

FRACTURE ANALYSIS OF LITTLE SHEEP MOUNTAIN ANTICLINE, EASTERN
BIGHORN BASIN, WYOMING: STRUCTURAL CONTROLS ON FLUID
MIGRATION THROUGH A FAULT-CONTROLLED
LARAMIDE STRUCTURE

by

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of

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ABSTRACT

Little Sheep Mountain is a doubly-plunging asymmetric anticline in the northeastern Bighorn Basin, Wyoming. Anticlines in the basin provide subsurface structural traps for oil and natural gas, several of which produce from the Mississippian Madison Formation, a world-class fractured carbonate reservoir. Little Sheep Mountain anticline has been uplifted and the hydrocarbon trap has been breached by erosion, exposing reservoir rocks analogous to these proximal subsurface structures. An outcrop-scale investigation of fracture geometry and geochemical analysis of breccia bodies in the anticline provides insight into the history of fluid migration and structurally-controlled diagenesis within the anticline.

A combination of field techniques and analytical methods were used to characterize the relationship between fracture patterns and subsurface paleofluid migration. Field-based analyses of fractures and breccias were conducted to characterize structural elements of the anticline with respect to fluid flow. Geochemical analysis was used to constrain the origin and migration history of paleofluids. Diagenetic characteristics and alteration associated with fluid migration within the fracture network were examined using strontium and stable isotopes in conjunction with petrography.

Faulting related to Laramide deformation has led to extensive fracturing and brecciation in Little Sheep Mountain anticline. Fracture network geometry was identified as a major control on fluid migration within the structure that has provided conduits for episodic hydrothermal fluid flow. Progressive deformation during Laramide fold growth maintained and enhanced fluid flow networks and locally enhanced porosity. Mississippian-age collapse breccia bodies were identified as preexisting weak horizons for focused hydrothermal fluid flow during the Laramide. Low-temperature hydrothermal mineralization resulting from episodic fluid flow led to complex diagenetic alteration.

Fracture sets parallel to and perpendicular to the Laramide shortening direction acted as primary fluid flow conduits within Little Sheep Mountain anticline and provided enhanced porosity and permeability in the subsurface reservoir rocks. Hydrothermal breccia bodies represent discrete vertical fluid conduits controlled by fracture geometry through which hydrothermal fluids migrated. Brecciation associated with Laramide deformation and late-stage diagenetic alteration was found to generally reduce the porosity of Madison reservoir rocks adjacent to breccia bodies by the infilling of fractures and occlusion of pores with late-stage calcite cement.

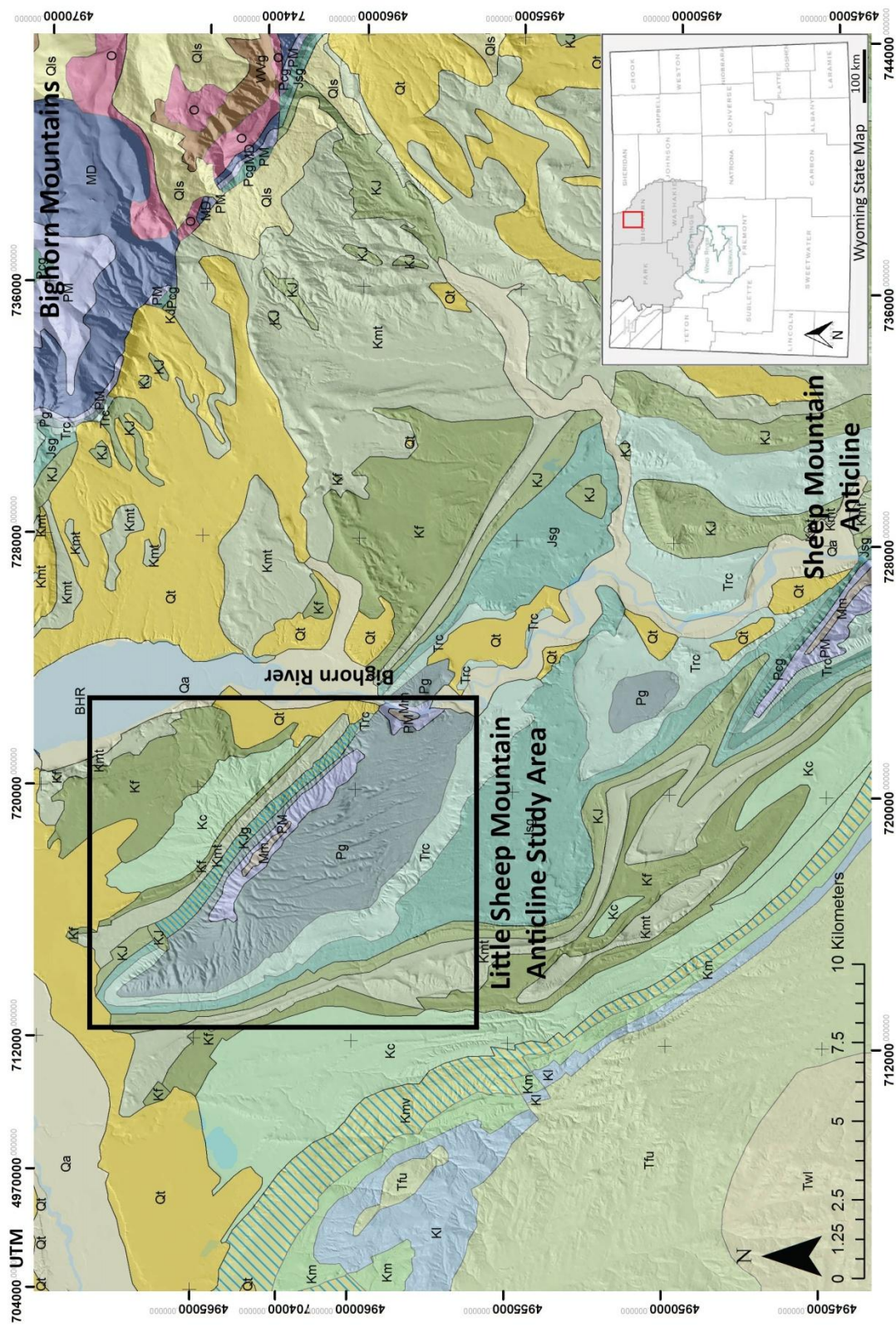
INTRODUCTION

Paleozoic reservoir rocks in the Bighorn Basin, Wyoming have experienced a long history of tectonic deformation in the Rocky Mountain foreland of the western U.S. (Schmidt et al., 1993). This deformation has resulted in an anastomosing series of northwest-southeast trending anticlines within the basin (Banerjee, 2008).

Anticlines are important structures which can provide traps for oil and natural gas (Fox and Dolton, 1996) and fracture networks developed within these anticlines provide major controls for fluid flow within these structures (Beaudoin et al., 2013).

Understanding fluid migration mechanisms within anticlines is important for unraveling basin-scale fluid migration and for unconventional hydrocarbon exploration in deep basin structural plays in the Bighorn Basin (Fox and Dolton, 1996; Wyoming Geological Survey, 2014).

This project aims to contribute an in-depth, outcrop-scale fracture analysis of Little Sheep Mountain anticline, combined with geochemical isotopic analyses, to the accumulating database available for the Bighorn Basin. The northwest-southeast trending anticline is located in the eastern portion of the Bighorn Basin, 15 km north of the more famous Sheep Mountain anticline (Figure 1). The Mississippian Madison Limestone exposed on Sheep Mountain and Rattlesnake Mountain anticlines is considered to be a world-class analogue of a fractured carbonate reservoir (Barbier et al., 2012). Little Sheep Mountain anticline is another important, yet often overlooked, surface analogue for fractured carbonate reservoirs in basement-involved foreland regions, due to the excellent exposures of Mississippian Madison



Cenozoic Qa Alluvium & Colluvium Qt Gravel, pediment, & fan deposits Qls Landslide deposits Twl Intrusive igneous Wiggins Fm Tfu Fort Union Fm Mesozoic Kl Lance Fm Km Meeteetse Fm Kmv Mesaverde Group Kc Cody Shale Kf Frontier Fm Kmt Mowry & Thermopolis fms KJ Cloverly & Morrison fms KJg Cloverly, Morrison, Sundance, & Gypsum Springs fms Jsg Jurassic Sundance & Gypsum Spring fms Trc Chugwater Fm	Paleozoic Pcg Chugwater & Goose Egg fms Pg Goose Egg Fm PM Tensleep Sandstone & Amsden Fm Mm Madison Group O Ordovician & Cambrian undifferentiated Precambrian WVg Plutonic rocks
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Figure 1. (Previous page and this page). Field area map of Little Sheep Mountain anticline. Field area is boxed and Sheep Mountain anticline and the Bighorn Mountains are also shown over a geologic map of Wyoming. BHR = Bighorn Reservoir. Geologic map from Bedrock Geology at 1:500,000 (Wyoming State Geologic Survey). Wyoming state map modified from Lynds (2013).

rocks in the hinge of the anticline.

Geochemical data from similar anticlines associated with Laramide deformation in the Bighorn Basin indicate that precipitation of cements by basement-derived fluids occurred earlier during Laramide shortening in the western part of the asymmetrical basin than in the eastern part (Beaudoin et al., 2013). Basement-derived fluids diluted by meteoric waters dominated the eastern part of the basin during strata folding and were most likely conducted by basement thrusts. An eastward, basin-scale migration of basement-derived fluids occurred in the cover rocks due to thermal gradients coupled to lateral variation in topography,

and enhanced by progressive stress buildup within the Laramide foreland (Beaudoin et al., 2013).

Little Sheep Mountain shows extensive evidence of paleofluid flow, including hydrocarbons, as well as modern hydrothermal fluid flow throughout the fracture network of the anticline (Beaudoin et al., 2013; Engel, 2004). Little Sheep Mountain is hypothesized to be cored by a southwest-dipping basement-involved thrust fault similar to that found in the core of Sheep Mountain anticline (Bellahsen et al., 2006). Basement-rooted faults may serve as conduits for saline hydrothermal brines to travel into overlying sedimentary rocks. An eventual loss of thermally-driven hydrodynamic pressure will terminate the upward progression of hydrothermal brines, leaving a distinctive hydrothermal collapse breccia with an assemblage of sulfide minerals, bitumen, and saddle dolomite (Davies and Smith, 2006). These areas of hydrothermal alteration may be important areas of enhanced porosity and permeability in reservoir rocks.

Statement of Purpose

Excellent exposures of fractured Mississippian Madison carbonate reservoir rocks in Little Sheep Mountain anticline provide an opportunity to study the geometry of fracture networks in a surface analogue for buried structures. Basement-involved faults in the eastern Bighorn Basin provide conduits for fluids migrating into sedimentary cover rocks. The goal of this study was to identify the controls that the geometry of the fracture network exerted on paleofluid migration

within the anticline, and the effects of these controls on the quality of Madison reservoir rocks. To address this question, research is needed that: 1) determines the geometry of the fracture network, 2) identifies the relationships between the fracture patterns and subsurface paleofluid migration, and 3) examines the effects of fracture geometry and paleofluid flow on reservoir rocks in the anticline.

(1) *What is the geometry of fracture networks at Little Sheep Mountain anticline and how does the fracture pattern and distribution compare to other similar anticlines in the Bighorn Basin?* The geometry, connectivity, and extent of fracture systems are important in understanding the history of deformation and paleofluid flow within the anticline. Comparison with fracture systems associated with Laramide deformation identified in the nearby Sheep Mountain anticline and Rattlesnake Mountain anticline in the western part of the basin can help to determine local versus basin-wide controls on fracture systems (e.g. Beaudoin et al., 2013; Bellahsen et al., 2006). It is hypothesized that major fracture sets identified at Little Sheep Mountain anticline will be similar to Sheep Mountain anticline in the eastern portion of the basin due to similarities in structural setting and local stress fields. Field fracture measurements and Google Earth Pro lineament measurements were analyzed to determine the structural and tectonic controls on the anticline, as discussed in more detail in the methods section.

(2) *How did the fracture networks of Little Sheep Mountain anticline affect the migration and types of fluids within the structure?* The orientation and distribution of fracture sets affects the circulation of fluids within an anticline, including top-down

meteoric waters and bottom-up hydrothermal fluids and hydrocarbons (Katz et al., 2006). The infiltration of meteoric waters mixing with basinal fluids is largely controlled by fracture connectivity (Beaudoin et al., 2012). The working hypothesis herein is that Little Sheep Mountain exhibits geochemical evidence of mixed meteoric waters and basinal fluids that have interacted with basement rocks due to its updip position on the eastern flank of the basin. Stable isotope analysis was used to elucidate paleofluid circulation within the anticline, while strontium isotopes were used to determine whether fluids circulated in contact with basement rocks or if the fluids were confined to the upper crust, as further discussed in the methods section.

(3) *Did breccia pipes preferentially form along certain fracture sets?* Breccia pipe distribution is expected to preferentially follow fracture networks during fluid migration (Katz et al., 2006). After formation, breccia pipes may act as fluid flow barriers or conduits to further fluid migration (Davies and Smith, 2006). It is hypothesized that breccia pipes in Little Sheep Mountain anticline formed along major fracture sets during fold formation. Field outcrop observations and petrography were used to determine the distribution of breccia pipes in relation to the fracture network, and are discussed in further detail in the methods section.

(4) *Has hydrothermal diagenesis near breccia pipes affected porosity of reservoir rocks?* Fracturing due to tectonic deformation increases fracture porosity and permeability in carbonate rocks (Hooker et al., 2012), and transport of hydrothermal fluids within a fracture network contributes to late-stage diagenesis

in carbonate host rocks (Davies and Smith, 2006). The working hypothesis is that hydrothermal diagenesis near breccia pipes reduced secondary porosity of the host rock due to abundant late-stage calcite cementation. Petrography and stable carbon and oxygen isotopes, which are detailed in the methods section, were used to determine the effects of diagenesis near breccia pipes.

Applications for Oil and Gas Exploration

The Bighorn Basin is a highly productive Laramide basin, containing 134 oil fields that are producing or have produced from 60 reservoirs (Wyoming Enhanced Oil Recovery Institute, 2011). The first producing oil well was drilled into the Tensleep Sandstone in 1905 after the discovery of an oil spring on the Bonanza anticline (Wyoming Geological Survey, 2014). As of 2013, cumulative production in the Bighorn Basin exceeds 2.67 billion barrels of oil and 1.8 trillion cubic feet of natural gas (Wyoming Geological Survey, 2014). Although oil and gas production has steadily decreased over the past 35 years, most fields still contain significant recoverable oil. Nine fields in the Bighorn Basin are in the top 25 producing fields in Wyoming, and seven fields are in the top ten producing fields in the state (Wyoming Geological Survey, 2014).

Hydrocarbons in Paleozoic stratigraphic traps in the Bighorn Basin were remigrated as a result of fracturing and faulting associated with deformation (Stone, 1967). The Madison Formation is ranked third in importance as a producing reservoir rock in the Bighorn Basin (Stone, 1967). It accounts for more than 13

percent of proved reserves and produces in 16 of the basin's fields. Deep basin structural plays are important in Paleozoic rocks in the Bighorn Basin, and exposed anticlines such as Little Sheep Mountain can provide analogues for these structures at depth (Fox and Dolton, 1996).

Little Sheep Mountain anticline is breached with respect to carbonate reservoir rocks in the Mississippian Madison Formation. Hydrocarbon staining and bitumen found in vugs in the Madison of the Upper and Lower Kane Caves indicate that Little Sheep Mountain anticline once served as a reservoir for oil until it was breached. Calculations of Bighorn River incision indicate that the Madison Formation was exposed ~1.5 Ma (Jastram, 1990). Due to high formation pressures, drainage probably occurred prior to exposure by incision.

Secondary and tertiary enhanced oil recovery techniques, combined with unconventional reservoir plays, could again make the Bighorn Basin a major player in oil and gas in Wyoming (Wyoming Enhanced Oil Recovery Institute, 2011). Understanding paleofluid flow via fracture networks within the basin is integral to fostering new oil and gas exploration, and understanding fracture geometry and connectivity is essential to understanding reservoir quality and connectivity. Applications of fracture system geometry are not limited to the Bighorn Basin and are important to structural plays in other basement-involved foreland basins.

GEOLOGIC SETTING

The northwest-southeast trending Little Sheep Mountain anticline is located in the eastern part of the Bighorn Basin near the town of Lovell in northwestern Wyoming. It is one of several asymmetric basement-cored anticlines within the basin which resulted from Laramide shortening (Erslev, 1993). It is doubly-plunging and asymmetrical, and it forms a topographic high due to the resistant Paleozoic carbonates exposed in the core (Jastram, 1999). The anticline is 14 km long and 10 km wide and is cored by a southwest-dipping, basement-involved thrust fault (Bellahsen et al., 2006). The northwest plunge-end exhibits semi-conical fold geometry, and toward the south the asymmetry of the fold increases while the hinge area becomes more cylindrical (Rioux, 1994). The hingeline of the more cylindrical portion of the anticline trends at approximately 320° , but the northern, semi-conical plunge-end is slightly deflected with a trend of 335° (Figure 2). The steep northeast forelimb dips between 40° and 60° NE, while the gentler slope of the southwest backlimb dips 10° to 40° SW.

The Bighorn River has cut through the center of the anticline at an angle oblique to the trend of the axis, forming the Little Sheep Mountain Canyon. The segment of the anticline exposed at the canyon is generally cylindrical and non-plunging. The field area in this study was confined to the northern portion of the anticline, west of where the Bighorn River cuts obliquely through the anticline, due to ease of accessibility and quality of outcrop exposure of formations of interest.

Little Sheep Mountain anticline lies along the eastern flank of the Bighorn

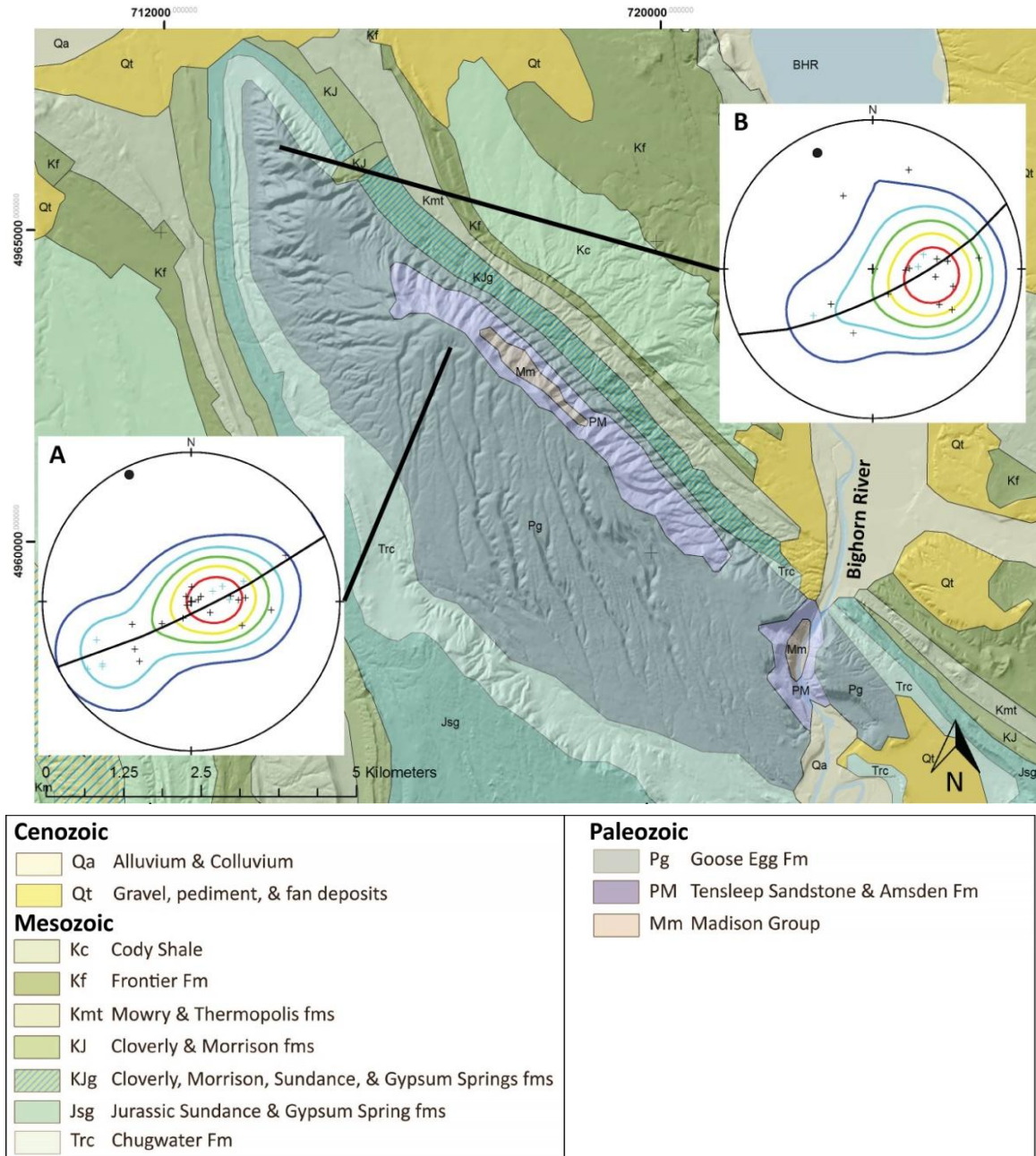


Figure 2. Equal area, lower-hemisphere projections of poles to bedding in Little Sheep Mountain anticline. Pi diagrams show trend of hinge line. A) Poles to bedding in multiple lithologies measured in the more cylindrical central portion of the anticline. B) Poles to bedding in multiple lithologies measured in the semi-conical plunge-end of the anticline. Black crosses represent field bedding orientations measured in this study; light blue crosses represent bedding strikes and dips from Rioux (1994); solid circle = pi axis (fold axis). Blue contour lines represent relatively low density; red contour lines represent high density. Geologic map from Bedrock Geology at 1:500,000 (Wyoming State Geologic Survey). BHR = Bighorn Reservoir.

Basin and is classified as a fault-propagation fold (Mitra, 1990). Fault-propagation folds are those produced by the deformation in front of the propagating fault (Suppe, 1985). In this type of fold, the fault tip propagates through the lower part of the section and the fold develops above the ramp with uniform forelimb angles (Erslev, 1991). Laramide fault-propagation folds are characterized by broad zones of folding that constrict downward into narrow fault zones that separate basement blocks with minimal penetrative deformation (Mitra, 1988). Axial planes of these folds converge downward toward the basement-cover interface, where fault zones abruptly cut this interface (Erslev, 1991). This downward convergence of deformation creates a triangular shear zone, and this type of fold defined as a trishear fold. The anticline is characterized by a progressive tightening of the fold hinge and a steepening of the front limb, typical of a fault-propagation fold (Mitra, 1990). The southwest-dipping backlimb represents the hanging wall of the fault, while the northeast-dipping forelimb is the footwall.

Regional Tectonic Framework

The Wyoming craton experienced deformation during the Pennsylvanian-Permian Ancestral Rocky Mountain orogeny, resulting in local, low-relief structures and regional southwestern tilting (Fanshawe, 1971; Thomas, 1965). This resulted in a northwest-trending structural grain and variable thickness of Mississippian and Pennsylvanian units which became the precursors for comparable Laramide structural trends (Blackstone, 1963).

The Sevier fold-and-thrust belt began forming in the early Jurassic and continued into the Eocene due to subduction of the Farallon and Kula plates beneath the western edge of the North American plate (Amrouch et al., 2010). A large foreland basin formed synchronously to the east of the Sevier orogen, and both developed together until the early Cenozoic (DeCelles, 2004).

Beginning in the Late Cretaceous and continuing into the Early Eocene, the thick-skinned basement-involved uplifts, which segmented the Cordilleran foreland into a series of sedimentary basins, were activated during Laramide contractile orogenesis (May et al., 2013). The Laramide orogeny initiated shortening parallel to the vector of subduction of the Farallon plate in concert with a change from steep to shallow slab subduction (Erslev, 1993). The northwest-trending average orientations of Laramide faults, folds and uplifts, in addition to kinematic chain, suggest that slip was directed northeast-southwest throughout the entire province (Erslev, 1993). Geophysical evidence indicates that the master faults are listric and that they merge in a subhorizontal detachment in the lower crust (Erslev, 1993). Furthermore, Laramide shortening may have preferentially reactivated preexisting basement-rooted structures (Brown, 1993). Preexisting basement-cored structures that were oriented east-northeast, east, or east-southeast were reactivated as left-lateral oblique-slip faults, and those oriented southeast, south-southeast, or north-south were reactivated as right-lateral, low-angle dip-slip reverse faults (Nelson, 1993).

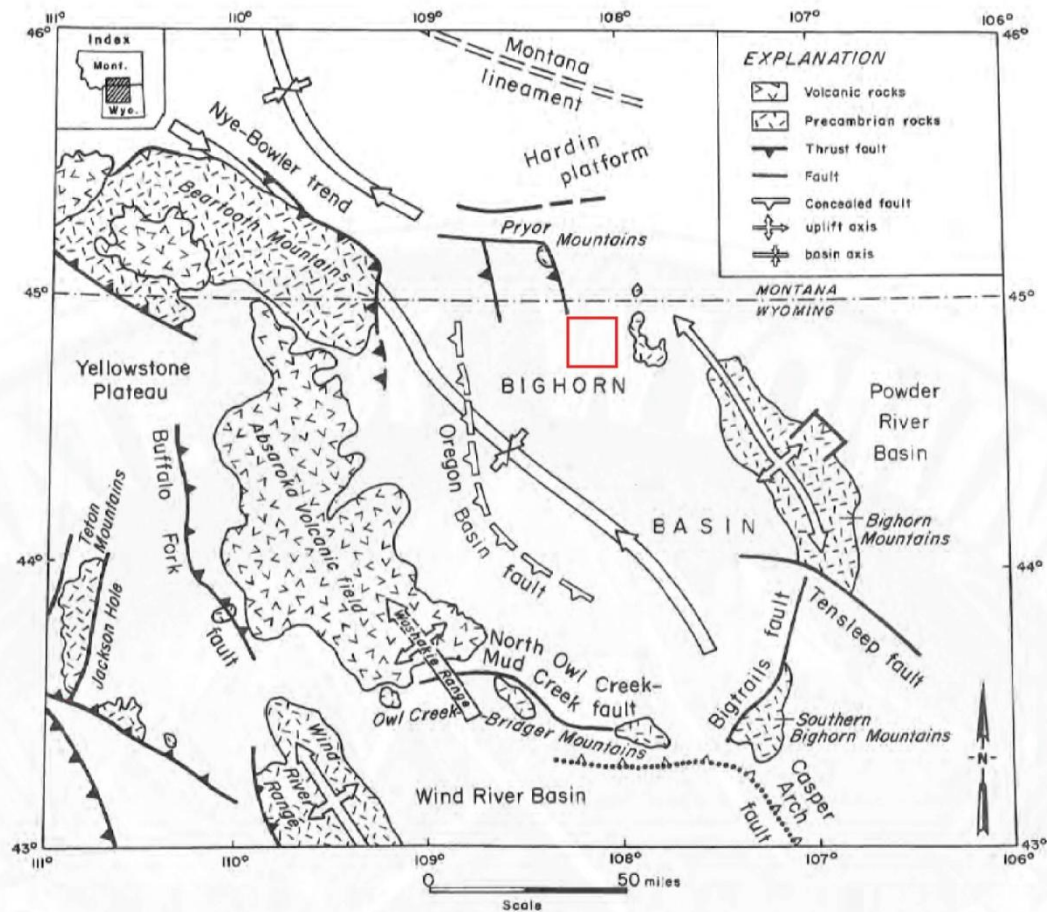


Figure 3. Index map of the Bighorn Basin in Wyoming and Montana, showing uplifts and associated faults (modified from Blackstone, 1986). Red box outlines study area.

Bighorn Basin

The Bighorn Basin in northwestern Wyoming and south-central Montana is a northwest-southeast trending, asymmetric, elliptical basin that lies in the central Rocky Mountain Laramide foreland (Figure 3) (Blackstone, 1940). The basin is approximately 200 km long and 120 km wide (Banerjee, 2008). The deepest part of the basin is along the western margin, resulting in a gently-sloping northeast flank

and a steep to overturned west flank. The basin is both a structural and topographic low. Beginning in the Late Cretaceous, Laramide shortening was accommodated by uplift of broad basement arches which eventually isolated the basin (Amrouch et al., 2010). Formation of anticlines along the basin margins also served to accommodate regional shortening (Fanshawe, 1971; Thom, 1947).

The bounding uplifts of the Bighorn Basin are the Pryor Mountains to the north, the Beartooth Mountains to the west, the Owl Creek Mountains to the south, and the Bighorn Mountains to the east. In addition, the Absaroka-Yellowstone volcanic fields conceal the structure of sedimentary rocks on the west side of the basin (Blackstone, 1986). The Nye-Bowler lineament is a left-lateral wrench fault marked by a continuous zone of structural disturbance extending from Livingston, Montana, to the eastern side of the Pryor Mountains (Stone, 1967).

Stratigraphic Framework

In the Bighorn Basin, Cambrian to Eocene age sedimentary rocks are capped by Late Tertiary Yellowstone volcanics (Banerjee, 2008). Total sedimentary rock thickness in the deepest part of the basin is greater than 6 km (Banerjee, 2008; Jastram, 1999). Sedimentary cover on the eastern flank of the basin is a 3.2-km thick conformable sequence of basement to Cretaceous rocks (Beaudoin et al., 2013; Bellahsen et al., 2006). Exposed formations examined at Little Sheep Mountain anticline included the Mississippian Madison through Jurassic Sundance Formations (Figure 4).

The Mississippian Madison Formation is the oldest formation exposed at Little Sheep Mountain and is primarily exposed in the core of the anticline along the Bighorn River cut. This formation has a total thickness of approximately 250 m of massive dolomite interbedded with limestone, with the upper ~100 m exposed in the hinge along the Little Sheep Mountain Canyon outcrop (Jastram, 1999; Stone, 1967; Westphal et al., 2004). The top of the Madison Formation is marked by a regional karsted disconformity that resulted from 10 to 12 Ma of uplift and subaerial exposure of the highly soluble limestone during the Late Mississippian (Barbier et al., 2012). This karstification has been enhanced at Little Sheep Mountain anticline by hydrothermal fluid flow from natural thermal springs (Engel et al., 2004; Stock et al., 2006).

The Madison Limestone is overlain by an approximately 70 m-thick, carbonate-dominated sequence of Mississippian-Pennsylvanian Amsden red shale and sandstone (Sando et al., 1975). Sandstones of the Pennsylvanian Tensleep Formation overlie the Amsden with a total thickness of approximately 100 m (Mou and Brenner, 1982). The Mississippian through Pennsylvanian formations are most easily observed in the Bighorn River cut, but are also exposed in the drainages of the steeply-dipping forelimb.

A relatively thin interval of Permian Goose Egg carbonates, dolomite and limestone interbedded with shale and cherty carbonate, caps the Bighorn River cut sequence of Paleozoic rocks and is also the primary formation found on the surface on the backlimb of the anticline. The Goose Egg Formation is time equivalent to the

Permian Phosphoria Formation; however, it is primarily found in the eastern portion of Wyoming, and is also recognized in the Bighorn Basin (Lane, 1973).

Little Sheep Mountain, like Sheep Mountain, demonstrates a distinctive thinning of the Tensleep and Goose Egg Formations over the anticlinal crest (Bellahsen et al., 2006). This lateral thinning suggests that the anticlines may have formed over highs inherited from movement on Paleozoic faults active during the Ancestral Rocky Mountain orogeny (Amrouch et al, 2010). Facies transitions in the Goose Egg Formation of Little Sheep Mountain indicate a correlation between the paleo-highs and the present anticline. This suggests that the Permian relief resulted from syndepositional uplift and was not inherited from the tectonism and erosion of the Pennsylvanian (Simmons and Scholle, 1990). At Little Sheep Mountain, syndepositional faulting of the Goose Egg Formation exhibits the same eastward vergence as the Laramide structures, indicating the reactivation of a Paleozoic structural framework.

Outcrops of red shale and siltstone of the Red Peak Shale Member of the Triassic Chugwater and the greenish-grey shale, glauconitic sandstone, and fossiliferous limestone of the Upper Jurassic Sundance Formation are primarily found on the outer margins of the southwest-dipping backlimb (McMullen et al., 2014; Picard and Wellman, 1965). The gypsum, shale and siltstone of the Jurassic Gypsum Springs Formation lie between the Chugwater and Sundance Formations.

Age			Formation	Mechanical Stratigraphy
Paleozoic	Jurassic	Upper	Morrison Fm.	
			Sundance Fm.	Incompetent Unit
		Middle	Gypsum Spring Fm.	Ductile Incompetent Unit
		Lower		
	Triassic		Chugwater Group	Thick Incompetent Unit
			Dinwoody Fm.	
	Permian		Phosphoria Fm. Goose Egg Fm.	Competent Upper Unit Incompetent Lower Shale Unit
	Pennsylvanian		Tensleep Sandstone	Competent Unit
			Amsden Fm.	Incompetent Shale Unit
Paleozoic	Mississippian		Madison Limestone	Thick Competent Unit
	Devonian		Darby Fm.	
	Silurian		Beartooth Butte Fm.	
	Ordovician		Bighorn Dolomite	
	Cambrian	Upper	Gallatin Group	
		Middle	Gros Ventre Fm.	
		Lower	Flathead Ss.	
	Precambrian			

Figure 4. Generalized stratigraphic column of the Bighorn Basin from Precambrian basement rock to Jurassic sediments (modified from May et al., 2013). Mechanical stratigraphy is shown for litho-tectonic units discussed in the text.

Mechanical Stratigraphy

Lithology plays an important role in controlling fracture attributes (Wennberg et al., 2007). Lithologic contrasts and variations can affect the style, distribution, and scale of deformation. Propagation of fractures, with internal fluid overpressure remaining constant, can be enhanced by mechanically stiff layers but may be arrested by mechanically soft layers or at contacts between mechanically different rock layers (Brenner and Gudmundsson, 2002). Mechanical stratigraphy is a method of subdividing rocks into mechanical units based on the style of deformation or types of structures found within individual units (Chester, 2003). In competent lithologies, brecciation may progress in a vertical direction due to the upward propagation and hydrofracturing of overpressured fluids (Phillips, 1972). When brecciation reaches an argillaceous layer, the propagation may continue laterally along the contact (Katz et al., 2006).

The Paleozoic stratigraphy of Little Sheep Mountain anticline is considered to be competent and mechanically brittle (Fanshawe, 1947). The Madison Formation is a major controlling litho-tectonic unit for large-scale folding of the stratigraphic section above basement-involved faults. Individual bedding planes may represent flexural-slip surfaces, and small-scale folds may result from the deformation of individual beds within the Madison Formation (Hennier and Spang, 1983). The Amsden Formation is an incompetent unit which serves as a major structural detachment horizon; however, the relatively thin shale beds on Little Sheep Mountain anticline have little effect on the behavior of the rest of the Paleozoic units

(Willis and Groshong, 1993). Although the Tensleep is a competent unit, it folds at wavelengths influenced by the Madison Formation, as well as folding at smaller wavelengths in response to Amsden Formation detachments (Willis and Groshong, 1993). The upper unit of the Goose Egg consists primarily of limestone and is mechanically competent, while the lower unit of siltstone and shale readily detaches along bedding-parallel faults (Jastram, 1999).

In contrast to Paleozoic units, the overlying Mesozoic section is composed of variable units that commonly deform independently (Fanshawe, 1947). The Chugwater Formation is a thick, incompetent clastic sequence. Gypsum in the Jurassic Gypsum Springs Formation is ductile and creates a structurally incompetent unit. The Sundance Formation is easily deformable and thus structurally incompetent (Jastram, 1999).

PREVIOUS WORK

Historical Geologic Investigations

Early geologic exploration of the Bighorn Basin began in the late 1800s, and a comprehensive review of this early work is presented by Brown (1993).

Investigations in the early 1900s were dominated by the concept of foreland uplifts bounded by low-angle reverse faults (Brown, 1993). D.L. Blackstone, Jr., investigated the structure of the Pryor Mountains and interpreted the monoclines to have been created by movement on curved, low-angle reverse faults. J.R. Fanshawe and W.T. Thom, Jr., conducted early investigations of the structural elements and tectonic development of the Bighorn Basin in 1947, interpreting Laramide uplifts as being cored by low-angle reverse faults. Blackstone published interpretations of several foreland structures (1947, 1948, 1949, 1951, 1956, 1963, 1970), which set the template for investigation of central Rocky Mountain foreland structures (Brown, 1993).

In the 1960s, structural interpretations of Laramide uplifts began to expand, including the vertical uplift concept (Osterwald, 1961), drape folds (Stearns, 1971) and upthrusts (Prucha et al., 1965), and fold-thrust models of basement-involved foreland uplifts (Berg, 1962), as well as other models (Brown, 1993). Major investigations on the role and mode of deformation of basement rocks in the Beartooth, Bighorn, and Owl Creek Mountains led to the development of ideas about

basement deformation by brittle fracture and reactivation of Precambrian zones of weakness by Laramide stresses (Brown, 1993; Miller and Lageson, 1993).

