encountered in the field area. The thickness ranges are an accumulation of previous measurement and current measurement.
1.1.1 Madison Group

The Mississippian Madison Group consists of two distinct formations (Fig. 1.2). The Allan Mountain Formation, the lowest stratigraphic unit of the Madison, is almost entirely carbonate. Three members of the Allan Mountain further classify the formation by subtle differences in facies descriptions (Balster, 1971; Mudge and Earhart, 1978).

The lower Gunther Member is ~90m thick in the study area. Most of the member is composed of dark gray argillaceous limestone with thin shaly partings in places. The Gunther is a massive, gray limestone interbedded with dark gray fossiliferous mudstone. Mudstones contain crinoidal stems, bryozoans, and various corals. Gunther limestone is observed at the sole of thrust sheets and in the core of Teton Anticline.

The middle Jose Member is ~45m thick in the study area. The Jose Member exhibits fine to medium bedded, fine grained, dark gray limestone and contains continuous and discontinuous chert beds. There is bryozoa hash on bedding planes along with numerous brachiopods, corals, and crinoids. In some localities, there are thick calcareous encrinite beds 1-2 meters thick.

The upper Badger Member is ~90m thick in the study area. It exhibits massively bedded, coarsely crystalline limestone with interbeds of dolomitic mudstone and discontinuous layers of chert. Biologically, these beds contain rugose corals and brachiopods. Upper portions of the Badger contain dolomitic mudstone, thin fossil hash layers, and occasional beds of magnesian limestone. Magnesian carbonate sequences in the Badger resemble the bottom portion of the lower member of the Castle Reef Dolomite.

Castle Reef Dolomite lies conformably above the Allan Mountain Formation and shows a distinct facies change. The lowest member of the Castle Reef is unnamed whereas the upper member is named the Sun River Dolomite. To assist in the field, the lower member was referred to as the Log Cabin Member.
The Log Cabin Member is ~80m thick in the study area. The Log Cabin Member shows similarities to the upper portion of the Badger Member in the Allan Mountain Formation. Coarse magnesian limestone beds, dolomitic mudstone, thin fossil hash layers dominate this member. A difference between the Badger Member and the Log Cabin Member is the presence of large calcite mineralization within the coarse magnesian limestone and some of the dolomitic mudstone in the Log Cabin Member. The upper portion of the Log Cabin contains 1-2m thick dolomitic encrinite layers that exhibit extensive bedding parallel stylolitization.

The upper Sun River Member is an important unit because most exposures in the field area are in the Sun River Member. The Sun River Member is ~100m thick in the field area. The Sun River Member is likely a complete record of sedimentation because the thickness in the field is near the maximum reported thickness of 105m (Gardner and Achuff, 1992). The bottom portion contains dolomitic mudstone, discontinuous layers of chert, and tabular to rugose corals. As the beds get younger, the sediment changes very little, but the fossils vary. The oldest layer consists of tabular and rugose corals, the next layer contains only rugose corals, and then the youngest layer contains very little to no fossils. Above this bottom sequence, a sequence of fossil free dolomitic mudstone with discontinuous chert and dolomitic encrinite layers begins. The very top of the Sun River is an intertidal dolomitic mudstone and banded chert, consistent with a regression sequence (Mudge, 1982).

1.1.2 Swift Formation

The Swift Formation is the upper portion of the Ellis Group of marine siliciclastics in northwestern Montana. It is described as marine siliciclastic shelf deposits during incipient Sevier loading and asymmetric basin creation (Mudge, 1982). Thickness of the Swift Formation is ~35m in the field area. Lower portions of the Swift Formation are composed of grayish-brown,
fine to medium grained sandstone with ripple laminations and cross-bedding. Alternating with those layers is a fine to medium grained, gray sandstone. They have an appearance of red beds, however upon sampling the red color is only a staining at the outcrop surface. Above these alternating layers is a laterally continuous greenish-gray (glaucicnic), fine to medium grained sandstone, indicative of marine deposition. Above this bed is a thick bed of gray, fine to medium grained sandstone that contains discontinuous layers of concretionary mats. These concretions are calcareous and differential compaction in the surrounding sandstone suggests they were formed early in diagenesis. The concretions are reddish-brown when exposed, and a fresh face exhibits a reddish-gray color. The Swift Formation creates resistant ridges in the field area that assist in recognition of structure (Fig. 1.3).

### 1.1.3 Morrison Formation

The Upper Jurassic Morrison Formation is composed of terrestrial clastics (Fig. 1.2). Morrison deposition is a key regional marker for initial terrestrial deposition of sediments derived from the Sevier Orogen. The Morrison is well known for its prolific dinosaur fossils and is researched extensively (Dodson et al., 1980; Lockley et al., 1986). Researchers determine the Morrison Formation is the result of a broad plain of deposition, most likely at the distal end of the fluvial reach from the hinterland (Dunagan and Turner, 2004). The Morrison is proposed to be a large scale aquifer system, during deposition, transmitting meteoric waters from areas of denudation to distal lowlands, creating lacustrine and estuarine environments down slope (Dunagan and Turner, 2004).

The Morrison has an average thickness of ~45m thick in the field area. Thickness is hard to gauge because the lateral changes are great. The presence of the Sub-Cretaceous Unconformity
Figure 1.3: Photograph showing the resistant nature of the Swift Sandstone. The highlighted ridges are pervasive throughout the Sawtooth Salient, whenever preferential weathering of structures occurs.
at the top of the Morrison Formation is a possible explanation for the lateral discontinuity in thickness (Gillespie and Heller, 1995). Documented average thickness of the Morrison is reported to be 20-40m (Gardner and Achuff, 1992).

The Morrison exhibits complex sedimentary deposition in all outcrops. The oldest facies is a brown limestone. This does not outcrop anywhere except for the area along the forelimb of Teton Anticline south of the South Fork Teton River. A contemporaneous stratum is described as brittle, conchoidally fractured; orange-brown, chert-like sediment that outcrops at one locality well north of the North Fork Teton River.

Above this carbonate and chert-like sediment is a laterally diverse stratum. An important bed to this study is a green-gray sandy siltstone containing discontinuous layers of carbonate concretions. The green-gray siltstone suggests a reducing environment, coupled with calcium rich pore waters and presence of bentonite can produce optimal conditions to produce spheroidal concretions (Raiswell, 1976; Coleman, 1993). The mechanical and fracturing characteristics of the concretions are important for the determination of stress orientations during continuous deformation of the Northern Disturbed Belt (Appendix A).

The most common facies in the Morrison is fissile, reddish-brown shale that forms valleys. This shale lies at the top of the section of the Morrison Formation in the study area. A fissile, green-gray shale overlies this red shale, possibly indicating changing oxidation/reduction environments.
1.2 Structural Background

The Northern Disturbed Belt is a small part of the North American Cordilleran Orogenic Belt. This belt formed during oceanic subduction beneath the North American Plate in the mid-Mesozoic to Cenozoic times (Coney and Evenchick, 1994; DeCelles, 2004). During initial opening of the Atlantic, the western portion of the North American continent switched from a temporary passive margin (quiescence after Antler and Sonoma Orogenies) to an active margin (DeCelles, 2004). The increased spreading of the Atlantic during mid- to late-Jurassic times saw an increase in subduction to the west and the Sevier orogenic belt began to form (DeCelles, 2004). Continued subduction in the Late Jurassic and Cenozoic saw the complete consumption of the Farallon Plate and subsequent back arc closure to fully accrete the western portion of present day North America.

This tectonic history is the backdrop for the deformation of the Northern Disturbed Belt in northwest Montana. The report will focus upon the structural geology of the Northern Disturbed Belt as it pertains to the field area. Northern Disturbed Belt is broken into a series of sub-belts that show different character to their deformation (Mudge, 1982: Fig. 1.4). For the next several paragraphs we will discuss each of these sub-belts using previous work and current field observations.

1.2.1 Flathead Range Complex

The Flathead Range Complex is the westernmost sub-belt of the Northern Disturbed Belt and includes Glacier National Park, the Lewis and Clark Range, the Flathead Range, and the Whitefish Ranges. The eastern edge of the sub-belt is the Lewis-Eldorado-Hoadley Thrust System and the western border is the South Fork Flathead River. Eastern structures include the Lewis-Eldorado-Hoadley Thrust System and the Steinbach Thrust. The middle of the belt contains first order synclines. The western portion contains extensional normal faults. The
stratigraphy of the sub-belt consists of Proterozoic Belt Supergroup translated east by Lewis-Eldorado-Hoadley thrusting. The Continental Divide Syncline and hanging walls of listric normal faults exposes Lower Paleozoic rocks (Fig. 1.4).

The Lewis Thrust is ~450 kilometers in length and carries Proterozoic Belt Supergroup rock. In the vicinity of the Sawtooth Salient, the Lewis Thrust translated ~100 kilometers. The age of Lewisian thrusting has been dated between 82 Ma and 59 Ma (Hoffman et al., 1978; Sears, 2001). The strike of the Lewis Thrust varies along its surface trace according to map analysis. To the north, the Lewis Thrust strikes NNW-SSE, translating Proterozoic rock over Upper Cretaceous rock. At the southern end of Glacier National a sharp bend occurs in the surface trace of the Lewis Thrust. South of the park the Lewis reacquires a NNW-SSE strike. Hanging wall denudation is postulated for the presence of this hinterland directed step in the Lewis Thrust (Sears, 2001; DeCelles, 2004). The thrust pivots to a strike of NW-SE at the junction of West Fork Sun River and Indian Creek. Previous work deemed this the hinge point for greater eastward translation north of this location (Mudge and Earhart, 1980; Sears, 2001).

In the central portion of the Northern Disturbed Belt the Eldorado Thrust is the eastern boundary of the Flathead Range Complex. Sixteen kilometers southeast of the southern border of Glacier National Park, map analysis exhibits truncation of the Lewis Thrust at Morrison Creek. The southern end is truncated by a normal fault 60 kilometers south of the town of Wolf Creek. In the central portion of the Flathead Range Complex the Eldorado mirrors the Lewis Thrust and parallels the Hoadley Thrust in the southern part. The Eldorado displaces east 8 kilometers and has a stratigraphic throw of 4,200 meters (Mudge, 1972).
Delineation of the sub-belt positions within the Northern Disturbed Belt. 1-High Plains Complex. 2-Sawtooth Range Complex. 3-Sun River Valley. 4-Flathead Range Complex.
The Hoadley Thrust originates in the Lewis Thrust plate and follows the same hinge point turn and continues along a similar strike for roughly 150 kilometers. However, the easterly translation increases to the south of the hinge point for the Hoadley, opposite of the translation vector of the Lewis Thrust (Mudge and Earhart, 1980). The maximum eastern translation of the Hoadley is ~70 kilometers with a stratigraphic throw of 3,300 meters (Mudge, 1982).

The Steinbach Thrust is only present in the southern portion of the Flathead Range Complex. It is truncated by the Eldorado Thrust to the north and extends for 65 kilometers to the town of Wolf Creek. The Steinbach Thrust is a lesser order structure in the Lewis-Eldorado-Hoadley Thrust System because it translates only ~19km, throws 3,600 meters, and exhibits a small strike length (Mudge, 1982).

The shortening of the Lewis-Hoadley-Eldorado Thrust System was compared to other Sevier thrust systems along the North American Cordilleran. The Purcell Thrust System in Canada is linked to the Lewis-Hoadley-Eldorado Thrust System south of Calgary, Alberta (DeCelles, 2004). The Utah/Wyoming Sevier Thrust Belt is separated from the Lewis-Eldorado-Hoadley Thrust System by Absaroka Volcanic Complex and the later emplaced Helena Salient (DeCelles, 2004). The Lewis-Eldorado-Hoadley Thrust System is assumed to have emplaced between 82Ma and 59Ma (Hoffman et al., 1976; Sears, 2001). Age data for each thrust was not available in the field area, so it was assumed that each thrust displaced over an equal time. Also assumed was a forward breaking thrust sequence, confirmed at other locations along the Sevier Cordilleran (Sears, 2001; DeCelles, 2004). Using these assumptions, a shortening rate of 4.7 mm/yr was calculated for the Lewis-Eldorado-Hoadley Thrust System (Fig. 1.5).

The north striking, west dipping extensional faults in the western portion of the sub-belt comprise the final major structures. The Flathead Fault is a listric extensional fault that formed after Lewis Thrust emplacement by tectonic inversion (Bally et al., 1966). The Flathead,
Roosevelt, and the South Fork are the major extensional faults in the sub-belt. This graben type terrain is postulated to be Late Paleocene foreland fold thrust belt collapse (Constenius, 1996). Stratigraphic separation on the major extensional faults varies greatly; the Flathead Fault, 6,000 meters; Roosevelt Fault, 2,700 meters; and the South Fork Fault, 5,300 meters (Bally et al, 1966; Sommers, 1966).

1.2.2 Sun River Valley

Sun River Valley consists of thrust-faulted and folded Mesozoic rocks between the Flathead Range Complex and the Sawtooth Range Complex. It follows the general arcuate trend of the Sawtooth Range Complex. Length of the sub-belt is similar to the Sawtooth Range Complex with a width of ~10 kilometers. No field observations were made in this sub-belt because of the remote nature of this area to the researchers, therefore all interpretations will be from map analysis and literature review.

Thrust faults in Sun River Valley repeat Cretaceous rocks; have general dips of 50-60 degrees W and stratigraphic throws of 150-450 meters (Mudge, 1982). The high angle of thrust planes is due to progressive shortening of the Sun River Valley during Lewis-Eldorado-Hoadley thrusting. One anomalous thrust in the southern part of the sub-belt is a Mississippian plate thrust to the east with a stratigraphic throw of 1200 meters (Mudge and Earhart, 1983). In the South Fork of the Sun River lower Cretaceous rocks and a Late Cretaceous or early Tertiary trachyandesite sills are complexly thrust faulted and folded in the Pretty Prairie fault complex (Mudge, 1972). A large syncline exposes Upper Cretaceous rocks within the North Fork Sun River valley. The west limb of this syncline is locally overturned and truncated by thrust faults displacing older Cretaceous rocks. The eastern limb is cut by a longitudinal normal fault, supporting fold thrust belt collapse (Constenius, 1996). The length of the fault is ~42 kilometers and stratigraphic displacement of nearly 150m (Mudge and Earhart, 1983).
Fig. 1.5: Plot representing the cumulative displacement versus age of thrusting in Utah/Wyoming, Montana, and Canada Sevier belts. The time span of thrusting was divided by the number of thrust faults present to determine age of thrusting for Canada and Montana. This relationship is used because there is no age of emplacement for any thrust there. The Utah/Wyoming thrusts produce a shortening of ~1.7 mm/yr. The shortening in Montana is ~4.7 mm/yr. Finally, the shortening in Canada is ~12 mm/yr, by far the fastest shortening.
1.2.3 Sawtooth Range Complex

The Sawtooth Range Complex consists of closely spaced thrust-faulted and folded Paleozoic and Mesozoic rocks (Fig. 1.6). The sub-belt is ~100 kilometers along strike and ~20 kilometers in width. The eastern boundary of the belt is the last basin-directed carbonate thrust front, whereas the western boundary is arbitrarily drawn along the east side of the North Fork Sun River valley (Mudge, 1982). To the north, the belt’s structure exhibits northwestern plunge and is truncated by the Lewis Thrust as it steps forward in the Northern Disturbed Belt to the east. The belt is overprinted by the southern extensions of the Lewis-Eldorado-Hoadley Thrust System as it continues southeast into the bend of the Laramide Helena Salient.