Beginning in the 1970s, differential vertical uplift with little to no crustal shortening was a popular model in foreland structural studies (Brown, 1993). Stearns presented his interpretation of Rattlesnake Mountain anticline as a drape fold in 1971 and this became a template for Laramide structural studies (Brown, 1993). In the 1980s, the concept of differential vertical uplift was challenged by proponents of horizontal compression and crustal shortening (Brown, 1993). New interpretations of Rattlesnake Mountain anticline, interpreting it in a compressional regime, presented an alternative to Stearns' (1971) drape fold interpretation (Brown, 1993). D.L. Blackstone, Jr., provided a structural analysis and interpretation of the southern Bighorn Basin in 1986 in which he documented the basement-involved nature of asymmetric, low-angle faults.

Modern seismic lines and profiles shot by the Consortium on Continental Reflection Profiling (COCORP) revealed shallow-dipping boundary faults and large basement overhangs of major Laramide uplift faults that could only be caused by horizontal shortening (Brown, 1993). Numerous other publications have contributed to the body of knowledge on Laramide uplifts and have helped to develop the current models for basement-involved uplifts and basin evolution.

Recent Fracture and Geochemical Investigations

Recent fracture studies and geochemical research in the Bighorn Basin have focused on understanding basin-scale deformation history by analyzing individual anticlines within the basin (e.g. Beaudoin et al., 2012; 2013; Bellahsen et al., 2006). Studies conducted at the micro- and mesoscale, which seek to understand the deformation history of northwest-southeast trending Laramide-related basement-cored anticlines, can be used to refine the geometric and kinematic evolution of the basin as a whole (Beaudoin et al., 2012). These studies have focused on fracture analyses and geochemical analyses of paleofluid flow in fractures to constrain deformation history and fluid flow on a basin scale (e.g. Amrouch et al., 2010; Beaudoin et al., 2011; Beaudoin et al., 2013).

Bellahsen et al. (2006) investigated fracture sets at Sheep Mountain anticline to constrain the structural evolution of the fold. This study suggested that brittle deformation was concentrated in the fold hinge of the anticline, and where curvature was significant in the limbs. Beaudoin et al. (2012) used fracture and petrographical information to analyze the stress and strain evolution of Rattlesnake Mountain anticline. They compared this model with Sheep Mountain anticline data from Bellahsen et al. (2006) and other workers to infer a conceptual model for the geometric and kinematic evolution of Laramide-related basement-cored anticlines in the Bighorn Basin.

Beaudoin et al. (2013) investigated the paleohydrological evolution of the Bighorn Basin as a whole using stable isotopes, $^{87}/^{86}\text{Sr}$ values, and fracture

populations at several anticlines across the basin, including Little Sheep Mountain anticline. This study identified a series of tectonically-induced pulses of basement-derived hydrothermal fluid flow controlled by fractures and faults that occurred prior to, during, and after Laramide deformation. Between these pulses, the system was dominated by residual basement-derived fluids mixed with basinal fluids. The authors identified a basin-scale eastward, upper crustal-scale fluid migration event in sedimentary cover and basement rocks during contractile orogenesis.

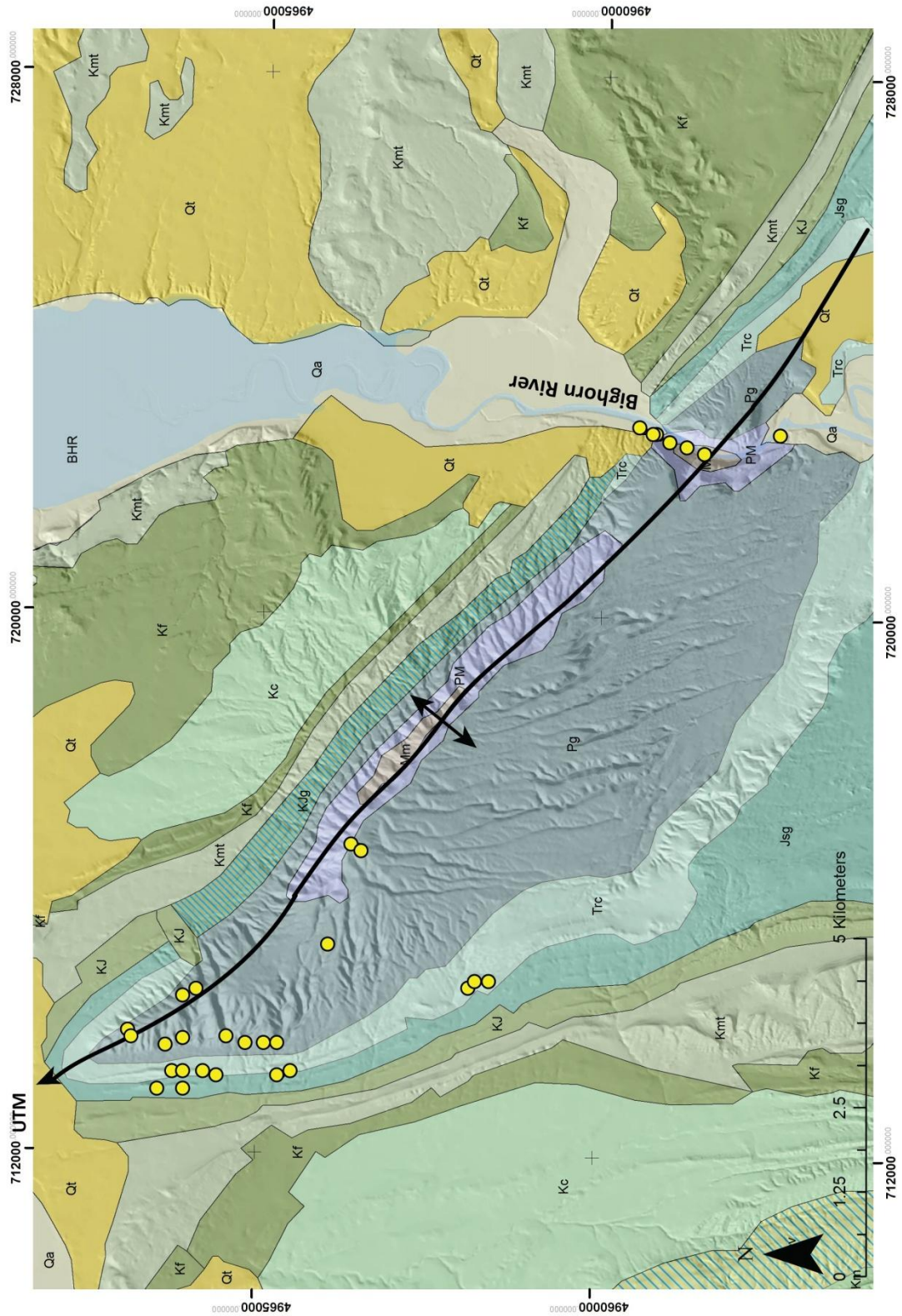
METHODS

In order to understand the geometric distribution of fractures, the structural controls on fluid migration, and the history of deformation at Little Sheep Mountain anticline, a field-based analysis of fractures and a geochemical analysis of stable isotopes were conducted. The analyses focused on brittle deformation in the exposed Mississippian to Jurassic rocks and late-diagenetic alteration of the Mississippian Madison Formation.

Fracture Analysis

Field fracture analysis involved detailed characterization of fracture, joint, and fault systems in exposed formations across the anticline. Fractures were collected at 34 stations along the hinge and on the limbs of Little Sheep Mountain anticline, and eight of these stations were along the Little Sheep Mountain Canyon transect through the center of the anticline (Figure 5). Fracture station locations were selected based on quality of exposures of formations of interest and accessibility, and thus sampling was focused on the portion of the anticline to the north and west of the Bighorn River.

A total of 1,308 fractures were measured in the Paleozoic Madison, Amsden, Tensleep, and Goose Egg Formations, and the Mesozoic Chugwater and Sundance Formations. An average of 21 fractures was collected per station, from a minimum of nine fractures to a maximum of 81 fractures. Fracture station locations were recorded using a Garmin Rino 120 Global Positioning System (GPS) receiver using



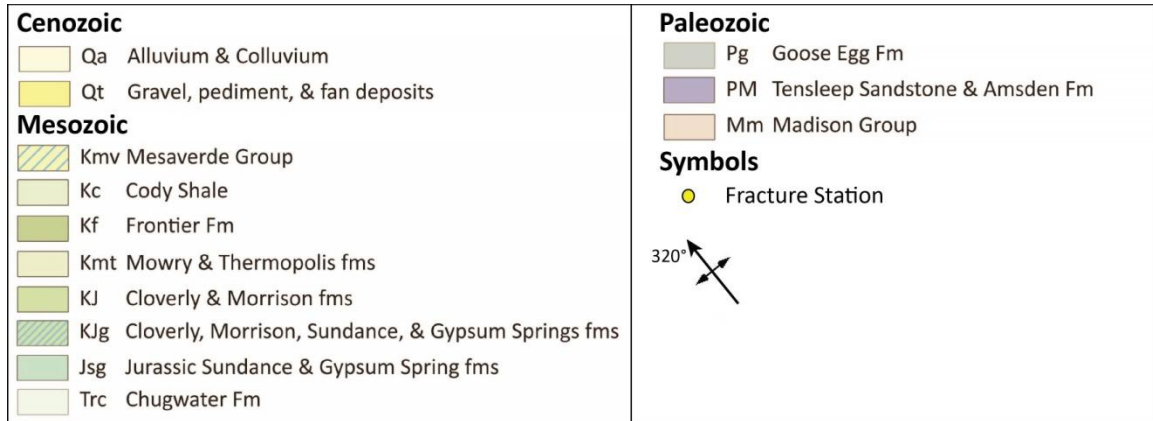


Figure 5. (Previous page and this page). Geologic map showing 34 fracture stations at Little Sheep Mountain anticline (red dots). BHR = Bighorn Reservoir. Geologic map from Bedrock Geology at 1:500,000 (Wyoming State Geologic Survey).

UTM NAD 27 Zone 12 datum.

The majority of fractures were recorded using the selection method of field fracture analysis (Davis and Reynolds, 1996). This method involves visually selecting fractures that appear to be systematic in the outcrop. Systematic fractures are generally evenly spaced and parallel to sub-parallel to the majority of fractures on an outcrop. A group of systematic fractures comprises a fracture set (Goldstein and Marshak, 1988). The selection method is useful for identifying general patterns of systematic fracture sets. Fracture stations L001 and L002 were measured using the traverse method (Goldstein and Marshak, 1988). This method involves laying out a traverse line and measuring its orientation, then measuring every fracture that crosses the traverse line. Fractures with lengths ranging from centimeters to meters which were observable within a single, continuous exposure were measured using this method. However, the high density of fractures at each outcrop rendered the selection method the most practical way to maximize the number of fracture

stations and the number of measurements collected for primary fracture sets that were visually identifiable at each fracture station. The traverse method and inventory method, which involves measuring every fracture at a station, proved to be less practical due to the abundance of fractures at a single station and time limitations (Davis and Reynolds, 1996). The goal of fracture measurement was to determine fracture sets that exerted primary control on paleofluid migration rather than to record every single fracture, and thus the most common fractures with the most connectivity in outcrop were selectively recorded.

Rockware StereoStat version 1.6.1 was used to plot fracture orientation data on rose diagrams and on equal area, lower hemisphere stereographic projections (stereonet). These plots were constructed to visually represent the dominant fracture orientations of Little Sheep Mountain anticline.

Recorded fracture attributes included: orientation, length, spacing, aperture, crosscutting relationships, slip indicators (if present), vein fill (if present), and other notable characteristics. Structural orientation data were collected using a Silva compass for the purpose of stereographic analysis. Length was measured at the outcrop scale as the fracture trace on the exposed outcrop surface. Fractures which extend into the cover could not be measured at the full extent. Fracture spacing was measured with a metric tape as the average orthogonal distance between surfaces of parallel to sub-parallel, adjacent fractures. Fracture spacing is an important parameter in rock permeability, because it depends on the material properties of the host rock, the thickness of the mechanical layer, and the structural position of



Figure 6. Example fracture station along the Bighorn River at Little Sheep Mountain anticline. Station L013 is on the forelimb (NE limb) of the anticline. The photo is taken facing northwest and shows fractures recorded in the Mississippian Madison Limestone using the selection method. s_0 = bedding, s_1 = Group 1 (b-c) fractures. Clipboard for scale is 22 cm x 30 cm.

the outcrop on the fold (Goldstein and Marshak, 1988). Vein fill material was qualified using an index of zero to five, where zero indicates that no vein fill material was present, and five indicates that the vein was completely filled. The surface of the anticline has been exposed to weathering and it has been exhumed by recent epeirogenic uplift, thus fracture aperture has likely been enhanced by meteoric water dissolution and unloading due to exhumation. Original vein fill material has also likely been reduced by meteoric dissolution and chemical weathering, although

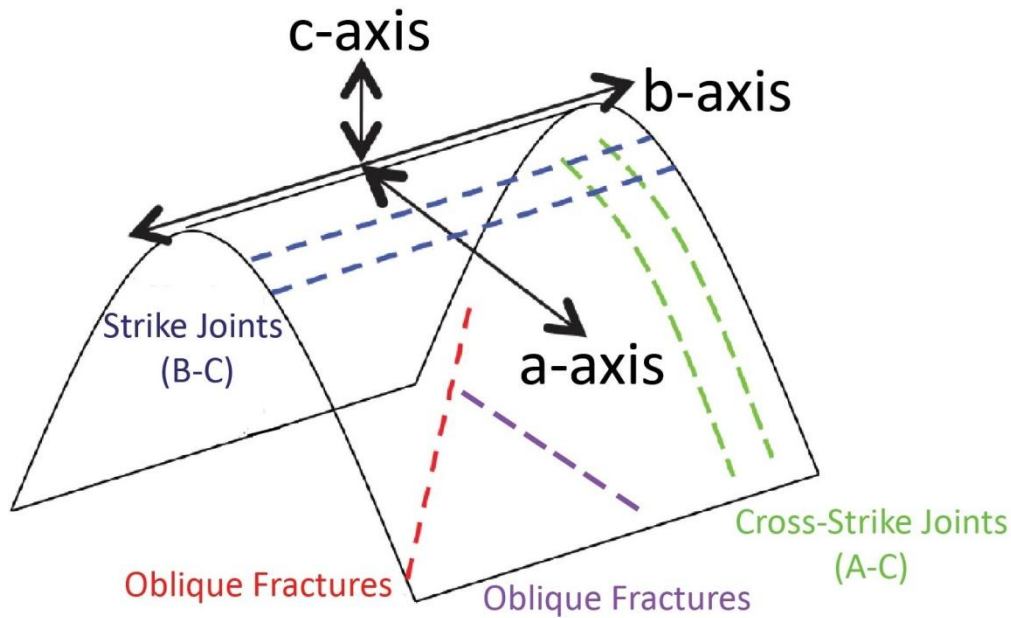


Figure 7. Schematic diagram of fold-related fractures showing relationship between fracture planes and the three orthogonal axes. (Modified from Hancock, 1985).

meteoric water can also precipitate calcium carbonate. Since all fractures measured at the surface of the anticline were subject to similar weathering and unloading conditions, aperture and vein fill can be reasonably compared among fractures. Thorough lithologic descriptions and orientations of bedding surfaces were recorded at each station (Figure 6).

Fractures in Little Sheep Mountain anticline are associated with the progressive growth of the fault-propagation fold which can cause rotation or reactivation of preexisting fracture sets as well as the development of new fracture sets. Fracture sets that develop in folds composed of multiple layers of sedimentary rocks are generally systematically oriented with respect to attitude of bedding and the plunge of the fold hinge (Hancock, 1985). Fractures can be identified with

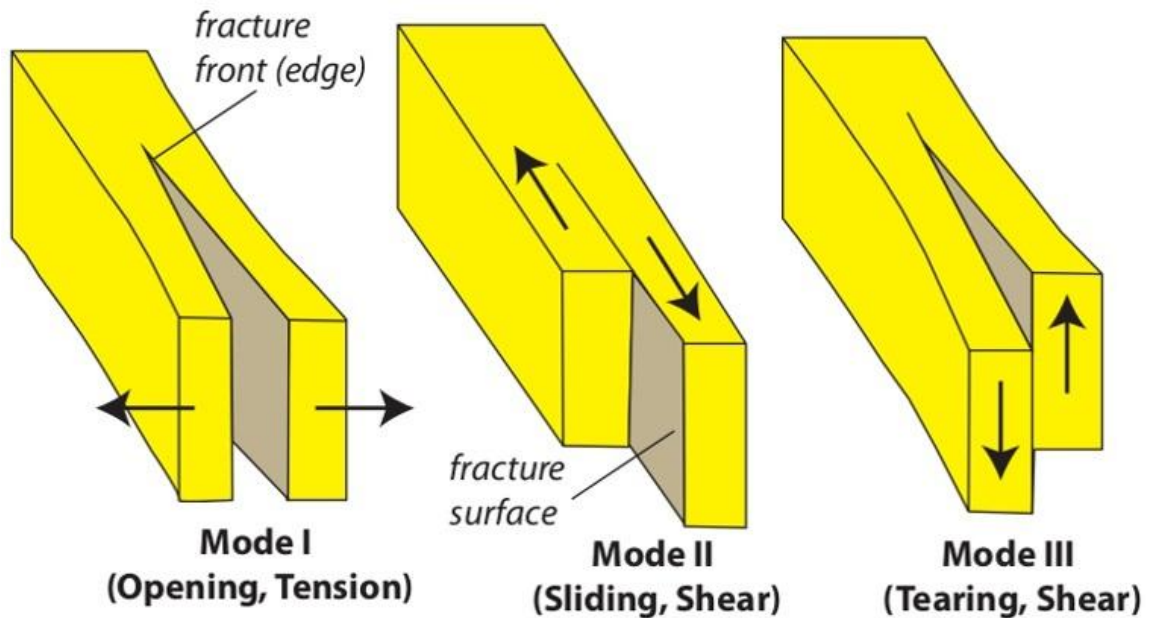


Figure 8. Ideal displacement modes of fractures according to Ramsay and Huber (1987). (Modified from Gudmundsson, 2011).

respect to the geometry of a fold using three orthogonal axes: a, b, and c (Goldstein and Marshak, 1988). The plane that contains a fracture set can be described with a combination of the axes it contains (Figure 7). The b-axis is parallel to the hinge line, while the a-axis is perpendicular to the hinge, and both axes are horizontal. The c-axis is also perpendicular to the hinge, but in a vertical position. Thus, b-c fractures are parallel to the hinge of the anticline, and fractures that are perpendicular to the hinge are a-c fractures. Fractures that do not contain two out of three orthogonal axes are classified as oblique fractures (Goldstein and Marshak, 1988).

There are three ideal displacement modes of fractures based on the angle with respect to σ_1' : mode I, mode II, and mode III (Figure 8) (Ramsay and Huber, 1987). Mode I displacement is referred to as opening or tensile mode and is purely tensional. These fractures develop at an orientation perpendicular to σ_3' and within

the σ_1' stress plane (Hancock, 1985). Mode II displacement is referred to as forward shear mode, where the fracture surfaces slide over one another in a direction perpendicular to the fracture tip. Mode III displacement is referred to as transverse shear mode, where the fracture surfaces move relative to one another in a direction parallel to the fracture tip (Ramsay and Huber, 1987). Both mode II and III fracture planes are oriented parallel to σ_2' and at an angle less than 45° to σ_1' (Hancock, 1985).

Satellite Lineament Analysis

Google Earth Pro (GEP) version 7.2.1 was used to identify dominant lineament orientations at the macroscale (tens of km) of Little Sheep Mountain. Lineaments were defined as straight, linear features (or “linears”) visible on GEP aerial imagery and were measured over the same northwestern portion of the anticline as in the field. Lineaments visible on aerial images may be linear features associated with structural, sedimentological, or geomorphological processes. Structural lineaments may be related to tectonically-controlled brittle deformation structures such as faults and fractures that created discontinuous features. Dip information and mode of opening for fractures (mode I, II, or III) cannot be provided by GEP lineament analysis. Major drainages may be related to the line of steepest descent of channels that have been widened by erosional processes. Low angle faults and fractures are underrepresented with remote lineament mapping due to the oblique angle at which these low angle features intersect the Earth’s surface (Lageson et al., 2012). Lineament measurements using GEP cannot provide

information about the processes that formed lineaments seen in aerial photography, and field work must be performed in order to distinguish fractures from other lineaments, but a catalogue of regional linear features can be recorded and used for comparison with fracture orientations collected during field work at the outcrop scale.

All visible lineaments were manually marked by a colored line in GEP to indicate trend and length. A total of 1,005 lineaments were recorded. The inventory method was used to collect lineament measurements at a variety of scales of observation. At the fullest extent, the entire anticline was observed at 1:65,000 scale and visible lineaments were measured. The satellite imagery was gradually zoomed in to comprehensively measure all lineaments down to a scale of 1:5,000, beyond which GEP imagery begins to distort. Rockware StereoStat version 1.6.1 was used to plot the lineament orientation data on rose diagrams. These plots were then compared to those from fracture measurements taken at mesoscale (outcrop scale).

Geochemical Characterization

Oxygen and Carbon Stable Isotope Analysis

Stable isotope analysis is a useful aid in understanding the influences of meteoric and marine waters on carbonates by assisting in identification of sources of dissolved carbonate and the nature of rock-water interactions involved in carbonate diagenesis (Arthur et al, 1983). Values for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ were measured from 33 samples at the University of Michigan Stable Isotope Laboratory from host

rocks, veins, and breccia material from Little Sheep Mountain to constrain the origin of carbonate material in the matrix and vein fill. Of these samples, 15 were exclusively prepared for this project, and 22 were used with permission from Anita Moore-Nall, a PhD candidate at MSU working on an associated geochemical characterization of the Big Pryor Mountain-Little Mountain area. Samples were hand-ground with a mortar and pestle, with veins hand drilled to avoid mixing with host rock.

An isotopic analysis was performed by Lora Wingate at the University of Michigan by reacting a minimum of ten micrograms of powdered sample in a stainless steel boat with four drops of anhydrous phosphoric acid for a minimum of eight minutes and a maximum of twelve minutes (for predominantly dolomitic samples) in a borosilicate reaction vessel at $77 \pm 1^\circ\text{C}$. The reaction vessels were then placed in a Finnigan MAT Kiel IV preparation device coupled with a Finnigan MAT 253 triple collector isotope mass spectrometer. O^{17} data was corrected for acid fractionation and source mixing by correcting to a best fit regression line defined by the standard NBS-19. Machine precision is accurate to within 0.1‰ (Wingate, 2013). The results were provided in spreadsheet format with an identification number based on fracture station and sample material.

Stable isotope results are reported in comparison to the standard VPDB, which is calibrated by the U.S. Natural Bureau of Standards (NBS) through the analysis of an international reference laboratory standard (Arthur et al, 1983). NBS-19 is a standard derived from a homogenized white marble of unknown origin. The

Standard Mean Ocean Water (SMOW) is a hypothetical standard in which hydrogen and oxygen ratios are similar to that of average ocean water. The SMOW is compared to VPDB by the equation

$$\delta^{18}\text{O}_{\text{SMOW}} = 1.03086 \delta^{18}\text{O}_{\text{VPDB}} + 30.86 \quad (1)$$

(Faure, 1998). Results are reported in delta (δ) notation, which is a ratio of stable isotopes given by the equation

$$\delta = \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \times 1000 \quad (2)$$

where R is the ratio between either $^{13}\text{C}/^{12}\text{C}$ or $^{18}\text{O}/^{16}\text{O}$, the standard is either SMOW or VPDB, and units are per mil (‰) (Faure, 1998).

Strontium Isotope Analysis

$^{87}\text{Sr}/^{86}\text{Sr}$ isotope measurements were performed on seven samples collected from Little Sheep Mountain anticline. Three host rock samples came from the Salamander Cave along the Bighorn River. One breccia sample came from inside the Upper Kane Cave, which lies above the Bighorn River, and one calcite vein sample came from breccia station LSMB03 outside of the Upper Kane Cave. Another calcite vein sample came from breccia station LSMB05, not associated with a cave. $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios were then used to infer the origin and migration pathways of paleofluids by comparison of ratios obtained in other studies (Katz et al., 2006; Beaudoin et al., 2013). Powdered samples were prepared at MSU and strontium analyses were performed at the University of Wyoming Geology and Geophysics

Radiogenic Isotope Laboratory in Laramie by Anita Moore-Nall. Samples were prepared for collaborative use in the current study and in the associated geochemical characterization study by Anita Moore-Nall. The following is a detailed summary of the sample preparation procedure as outlined by Ken Sims, and edited by Erin H.W. Phillips, at the University of Wyoming.

Approximately 100 mg of each powdered sample was weighed out and put into Teflon beakers. Calcite, limestone, and dolomite were each dissolved in 3 ml 1N hydrochloric acid (HCl) for 24-48 hours at room temperature. Breccia samples were dissolved with 3 ml concentrated HNO_3 + 1 ml HClO_4 + 2 ml concentrated hydrofluoric acid (HF) on a hot plate set for 48 hours at 130°C. After dissolution, samples were centrifuged for 2 minutes at 3000 rpm. The supernatant was retained and dried down on a hot plate at 130°C for at least 8 hours. When dried, 8-10 ml 7N HNO_3 was added to each sample to convert to nitrate form prior to loading onto columns. Samples were capped and dried on a hot plate at 130°C for at least 8 hours.

For each batch of samples, strontium was purified using Sr Resin microcolumns, which are HDPE transfer pipettes fitted with polyethylene frits with a reservoir capacity of ~4 ml. Approximately 500 μl of Eichrom 50-100 μm Sr Resin was added to each column. Sr Resin microcolumns were cleaned with successive reservoirs of ultrapure H_2O , 6N HCl, ultrapure H_2O , 0.5 N HCl, and ultrapure H_2O . Columns were conditioned with one reservoir 3N HNO_3 . Samples were dissolved in 6 ml 3N HNO_3 on a hot plate for 30 minutes then centrifuged for 2 minutes at 3000 rpm. 1.5 to 3 ml of sample was loaded onto columns, excluding precipitate. Columns

were rinsed with 1 ml 3N HNO₃ and matrix was eluted with 4 ml 3N HNO₃. Strontium was collected by two successive additions of 3 ml H₂O to each column. Collection beakers were dried on a hot plate at 90°C for at least 8 hours.

To reduce organics prior to mass spectrometry analysis, three drops of concentrated HNO₃ and one drop of H₂O₂ were added and dried on a hot plate. Mass spectrometry was performed at the University of Wyoming High-Precision Isotope Laboratory on the NEPTUNE Plus next-generation Multicollector Inductively-Coupled Plasma Mass Spectrometer (MC-ICPMS). Samples were dissolved in 1 ml 1N HNO₃ and diluted prior to analysis. ⁸⁷/₈₆Sr values were reported relative to NBS-987 Sr standard of 0.710240. Two other standards were used during the analyses, including BCR (Columbia River basalt) and SRM-915 (a CaCO₃ standard) (Moore-Nall, 2014).

Breccia

Outcrops of brecciated rock were most easily observed along Little Sheep Mountain Canyon where the Bighorn River cuts through the anticline. Discrete breccia bodies were examined and sampled at 11 stations along the canyon (Table 1). In addition to breccia material, host rock samples were collected at two stations, calcite cement hand samples were collected at two stations, and both host rock and vein fill samples were collected at four stations. Field observations focused on the relationship between deformation, brecciation, and fluid migration. Breccia are defined as consolidated or unconsolidated rock of any origin, consisting of

Breccia Station #	Host Rock Sample	Vein Fill Sample
LSMB01	✓	
LSMB02	✓	✓
LSMB03	✓	✓
LSMB04		✓
LSMB05		✓
LSMB06		
LSMB07		
LSMB08-1		
LSMB08-2		
LSMB08-3		
LSMB09	✓	✓

Table 1. List of breccia stations where samples were collected along Bighorn River at Little Sheep Mountain anticline. Stations where host rock and vein fill samples were taken are indicated.

fragments that are greater than 2 mm in diameter and generally angular (Laznicka, 1988). Breccia classification and nomenclature are not standardized, resulting in a variety of breccia classification schemes. Therefore, breccia classification in this study follows Katz et al. (2006) for the Mississippian Madison Formation in the Bighorn Basin, using fracture density, clast orientation, and volume and type of matrix material.

Four major breccia types have been previously identified in the Madison Formation of the Bighorn Basin and this classification was followed for breccia

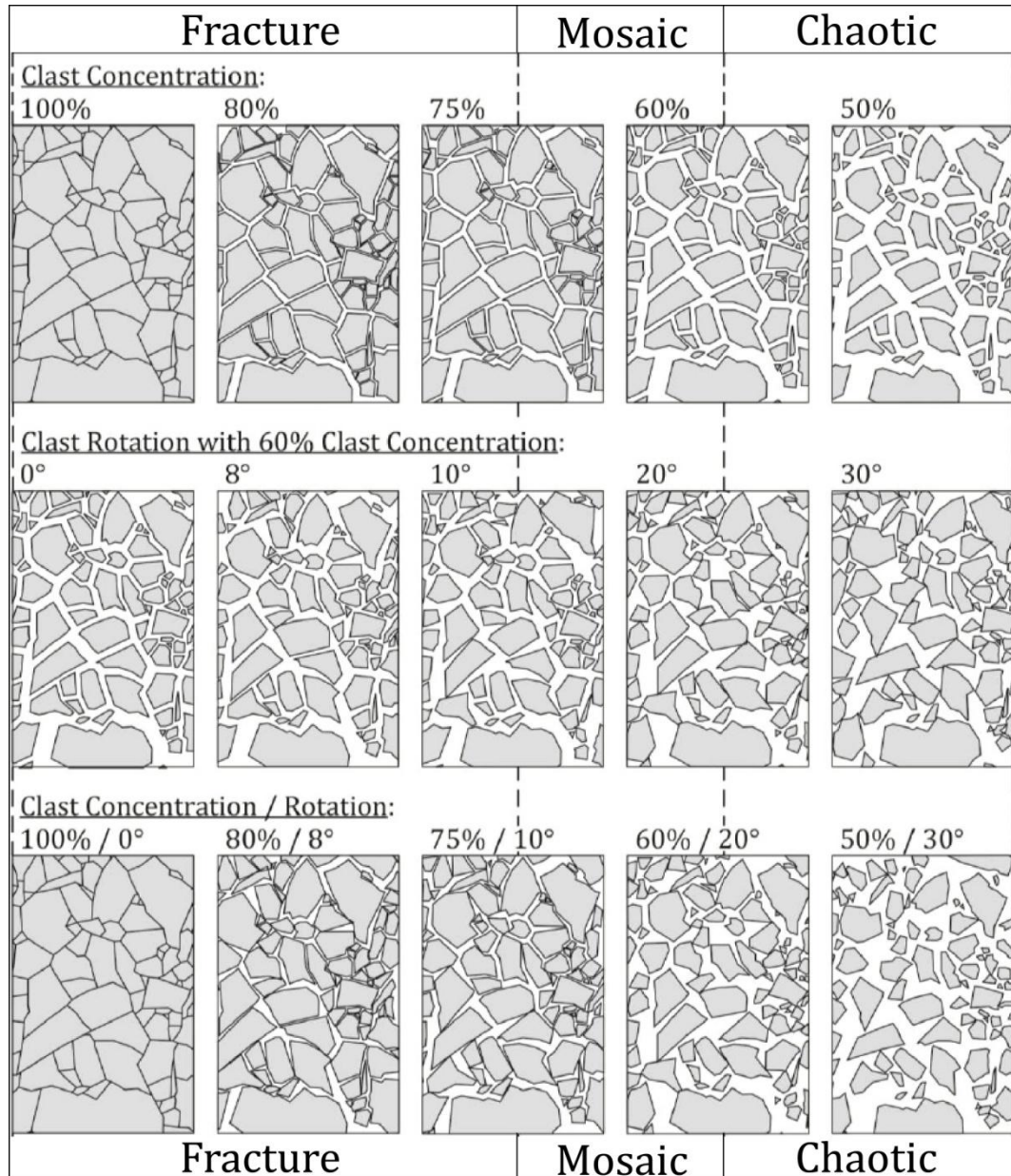


Figure 9. Breccia classification showing fracture, mosaic, and chaotic breccia fabrics at different levels of clast rotation (modified from Mort and Woodcock, 2008).

bodies at Little Sheep Mountain anticline (Katz et al., 2006). Surficial karst breccia are identified as chaotic breccia with a dolomite matrix, which mark sequence boundaries and do not cut across bed boundaries. Evaporite solution collapse

breccia are chaotic breccia with argillaceous dolomite matrix, which form at the base of sequences and form by one of two methods: the collapse of a lithified formation into solution cavities, or the dissolution of massive evaporate beds followed by the collapse of overlying and intercalated beds into voids. Intrusive karst collapse breccia are chaotic breccia with a siliciclastic matrix, which occur in pipes or sinkholes cut into the Madison. Surficial karst, evaporite solution collapse breccia, and intrusive karst breccia all formed in the Late Mississippian.

Hydrothermal breccia are calcite-cemented breccia that cross-cut stratigraphy, forming vertical breccia and corridors or following bedding for a short distance before cutting to higher levels. Hydrothermal brecciation indicates sudden, explosive genesis due to fluid migration. Hydrothermal breccia formed during Laramide shortening (Katz et al., 2006).

Breccia fabric classification criteria, summarized by Katz et al. (2006), comprise three primary types that were used in identification of breccia fabrics at Little Sheep Mountain anticline (Figure 9). Fracture breccia are characterized by a low amount of calcite cement and matrix material (< 5%) and angular clasts with little to no rotation. Shatter breccia are a type of fracture breccia that are very similar to fracture breccia except that they are characterized by a high fracture density. Mosaic breccia contain 5-20% calcite cement and matrix material, and angular clasts with slightly rotated to highly rotated clasts. They are characterized by fitted clasts, separated by cement and matrix, which can be fit back together like

a jigsaw puzzle if the rotation is minimal. Chaotic breccia have up to 80% cement and matrix material and highly rotated, angular clasts.

Petrography

Hand samples from carbonate host rocks and breccia pipes were cut and prepared as thin sections at Montana State University using a Pelcon automatic thin section machine. Each slide made was standard size and ~30 μm thick. 23 thin sections were analyzed with a petrographic microscope to determine mineralogical composition and diagenetic state of host rocks, veins, and breccia material.

Carbonate vein fill type was distinguished using chemical staining with Alizarin red potassium ferricyanide. Using this stain, dolomite will remain unstained, calcite will stain red, ferroan (iron-rich) dolomite will stain turquoise blue, and ferroan calcite will stain purple (Friedman, 1959). Photomicrographs of thin sections were taken using a Leica DM2500P microscope coupled with a camera and Leica Application Suite version 4.1 software.

ImageJ Pore-Space Analysis

Thin section photographs of host rock, breccia matrix, and limestone clasts found within breccia thin sections from the Madison Formation were taken with a Nikon Super Coolscan 5000 film scanner. Thin section images were used to quantitatively determine the secondary porosity associated with diagenesis by calculating porosity in ImageJ. Thin sections were selected based on a lack of fracture opening and grain plucking due to thin section preparation. Photographs

were cropped to portions that were located in the center of the thin section, away from edges, and excluding any region that appeared to have been heavily distorted by thin section preparation. Thin sections which were impregnated with clear epoxy were converted to grayscale, while thin sections impregnated with blue-stained epoxy were converted to an 8-bit color scheme using the ImageJ plug-in jPOR (Grove and Jerram, 2011). Photographs were then imported into ImageJ version 1.48 to determine two-dimensional cross-sectional porosity using ImageJ and the plug-in jPOR. Thin sections which were subject to grain plucking or fracture widening due to thin section preparation were not used in this analysis in order to provide a more accurate estimate of porosity.

RESULTS

Fracture Analysis

Fracture analysis of Little Sheep Mountain anticline reveals four distinct fracture sets (Figure 10). Fracture sets are groups of generally parallel fractures of the same type and relative age, consisting of a dominant fracture orientation. The four fracture sets identified in this study were based on similarity in orientation and descriptive characteristics. The fracture sets are described in Table 2.

Fracture Set	Strike (000°)	Description
Group 1	120° - 160° and 300° - 340°	Parallel to hinge
Group 2	060° - 080° and 240° - 260°	Perpendicular to hinge
Group 3	090° - 110° and 270° - 290°	Oblique
Group 4	025° - 045° and 195° - 225°	Oblique

Table 2. Explanation of nomenclature and strike ranges for each fracture set.

The hinge line of Little Sheep Mountain anticline has an azimuth of 320°. Group 1 fractures are hinge-parallel, while Group 2 fractures are hinge-perpendicular with respect to the trend of the anticline. Group 1 is the most frequently measured fracture set in the anticline and is perpendicular to the general Laramide shortening direction of 067° (Erslev and Koenig, 2009). Group 2 fractures are the second most abundant fractures and are parallel to the shortening direction.

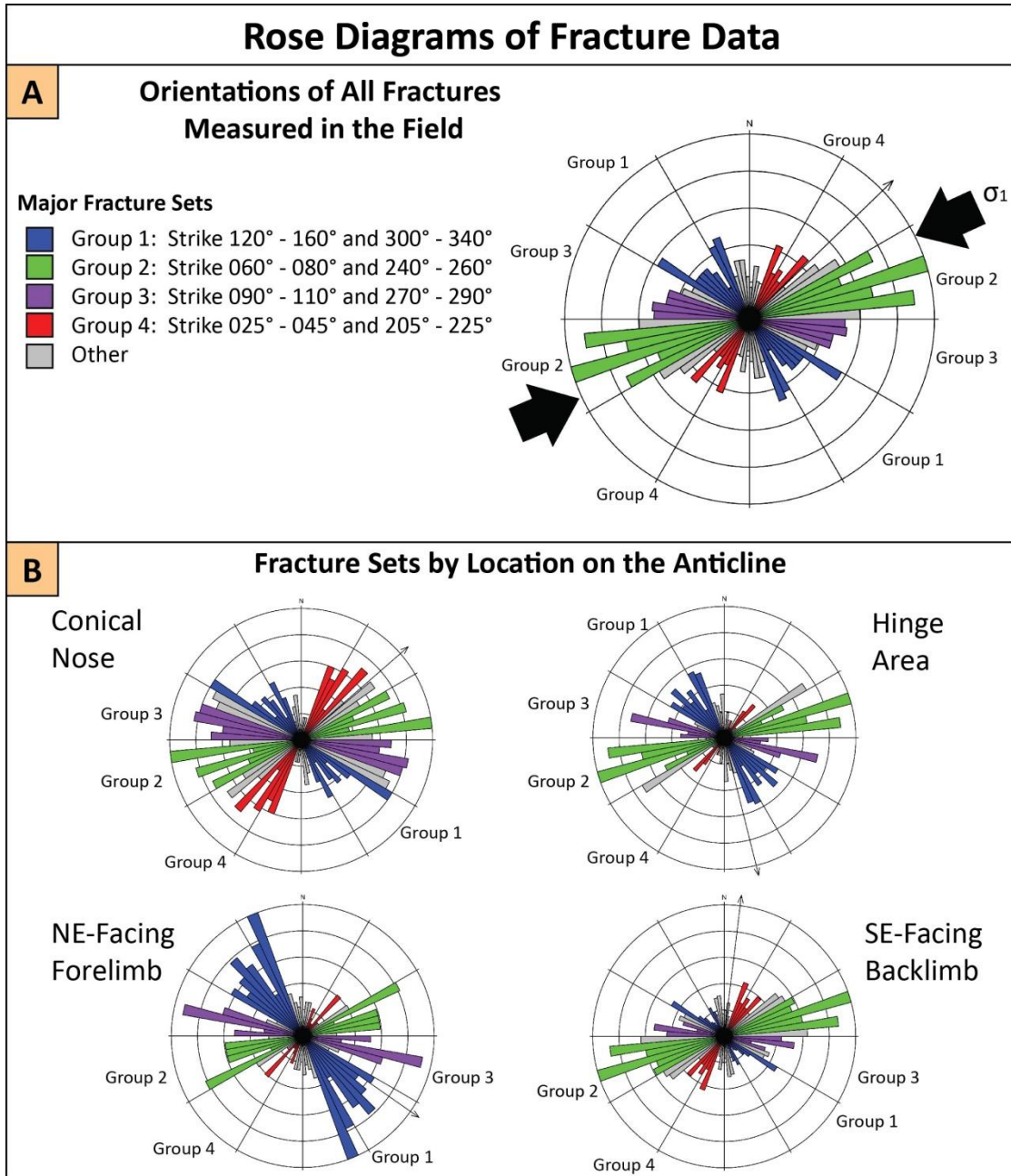


Figure 10. Fracture data divided into 4 groups based on orientation. A) Rose diagram showing orientation of all field fractures. Rose diagram petals represent 5° orientation classes. Petals are scaled by area relative to data count. Total data count is 1,308 fractures. Regional horizontal shortening direction (σ_1) for the central Rocky Mountains (067°) is represented by black arrows (Erslev and Koenig, 2009). B) Rose diagrams showing fracture data plotted by structural position on the anticline: conical plunge-end (nose, 605 fractures), hinge area (453 fractures), NE-facing forelimb (400 fractures), and SE-facing backlimb (908 fractures).

Group 3 and 4 fractures lie oblique to the Laramide shortening direction. Both sets lie within about 30° of Group 2 fractures. Group 1 fractures are prominent throughout the anticline, and are the dominant set in the northeast-dipping forelimb, which is the footwall of the anticline. Group 2 fractures are prominent in the southwest-dipping backlimb of the anticline, which forms the hanging wall. Groups 1 and 3 are the most frequently measured groups in the plunging anticlinal nose. Group 1 fractures dominate in the hinge area of the anticline. Group 4 fractures are the least common fractures measured across the anticline, but are found most often in the backlimb and the nose of the anticline.

Fold-Related Fracturing

The four major fracture sets identified at Little Sheep Mountain anticline were defined with respect to the geometry of the fold (Figure 11). Group 1 (b-c) fractures at Little Sheep Mountain are interpreted as b-c hinge-parallel joints, while Group 2 (a-c) fractures are interpreted as a-c hinge-perpendicular joints. Groups 1 and 2 form an orthogonal system. Groups 3 and 4 are classified as oblique fractures and fall within 30° of the main tectonic compression direction. These fractures form at conjugate angles, but are not interpreted as true conjugates.

Kinematic indicators found at Little Sheep Mountain anticline were primarily slickenlines in Group 4 oblique fracture walls (Figure 12A). Slickenline strikes were most commonly parallel to the Group 4 fracture direction (205°-225°) when observed. Stylolites were rarely observed, but were parallel to bedding and were not opened as fractures when observed in outcrop (Figure 12B). Bedding-parallel

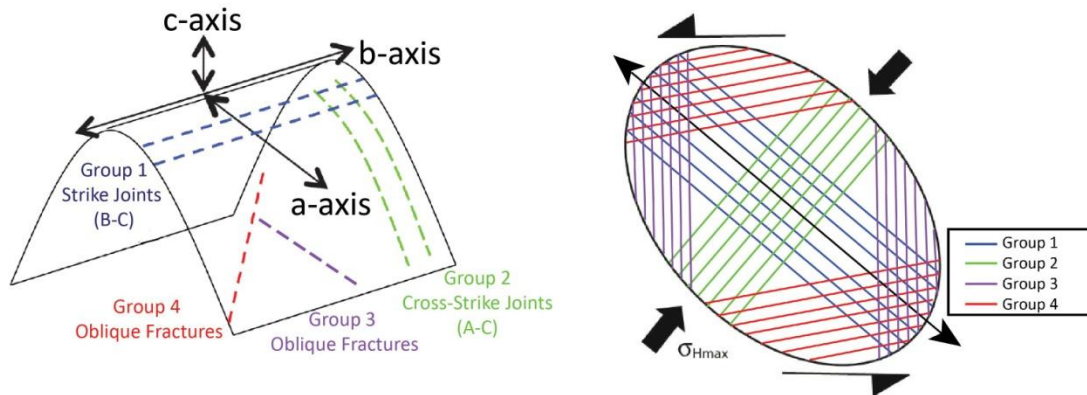


Figure 11. Fractures identified with respect to fold geometry of the anticline. (Left) Group 1 strike (b-c, dark blue) joints, Group 2 cross-strike (a-c, green) joints, and oblique (Group 3, purple; Group 4, red) fractures are represented in relation to the geometry of the Little Sheep Mountain anticline. (Right) All fracture sets shown in relation to maximum direction of shortening ($\sigma_{\max}$) on a strain ellipse. Fold trend is superimposed as black line tipped by arrows (modified from Lageson et al., 2012).

stylolites form due to overburden pressure and pressure solution, leaving an insoluble residue of clay and a serrated surface.

Groups 1 and 2 are both interpreted as mode I tensional fractures. Group 1 (b-c) fractures are plunge-parallel extension fractures, dominant throughout the anticline, and are found primarily in the fold hinge area, plunging nose, and the steeply northeast-dipping forelimb. Group 1 fractures formed from outer-arc extension of bedding associated with flexural slip at the location of maximum curvature in the fold hinge during anticline formation. Group 2 (a-c) fractures are most common in the southwest-dipping backlimb and formed parallel to the main shortening direction with respect to folding. Both Group 1 and Group 2 fractures at Little Sheep Mountain are interpreted as mode I tensional joints based on geometric distribution and spatial distribution with respect to the hinge of the anticline.

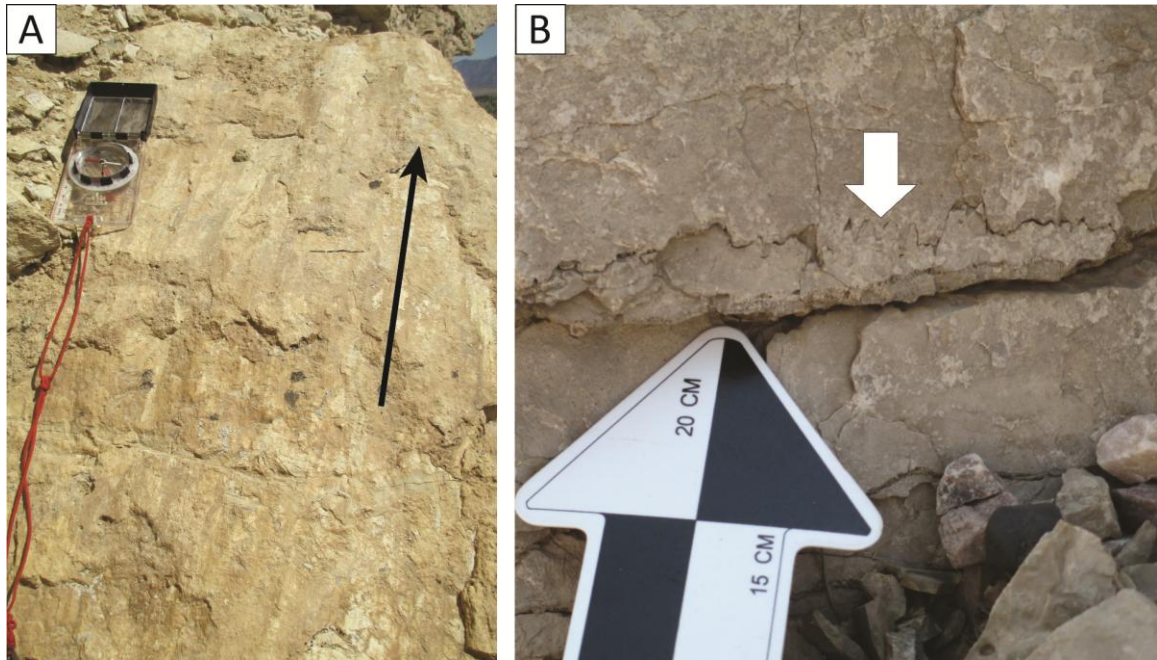


Figure 12. A) Slickenlines at fracture station L010 in the Goose Egg Formation. Black arrow indicates direction of motion of fracture surface. Associated fracture belongs to Group 4. Silva compass for scale. B) Stylolite parallel to bedding in the Madison Formation. Serrated surface indicated by white arrow.

Group 3 and 4 oblique fractures were dominantly observed in the backlimb and the plunging nose of the anticline. Field evidence of slickenlines parallel to fractures and small amounts of offset indicates that Group 4 fractures are mode II shear fractures or mode III hybrid-shear fractures. Group 3 fractures are inferred to be mode I extension fractures because of a lack of field slip indicators.

Fracture Attributes

Field measurements of fracture attributes included length, spacing, aperture, and amount of vein fill (Figure 13). Lithologic unit (formation in which fractures were measured) and location on the anticline (conical plunging nose, hinge area, or

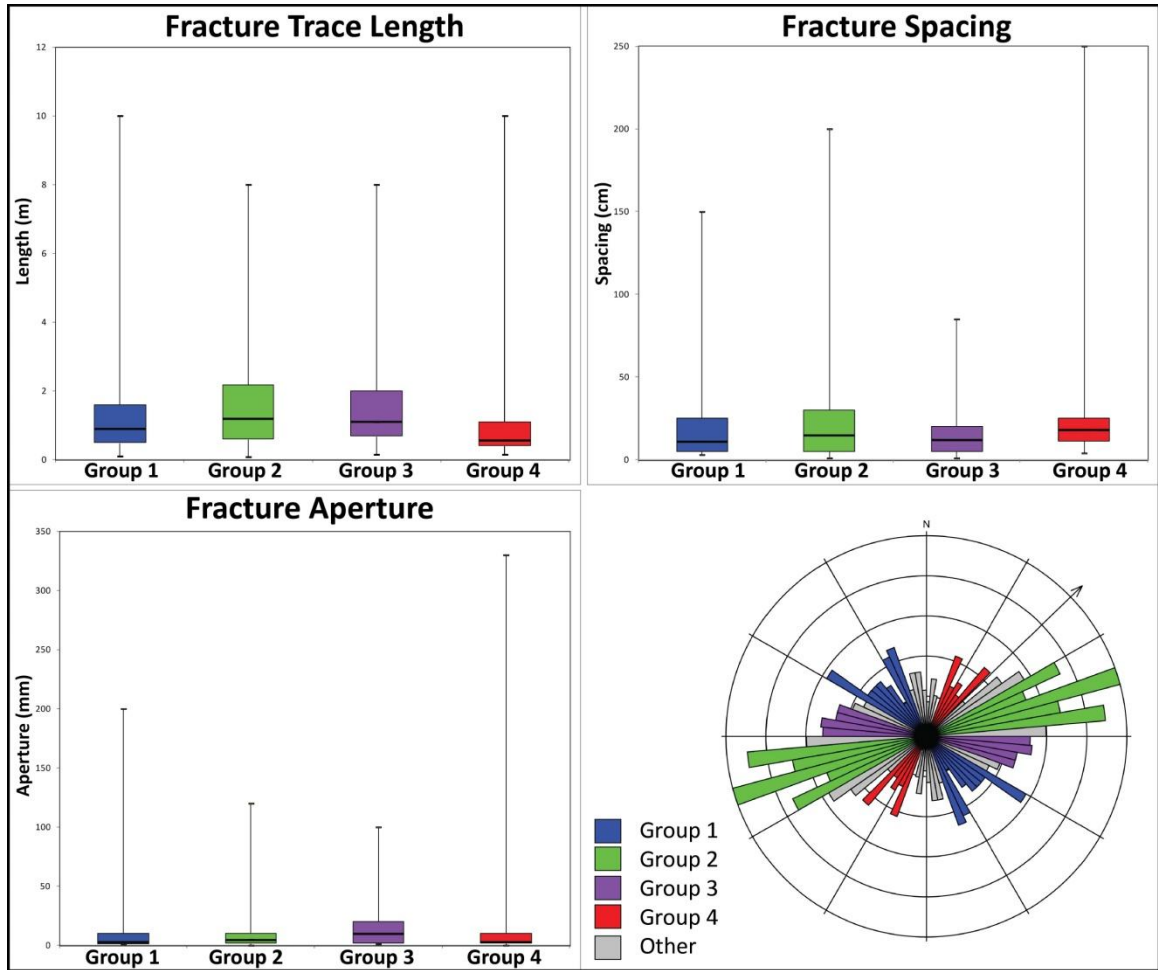


Figure 13. Boxplots showing length, spacing, and aperture fracture attributes for the 4 fracture sets. Rose diagram of fracture sets for reference.

limbs) are variables which may affect fracture attributes. On average, Group 2 (a-c) fractures were the longest fractures with an average length of 1.79 m and a median length of 1.20 m. Group 4 (oblique) fractures were the shortest fractures with an average length of 1.02 m and a median length of 0.56 m. Fracture spacing is fairly consistent among all fracture groups, although Group 3 (oblique) fractures have the longest average spacing.

The largest average apertures were recorded in Group 3 oblique fractures, with an average aperture of 11.38 mm and a median aperture of 10 mm. This large average aperture supports the mode I interpretation for Group 3 fractures. The smallest average apertures were in Group 1 (b-c) fractures, with an average aperture of 7.41 mm and a median aperture of 3 mm. Apertures in all fracture sets tended to be very small, around 1-5 mm median aperture, although the largest apertures were up to 330 mm. Vein fill was recorded most often in Group 2 (a-c) fractures, with the highest qualitative measurements also recorded in these fractures. Vein fill recorded in outcrop was predominantly syntaxial, with calcium carbonate precipitation proceeding from the fracture wall towards the center of the vein, perpendicular to the fracture wall. Vein fill composition was predominantly calcite and formed as coarse, blocky spar.

Termination patterns and cross-cutting relationships are useful in determining relative timing of fracture formation. Although many fractures extended into cover or were cut off by erosion, other termination patterns observed were primarily straight, dying out terminations and J-intersection or hooking terminations. A J-intersection termination pattern occurs when a fracture intersects a previously-formed fracture and hooks around to form a "J" shape in order to intersect the earlier fracture at an orthogonal angle (Goldstein and Marshak, 1988). Group 1 (b-c) fractures are primarily bedding-parallel and cut through bedding, with J-intersections commonly observed, most often terminating against Group 2 (a-c) fractures. Fractures belonging to Group 2 are also bedding-perpendicular and cut

across bedding planes, terminating in J-intersections against Group 4 oblique fractures. Group 3 oblique fractures are commonly oblique to bedding and confined within the bedding planes, and hooking terminations intersecting with Group 4 fractures were observed in the field. Terminations which die out are most common in Group 4 fractures, and no J-intersection terminations were observed in this set. Group 4 fractures are commonly bed-confined and perpendicular to bedding. Termination patterns indicate that, despite having a conjugate geometry, Groups 3 and 4 are not true conjugate fracture sets.

Satellite Lineament Analysis

Lineament mapping was conducted using Google Earth Pro satellite imagery to obtain a regional overview of lineament orientations at Little Sheep Mountain anticline (Figure 14). Lineaments were classified using the same orientation scheme as fractures in outcrops and were separated by structural domain as well (Figure 15). The most numerous lineaments mapped on satellite imagery across the anticline belonged to Group 2 hinge-perpendicular lineaments and Group 4 oblique lineaments. The primary trend of all lineaments is approximately N60°E, which is nearly orthogonal to the trend of the anticline.

Group 1 b-c lineaments and Group 2 a-c lineaments were the most common lineaments measured in the backlimb, while Group 2 and Group 4 oblique lineaments were the most common in the forelimb. Group 2 lineaments were measured most frequently in the conical nose and Group 1 lineaments were most common in the hinge area.

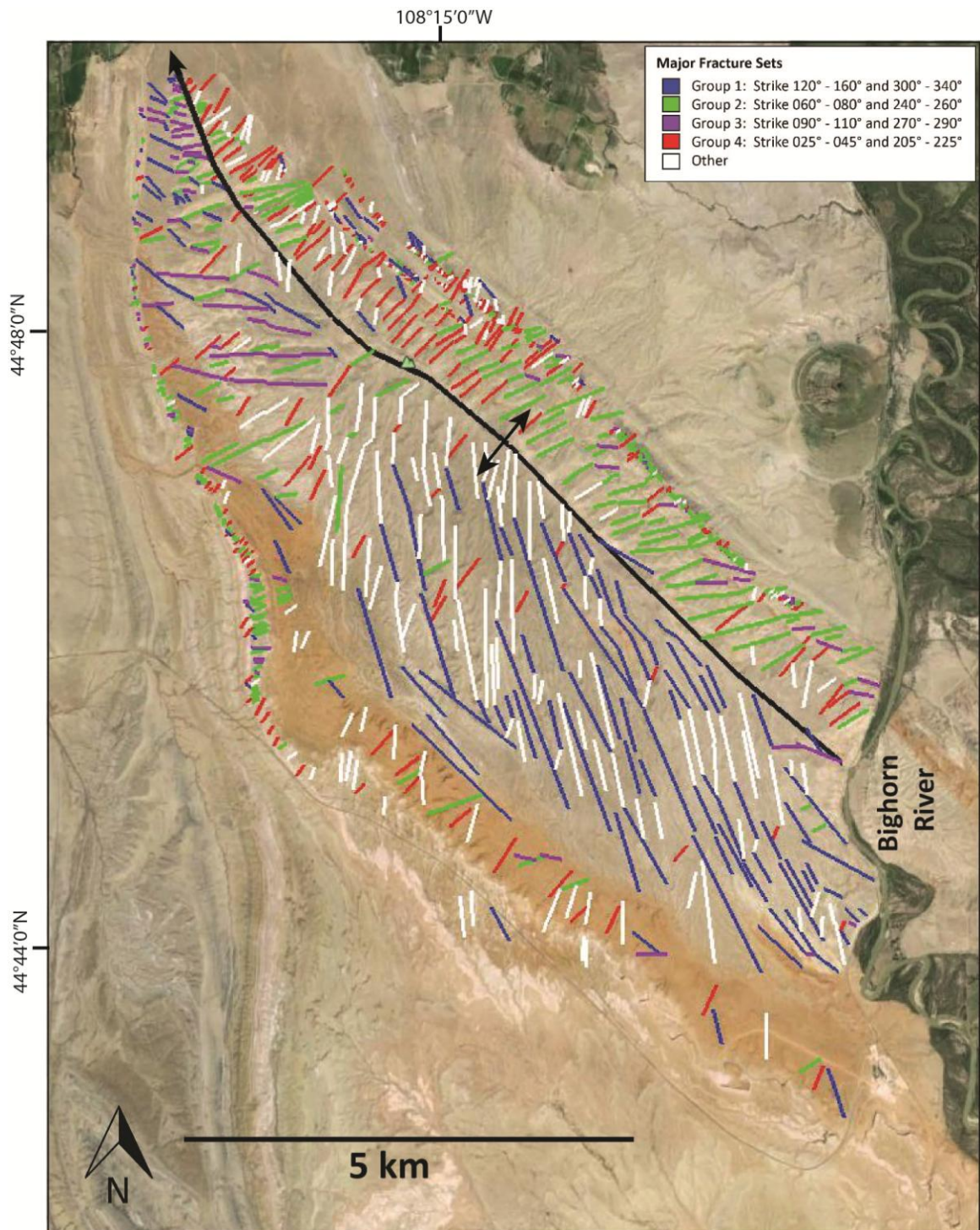


Figure 14. Google Earth Pro map of lineaments measured using aerial imagery. Lineament groupings are based on the orientation scheme used for field measurements (Table 2).

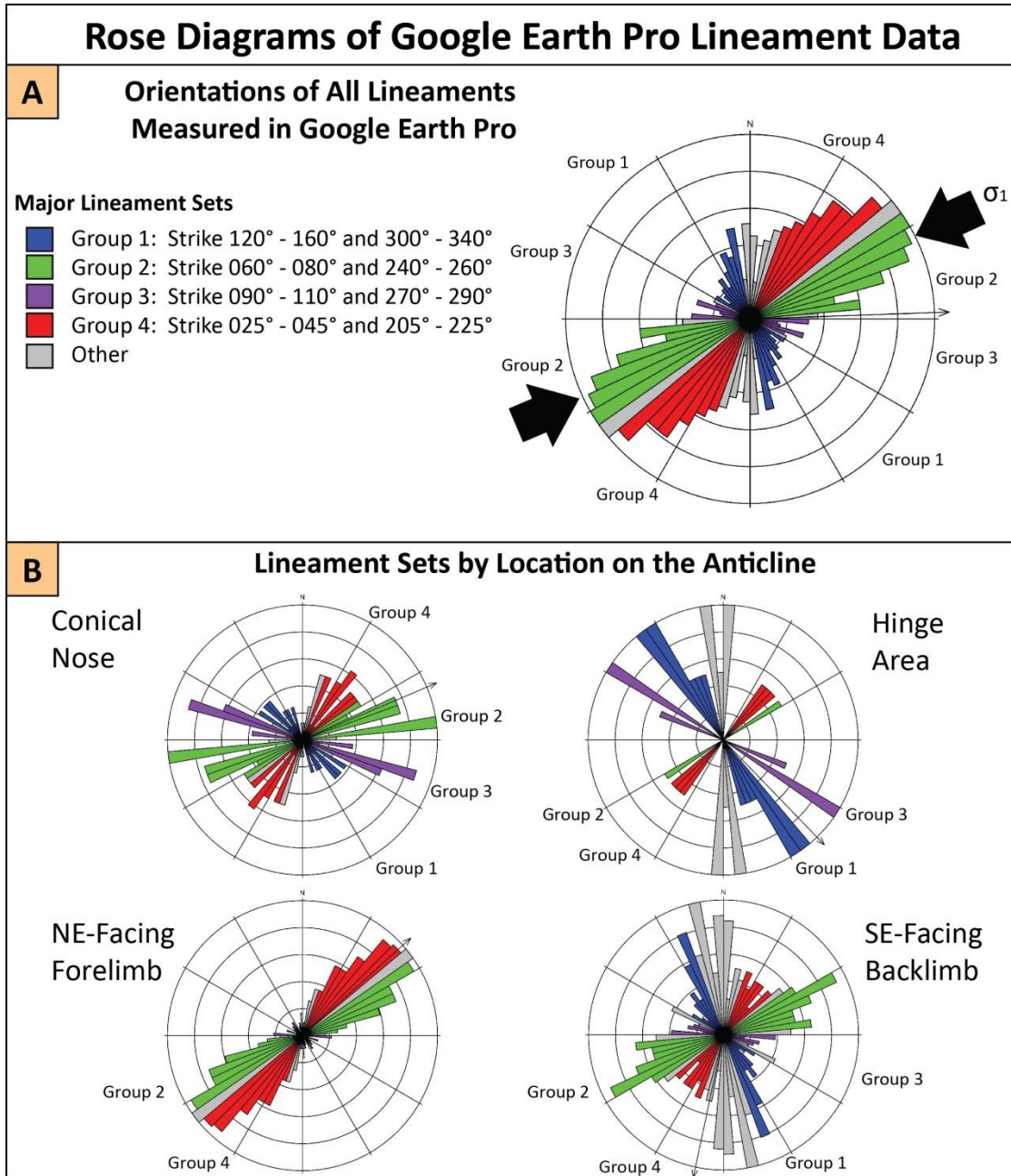


Figure 15. Google Earth Pro lineament data divided into 4 groups based on orientation. A) Rose diagram showing orientation of 1,005 lineaments measured on a Google Earth Pro aerial image of Little Sheep Mountain anticline. Rose diagram petals represent 5°. Regional Laramide shortening direction ($\sigma_1 = 065^\circ$) indicated by black arrows (Erslev and Koenig, 2009). B) Rose diagrams of lineament data plotted according to structural position on the anticline: conical nose (98 lineaments), hinge area (19 lineaments), NE-facing forelimb (461 lineaments), and SE-facing backlimb (447 lineaments).

Geochemical Characterization

The isotopic signature of marine water is governed by $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, and fluid temperature (Arthur et al., 1983). The isotopic signature of carbonates can be used to determine the source of the fluids that precipitated vein fill and breccia in Little Sheep Mountain anticline.

Oxygen and Carbon Stable Isotope Analysis

Stable isotope analysis was used to compare Madison carbonate host rock with late-stage calcite vein fill and breccia material. Stable isotope analyses of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ were performed on Mississippian Madison host rock, vein fill, and breccia samples collected along the Bighorn River cut in Little Sheep Mountain anticline. $\delta^{18}\text{O}$ values are plotted against $\delta^{13}\text{C}$ for each sample (Figure 16).

Host rocks in the Mississippian Madison Limestone have the most enriched and the narrowest range in $\delta^{18}\text{O}$ values, and fall within the Mississippian seawater isotopic composition as defined by Katz et al. (2006) for the Madison in the Bighorn Basin (Table 3). Vein fill materials have the most depleted and the greatest range in $\delta^{18}\text{O}$ values. Breccia samples have $\delta^{18}\text{O}$ values ranging from values similar to the Mississippian isotopic range to more depleted values. Host rock $\delta^{13}\text{C}$ values also fall within the Mississippian isotopic range. Vein fill materials have the most depleted and the narrowest range in $\delta^{13}\text{C}$ values. Breccia in the Madison have the most enriched but the greatest range in $\delta^{13}\text{C}$ values. It should be noted that the difference in the highest and lowest $\delta^{18}\text{O}$ values is very large

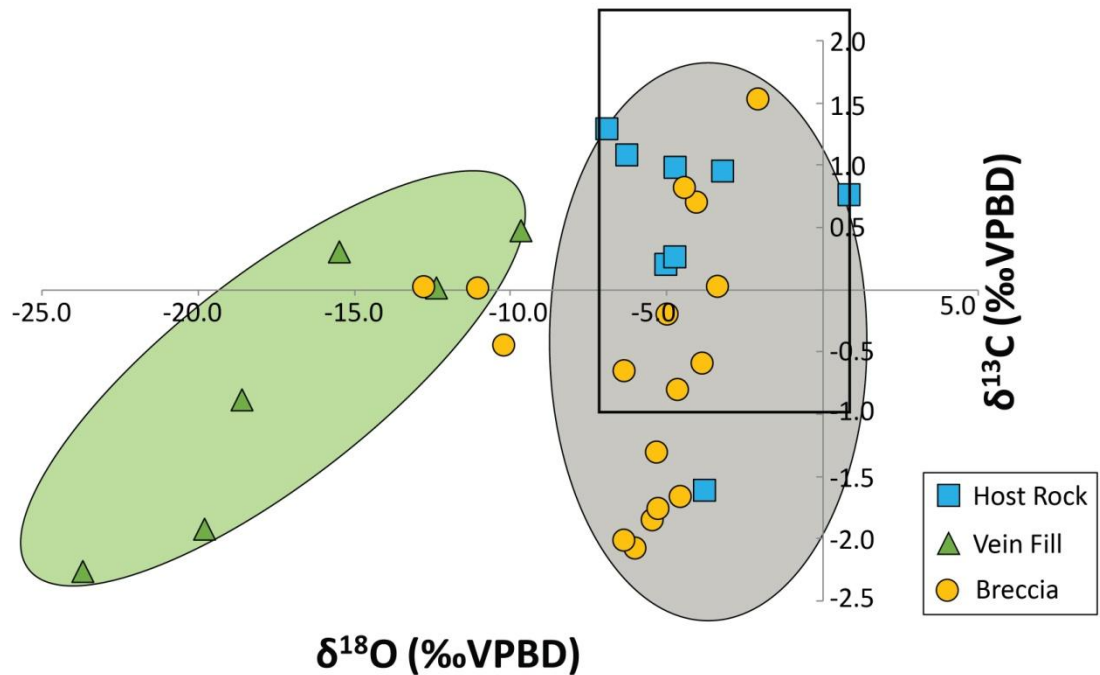


Figure 16. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ isotopic values for host rocks, vein fill, and breccias in Little Sheep Mountain Anticline. The Mississippian Madison limestone (Mm) isotopic range in the Bighorn Basin is reported after Katz et al. (2006). Green circle on left groups vein fill values; grey circle on right groups breccia values. All values expressed in ‰ Vienna Pee Dee Belemnite (‰VPDB). Error for $\delta^{18}\text{O}$ values is ± 0.04 ‰, error for $\delta^{13}\text{C}$ values is ± 0.04 ‰, based on NBS 19 Standard.

(14.04‰), but the $\delta^{13}\text{C}$ values have a narrow range and little variation in reported values.

Gross lithology for each sample was identified by XRD and XRF, as limestone or dolomite, prior to stable isotope analysis. All vein fill was identified as calcite. Two Madison host rock samples and three Madison breccia clast samples were identified as dolomite, while the rest were determined to be limestone. Limestone host rock and breccia samples were more depleted in $\delta^{18}\text{O}$ relative to dolomite

Mississippian Madison $\delta^{18}\text{O}$ & $\delta^{13}\text{C}$ Statistics

$\delta^{18}\text{O}$	Mean (‰)	Standard Deviation	Number of Samples (n)	Range (‰)
Host Rock	-4.24	± 2.37	8	-6.93 to 0.83
Vein Fill	-15.50	± 4.53	6	-23.72 to -9.68
Breccia	-5.81	± 2.70	19	-12.80 to -2.09

$\delta^{13}\text{C}$	Mean (‰)	Standard Deviation	Number of Samples (n)	Range (‰)
Host Rock	0.49	± 0.93	8	-1.61 to 1.30
Vein Fill	-0.46	± 1.01	6	-2.26 to 0.48
Breccia	-0.59	± 1.09	19	-2.07 to 1.54

Table 3. Mean, standard deviation, number of samples (n), and range for $\delta^{18}\text{O}$ (top) and $\delta^{13}\text{C}$ (bottom) values of host rock, vein fill, and breccia samples in the Mississippian Madison Formation.

values, but host rock values still fell within the range of Mississippian seawater isotopic composition (Table 4). Limestone breccia $\delta^{18}\text{O}$ values were much more depleted relative to limestone and dolomite host rocks, while dolomite breccia were closer to Mississippian seawater values. $\delta^{13}\text{C}$ values had much less variation than $\delta^{18}\text{O}$ values in both lithologies.

Limestone $\delta^{18}\text{O}$ & $\delta^{13}\text{C}$ Statistics

$\delta^{18}\text{O}$ Limestone	Mean (‰)	Standard Deviation	Number of Samples (n)	Range (‰)
Host Rock	-5.25	1.14	6	-6.93 to -3.80
Breccia	-6.30	2.65	16	-11.07 to -3.88

$\delta^{13}\text{C}$ Limestone	Mean (‰)	Standard Deviation	Number of Samples (n)	Range (‰)
Host Rock	0.37	1.06	6	-1.61 to 1.30
Breccia	-0.84	2.65	16	-2.07 to 0.83

Dolomite $\delta^{18}\text{O}$ & $\delta^{13}\text{C}$ Statistics

$\delta^{18}\text{O}$ Dolomite	Mean (‰)	Standard Deviation	Number of Samples (n)	Range (‰)
Host Rock	-1.19	2.86	2	-3.22 to 0.83
Breccia	-3.17	1.00	3	-4.06 to -2.09

$\delta^{13}\text{C}$ Dolomite	Mean (‰)	Standard Deviation	Number of Samples (n)	Range (‰)
Host Rock	0.86	0.13	2	0.77 to 0.96
Breccia	0.76	0.75	3	0.03 to 1.54

Table 4. Mean, standard deviation, number of samples (n), and range for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of host rock, vein fill, and breccia limestone samples in the Mississippian Madison Formation. Gross lithology identified by XRD and XRF. Top: Limestone values. Bottom: Dolomite values.

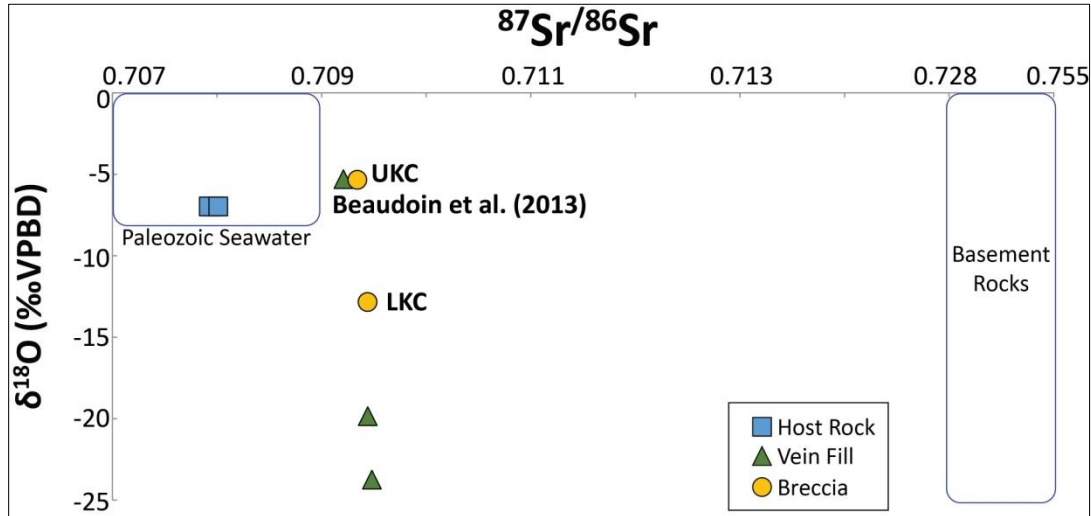


Figure 17. Strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) vs. $\delta^{18}\text{O}$ (‰ Vienna Pee Dee Belemnite) plot from host rock, vein fill material, and breccia samples, including one vein fill value from Beaudoin et al. (2013) for comparison. Paleozoic seawater radiogenic isotope ratios and radiogenic isotope ratios for basement rocks (e.g. granites and gneisses) are indicated with boxes, labeled respectively. UKC = Upper Kane Cave, LKC = Lower Kane Cave. Error (2σ) is $\pm 8 \times 10^{-6}$.

Strontium Isotope Analysis

Strontium isotope analysis was used to determine if fluids responsible for calcite vein fill precipitation interacted with high-Rb source rocks (e.g. granites and gneisses – basement rocks). Values are reported for Mississippian Madison vein fill, host rock, and breccia samples also collected along the Bighorn River cut at Little Sheep Mountain. $^{87}/^{86}\text{Sr}$ ratios are plotted against $\delta^{18}\text{O}$ values (Figure 17). A single value obtained by Beaudoin et al. (2013) is included in the plot for comparison.

Despite the small sample size, breccia and vein fill strontium values group together and the host rock plots at a significantly lower value, although the vein fill sample from Beaudoin et al. (2013) plots near the Upper Kane Cave breccia. The Madison limestone host rock plots within the range of lower Mississippian seawater

values (0.7075-0.7085) at 0.7079, indicating that it is unlikely that this sample has been reset by diagenetic fluids (Katz et al., 2006). The breccia and vein fill samples are more radiogenic than the host rock and Mississippian seawater, indicating interaction with high-Rb source rocks.