The belt is arcuate and follows the general trend of the Lewis Thrust to the west (Fig. 1.4). Main composition of these stacked thrust sheets is the entire Mississippian Madison Group. The resistant carbonates make remarkable palisade fronts of all thrust sheets in the sub-belt. Rocks of the Ellis Group, Morrison, and lower Cretaceous rocks occupy the valleys between thrusts. Western sheets are thrust upon lower Cretaceous rocks and the sequence repeats again. In some areas, portions of the Devonian section are carried up with the Madison Group from the basal detachment. In other localities Cambrian carbonates are also thrust up to the surface from deep soled thrusts. These locations include the rocks of the Swift Reservoir area adjacent to the frontal Mississippian thrusts and relatively thin outcrops southwest of the Gibson Reservoir. Stratigraphic throw in the Sawtooth Range Complex is approximated at 920-1800 meters (Mudge, 1982).
Fig. 1.6: Representation of thrusting in the Teton River area along with a photograph of the imbricate nature of the thrusting west of Teton Anticline. Bold arrow on line map indicates the position and direction that the picture was taken.
Two interesting aspects of the sub-belt is the change in topographic height of the thrusts along strike and its doubly plunging nature. The greatest topographic elevation of thrust is between Dupuyer Creek and Sun River. Topographic elevations of thrusts to the south and north are lower than the middle section. Reconnaissance of geologic maps agree with field evidence showing thrust structures of the Sawtooth Range Complex plunging to the northwest north of Dupuyer Creek and to the south, south of Sun River (Mudge and Earhart, 1983).

### 1.2.4 High Plains Complex

The High Plains Complex of the Northern Disturbed Belt is contained between the Sweetgrass Arch and the thrust front of Proterozoic and Paleozoic rocks (Fig. 1.4). Documented position of the eastern extent of the High Plains Complex is the eastern edge of splay thrusting (Mudge, 1982). Inferred thrusts from published maps and field observation of small scale stratigraphic throw show that this limit is diffuse (Mudge and Earhart, 1983). Seismic data contains evidence of inferred thrusts marking the eastern edge (Burberry et al., 2007). A characteristic of the High Plains Complex is that deformation is restricted to Mesozoic rocks. It is the western boundary that marks the major ramp in the basal decollement from the Devonian Jefferson-Three Forks shales to Cretaceous Colorado Group shales (Fig. 1.7).

The style of deformation within High Plains Complex is described as imbricate splay thrusting with the presence of a large scale 1st order fold (Teton Anticline) at the laterally thin portion (Mudge, 1982). All thrusts in the High Plains Complex have less than 550m of displacement with most below 200m of displacement (Mudge, 1982). Smaller thrust displacement is commonplace in a deformed foreland basin adjacent to major thrusting. This
behavior is seen in the Appalachian Plateau adjacent to the Valley and Ridge structural front (Gwinn, 1964).

1.2.4.1 Teton Anticline

The most prominent structure of the High Plains Complex is Teton Anticline. To most, Teton Anticline is a symmetrical fold that dips gently to the south (Stearns, 1968; Mudge, 1982). Extensive field mapping and seismic observation of the anticline shows that the fold is more complex.

The northern portion of the anticline appears to nucleate within the Volcano Reef Thrust (Fig. 1.8). Tracing the fold axis to the south a second fold forms directly to the east of Teton Anticline, called Lesser Teton Anticline. At its southern extent, Teton Anticline plunges out of surface expression just north of the Sun River, but seismic interpretation show that it continues subsurface (Burberry et al., 2007). Lesser Teton Anticline is a doubly plunging fold with a surface trace of about 8 kilometers. It plunges to the north, south of Volcano Reef and plunges to the south underneath the South Fork of the Teton River. As Teton Anticline parallels Lesser Teton Anticline it is nearly symmetric to slightly asymmetric (Fig. 1.9). Back limb dips average 25-30 degrees and fore limb dips average 30 degrees. A change in symmetry is seen in Teton Anticline as Lesser Teton Anticline plunges under the surface. The back limb dips retain 25-30 degrees and the fore limb now exhibit dips of 50-60 degrees.
Fig. 1.7: Seismic line shot along an E-W transect within the Teton River area. Notice that thrust steps up slightly east of a zone of imbricate thrusts and detachment folding within Paleozoic sheets. This step then carries the deformation to the top layer to the east above the dotted line. (Seismic section provided by SEI Inc.)
Fig. 1.8: Line drawing of thrust locations in the Sun River Valley, Sawtooth Range Complex, and the High Plains Complex. The position of Teton Anticline and Lesser Teton Anticline are shown at the frontal edge of the Sawtooth Range Complex. The northern end of Teton Anticline nucleates within the Volcano Reef Thrust. To the south Lesser Teton Anticline parallels Teton Anticline and they both are located within the Crab Butte Thrust for the remainder of their respective traces.
Figure 1.9: Panoramic photograph of Teton Anticlines. LTA is situated to the right of the anticlinal pair. The nose of LTA is evident from this vantage point.
1.2.5 Basement Influence of Northern Disturbed Belt Development

Development of the Northern Disturbed Belt is mainly controlled by basement topography. Gentle basement dips or dips in on basement cover contacts in southern Canada caused the Southern Canadian Rockies to be less affected by basement topography (Lemieux et al., 2000). Recent seismic and magnetic studies exhibit a possible suture zone between the Archean Wyoming Province and the Medicine Hat Block (Mueller et al., 2002). Others postulate that this part of the basement is a shear zone, genetically related to the Lewis and Clark Line further to the south (Boerner et al., 1998). The zone is ~250 kilometers in width, strikes to the ENE-WSW, and is called the Great Falls Tectonic Zone. A series of parallel trending lineaments related to the Great Falls Tectonic Zone run through the field area in the Northern Disturbed Belt (Mudge, 1972). Underneath Swift Reservoir an inferred basement normal fault with down dip to the north is the northern most lineament (O’Neill and Lopez, 1985). The next lineament is the Pendroy Fault adjacent to the Blackleaf Canyon area. It is another normal fault cutting the northern end of the South Arch and dropping it down to the north. Next, the Brown Sandstone Peak Brady Trend follows the trend of the Great Falls Tectonic Zone just south of the Teton Anticline field site at Teton River (Kleinkopf and Mudge, 1972). Finally, the major trend is the Scapegoat-Bannatyne Trend. This basement lineament runs adjacent to the Sun River Canyon and is conspicuously located at the pivot point for Lewis-Eldorado-Hoadley thrusting (Mudge, 1982) (Fig. 1.10).

The influence of these trends and the South Arch are seen in field observation. At Swift Reservoir, there is a conspicuous lateral change along strike from predominately flat lying sequence to a broad zone of low strain, evident by a series of splay thrusts and folds breaking the surface in the Cretaceous sequence. This change follows an ENE trend, the same trend of the basement lineament here.
The basement lineament passing under the Swift Reservoir is only postulated because there was inconclusive evidence for its existence (Kleinkopf and Mudge, 1972). The presence of a lateral ramp above this lineament may provide some proof as to its existence (Fig. 1.11). Past studies show lateral changes in strain profiles can be caused by crustal lineament (Krab bendam and Leslie, 2004).

A conspicuous change in fold geometry along strike of Teton Anticline is observed in the vicinity of the Brown Sandstone Peak-Brady Trend (Fig. 1.12). The effect of thrust transfer zones on lateral strain profiles is replete in the literature (O’Keefe and Stearns, 1982; Marshak, 1986; Cooper, 1992; Burberry et al., 2007). Seismic investigation shows that the character of thrusting and folding at Teton Anticline does change from its northern portion to the southern portion (Fig. 1.12).

The South Arch creates a topographic high in the basement block under the Northern Disturbed Zone deformation front (Fig. 1.10). Structures in the Proximal Foreland and the Sawtooth Range Complex reflect this increase in basement elevation only within the vicinity of the South Arch, between Birch Creek (Swift Reservoir) and South Fork of Teton River. The thrusts are closely spaced and contain only Paleozoic rocks, whereas to the north and south the thrust spacing is wider and the sheets contain Jurassic and Cretaceous rocks. The basement topography underneath the Northern Disturbed Belt plays a large role in altering the structure in the cover rocks. This difference in structure along strike may have implications for fracture characterization. Changes in structural style may cause overprinting of the resultant strains, causing a much more complex pattern maybe not seen in previous studies.
Fig. 1.10: Basement contour map in the Foreland of the NDB. Structure 1 is the unnamed lineament that trends under the Swift Reservoir Area. Structure 2 is the Pendroy Fault which extends into the Blackleaf Canyon. Structure 3 is the Brown Sandstone-Peak Brady Trend influencing the Teton Anticline area. Structure 4 is the Scapegoat-Bannatyne Trend influencing the Sun River Canyon. An important observation here is the structure basement topography is higher in the middle of the NDB as compared to the north and south ends. (Map modified from Mudge, 1982).
Fig. 1.11: Lateral ramp seen near Swift Dam. Rock to the left is the Sun River Dolomite and has relative movement towards the reader and the dark shale with a relative movement into the paper is the Sawtooth Formation.
Fig. 1.12: The left diagram shows a north to south progression of seismic traces in the vicinity of Teton Anticline. The character change in Teton Anticline shows fault-bend folding within a thrust sheet to the north, to a more fault-cored fold to the south. The Brown Sandstone Peak-Brady Trend is situated between lines 3 and 4. (Diagrams from Burberry et al., 2007 – Seismic data from SEI Inc.)
2 - Transport Related Fracturing

Joint sets form a penetrative deformation fabric at the outcrop scale that is used to determine shortening directions (Kwon and Mitra, 2004). These joint sets develop progressively throughout the deformation of a foreland. To properly interpret these structures, the crosscutting relationships between joint sets must be established (Engelder and Geiser, 1980; Cooper, 1992; Younes and Engelder, 1999).

The development of the Sawtooth Salient is important to the formation and orientation of joints in the field location. The transport related to salient development can determine orientation of joints formed in response to deformation front stresses. Previous study has determined that there are five varieties of structural salients; bow and arrow, orocline, divergent transport, tear fault boundaries, and lateral or oblique ramp boundaries (Kwon and Mitra, 2004). These different structural styles can be determined by observing the transport directions along the deformation front. Salient style in the field is found using interpreted thrust faults on the area’s structure map confirmed with field observation and salient line form analysis. The salient style that most closely represents the Sawtooth Salient is the orocline. Joints should respond to orocline development by forming a radial pattern, normal to the structural front.

2.1 Sawtooth Salient Development

The arcuate form of the Sawtooth Salient looks similar to an orocline. The Appalachian Pennsylvania Salient is a documented orocline that can be used for comparison to see if their forms are similar. Using aerial photography of both salients and overlaying them shows they are two different forms (Fig. 2.1). In order to overlay the Sawtooth Salient on the Pennsylvania Salient with consistent length relationships, inclusion of the straighter line segments of the Lewis
Thrust north of the Sawtooth Range is required. This creates a thrust front that is straighter than the arcuate thrust front of the Pennsylvania Salient. However, observation of just the Sawtooth Salient shows similar curvature and form to the Pennsylvania Salient.

Drawing the strike of thrust fronts and fold axes of the Sawtooth Salient reveal strikes of 358°, 345°, and 332° which when rotated 90° west indicate transport directions of 088°, 066°, and 050°, respectively. The strike lines were digitized from an electronic copy of the main geological maps for the Northern Disturbed Belt (Mudge and Earhart, 1983). Strike direction and length of the thrust fronts were measured using ESRI Inc. ArcMap©. Measured strike lengths were carefully chosen to avoid thrust fault trends due to topography. To mitigate this effect thrust strikes measured were chosen away from streams or any major erosional feature. After measurement, a dominant transport direction of ENE, or ~070°, is clear.

The divergent transport directions coupled with the overall arcuate form of the salient front suggests an orocline formation. Complex basement topography mentioned in the previous chapter may contribute to localized orocline development in the Sawtooth Range. A characteristic of orocline development is outer arc stretching (Marshak, 1988). The stretching is parallel to strike along the deformation front and may assist the driving mechanism for jointing in the Northern Disturbed Belt.
Fig. 2.1: Comparison of the Sawtooth Salient to the Appalachian Pennsylvania Salient. The Northern Disturbed Belt keeps a straighter line than the Pennsylvania Salient when both are overlain. Drawing lines normal to the multiple front segments also exhibits the difference between the two. However, focusing upon just the arcuate Sawtooth Salient within the Northern Disturbed Belt, the form is very similar to the Pennsylvania Salient, with a distinct focal point of the drawn normal lines.
Fig. 2.2: Strike lines showing major thrusts and folds within the Northern Disturbed Belt (Sun River Valley, Sawtooth Range Complex, and High Plains Complex).
2.2 Fracturing in Thrust Sheets

The principal stresses acting upon a body of rock at depth within a thrust regime are compressive. As a consequence of stress concentration and lowered effective stresses from pore pressure effects, local tensile stresses can occur in the vicinity of a flaw within a compressive stress field (Pollard and Aydin, 1988). This holds true as long as the tensile stress overcomes the least horizontal compressive stress. Depending on the magnitude of the compressive stresses involved and the geometric boundary conditions of the flaw joints can develop. Grain contacts are among the smallest flaws that can initiate a fracture. A small angle of grain contact, $2\Phi$, stresses at the grain center can be estimated by the following equation.

$$\sigma_{\text{grain}} = -\sigma_1\left[\frac{2\phi}{\pi}\right]$$  
(Jaeger et al., 2007, p. 169-173)

Localized tension can also occur for flaws like inclusions, pores, and microcracks. When a remote compressive stress is applied to a circular inclusion, i.e. pore space, tangential stresses build at the four points of the inclusion that interact with the principal stress planes. Compressive stress is concentrated 3 fold tangential to the points in the least compressive stress plane. At the points in the maximum compressive stress plane the tangential stress is tensile and equal to the magnitude to the remote stress. The stress concentration is summed using the Ingles Equation (modified from Jaeger et al., 2007).

$$\sigma_c = \sigma_r\left(1 + \frac{2c}{b}\right)$$

The situation also holds true for an elliptical crack (Griffith, 1924). The stress concentration around an elliptical crack is greater due to its geometric properties. The length $c$ in
an ellipse is greater than a circle and increases the value of $2c/b$, effectively increasing the multiplier for remote stresses.

If rock, particularly the Madison Group, is subject to a remote stress then any pores, microcracks, or grain contacts within the rock could serve as initiation points for joint formation driven by low effective stress and pore pressure increases as the body of rock compresses. As the stress field changes orientation with continued progressive deformation, the joints propagated should also change orientation. Mode I fractures always propagate in the plane of maximum compression, so any change in the orientation of principal stresses will change the orientation of the fracture.

### 2.3 Measurement of Fractures in the Field

Three distinct localities are used to measure jointing in multiple thrust sheets; the Swift Reservoir, Teton River Canyon, and Sun River Canyon. These locations are located along stream cuts normal to the thrust faults. Locations were chosen due to their accessibility and exposure (Fig. 2.3). This of course introduces an inherent bias to all measurements that cannot be avoided without sacrificing safety in the field. Strike and dip measurements were made at each station. Cleavages, mini-joints, and styolites were measured if observed. Pavement style outcrops did not allow us to observe joints in the third dimension. Graphical representations, particularly rose diagrams, of the data were made after field measurement. Joint orientations are clear using rose diagrams rather than pole plots.
Fig. 2.3: Locator map for all field sites within the Northern Disturbed Belt.
Measurements are broken into two categories, High Plains Complex fractures and Sawtooth Range Complex fractures. The Sawtooth Range Complex fractures are measured in the first several thrust sheets west of the eastern edge of the allochthonous Mississippian Madison Group. Changes in lithology are evident in all field areas. This effects joint orientation because differing elastic media reacts in different ways to a stress field (Jaeger et al., 2007).

The Ellis Group contains a majority of High Plains Complex joints. The jointing in the High Plains Complex gives a better indication of stress trajectory rotations during development of the Northern Disturbed Belt. Jointing within the thrust sheets indicates the individual stresses within that particular thrust sheet, whereas the Jurassic and Cretaceous sedimentary sequence of the High Plains Complex is subject to all stress fields without major basin orientation change during progressive deformation. An example of this is located in the Appalachian Plateau of NW Pennsylvania and South-Central New York State (Engelder and Geiser, 1980). The Appalachian Plateau exhibits a multi-modal array of joint sets that have been associated with different tectonic events to the south (Younes and Engelder, 1999). If the tectonic stress fields changed over time, joints in the High Plains Complex should show patterns of stress field rotation by exhibiting multi-modal orientations.