Breccia

Breccia bodies were examined along the western cliff of Little Sheep Mountain Canyon where the Bighorn River crosses the anticline obliquely and exposes part of the center of the anticline (Figure 18). The primary breccia types found in the anticline are solution collapse and hydrothermal breccia. Breccia bodies were described in the field using characteristics identifiable in outcrop and hand sample (Table 5). Each discrete breccia body was examined separately, with a total of 13 breccia bodies identified at 11 stations (Table 6). Brecciated bodies may form breccia pipes, breccia sills, or other geometries. Breccia pipes are vertical to sub-vertical bodies that form columns which cross-cut stratigraphy (Laznicka, 1988). Breccia sills follow bedding, and eventually cut up-section through strata.

Collapse breccia are interpreted to have formed by the collapse of a lithified formation due to spalling of fragments from fracture walls into solution cavities (Laznicka, 1988). This type of breccia may also form due to dissolution of thick evaporite beds, when overlying and intercalated strata collapsed into the resulting solution cavity during exposure of the Madison Formation in the Late Mississippian (Katz et al., 2006).

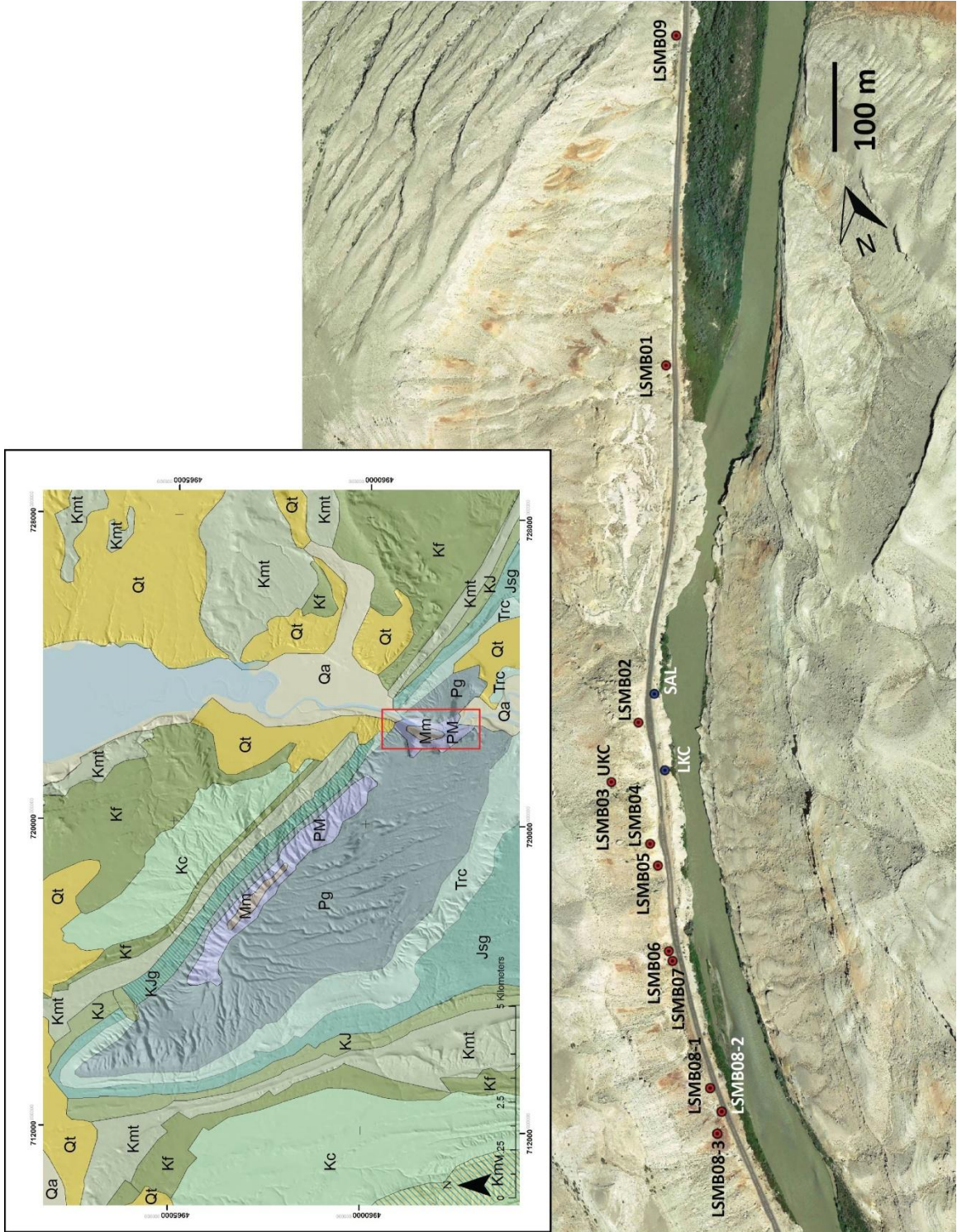
Breccia Type	Fracture	Mosaic	Chaotic
Clast Orientation	Unrotated	Rotated	Rotated
Carbonate Cement	< 5%	5-20%	≤ 80%

Table 5. Breccia fabric classification scheme (modified from Katz et al., 2006).

Breccia Descriptions

LSMB09 is the northernmost breccia station and is located in the forelimb of the anticline in the Permian Goose Egg Formation. This breccia body contains angular clasts that exhibit little to no rotation, and could easily be fitted back together (Figure 19A). These angular clasts are often rhombohedral in shape, indicating that the shapes of these fragments are fracture controlled. Acute 60° angles at the corners of some rhombohedral clasts indicate that fragment formation was facilitated by cross-cutting fractures with a conjugate geometric configuration.

The fractures are not associated with any of the four groups identified in the fracture analysis, but may belong to other fracture sets not recorded by the selection method used in this study. The fragment variety is monolithologic, with one type of clast sourced from the Goose Egg Formation. The breccia body is matrix-supported with ~40% matrix, separating the fragments so that they are not in tangential contact with other fragments. The breccia body is bed-parallel, and the lack of rotation or sorting of clasts indicates that this is an in situ breccia. This breccia is



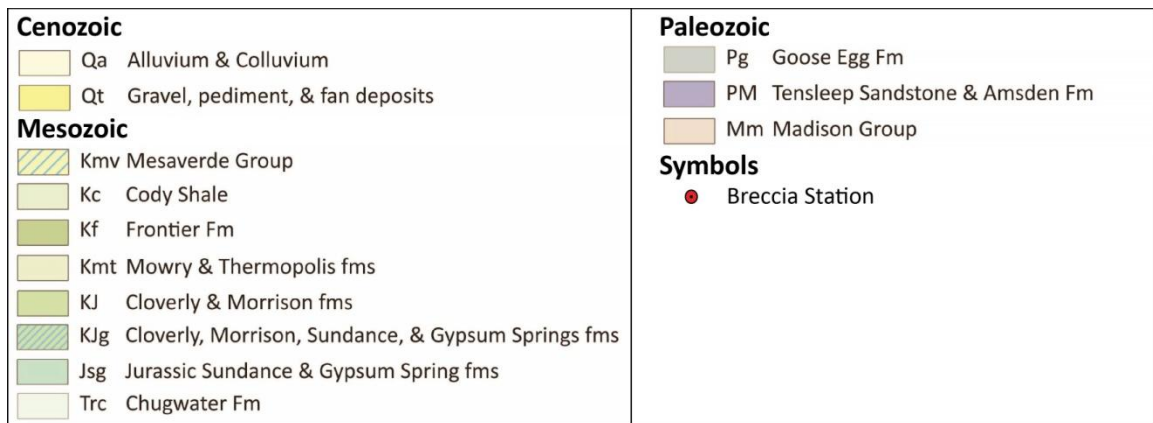


Figure 18. (Previous page and this page). Google Earth Pro map showing 11 breccia stations along the Bighorn River cut at Little Sheep Mountain anticline (yellow dots). UKC = Upper Kane Cave, LKC = Lower Kane Cave, SAL = Salamander Cave. Inset shows Little Sheep Mountain Canyon area in red box. Geologic map on inset from Bedrock Geology at 1:500,000 (Wyoming State Geologic Survey).

classified as a stratabound mosaic solution collapse breccia that likely formed during the Permian. Bitumen staining is present along fracture walls that exhibit dissolution texture, and there is a strong hydrocarbon smell (Figure 19B). Bitumen and relict sulfides are common along fractures associated with both collapse and hydrothermal breccia bodies.

LSMB01 is located in the forelimb of the anticline, near the hinge area. The breccia consists of unsorted, angular fragments which exhibit rotation. The breccia is cohesive and monolithologic, containing Madison Limestone clasts that range from millimeters to centimeters in scale. There is no visible gradation of clast size or preferred fragment orientation. Clasts are cemented by ~20% calcium carbonate, giving the breccia positive relief with respect to the adjacent rock. Relict sulfides are found along fracture surfaces near the breccia. The breccia is characterized as chaotic, due to the presence of rotated, angular clasts. This breccia body is sub-

Station	Interpreted Breccia Type	Structural Position	Distance to Next Station (m)
LSMB01	Solution collapse	Forelimb	435
LSMB02	Solution collapse	Backlimb	81
LSMB03	Solution collapse	Backlimb	87
LSMB04	Paleokarst collapse	Backlimb	28
LSMB05	Paleokarst collapse	Backlimb	101
	Hydrothermal		
LSMB06	Hydrothermal	Backlimb	12
LSMB07	Hydrothermal	Backlimb	149
	Hydrothermal		
	Hydrothermal		
LSMB08-1	Solution collapse	Backlimb	28
LSMB08-2	Solution collapse	Backlimb	24
LSMB08-3	Solution collapse	Backlimb	24
LSMB09	Solution collapse	Forelimb	392

Table 6. Interpreted breccia types according to station and structural position on the anticline. Distance to the next station (in m) is between the station listed and the next station to the south. Note that LSMB09 is the northernmost breccia station, and LSMB08-3 is the southernmost breccia station (and thus the distance listed is between LSMB08-2 and LSMB08-3).

horizontal and parallel bedding in outcrop (Figure 20). The sub-horizontal orientation of the breccia body and the unsorted, angular nature of rotated fragments suggest that this is a layer-parallel solution collapse breccia of Mississippian age.

LSMB02 is a sub-horizontal breccia body in the backlimb of the anticline,

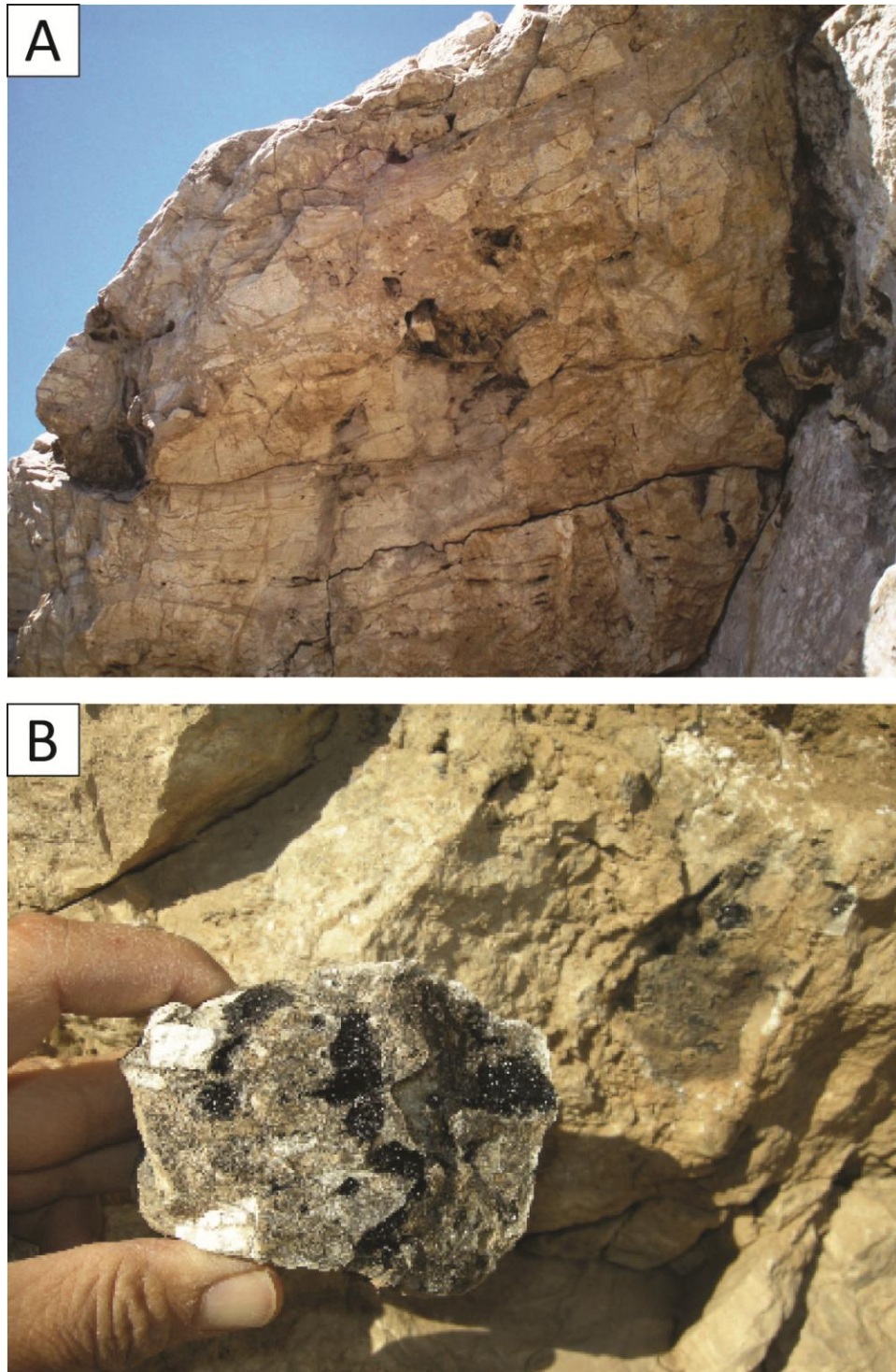


Figure 19. Outcrop photo of mosaic solution collapse breccia at station LSMB09. A) Angular clasts exhibit low rotation and can be fitted back together. B) Bitumen staining occurs along fractures and between clasts, as seen in hand sample. This photo was taken facing northwest.



Figure 20. Sub-horizontal solution collapse breccia at station LSMB01. Cemented breccia body exhibits positive relief with respect to the surrounding yellow and red host rock. Hammer for scale. Facing northwest.

near Salamander Cave which lies along the Bighorn River. Clasts supported by a high matrix percent (~70%) are angular and exhibit rotation, and are derived from the Madison Formation. This breccia is characterized as chaotic due to the presence of the angular, rotated clasts “floating” in cement matrix. Calcite is present as vein fill in fractures or as vug fill within the breccia body. Bedding-parallel and bedding-perpendicular Group 3 oblique fractures cut through the breccia body (Figure 21A). Linear features are observed in the adjacent host rock, but small, rotated chert fishes are common within the brecciated zone (Figure 21B). The breccia body is

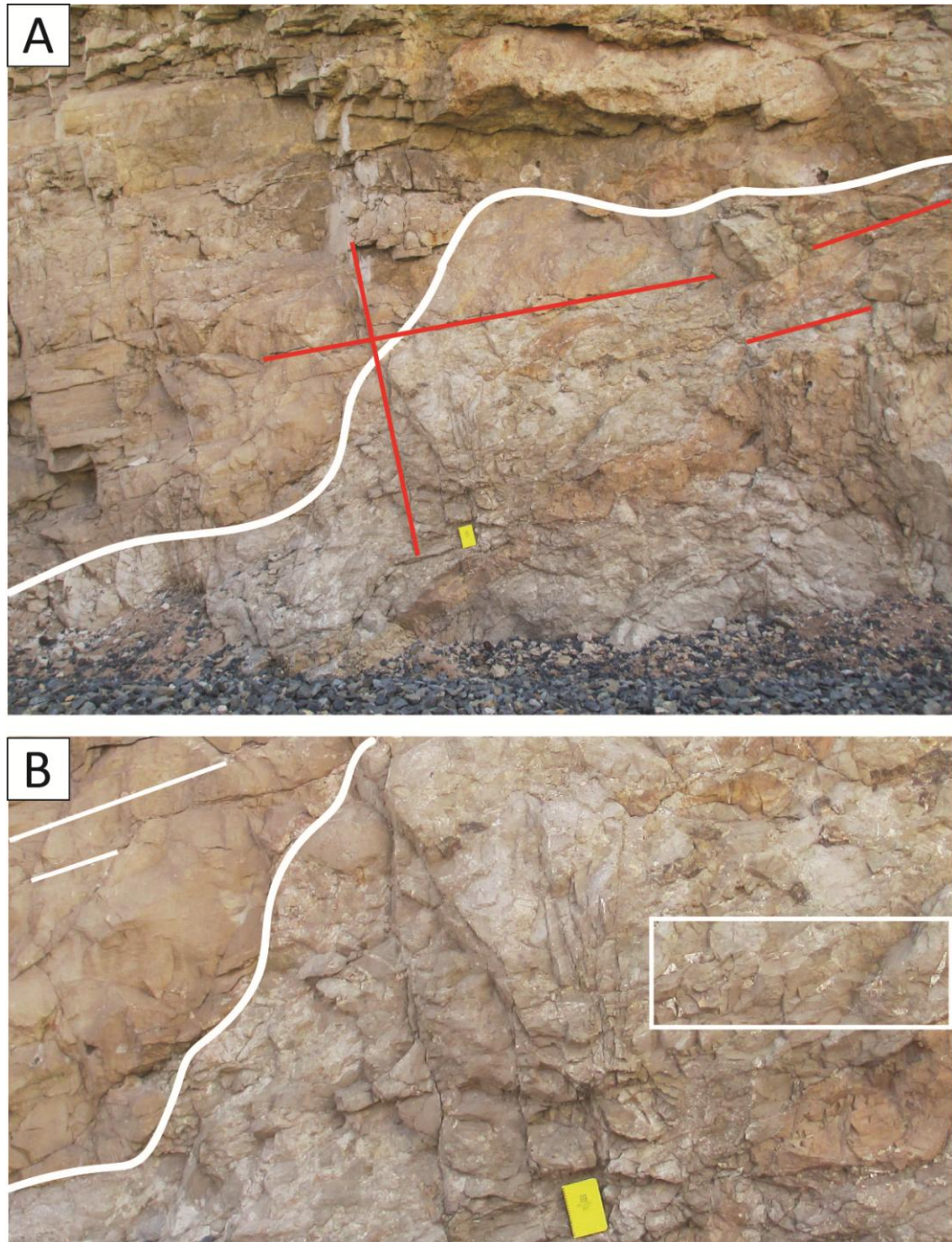


Figure 21. Solution collapse breccia at station LSMB02. A) Bedding-parallel and bedding-perpendicular fractures (shown in red) originating in the host rock cut through the brecciated body. Contact (white line) between the host rock (to the left and above) and the brecciated zone (to the right and below). B) Linear fracture fill is observed in host rock (white lines at left), while rotated chert fishes are seen in the breccia body (white square at right). Field notebook for scale. Facing west.



Figure 22. Solution collapse breccia outside the entrance to the Upper Kane Cave at station LSMB03. Red lines depict bedding, brecciated zone is outlined in white. Breccia body lies between beds and exhibits negative relief compared to the beds. Facing west.

characterized as a solution collapse breccia due to the rotation of angular fragments within the brecciated zone.

LSMB03 is located just outside of the entrance to the Upper Kane Cave, on the backlimb of the anticline. This breccia body is bed-parallel and exhibits negative relief compared to the wall rock (Figure 22). The fragments are angular to sub-rounded and rotated within the matrix, which makes up about 50% of the breccia body. The breccia body is cohesive and monolithologic. The rotated clasts “floating”

in the matrix characterizes this as a chaotic breccia. The bed-parallel horizontal geometry of the body and the lack of sorting of rotated clasts indicates that this is a solution collapse breccia that likely formed during the Mississippian.

LSMB04 is located in the backlimb and forms a vertical body that tapers at the bottom (Figure 23). This breccia body has negative relief with respect to the surrounding wall rock. A cavity is observed in the strata at the top of the vertical body. Clasts are angular and exhibit rotation, and are millimeters to tens of centimeters in diameter. Fragments and matrix are from multiple lithologies, including Madison and Amsden Formations, making the brecciated zone heterolithologic. Combined with the vertical pipe shape of the brecciated zone and cavity collapse feature at the top, this indicates that this is a paleokarst collapse breccia. There is no evidence of hydrothermal alteration, indicating that the breccia collapsed into a paleocavity. The original collapse probably occurred at the end of the Mississippian or in the Pennsylvanian and may have been enhanced during folding of the anticline due to Laramide compression. Clasts exhibit no visible sorting or gradation and are matrix supported, and thus this is characterized as a chaotic breccia.

LSMB05 is located on the backlimb, with two breccia bodies identified at this station (Figure 24). The upper breccia body exhibits negative relief with respect to the surrounding wall rock. There is a cavity capping the brecciated zone that is deeper on the north side. Fragments are angular and exhibit some rotation, ranging in size from millimeters to tens of centimeters. There is no apparent sorting or

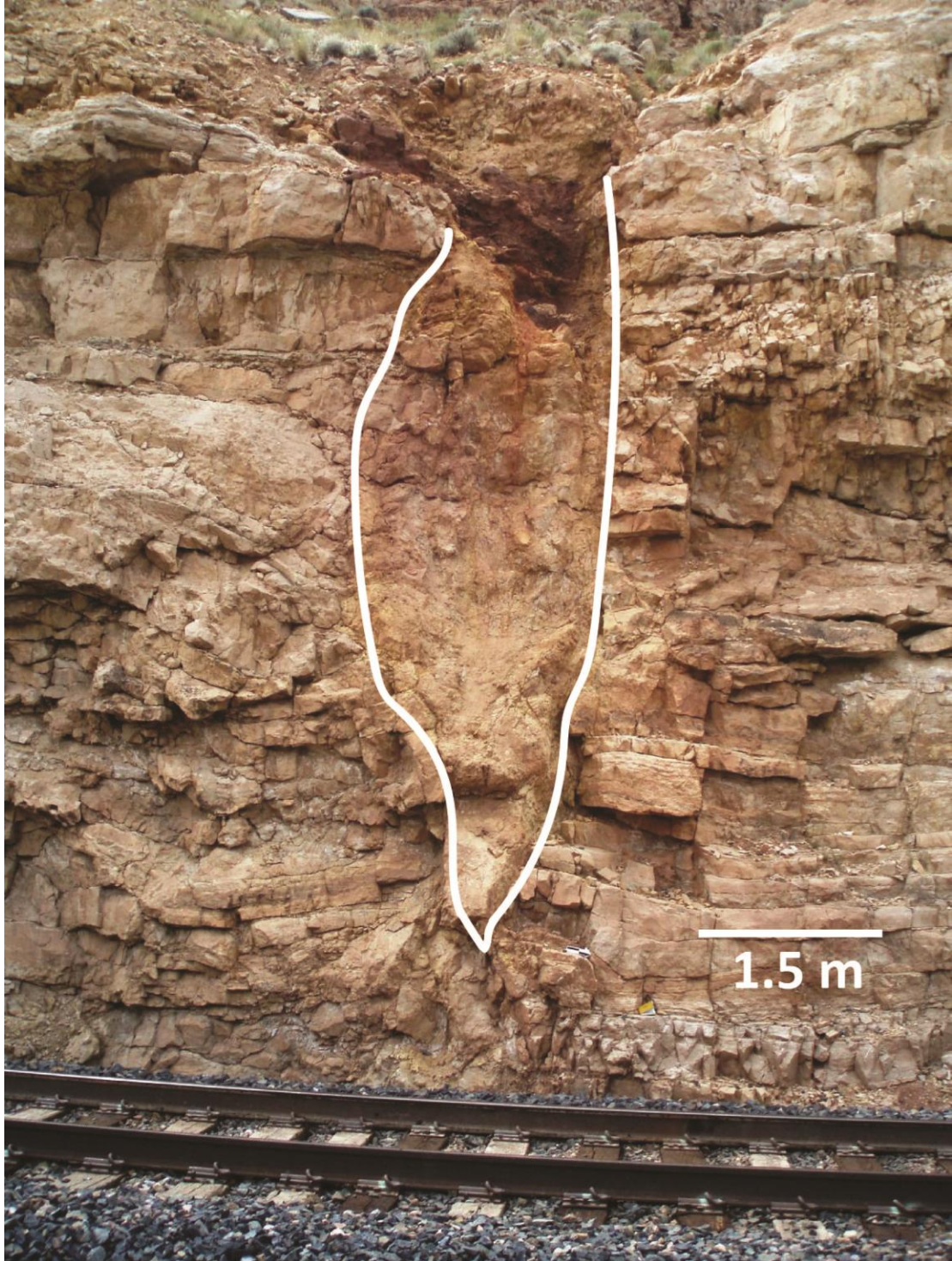


Figure 23. Paleokarst collapse pipe breccia with negative relief at station LSMB04. Brecciated area cutting down into Madison Formation is outlined in white, and is capped by a cavity infilled with Amsden Formation (dark red lithology). Facing west

gradation of fragments within the breccia body, and the breccia is fragment-supported with low matrix content. The rotated fragments that are not easily fitted back together classify this as a chaotic breccia. The chaotic character of the breccia, the apparent cavity capping the breccia body, and the heterolithologic nature of the fragments indicates that this was a collapse breccia formed in a paleokarst in the Madison. This breccia probably formed during the Late Mississippian, although collapse also likely occurred after the Laramide and after exposure of the breccia by the incising of the Bighorn River.

The lower breccia body identified at LSMB05 exhibits positive relief with respect to the collapse breccia overlying it and the surrounding wall rock. The positive relief indicates that the breccia is cohesive and cemented with calcium carbonate cement. The irregular geometry of the breccia appears to intrude into the breccia body directly above it (Figure 24). Fragments are angular to sub-rounded and are highly rotated. Clast size ranges from centimeters to tens of centimeters in scale, and fragments exhibit no sorting or gradation. Clasts are heterolithologic, suggesting cross-strata transport. The breccia body is classified as a chaotic breccia due to the presence of highly rotated fragments in ~40% matrix proportion. The random orientation of fragments of a wide variety of sizes, derived from multiple lithologies, indicates some sort of transport, indicating that this is not an in situ breccia. The chaotic breccia and calcium carbonate cementation indicates that this is an intrusive karst breccia that infilled a paleocavity. The presence of sub-rounded fragments, lack of sorting, and the indication of transport suggests that the breccia

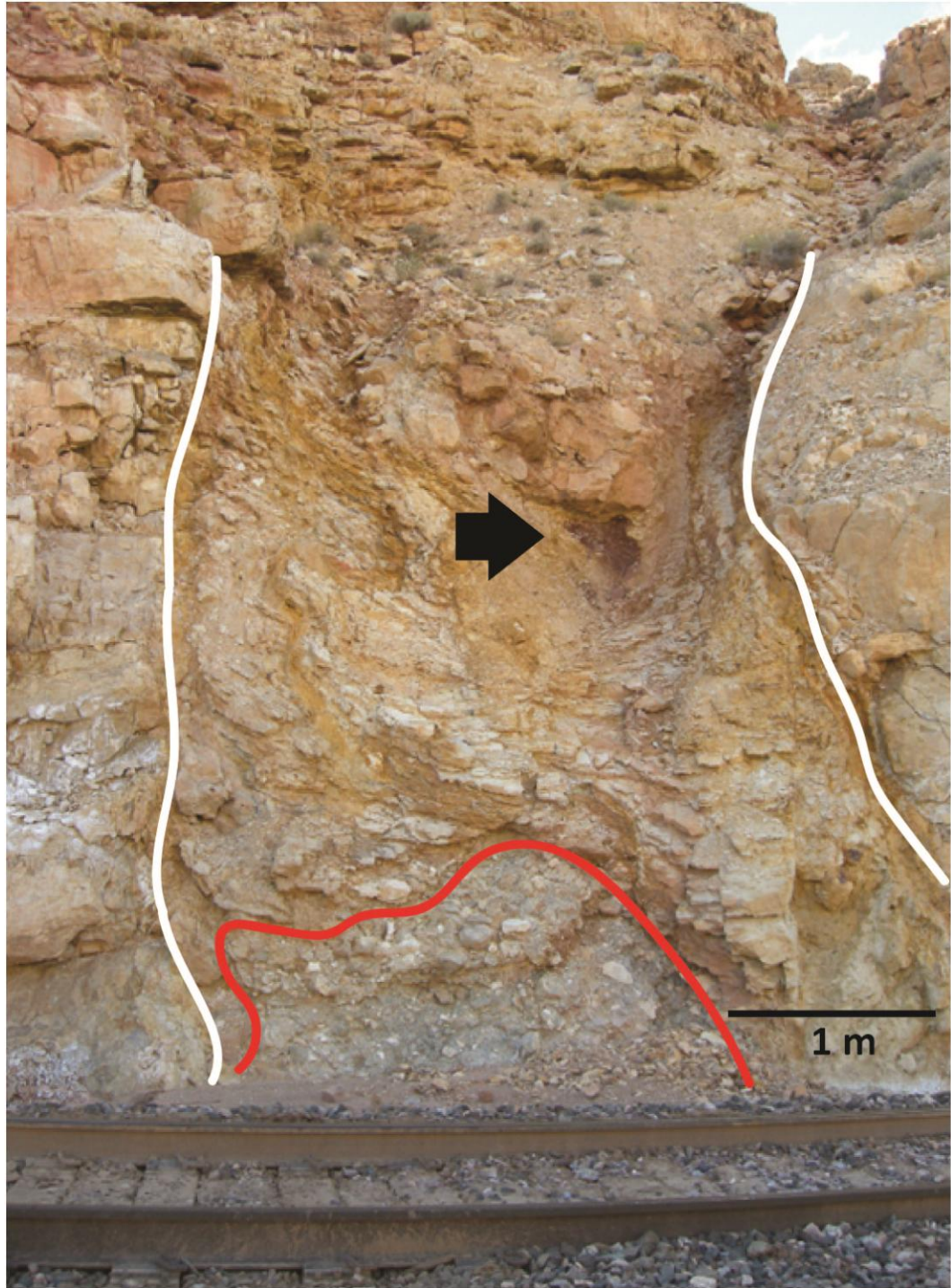


Figure 24. Paleokarst collapse breccia at station LSMB05 outlined in white, capped with dark red Amsden Formation within a cavity (indicated by black arrow). A hydrothermal breccia body outlined in red is at the base of the brecciated zone. Collapsed portion is likely enhanced by later collapse and weathering of material. Facing west.

may have been deposited in the paleocavity through some type of flow event (e.g. mudflow). This breccia is also likely Mississippian in age or younger.

LSMB06 is located on the backlimb of the anticline and exhibits two lobes of brecciation (Figure 25). Both breccia lobes exhibit positive relief and have a sub-vertical orientation with respect to the surrounding rock. The breccia bodies are bounded by Group 1 (b-c) fractures, one of which separates the two lobes. Each body is elliptical in horizontal cross section. Fragments are large, from centimeters to tens of centimeters in diameter, angular, and exhibit rotation. Clasts within the breccia bodies are heterolithologic and both bodies are matrix-supported. The contact between the lobes and the surrounding rock is sharp and defined by a change in color from reddish in the breccia bodies to the pale yellow bleached wall rock. These breccia bodies are classified as chaotic due to the presence of rotated, angular fragments “floating” in the matrix. The distinctive bleaching at the contact between breccia zone and host rock indicates a hydrothermal origin for these breccia bodies. Bleaching of host rock is caused by the migration of hydrothermal fluids and CO₂ degassing reactions (Nelson, 1993). The presence of hydrothermal alteration in outcrop is supported by the alteration in color due to addition and redistribution of iron, formation of crusts and veins of limonite and manganese oxide, and the resultant formation of sharp linear contacts separating the brecciated area from unbrecciated host rock on either side.

At least two distinct breccia bodies were identified at LSMB07 on the backlimb (Figure 26A). The first breccia body has positive relief with respect to the

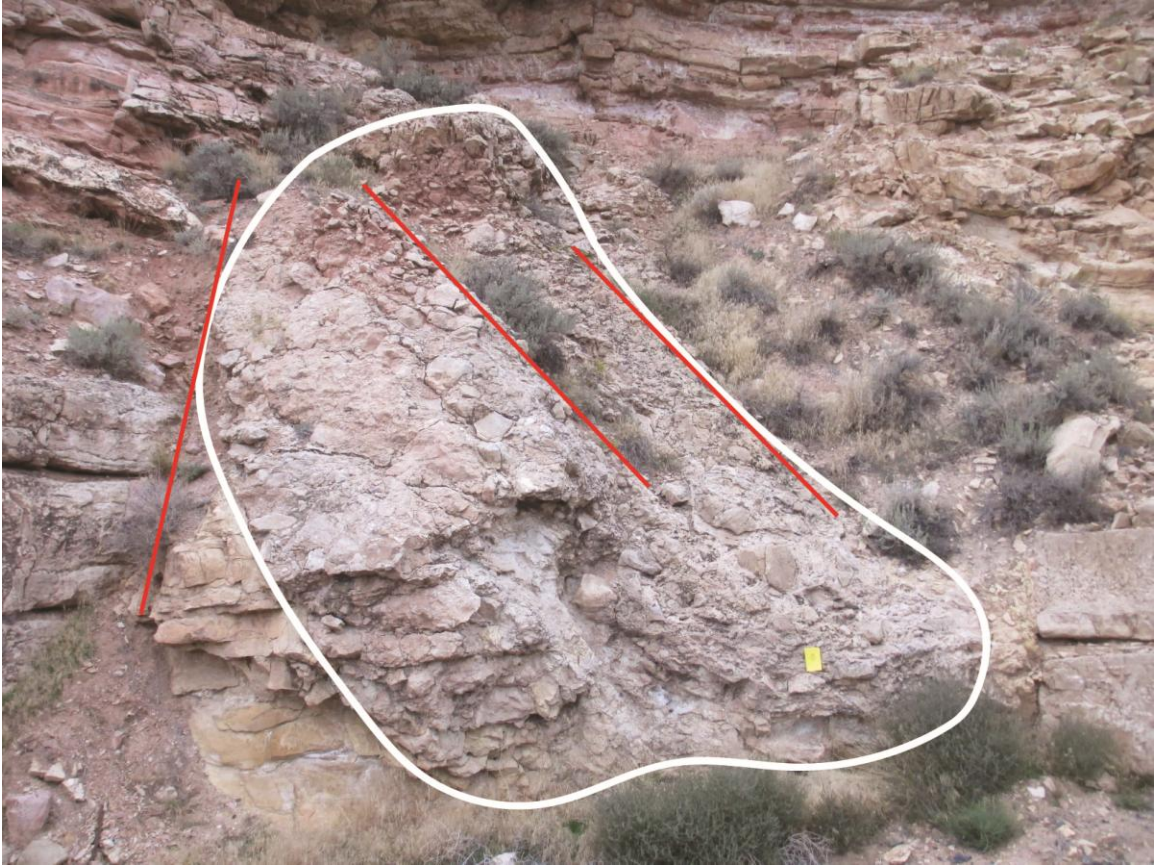


Figure 25. Hydrothermal breccia body at station LSMB06 outlined in white. Red lines indicate Group 1 (b-c) fractures bounding the two lobes of the breccia body. Field notebook for scale. Facing northwest

surrounding rock and contains rotated, angular clasts that are centimeters to tens of centimeters in diameter and are sourced from multiple lithologies. Calcite cementation creates the positive relief and matrix composes ~40% of the breccia body. The oblique position of the breccia body is oriented parallel to other bed-oblique, cross-cutting, east-west fractures of Group 3. The base of the breccia body is defined by an oblique fracture perpendicular to the bounding fractures. The overall breccia body is characterized as chaotic breccia. It is classified as a hydrothermal breccia pipe, based on the distinct contacts between the reddish

breccia body and the bleached host rock. There is a cavity at the top of the breccia station that is related to a paleokarst feature, possibly a sinkhole. It cuts across the upper breccia body.

The lower breccia body exhibits less relief with respect to the wall rock and is bleached where it contacts the breccia pipe (Figure 26B). This indicates that the second breccia zone is a hydrothermal breccia. This brecciated zone is chaotic, due to the rotated, angular clasts that are millimeters to centimeters in size. Group 3 fractures are also associated with the contacts of this breccia body with the wall rock. Matrix is ~20-50% of the breccia body. Both of these hydrothermal breccia are related to Laramide deformation, and may represent multiple pulses of brecciation. LSMB08-1 is the northern part of a ~25-m long section of breccia at the southern end of the Bighorn River cut, in the backlimb of the anticline. This section of breccia can be followed from the north to the south, and is segmented into three separate breccia bodies which were individually investigated by the author. The northern breccia body contains angular fragments ranging in size from centimeters to tens of centimeters. The fragments lack sorting or gradation, and exhibit rotation. Matrix is ~40% of the breccia, and the breccia body is characterized as chaotic (Figure 27A). This is a solution collapse breccia that developed due to infilling of a cavity created by dissolution and disaggregation of wall rock during the Mississippian.

LSMB08-2 is the middle breccia body, and has fragments which are centimeters to tens of centimeters in diameter that exhibit rotation. There is no apparent sorting of fragments. There is a moderate proportion of matrix (~50%) in

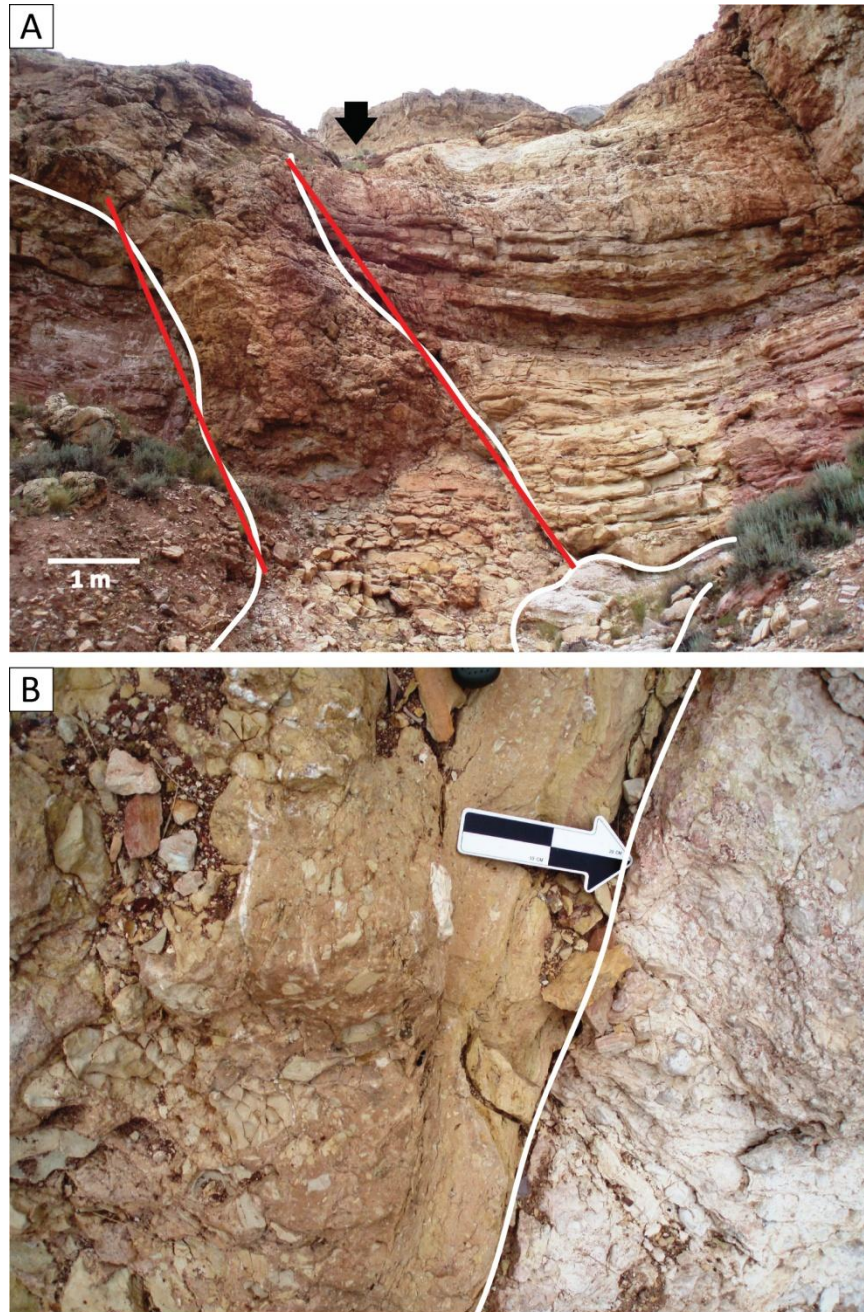


Figure 26. Two breccia bodies identified at station LSMB07, outlined in white. Facing west. A) Distinct contacts associated with Group 3 oblique fractures (in red) separate the upper left pipe-shaped breccia body and the bleached host rock. The morphology of the lower breccia body is less distinct (bottom, white) and hidden by some vegetation, but is adjacent to the upper breccia pipe. Cavity at top of outcrop indicated by black arrow. B) Contact (white line) between breccia pipe (beige) and adjacent lower breccia body (white) is distinctly altered by hydrothermal fluids and is associated with Group 3 fractures.

this matrix-supported breccia body, and it is characterized as a chaotic breccia. The center of the breccia body has a lens-shaped geometry. This is also classified as a solution collapse breccia (Figure 27B).

LSMB08-3 is the southernmost breccia body, with angular, rotated fragments with no sorting or gradation. Fragment size ranges from centimeters to tens of centimeters. Matrix proportion is up to 60% in this matrix-supported breccia body. Group 3 east-west oriented fractures cut through the breccia body (Figure 28). This breccia body is also identified as a solution collapse breccia. Folding in the outcrop in the same wavelength as the rest of the section indicates response to Laramide deformation. The similarities among these three breccia bodies and their close proximity in the anticline indicate that they may be genetically related.

Breccia Distribution

Distribution of the identified breccia bodies was examined using the distances between breccia stations measured in ArcGIS. The average distance between breccia bodies across the anticline is 133 m. Breccia bodies identified in the backlimb are more closely spaced than those in the forelimb. The distance between the two breccia identified in the forelimb is 392 m, while the average distance between breccia bodies in the backlimb is 63 m. The average distance between hydrothermal breccia stations is 56 m, and the average distance between collapse breccia in the anticline is 166 m, although the range of distances between collapse breccia varies greatly (24 to 400 m).

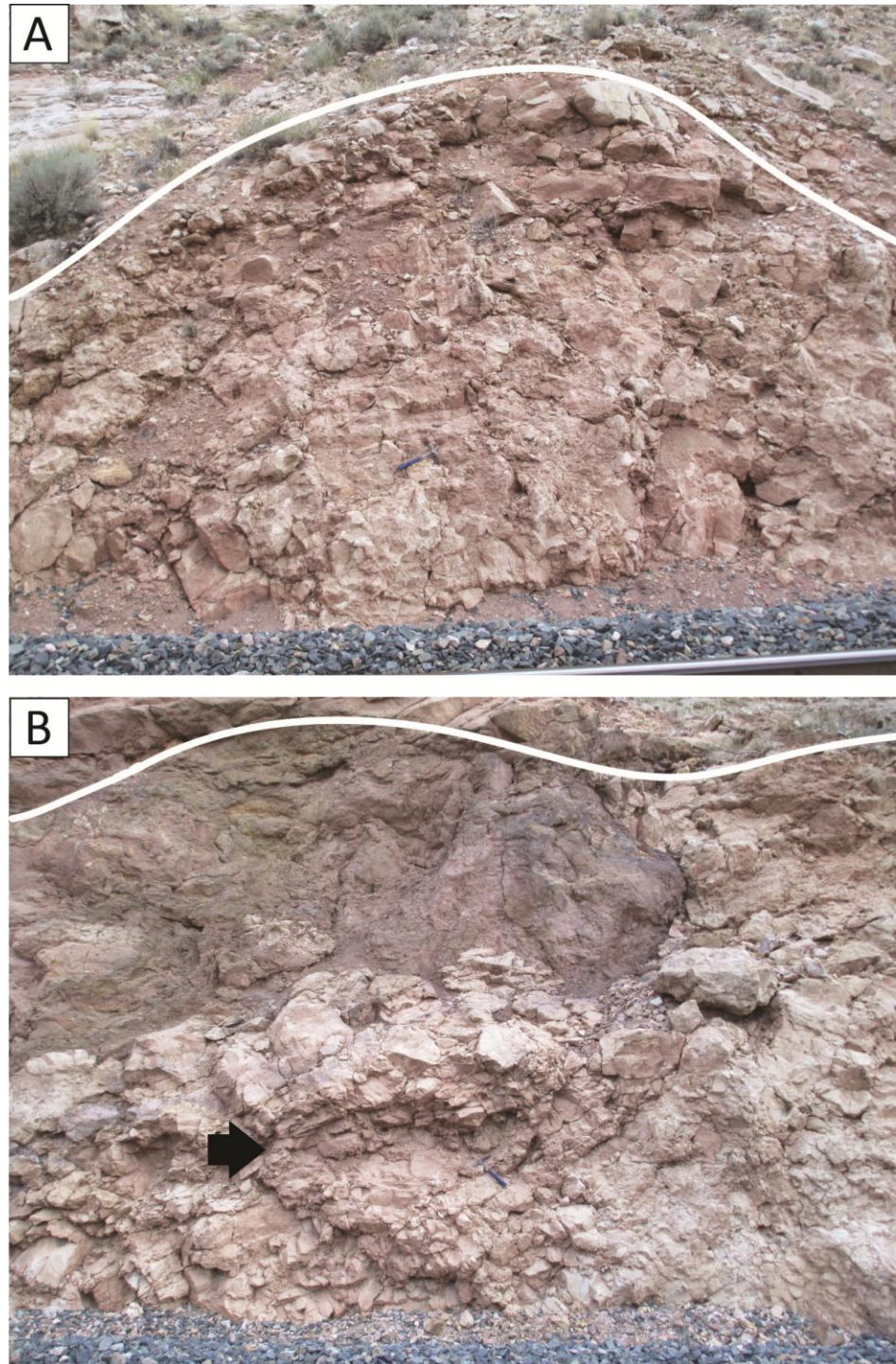


Figure 27. Chaotic solution collapse breccias at stations LSMB08-1 and LSMB08-2. A) LSMB08-1, northern breccia body, exhibiting chaotic brecciation. B) LSMB08-2, with lens-shaped geometry in the middle of the collapse breccia body. Rock hammer for scale.

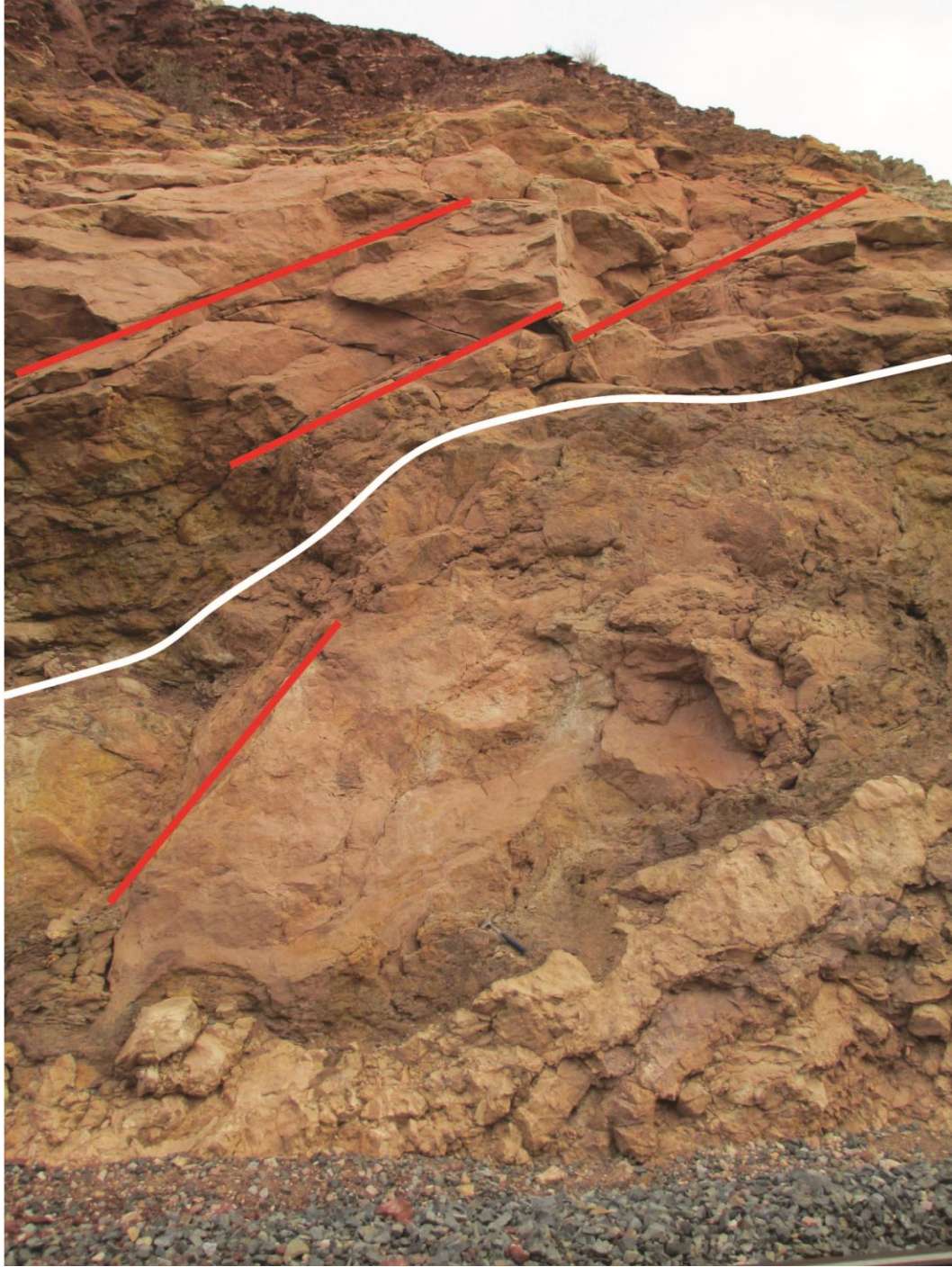


Figure 28. Chaotic solution collapse breccia at station LSMB08-3. Group 3 (oblique) east-west oriented fractures (in red) penetrate the breccia body.

Petrography

Thin section petrography conducted on limestone host rock and breccia samples from Little Sheep Mountain anticline reveals secondary fracture porosity created by tectonic deformation that formed conduits for fluid migration and localized late diagenetic alteration. Samples of Madison host rock and limestone clasts in breccia consist of micrite and peloidic or oolitic packstone or grainstone. Fabrics with multiple generations of cement in void space and fractures were observed in the Mississippian Madison Formation (Figure 29a). Cement types include fine to coarse crystalline block isopachous cement and block to coarse mosaic cements, which line cavities, veins, fractures, and clast fragments (Figure 29b). Cement compositions include euhedral to anhedral calcite and dolomite. Cements are generally blocky and often twinned. Anhedral quartz inclusions were observed in one sample. Dolomite cements are typically present as in-situ replacement within the crystalline limestone host rock (Figure 29c,d). Saddle dolomite was identified in some dolomitic cements by curved crystal surfaces and undulose extinction (Figure 29e).

Crack-seal texture was identified by syntaxial bands of cement oriented parallel to fracture walls (Laubach, 2003). Fracture-fill fabrics are primarily layered or banded and parallel to fracture walls. Veins primarily contain layers of calcite cements lining fracture walls, with coarse, blocky cements most commonly found in the center of veins. Dolomite cements are often associated with calcite cements; in some samples dolomite cross-cuts earlier formed calcite cement. Many fractures

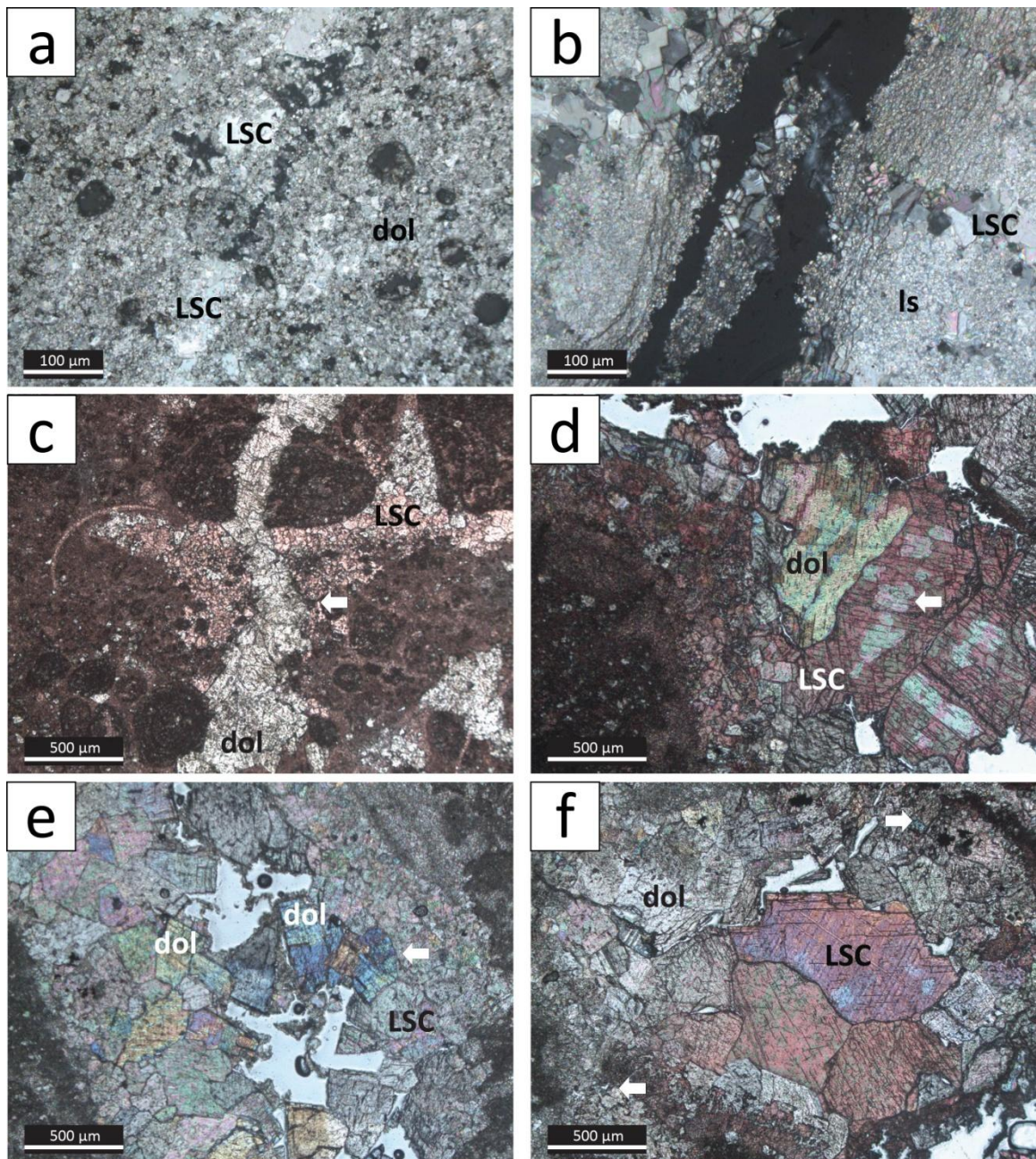


Figure 29.

Figure 29. (Previous page). Thin section photomicrographs exhibiting textures and cements seen in the Mississippian Madison Formation of Little Sheep Mountain anticline. (a) Fine crystalline dolomite (dol) with late-stage calcite (LSC) vein cutting from center top of photo to center bottom. Host rock clast in hydrothermal breccia. (Large, round dark areas are fenestrae, which may be caused by grain plucking during thin section preparation). Cross-polarized light. (b) Fine crystalline limestone (ls) breccia clast with LSC cement cut by an open vein. Chaotic solution collapse breccia. Cross-polarized light. (c) Micritic limestone host rock (stained). Peloidic packstone or grainstone; large, round dark grains are peloids. Unstained dolomite vein running from top to bottom of photo cuts through preexisting calcite cement (arrow). Plane-polarized light. (d) Stained LSC crystals sealing a vein in limestone host rock partially replaced by dolomite within the crystal (e.g. arrow). Cross-polarized light. (e) Layers of LSC lining a vein and a dolomite bridge between the walls of the fracture. Arrow indicates curved crystal surface of saddle dolomite. Cross-polarized light. (f) LSC crystals within filled fracture, surrounded by dolomite. Fracture walls indicated by arrows. Cross-polarized light.

show the growth of carbonate cements bridging fractures (Figure 29e,f). The majority of fractures observed in thin section are completely sealed in both host rock and breccias, although some small open fractures were observed in host rock. Late-stage calcite is frequently observed filling fractures and occluding pore space in clasts of host rock and breccia samples.

Madison Limestone host rock and clasts from brecciated areas are dominantly micrite, with coarsely crystalline calcite. Micritic, coarse crystalline dolomite with fractures and pores filled by late-stage calcite is also common. Peloidic and micritic host limestones are often associated with relict sulfides. Late-stage sulfides are present as framboids in interparticle spaces or cubic crystals filling void spaces and are associated with iron oxides. Bitumen (residual hydrocarbon) is often found in minor amounts surrounding grains in interparticle voids and fractures as black residue.

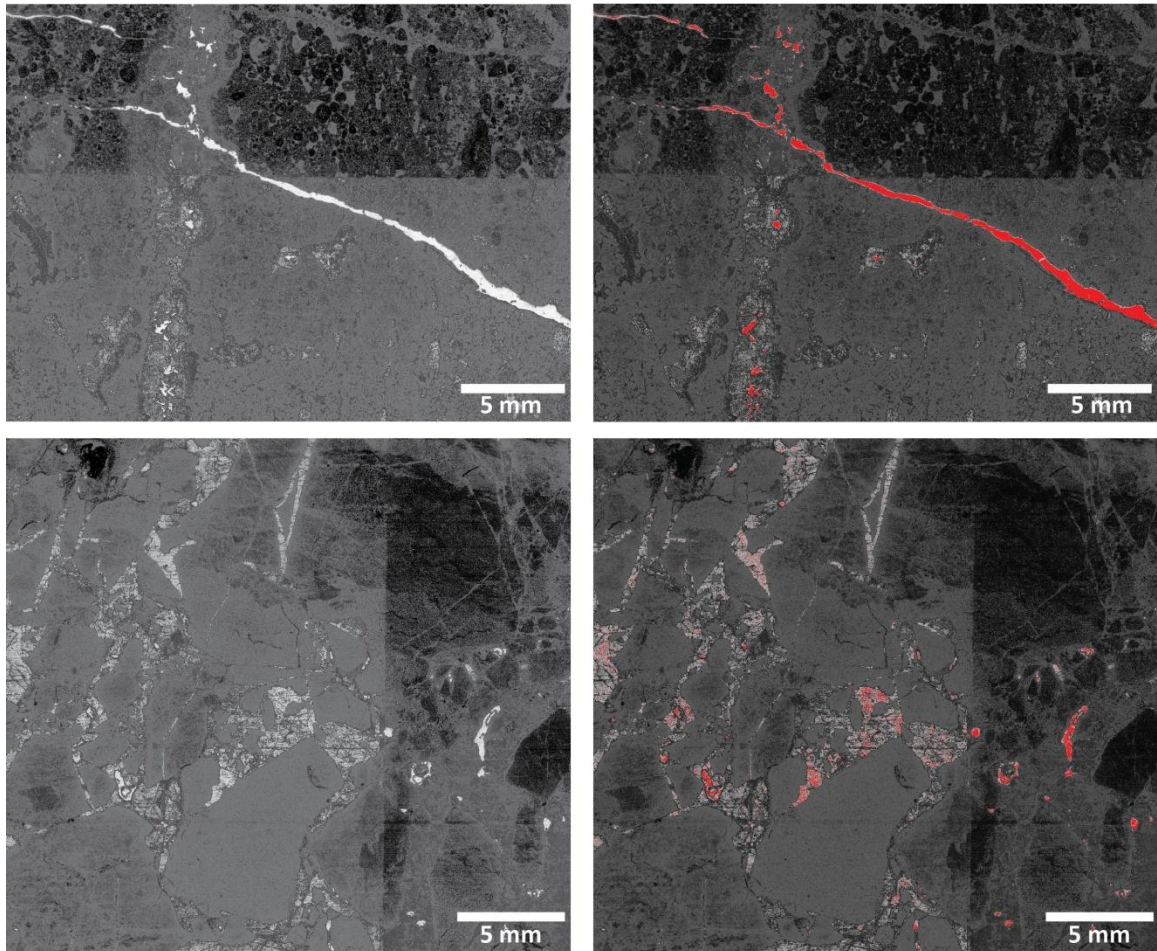


Figure 30. Thin section slide scans used in estimating porosity within Madison Limestone. Left: Greyscale thin section photographs. Right: ImageJ porosity measurements with red portions detecting pore/fracture spaces. Top: Limestone host rock. Bottom: Breccia. Porosity measurements are listed in Appendix F.

ImageJ Pore-Space Analysis

Thin section photographs were used to quantitatively determine the effects on porosity in the Mississippian Madison Formation associated with late-stage diagenesis (Figure 30). Madison Limestone is finely crystalline and characterized by low intrinsic porosity. Porosity measurements of unaltered limestone host rock indicated an average of 0.34% porosity, calculated using ImageJ and the plug-in

	Host Rock (unmodified)	Host Rock (modified)	Breccia
Mean (% porosity)	0.34	1.20	1.29
Standard Deviation	±0.002	±0.014	±0.007
Number of Slides (n)	3	8	6

Table 7. Mean, standard deviation, and number of slides (n) for porosity calculations of unmodified host rock, modified host rock, and breccia using ImageJ.

jPOR (Table). Porosity in limestone clasts with filled veins and pores was an average of 1.20%, while breccia had an average of 1.29% porosity (Table 7). This indicates an average increase in porosity of 0.86% in limestone host rock and 0.95% in breccia. ImageJ porosity measurements are overestimations of actual porosity (Grove and Jerram, 2011).

DISCUSSION

Fracture Analysis

Fracture set geometry combined with observations of fracture attributes collected at field stations on Little Sheep Mountain anticline and comparisons with proximal fracture studies provide insight into the relative timing of fracture formation.

Relative Timing of Fracture Formation

Fracture set relationship data is useful in deducing the relative timing of fracture formation (Goldstein and Marshak, 1988). Rotation of dipping beds to horizontal using Rockware StereoStat software shows that systematic fracture sets in Little Sheep Mountain generally become less distinct and poles to fractures become more scattered with unfolding (Figure 31). Scatter of systematic fracture sets increases the most in the backlimb and the forelimb of the anticline. Fractures in the hinge area and the conical plunge-end nose of the anticline exhibit less scatter with the removal of the tilt of bedding. Group 2 (a-c) fractures generally exhibit the most increase in scatter across the anticline, while Group 4 oblique fractures exhibit the least increase in scatter.

Fracture sets that become less systematic and have increased scatter in poles with unfolding are generally interpreted as having formed synkinematically with folding and thrusting (Goldstein and Marshak, 1988). This interpretation is supported by the geometric orientation of fracture sets relative to the northeast-

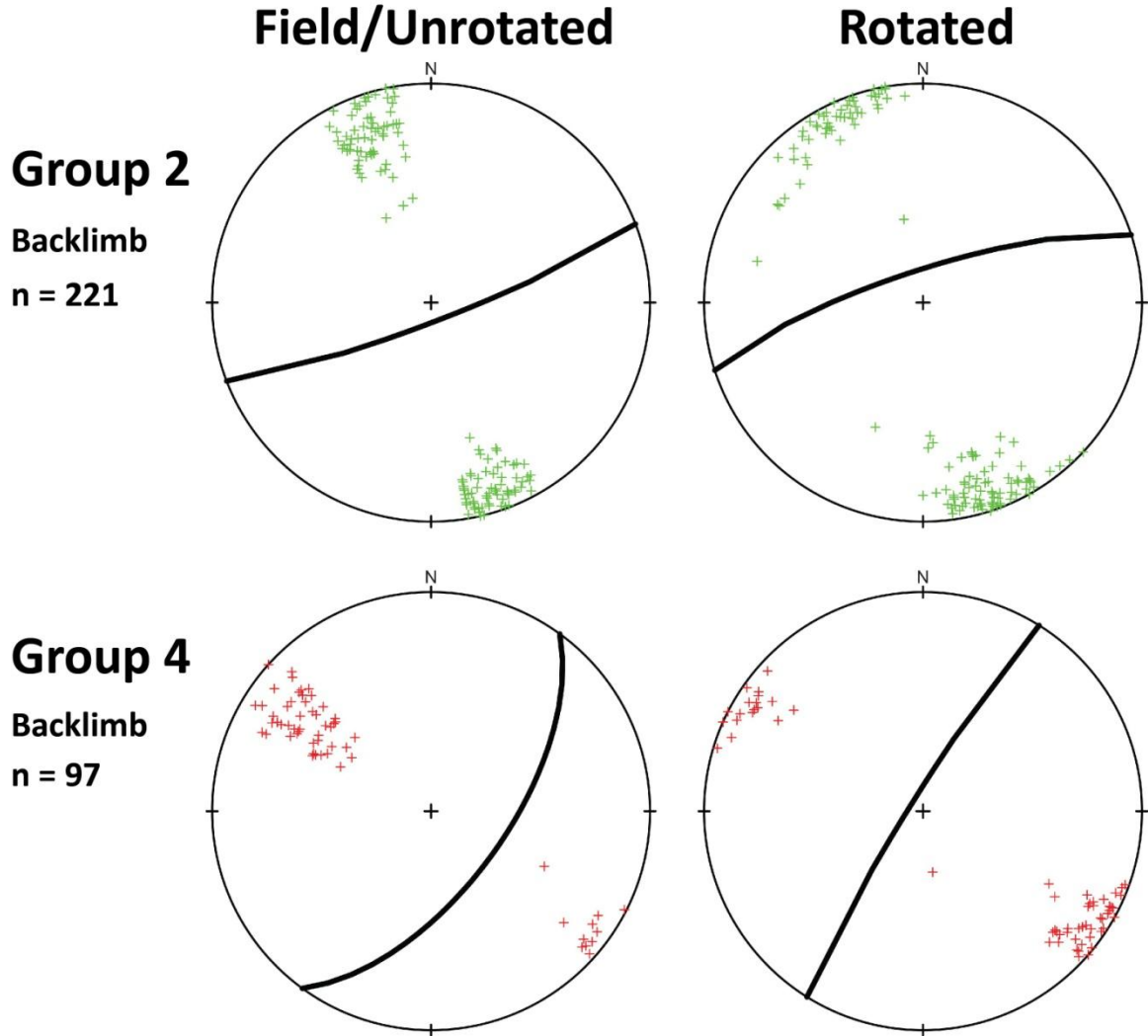


Figure 31. Lower hemisphere stereonet projections of poles to fractures measured in the backlimb at Little Sheep Mountain anticline. Field fracture measurements as measured in the current folded attitude (left) are compared with unfolded fracture measurements after rotation of dipping bedding planes back to horizontal (right) in order to visually examine the increase or decrease in scatter of data. Group 2 (a-c) fractures exhibit more scatter when bedding is rotated to horizontal than Group 4 oblique fractures. Color coding of poles to fractures is according to fracture group membership. Data for each fracture set at each structural position on the anticline can be found in Appendix G.

southwest Laramide shortening direction and the overall trend of Little Sheep Mountain anticline. Groups 1, 2, and 3 are all interpreted to have formed synkinematically with folding due to the loss of systematic geometry and increase in scatter of poles to fractures when rotated to horizontal. Group 4 fractures do not lose their systematic geometry with rotation of dipping beds to horizontal and are therefore interpreted to have formed prior to folding or early in folding, before any significant fold development.

Group 1 b-c hinge-parallel fractures are primarily found in the hinge area and forelimb and are associated with outer-arc extension during folding and local changes in stress field orientation (Goldstein and Marshak, 1988). These fractures most likely accommodated slip related to layer curvature during folding and tend to be concentrated in areas of maximum curvature in the fold hinge. Group 2 a-c fractures are hinge-perpendicular and were primarily observed in the backlimb. These fractures are associated with plunge-parallel extension, especially at the semi-conical nose where “instant plunge” occurs and accommodated slip due to layer-parallel shortening in the early stages of folding (Goldstein and Marshak, 1988). Fractures belonging to Group 4 do not lose their systematic geometry, indicating that these joints developed early in fold formation.

Geometric relationships between fracture attributes such as crosscutting relationships, conjugate sets, and termination patterns described in the field were also used to determine relative timing of fracture formation. Although many terminations of fractures were hidden under cover or cut off by erosion, the most

common termination patterns observed in the field were dying-out or straight terminations and J-intersections or “hooking” terminations. J-intersections are formed when a fracture approaches a preexisting joint at an angle and subsequently bends (or hooks around) to intersect the existing fracture at an orthogonal angle (Goldstein and Marshak, 1988). The new fracture will behave this way in order to intersect the preexisting fracture orthogonal to the direction of minimum principal stress (σ_3). This is a common form of fracture interaction in propagating tension fractures, and suggests age relationship among fractures.

Field evidence indicates that the earliest formed fractures belonged to Group 4 oblique fractures. Most other fracture sets terminate against Group 4 fractures, which commonly are observed in dying-out or straight termination patterns. Group 4 fractures are the shortest fracture group recorded, and are commonly bed-confined in outcrop. Slickenlines parallel to fracture surfaces were primarily associated with Group 4 fractures. This suggests that these fractures are mode II or III shear fractures. Group 3 oblique fractures are bedding-perpendicular and penetrate through bedding planes. These fractures have the largest apertures and occasionally link with Group 4 fractures, terminating against Group 4 in a J-intersection. This indicates that Group 4 fractures formed earlier than Group 3 fractures, and thus, although they have conjugate geometry, they are not true conjugates.

Group 1 (b-c) fractures occasionally terminate against Group 2 (a-c) fractures in a “J”-shaped hooking pattern in Group 1 fractures that curves towards

the earlier-formed Group 2 fractures. Group 2 fractures were observed terminating against Group 4 fractures in a J-intersection. This termination pattern indicates that Group 2 fractures formed earlier than Group 1 fractures, and that Group 4 fractures formed earlier than Group 2 and Group 1 fractures.

Satellite Lineament Analysis

Lineaments mapped using satellite imagery in Google Earth Pro were grouped based on the orientation scheme used for field fracture sets. A plot of the orientation data on a rose diagram demonstrates that the lineament data do not exactly match the outcrop fracture measurements (Figure 32). Group 4 oblique lineaments are more commonly observed on the scale of the aerial imagery than the associated in lineaments in outcrop measurements, while Group 3 oblique fractures are more commonly observed in outcrop than in GEP imagery. Group 1 b-c fractures have a wider range of orientations in outcrop than when measured on aerial imagery. Group 2 a-c fractures are the dominant fracture set measured in both outcrop and aerial imagery. The dominant trend of recorded lineaments is approximately 060° , which is slightly askew from the 075° trend of the field fractures and the Laramide regional shortening direction of 067° for the central Rocky Mountains (Erslev and Koenig, 2009).

The rose diagram for outcrop fractures shows a trend that is rotated 15° clockwise from the lineament rose diagram. Rotation of the outcrop fracture rose diagram by 15° counterclockwise gives a more visually similar orientation of fractures when compared to the GEP lineament rose diagram. This suggests that

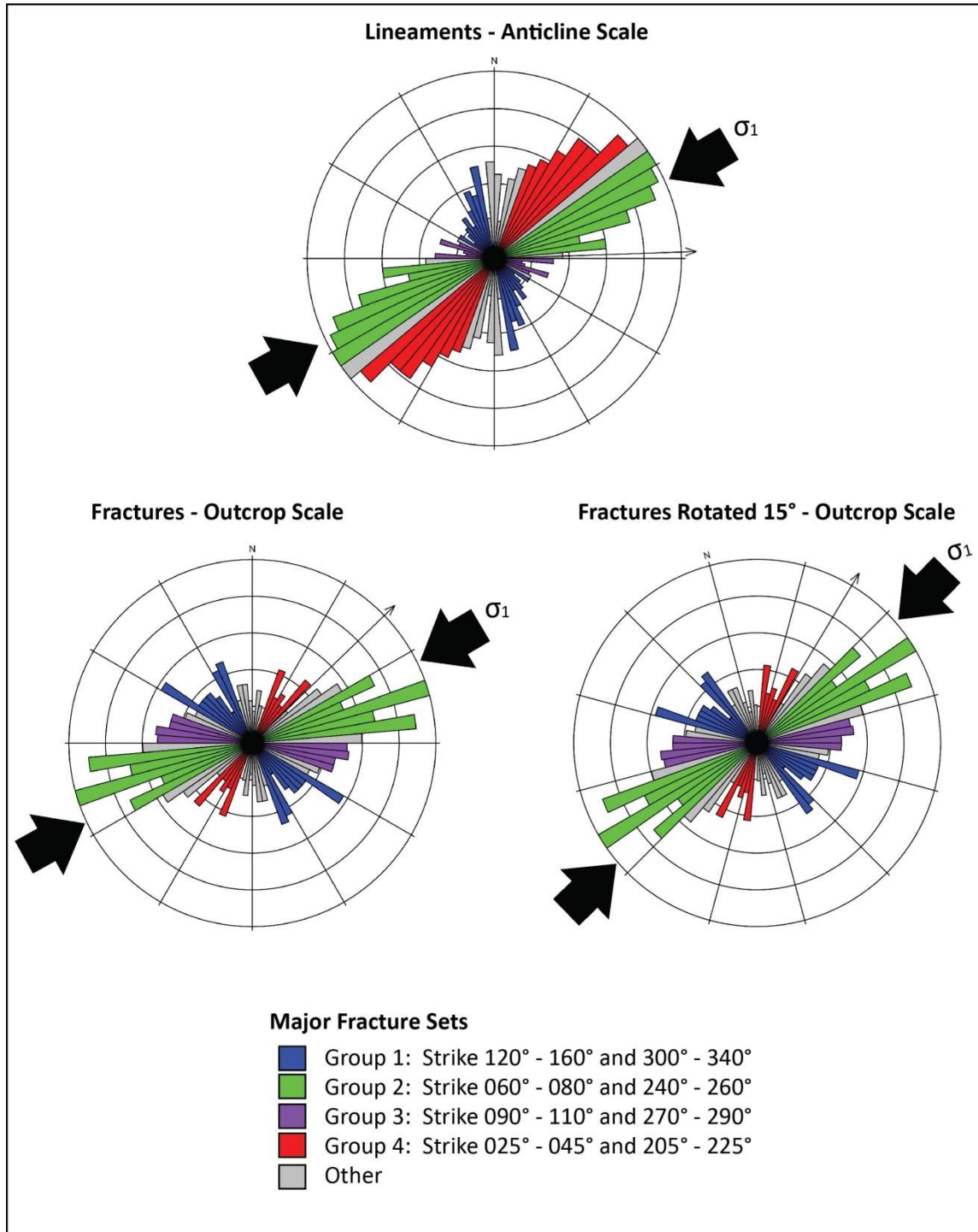


Figure 32. Rose diagram plots of orientation of lineaments mapped from Google Earth Pro aerial imagery of the anticline and fractures measured at the outcrop. A 15° rotation of the outcrop fracture data is included for comparison.

there may be an additional structural control on planes of weakness at the anticline, possibly due to structural grain formed during the Ancestral Rocky Mountain orogeny. Preexisting tectonic weaknesses may be reactivated and provide local control on deformation (Erslev and Koenig, 2009). Additionally, there may be differences in lineaments observed at the anticline scale (tens of km) versus the fractures that were measured at the outcrop scale. More importantly, although the recording of lineaments from aerial imagery provides an analysis that reflects an overall geometric compatibility with observations at outcrop scale, distinction in the lineament analysis cannot be made among lineaments related to structural, sedimentological, or geomorphological processes. GEP lineament analysis is a useful first step in understanding fracture geometry, but it must be ground-checked by field work over the same area in order to interpret the types of lineaments observed and to bolster the information with kinematic data on fracture and fault surfaces.