Age relationships play a role in determining stress field timing. If joints truly showcase progressive deformation over time, the joints should follow abutment rules (Pollard and Aydin, 1988: Fig. 2.4). A joint set develops when an initial compressive stress acts on the rock (Fig. 2.4-A). During a shift in stress field orientation (~15°) another joint set forms in response (Fig. 2.4-B). The jointing that propagates in response to stress field B abuts the joints of stress field A. A shift in stress field orientation will allow the first joint set to remain dilated, because the resolved shear stress on the surface is greater than the normal stress.
Fig. 2.4: Hypothetical abutting sequence within an arbitrary body of rock.
The propagation energy for the second joint will increase as it approaches the open interface. When the joint tip encounters the interface, the crack tip blunts, which dramatically decreases the joint’s propagation energy, and the joint will terminate (Pollard and Aydin, 1988). The same results hold true if the interface is closed but can slip. Time C exhibits a drastic change in stress field orientation. This closes the joints made during time A because the compressive stress is now normal to them. It also closes the joints of time B, because the resolved normal stress on the old joint is high. Granular cohesion of the rock counteracts the small resolved shear stress on the joint plane. The third joint set can propagate across the interface because there is no drop in propagation energy due to a lack of an encountered free surface (Pollard and Aydin, 1988). Observing this behavior helps resolve the relative time sequence of stress field orientations during progressive deformation.

2.3.1 Swift Reservoir
Swift Reservoir is the northern field site on the leading edge of the Sawtooth Range Complex. The field site shows complex thrusting west of the leading edge. Cambrian carbonates comprise the leading thrust sheet. The thrust sheet complex includes 3 individual thrusts with strike normal width of ~5 kilometers. Cambrian rock observed here is only one of two localities in the entire Northern Disturbed Belt. Cambrian shows examples of disharmonic folding attributed to ductile properties of the Cambrian carbonates (Singdahlsen, 1984). Leading edge thrusts of Mississippian Madison Group lie to the east of the Cambrian thrusts (Fig. 2.5).
Fig. 2.5: Panoramic shot of the south end of Swift Reservoir. The Cambrian sheet (right hand side) is characterized by tight, disharmonic folding, whereas the Mississippian sheet (left-hand side) form large plate-like thrusts with little folding.
Table 2.1: Fracture Measurement at Swift Reservoir

<table>
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<th>Location</th>
<th>Measurement Population</th>
<th>Lithology</th>
<th>Orientation Mode</th>
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<tr>
<td>Thrust 1</td>
<td>139</td>
<td>Cambrian Devil's Glen Dolomite</td>
<td>073</td>
</tr>
<tr>
<td>Thrust 2</td>
<td>112</td>
<td>Cambrian Devil's Glen Dolomite</td>
<td>078</td>
</tr>
<tr>
<td>Thrust 3</td>
<td>48</td>
<td>Cambrian Devil's Glen Dolomite</td>
<td>052</td>
</tr>
<tr>
<td>Thrust 4</td>
<td>46</td>
<td>Mississippian Castle Reef Dolomite</td>
<td>NA</td>
</tr>
<tr>
<td>Thrust 5</td>
<td>232</td>
<td>Jurassic Ellis Group</td>
<td>009, 070</td>
</tr>
<tr>
<td>Thrust 6</td>
<td>660</td>
<td>Mississippian Castle Reef Dolomite</td>
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</tbody>
</table>

The joints measured are usually normal to thrust strike (Table 2.1, Fig. 2.6). In the Sawtooth Range Complex, thrust sheet exhibits a joint orientation that is unique to each sheet, whereas the joints of the High Plains Complex record multiple joint sets (Table 2.1, Fig. 2.6; 2.7).
Fig. 2.6: Rose diagrams depicting strike of fractures within each thrust sheet and the foreland at Swift Reservoir. The difference in outcrop characteristic can be seen here between the Cambrian dolomites and the Mississippian dolomites. The area marked Foreland, is within the High Plains Complex.
Fig. 2.7: The concretionary mat with dominant 065° fractures and a few abutting 050° fractures.
Fig. 2.8: Teton Anticline and the Paleozoic thrusts to the west. Photo is looking WNW. Notice that the Paleozoic thrusting is tighter here, field evidence shows there is little to no Mesozoic siliciclastics between the Paleozoic thrust sheets in Teton River Canyon.
2.3.2 Teton River Canyon

The Teton River Canyon is the middle location in the study area. It contains Paleozoic thrust sheets with the Mississippian Madison Group creating palisades where the thrusts break the surface (Fig. 2.8). East of the last major Paleozoic thrust are outcrops of breached Mississippian of Teton Anticline. Previous work has concluded that Teton Anticline is part of the High Plains Complex (Mudge, 1982). This report will conform to this standard.

The jointing at Teton River Canyon shows similar patterns of orientations seen at Swift Reservoir. A 065° strike is the common mode of joint orientations in the thrust sheets. This is sub-normal to the local thrust strike. This strike is close to the 070° transport direction asserted from strike drawings (Fig. 2.2).

The Indian Head Thrust Sheet contains conjugate patterns with a hypothetical bisector at ~090°. Other localities that exhibit conjugate patterns of fractures are at Teton Anticline and Choteau Thrust. Teton Anticline shows large scale conjugate fractures with plane sub-normal slip. At Choteau Thrust fractures have bedding sub-normal slip and contain a bisector direction of 071°. Further investigation of these structures is contained in the next chapter.

The joints of the High Plains Complex at Teton River Canyon are a combination of joint measurements made on Teton Anticline and Lesser Teton Anticline. The jointing is along strike and normal to strike of the fold structure. A lesser mode directed generally E-W appears as well (Table 2.2, Fig. 2.9). Abutment relationships are hard to find in the carbonate sections. However, concretions within the Morrison Formation at the nose of LTA exhibit an abutting sequence (Appendix A). The best estimation for an abutting sequence is from fractures within the carbonates of Teton Anticline (Fig. 10). It shows that the E-W oriented 085° joint set abuts the 060-065° set.
Fig. 2.9: Rose diagrams depicting fracture orientations within each thrust sheet and the High Plains Complex (Teton Anticline) in the Teton River Canyon area. (OP Thrust – Overprinted Fold Thrust: It is a small thrust sheet that has been overrun by Choteau Thrust and exhibits a very tight slightly overturned fold.)
Fig. 2.10: Fracturing within the Castle Reef Dolomite that has abutment relationships.
Table 2.2: Fracture Measurement at Teton River Canyon

<table>
<thead>
<tr>
<th>Location</th>
<th>Measurement Population</th>
<th>Lithology</th>
<th>Orientation Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust 1</td>
<td>29</td>
<td>Mississippian CRD</td>
<td>061</td>
</tr>
<tr>
<td>Thrust 2</td>
<td>27</td>
<td>Mississippian CRD</td>
<td>060</td>
</tr>
<tr>
<td>Choteau Thrust</td>
<td>776</td>
<td>Mississippian CRD</td>
<td>064</td>
</tr>
<tr>
<td>OP Thrust</td>
<td>252</td>
<td>Mississippian CRD</td>
<td>064</td>
</tr>
<tr>
<td>Indian Head Thrust</td>
<td>75</td>
<td>Mississippian CRD</td>
<td>061, 104</td>
</tr>
<tr>
<td>HPC</td>
<td>1287</td>
<td>Mississippian – Cretaceous</td>
<td>072, 164, 090</td>
</tr>
</tbody>
</table>

HPC – High Plains Complex
CRD – Castle Reef Dolomite

2.3.3 Sun River Canyon

The southernmost locality is the Sun River Canyon. Many studies were carried out along the Sun River (Mudge, 1972; Mudge, 1982; Holl and Anastasio, 1992; DeCelles, 2004; Fig. 2.11). It is still chosen as a world class example of imbricate thrust geometry. Joint measurements were taken in individual thrust sheets and a series of joints were measured in the High Plains Complex. The jointing in the thrust sheets exhibits the similar orientation relationships as the other locations. There are only two general joint orientations here. The same 065° joint set that is pervasive through the Northern Disturbed Belt and an E-W 085-090° joint set (Table 2.3; Fig. 2.12).

Some characteristics of the Sun River Canyon joint measurements show similarities to those measured at Teton River Canyon. An apparent conjugate set of fractures occurs in Sun River Canyon, with a bisector orientation of ~E-W. Another similarity is the pattern of 065° - 070° joints in the thrust sheet measurements. The High Plains Complex jointing has a strong 065° trend along with a lesser 090° trend. Using fringe crack type joint interaction, the 090° set abuts the 065° trend (Fig. 2.13).
Fig. 2.11: Examples of thrust sheets at Sun River Canyon. Notice on the picture to the right, below the thrust is the Jurassic siliciclastic package lying above the Mississippian Madison in the thrust sheet to the right. The picture to the left gives the kind of scale that these palisades of Madison make in the field. The cliff face is roughly 150-200 meters.

Fig. 2.12: Rose diagrams depicting the fracture orientations within individual thrust sheets and the foreland of the Sun River Canyon field area.
Fig. 2.13: An outcrop of the Swift Formation show evidence of fringe cracks. The first fracture set was the joints seen in the resistant siltstone. This earlier stress preferentially fractured the siltstone parallel to the then current maximum compressional stress. After stress rotation, fractures grow from tip of the parent joints in the siltstone along the new orientation of maximum compression. Analogs to this behavior are seen in the Ithaca Formation of the South Central Finger Lakes Region of New York State (Younes and Engelder, 1999).
2.4 Fractures along Sawtooth Salient (High Plains Complex)

Combining all High Plains Complex joint data together from the three field areas three distinct joint sets reveal themselves (Table 2.4). The major direction appears to be a joint set azimuth of 065°-070°. The 090° joint set is seen in all three field locations. This set abuts against the 065°-070° set at both Teton River Canyon and Sun River Canyon. The next numerous joint sets are the strike and cross-strike oriented joints at Teton Anticline and Lesser Teton Anticline. These joints are directly related to fold development and will be discussed in the next chapter. The final fracture set is a 050° set that only manifests in the Swift Reservoir area. This joint set abuts against the 065°-070° set only in the Swift Reservoir site.
2.5 Discussion

A boundary condition for salient formation in the NDB is the presence of complex basement topography. The structural low to the north, the presence of a structural bulge in the form of the South Arch, and the topography changes across the GFTZ could cause a disruption in transport directions as the cover rock is forced to encounter these irregularities (Krabbendam and Leslie, 2004). The result of this disruption is the oroclinal form of the Sawtooth Salient.

During a thrust regime state of stress $\sigma_1$, or the maximum principal stress, is oriented horizontally in the direction of regional transport, whereas $\sigma_3$ is directed vertical (Anderson, 1905). Jointing propagates within a principal plane of stress, particularly the $\sigma_1$-$\sigma_2$ plane, during Mode I failure. Additionally, the plane of a joint is normal to the minimum stress, $\sigma_3$. The Andersonian stress regime for thrust faulting should produce joints that are horizontal (Fig. 2.14). Joints observed in the Northern Disturbed Belt are vertical but strike in the direction of the maximum principal stress. A vertical joint indicates the least stress is horizontal (Fig. 2.14). An additional mechanism is needed to facilitate vertical joint development.

Fluids such as brine, oil, or gas can occupy the pore volume in rock. During compressional deformation pore fluids are forced to occupy smaller volumes, thus increasing the pore pressure acting upon the rock. Because pore pressure acts outward from the pore space, it is intuitive to consider pore as acting like a tensile stress. Terzaghi (1936) deduced that the outward direction of pore pressure would counteract three mutually compressive principal stresses, creating an effective stress state within the body.
Fig. 2.14: Andersonian stress regimes for thrust faulting and strike-slip faulting. Within a thrust faulting regime, joint development should be horizontal, normal to the least principal stress. In strike-slip faulting regimes the jointing is vertical, normal to the least principal stress. The Sawtooth Salient is a modification of both stress regimes. Outer arc stretching causes the horizontal compressive stress to become the least principal stress, allowing joints (dashed lines) to develop vertically within a thrust regime.
Overpressuring of the pore fluid, caused by compression within the foreland, can reduce the least effective stress to zero or shift it into the tensile range (Fig. 2.15). This mechanism can initiate vertical natural hydraulic joints that will be parallel to the maximum horizontal stress trajectories. During continued foreland thrusting, stress trajectories may shift causing joint sets of different orientations to form (Engelder and Geiser, 1980).

All three foreland locations have different joint set orientations and abutment relationships. At Swift Reservoir the 050° joint set abuts the 070° set in carbonate concretions (Fig. 2.7). This suggests that the 070° joint set pre-dates the 050° set here. At Teton River Canyon the 090° joint set abuts the 070° joint set, suggesting the 070° set is the oldest. At Sun River Canyon fringe cracks (abrupt twist hackles) exhibit the 090° joint set being younger than the 070° set. Abrupt fringe cracks showcase the mixed mode loading that can occur during a temporally controlled angular change in remote stress (Younes and Engelder, 1999). Abrupt twist hackles commonly occur in shale and initiate from the tip line of the parent joint in a stiffer rock member (at Sun River Canyon the stiffer rock is silty sandstone). No temporal relationship could be deduced for the 050° and 090° joint sets. It is clear that the 070° pre-dates both the 050° and 090° sets in all locations. If these joint orientations are parallel to paleostress trajectories the 070° stress trajectory occurred first followed by both 050° and the 090° trajectories (Fig. 2.16).

The ubiquitous 070° joint orientation indicates that the entire Sawtooth Salient underwent this stress trajectory. Using stress trajectories as proxies for transport direction it is clear that the main transport direction of the entire Northern Disturbed Belt and the southern Canadian Rockies is 070°.
Fig 2.15: Mohr circle diagram illustrating the effect overpressure has upon a normally pressured system.
Fig. 2.16: Fracture orientations within the foreland related to transport direction in the fold and thrust belt.
3 Fracturing at Teton Anticline

Early studies of jointing at Teton Anticline largely attribute fractures to stresses induced during folding (Stearns, 1968; Friedman and Stearns, 1971; Sinclair, 1980). Early fracture models involve a series of conjugate shear fractures bisected by extensional fractures as the orientation of minimum and maximum compressive stresses changes during folding (Fig. 3.1; Stearns, 1968). However, later work using modern fracture mechanics and advances in understanding based on other field areas reveals different explanations for fold related fracturing at Teton Anticline (McQuillan, 1974; Almadhadi et al., 2006; Bellahsen et al., 2006). The current interpretation of fracturing at Teton Anticline and Lesser Teton Anticline confirms some earlier conclusions but disagrees with other conclusions.

One of the disagreements over interpretation at Teton Anticline is the identification of fracture types. Fractures in dispute include the conjugate shear fractures and extensional fractures of Sterns’ Set I and the conjugate shear fractures of Sterns’ Set II. Fractures in these common orientations are found in most outcrops of Teton Anticline and other anticlines (Ahmadhadi, Lacombe and Daniel, 2006; Bellahsen et al., 2006). The purpose of this chapter is to update the characterization of fractures on Teton Anticline so that fold-related fracture development may be better understood.

3.1 Structural Evolution of Teton Anticline

Teton Anticline is a symmetric fold according to previous interpretations (Fig. 3.1). Present field observation show that Teton Anticline is not a symmetric fold. The surface expression of the fold exhibits a fault-bend fold to the north grading into an asymmetric fault-propagation fold to the south.
Fig. 3.1: The Stearns model based on laboratory experiments with sand-box type modeling and field observation and measurement. These four loading configurations are solely based on rotation of least and most compressive stresses during the development of a fold. The diagram to the right is the graphical representation of these four sets as they would appear on a fold.
The presence of Lesser Teton Anticline to the northern end of the field area is the best indication of fold variation along strike. Teton Anticline becomes distinctly asymmetric as Lesser Teton Anticline plunges south out of surface expression. The lateral change in geometry shows that there is a change in deformation degree. The next few sections will elucidate this observation and its importance to a new fracture model.