Proximal Fracture Studies in the Bighorn Basin

Comparison of observed fracture data with data from proximal outcrop-scale studies in the Bighorn Basin can lend further insight into regional fracture patterns. Recent fracture studies and geochemical research in the Bighorn Basin have focused on understanding basin-scale deformation history by analyzing individual Laramide-related basement-cored anticlines within the basin (e.g. Amrouch et al., 2010; Barbier et al., 2012; Beaudoin et al., 2013).

Bellahsen et al. (2006) focused on the northwest-southeast trending Sheep Mountain anticline, located southeast of Little Sheep Mountain anticline, and conducted a fracture analysis to constrain the kinematic evolution of the fold. They identified the formation sequence of four main fracture sets: 1) a set of pre-Laramide fractures oblique to the fold trend that were reactivated as reverse faults during late-stage fold growth; 2) early synkinematic Laramide fractures parallel to the shortening direction that formed prior to significant fold development; 3) synkinematic Laramide fractures perpendicular to the shortening direction; and 4) one set of vertical joints interpreted to have formed late in fold growth. The results of the Sheep Mountain fracture analysis tentatively fit with the fractures measured in the Little Sheep Mountain anticline. The inferred earliest formed fractures (Group 4) are oblique to the trend of the fold, and fractures that developed parallel to (Group 1 b-c) and perpendicular to (Group 2 a-c) the trend of the fold formed synkinematically during fold formation. Late-formed east-west trending bed-perpendicular fractures (Group 3) are oblique to the fold trend.

Beaudoin et al. (2012) used fracture and petrographical information to analyze the stress and strain evolution of Rattlesnake Mountain anticline, located 40 km southwest of Little Sheep Mountain anticline in the western part of the basin. Beaudoin et al. (2012) identified the formation sequence of six fracture sets at Rattlesnake Mountain: 1) three fracture sets that are interpreted to have formed due to Sevier deformation; 2) an early Laramide synkinematic bed-perpendicular fracture set that is parallel to the shortening direction; 3) a synkinematic Laramide

fracture set perpendicular to the shortening direction that formed due to layer curvature during folding; 4) a reactivated set of Sevier strike-faults and reverse faults that formed during late-stage fold tightening; and 5) a north-south trending group of fractures that are interpreted to have formed during post-Laramide extension that were only identified in the western part of the basin. The synkinematic Laramide fracture sets 2, 3, and 4 identified at Rattlesnake Mountain anticline generally correlate with fracture sets identified by Bellahsen et al (2006) at Sheep Mountain anticline and with fracture sets identified by this study at Little Sheep Mountain anticline.

Beaudoin et al. (2013) found that fracture sets identified at various anticlines throughout the basin varied by the position of the anticline within the basin. Using the fracture set nomenclature of Beaudoin et al. (2012), the 2013 study identified four fracture sets in Little Sheep Mountain anticline: 1) two sets associated with Sevier deformation; 2) the early Laramide synkinematic bed-perpendicular fracture set that parallels the compression direction; and 3) the synkinematic Laramide fracture set formed parallel to the trend of the fold. The variation in fracture sets among anticlines was attributed by Beaudoin et al. (2013) to regional variation between the eastern and western portions of the basin. Variation within anticlines in the eastern portion of the basin is likely due to differences in local preexisting weaknesses and the subsequent influence on deformation.

Sequence of Fracture Formation

Based on field observations of fracture attributes and comparison with fracture formation sequences identified in proximal fracture studies, a sequence of fracture formation was identified at Little Sheep Mountain anticline. Group 4 oblique shear fractures are interpreted to have formed early in fold formation. This is based on field cross-cutting relationships that demonstrate that all other fracture sets terminate at Group 4 fractures. Group 2 a-c fractures that are parallel to the direction of Laramide shortening are interpreted to have formed synkinematically with folding, prior to the formation of Group 1 b-c fractures, which are also synkinematic. Field evidence of Group 1 fractures terminating in a hooking pattern against Group 2 fractures indicates that Group 2 fractures were formed first. Both Bellahsen et al. (2006) and Beaudoin et al. (2012, 2013) interpreted fractures oriented parallel to the Laramide shortening direction to have formed earlier than those parallel to anticline fold trends in anticlines throughout the Bighorn Basin. Group 3 oblique fractures are commonly observed to terminate against Group 4 fractures in the field, suggesting that Group 3 fractures postdated Group 4 fractures. Field evidence does not offer clarification of the relationship of Group 3 fractures with Group 1 and 2 fractures, but comparison of Group 3 fractures with the fourth group of fractures identified by Bellahsen et al. (2006) shows some similarities between the two fracture sets. Both sets are bedding-oblique and oriented at $\sim 100^\circ$, oblique to the trend of both Sheep Mountain and Little Sheep Mountain anticlines.

Geochemical Characterization

The geochemical data indicate that the Madison Formation was affected by fluids of varying compositions and temperatures during diagenesis. Isotopic signatures of calcite vein fill precipitates and breccia are distinct from those of host rocks, and are also distinct from each other.

Host Rock

Mississippian marine seawater $\delta^{18}\text{O}$ values range from -4.80 to -3.00‰, which is depleted relative to modern marine carbonates ($\delta^{18}\text{O} = 0$ to 2.0‰) (Veizer et al., 1999). Mississippian carbonate host rock $\delta^{18}\text{O}$ values in this study were also depleted relative to modern carbonates ($\delta^{18}\text{O} = -6.93$ to 0.83‰) and similar to Mississippian seawater values, suggesting that these values have not been reset by diagenesis. Strontium isotope ratios also indicate that it was unlikely that Mississippian carbonate host rocks were reset by diagenetic fluids since they fall within the range of lower Mississippian seawater values (Figure 16). The narrow range of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values indicates that early diagenesis of host rocks was controlled by a rock-buffered system in which fluids did not move freely throughout the system (Katz et al., 2006). This indicates a closed diagenetic system at thermal equilibrium with standard geothermal gradients. Dolomite $\delta^{18}\text{O}$ values are enriched compared to limestone host rock values in the Madison and Mississippian marine seawater, suggesting that these dolomites were derived from fluids enriched in ^{18}O relative to the fluids from which the limestones were derived.

Phanerozoic values of $\delta^{13}\text{C}$ have been identified as -0.99 to 2.11‰ for marine fluids and -7.68 to -2.18‰ for non-marine fluids (Ripperdan, 2001). Host rock $\delta^{13}\text{C}$ values in this study were between -1.61 and 1.30‰. The range of Mississippian $\delta^{13}\text{C}$ marine values is between 2.00 and 5.00‰ (Ripperdan, 2001). The $\delta^{13}\text{C}$ values for this study were slightly depleted relative to Mississippian values, but still fall close to the values for Phanerozoic seawater. Thus, $\delta^{13}\text{C}$ values confirm that the host rock carbonates are from marine origins.

Breccia and Vein Fill

Stable isotope signatures of vein fill and hydrothermal breccia samples are distinct from the respective host rocks (Figure 33). Both breccia and vein fill material are significantly depleted in $\delta^{18}\text{O}$ compared to Madison host rocks. This indicates that fluids with elevated temperatures were present during formation. Hydrothermal breccia in the Madison Formation are more enriched in $\delta^{18}\text{O}$ than calcite vein fill material. This indicates that calcite vein fill was derived from a significantly more depleted fluid than the calcite cement in the breccia and precipitated at a higher temperature (Katz et al., 2006).

Carbon and oxygen isotopes are controlled by the variation in isotopic composition of source carbonates and fluids that precipitate the late-stage calcite in veins and breccia, as well as by the temperature at which the cement precipitates, which controls the fractionation of these isotopes (Faure, 1998). The large range of vein fill and breccia $\delta^{18}\text{O}$ values suggests that the late-stage calcite cements derived from fluids of varying compositions and temperatures. The fluids involved were

likely a mix of meteoric recharge and subsurface hydrothermal brines (Katz et al., 2006). The meteoric recharge fluids probably infiltrated during Laramide times during fracturing related to fold growth. The large range in $\delta^{18}\text{O}$ values also suggests that the vein fill precipitated in a water-dominated, open diagenetic system.

Vein fill and breccia $\delta^{13}\text{C}$ values have a much more limited range and overlap between Phanerozoic marine and non-marine $\delta^{13}\text{C}$ values. The similarity in sample $\delta^{13}\text{C}$ values is attributed to the similarity in structural setting and carbon source at Little Sheep Mountain anticline for all samples in this study. Late-stage calcite in veins and breccia sampled in this study precipitated in equilibrium with CO_2 produced from the dissolution of the host rock carbonate by meteoric water mixed with hydrothermal brines in the subsurface (Katz et al., 2006). While temperature played a role in $\delta^{13}\text{C}$ fractionation, the low variation in $\delta^{13}\text{C}$ values reflects the primary contribution of the Madison host carbonates of Little Sheep Mountain anticline to the stable carbon isotope ratios.

Calcite vein fill and breccia reveal a wide range of $\delta^{18}\text{O}$ values, indicating that fluid flow did not occur simultaneously through all fractures with a single fluid temperature and composition. Katz et al. (2006) suggests episodic earthquakes during Laramide time as an explanation for a wide range of $\delta^{18}\text{O}$ values seen in calcium carbonate vein fill in the Madison Formation. Each rupture event would have injected fluid into fractures in the Madison Limestone with variable temperatures and variable $\delta^{18}\text{O}$ values, but with low variance in $\delta^{13}\text{C}$ values. The anticline is cored by a basement-involved fault, which is interpreted to be a conduit

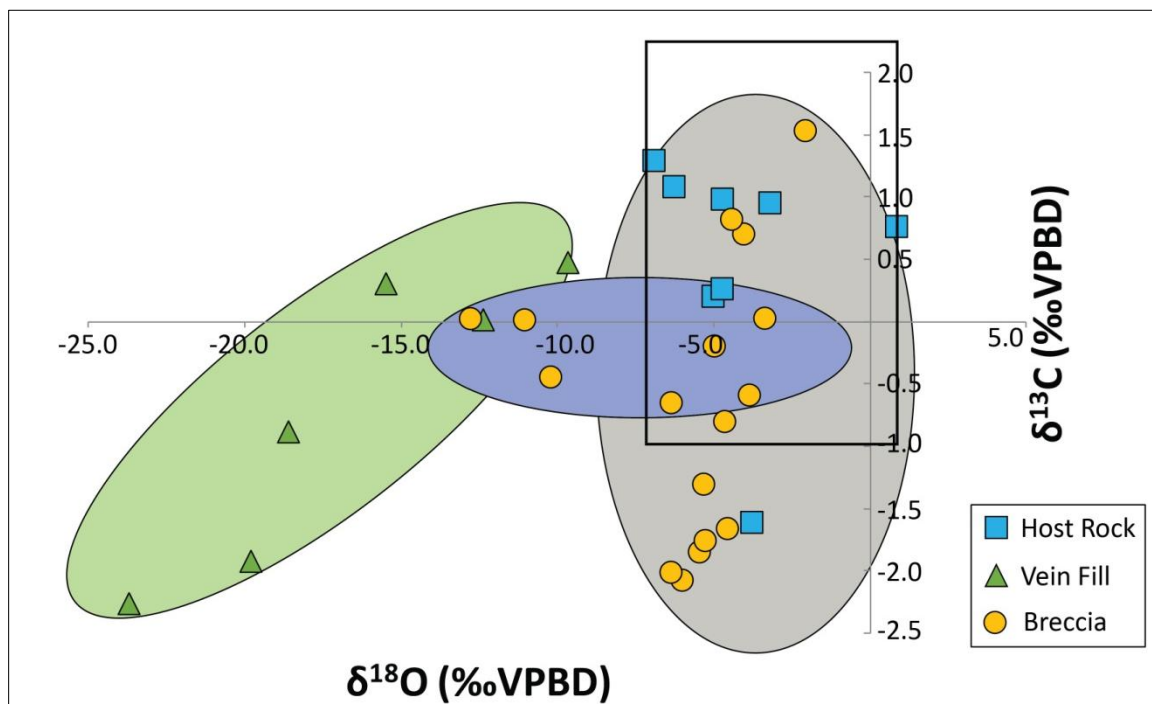


Figure 33. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ isotopic values for host rocks, vein fill, and breccias in Little Sheep Mountain Anticline. The Mississippian Madison limestone (Mm) isotopic range in the Bighorn Basin is reported after Katz et al. (2006). Green circle on left indicates trend of vein fill values; grey circle on right indicates trend of collapse breccia values. Blue circle at center indicates hydrothermal breccia samples. All values expressed in ‰ Vienna Pee Dee Belemnite (‰VPDB). Error for $\delta^{18}\text{O}$ values is $\pm 0.04\text{‰}$, error for $\delta^{13}\text{C}$ values is $\pm 0.04\text{‰}$, based on NBS 19 Standard.

for vertical migration of fluids from basement rocks to the Madison Formation during episodes of tectonic activity (Smith and Davies, 2006). The strontium isotope values of breccia and vein fill material in this study were 0.7093 and 0.7094, which are slightly higher than the Madison seawater values of 0.7075-0.7085. This suggests that fluids incorporated strontium isotopes from circulation with high-Rb basement rocks such as granites, Precambrian gneisses, or continental crust, which range from 0.7120-0.7300 (Katz et al., 2006). The basement-derived fluids were then mixed with meteoric waters of low radiogenic signature.

Breccia from the Lower Kane Cave falls out separately from the Upper Kane Cave breccia and the rest of the breccia $\delta^{18}\text{O}$ values. The Lower Kane Cave is still undergoing cave formation and is currently affected by hydrothermal processes, but it is more depleted in $\delta^{18}\text{O}$ than breccia in the Madison Formation and modern carbonate values. This may be due to the composition of hydrothermal fluids currently circulating in the cave, which may be relatively depleted due to interaction with meteoric waters and carbonates and calcite cements in the anticline. The Upper Kane Cave plots close to the Madison breccia $\delta^{18}\text{O}$ values, even though there is still fluid flow within the cave.

The solubility of carbonate material decreases with increasing temperature, thus precipitation of carbonate material may not be related to the cooling of hydrothermal fluids within a closed system (Faure, 1998). An open system is required in order to facilitate CO_2 degassing, fluid mixing, and fluid-rock fractionation processes to precipitate carbonate materials. Earthquake rupturing can initiate hydrothermal fluid movement and large pressure changes, causing CO_2 effervescence and leading to rapid hydrothermal cementation (Katz et al., 2006; Sibson, 1985).

Proximal Geochemical Characterizations in the Bighorn Basin

Katz et al. (2006) investigated the geochemical characteristics of fluids related to hydrothermal breccia in the Madison Formation of the Bighorn Basin and surrounding uplifts. Stable isotope values combined with fluid inclusion analysis of late-stage calcite vein fill indicate that fluids between 120 and 180°C precipitated

the vein fill. Vein fill strontium isotope values indicate that hydrothermal brines circulated in contact with radiogenic basement rocks and subsequently mixed with formational fluids in sedimentary cover rocks while circulating through fracture networks within the basin. The depletion of $\delta^{18}\text{O}$ values in vein fill the Madison corroborates the mixture of basement-derived hydrothermal brines and meteoric waters. Similar geochemical results in Sheep Mountain anticline (Beaudoin et al., 2011) and Little Sheep Mountain anticline (this study) indicate that mixed radiogenic hydrothermal fluids and formational waters precipitated vein fill with isotopic compositions depleted in $\delta^{18}\text{O}$ relative to Mississippian seawater.

Beaudoin et al. (2013) used stable oxygen and carbon isotopes and strontium isotope analyses to investigate the paleohydrological evolution of the Bighorn Basin, and suggested that episodic pulses of radiogenic, basement-derived fluids migrated upward from basement rocks to sedimentary cover rocks. These radiogenic basement-derived fluids migrated eastward on a basin-scale and mixed with formational fluids, diluting the radiogenic signature of fluids in eastern anticlines. Three pulses were identified prior to, during, and after Laramide deformation. Synkinematic fracture formation is attributed to the migration of the fluids, particularly in relationship to the latest hydrothermal fluid migration pulse. The high variation in $\delta^{18}\text{O}$ values reported across Little Sheep Mountain anticline in this study agrees with the scenario of hydrofracturing during episodic earthquake ruptures providing a control on fluid migration within the anticline.

Breccia

Breccia in the Bighorn River cut of the Little Sheep Mountain anticline were primarily identified as collapse breccia or hydrothermal breccia pipes. Collapse breccia in the Madison Formation are primarily solution collapse chaotic breccia capped with paleokarst cavities related to karsting on the tops of depositional sequences within the Madison Formation that formed during the Mississippian or Pennsylvanian periods (Sonnenfeld, 1996). All hydrothermal breccia bodies identified were located on the backlimb of Little Sheep Mountain anticline, which is the hanging wall of the fault; the structural location associated with hydrothermal breccia formation (Laznicka, 1988).

Hydrothermal is used here to refer to a system characterized by saline aqueous solutions that are at a higher temperature (at least 5°C higher) and pressure than the ambient conditions within the host rock (Smith and Davies, 2006). Hydrothermal diagenesis often occurs at relatively shallow burial depths of less than 1000 m with the rapid introduction of fluids under much higher pressure and temperature conditions (Davies and Smith, 2006). Hydrothermal breccia develops due to the formation of vertical, fluid-filled tension fractures during hydraulic fracturing associated with hydrothermal solutions (Phillips, 1972; Jébrak, 1997). A slow build up of differential stress within a host rock occurs until critical stress conditions are reached. Shear failure along a normal or thrust fault creates an abrupt fracturing which results in a temporary reduction in pore fluid pressure that

allows high pressure fluids to permeate the fracture and propagate it some distance (Phillips, 1972).

With each subsequent rupture, the thermal buoyancy of the fluids initiates hydrofracturing at the fracture tip, extending the fault in a vertical direction, resulting in vertical breccia pipes and hydrothermal alteration generally confined to the hanging wall of faults (Phillips, 1972). The temporary drop in fluid pressure as the fracture propagates causes the adjacent rock permeated by hydrothermal solution to break and form angular breccia. As fluids progressively permeate into the fault tip, they preferentially fill rock pore space peripheral to the fault, often resulting in a zone of alteration or mineralization. Factors controlling the size and extent of the zone of mineralization include the stress acting on the fault, the properties of the damage zone, and the porosity and permeability of the carbonate rock (Phillips, 1972). Once the fault fails, the abrupt drop in pressure and loss of CO₂ by effervescence drives brecciation (Davies and Smith, 2006). This cycle repeats as episodic fault reactivation continues and can result in polygenic breccia related to multiple phases of tectonic activity and hydrothermal fluid-flow events (Lopez-Horgue et al., 2010).

Hydrothermal activity within seismically active compressional regimes is enhanced due to crustal thickening, maintaining suprahydrostatic pressure gradients (Katz et al., 2006). Active faults have been identified as the mechanism and conduit of rapid migration of high temperature and high pressure fluids into reservoir units. Basement-involved faults such as the fault interpreted to underlie

Little Sheep Mountain anticline provide conduits for higher temperature, overpressured fluids from deeper sources (Smith and Davies, 2006). Hydrothermal fluid movement is initiated by rupturing during earthquake activity, causing CO₂ effervescence during large pressure changes (Katz et al., 2006). Following large changes in pressure, rapid hydrothermal cementation occurs, leading to brecciation (Sibson, 1985).

Among all types of breccia identified in this study, chaotic breccia fabric is the most common. Chaotic fabric in solution collapse and paleokarst collapse breccia indicates spalling from fracture walls into solution cavities. Many collapse breccia identified in this study are bed-parallel or stratabound and are not associated with a particular fracture set. Collapse breccia in the anticline are often capped by cavities that likely formed due to dissolution or karsting. These cavities may have formed prior to or during Laramide deformation due to collapse of lithified beds into solution cavities, and are most likely modified by later weathering processes that enhanced the paleocavities after exposure. Unlithified collapse breccia bodies are also likely modified by Laramide deformation and later exposure due to incision of the anticline by the Bighorn River. Collapse breccia are apparently randomly distributed in the backlimb, with some bodies clustered together and some more widely spaced. A more thorough examination of the lateral extent of breccia bodies in Little Sheep Mountain anticline would be necessary to improve understanding of the spatial distribution of breccia in the anticline.

Hydrothermal chaotic breccia fabrics indicate continued movement of brecciated fragments after initial fracturing of the host rock. This type of fabric may be dilational and is attributed to isothermal effervescence of CO₂, which causes forceful brecciation of host rocks (Laznicka, 1988). Isothermal effervescence is induced by rapid ascent of CO₂-charged waters, which causes a rapid volume expansion of the fluid that hydraulically fractures the surrounding wall rock (Katz et al., 2006). The rapid rise of the fluid can entrain and transport brecciated fragments, and may be followed by rapid calcite precipitation into the voids (Simmons and Christenson, 1994).

The regional distribution of hydrothermal breccia and associated fractures in the backlimb of the anticline has implications for understanding lateral variability of structurally-controlled fluid conduits and variations in the geochemistry of pore fluids within the anticline (Katz et al., 2006). The relatively close proximity of hydrothermal breccia bodies in outcrop suggests that they may be genetically related, and may have formed from the same fluid system. These breccia bodies likely formed in association with folding during Laramide deformation. Group 1 (b-c) and 3 (oblique) fractures are associated with hydrothermal breccia bodies in the anticline, and Group 3 fractures are associated with the Kane Cave system, suggesting that these fracture sets exert control on fluid flow in the hanging wall of the fault. Group 3 fractures may be related to preexisting tectonic weaknesses related to the Ancestral Rocky Mountain orogeny that were reactivated by Laramide shortening, providing a permeability network to facilitate ascent of hydrothermal

fluids and karst formation. A more thorough analysis of the lateral extent of hydrothermal breccia would be needed to elucidate the clustering of breccia bodies across the anticline.

Several breccia stations exhibited evidence of multiple episodes of brecciation, including multiple lobes in close proximity, which may represent different pulses of brecciation. Distinct morphologies of adjacent lobes of breccia bodies are determined by sharp contacts exhibiting leaching or color differences and by fractures which bound the brecciated zones. Variation in $\delta^{18}\text{O}$ values measured in adjacent hydrothermal breccia lobes or bodies sampled in LSMB06 and LSMB07 was as great as $\pm 6.40\text{‰}$, which suggests that hydrothermal fluids of variable compositions were responsible for the formation of each lobe. This could indicate multiple pulses of hydrothermal brecciation at episodic intervals.

Thermal and non-thermal springs discharge where the Bighorn River cuts through the Little Sheep Mountain anticline and have led to the formation of caves in the soluble carbonate rocks of the Madison Limestone (Engel et al., 2004; Stock et al., 2006). The Lower and Upper Kane Caves of Little Sheep Mountain anticline are larger examples of these caves. The Upper Kane Cave is likely an earlier phase of the Kane Cave system, representing paleokarst development when the Bighorn River was at a higher level, while the Lower Kane Cave is actively forming adjacent to the current level of the river (Stock et al., 2006). Within the Lower Kane Cave there are presently four springs discharging into the Lower Kane Cave phreatic passage, at least one of which follows a large, open fracture within the cave that strikes east-



Figure 34. Photo of brown calcite accumulation on south wall of Upper Kane Cave. Precipitation from water seeping down into cave from fractures in ceiling. Calcite precipitation indicates circulation of calcite-rich hydrothermal fluids within the Kane Cave system. Brown is likely due to presence of impurities. White mineral is gypsum. Photo by Anita Moore-Nall.

west (Engel, 2004). Several faults with measurable offset occur perpendicular to this fracture, and correspond to spring outlets (Engel, 2004). Calcite has precipitated in the walls of both Kane Caves, indicating the circulation of calcite-rich hydrothermal fluids (Figure 34). Group 3 fractures, and possible faults parallel to the orientation of Group 3, are associated with the Kane Cave system. The presence of several thermal, sulfidic springs in Little Sheep Mountain combined with the flow of groundwater within Paleozoic aquifers parallel to the axis of the anticline suggests

that circulation of hydrothermal fluids is still occurring and may have been continuously active since the Laramide orogeny (Spencer, 1986). Structural analysis of the Kane Cave system would further elucidate the relationship of Group 3 fractures to the fluid system in the anticline.

Breccia in the backlimb are generally more depleted in $\delta^{18}\text{O}$ relative to Mississippian seawater values and limestone and dolomite host rock in the backlimb. In general, limestone breccia are more depleted in $\delta^{18}\text{O}$, while dolomite breccia samples are closer to Mississippian seawater values. Hydrothermal breccia are generally more depleted in $\delta^{18}\text{O}$ with respect to collapse breccia, although a larger sample size of hydrothermal breccia would be necessary to confirm this trend. The vein fill materials in host rocks associated with all breccia stations are depleted in $\delta^{18}\text{O}$ relative to Mississippian seawater and carbonate host rock throughout the Bighorn River cut. Lateral variation of breccia across the Bighorn River cut of Little Sheep Mountain anticline is related to geochemical variability in subsurface fluids within the anticline, and multiple phases of fluid flow within the fracture system of the anticline.

The morphology and geochemistry of breccia suggest that brecciation was episodic and caused by the explosive injection of hydrothermal fluids into strata. It is likely that undersaturated meteoric waters migrated into the burial environment and incorporated dissolved calcium carbonate from the surrounding host rock. Once the meteoric fluids reached the burial environment, they were heated and mixed with hypersaline brines that circulated in contact with deeply buried radiogenic

basement rocks. Tectonic activity due to Laramide shortening forced fluid migration along the basement-cored thrust fault as overpressured injections into the Madison Formation. Fluid injection opened hydrofracture pathways in an irregular and unpredictable subvertical pattern and hydrothermal brecciation exploited preexisting weaknesses in the structural grain and collapse breccia and used them as conduits for fluid migration. The calcite cement in hydrofractures and breccia precipitated rapidly during pressure release due to earthquake rupturing and brecciation in the host rock (Katz et al., 2006).

Petrography

Petrographic examination of rock samples indicates a complex late-stage diagenetic history, including brittle deformation, hydrocarbon migration, host-rock dissolution, brecciation, and late-stage calcite cementation of the Mississippian Madison Formation. Fractures at the microscale provide an important control the episodic migration of fluids within the host rock by creating fluid migration pathways. Episodic fluid migration alternately enhanced and degraded reservoir quality of rocks. Dissolution and dolomitization enhanced porosity, while calcite cementation reduced fracture and matrix porosity.

Early diagenetic processes such as compaction, cementation, and suturing of grains led to a decrease in primary porosity in Madison carbonates of the Little Sheep Mountain anticline. Micritic linings around ooids and peloidal grains in the limestone wall rock indicate early marine diagenesis and are the oldest features observed in thin section (Figure 35a,b). Early diagenetic dolomitization led to

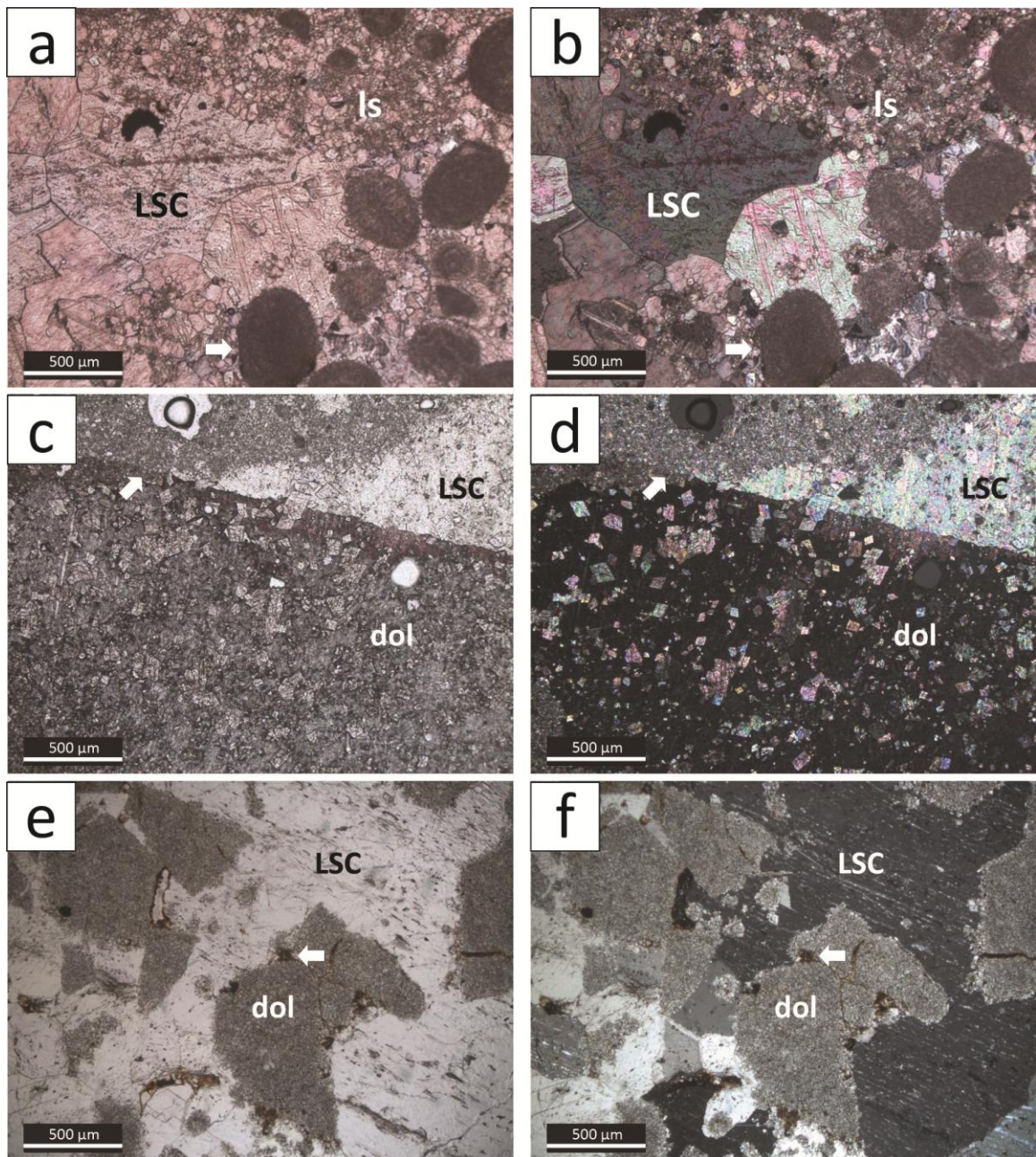


Figure 35.

Figure 35. (Previous page). Thin section photomicrographs showing diagenetic features observed in limestone host rock and breccia samples of Madison Formation. (a) Peloids with rims of isopachous calcite cements (arrow) surrounded by fine crystalline limestone (ls) and late-stage calcite (LSC) crystals. Host rock from Upper Kane Cave. Plane-polarized light. (b) Same image, crossed polars. (c) Dolomite crystalline matrix and LSC. Distinction between dolomite and calcite is highly visible at line between stained portion and unstained portion of slide (arrow). Chaotic hydrothermal breccia. Plane-polarized light. (d) Same image, crossed polars. (e) Fractured micritic dolomite clasts in matrix of LSC with minor bitumen residue along rims and lining some fractures (arrow). Chaotic hydrothermal breccia. Plane polarized light. (f) Same image, crossed polars.

compartmentalization based on facies, and host rock dolomitization is generally fine crystalline (Figure 35c,d). During extensive solution collapse brecciation along sequence boundaries in the Madison, secondary in-situ dissolution and matrix dolomitization may have led to an increase in intercrystalline porosity (Figure 35e,f). The coarse, blocky anhedral to subhedral calcite cements commonly seen in limestone clasts and brecciated samples are generally associated with late-diagenetic processes. Porosity calculations using ImageJ suggest that porosity of limestone clasts increased more than the porosity of brecciated samples. This is in agreement with the abundance of late-stage calcite filling fractures and occluding pores observed in thin sections of brecciated rock.

Fractures in thin section are characterized by complex cross-cutting relationships and multiple types and generations of cementation. Anhedral crystals are indication that crystal growth began in an open void that was later overprinted with fracture sealing (Laubach, 2003). Anhedral calcite crystals are often found in bridges sealing fractures and lining fracture walls in layers. Euhedral crystals are

less common, but euhedral dolomite crystals are commonly found filling larger void spaces. Precipitation of calcite cements occurs more rapidly on broken surfaces than on euhedral surfaces (Hooker et al., 2012). This implies that bridges likely formed preferentially on anhedral surfaces along fracture walls. Carbonate cement bridges along fractures act to seal the fractures and decrease the secondary porosity originally produced by brecciation and fracturing.

The presence of saddle dolomite, with curved crystal surfaces and undulose extinction in cross-polarized light, as well as sulfide mineralization, indicates that an episode of hydrothermal fluid migration affected breccia. Sulfide mineralization is primarily associated with intercrystalline porosity and late-stage calcite veins. Residual bitumen is common along fracture walls and in intercrystalline porosity of dolomitic micrite facies, and indicates that fractures influenced the migration and accumulation of hydrocarbons within the anticline (Figure 35e). Hydrocarbon residue is less common in limestone facies, and is primarily associated with fractures. Multiple generations of cements filling fractures indicate that there were many pulses of fluid migration associated with episodic deformation in the anticline. Hydrothermal fluid systems are characterized by dynamic processes involving deformation and fluid migration. Episodic fluid flow responds to abrupt changes in pore fluid pressure and applied stress in response to fluctuations in seismic processes that control fault zone permeability (Davies and Smith, 2006).

Late-stage calcite crystals seen in thin section often exhibit twinning and undulose extinction. These features represent fracturing events possibly related to

faulting (Beaudoin et al., 2013). Precipitation of coarse, blocky late-stage calcite cement during episodic tectonic-hydrothermal activity ultimately reduces the porosity and permeability of reservoir quality in carbonate rocks by compartmentalizing horizontal flow units (Katz et al., 2006). The preexisting fracture, intercrystalline, and vuggy porosity is occluded by calcite cementation, reducing the secondary porosity. Unsealed fractures are important in determining reservoir quality, and linked, open fractures reduce facies-dependent vertical compartmentalization. Multiple cementation events related to hydrothermal brecciation indicate an extended deformation period, which may have helped to maintain permeability networks. Fractures seen in outcrop are generally open and may have been affected by recent meteoric dissolution, but the majority of fractures observed in thin section were filled by late-stage calcite.

The history of fluid migration and late-stage diagenesis within the Madison Formation of Little Sheep Mountain anticline is complex, involving overprinting of deformation and brecciation textures as well as complex dissolution and cementation. Structurally controlled, late-stage diagenesis within the formation was facilitated by permeability networks that formed due to pervasive deformation in the anticline. The random distribution of brecciated bodies sampled in thin section suggests lateral variation in hydrothermal fluid flow throughout the anticline that was primarily confined to the backlimb.

Early diagenesis of Madison carbonates created intercrystalline porosity via dissolution and dolomitization which enhanced the reservoir quality of this unit.

Permeability networks formed due to fracturing and further enhanced the porosity and permeability of the rock. This fracture network reduced vertical compartmentalization of the formation and allowed for fluid migration of hydrothermal saline brines and hydrocarbons within the Madison. Deformation associated with Laramide shortening led to continued episodic fracturing which helped to maintain permeability networks, and episodic fluid flow controlled late-stage diagenesis along these networks. Late-stage coarse, blocky calcite cements reduced the porosity and permeability of the Madison by sealing fractures and filling pore spaces.