3.1.1 Field and Seismic Evidence of Along Strike Variation

With the use of well data and seismic lines at Teton Anticline, a closer inspection provides evidence of fold linkage in the area of the South Fork Teton River. To the north of the field area, a seismic cross-section shows Teton Anticline to be a fault-bend fold (Fig. 3.2). It also appears that the thrust sheet forms the top of a frontal imbricate fan driving foreland triangle zone at the major step in detachment from Devonian Jefferson-Three Forks to the Cretaceous Colorado Group. Moving south along strike of the structure shows the termination of Lesser Teton Anticline and the dissipation of the frontal imbricate fan. The fold still could be considered a ramp anticline. The interpretation of a small splay thrust between Teton Anticline and Lesser Teton Anticline marks a deformation change from a ramp anticline to a fault-propagation fold. Steeply dipping beds validates the presence of the oversteepened fore limb of Teton Anticline south of South Fork Teton River. The final diagram is the southern end member of seismic lines shot through the field area. The structural style is different from that of the north, showing an asymmetric, fault-propagation fold.
Figure 3.2: Line drawings of cross-sectional seismic interpretations along strike of structure in the Northern Disturbed Belt. These drawings are aligned north (upper drawing) to south (lowest drawing) as well as aligned to structure (Teton Anticline). The change in structural style is at its greatest between Line 2s and Line 4.
The three types of folding within thrust sheets could be considered a cumulative process. Initial strain is accommodated by detachment folding. As the detached material becomes strain hardened, fault ramp formation translates and further deforms an anticline as a fault-propagation fold. Finally, when the fault ramp tips into another ductile rock and creates a thrust flat, or higher detachment, the change in geometry will transform the fault-propagation fold into a fault-bend fold. Using this reasoning, Teton Anticline changes mode of deformation along strike. At Teton River, Teton Anticline is a fault-bend fold, or the mature end member of the foreland deformation. To the south, the change of fold style to fault-propagation fold, or the intermediary stage, might suggest a lessening of the degree of deformation.

Topographic and structural measurements include a significant plunge of the Mississippian carbonates south of the South Fork Teton River. For Teton Anticline North the plunge to the south of the top of Mississippian carbonates at the crest of the anticlines remains constant at 3° to 4°. South of South Fork Teton River the plunge increases to ~8° to 10° (Fig. 3.3). This increasing southward plunge can be attributed to a change in deformation style from fault-bend folding to fault-propagation folding.

3.1.2 Significance of new Teton Anticline interpretation

The presence of along strike variation may cause different fracture characteristics. The presence of a distinct fold nose in Lesser Teton Anticline and the over-steepened forelimb of Teton Anticline at the southern end of the field area can bias the interpretation of symmetric fold related fracturing discussed by Stearns (Stearns, 1968). The study of fractures related to a nearly symmetric Teton Anticline and Lesser Teton Anticline will be confined to the northern portion of the field area. Teton Anticline to the south is not a symmetric fold, therefore cannot be related to
Figure 3.3: Photograph looking west at the forelimb of Teton Anticline. The lines represent the plunge of the crest of Teton Anticline. The angles were determined by photographic evidence and structural measurements made along the crest of Teton Anticline.
the Stearns model. The fractures measured on Teton Anticline to the south are interpreted as fractures formed in response to asymmetric, fault-propagation folding.

3.2 Field Measurement of fold-related fractures

Measurement of joints at Teton Anticline and Lesser Teton Anticline spanned two field seasons. Data from 160 stations on both anticlines include joint orientations, large scale fracture orientations (shear fractures), and mini-joint orientations. Strike and dip measurements were taken at each station. Graphical representation of the data includes rose diagrams and stereonet pole plots (Appendix B).

3.2.1 Joints

For both anticlines, a total of 1757 joint orientations were collected. Structural positions recorded in this study include backlimb (west limb), crest, and forelimb (east limb). Teton Anticline and Lesser Teton Anticline are broken into zones based upon the two forks of the Teton River. The first zone is north of the North Fork Teton River, the second zone is between the North Fork Teton River and the South Fork Teton River, and the final zone is south of the South Fork Teton River.

Joint orientations on Teton Anticline appear to follow the local structure and form normal to fold strike and parallel to fold strike (Fig. 3.4). Joint orientations on Lesser Teton Anticline do not conform exactly to the local structure. The joints there follow a strong 070° trend with a lesser 345° trend (Fig. 3.4).

When the data is initially analyzed by structural position the jointing loses some of the structural relationships stated above. North of the North Fork Teton River the development of an acute dihedral pattern with a bisector normal to fold strike occurs (Fig. 3.5). This bisector closely
resembles the cross-fold orientation and will be explained in the discussion. Joints normal to this trend are parallel or sub-parallel to strike of the fold (Fig. 3.5). Between the two forks of Teton River a shift in fold strike occurs, becoming more parallel to N-S. The cross-fold joint orientation has a maximum at 073°. The dihedral pattern observed north of the Teton River is less between the two forks. Also, joints normal to the 073° set deviate from the strike of Teton Anticline by 005°, unlike the joints witnessed north of the North Fork Teton River (Fig. 3.5).

South of the South Fork Teton River contains the least measurements of all data collected. This is a manifestation of fewer outcrops available for measurement. The cross-fold joints are widely spread, with a maximum striking ~090° (Fig. 3.5). Also, development of a dihedral pattern with a bisector normal to fold strike appears to be reinstated south of the South Fork Teton River. Joints normal to this again deviate from the strike of the fold by ~005°.

Joints measured on Lesser Teton Anticline show a distribution change to those found on Teton Anticline. Joints that form sub-normal to the fold strike all have a consistent orientation of 070°. The most striking feature is the manifestation of this prominent 070° on the nose of the fold between the forks of Teton River (Fig. 3.5). Jointing north of the North Fork Teton River has a dominant 070° set and a lesser 085° set. The 085° joint set is normal to the fold strike of 355°. Also, joints sub-parallel to strike deviate from the strike of the fold by 005°, the same deviation seen at Teton Anticline.

The next analysis examines change in joint orientation with change in structural position along strike and normal to strike (backlimb and forelimb). On the backlimb of Teton Anticline north of the North Fork Teton River shows a dominant 075° set along with a fold strike parallel set at 350°. Development of a dihedral pattern is also observed in the cross-fold orientation (Fig. 3.6). The backlimb section of Teton Anticline between the forks of Teton River shows
Fig 3.4: Joint orientations at Teton Anticline and Lesser Teton Anticline. Joint measurement populations found in rose diagrams.
a strong joint orientation of 070° and 345°. The 070° set is sub-normal to local fold strike, with a deviation of ~010°, whereas the 345° deviates from the local strike of the fold by 005° (Fig. 3.6). The backlimb section of Teton Anticline south of the South Fork shows two distinct dihedral geometries. The first dihedral pattern has a bisector parallel to 090°, deviating from the cross-fold orientation by 015°. The second dihedral pattern has a bisector parallel to 355°, deviating from the local fold strike by 005° in the opposite sense as the northern sections (Fig. 3.6).

The forelimb section of Teton Anticline north of the North Fork Teton River has a dihedral pattern sub-normal to local fold strike and a set parallel to local fold strike. The dihedral set has orientations of 065° and 114° with a bisector forming parallel to 090°. The strike parallel set has an orientation of 350°, parallel to the local fold strike (Fig. 3.6). The forelimbs section of Teton Anticline between the forks of Teton River form two dihedral sets. The first is oriented 065° and 090° with a bisector oriented 078°. The second dihedral set is oriented 002° and 350° with a bisector that would be parallel to the local fold strike of 355° (Fig. 3.6). The forelimb section of Teton Anticline south of the South Fork Teton River contains a dihedral set forming sub-normal to the local fold strike. It is oriented roughly 065° and 120° with a bisector of 090°. The 090° set is strong in this locality, whereas the dihedral set is more diffuse graphically (Fig. 3.6).

The crest of Teton Anticline has a small population of joints. Joints were determined to be on the crest if the dip of bedding was less than 05°. The jointing here has a strong strike parallel pattern. The joints in this orientation are 345°, deviating from the local strikes of the fold from 005° to 010°. Cross-fold joints are less numerous on the crest compared to the limbs of Teton Anticline. Also, the presence of dihedral joint patterns exist to a lesser degree.
Fig. 3.5: Joint orientations at Teton Anticline and Lesser Teton Anticline compartmentalized according to along-strike position bordered by the forks of the Teton River. Joint orientation populations in rose diagram boxes.
The backlimb of Lesser Teton Anticline is considered by the author to be any part of the backlimb north of the North Fork Teton River. The same reasoning applies to the forelimb. The backlimb of Lesser Teton Anticline shows two distinct joint sets, 070° sub-normal to fold strike and 347° sub-parallel to fold strike. They both deviate by 010° from the fold strike normal and parallel positions. Another trend is observed that strikes 084° and is normal to local fold strike (Fig. 3.6). The forelimb has two distinct joint orientations of 070° and 350°. Again, they both deviate from the fold strike parallel and normal positions. Also, the 084° set developed on the backlimb is more prominent on the forelimb. This joint set is normal to local fold strike (Fig. 3.6). Probably the most striking feature of jointing at both anticlines, is the orientation of joints at the nose of Lesser Teton Anticline. The jointing here follows a very strong orientation trend at 070°. This orientation is seen at all stations on the nose of Lesser Teton Anticline. There is a small cluster of joints that orient 350°, deviating 005° from local fold strike (Fig. 3.6).
Fig 3.6: Joint orientations at Teton Anticline and Lesser Teton Anticline compartmentalized by structural position on the fold. Joint populations: TA Backlimb (North)-279; TA Backlimb (Center)-268; TA Backlimb (South)-81; TA Crest-58; TA Forelimb(North)-122; TA Forelimb(Center)-234; TA Forelimb (South)-120; LTA Fore-157; LTA Back-75; LTA Nose-416.
3.2.2 Mini-Joints

Mini-joints are small joints (usually less than ½ meter long) and are only found in the pelagic mudstones of the Castle Reef Dolomite, Sun River Member. Due to the size of these joints, only orientations of strike can be collected, because no joint plane is available for measurement. Upon initial observation, these joints do not appear to have a preferred orientation. However, collection and graphical representation of the data tell a different story. Over 1700 mini-joint orientations were collected with some measurements on most outcrops of Teton Anticline. Mini-joints were evident on Lesser Teton Anticline but not as dense as those seen on Teton Anticline, because the Sun River Member only comprised of four stations on Lesser Teton Anticline. Taking this into account, mini-joints were processed only on Teton Anticline. The same data presentation is followed as the joint orientations.

The mini-joints observed and measured on Teton Anticline have two very strong preferred orientations. The first orientation is ~352° and is slightly sub-parallel to the strike of Teton Anticline. The second orientation is ~072° and is sub-normal to the strike of Teton Anticline. Other orientations include a wide array of directions which give the impression of a more uniform distribution (Fig. 3.7).

The orientations of mini-joints show variations due to structural position. Mini-joints on the backlimb of Teton Anticline north of the North Fork Teton River form two distinct orientation sets. The first is 350° and is parallel to the local fold strike. The second is directed 080° and is normal to the strike of Teton Anticline (Fig. 3.8). Mini-joints on the backlimb of Teton Anticline between the forks of Teton River show a more diffuse pattern. There appears to be two dihedral patterns with evident bisectors. The first dihedral set forms at ~050° and ~090° with a bisector at 070°. The second set is 000° and 335° with a bisector of 347° (Fig. 3.8). The
backlimb of Teton Anticline south of the South Fork Teton River has a strong mini-joint orientation of 100° and secondary sets forming at 350°, 030°, and 080°. The 350° set is parallel to local fold strike and the 080° set is normal to local fold strike (Fig. 3.8).

The forelimb of Teton Anticline north of the North Fork Teton River shows three distinct orientations of mini-joints. The first is ~357° and is sub-parallel to the local fold strike. The second is 080° and is normal to the local fold strike. The third set is the 125° set. The forelimb of Teton Anticline between the forks of the Teton River has two distinct patterns. The first orientation is 000° and is sub-parallel to the local fold strike with a deviation of ~010°. The second is 060° which is not normal to the local fold strike. The third set is directed ~090° and is sub-normal to the local fold strike (Fig. 3.8). The final location is along the crest of Teton Anticline. As seen with the joint orientations, the mini-joints follow the same diffuse pattern with a multitude of trends at 345°, 020°, 075°, and 090° (Fig. 3.8).
Fig. 3.7: All mini-joint orientations plotted onto a master rose plot for Teton Anticline.
Fig 3.8: Mini-joint orientations as a function of structural position. Mini-joint populations: TA Backlimb(North)-721; TA Backlimb(Center)-525; TA Backlimb(South)-110; TA Crest-199; TA Forelimb(North)-99; TA Forelimb(Center)-60.
3.2.3 Shear Zones

Large fractures are observed in the field to have a dihedral pattern. Previous investigations have termed these fractures as a conjugate fracture set (Friedman and Stearns, 1971). These fractures form highly visible tree lines on the limbs of Teton Anticline and Lesser Teton Anticline because of differential soil development. These fractures are the Set I conjugate shear fractures of Stearns’. The best-developed fractures are found on the backlimb of Teton Anticline north of the North Fork Teton River. 21 of these large scale fractures were included because of their outcrop exposure and accessibility. Of the 21 fractures that were measured, 17 fractures had a similar orientation of 065°. Only 4 of them carried the opposite orientation (095°) of the conjugate shear set. At these large fractures, both joints and mini-joints that were within 2 meters of the fracture trend were measured. Most measurements were of joints that cut the large fracture plane itself.

The major joint orientations are 345° and 075°. The 075° set forms at a small acute angle to the large fracture plane. The 345° set is sub-parallel to the local fold strike, deviating by 005° (Fig. 3.9). The mini-joints show the same 075° trend of joints, forming an acute angle to the large fracture plane. The fold strike sub-parallel set seen in the joint measurements are much more diffuse. The mini-joints aligned to fold strike vary by 040° from 320° to 000° (Fig. 3.9).
Fig 3.9: Measurement of joints and mini-joints near large fractures on the backlimb of Teton Anticline. An example of these large fractures is shown with the aid of the white lines overlaid on the aerial photograph.
3.3 Discussion

The Stearns Model for fracturing during fold development is dependent upon changing stress orientations within the folding body. Table 3.1 shows the stress configurations that initiate each set of fractures characterized by Stearns. The current observations at Teton Anticline find some but not all the fractures originally described by Stearns for Teton Anticline. The following sections will illustrate the differences of the proposed model to the previous model of Stearns.

3.3.1 Set I Examples

Set I consists of conjugate shear fractures that form at a small dihedral angle bisected by the extension fracture oriented in the dip direction (Stearns, 1968). The geometry of Set I is seen from a distance and from an aerial view of the anticline in the field (Fig. 3.10). This conjugate shear fracture set is postulated to be an artifact of compression within the fold limbs as bending increases during structure development (Stearns, personal communication 2006). Using calcite twin analysis, Friedman and Stearns (1971) showed that maximum compression was subparallel to dip direction during fold development.
Table 3.1
Fracture Geometry of Folds (Stearns Model)

<table>
<thead>
<tr>
<th>Type Set</th>
<th>$\sigma_1$</th>
<th>$\sigma_2$</th>
<th>$\sigma_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Parallel to dip direction</td>
<td>Normal to bedding</td>
<td>Parallel to bedding</td>
</tr>
<tr>
<td></td>
<td>Parallel to bedding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Normal to dip direction</td>
<td>Normal to bedding</td>
<td>Parallel to bedding</td>
</tr>
<tr>
<td></td>
<td>Parallel to bedding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>a) Normal to bedding</td>
<td>a) Parallel to bedding strike</td>
<td>a) Parallel to dip direction</td>
</tr>
<tr>
<td></td>
<td>b) Parallel to dip direction</td>
<td>b) Parallel to bedding strike</td>
<td>b) Normal to bedding</td>
</tr>
<tr>
<td>IV</td>
<td>Parallel to bedding</td>
<td>Parallel to bedding strike</td>
<td>Normal to bedding</td>
</tr>
<tr>
<td>V</td>
<td>Dihedral angle to bedding plane</td>
<td>Parallel to bedding strike</td>
<td>At an angle to bedding plane (90° - dihedral angle)</td>
</tr>
</tbody>
</table>

I – associated with compression in fold limbs parallel to dip
II – associated with compression of fold directed along strike
III – associated with compression of fold normal to bedding
IV – associated with fold related thrusting
V – associated with bedding plane slip

The pre-folding development of conjugate shear fractures is indicated by slip parallel to bedding when the maximum compressive stress is parallel to bedding. Such fracturing should leave slip fibers in the form of slickenlines on the surface of these fractures. Extensive field investigation of 25 macro scale and numerous meso scale examples of “conjugate shear fractures” yield no evidence of slip parallel to bedding. Previous studies found no field evidence for any slip on these fractures despite the fact that bedding-parallel stress was indicated by calcite twinning analysis possibly indicative of a strike-slip stress regime (Friedman and Stearns, 1971).
Fig. 3.10: Aerial and photograph (looking 270°) of Teton Anticline. Conjugate fractures and extensional fractures normal to the strike of the fold are seen at the macrostructure scale.
Evidence of bedding normal slip is observed at three stations on Teton Anticline where slickenlines are oriented normal to bedding (Fig. 3.11). These stations are located in the Swift Sandstone at the southern field area near the point that Teton Anticline switches from fold-bend fold to fault-propagation fold. Bedding normal slip is seen in thrust sheets to the west. In fact, the slickenlines there are much better expressed on the fracture plane (Fig. 3.12). The slip lineations at Choteau Thrust are presently horizontal and post-dates thrusting.

On the backlimb of Teton Anticline North, north of the North Fork Teton River is a series of outcrops that allow observation of large scale conjugate sets. The macro scale fracture sets become lines of vegetation that grew preferentially due to trapping of soil in the fractures. An uneven topography is associated with the large conjugate fractures on the backlimb of Teton Anticline North (Fig. 3.13). Outcrop in the depression between conjugate fractures are stratigraphically younger than those rocks found at the ridges on the outside of the conjugate fractures. This suggests that differential movement relatively normal to bedding occurred to juxtapose the dichronous beds.

To the east of Teton Anticline is Lesser Teton Anticline, where there is an excellent example of fracture development at a fold nose. One would expect localized strike parallel stretching to be the driving mechanism for joint formation here. Field measurements at various locations on Lesser Teton Anticline show a different pattern. The 070° joint persists at all localities on the nose and fold limbs of Lesser Teton Anticline (Fig 3.14: Fig. 3.15). Plus, the 070° joint set is slightly rotated along with the folded bedding, suggesting that it pre-dates the folding. Pre-folding joints could have been mistaken for cross-fold jointing due to their coincidence of orientation being roughly normal to fold strike.
Station TA-97 exhibits evidence of slip normal to bedding. Both of these outcrops were found on separate conjugate sets within the Swift Sandstone. The observation of slight slip fabric on these fractures could be caused by either reactivation of a joint or excessive weathering could have desiccated the fabric.
Fig. 3.12: Wrench slip seen in the Castle Reef Dolomite within the Choteau Mountain Thrust Sheet to the west of Teton Anticline. The white mineralization seen on the fracture surface is the slickenline fabric oriented in the direction denoted.
Fig. 3.14: Graben formation between two conjugate fracture zones with stratigraphically younger rock in the low portion of the structure and older rock occurring at the topographically higher parts.
Using the juxtaposition of stratigraphy between conjugate fractures and rotated 070° joints the conjugate fracture set, labeled by Stearns as Set I, is not related to folding. Fold growth occurred late during Sawtooth deformation (Mudge, 1982). Joints parallel to dip are common. However the conjugate fractures are not directly related to fold development, evident from the previous proof. During progressive deformation, a fold-thrust-belt-wide shift in stress regime is apparent. Initially, thrust faulting regime created the imbricate thrusting to the west. Then, strike parallel-stretching or tectonically induced pore pressures counteracted the least horizontal stress and according to Andersonian regimes, the area may become a strike-slip faulting regime.

The predominance of the 070° joint set throughout Teton Anticline suggests that it formed before fold development. Its genetic relation to the 070° direction seen within the Sawtooth Range Complex and other parts of the High Plains Complex suggests that they are all formed during the same stress orientation. They are parallel to the main transport direction of thrusts in the Sawtooth Range Complex and the Sun River Valley. The 070° joint set formed first, prior to folding. Their coincidence with the dip direction of Teton Anticline can confuse them with cross-fold joints that form during folding. Subsequent folding rotated the joint plane, evident at the nose of Lesser Teton Anticline.
Fig. 3.14: Aerial photograph of the Teton Anticline and Lesser Teton Anticline field areas. The rose plots correspond to each structural element of Lesser Teton Anticline. Both backlimb and forelimb fractures were not just measured within the localities denoted by the arrows. Areas to the north, off of the current photo, were used utilized for fracture measurement of the forelimb and backlimb. Dominance of the 070° set is illustrated here. The next common joint orientation is fold strike parallel. Number of data; Forelimb – 258, Backlimb – 175, Nose – 341.
Fig 3.15: Orientations of measured joints around the nose of Lesser Teton Anticline. Measurements in the bottom-left hand side of the map are actually on Teton Anticline. The rose diagram in the upper-left plots the circular means of all measurements at each locality (Number of stations: 38). The dominance of the 070° suggests that this joint set formed independent of structural position.
3.3.2 Set II Examples

The Stearns Model calls for a conjugate pair of shear fractures along with a bisecting joint forming parallel to the strike of the fold. Field evidence for the complete fracture set is weak but the strike-parallel joint is common. The presence of conjugate fracture sets in this orientation is completely absent on both Teton Anticline and Lesser Teton Anticline. Very sparse, smaller scale examples are at various locations along the crest of Teton Anticline. The best example of conjugate fractures is at the nose of Lesser Teton Anticline (Fig. 3.14). The lack of observations suggests that the conjugate fracture pattern may not manifest during the fracture history of these anticlines.

The most numerous fracture of this type is the formation of strike-parallel joints. These structures are observed at the macro and meso-scale on Teton Anticline and Lesser Teton Anticline (Fig. 3.16). Previous study argues the possibility that these joints may be attributed to the stretching across a fold crest above some neutral surface within the package of rock that is undergoing the deformation (Friedman and Stearns, 1971). During flexure, a neutral surface will manifest itself within the body. This surface acts as a stress reflection surface, with bedding parallel tensile stresses above the line and bedding parallel compressive stresses below the line (Casey and Butler, 2004).

The possibility that previous study at Teton Anticline measured cleavage planes as fractures of Set II is strong. Planar penetrative cleavage is developed during layer-parallel shortening directed normal to the cleavage surface. This can be related to a state of compressive stress oriented normal to the planar cleavage (Alvarez, Engelder, and Geiser, 1978; Engelder and Marshak, 1985). A general state of compressive stress is seen below the neutral surface of the fold. Other examples of compressive fabric at Teton Anticline are bedding normal styolites normal to the compressive stress direction.
Fig. 3.16: Strike parallel fractures at Teton Anticline. Like the macro-scale fractures seen for set one, these fractures also create preferential growth of conifers which allow them to be seen easily from aerial photographs. The meso-scale features of this set can be seen at or near the crest of Teton Anticline.
At Teton Anticline planar penetrative cleavage is observed near the core of the fold. Domain spacing for the cleavage varies from slightly strong to moderate, or 3/4cm to 2cm (Fig. 3.17). This planar cleavage is oriented parallel to strike and normal to bedding and, hence, in the same orientation as Set II joints. It is possible that cleavage in some outcrops was mistaken for jointing in previous fracturing models for Teton Anticline.

3.3.3 Set IV Examples

Set IV fractures are characterized as shear fractures related to the maximum compressive stress oriented parallel to bedding (Stearns, 1968). These fractures occur below the neutral surface of the fold, where the stresses are generally compressive. They consist of detachments on two vertically adjacent bedding planes with a climb in the detachment in the form of a brittle fracture at a low angle to maximum compression. There is no evidence of any extension joint forming parallel to the maximum compression direction and normal to bedding (Stearns, 1968).

At Teton Anticline and Lesser Teton Anticline, current observation confirms the presence of Set IV fractures. These fractures appear as thrust wedges in between bedding planes. They are found below the neutral fiber of Teton Anticline and Lesser Teton Anticline and best expressed in the lower members of the Allan Mountain Limestone. The following figures (3.18, 3.19, and 3.20) exhibit field examples of this fracture set.

3.3.4 Mini-Joints

At all field stations on Teton Anticline and Lesser Teton Anticline a conspicuous fracture system confined to pelagic mudstones is observed. This fracture system consists of small scale, bedding normal fractures that do not break out of a single bed of mudstone. These fractures shall be called mini-joints. The mini-joints have the look of fine desiccation cracks with two distinct
geometries of fracturing. The first pattern is a network of fractures with a uniform orientation distribution. The second and more numerous pattern of fracturing have a preferred orientation that varies as a function of structural position. The first group of fractures that exhibit no preferential orientation will be known as uniform mini-joints and the second group of fractures that have preferential orientations will be known as oriented mini-joints. This section will investigate each of these modes of fracturing.

Some examples of mini-joints are calcite veins in carbonate mudstones (Graham Wall et al., 2006). Mini-joints appear to initiate on a styolitic surface, either bedding normal or bedding parallel. Their limited growth from the styolitic surface may be related to the possibility of fluid pressure driving the crack. As fluid pressure decreases due to surface area increase after initial propagation confining stress can stop propagation (Graham Wall et al., 2006).

Another explanation for mini-joint development is the controversial process of synaeresis. Synaeresis is a chemical process of bulk volume reduction within sediments by subaqueous or subsurface dewatering (Nelson, 2001). Normally it occurs during the dewatering of clays deposited within mudstones. Due to their formation by internal body forces, synaeresis cracks generally form regularly spaced cracks. They are observed in shales, siltstones, limestones, dolomites, and fine- to medium-grained sandstones (Nelson, 2001). Another indication of synaeresis is the infilling of the cracks with different material that is transported during the process of dewatering.

The uniform mini-joints are pervasive throughout outcrops of dolomitic mudstones of the Sun River Member of the Castle Reef Dolomite. An important qualifier for uniform mini-joints is that they are found in beds that are undisturbed by large joints. They are also found on bedding surfaces that exhibit styolites.
Fig. 3.17: Penetrative cleavage within the Jose Member of the Allan Mountain Limestone. This outcrop is located on the backlimb close to the fold axis under the neutral fiber of the fold. Cleavage within the field locality forms in distinct zones instead of being pervasive throughout the entire axial region.

Fig. 3.18: Set IV fractures seen in the Jose Member of the Allan Mountain Limestone in the axial area of Teton Anticline. Notice the classic example of structural thickening as the imbricate thrusts develop.
Fig. 3.19: Another example of Set IV fracturing in the Log Cabin member of the Castle Reef Dolomite. Imbricate thrusts are highly evident in the chert beds here, likely due to its brittle mechanical properties.

Fig. 3.20: Macro-scale fracture of Set IV. Upon closer inspection, some slip fibers can be seen and the correct slip sense has been denoted on the photograph for all three fractures. These fractures cut through beds of the Log Cabin Member of the Castle Reef Dolomite.
In other words, uniform mini-joints occur adjacent to bedding plane styolites (Fig. 3.21). The presence of initiation points on styolites is not consistent with the synaeresis mechanism. Synaeresis cracks form early during diagenesis as the formation dewateres. The uniform mini-joints relative timing is between bedding plane styolitization and oriented mini-joint formation.

The second type of mini-joint, oriented mini-joints, exhibit preferential orientation of propagation. This alignment suggests that these mini-joints formed in a deviatoric stress field. A majority of the preferred orientations are sub-parallel to or sub-normal to strike of Teton Anticline and Lesser Teton Anticline. Some of them also form independent of structural position (Fig. 3.7; Fig. 3.22). This suggests that the mini-joints responded to a stress related to the formation of Teton Anticline and Lesser Teton Anticline. They abut against spaced cleavage. This temporal relationship puts the relative timing of oriented mini-jointing after the cleavage event. With regard to the timing of both orientations, the mini-joints tend to cross-cut each other generally in an orthogonal pattern. It can be common for the oriented mini-joints to be parallel to and normal to strike of the specific structure that they are found on.

Mini-joints are by far the most numerous fractures at outcrops of the dolomitic mudstones of the Sun River Member. Uniform mini-joints cannot be used in fold related fracture set population because of their pre-dating of fold development. However, the strike parallel and strike normal oriented mini-joints could be related to fold development. However, the lack of clear abutment relationships between these two directions does not allow the exact placement in time when these mini-joints formed.
Figure 3.21: Example of uniform mini-joint. The very faint traces of these mini-joints can be seen throughout the outcrop below. Outcrops exhibiting solely uniform mini-joints is rare, and is usually coupled with overprinting from oriented mini-joints.

Figure 3.22: The oriented mini-joints in this locality show a strong preferential direction of parallel to and normal to strike of the bedding. This is the most common interaction of oriented mini-joints. Generally, the mini-joints will mutually cross-cut each other, thereby giving ambiguity to their relative age relationships.
4 Conclusions

Jointing and faulting observed in all structural provinces in the Sawtooth Salient provide
the answer to the stress history question posed for this area. Fractures glimpse a single moment
in geologic time, allowing the investigator to see a progression of deformation in space and time.
Fractures observed in thrust sheets and those found in the foreland basin describe events
affecting the entire Sawtooth Salient. Those fractures investigated at Teton Anticline describe
events affecting the Sawtooth Salient and the local structure (Teton Anticline).

Fractures observed in the thrust sheets were related to the transport direction of those
thrust sheets. Orientation data confirms that the joints measured in each thrust sheet was
generally normal to the strike of the thrust front (Figs: 2.6, 2.9, 2.12). Fractures found in the
foreland basin generally showed three orientations; 050°, 070°, and 090°. At Swift Reservoir, the
joints exhibited abutment relationships that suggested the 070° set formed before the 050°. At
Teton River Canyon, the only orientation is 070°. At Sun River, the foreland basin fractures are
oriented 070° and 090°. Abutments and fringe cracks suggest that the 070° set pre-dates the 090°
set. Unfortunately, the 050° and 090° do not co-exist, not allowing a timing relationship to be
determined. However, it is known that the 070° joint set formed first and the 050° and 090°
subsequent sets formed at later time.

Oroclinal development of the Sawtooth Salient may explain the timing of these joints.
When the initial transport began, its direction may have been the 070°. As the structural front
became arcuate, differential transport created the stress fields required for the localized 050° and
090° joint sets. Further proof of the 070° joint set formed early in the deformation history of the
Sawtooth Salient is in the fractures found in the thrust sheets. In all thrust sheets are a portion of
fractures that belong to the 070° fracture set. Most of these fractures have been rotated due to the
bedding rotation that comes with thrusting. When the data is rotated back to horizontal, a significant portion of the fractures are a vertical set oriented 070°. This would suggest that the 070° joint set pre-dated the thrusting at the foreland edge of the Sawtooth Salient. Abutment of these older joints by younger vertical joints oriented normal to thrust strike proves further that the 070° pre-dates thrusting.