The presence of sulfides in thin section and outcrop indicate that acidic hydrothermal fluids enriched in H_2S or CO_2 migrated through the anticline. The presence of hydrothermal breccia pipes and chaotic breccia textures suggests that hydrothermal fluids enriched with CO_2 were involved in the late-stage diagenesis of the Madison Formation. Isothermal effervescence of CO_2 can lead to hydrofracturing of host rock from fracture walls and rapid transport of fragments upsection. This process often forms vertical to sub-vertical pipe morphology of brecciated bodies. Effervescence may also lead to rapid precipitation of coarse calcite cements that reduce porosity (Katz et al, 2006).

CONCLUSIONS

Little Sheep Mountain anticline has undergone extensive fracturing and deformation due to shortening associated with the Laramide orogeny. Systematic fracture sets identified in the anticline have geometric configurations associated with faulting and folding. The geometry of the fracture network has controlled the migration of hydrothermal fluids through the anticline and late-stage diagenesis in Madison reservoir rocks. Four major findings provide new insight into the relationship between fracture networks and subsurface paleofluid migration:

(1) *What is the geometry of fracture networks at Little Sheep Mountain anticline and how does the fracture pattern and distribution compare to other similar anticlines in the Bighorn Basin?* Determination of the fracture geometry and observations of field fracture attributes at Little Sheep Mountain anticline provides a tentative fracture formation sequence. The earliest formed fracture set identified in Little Sheep Mountain anticline (Group 4) is also the least common fracture set identified in outcrop. Slickenlines associated with these fractures suggest that they are shear mode II or mode III fractures. Group 4 fractures lie oblique to the trend of Laramide shortening. A fracture set formed parallel to the Laramide shortening direction (Group 2 a-c) is associated with plunge-parallel extension and is most common in the backlimb of the fold. These mode I tensional fractures facilitated fluid flow parallel to the overall tectonic shortening direction. The dominant fracture set (Group 1 b-c) consists of cross-cutting, bed-perpendicular fractures that formed orthogonally to the trend of the anticline and are interpreted as mode I

tensional fractures. This set is prominent in the forelimb and along the hinge area, and formed in response to outer arc extension during folding. The final fracture set (Group 3) is a group of east-west trending fractures oblique to the direction of Laramide shortening that are interpreted to have formed during later Laramide deformation. These mode I fractures are most common in the plunging anticlinal nose. They form oblique to bedding and cut through bedding in outcrop.

Fracture set geometry identified by other authors varied among individual anticlines in the Bighorn Basin with respect to orientation; however, Group 1 b-c and Group 2 a-c fractures were correlated across the basin (Beaudoin et al., 2013; Bellahsen et al., 2006). This is reasonable considering that these fractures are perpendicular and parallel to the primary Laramide shortening direction, which acted across the entire basin. The variation in fracture sets seen in other anticlines examined in the basin is most likely due to local variations in deformation caused by preexisting weaknesses and differences in local stress fields at each locality (Erslev and Koenig, 2009). The similarity of fracture systems at Little Sheep Mountain and Sheep Mountain confirms that fracture systems in the eastern portion of the basin can be correlated, and this similarity is attributed to the proximity of the anticlines and the similarity in local stress fields. Characterization of the fracture system at Little Sheep Mountain anticline contributes to the existing fracture data available for anticlines in the Bighorn Basin and can be used in understanding fracture systems across the basin.

(2) *How did the fracture networks of Little Sheep Mountain anticline affect the migration and types of fluids within the structure?* Fracture permeability networks formed at Little Sheep Mountain anticline facilitated focused fluid flow throughout the anticline. Group 2 (a-c) fractures allowed fluid migration parallel to the Laramide shortening direction, while Group 1 (b-c) fractures facilitated fluid flow parallel to the trend of the anticline. Group 1 fractures also would have allowed fluids to flow into and accumulate along the strike of structural highs. These groups were likely the primary fracture sets facilitating fluid flow in the anticline. They were the most common, with large apertures and the greatest lengths. Modern fluid flow in the Kane Cave system is facilitated by Group 3 oblique fractures, and hydrothermal breccia bodies are associated with Group 1 and Group 3 fractures. The distribution of hydrothermal breccia bodies in the backlimb is clustered, and no hydrothermal breccia bodies have been identified in the forelimb. This suggests that the geometry of the underlying fault confines hydrothermal fluid flow within the hanging wall. Group 4 oblique fractures exhibited evidence of shear movement. Shearing can increase dilational strain and enhance fluid migration pathways through these fractures.

Episodic earthquake rupturing due to tectonic activity led to the formation of hydrofracture permeability networks, creating anisotropy in fluid flow systems, localized zones of alteration, and focused fluid flow conduits. Focused conduits can conduct hydrothermal fluids from deeper basement areas upwards into the subsurface. There is a clear tectonic control over late-stage calcite precipitation

associated with late-stage diagenesis in the Madison Formation of Little Sheep Mountain anticline. Hydrothermal fluids were responsible for enhancing structurally-controlled conduits during fracturing, dolomitization, and brecciation.

Petrographic analysis indicates that fractures served as fluid conduits at both the outcrop and the microscopic scale in the Madison Formation. Evidence of saddle dolomite and sulfides in thin sections suggest that low-temperature hydrothermal fluids migrated within the fracture network. Geochemical evidence indicates that these hydrothermal fluids had variable compositions, which suggests that meteoric fluids mixed with subsurface basin fluids, including those that contacted radiogenic basement rocks. Fracture network geometry and the southwest-dipping thrust fault that cores Little Sheep Mountain likely allowed hydrothermal fluids to circulate in contact with high-Rb basement granites and gneisses.

(3) *Did breccia pipes preferentially form along certain fracture sets?* The fracture system in Little Sheep Mountain anticline facilitated focused fluid flow through the anticline by the linking and interaction of systematic fracture sets. Group 1 b-c and Group 3 oblique fractures are associated with hydrothermal breccia pipes in outcrop in the backlimb, indicating that these fractures exerted control on the upward migration of hydrothermal fluids. Group 1 fractures allowed fluid migration parallel to the trend of the anticline and the accumulation of fluids in structural highs, and Group 3 fractures are associated with karsting in the anticline. Breccia pipes utilized preexisting weaknesses associated with fractures, paleokarsts and solution collapse breccias, primarily controlled by east-west striking Group 3

fractures, to escape upward in the anticline. Brecciation associated with tectonic deformation and fracturing has created secondary porosity and permeability in the Madison, and reduced the vertical compartmentalization of alternating carbonate reservoirs within the formation.

(4) *Has hydrothermal diagenesis near breccia pipes affected porosity of reservoir rocks?* Fracturing associated with the development of Little Sheep Mountain anticline created conduits for fluid migration, increased vertical connectivity of the Madison Formation, and enhanced the secondary of reservoir rocks. Carbonate cements, secondary mineralization, and dissolution within the Madison suggest that fractures exerted a primary control on late-stage diagenetic alteration during episodic fluid migration in the anticline. Fluids migrating in contact with Madison carbonates included low-temperature hydrothermal fluids and hydrocarbons.

Subsurface fluids of variable compositions were responsible for late diagenetic alteration of Madison carbonates. These fluids were transported through the anticline in episodic events. As a result, fluid composition may have evolved over time as a result of mixing of formational fluids and hydrothermal brines and fluid-rock interactions, forming a complex suite of diagenetic minerals, dissolution and replacement textures. Episodic fluid migration through the anticline precipitated late-stage calcite, which fills pores and seals fractures in thin section. This reduced secondary porosity in the Madison Formation created by dolomitization, fracturing,

and brecciation. This led to a reduction in pore space as well as a decrease in the aperture and length of fractures.

When porosity of unaltered limestone host rock was quantitatively compared to limestone clasts and breccia that demonstrated diagenetic features in thin section, the porosity increase in the clasts was higher than in the breccia samples. This indicates that porosity of limestone clasts increased due to late-stage diagenesis due to hydrothermal fluids more than the porosity of brecciated samples.

Early diagenesis enhanced the porosity of the Madison Formation via dissolution and dolomitization, while compaction and cementation reduced porosity. Fracturing during Laramide deformation enhanced the porosity and permeability and also led to hydrothermal fluid migration through the fracture network. Late-stage diagenesis due to hydrothermal fluid migration led to abundant late-stage calcite precipitation in fractures and pores, reducing the secondary porosity of reservoir rocks.

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APPENDICES

APPENDIX A

FIELD FRACTURE DATA

Appendix A contains all of the fracture data collected in the field. MM = Mississippian Madison Formation, MPA = Mississippian-Pennsylvanian Amsden Formation, PG = Permian Goose Egg Formation, TC = Triassic Chugwater Formation, JS = Jurassic Sundance Formation.

Fracture Station	Fracture Group	Strike	Dip	Length (m)	Aperture (mm)	Spacing (cm)	Structural Domain	Lithology	Vein Fill Index
L001		195	58	0.065	15		FW	PG	0
L001		172	54	0.14	20		FW	PG	0
L001		238	60	0.9	20		FW	PG	0
L001		024	70	0.14	5		FW	PG	0
L001	4	208	52	0.29	25		FW	PG	0
L001	4	034	18	0.2	10		FW	PG	0
L001		184	28	0.5	15		FW	PG	0
L001		050	28	0.67	20		FW	PG	0
L001	1	308	56	0.22	10		FW	PG	0
L001	1	160	18	0.5	20		FW	PG	0
L001		174	40	0.55	5		FW	PG	0
L001	1	157	49	0.14	1		FW	PG	0
L001	1	156	49	0.24	10		FW	PG	0
L001		353	60	0.27	10		FW	PG	0
L001		170	26	0.3	8		FW	PG	0
L001	1	158	34	0.3	20		FW	PG	0
L001	1	155	31	0.33	30		FW	PG	0
L001		162	56	0.3	20		FW	PG	0

L001	1	146	70	0.61	20		FW	PG	0
L001	1	139	60	0.54	15		FW	PG	0
L001	1	139	63	0.54	25		FW	PG	0
L001	1	160	80	0.25	5		FW	PG	0
L001	1	122	37	0.28	5		FW	PG	0
L001	1	152	50	0.4	5		FW	PG	0
L001	1	140	65	0.1	15		FW	PG	0
L001	1	142	58	0.19	10	10	FW	PG	0
L001	1	150	43	0.26	10	10	FW	PG	0
L001	1	144	80	0.15	15	10	FW	PG	0
L001	1	146	52	0.14	15	10	FW	PG	0
L001	1	124	66	0.16	30		FW	PG	0
L001	3	100	60	0.4	10		FW	PG	0
L001	2	074	56	0.86	10		FW	PG	0
L001	2	070	58	0.75	10		FW	PG	0
L001	2	076	63	1	10		FW	PG	0
L001	4	219	56	0.15	15		FW	PG	0
L001	3	283	53	0.22	30		FW	PG	0
L001		088	55	1.1	10		FW	PG	0
L001		082	58	0.6	20		FW	PG	0
L002	3	100	63	0.6	20		FW	PG	0
L002	4	042	46	0.7	5		FW	PG	0
L002	2	064	46	0.08	5		FW	PG	0
L002	2	065	73	0.08	5		FW	PG	0
L002		082	71	0.4	1		FW	PG	0
L002		083	66	0.48	5		FW	PG	0

L002		089	80	0.5	2		FW	PG	0
L002	2	258	86	0.23	10		FW	PG	0
L002		263	70	0.28	15		FW	PG	0
L002	2	260	85	0.5	10		FW	PG	0
L002	2	254	79	0.57	10		FW	PG	0
L002	1	156	82	0.68	10		FW	PG	0
L002	3	102	65	0.75	10		FW	PG	0
L002	2	251	70	0.6	5		FW	PG	0
L002	2	258	62	0.44	5	1	FW	PG	0
L002	2	258	62	0.44	5	1	FW	PG	0
L002	2	258	62	0.44	5	1	FW	PG	0
L002	2	258	62	0.44	5	1	FW	PG	0
L002	2	258	62	0.44	5	1	FW	PG	0
L002	2	258	62	0.44	5	1	FW	PG	0
L002		172	77	0.36	35		FW	PG	0
L002		055	80	0.7	15		FW	PG	0
L002	2	069	72	0.74	30		FW	PG	0
L002	4	214	60	0.3	15		FW	PG	0
L002	4	222	70	0.35	5	5	FW	PG	0
L002	4	222	72	0.37	40	5	FW	PG	0
L002		228	60	0.26	10	5	FW	PG	0
L002	1	124	44	0.27	10		FW	PG	0
L002	2	260	57	0.55	10		FW	PG	0
L002		058	68	0.2	30		FW	PG	0
L002		088	80	0.23	10	5	FW	PG	0
L002		088	80	0.23	10	5	FW	PG	0

L002	3	095	52	0.9	30		FW	PG	0
L002		084	72	0.45	20		FW	PG	0
L002		056	70	0.5	5		FW	PG	0
L002	2	080	85	0.6	10		FW	PG	0
L002	3	284	80	0.7	10		FW	PG	0
L002	3	272	84	0.15	10	5	FW	PG	0
L002	3	272	84	0.15	10	5	FW	PG	0
L002	3	272	84	0.15	10	5	FW	PG	0
L002	3	272	84	0.15	10	5	FW	PG	0
L002	3	272	84	0.15	10	5	FW	PG	0
L002		263	84	0.6	30		FW	PG	0
L002	3	092	80	0.8	20		FW	PG	0
L002	2	060	64	0.65	10		FW	PG	0
L003	3	100	50	0.9	25	12	FW	PG	0
L003	3	100	50	0.9	25	12	FW	PG	0
L003	3	100	50	0.9	25	12	FW	PG	0
L003	3	100	50	0.9	25	12	FW	PG	0
L003	3	098	50	0.85	10		FW	PG	0
L003	1	142	58	0.9	10	5	FW	PG	0
L003	1	142	58	0.9	10	5	FW	PG	0
L003	1	142	58	0.9	10	5	FW	PG	0
L003		343	26	0.38	5		FW	PG	0
L003	1	150	40	0.8	10	3	FW	PG	0
L003	1	150	40	0.8	10	3	FW	PG	0
L003	1	150	40	0.8	10	3	FW	PG	0
L003	1	150	40	0.8	10	3	FW	PG	0

L003	3	104	30	0.2	10		FW	PG	0
L003		111	20	0.32	5		FW	PG	0
L003	3	280	42	1.6	30	3	FW	PG	0
L003	3	280	42	1.6	30	3	FW	PG	0
L003	3	280	42	1.6	30	3	FW	PG	0
L003	1	305	54	1.1	15		FW	PG	0
L003		296	88	1	15	6	FW	PG	0
L003		296	88	1	15	6	FW	PG	0
L003	3	105	60	1.2	2	5	FW	PG	0
L003	3	105	60	1.2	2	5	FW	PG	0
L003	3	105	60	1.2	2	5	FW	PG	0
L003	3	105	60	1.2	2	5	FW	PG	0
L003		084	82	1.4	20		FW	PG	0
L003	1	301	74	0.4	10		FW	PG	0
L003		190	72	1	1		FW	PG	0
L003		194	62	0.65	10	18	FW	PG	0
L003	1	126	80	0.42	10	4	FW	PG	0
L003	1	126	80	0.42	10	4	FW	PG	0
L003	1	126	80	0.42	10	4	FW	PG	0
L003	1	126	80	0.42	10	4	FW	PG	0
L003	1	130	76	0.5	20	3	FW	PG	0
L003	1	130	76	0.5	20	3	FW	PG	0
L003	1	130	76	0.5	20	3	FW	PG	0
L003	1	130	76	0.5	20	3	FW	PG	0
L003	1	330	38	1.1	30	5	FW	PG	0
L003	1	330	38	1.1	30	5	FW	PG	0

L003	1	330	38	1.1	30	5	FW	PG	0
L003	1	330	38	1.1	30	5	FW	PG	0
L003	1	330	38	1.1	30	5	FW	PG	0
L003	1	304	62	1.7	20		FW	PG	0
L003	3	290	58	1.2	30		FW	PG	0
L003	3	290	58	0.9	30		FW	PG	0
L003		228	62	0.42	10		FW	PG	0
L003	2	242	75	0.7	20	4	FW	PG	0
L003	2	242	75	0.7	20	4	FW	PG	0
L003	2	242	75	0.7	20	4	FW	PG	0
L003	2	242	75	0.7	20	4	FW	PG	0
L003	2	242	75	0.7	20	4	FW	PG	0
L003	2	072	70	1.6	10	6	FW	PG	0
L003	2	072	70	1.6	10	6	FW	PG	0
L003	2	072	70	1.6	10	6	FW	PG	0
L003	2	072	70	1.6	10	6	FW	PG	0
L003	2	257	70	1.2	20	5	FW	PG	0
L003	2	257	70	1.2	20	5	FW	PG	0
L003	2	257	70	1.2	20	5	FW	PG	0
L003	2	257	70	1.2	20	5	FW	PG	0
L003	1	124	74	0.7	10		FW	PG	0
L003	1	125	72	0.26	5		FW	PG	0
L003	1	120	77	0.58	10		FW	PG	0
L003	3	278	64	0.97	20	10	FW	PG	0
L003	3	278	64	0.97	20	10	FW	PG	0
L003	3	278	64	0.97	20	10	FW	PG	0

L003		189	60	0.74	20		FW	PG	0
L004	2	080	69	1.5	10		FW	PG	0
L004		113	80	1.5	10		FW	PG	0
L004	3	100	83	1.35	5	2	FW	PG	0
L004	3	100	83	1.35	5	2	FW	PG	0
L004	2	070	65	1	5		FW	PG	0
L004	1	134	73	0.9	5		FW	PG	0
L004	1	142	70	1.74	30		FW	PG	0
L004	2	070	59	1.19	30		FW	PG	0
L004	1	136	48	0.78	5	10	FW	PG	0
L004	1	136	48	0.78	5	10	FW	PG	0
L004	1	136	48	0.78	5	10	FW	PG	0
L004	1	136	48	0.78	5	10	FW	PG	0
L004	1	136	48	0.78	5	10	FW	PG	0
L004	1	136	48	0.78	5	10	FW	PG	0
L004		299	48	0.67	3	10	FW	PG	0
L004		299	48	0.67	3	10	FW	PG	0
L004		299	48	0.67	3	10	FW	PG	0
L004		299	48	0.67	3	10	FW	PG	0
L004		023	54	0.4	30		FW	PG	0
L004	4	036	52	0.52	30		FW	PG	0
L004	3	110	28	2.5	30		FW	PG	0
L004	3	105	36	2	30		FW	PG	0
L004	3	110	44	0.7	20		FW	PG	0
L004		111	60	1.2	10		FW	PG	0
L004	4	042	80	1.2	30		FW	PG	0

L004	3	108	58	1	40		FW	PG	0
L004	3	101	69	1.3	15		FW	PG	0
L004		056	66	0.9	10		FW	PG	0
L004	3	096	46	0.95	15		FW	PG	0
L004	3	100	63	0.8	20	10	FW	PG	0
L004	3	100	63	0.8	20	10	FW	PG	0
L004	3	100	63	0.8	20	10	FW	PG	0
L004	3	108	68	1.5	20	7	FW	PG	0
L004	3	108	68	1.5	20	7	FW	PG	0
L004	3	108	68	1.5	20	7	FW	PG	0
L004	3	108	68	1.5	20	7	FW	PG	0
L004	3	108	68	1.5	20	7	FW	PG	0
L004		017	79	0.7	5		FW	PG	0
L004	4	040	84	1	5		FW	PG	0
L004	1	120	47	1	10		FW	PG	0
L004	3	102	53	1	15	4	FW	PG	0
L004	3	102	53	1	15	4	FW	PG	0
L004	3	102	53	1	15	4	FW	PG	0
L004	3	102	53	1	15	4	FW	PG	0
L004	3	102	53	1	15	4	FW	PG	0
L004		024	72	0.5	5		FW	PG	0
L004	4	043	81	0.55	10		FW	PG	0
L004		264	80	0.5	10		FW	PG	0
L004		262	83	0.78	20		FW	PG	0
L004	1	122	56	0.84	1		FW	PG	0
L004	1	312	57	0.3	15		FW	PG	0

L005		353	76	0.7	80		FW	PG	0
L005	2	074	82	1.4	100		FW	PG	0
L005	4	032	77	2	330		FW	PG	0
L005	3	109	60	0.75	70		FW	PG	0
L005	3	108	77	0.55	10		FW	PG	0
L005	3	095	75	2.2	15		FW	PG	0
L005	3	092	76	2.5	10		FW	PG	0
L005		179	81	0.46	5		FW	PG	0
L005		234	77	0.47	10		FW	PG	0
L005		057	64	1.1	50		FW	PG	0
L005		012	78	0.45	15		FW	PG	0
L005	3	104	81	1.1	30		FW	PG	0
L005		058	76	1	15		FW	PG	0
L005	2	060	69	1	30		FW	PG	0
L005	2	063	74	0.45	10		FW	PG	0
L005	4	220	88	1.5	3		FW	PG	0
L005	4	043	63	0.5	2	4	FW	PG	0
L005	2	073	62	1.4	30		FW	PG	0
L005	2	072	63	1.3	30		FW	PG	0
L005	2	074	80	0.4	30		FW	PG	0
L005		084	67	0.8	20		FW	PG	0
L005	2	067	77	0.8	30		FW	PG	0
L005		050	75	0.65	20		FW	PG	0
L005		176	65	0.74	50		FW	PG	0
L005		189	69	0.7	10		FW	PG	0
L006	3	096	81	2.4	15	1	HW	MM	0

L006	3	096	81	2.4	15	1	HW	MM	0
L006	2	079	72	4	5		HW	MM	3
L006		114	74	1.4	10		HW	MM	0
L006	3	103	62	2	2		HW	MM	5
L006	1	151	78	5.7	20		HW	MM	0
L006	2	064	72	3	100		HW	MM	0
L006	3	285	80	4.4	2 to 10	85	HW	MM	5
L006	3	285	80	4.4	2 to 10	85	HW	MM	5
L006		082	68	4	10		HW	MM	0
L006	2	072	78	3.9	10		HW	MM	0
L006	2	060	74	0.7	50		HW	MM	0
L006	1	334	78	3.4	5		HW	MM	0
L006	1	332	64	0.86	5		HW	MM	0
L006	1	126	54	2	20		HW	MM	0
L006	1	120	76	3	20		HW	MM	0
L006	2	078	78	3.5	40		HW	MM	0
L006	3	110	86	2	30		HW	MM	0
L006		195	85	1.1	80		HW	MM	0
L006		020	82	0.7	20		HW	MM	0
L006		088	85	1.1	10		HW	MM	0
L006	2	073	72	0.7	20		HW	MM	0
L006		083	76	1.1	3		HW	MM	0
L006	1	120	72	1.3	30		HW	MM	0
L006	2	071	73	0.6	3		HW	MM	0
L006	1	125	82	2.3	50		HW	MM	0
L006		180	80	2	100		HW	MM	0

L006		086	80	2.6	10		HW	MM	0
L006	1	120	80	2.5	200		HW	MM	0
L006		082	70	0.8	10		HW	MM	0
L006		084	60	3	1		HW	MM	0
L006		085	78	1.25	20		HW	MM	0
L006	3	102	66	0.7	2		HW	MM	5
L006	3	110	68	2.7	100		HW	MM	0
L006	2	062	68	1.2	2.5	70	HW	MM	0
L006	2	062	68	1.2	2.5	70	HW	MM	0
L006	2	062	68	1.2	2.5	70	HW	MM	0
L006	4	221	83	1.1	15		HW	MM	0
L006	2	248	70	1.5	5		HW	MM	0
L006	3	104	80	1.65	2 to 15		HW	MM	5
L006	2	253	80	1.2	120		HW	MM	0
L006	2	066	62	1.5	100	80	HW	MM	0
L006	2	066	62	1.5	100	80	HW	MM	0
L006	2	072	75	1.9	10		HW	MM	0
L006	4	036	70	1.45	30		HW	MM	0
L006	3	107	78	1.3	2		HW	MM	0
L006		236	75	1.4	2		HW	MM	0
L006	1	134	68	1.9	50		HW	MM	0
L006	2	063	70	2.3	1		HW	MM	0
L007	2	249	89	0.65	10	22	HW	PG	0
L007	2	249	89	0.65	10	22	HW	PG	0
L007	2	249	89	0.65	10	22	HW	PG	0
L007		262	83	1	20		HW	PG	0

L007	2	258	83	0.9	2		HW	PG	0
L007	2	260	80	0.2	3	6	HW	PG	5
L007	2	260	80	0.2	3	6	HW	PG	5
L007	2	260	80	0.2	3	6	HW	PG	5
L007	2	260	80	0.2	3	6	HW	PG	5
L007	2	254	86	0.26	20		HW	PG	0
L007	2	254	86	0.26	20		HW	PG	0
L007	2	254	86	0.26	20		HW	PG	0
L007	2	254	86	0.26	20		HW	PG	0
L007	2	254	82	0.3	1	3	HW	PG	3
L007	2	254	82	0.3	1	3	HW	PG	3
L007	2	254	82	0.3	1	3	HW	PG	3
L007	2	254	82	0.3	1	3	HW	PG	3
L007	2	254	82	0.3	1	3	HW	PG	3
L007	2	250	89	0.6	1	4	HW	PG	0
L007	2	250	89	0.6	1	4	HW	PG	0
L007	2	250	89	0.6	1	4	HW	PG	0
L007	2	256	86	0.14	1		HW	PG	0
L007	1	338	87	57	1		HW	PG	0
L007	1	332	86	0.27	2		HW	PG	0
L007		342	83	0.19	8		HW	PG	0
L007	1	322	84	0.24	2		HW	PG	0
L007		351	82	0.17	5		HW	PG	0
L007		357	80	0.17	3		HW	PG	0
L007		356	80	0.57	2		HW	PG	0
L007		348	88	0.72	2		HW	PG	0

L008	2	252	78	6	20	16	HW	PG	0
L008	2	252	78	6	20	16	HW	PG	0
L008	2	252	78	6	20	16	HW	PG	0
L008	2	252	78	6	20	16	HW	PG	0
L008	2	255	72	5	10	15	HW	PG	0
L008	2	255	72	5	10	15	HW	PG	0
L008	2	255	72	5	10	15	HW	PG	0
L008	2	241	82	6	10		HW	PG	0
L008		264	81	4	20		HW	PG	0
L008		236	86	1	3		HW	PG	0
L008	2	248	75	5	10		HW	PG	0
L008	2	248	84	1	15		HW	PG	0
L008	2	260	76	1.1	5		HW	PG	0
L008		356	82	1.3	10	13	HW	PG	0
L008		356	82	1.3	10	13	HW	PG	0
L008		356	82	1.3	10	13	HW	PG	0
L008	1	339	78	0.55	3	12	HW	PG	0
L008	1	339	78	0.55	3	12	HW	PG	0
L008	1	339	78	0.55	3	12	HW	PG	0
L008	1	325	79	2	10		HW	PG	0
L008		342	74	1.5	20		HW	PG	0
L008		341	68	1.5	10		HW	PG	0
L008	1	331	71	1.5	10		HW	PG	0
L008	1	334	78	0.83	10		HW	PG	0
L008	1	339	81	1.34	10		HW	PG	0
L009	3	108	55	8	5	16	FW	TC	0

L009	3	105	40	8	5	15	FW	TC	5
L009		058	38	1.7	1		FW	TC	0
L009		236	90	0.8	1		FW	TC	0
L009		046	16	1	1		FW	TC	0
L009	1	137	63	1	1		FW	TC	0
L009	1	137	63	1	1		FW	TC	0
L009	1	137	63	1	1		FW	TC	0
L009	1	137	63	1	1		FW	TC	0
L009	1	137	63	1	1		FW	TC	0
L009	1	137	63	1	1		FW	TC	0
L009	1	137	63	1	1		FW	TC	0
L009	1	120	68	5	3		FW	TC	0
L009	1	146	42	6	3		FW	TC	0
L009	3	090	68	1.4	1	13	FW	TC	0
L009	3	090	67	1.5	1	12	FW	TC	0
L009		202	55	1.3	5		FW	TC	0
L009	4	028	5	8	10		FW	TC	0
L010		194	48	3	2	50	FW	PG	0
L010		194	48	3	2	50	FW	PG	0
L010	1	144	64	3	3		FW	PG	0
L010	1	146	26	4	3		FW	PG	0
L010	1	134	35	6	5		FW	PG	2
L010	1	159	60	4	1		FW	PG	0
L010	1	159	77	4	2	15	FW	PG	0
L010	1	159	77	4	2	15	FW	PG	0
L010	1	146	83	10	10		FW	PG	0

L010	4	041	42	10	20	250	FW	PG	0
L010	4	041	42	10	20	250	FW	PG	0
L010	2	065	65	6	10		FW	PG	0
L010	1	338	40	10	10	150	FW	PG	0
L010	1	338	40	10	10	150	FW	PG	0
L010	1	338	40	10	10	150	FW	PG	0
L010	1	338	40	10	10	150	FW	PG	0
L010	1	338	40	10	10	150	FW	PG	0
L010	1	338	40	10	10	150	FW	PG	0
L010	1	338	40	10	10	150	FW	PG	0
L010	1	338	40	10	10	150	FW	PG	0
L010	1	338	40	10	10	150	FW	PG	0
L010	1	158	36	2	10		FW	PG	0
L010	2	060	82	2.5	50	100	FW	PG	0
L010	2	060	82	2.5	50	100	FW	PG	0
L010	2	060	82	2.5	50	100	FW	PG	0
L010	2	060	82	2.5	50	100	FW	PG	0
L010	2	060	82	2.5	50	100	FW	PG	0
L010	2	060	82	2.5	50	100	FW	PG	0
L011	1	120	68	1.6	2		FW	PG	0
L011	1	140	68	2	2		FW	PG	0
L011	1	144	78	6	1		FW	PG	0
L011	1	122	67	5	1		FW	PG	0
L011	1	138	70	7	2		FW	PG	0
L011	2	246	84	8	20		FW	PG	0
L011	3	107	82	5	30		FW	PG	0

L011	1	140	68	5	10		FW	PG	0
L011	1	127	70	1.6	2		FW	PG	0
L012	1	124	51	3.4	2		FW	MM	4
L012	2	080	72	1.3	1	60	FW	MM	0
L012	2	080	72	1.3	1	60	FW	MM	0
L012		179	50	0.8	1		FW	MM	0
L012	4	035	90	4	1		FW	MM	0
L012	1	128	48	1	1	70	FW	MM	0
L012	1	128	48	1	1	70	FW	MM	0
L012		164	80	2	2	30	FW	MM	0
L012		164	80	2	2	30	FW	MM	0
L012		164	80	2	2	30	FW	MM	0
L012	3	099	57	1.3	3		FW	MM	0
L012	1	129	54	1.1	20		FW	MM	0
L012		086	50	1.2	10	80	FW	MM	0
L012		086	50	1.2	10	80	FW	MM	0
L012		086	50	1.2	10	80	FW	MM	0
L012	1	153	53	0.7	3	10	FW	MM	0
L012	1	153	53	0.7	3	10	FW	MM	0
L012	1	153	53	0.7	3	10	FW	MM	0
L012	1	153	53	0.7	3	10	FW	MM	0
L012	2	064	82	0.8	1	30	FW	MM	0
L012	2	064	82	0.8	1	30	FW	MM	0
L013	1	153	67	2.8	2		FW	MM	0
L013	1	131	64	3	2		FW	MM	0
L013	1	132	68	2	20		FW	MM	0

L013	1	120	74	2	5		FW	MM	0
L013	4	207	75	0.72	5		FW	MM	0
L013		192	75	0.85	2		FW	MM	0
L013		202	70	0.74	10		FW	MM	0
L013	1	131	71	0.25	10		FW	MM	0
L013		201	75	0.25	5		FW	MM	0
L013	1	120	53	0.3	10		FW	MM	0
L013		192	80	0.25	5		FW	MM	0
L013	1	126	76	0.27	1		FW	MM	0
L013	4	207	60	0.26	10		FW	MM	0
L013	1	140	78	0.58	3		FW	MM	0
L013	1	128	24	2	1		FW	MM	0
L013		114	76	0.86	2		FW	MM	0
L013	1	300	88	1	2		FW	MM	0
L013	2	070	70	0.8	10		FW	MM	0
L014		168	72	1.2	1		FW	MM	0
L014	1	156	73	1.3	1		FW	MM	0
L014		046	89	1.2	3		FW	MM	5
L014		057	88	0.48	2		FW	MM	5
L014		232	22	0.3	1		FW	MM	0
L014	1	149	70	0.95	1		FW	MM	0
L014	1	148	66	1.6	2		FW	MM	0
L014	4	042	80	0.6	2		FW	MM	0
L014	1	130	85	1.1	1	10	FW	MM	0
L014	1	130	85				FW	MM	0
L014	1	130	85				FW	MM	0

L014	1	130	80	1.2	5	10	FW	MM	0
L014	1	130	80				FW	MM	0
L014	1	314	84	0.76	1		FW	MM	0
L014		057	84	0.47	1		FW	MM	0
L014	1	139	86	0.42	1		FW	MM	0
L014	1	128	74	1.3	2		FW	MM	0
L014		162	88	0.23	1		FW	MM	0
L014	1	139	74	1	3	35	FW	MM	0
L014	1	139	74				FW	MM	0
L014	1	139	74				FW	MM	0
L014	1	154	78	0.24	1	5	FW	MM	0
L014	1	154	78				FW	MM	0
L014	1	154	78				FW	MM	0
L014	1	154	78				FW	MM	0
L014	2	078	88	0.5	2		FW	MM	0
L014	2	068	87	1	1		FW	MM	0
L014	2	063	85	0.55	2		FW	MM	0
L014	2	064	88	0.23	1		FW	MM	0
L014	2	064	85	0.2	2		FW	MM	0
L014	1	156	87	0.2	1	5	FW	MM	0
L014	1	156	87				FW	MM	0
L014	1	156	87				FW	MM	0
L014	1	156	87				FW	MM	0
L014	1	156	87				FW	MM	0
L014	1	156	87				FW	MM	0
L014	1	156	87				FW	MM	0

L014	1	156	87				FW	MM	0
L014		358	83	1	1		FW	MM	0
L014		358	83				FW	MM	0
L014		358	83				FW	MM	0
L014		358	83				FW	MM	0
L014		358	83				FW	MM	0
L014	3	108	90	1.7	1		FW	MM	0
L014	2	060	87	1.7	2		FW	MM	0
L014	2	078	89	1.4	1		FW	MM	0
L014	1	140	74	1.1	1	8	FW	MM	0
L014	1	140	74				FW	MM	0
L014	1	140	74				FW	MM	0
L014	1	140	74				FW	MM	0
L014	1	145	55	1.3	2		FW	MM	0
L014	1	319	40	1.3	2		FW	MM	0
L014		165	70	0.88	1	10	FW	MM	0
L014		165	70				FW	MM	0
L014		165	70				FW	MM	0
L014		165	70				FW	MM	0
L014		165	70				FW	MM	0
L014	3	273	78	0.7	1	40	FW	MM	0
L014	3	273	78				FW	MM	0
L014	3	273	78				FW	MM	0
L014	3	273	78				FW	MM	0
L014	3	273	78				FW	MM	0
L014	1	146	36	0.7	1		FW	MM	0

L014	1	141	31	1.2	5		FW	MM	0
L014	1	334	88	1.8	1		FW	MM	0
L014	1	300	79	1	1		FW	MM	0
L014	1	160	40	1	2		FW	MM	0
L014	1	146	58	0.7	2		FW	MM	0
L014	1	320	41	0.9	3		FW	MM	0
L014	2	074	81	0.4	5		FW	MM	0
L014	2	066	88	1.5	2		FW	MM	0
L014	2	244	87	0.9	1		FW	MM	0
L014		166	73	2.5	1		FW	MM	0
L014		189	81	0.6	3	20	FW	MM	0
L014		189	81				FW	MM	0
L014		189	81				FW	MM	0
L014		189	81				FW	MM	0
L014		189	81				FW	MM	0
L014	1	134	77	5	3		FW	MM	0
L014	2	256	80	4	5	200	FW	MM	0
L014	2	256	80				FW	MM	0
L015		239	83	7	1	60	HW	MM	0
L015		239	83	7	1	60	HW	MM	0
L015		239	83	7	1	60	HW	MM	0
L015		239	83	7	1	60	HW	MM	0
L015		239	83	7	1	60	HW	MM	0
L015		239	83	7	1	60	HW	MM	0
L015		239	83	7	1	60	HW	MM	0
L015		239	83	7	1	60	HW	MM	0

L015		000	65	7	1		HW	MM	0
L015		341	27	3	20		HW	MM	0
L015		238	85	1.9	1		HW	MM	0
L015	2	260	88	1.8	1		HW	MM	0
L015	2	257	70	2.1	1		HW	MM	0
L015	2	241	80	2	1		HW	MM	0
L015	3	102	23	0.9	1		HW	MM	0
L015		262	90	4	2		HW	MM	0
L015	2	246	63	1.1	1		HW	MM	0
L015		261	82	2	1		HW	MM	0
L015	3	099	58	4	5		HW	MM	0
L015	2	257	90	4.8	4		HW	MM	2
L015	2	242	87	4	5		HW	MM	0
L015		084	42	1	10		HW	MM	0
L015	2	080	40	1.3	5		HW	MM	0
L015		086	28	0.74	2		HW	MM	0
L015	2	260	83	1	5		HW	MM	5
L015	3	285	80	2	30		HW	MM	5
L015	2	244	78	0.8	1		HW	MM	0
L015	1	146	82	0.4	1		HW	MM	0
L015	1	130	82	1.3	5		HW	MM	0
L015	2	260	78	1.7	1		HW	MM	5
L015		264	82	1.4	2	25	HW	MM	0
L015		264	82	1.4	2	25	HW	MM	0
L015		264	82	1.4	2	25	HW	MM	0
L015		264	82	1.4	2	25	HW	MM	0