Jointing at Teton Anticline exhibits the same 070° joint set observed cutting across the nose of Lesser Teton Anticline. Other joints and structures at Teton Anticline contribute to the deformation history of the anticline itself. Originally, all fractures were determined to be related to folding stresses (Stearns, 1968). This study showed that some of the fractures and structures observed can be related to stresses prior to folding, stresses related to folding, and stresses after folding. Previously stated, the 070° joint set formed prior to folding. The majority of strike-parallel joints and cross-fold joints (normal to fold strike) formed during folding. The conjugate shears may have formed post-folding because the slip is normal to bedding and may be indicative of wrench faulting during a possible stress regime change. Finally, a majority of the fractures possibly used for fold-related fracture models are actually bedding normal cleavage structures or bedding plane styolite controlled mini-joints. This new interpretation of joints and other structures for Teton Anticline and the Sawtooth Salient leads us to believe that the fractures observed can tell us about the progressive deformation that occurs during thin-skinned thrust tectonics.
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Appendix A

Modeling joint initiation and interactions within Morrison Formation concretions at the Northern Disturbed Belt, Montana.

Abstract

At the front of the Sawtooth Salient there is a field of carbonate concretions with tension joints that denote dichronous stress events. Evidence from previous studies have shown that joints initiating in carbonate concretions within a sandstone matrix prior to matrix jointing develop during lithification of the matrix. Modeling of this situation has proven that tensile stress concentrates in a carbonate concretion subjected to shortening, while the compliant matrix undergoes net compression. Lithification of the Morrison Formation has been timed between 136-146 Ma, synchronous with an E-W compressional stress field developed during incipient Sevier Orogenic thrusting. The second phase of jointing within the concretion occurred during Lewisian Thrusting at the time of Sawtooth Salient formation between 74-59Ma. Joint abutment within the concretion exhibits an acute angle between the two joints with no apparent curving parallel or perpendicular relationships. Using multiple loading configurations, a loading configuration involving uniaxial extension and pore pressure conditions resembles what is observed in the field.

Keywords: concretion, jointing, pore pressure, crack propagation, driving mechanisms, Sevier Orogeny, Sawtooth Salient
Introduction

Joints within concretions provide an opportunity to infer both joint driving mechanisms and the temporal relationships of joint formation (Nickelsen, 1979; McConaughy and Engelder, 1999; Bessinger, et al., 2003). Concretions act as stiff inclusions in a compliant matrix, preferentially jointing in response to a remote stress. Examples of this behavior are concretions found within Pennsylvanian Llewellyn Formation of Bear Valley (Nickelsen, 1979). In other instances, concretions serve as fracture barriers, as is the case for concretions in Devonian black shale of the Appalachian Plateau (McConaughy and Engelder, 1999). In the former case, internal jointing responds to tensile stress concentration during compressional tectonics of the Alleghenian Orogeny. In the case of Devonian concretions, a natural hydraulic fracture will not cleave a concretion because crack tip stress intensity decreases after a fluid loaded joint crosses the interface.

Preferential fracturing relies upon the difference in elastic moduli of two materials. A stiff inclusion with a high Young’s Modulus and low Poisson’s Ratio will tend to concentrate greater stresses than those materials with low Young’s Modulus and high Poisson’s Ratio (Jaeger, Cook, and Zimmerman, 2007). Concretions in the Late Cretaceous DeCourcy Formation in Vancouver Island lie in a sandstone matrix, similar to the Morrison Formation concretions in the Northern Disturbed Belt of Montana (Bessinger et al., 2003). It was found that preferential jointing in these concretions developed during lithification of the matrix, concentrating tensile stress in a stiff inclusion surrounded by compliant material (Bessinger et al., 2003).
**Geologic Background**

The Sawtooth Salient of the Northern Disturbed Belt in northwestern Montana is part of the Sevier Orogenic Thrust Belt. The Northern Disturbed Belt has four sub-belts that characterize their structural style and stratigraphic character (Mudge, 1982: Fig. 1). The High Plains Complex includes Mesozoic sediments of the Jurassic Ellis Group, Jurassic Morrison Formation, Cretaceous Kootenai Formation, and the Cretaceous Colorado Group Shales. It exhibits thrust faulting and folding that is related to a foreland basin directed style of deformation. Immediately to the west, the Sawtooth Range Complex consists of mostly Paleozoic sediments conformably overlain by Mesozoic Ellis Group sediments. The deformation style in this sub-belt is mostly imbricate stack thrust sheets dipping to the west at fairly high angles (40-60 degrees). Increased shortening caused thrust planes to rotate to current angles. To the west, the Sun River Valley contains the same Mesozoic sediments seen in the High Plains Complex; however the structural style is similar to the Sawtooth Range Complex. The Flathead Range Complex consists of the Proterozoic Belt Supergroup rocks that have been emplaced by the Lewis-Eldorado-Hoadley Thrust System. The emplacement of the Flathead Range Complex occurred between 74-59 Ma (Sears, 2001).

Teton Anticline is the site of work on fracture development related to folding stresses (Stearns, 1968). Concretion fracturing is exposed on the nose of Lesser Teton Anticline, a fold just to the east of Teton Anticline (Fig. 1). Seismic investigation determined that these two anticlines are a pair of detachment type folds situated within the same thrust sheet (Burberry, et al, 2008). Additional concretion fracturing occurs in an imbricate fan of Jurassic sediments between Indian Head Thrust and Teton Anticline and also in the High Plains Complex east of Swift Reservoir (Fig. 1).
Fig. 1: Line drawing of the central portion of the Northern Disturbed Belt. All four sub-belts are visible in this diagram. The concretion sites are denoted by star markers. The two northern concretion sites are adjacent to Swift Reservoir. The southern concretion sites are situated on and near Teton Anticline. The concretion site at the nose of Lesser Teton Anticline is the right most marker of the southern group.
The Northern Disturbed Belt experienced progressive deformation. Early development (150Ma) of an E-W directed maximum compressive stress is evidenced by continental interior calcite twinning analysis (Craddock and van der Pluijm, 1999). During the 15 My Lewis-Eldorado-Hoadley shortening (74-59Ma) an ENE direction of transport dominates. Structural evolution of the Sawtooth Salient possibly contained three transport directions. Transport directions are estimated from geologic map reconnaissance of thrust faults in the Sun River Valley, Sawtooth Range Complex, and High Plains Complex. Joint orientations were measured throughout the salient and coincide with the maximum compressive stress direction. Abutment relationships observed in the field provide relative timing of joint formation. A regional joint is oriented ENE. The NE and E joint sets are localized to similar transport directions. Joint set interaction within concretions in the field supplement regional joint set data.

**Joint development in Morrison concretions**

The Morrison Formation in the vicinity of the Sawtooth Salient contains layers of discontinuous concretionary bedding between other beds of fine-grained sandstone. Discontinuous concretions in the Morrison have a range of depositional styles. The most common concretion-bearing strata develop mats that consist of carbonate, known from field acid tests. High iron content in the concretions is suspected, but not confirmed. Weathered concretions show a deep red color. Less common concretion-bearing strata are populated with isolated, round to oblate carbonate concretions. Matrix in the encapsulating strata is composed of fine to medium-grained, greenish-gray sandstone. De-bonding fractures seen in the DeCourcy Formation concretions of British Columbia are not evident in the Morrison concretions. De-bonding fractures form tangential to concretion/matrix interface.
Three separate joint sets cut the concretions; internal joints, external joints, and cross joints. The internal joint set propagates internally without crossing from the concretion into the sandstone matrix. Internal joints propagate only in the isolated concretions at Lesser Teton Anticline and strike 270° ±003°. One or two internal joints will populate a concretion and most will traverse the entire concretion (Fig. 2). All exposed internal joint planes had no mineralization or recognizable plumose morphology.

The external joints penetrate into the concretion from the sandstone matrix. These joints are several meters long and strike 240° ±004°. A small percentage of the joints are mineralized with plumose morphology upon the joint plane. External joints do not have vertical planes. Scanline data reveals that joint spacing is small compared to length. Median spacing of 8 centimeters ±5 centimeters is observed. Not all concretions have penetrating external joints. One particular concretion contains only penetrating external joints (Fig. 3). A significant characteristic of external joints is its abrupt termination against internal joints at an acute angle.

The cross joints strike 181° ±004° and abut internal and external joints (Fig. 4). Matrix sandstone contains cross joints similar in orientation as those within concretions (Fig. 5). Joint planes have nearly vertical dips and small lengths compared to external joints. Most cross joints form between two external joints and terminate at the external joint plane.
Fig. 2: Field photograph of internal joints contained within a concretion of the Morrison Formation. Kennedy half-dollar coin for scale.

Fig. 3: Field photograph of external joints penetrating through a concretion in the Morrison Formation.
Fig. 4: Field photograph of cross joints in a concretion of the Morrison Formation. Cross joints run from the top to the bottom of the photograph.

Fig. 5: Field photograph of cross joint in matrix sandstone of the Morrison Formation. Cross joint are features directed from upper left to lower right in the picture.
Interpretation

Primary internal joints

Internal joints can preferentially form in stiff inclusions because of differences in elastic properties between concretion and matrix (Pollard and Aydin, 1988). In the Appalachian Basin examples of internal jointing are found in the Pennsylvanian Llewellyn Formation of Bear Valley (Nickelsen, 1979). Consider a stiff inclusion with elastic moduli \{E_i, \nu_i\} and the rock matrix \{E, \nu\} and a perfectly welded interface. Stress will intensify in the inclusion if \(E_i>E\) and \(\nu_i<\nu\). This relationship is apparent in the aforementioned Llewellyn Formation (Nickelsen, 1979).

DeCourcy Formation concretions in British Columbia have similar jointing. Modeling shows that the internal joint set crossed the tensile failure envelope if the matrix sandstone has elastic moduli congruent with non-lithification (Bessinger et al., 2003). Morrison concretions have field observational similarities to the DeCourcy concretions. Both concretions are carbonate and both matrices are medium-grained sandstone. Because of these similarities, elastic moduli of the DeCourcy Formation, determined from Schmidt Hammer tests, are used as proxies for Morrison concretion and matrix elastic moduli (Bessinger et al., 2003).

An E-W oriented tectonic compression is synchronous with the deposition and subsequent lithification of the Morrison Formation in northwest Montana (150-140Ma; Craddock and van der Pluijm, 1999; Gillespie and Heller, 1995). Subsequent concentrations of joint driving stress can develop near internal flaws. During this time, we theorize that the internal joint set developed within the Morrison concretions before the matrix sandstone lithified.
External Joint Set

The general strike of the external joints coincides with a large regional joint set developed throughout the Sawtooth Salient (Fig. 6). The external joint set and the regional joint set form independent of structural position. This possibly suggests that the regional joint set and external joint set are of the same origin. Decreasing dip angle of the joint planes due to bed rotation leads to the supposition that their formation came some time before folding. Study of the regional joint set in other localities confirms that it is the earliest joint set related to ENE directed transport of the Lewis-Eldorado-Hoadley Thrust System.

Joints driven in tension can penetrate into and through a concretion as long as the height of the approaching joint is equal to or greater than the concretion itself (McConaughy and Engelder, 1999). Another important caveat is the joint must have enough energy to reach the concretion interface. Stress intensity decreases when a joint approaches a concretion interface. If the joint does not have enough energy to overcome this significant decrease in stress intensity, it will tend to curve away from the concretion (McConaughy and Engelder, 1999). Field evidence shows that external joints cut into concretions. This suggests that the external joints are taller than the concretions and have enough energy to propagate through low stress intensities.

The acute angle of termination at the internal joint plane is an unusual geometry. Typically, preexisting open joints disrupt the crack-tip stress field of the approaching joint thereby forcing it along a curving trajectory (Dyer, 1988). If the preexisting joint undergoes plane parallel compression, the advancing joint will curve parallel to the free surface. However, if the preexisting joint undergoes plane parallel tension, the advancing
Fig. 6: Directional presentation of joint orientations along the Sawtooth Salient in the Northern Disturbed Belt. Notice the joints measured at the nose of Lesser Teton Anticline have the same orientation of the regional set.
joint will curve perpendicular to the free surface and not interact directly with the previous joint (Dyer, 1988). Conversely, if the preexisting joint is closed and has a frictional strength under relatively high normal stress, the approaching joint will propagate in-plane and through the interface. In the case of Lesser Teton Anticline, external joints penetrate the concretions and abut without curving, suggesting another joint interaction mechanism than those stated above.

*Cross joints (The secondary internal set)*

The secondary internal set has an orientation similar to the overall strike of Little Teton Anticline. Due to the orientation of the joints, they may be interpreted as fold strike-parallel joints associated with stretching above the neutral surface of the fold. The formation of strike-parallel fractures during the development of folds typically occur late (Nickelsen, 1979). The position of the concretion field on the fold raises doubt that these cross-joints are related to strike-parallel jointing. The position of the concretion field is on the southwestern curvature of the nose, suggesting strike parallel stretching around the nose (Fig. 6). These joints are not parallel to dip direction and cannot be considered a cross-joint. These cross-joints possibly are the result of relaxation stress during denudation of the Sawtooth Salient and extensional collapse of the Northern Disturbed Belt (Constenius, 1996). The vertical orientation of the joint plane suggests jointing occurred after folding attained its current form.

*Modeling of joint initiation and interaction*

Mathematical modeling helps elucidate conditions for joint initiation, propagation, and interaction observed in the field. Of the three jointing mechanisms stated before, only the joint initiation within concretions and external joint interactions with internal joints will be modeled. The initiation and propagation of cross joints is not uncommon. For the other two situations an appropriate model must be constructed to simulate field behavior.
Software

A finite element code is used for modeling joint interactions. Comsol Multiphysics™ Structural Mechanics Module is used for this study. It contains a pre-formed set of finite element codes that are utilized for modeling. Because this program is engineering software, stresses have opposite signs. Compression is negative and tension is positive in Comsol Multiphysics™. 2-D plane strain models are used for simplicity in this exercise. 3-D models were initially created, but diagrams are difficult to read in printed formats.

A good calibration test for the modeling software is to load a singular crack in normal, uniaxial elongation and compare the principal stress field to known standards (Fig. 7a). Another calibration is to conduct a Brazilian tensile test, where point loads are applied to a disk until it reaches tensile failure, and compare to known results (Fig. 7b: Fig 7c).

Model Configurations

The first situation involves joint initiation in a concretion under compression. The interpreted field loading configuration is uniaxial compression caused by tectonic layer parallel shortening (Craddock and van der Pluijm, 1999). Proposed earlier, internal joints formed during lithification of the Morrison Formation. Two separate model configurations will be tested. Both models are configured in 2-D plane strain. Each will be subjected to the same uniaxial shortening strain of 0.015%. Shortening is used instead of line loads because internal stresses may be calculated if elastic moduli are known. The calculation of internal stress will provide a check to make sure the model is performing correctly.
Fig. 7: Calibration exercises to test modeling software. a) Internal crack within a body subjected to crack normal extension and its subsequent map of principal stresses. b) Brazilian tensile test result of $S_{xx}$. The middle of the body shows tension suggesting crack initiation will occur. c) Graph of stress across the x-axis diameter of the disc in the Brazilian tensile test. The smooth increase of tensile stress towards the center of the disc complies to standard models of this behavior.
The first configuration has a matrix material (600cm x 800cm) assumed to be lithified containing a concretion (r=20cm)(Fig. 8a). The second configuration has a non-lithified matrix and a lithified concretion (Fig. 8b). Differential lithification is a characteristic of concretion formation during early diagenesis (Coleman, 1993). A final boundary condition is the interface between the concretion and matrix is fully bonded. Field evidence supports a fully bonded interface because no tangential fractures exist (de-bonding fractures) at the concretion/matrix interface in the Morrison Formation.

The second situation is an external joint interacting with an internal joint in a concretion. A regional transport and subsequent strike-parallel stretching developed the ENE directed external joint set. A likely driving mechanism is strike-parallel stretching reducing the least horizontal stress, switching the principal stress configurations, to facilitate vertical joints (least compressive stress is horizontal) in an Andersonian thrust faulting stress regime (least compressive stress is vertical). Each model configuration will have uniaxial elongation strain normal to the joint at 0.015%. The rectangular body (600cm x 800cm) the joint propagates in has the same mechanical properties as the concretions in British Columbia, used as proxies for Morrison concretions. The model construct is again 2-D plane strain.

The first configuration involves a long joint (300cm crack length) approaching at 30 degrees a much smaller (40cm) open fracture. The internal joint is set to be a free surface; subject to neither normal nor shear stress (Fig. 9a). The elongation strain will induce tensile stresses at the crack tip to propagate the external joint towards the internal joint. The next configuration adds one more parameter. A pore pressure equal to hydrostatic stress is subjected to both the external and internal joints as a normal line load of 9800 N/m.
Fig. 8: Model configurations for internal joint formation in concretions. The pictures are not to scale for ease of viewing. a) Lithified matrix configuration. b) Unlithified matrix configuration.
Elongation strain of 0.015% remains the same. Both the external and internal joints are free surfaces (Fig. 9b). The third configuration has the same loading configurations as the second model. Instead of a free surface on the internal joint, it is now considered a roller constraint. A roller constraint allows the surface to slip but there is no displacement normal to the joint plane. A roller constraint is appropriate because internal pore water is incompressible to a first order of magnitude and will support a subjected load.

Concretion Models

The results of the two concretion loading configurations provide evidence for which natural condition caused the internal jointing. The first loading configuration involved both materials being lithified. During uniaxial shortening, internal compressive stresses develop in the concretion in both $S_{xx}$ and $S_{yy}$ directions (Fig. 10). Small tensile stresses develop in the matrix in the $S_{xx}$ direction. The second loading configuration involved the matrix being unlithified and the concretion being lithified. Uniaxial shortening induced compressive stress in the $S_{yy}$ direction and tensile stress in the $S_{xx}$ direction within the concretion (Fig. 11). Tensile stresses build outside of the concretion in the unlithified matrix.

A possible explanation of the difference in $S_{xx}$ is the elastic properties of the matrix. When the matrix is unlithified, Young’s Modulus is low and Poisson’s Ratio is high. During unaxial shortening, the matrix possibly accommodated the elongation of the concretion along the x-axis. When the matrix is lithified, Young’s Modulus is higher and Poisson’s Ratio is low. This creates a stiffer matrix, but not as stiff as the concretion. During uniaxial shortening, the stiffer matrix has less ability to accommodate the concretion’s x-axis directed elongation. This translates into a compression because the stiffer matrix creates a confinement condition.
Fig. 9: Loading configurations for external-internal joint interactions. a) External joint propagates towards internal joint with free surfaces and no pore pressure. b) External joint propagates towards internal joint with free surface and pore pressure found at 1km burial.
Fig. 10: Stress map of the $S_{xx}$ component. Scale at right is in MPa. As stated before, tensile stresses are positive and compressive stresses are negative in this software. The concretion concentrates the greatest compressive stress in this model when the matrix is lithified. Arrows with inverted arrows are principal stress directions. Inverted arrows denote a compressive principal stress. Measurement scale at bottom and left side are in centimeters. The visible portion in this diagram represents a small portion of the actual size of the model construct (See Fig. 8 for configuration dimensions).
Fig. 11: Stress map of the $S_{xx}$ component with an unlithified matrix. Scale at right is in MPa. As stated before, tensile stresses are positive and compressive stresses are negative in this software. The concretion concentrates tensile stress in this model when the matrix is unlithified. Arrows with inverted arrows are principal stress directions. Inverted arrows denote a compressive principal stress. Measurement scale at bottom and left side are in centimeters. The visible portion in this diagram represents a small portion of the actual size of the model construct (See Fig. 8 for configuration dimensions).
Internal-External Crack Interaction Models

A crack tip approaching a free surface at an angle less than 90° will either curve parallel or perpendicular based upon plane parallel stress conditions at the pre-existing crack (Dyer, 1988). Modeling the free surface configuration with no pore pressure explicitly shows the principal stress field configuration will induce curving perpendicular behavior (Fig. 12). The second configuration added pore pressure normal to the internal crack. The principal stress directions are different than the first configuration (Fig. 13). The $S_{yy}$ stress contour map shows less asymmetry at the crack tip than the first configuration. The final model configuration applies both pore pressure and roller constraints on the internal joint. The principal stress directions are nearly opposite to those seen in the first model (Fig. 14).

The first model has principal stress directions that coincide with previous results of a crack tip interacting with a free surface (Dyer, 1988). Previous work has found that curving perpendicular relationships occur due to existing joint parallel tensile stress. The current model presented shows that the principal stress in front of the crack tip, along the existing joint is compressive. The tensile stress developed at the crack tip would intuitively determine the propagation direction of future crack growth. This stress is rotated so that the normal plane is directed towards the crack at a high angle. Further iterations of the same model at smaller distances have the same principal stress field pattern. The current model then shows that the crack will deflect from its current plane and rotate normal to the existing joint surface, even though the existing joint surface is under plane parallel compression. The one drawback of the software used, is that it cannot propagate a crack.
Fig. 12: External joint interacting with the free surface of an internal joint. Contour map is of crack tip normal stress ($S_{yy}$). Both joints are not subject to pore pressure. Principal stress directions suggest the crack tip will deflect down to curve perpendicular to the internal joint. Scale to the right is in MPa. Scale on bottom and left are in centimeters. Visible portion does not represent the entire body (See Fig. 9 for model construct dimensions).
Fig. 13: External joint interacting with the free surface of an internal joint. Contour map is of crack tip normal stress ($S_{yy}$). Both joints are subject to pore pressure of 9.8 MPa. Principal stress directions suggest the crack tip might have no to slight deflection to the internal joint. Scale to the right is in MPa. Scale on bottom and left are in centimeters. Visible portion does not represent the entire body (See Fig. 9 for model construct dimensions).
Fig. 14: External joint interacting with the free surface of an internal joint. Contour map is off the crack tip normal stress ($S_{yy}$). Both joints are subject to pore pressure of 9.8 MPa. Principal stress directions suggest the crack tip will deflect up to curve parallel to the internal joint. Scale to the right is in MPa. Scale on bottom and left are in centimeters. Visible portion does not represent the entire body (See Fig. 9 for model construct dimensions).
The third model has a crack tip principal stress field that suggests curving parallel interactions. Pore pressure has been added to both cracks and roller constraint on the surface of the existing crack. To reiterate, a roller constraint means that the surface is allowed to slip under an applied load, but no normal displacement can occur. Roller constraints are useful when dealing with pore pressures because pore water is incompressible. Tensile principal stresses normal to the internal joint wall adjacent to the approaching crack tip. This suggests the internal joint wants to open further, but roller constraint does not allow this displacement. This tension perturbs the principal stresses at the approaching crack and causes it to curve parallel to the existing joint plane.

Compared to both end members stated above, the second configuration can be the possible explanation of field behavior. This model applies pore pressure to both cracks, but the surfaces are instructed to be free. The pattern of crack tip normal stress is similar to the first configuration. Closer inspection reveals less asymmetry in the vicinity of the crack tip. Also, the principal stress field is different. The principal stresses in this model possibly suggest in-plane crack propagation to slight deviation. The stresses at the internal joint plane show higher normal compressive stresses due to pore pressure acting upon the free surface. The author postulates it is this compressive stress, normal to the internal joint plane, which counteracts the stress field that would develop if the internal joint was just a free surface (First model).

**Discussion**

The modeling helps understand the joint driving mechanisms in the field. For the concretions, modeling explicitly shows that tensile stress will concentrate within a stiff inclusion.
surrounded by a compliant matrix. Conversely, compressive stresses will concentrate within a stiff inclusion when the matrix has higher elastic moduli. The field behavior is internal joints forming in concretions, suggesting a stiff inclusion within a compliant matrix. Internal joints rarely break out of the concretions. Stress intensity at the internal crack tip must decrease as it reaches the concretion interface. Graphical representation of the unlithified model show compressive stress normal to the crack plane ($S_{xx}$) increases greatly in the matrix past the interface (Fig. 15). Increased normal compression can slow or terminate crack tip propagation. The lithified model has the opposite behavior (Fig. 16). The crack plane normal stress is tensile and would facilitate continued propagation. However, the manifestation of crack plane normal ($S_{xx}$) compression within the concretion would prohibit crack formation and propagation. The introduction on a pre-existing flaw further concentrates crack normal tensile stress and crack propagation (Fig. 17).

The models depicting internal-external crack interaction show three possible field behaviors. The field behavior is an external joint approaching an internal crack surface with little to no out of plane propagation. The best fit model is the second loading configuration. In this model both cracks are loaded with pore pressure and surface are allowed to displace freely (free surface behavior). The crack tip principal stress field appears to be less asymmetric compared to the other models. Plus, stress concentration at the crack tip is larger in this model compared to the others. Pore pressure adds crack normal driving stress to the external crack and can help keep the joint in plane as it approaches the internal joint. The other two models show crack tip driving stresses that are reduced due to shielding from the adjacent crack tip of the internal joint.
Fig. 15: Graph of potential crack normal stress ($S_{xx}$) in a concretion within an unlithified matrix. The line of values used for graphing is the y-axis through the center of the concretion. The concretion carries a positive (tensile) stress value. The matrix along the y-axis (or axis of potential crack propagation) show negative (compressive) stress values. Crack normal compressive stress may retard or terminate crack growth out of a concretion. $S_{xx}$ values in MPa and Arc-Length values in centimeters.
Fig. 16: Graph of potential crack normal stress ($S_{xx}$) in a concretion within an lithified matrix. The line of values used for graphing is the y-axis through the center of the concretion. The concretion carries a negative (compressive) stress value. The matrix along the y-axis (or axis of potential crack propagation) has positive (tensile) stress values. Potential crack normal compression in the concretion does not facilitate crack generation to propagate to the interface. $S_{xx}$ values in MPa and Arc-Length values in centimeters.
Fig. 17: Stress contour map of $S_{xx}$ of a concretion with an internal flaw within an un lithified matrix. Notice at the tips of the flaw, crack normal tensile stress is concentrated and can facilitate crack growth more than a concretion with an internal flaw. Arrows with inverted arrows are principal stress directions. Inverted arrows denote a compressive principal stress. Measurement scale at bottom and left side are in centimeters. The visible portion in this diagram represents a small portion of the actual size of the model construct (See Fig. 8 for configuration dimensions).
Conclusions

Elastic modeling can assist in the determination of driving mechanisms for natural fracture formation and interaction. In the Morrison Formation of the Northern Disturbed Belt, concretions have distinct jointing patterns that have interesting initiation conditions and interactions. Mechanical properties found for concretions and matrix material in British Columbia were used as proxies for this study because of their compositional similarities to Morrison concretions and matrix material. The internal joints are contained completely in concretions and rarely propagate across the interface. Modeling shows that joint initiation is favorable during uniaxial shortening when the matrix material is considerably more compliant than the stiff inclusion. Because the matrix material is medium grained sandstone low elastic moduli would occur during lithification upon burial. The age of Morrison deposition suggests that internal joints developed during initial Sevier shortening 150-140Ma.

The external joint set in Morrison concretions are congruent with a regional ENE joint set developed during early transport of the Lewis-Eldorado-Hoadley Thrust System. The joint driving mechanism is attributed to strike parallel extension during strike normal foreland shortening. At concretion outcrops, the external joint penetrates through the concretion interface and abuts the pre-existing internal joints at an acute angle. In-plane propagation near an existing joint is an unusual circumstance. Typical interactions include curving parallel or perpendicular. This behavior manifests during crack propagation towards a free surface with no consideration of pore pressure. Modeling shows the most likely driving mechanism would be external joint normal extension coupled with pore pressure in both joints. Pore pressure loading of the external crack counteracts the stress perturbation at the crack tip as it approaches the internal joint surface.
References


Burberry, C.M., Cannon, D.L., Cosgrove, J., Engelder, T., 2008, Still have to get title from Caroline.


Appendix B

Raw Data

Joint measurements are represented by rose diagrams and stereonets. An example of the data presentation is below. All rose diagrams use a sector angle of 3°.

Station Names

TA: Teton Anticline
LTA: Lesser Teton Anticline
NFT: North Fork Teton River
SFT: South Fork Teton River
OF: Overprinted Fold (Sole of Choteau Thrust)
SR: Sun River
SW: Swift Reservoir

Station Name: Example Station
Number of Data: 26
Scale (Tick Interval): 10% (2.6 data)
Maximum: 34.6% (9 data)
Circular Variance: 0.65
Circular Standard Deviation: 1.4
Circular Dispersion: 0.43
Circular Kurtosis: 1.31
TA 050
Data: 7
Tick Interval: 3% (0.2 Data)
Maximum: 14.3% (1 Data)
Circular Variance: 0.59
Circular Std. Dev.: 1.3
Circular Dispersion: 0.35
Circular Kurtosis: 2.26

TA 051
Data: 20
Tick Interval: 5% (1 Data)
Maximum: 30% (6 Data)
Circular Variance: 0.43
Circular Std. Dev.: 1.1
Circular Dispersion: 0.95
Circular Kurtosis: -1.85

TA 052 (Red Bed – Swift)
Data: 14
Tick Interval: 3% (0.4 Data)
Maximum: 14.3% (2 Data)
Circular Variance: 0.74
Circular Std. Dev.: 1.6
Circular Dispersion: 3.29
Circular Kurtosis: -0.59

TA 052 (Non Red Bed – Swift)
Data: 7
Tick Interval: 5% (0.4 Data)
Maximum: 28.6% (2 Data)
Circular Variance: 0.23
Circular Std. Dev.: 0.7
Circular Dispersion: 0.55
Circular Kurtosis: -1.42

TA 053a
Data: 14
Tick Interval: 3% (0.4 Data)
Maximum: 14.3% (2 Data)
Circular Variance: 0.93
Circular Std. Dev.: 2.3
Circular Dispersion: 91.76
Circular Kurtosis: -0.20

TA 053b
Data: 12
Tick Interval: 5% (0.6 Data)
Maximum: 25% (3 Data)
Circular Variance: 0.58
Circular Std. Dev.: 1.3
Circular Dispersion: 1.06
Circular Kurtosis: -1.95

TA 054 (Cleavage Planes)
Data: 10
Tick Interval: 10% (1 Data)
Maximum: 40% (4 Data)
Circular Variance: 0.03
Circular Std. Dev.: 0.3
Circular Dispersion: 0.07
Circular Kurtosis: 5.40

TA 054
Data: 10
Tick Interval: 5% (0.5 Data)
Maximum: 20% (2 Data)
Circular Variance: 0.58
Circular Std. Dev.: 1.3
Circular Dispersion: 1.85
Circular Kurtosis: -1.01
**TA 060 (Mini-Joints)**
Data: 41
Tick Interval: 2% (0.8 Data)
Maximum: 9.8% (4 Data)
Circular Variance: 0.91
Circular Std. Dev.: 2.2
Circular Dispersion: 41.63
Circular Kurtosis: -0.31

**TA 062**
Data: 8
Tick Interval: 2% (0.2 Data)
Maximum: 12.5% (1 Data)
Circular Variance: 0.60
Circular Std. Dev.: 1.4
Circular Dispersion: 2.99
Circular Kurtosis: -0.03

**TA 062 (Mini-Joints)**
Data: 32
Tick Interval: 2% (0.6 Data)
Maximum: 9.4% (3 Data)
Circular Variance: 0.59
Circular Std. Dev.: 1.3
Circular Dispersion: 2.11
Circular Kurtosis: -0.43

**TA 063**
Data: 5
Tick Interval: 5% (0.3 Data)
Maximum: 20% (1 Data)
Circular Variance: 0.56
Circular Std. Dev.: 1.3
Circular Dispersion: 0.83
Circular Kurtosis: -1.12

**TA 063 (Mini-Joints)**
Data: 25
Tick Interval: 2% (0.5 Data)
Maximum: 12% (3 Data)
Circular Variance: 0.78
Circular Std. Dev.: 1.7
Circular Dispersion: 8.34
Circular Kurtosis: -0.04

**TA 064**
Data: 5
Tick Interval: 10% (0.5 Data)
Maximum: 40% (2 Data)
Circular Variance: 0.81
Circular Std. Dev.: 1.8
Circular Dispersion: 0.83
Circular Kurtosis: 1.42

**TA 064 (Mini-Joints)**
Data: 50
Tick Interval: 2% (1 Data)
Maximum: 8% (4 Data)
Circular Variance: 0.69
Circular Std. Dev.: 1.5
Circular Dispersion: 2.93
Circular Kurtosis: 0.25

**TA 065**
Data: 18
Tick Interval: 2% (0.4 Data)
Maximum: 11.1% (2 Data)
Circular Variance: 0.80
Circular Std. Dev.: 1.8
Circular Dispersion: 9.68
Circular Kurtosis: -0.37
TA 065 (Mini-Joints)
Data: 22
Tick Interval: 5% (1.1 Data)
Maximum: 18.2% (4 Data)
Circular Variance: 0.74
Circular Std. Dev.: 1.6
Circular Dispersion: 2.68
Circular Kurtosis: 0.30

TA 066
Data: 22
Tick Interval: 5% (1.1 Data)
Maximum: 22.7% (5 Data)
Circular Variance: 0.76
Circular Std. Dev.: 1.7
Circular Dispersion: 3.27
Circular Kurtosis: 0.43

TA 066 (Mini-Joints)
Data: 10
Tick Interval: 10% (1 Data)
Maximum: 40% (4 Data)
Circular Variance: 0.95
Circular Std. Dev.: 2.5
Circular Dispersion: 3.04
Circular Kurtosis: -1.09

TA 067
Data: 12
Tick Interval: 3% (0.4 Data)
Maximum: 16.7% (2 Data)
Circular Variance: 0.82
Circular Std. Dev.: 1.8
Circular Dispersion: 6.17
Circular Kurtosis: 0.79

TA 067 (Mini-Joints)
Data: 7
Tick Interval: 3% (0.2 Data)
Maximum: 14.3% (1 Data)
Circular Variance: 0.65
Circular Std. Dev.: 1.5
Circular Dispersion: 1.58
Circular Kurtosis: 0.49

TA 067 (Pavement)
Data: 15
Tick Interval: 5% (0.8 Data)
Maximum: 20% (3 Data)
Circular Variance: 0.62
Circular Std. Dev.: 1.4
Circular Dispersion: 1.98
Circular Kurtosis: -0.74

TA 068
Data: 11
Tick Interval: 5% (0.6 Data)
Maximum: 18.2% (2 Data)
Circular Variance: 0.76
Circular Std. Dev.: 1.7
Circular Dispersion: 2.11
Circular Kurtosis: 0.71

TA 068 (Mini-Joints)
Data: 34
Tick Interval: 3% (1 Data)
Maximum: 17.6% (6 Data)
Circular Variance: 0.83
Circular Std. Dev.: 1.9
Circular Dispersion: 12.74
Circular Kurtosis: 0.22

152
TA 093 (Mt. Pablo Fracture)
Data: 15
Tick Interval: 3% (0.5 Data)
Maximum: 13.3% (2 Data)
Circular Variance: 0.62
Circular Std. Dev.: 1.4
Circular Dispersion: 1.64
Circular Kurtosis: 0.77

TA 094
Data: 23
Tick Interval: 3% (0.7 Data)
Maximum: 13% (3 Data)
Circular Variance: 0.56
Circular Std. Dev.: 1.3
Circular Dispersion: 1.60
Circular Kurtosis: 0.26

TA 095
Data: 6
Tick Interval: 10% (0.6 Data)
Maximum: 33.3% (2 Data)
Circular Variance: 0.78
Circular Std. Dev.: 1.7
Circular Dispersion: 6.31
Circular Kurtosis: 0.11

TA 096
Data: 26
Tick Interval: 2% (0.5 Data)
Maximum: 11.5% (3 Data)
Circular Variance: 0.51
Circular Std. Dev.: 1.2
Circular Dispersion: 0.93
Circular Kurtosis: 1.30

TA 097
Data: 23
Tick Interval: 3% (0.7 Data)
Maximum: 13% (3 Data)
Circular Variance: 0.55
Circular Std. Dev.: 1.3
Circular Dispersion: 2.46
Circular Kurtosis: -0.09

TA 098
Data: 29
Tick Interval: 2% (0.6 Data)
Maximum: 10.3% (3 Data)
Circular Variance: 0.57
Circular Std. Dev.: 1.3
Circular Dispersion: 2.06
Circular Kurtosis: 0.37

TA 099
Data: 16
Tick Interval: 5% (0.8 Data)
Maximum: 18.8% (3 Data)
Circular Variance: 0.77
Circular Std. Dev.: 1.7
Circular Dispersion: 7.20
Circular Kurtosis: 0.05

TA 099 (Mini-Joints)
Data: 68
Tick Interval: 2% (1.4 Data)
Maximum: 11.8% (8 Data)
Circular Variance: 0.78
Circular Std. Dev.: 1.7
Circular Dispersion: 7.77
Circular Kurtosis: 0.06
TA 104
Data: 12
Tick Interval: 3% (0.4 Data)
Maximum: 16.7% (2 Data)
Circular Variance: 0.53
Circular Std. Dev.: 1.2
Circular Dispersion: 2.19
Circular Kurtosis: 0.00

TA 105
Data: 18
Tick Interval: 2% (0.4 Data)
Maximum: 11.1% (2 Data)
Circular Variance: 0.78
Circular Std. Dev.: 1.8
Circular Dispersion: 6.97
Circular Kurtosis: 0.40

BC 01
Data: 24
Tick Interval: 3% (0.7 Data)
Maximum: 16.7% (4 Data)
Circular Variance: 0.91
Circular Std. Dev.: 2.2
Circular Dispersion: 42.69
Circular Kurtosis: -0.07

BC 02
Data: 24
Tick Interval: 2% (0.5 Data)
Maximum: 8.3% (2 Data)
Circular Variance: 0.68
Circular Std. Dev.: 1.5
Circular Dispersion: 4.33
Circular Kurtosis: -0.06

BC 03
Data: 24
Tick Interval: 2% (0.5 Data)
Maximum: 8.3% (2 Data)
Circular Variance: 0.80
Circular Std. Dev.: 1.8
Circular Dispersion: 9.12
Circular Kurtosis: 0.27

Chouteau Thrust 01
Data: 25
Tick Interval: 3% (0.8 Data)
Maximum: 16% (4 Data)
Circular Variance: 0.26
Circular Std. Dev.: 0.8
Circular Dispersion: 0.53
Circular Kurtosis: 1.55

Chouteau Thrust 02
Data: 25
Tick Interval: 2% (0.5 Data)
Maximum: 8% (2 Data)
Circular Variance: 0.56
Circular Std. Dev.: 1.3
Circular Dispersion: 2.16
Circular Kurtosis: -0.23

Chouteau Thrust 03
Data: 25
Tick Interval: 5% (1.3 Data)
Maximum: 20% (5 Data)
Circular Variance: 0.42
Circular Std. Dev.: 1.0
Circular Dispersion: 0.66
Circular Kurtosis: 2.33
SZ 01 (Mini-Joints)
Data: 4
Tick Interval: 5% (0.2 Data)
Maximum: 25% (1 Data)
Circular Variance: 0.58
Circular Std. Dev.: 1.3
Circular Dispersion: 1.85
Circular Kurtosis: 0.49

SZ 02
Data: 32
Tick Interval: 5% (1.6 Data)
Maximum: 21.9% (7 Data)
Circular Variance: 0.80
Circular Std. Dev.: 1.8
Circular Dispersion: 7.36
Circular Kurtosis: 0.28

SZ 02 (Mini-Joints)
Data: 10
Tick Interval: 5% (0.5 Data)
Maximum: 20% (2 Data)
Circular Variance: 0.70
Circular Std. Dev.: 1.5
Circular Dispersion: 2.66
Circular Kurtosis: -0.28

SZ 03
Data: 51
Tick Interval: 2% (1 Data)
Maximum: 7.8% (4 Data)
Circular Variance: 0.83
Circular Std. Dev.: 1.9
Circular Dispersion: 7.05
Circular Kurtosis: 0.85

SZ 03 (Mini-Joints)
Data: 41
Tick Interval: 2% (0.8 Data)
Maximum: 7.3% (3 Data)
Circular Variance: 0.70
Circular Std. Dev.: 1.5
Circular Dispersion: 4.14
Circular Kurtosis: -0.20

SZ 04
Data: 24
Tick Interval: 2% (0.5 Data)
Maximum: 12.5% (3 Data)
Circular Variance: 0.80
Circular Std. Dev.: 1.8
Circular Dispersion: 9.83
Circular Kurtosis: -0.27

SZ 04 (Mini-Joints)
Data: 29
Tick Interval: 3% (0.9 Data)
Maximum: 13.8% (4 Data)
Circular Variance: 0.78
Circular Std. Dev.: 1.7
Circular Dispersion: 4.36
Circular Kurtosis: -0.89

SZ 05
Data: 23
Tick Interval: 3% (0.7 Data)
Maximum: 13% (3 Data)
Circular Variance: 0.77
Circular Std. Dev.: 1.7
Circular Dispersion: 3.73
Circular Kurtosis: 1.02
SZ 05 (Mini-Joints)
Data: 9
Tick Interval: 5% (0.5 Data)
Maximum: 22.2% (2 Data)
Circular Variance: 0.76
Circular Std. Dev.: 1.7
Circular Dispersion: 6.15
Circular Kurtosis: 0.34

SZ 06
Data: 27
Tick Interval: 5% (1.4 Data)
Maximum: 22.2% (6 Data)
Circular Variance: 0.84
Circular Std. Dev.: 1.9
Circular Dispersion: 5.20
Circular Kurtosis: 1.02

SZ 06 (Mini-Joints)
Data: 12
Tick Interval: 3% (0.4 Data)
Maximum: 16.7% (2 Data)
Circular Variance: 0.50
Circular Std. Dev.: 1.2
Circular Dispersion: 1.24
Circular Kurtosis: -1.03

SZ 07
Data: 40
Tick Interval: 2% (0.8 Data)
Maximum: 10% (4 Data)
Circular Variance: 0.73
Circular Std. Dev.: 1.6
Circular Dispersion: 2.93
Circular Kurtosis: -0.10

SZ 07 (Mini-Joints)
Data: 6
Tick Interval: 10% (0.6 Data)
Maximum: 33.3% (2 Data)
Circular Variance: 0.55
Circular Std. Dev.: 1.3
Circular Dispersion: 1.33
Circular Kurtosis: 1.31

SZ 08
Data: 40
Tick Interval: 2% (0.8 Data)
Maximum: 12.5% (5 Data)
Circular Variance: 0.66
Circular Std. Dev.: 1.5
Circular Dispersion: 1.46
Circular Kurtosis: 1.10

SZ 09
Data: 40
Tick Interval: 2% (0.8 Data)
Maximum: 12.5% (5 Data)
Circular Variance: 0.66
Circular Std. Dev.: 1.5
Circular Dispersion: 2.92
Circular Kurtosis: -0.76

SZ 09 (Mini-Joints)
Data: 74
Tick Interval: 1% (0.7 Data)
Maximum: 6.8% (5 Data)
Circular Variance: 0.81
Circular Std. Dev.: 1.8
Circular Dispersion: 10.40
Circular Kurtosis: 0.13
SR 18 (SS Fracture)
Data: 20
Tick Interval: 3% (0.6 Data)
Maximum: 15% (3 Data)
Circular Variance: 0.52
Circular Std. Dev.: 1.2
Circular Dispersion: 0.79
Circular Kurtosis: 1.83

SR 19
Data: 30
Tick Interval: 3% (0.9 Data)
Maximum: 13.3% (4 Data)
Circular Variance: 0.79
Circular Std. Dev.: 1.8
Circular Dispersion: 9.42
Circular Kurtosis: -0.23

SR 20
Data: 30
Tick Interval: 3% (0.9 Data)
Maximum: 16.7% (5 Data)
Circular Variance: 0.78
Circular Std. Dev.: 1.7
Circular Dispersion: 7.17
Circular Kurtosis: -0.50

SR 23
Data: 40
Tick Interval: 5% (2 Data)
Maximum: 20% (8 Data)
Circular Variance: 0.38
Circular Std. Dev.: 1.0
Circular Dispersion: 0.71
Circular Kurtosis: 1.35

SR 24
Data: 24
Tick Interval: 5% (1.2 Data)
Maximum: 29.2% (7 Data)
Circular Variance: 0.56
Circular Std. Dev.: 1.3
Circular Dispersion: 0.35
Circular Kurtosis: 2.53

SR 26
Data: 24
Tick Interval: 2% (0.5 Data)
Maximum: 8.3% (2 Data)
Circular Variance: 0.70
Circular Std. Dev.: 1.6
Circular Dispersion: 3.09
Circular Kurtosis: 0.90

SR 27
Data: 24
Tick Interval: 2% (0.5 Data)
Maximum: 12.5% (3 Data)
Circular Variance: 0.75
Circular Std. Dev.: 1.7
Circular Dispersion: 3.98
Circular Kurtosis: -0.20

SR 28
Data: 24
Tick Interval: 2% (0.5 Data)
Maximum: 12.5% (3 Data)
Circular Variance: 0.82
Circular Std. Dev.: 1.9
Circular Dispersion: 8.56
Circular Kurtosis: 0.46
SW 16
Data: 3
Tick Interval: 10% (0.3 Data)
Maximum: 33.3% (1 Data)
Circular Variance: 0.74
Circular Std. Dev.: 1.7
Circular Dispersion: 2.44
Circular Kurtosis: 1.11

SW 17
Data: 24
Tick Interval: 3% (0.7 Data)
Maximum: 16.7% (4 Data)
Circular Variance: 0.91
Circular Std. Dev.: 2.2
Circular Dispersion: 4.34
Circular Kurtosis: 0.81

SW 18
Data: 24
Tick Interval: 3% (0.7 Data)
Maximum: 16.7% (4 Data)
Circular Variance: 0.76
Circular Std. Dev.: 1.7
Circular Dispersion: 4.08
Circular Kurtosis: -0.38

SW 19
Data: 24
Tick Interval: 2% (0.5 Data)
Maximum: 12.5% (3 Data)
Circular Variance: 0.87
Circular Std. Dev.: 2.0
Circular Dispersion: 17.29
Circular Kurtosis: -0.51

SW 21
Data: 24
Tick Interval: 2% (0.5 Data)
Maximum: 8.3% (2 Data)
Circular Variance: 0.72
Circular Std. Dev.: 1.6
Circular Dispersion: 4.26
Circular Kurtosis: -0.67

SW 22
Data: 10
Tick Interval: 5% (0.5 Data)
Maximum: 20% (2 Data)
Circular Variance: 0.33
Circular Std. Dev.: 0.9
Circular Dispersion: 0.96
Circular Kurtosis: -0.81

SW 23
Data: 24
Tick Interval: 3% (0.7 Data)
Maximum: 16.7% (4 Data)
Circular Variance: 0.85
Circular Std. Dev.: 2.0
Circular Dispersion: 10.50
Circular Kurtosis: 0.76

SW 24
Data: 24
Tick Interval: 3% (0.7 Data)
Maximum: 16.7% (4 Data)
Circular Variance: 0.56
Circular Std. Dev.: 1.3
Circular Dispersion: 0.88
Circular Kurtosis: 0.21