L015	2	250	85	2	10		HW	MM	0
L015	1	120	85	1.3	1	18	HW	MM	0
L015	1	120	85	1.3	1	18	HW	MM	0
L015	1	120	85	1.3	1	18	HW	MM	0
L015		296	42	1.8	8	50	HW	MM	3
L015		296	42	1.8	8	50	HW	MM	3
L015	4	219	84	0.2	1	6	HW	MM	0
L015	4	219	84	0.2	1	6	HW	MM	0
L015	4	219	84	0.2	1	6	HW	MM	0
L015	4	219	84	0.2	1	6	HW	MM	0
L015	4	219	84	0.2	1	6	HW	MM	0
L015	4	219	84	0.2	1	6	HW	MM	0
L015	4	219	84	0.2	1	6	HW	MM	0
L015		239	89	0.25	1	5	HW	MM	0
L015		239	89	0.25	1	5	HW	MM	0
L015		239	89	0.25	1	5	HW	MM	0
L015		239	89	0.25	1	5	HW	MM	0
L015		239	89	0.25	1	5	HW	MM	0
L015		239	89	0.25	1	5	HW	MM	0
L015		227	90	2	1		HW	MM	0
L015	4	220	68	0.8	10		HW	MM	0
L015	2	251	80	1.2	5		HW	MM	0
L015		235	77	1.1	5		HW	MM	0
L015	1	120	78	0.9	5		HW	MM	0
L015	1	140	89	0.75	5		HW	MM	0
L015	2	250	85	0.9	5		HW	MM	0

L015	4	042	90	1	10		HW	MM	0
L015	2	251	79	1.4	1		HW	MM	0
L015	1	132	85	2.8	1		HW	MM	0
L015	4	222	82	1.2	1		HW	MM	5
L015	1	130	70	0.8	1		HW	MM	0
L015		117	84	1	1		HW	MM	0
L015	1	128	85	0.6	1		HW	MM	0
L015	1	126	90	1.5	1		HW	MM	0
L015	3	107	40	0.5	2		HW	MM	0
L015	3	275	74	0.7	2		HW	MM	0
L015	3	096	47	0.4	1		HW	MM	0
L015	1	127	77	0.65	1		HW	MM	0
L015	1	309	90	0.6	1		HW	MM	0
L015		348	80	0.3	1		HW	MM	1
L016	2	254	81	0.4	1	60	HW	MPA	0
L016	4	220	80	0.5	10		HW	MPA	0
L016		358	88	0.45	10		HW	MPA	0
L016	1	150	88	0.32	10		HW	MPA	0
L016	3	280	85	0.43	1		HW	MPA	0
L016	3	274	81	0.47	1		HW	MPA	0
L016	3	271	88	1	1		HW	MPA	0
L016	4	215	79	0.33	1		HW	MPA	0
L016	3	276	85	0.82	10		HW	MPA	0
L016		267	87	1.7	5		HW	MPA	0
L016		200	86	0.26	2		HW	MPA	0
L016	1	122	86	0.2	1		HW	MPA	0

L016	3	279	81	1.25	2		HW	MPA	0
L016	1	142	78	0.2	1		HW	MPA	0
L016	2	078	90	0.39	3		HW	MPA	0
L016	4	031	83	0.92	20		HW	MPA	0
L016	3	280	79	0.34	2		HW	MPA	0
L016		234	88	0.34	20	20	HW	MPA	0
L016		234	88	0.34	20	20	HW	MPA	0
L016		234	88	0.34	20	20	HW	MPA	0
L016		234	88	0.34	20	20	HW	MPA	0
L016		234	88	0.34	20	20	HW	MPA	0
L016	2	256	90	1.2	1		HW	MPA	0
L016		236	79	0.35	20		HW	MPA	0
L016	3	106	71	0.4	10	11	HW	MPA	0
L016	3	106	71	0.4	10	11	HW	MPA	0
L016	3	100	67	0.57	10		HW	MPA	0
L016	3	108	80	0.37	15		HW	MPA	0
L016	3	096	82	0.51	15		HW	MPA	0
L016	2	240	80	0.42	20		HW	MPA	0
L016	3	280	81	0.45	10		HW	MPA	0
L016	1	136	83	0.54	5		HW	MPA	0
L016	3	094	81	0.66	30		HW	MPA	0
L016	2	244	83	0.44	10		HW	MPA	0
L016	2	246	84	0.46	5		HW	MPA	0
L017	4	044	77	2	10		HW	JS	0
L017	4	039	52	0.5	10		HW	JS	0
L017	2	068	63	0.25	1	7	HW	JS	0

L017	2	068	63	0.25	1	7	HW	JS	0
L017	2	068	63	0.25	1	7	HW	JS	0
L017	1	330	72	1	15		HW	JS	0
L017		296	68	0.7	5	20	HW	JS	0
L017		296	68	0.7	5	20	HW	JS	0
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L017		296	68	0.7	5	20	HW	JS	0
L017	4	030	60	0.5	10	30	HW	JS	0
L017	4	030	60	0.5	10	30	HW	JS	0
L017	4	030	60	0.5	10	30	HW	JS	0
L017	4	030	60	0.5	10	30	HW	JS	0
L017		048	67	1	2		HW	JS	0
L017		051	62	0.8	1	20	HW	JS	0
L017		051	62	0.8	1	20	HW	JS	0
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L017	4	045	68	0.3	3	18	HW	JS	0
L017	4	045	68	0.3	3	18	HW	JS	0
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L017		346	48	0.33	3	34	HW	JS	0
L017		346	48	0.33	3	34	HW	JS	0
L017		055	44	0.55	3	26	HW	JS	0

L017		055	44	0.55	3	26	HW	JS	0
L017		055	44	0.55	3	26	HW	JS	0
L017		055	44	0.55	3	26	HW	JS	0
L017		112	87	0.68	10	30	HW	JS	0
L017		112	87	0.68	10	30	HW	JS	0
L017		112	87	0.68	10	30	HW	JS	0
L017	2	061	57	0.57	1	26	HW	JS	5
L017	2	061	57	0.57	1	26	HW	JS	5
L017	4	032	51	0.21	2		HW	JS	0
L017		058	55	0.24	1		HW	JS	0
L017	4	031	62	0.46	0		HW	JS	0
L017	1	311	67	0.23	10	20	HW	JS	0
L017	1	311	67	0.23	10	20	HW	JS	0
L017		059	68	0.24	10		HW	JS	0
L017	1	318	52	0.4	3		HW	JS	0
L017		054	62	0.44	2	20	HW	JS	0
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L017	4	042	50	0.45	2	10	HW	JS	0
L017	4	042	50	0.45	2	10	HW	JS	0
L017	4	042	50	0.45	2	10	HW	JS	0
L017	4	042	50	0.45	2	10	HW	JS	0
L017	1	320	48	0.77	5	20	HW	JS	0
L017	1	320	48	0.77	5	20	HW	JS	0
L017	1	320	48	0.77	5	20	HW	JS	0
L017	1	320	48	0.77	5	20	HW	JS	0

L017	4	034	52	0.38	2	16	HW	JS	0
L017	4	034	52	0.38	2	16	HW	JS	0
L017		089	76	0.57	5		HW	JS	0
L017	4	031	62	0.5	3		HW	JS	0
L017	1	310	58	0.47	1		HW	JS	0
L017		232	80	0.53	3	16	HW	JS	0
L017		232	80	0.53	3	16	HW	JS	0
L017		232	80	0.53	3	16	HW	JS	0
L017		232	80	0.53	3	16	HW	JS	0
L017	4	044	51	0.73	1		HW	JS	0
L017		057	56	0.86	1	10	HW	JS	0
L017		057	56	0.86	1	10	HW	JS	0
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L017		299	75	0.34	1	25	HW	JS	0
L017		299	75	0.34	1	25	HW	JS	0
L018	1	125	80	0.43	1	5	HW	JS	0
L018	1	125	80	0.43	1	5	HW	JS	0
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L018	1	125	80	0.43	1	5	HW	JS	0
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L018		118	87	0.4	2	10	HW	JS	0
L018		118	87	0.4	2	10	HW	JS	0
L018		118	87	0.4	2	10	HW	JS	0

L018		118	87	0.4	2	10	HW	JS	0
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L018	1	300	78	0.5	3		HW	JS	0
L018		020	38	1	2		HW	JS	0
L018	4	041	65	0.3	3	18	HW	JS	0
L018	4	041	65	0.3	3	18	HW	JS	0
L018	4	041	65	0.3	3	18	HW	JS	0
L018	1	124	72	1.1	10		HW	JS	0
L018	1	300	60	0.9	10	17	HW	JS	0
L018	1	300	60	0.9	10	17	HW	JS	0
L018	4	028	62	0.73	1	24	HW	JS	0
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L018		085	78	0.72	10	40	HW	JS	0
L018		085	78	0.72	10	40	HW	JS	0
L018	4	040	60	0.8	3		HW	JS	0
L018	1	122	84	0.63	2	20	HW	JS	0
L018	1	122	84	0.63	2	20	HW	JS	0
L018	4	043	70	0.31	3	17	HW	JS	0
L018	4	043	70	0.31	3	17	HW	JS	0
L018		057	67	1.2	2		HW	JS	0
L018	1	145	85	0.36	10		HW	JS	0
L018	1	123	84	0.72	20		HW	JS	0
L018	1	120	86	0.45	2	25	HW	JS	0
L018	1	120	86	0.45	2	25	HW	JS	0
L018	1	120	86	0.45	2	25	HW	JS	0
L018	4	040	50	1.15	3		HW	JS	0

L018	1	300	80	0.46	2		HW	JS	0
L018	4	032	60	0.57	0		HW	JS	0
L018		024	56	1.3	10		HW	JS	0
L018	2	080	62	1.76	0		HW	JS	0
L018	3	287	78	0.87	3	50	HW	JS	0
L018	3	287	78	0.87	3	50	HW	JS	0
L018	3	289	79	0.23	2	18	HW	JS	0
L018	3	289	79	0.23	2	18	HW	JS	0
L018	3	289	79	0.23	2	18	HW	JS	0
L018		023	30	1.45	3		HW	JS	0
L018	1	300	84	0.28	1	24	HW	JS	0
L018	1	300	84	0.28	1	24	HW	JS	0
L018	4	027	47	0.9	10		HW	JS	0
L018	3	288	81	0.6	2	20	HW	JS	0
L018	3	288	81	0.6	2	20	HW	JS	0
L018		014	66	0.25	2		HW	JS	0
L018		052	46	0.55	0	20	HW	JS	0
L018		052	46	0.55	0	20	HW	JS	0
L018	1	300	88	0.64	5		HW	JS	0
L018	4	026	38	0.57	2	15	HW	JS	0
L018	4	026	38	0.57	2	15	HW	JS	0
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L018	2	073	50	0.49	1	15	HW	JS	0
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L018	3	278	60	1.1	1	35	HW	JS	0
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L018	4	032	51	1.08	1	30	HW	JS	0
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L018	4	032	51	1.08	1	30	HW	JS	0
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L018	1	300	72	1.06	2	25	HW	JS	0
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L018	2	068	62	2.1	10	50	HW	JS	0
L018	2	068	62	2.1	10	50	HW	JS	0
L018	4	029	45	2	2		HW	JS	0
L018	4	042	70	0.55	5	20	HW	JS	0
L018	4	042	70	0.55	5	20	HW	JS	0
L018	4	042	70	0.55	5	20	HW	JS	0
L019	4	037	40	0.55	1	25	HW	JS	0
L019	4	037	40				HW	JS	0
L019	4	037	40				HW	JS	0
L019	4	037	40				HW	JS	0
L019	4	037	40				HW	JS	0

L019	3	286	66	1.6	5		HW	JS	0
L019	3	090	87	1.16	2		HW	JS	5
L019	1	334	38	0.77	2	36	HW	JS	0
L019	1	334	38				HW	JS	0
L019	3	271	74	4	10		HW	JS	5
L019	3	274	78	2	10		HW	JS	0
L019	3	284	84	2	1		HW	JS	5
L019	2	074	69	1.5	5		HW	JS	2
L019	3	276	70	2	3		HW	JS	2
L019	1	326	66	2	1	20	HW	JS	0
L019	1	326	66				HW	JS	0
L019	2	064	66	2.7	2	30	HW	JS	2
L019	2	064	66				HW	JS	2
L019	2	064	66				HW	JS	2
L019	2	064	66				HW	JS	2
L019	2	063	62	2	2	25	HW	JS	3
L019	2	063	62				HW	JS	3
L019	2	063	62				HW	JS	3
L019	2	063	62				HW	JS	3
L019		294	72	3	10		HW	JS	2
L019	1	336	70	1.8	1	35	HW	JS	2
L019	1	336	70				HW	JS	2
L019	4	025	72	2.3	2	40	HW	JS	3
L019	4	025	72				HW	JS	3
L019	4	025	72				HW	JS	3
L019	1	317	50	2	5	55	HW	JS	0

L019	1	317	50				HW	JS	0
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L019	2	061	55	2.2	2	10	HW	JS	0
L019	2	061	55				HW	JS	0
L019	1	335	60	1.86	2		HW	JS	0
L019	1	339	50	2.3	5	52	HW	JS	0
L019	1	339	50				HW	JS	0
L019	2	062	60	2.5	5	60	HW	JS	1
L019	2	062	60				HW	JS	1
L019		051	74	1.7	4		HW	JS	4
L020		046	72	0.67	5		HW	JS	0
L020	4	044	58	1.4	5		HW	JS	0
L020	1	327	58	0.86	5		HW	JS	0
L020	1	319	60	1	3	12	HW	JS	0
L020	1	319	60				HW	JS	0
L020		232	60	0.9	1	46	HW	JS	5
L020		232	60				HW	JS	5
L020		232	60				HW	JS	5
L020	2	066	75	1.66	2		HW	JS	0
L020	1	322	47	1.4	2		HW	JS	0
L020	2	066	71	1.9	2		HW	JS	4
L020	1	306	60	1.8	5		HW	JS	2
L020	4	025	50	0.68	2		HW	JS	0
L020	4	206	48	0.64	5		HW	JS	0
L020		004	54	0.67	5		HW	JS	0
L020		081	85	1.3	2		HW	JS	4

L020	4	030	68	0.8	2		HW	JS	1
L020	2	070	85	1.55	3	30	HW	JS	1
L020	2	070	85				HW	JS	1
L020	2	070	85				HW	JS	1
L020	4	038	70	1.3	1		HW	JS	0
L020	2	074	68	1.56	4		HW	JS	5
L020	4	036	63	0.55	3		HW	JS	1
L020	2	065	65	0.74	10		HW	JS	0
L020	2	061	78	1.86	4	70	HW	JS	2
L020	2	061	78				HW	JS	2
L020	1	334	60	1.38	1		HW	JS	0
L021		350	32	0.9	2		HW	JS	0
L021	2	074	69	0.38	5		HW	JS	0
L021		353	42	1	10		HW	JS	0
L021	2	072	88	0.82	1		HW	JS	0
L021	1	314	56	1.14	1		HW	JS	0
L021	2	060	70	1.8	5		HW	JS	5
L021		294	46	1.36	2		HW	JS	0
L021	1	316	78	0.6	5		HW	JS	1
L021		352	48	1.9	10		HW	JS	1
L021	1	339	42	2.6	10		HW	JS	0
L021	1	331	40	1.4	5		HW	JS	0
L021	2	062	36	1.5	5		HW	JS	0
L021	3	275	70	1.7	2		HW	JS	0
L021	2	072	71	1.3	2		HW	JS	0
L021	2	068	70	1.33	1		HW	JS	5

L021	2	073	88	1.03	1		HW	JS	3
L021	2	248	83	4	5		HW	JS	0
L021		084	46	0.77	1		HW	JS	5
L021	1	338	35	1.7	10		HW	JS	0
L021	2	069	54	0.68	2	15	HW	JS	5
L021	2	069	54				HW	JS	5
L021	2	069	54				HW	JS	5
L021	2	071	54	0.8	2	45	HW	JS	0
L021	2	071	54				HW	JS	0
L021	2	246	83	0.8	5		HW	JS	4
L021		352	37	0.63	10		HW	JS	0
L021		088	61	1.6	5		HW	JS	0
L021	2	257	88	0.8	1		HW	JS	0
L021	2	260	75	0.85	5		HW	JS	0
L021	3	091	30	1	5		HW	JS	0
L021		084	53	1.1	5		HW	JS	1
L021	1	311	38	0.9	4		HW	JS	0
L021	3	092	60	1.32	2		HW	JS	1
L021	2	072	56	2.5	2	40	HW	JS	4
L021	2	072	56				HW	JS	4
L022		262	80	3	10		HW	JS	2
L022	4	042	68	1.3	10		HW	JS	1
L022		350	70	0.88	3		HW	JS	0
L022	1	312	78	2	5		HW	JS	0
L022	2	074	38	0.57	4		HW	JS	4
L022		055	72	2	10		HW	JS	1

L022		294	55	0.8	1		HW	JS	0
L022	4	026	50	2.2	3		HW	JS	1
L022	1	313	58	0.87	4		HW	JS	1
L022	3	279	68	0.75	1		HW	JS	0
L022	3	274	48	1.5	1		HW	JS	0
L022		356	50	1.72	2		HW	JS	0
L022	2	079	68	1.7	40		HW	JS	4
L022	2	071	78	0.42	5		HW	JS	2
L022	2	254	54	0.57	2		HW	JS	0
L022	4	044	40	0.74	10		HW	JS	0
L022		024	52	0.55	3		HW	JS	2
L022	2	243	72	1.5	5		HW	JS	0
L022		086	38	2	2		HW	JS	3
L022	2	248	82	2	1		HW	JS	0
L022		351	43	1.5	2		HW	JS	0
L023	3	098	83	0.36	1	3	HW	JS	0
L023	3	098	83	0.36	1	3	HW	JS	0
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L023	3	098	83	0.36	1	3	HW	JS	0
L023		008	82	0.57	2		HW	JS	0
L023		266	87	0.76	2		HW	JS	0
L023		350	88	0.86	3		HW	JS	0
L023	3	092	82	0.9	1		HW	JS	4
L023		268	84	0.95	1		HW	JS	1
L023		266	88	1.07	1		HW	JS	0

L023		005	76	0.37	1		HW	JS	0
L023		354	72	0.27	1		HW	JS	0
L023		048	80	0.3	10		HW	JS	0
L023	4	038	80	0.58	1		HW	JS	1
L023		236	88	0.5	1		HW	JS	3
L023		004	76	0.2	2	6	HW	JS	0
L023		004	76	0.2	2	6	HW	JS	0
L023	2	260	82	0.34	2	10	HW	JS	0
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L023	2	257	86	0.3	3		HW	JS	0
L023	4	031	73	0.4	1		HW	JS	0
L023		008	78	0.5	10		HW	JS	0
L023		262	88	0.25	1		HW	JS	0
L023	2	080	89	0.3	10		HW	JS	0
L023		003	76	0.45	20	30	HW	JS	0
L023		003	76	0.45	20	30	HW	JS	0
L023		003	76	0.45	20	30	HW	JS	0
L023	4	029	72	0.5	5		HW	JS	0
L024	4	025	74	1.4	0		HW	JS	1
L024	2	260	71	2.8	10	30	HW	JS	0
L024	2	260	71	2.8	10	30	HW	JS	0
L024	2	260	71	2.8	10	30	HW	JS	0
L024	3	278	68	2.9	20	20	HW	JS	0
L024	3	278	68	2.9	20	20	HW	JS	0
L024	3	278	68	2.9	20	20	HW	JS	0
L024	3	278	68	2.9	20	20	HW	JS	0

L024		268	69	1.65	5	15	HW	JS	0
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L024		268	69	1.65	5	15	HW	JS	0
L024		352	74	0.34	1	20	HW	JS	0
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L024		352	74	0.34	1	20	HW	JS	0
L024	4	030	70	2.6	5		HW	JS	1
L024		196	83	2.8	5		HW	JS	0
L024	1	302	67	0.68	3		HW	JS	0
L024		297	74	0.5	2		HW	JS	0
L024	4	032	80	0.9	10		HW	JS	2
L024		266	73	0.62	1		HW	JS	1
L024	2	250	72	0.56	1		HW	JS	0
L024	1	302	81	0.5	2		HW	JS	0
L024		294	63	0.25	10		HW	JS	0
L024	4	222	87	0.5	3		HW	JS	4
L024		048	77	0.58	5		HW	JS	5
L024	4	212	79	0.32	3		HW	JS	0
L024	2	250	65	0.4	1		HW	JS	5
L024	2	245	69	0.31	1		HW	JS	0
L024	1	316	62	0.28	1		HW	JS	0
L024	2	260	72	1.78	2		HW	JS	0
L025		266	60	1.5	2		HW	JS	0
L025		202	76	0.4	3		HW	JS	0
L025		170	78	0.5	1		HW	JS	0

L025	2	246	62	0.55	5		HW	JS	0
L025	2	242	72	0.7	10		HW	JS	0
L025		183	72	0.25	10		HW	JS	0
L025		202	89	0.45	1		HW	JS	0
L025		020	85	0.46	10		HW	JS	0
L025	3	284	71	0.65	5		HW	JS	2
L025		349	78	0.4	10		HW	JS	0
L025		193	81	0.5	10		HW	JS	0
L025	2	256	76	0.23	5		HW	JS	5
L025	2	252	62	0.18	1		HW	JS	3
L025	2	249	78	0.37	3		HW	JS	2
L025		265	70	0.48	2		HW	JS	3
L025		347	65	0.58	10		HW	JS	0
L025	4	216	83	1.6	10		HW	JS	1
L025		008	77	0.44	10		HW	JS	0
L025	2	257	69	2	10		HW	JS	0
L025		226	85	0.7	3		HW	JS	0
L025		264	82	0.35	2		HW	JS	0
L026	2	069	84	2.5	5	15	HW	JS	0
L026	2	069	84	2.5	5	15	HW	JS	0
L026	2	069	84	2.5	5	15	HW	JS	0
L026	2	069	84	2.5	5	15	HW	JS	0
L026		056	75	0.5	1		HW	JS	0
L026		084	85	2.7	2	25	HW	JS	0
L026		084	85	2.7	2	25	HW	JS	0
L026		345	42	0.25	1		HW	JS	0

L026		024	65	0.4	1		HW	JS	0
L026		017	57	0.95	1		HW	JS	4
L026		002	40	0.8	2		HW	JS	2
L026		357	55	0.7	1		HW	JS	0
L026		354	48	0.33	1		HW	JS	2
L026	1	304	70	0.85	2		HW	JS	0
L026	1	311	57	0.88	3		HW	JS	0
L026	1	309	55	1.64	1		HW	JS	0
L026	4	040	58	2	2		HW	JS	0
L026		024	55	1.9	3		HW	JS	0
L026	1	304	60	4	5		HW	JS	0
L026	1	310	57	1.5	2		HW	JS	0
L026	1	310	57	1.5	2		HW	JS	0
L026		082	72	0.9	1		HW	JS	0
L026	1	304	64	3	5		HW	JS	0
L026		086	82	4	6		HW	JS	0
L026		086	82	4	6		HW	JS	0
L026		086	82	4	6		HW	JS	0
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L026		344	42	1.75	1		HW	JS	0

L026		020	60	0.8	1		HW	JS	0
L026		014	45	0.75	1		HW	JS	0
L026	2	072	86	0.82	1	5	HW	JS	0
L026	2	072	86	0.82	1	5	HW	JS	0
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L026		024	46	0.9	2		HW	JS	0
L026	4	043	50	1.64	1		HW	JS	0
L027		292	66	0.58	5	20	HW	JS	0
L027		292	66	0.58	5	20	HW	JS	0
L027		292	66	0.58	5	20	HW	JS	0
L027		292	66	0.58	5	20	HW	JS	0
L027		024	52	0.5	10		HW	JS	0
L027		294	68	0.38	5	8	HW	JS	0
L027		294	68	0.38	5	8	HW	JS	0
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L027		024	47	0.37	3		HW	JS	0
L027	3	285	65	0.93	10		HW	JS	0
L027	2	069	87	0.5	5	30	HW	JS	0

L027	2	069	87	0.5	5	30	HW	JS	0
L027	2	069	87	0.5	5	30	HW	JS	0
L027	2	074	68	1.25	5		HW	JS	0
L027		006	45	0.75	10		HW	JS	0
L027		086	68	0.38	15		HW	JS	0
L027	3	277	68	0.32	15		HW	JS	0
L027	3	094	70	0.6	2	15	HW	JS	0
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L027		348	42	1.45	10	25	HW	JS	0
L027		348	42	1.45	10	25	HW	JS	0
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L027	3	102	90	0.8	5		HW	JS	0
L027	4	034	36	0.6	10		HW	JS	0
L027		297	72	2.5	5	12	HW	JS	0
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L027		021	42	0.7	10	40	HW	JS	0
L027		021	42	0.7	10	40	HW	JS	0
L027		021	42	0.7	10	40	HW	JS	0
L027	3	290	76	1.57	10	20	HW	JS	0
L027	3	290	76	1.57	10	20	HW	JS	0
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L027		292	70	0.98	1	20	HW	JS	0
L027		292	70	0.98	1	20	HW	JS	0
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L027		021	42	0.52	10	20	HW	JS	0
L027	2	061	68	0.46	2		HW	JS	0
L027		020	40	0.98	1		HW	JS	0
L028	3	093	62	1.38	3	12	HW	PG	0
L028	3	093	62	1.38	3	12	HW	PG	0
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L028	2	251	82	0.71	10	14	HW	PG	0
L028	2	251	82	0.71	10	14	HW	PG	0
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L028		341	81	1.3	5		HW	PG	0
L028	3	093	76	4	10		HW	PG	0
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L028		048	68	0.94	1		HW	PG	0
L028	1	330	86	0.34	1		HW	PG	0
L028	1	338	70	0.51	1	20	HW	PG	0
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L028	3	109	88	0.79	3		HW	PG	0
L028		048	86	1.27	2		HW	PG	0
L028		261	89	1.6	5	10	HW	PG	0
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L028		006	88	1.2	1		HW	PG	0
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L028		020	56	1.3	2		HW	PG	0
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L028		234	67	2.5	2	30	HW	PG	0
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L029		014	64	2	6	85	HW	PG	0
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L029	2	080	72	4	20		HW	PG	0
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L029	2	258	85	2.5	10		HW	PG	0
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L029	3	102	70	2.5	20		HW	PG	0
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L029	3	098	76	1.4	10		HW	PG	0
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L030		298	82	0.8	5		HW	JS	0
L030		082	84	1.4	1	10	HW	JS	0
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L030		115	74	0.35	2		HW	JS	0
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L030		024	49	1.2	3	18	HW	JS	3
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L030		088	80	2	5	8	HW	JS	0
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L030	2	074	68	0.8	1	20	HW	JS	0
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L030		350	69	0.5	2		HW	JS	0
L030	3	103	80	2	5		HW	JS	1
L030	3	097	74	0.8	5		HW	JS	0
L030	3	107	70	0.9	5		HW	JS	1
L030	1	317	80	0.44	2		HW	JS	1
L030		350	60	0.92	5	27	HW	JS	1
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L030	3	107	79	1.77	1		HW	JS	0
L031	2	078	85	8	20		HW	PG	0
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L031	1	308	77	1.75	20		HW	PG	0
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L031		088	65	8	50		HW	PG	0
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L031		346	84	2.5	5		HW	PG	0
L031	2	060	82	6	15	190	HW	PG	0
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L032		015	76	1.34	2		HW	PG	0
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L034	2	243	81	0.77	10		HW	PG	0
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L034	3	279	79	2	5		HW	PG	0
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L034		266	88	5	3		HW	PG	0
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L034	2	258	86	1.15	5	10	HW	PG	0
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L034		292	75	1.4	3		HW	PG	0
L034	2	254	85	2.5	2		HW	PG	0
L034	1	340	83	1.4	5		HW	PG	0
L034		268	88	1.8	10		HW	PG	0

APPENDIX B

SUMMARY OF FRACTURE ATTRIBUTE DATA

Appendix B contains a statistical summary of length, spacing, and aperture fracture attributes for each fracture group.

Length	Group 1	Group 2	Group 3	Group 4
Minimum	0.1	0.08	0.15	0.15
Median	0.9	1.2	1.1	0.56
Mean	1.5	1.7	1.6	1
Maximum	10	8	8	10

Spacing	Group 1	Group 2	Group 3	Group 4
Minimum	3	1	1	4
Median	11	15	12	18
Mean	28.1	27.5	37.8	28.5
Maximum	150	200	85	250

Aperture	Group 1	Group 2	Group 3	Group 4
Minimum	1	0	1	0
Median	3	5	10	3
Mean	7.4	10.2	11.3	8.5
Maximum	200	120	100	330

APPENDIX C

GOOGLE EARTH PRO LINEAMENT MEASUREMENTS

Appendix C lists the strike (heading), dip (90°), ground length (m), and group (if applicable) of Google Earth Pro lineaments measured in aerial imagery.

Lineament	Strike (Heading)	Dip	Ground Length (m)	Group
1001	120	90	799	1
1002	119	90	965	1
1003	131	90	516	1
1004	138	90	823	1
1005	299	90	436	1
1006	129	90	364	1
1007	135	90	230	1
1008	116	90	256	1
1009	128	90	1525	1
1010	302	90	132	1
1011	321	90	338	1
1012	308	90	153	1
1013	315	90	212	1
1014	327	90	216	1
1015	326	90	376	1
1016	312	90	258	1
1017	310	90	485	1
1018	302	90	108	1
1019	306	90	136	1
1020	318	90	116	1
1021	323	90	257	1
1022	139	90	68	1
1023	119	90	415	1
1024	138	90	66	1
1025	120	90	278	1
1026	296	90	92	1
1027	296	90	67	1
1028	297	90	93	1
1029	121	90	266	1
1030	116	90	279	1
1031	120	90	402	1
1032	162	90	1977	1
1033	156	90	2453	1

1034	158	90	806	1
1035	161	90	1359	1
1036	139	90	418	1
1037	145	90	121	1
1038	165	90	679	1
1039	159	90	595	1
1040	163	90	937	1
1041	162	90	483	1
1042	166	90	606	1
1043	150	90	1049	1
1044	153	90	1811	1
1045	161	90	861	1
1046	157	90	827	1
1047	151	90	1044	1
1048	141	90	697	1
1049	161	90	1423	1
1050	157	90	584	1
1051	164	90	660	1
1052	157	90	476	1
1053	156	90	632	1
1054	156	90	485	1
1055	150	90	416	1
1056	149	90	541	1
1057	151	90	662	1
1058	154	90	506	1
1059	154	90	287	1
1060	141	90	376	1
1061	149	90	319	1
1062	153	90	477	1
1063	148	90	565	1
1064	141	90	369	1
1065	163	90	1001	1
1066	157	90	331	1
1067	155	90	336	1
1068	298	90	493	1
1069	327	90	164	1
1070	344	90	187	1
1071	314	90	207	1
1072	343	90	229	1
1073	156	90	362	1

1074	339	90	347	1
1075	152	90	1087	1
1076	146	90	617	1
1077	150	90	197	1
1078	154	90	301	1
1079	139	90	117	1
1080	161	90	372	1
1081	162	90	277	1
1082	161	90	564	1
1083	155	90	325	1
1084	150	90	314	1
1085	159	90	1641	1
1086	159	90	325	1
1087	141	90	450	1
1088	120	90	207	1
1089	157	90	1535	1
1090	143	90	115	1
1091	343	90	310	1
1092	157	90	730	1
1093	163	90	752	1
1094	341	90	153	1
1095	340	90	247	1
1096	310	90	129	1
1097	323	90	140	1
1098	159	90	573	1
1099	161	90	562	1
1100	312	90	69	1
1101	158	90	1064	1
1102	137	90	413	1
1103	155	90	123	1
1104	140	90	390	1
1105	130	90	345	1
1106	121	90	254	1
1107	131	90	579	1
1108	166	90	427	1
1109	146	90	176	1
1110	130	90	191	1
1111	297	90	67	1
1112	127	90	118	1
1113	128	90	88	1

1114	135	90	195	1
1115	135	90	490	1
1116	144	90	659	1
1117	151	90	84	1
1118	152	90	75	1
1119	140	90	343	1
1120	120	90	35	1
1121	301	90	48	1
1122	118	90	44	1
1123	143	90	175	1
1124	143	90	20	1
1125	128	90	401	1
1126	133	90	704	1
1127	139	90	976	1
1128	134	90	1670	1
1129	151	90	438	1
1130	163	90	592	1
1131	155	90	469	1
1132	119	90	435	1
1133	148	90	369	1
1134	140	90	280	1
1135	122	90	50	1
1136	137	90	80	1
1137	308	90	46	1
1138	302	90	56	1
1139	120	90	777	1
1140	146	90	1776	1
1141	159	90	590	1
1142	164	90	409	1
1143	166	90	1006	1
1144	144	90	423	1
1145	160	90	661	1
1146	142	90	1168	1
1147	151	90	953	1
1148	157	90	578	1
1149	147	90	547	1
1150	152	90	856	1
2000	66	90	296	2
2001	57	90	650	2
2002	58	90	576	2

2003	70	90	374	2
2004	257	90	619	2
2005	59	90	546	2
2006	66	90	417	2
2007	82	90	781	2
2008	72	90	847	2
2009	73	90	976	2
2010	55	90	628	2
2011	72	90	744	2
2012	55	90	510	2
2013	241	90	192	2
2014	67	90	138	2
2015	56	90	222	2
2016	260	90	162	2
2017	60	90	84	2
2018	66	90	71	2
2019	257	90	240	2
2020	57	90	197	2
2021	64	90	815	2
2022	60	90	385	2
2023	66	90	282	2
2024	61	90	281	2
2025	63	90	373	2
2026	62	90	539	2
2027	59	90	516	2
2028	235	90	182	2
2029	65	90	188	2
2030	75	90	442	2
2031	80	90	535	2
2032	68	90	360	2
2033	64	90	210	2
2034	60	90	220	2
2035	61	90	221	2
2036	69	90	218	2
2037	83	90	353	2
2038	70	90	225	2
2039	69	90	327	2
2040	68	90	271	2
2041	57	90	484	2
2042	77	90	261	2

2043	66	90	486	2
2044	79	90	285	2
2045	72	90	177	2
2046	72	90	106	2
2047	71	90	87	2
2048	71	90	92	2
2049	61	90	86	2
2050	58	90	76	2
2051	58	90	85	2
2052	84	90	104	2
2053	80	90	65	2
2054	60	90	49	2
2055	76	90	73	2
2056	55	90	760	2
2057	86	90	42	2
2058	63	90	51	2
2059	77	90	51	2
2060	56	90	58	2
2061	67	90	57	2
2062	64	90	204	2
2063	82	90	109	2
2064	85	90	41	2
2065	80	90	33	2
2066	67	90	39	2
2067	60	90	55	2
2068	55	90	50	2
2069	58	90	42	2
2070	85	90	69	2
2071	59	90	355	2
2072	78	90	210	2
2073	78	90	244	2
2074	64	90	74	2
2075	57	90	55	2
2076	61	90	27	2
2077	58	90	80	2
2078	57	90	81	2
2079	62	90	474	2
2080	75	90	84	2
2081	76	90	76	2
2082	70	90	122	2

2083	69	90	54	2
2084	63	90	53	2
2085	59	90	56	2
2086	72	90	58	2
2087	69	90	52	2
2088	58	90	70	2
2089	67	90	70	2
2090	69	90	89	2
2091	70	90	293	2
2092	67	90	80	2
2093	61	90	72	2
2094	74	90	86	2
2095	75	90	77	2
2096	73	90	69	2
2097	71	90	124	2
2098	57	90	167	2
2099	69	90	37	2
2100	83	90	384	2
2101	82	90	49	2
2102	71	90	42	2
2103	61	90	60	2
2104	55	90	69	2
2105	58	90	39	2
2106	67	90	120	2
2107	72	90	200	2
2108	67	90	98	2
2109	59	90	181	2
2110	69	90	132	2
2111	68	90	117	2
2112	80	90	53	2
2113	75	90	86	2
2114	73	90	587	2
2115	77	90	149	2
2116	74	90	419	2
2117	74	90	54	2
2118	59	90	210	2
2119	55	90	465	2
2120	72	90	175	2
2121	57	90	117	2
2122	82	90	106	2

2123	67	90	227	2
2124	58	90	289	2
2125	56	90	70	2
2126	72	90	75	2
2127	76	90	72	2
2128	246	90	128	2
2129	58	90	126	2
2130	69	90	173	2
2131	65	90	76	2
2132	78	90	863	2
2133	72	90	229	2
2134	61	90	244	2
2135	58	90	221	2
2136	238	90	45	2
2137	74	90	44	2
2138	237	90	40	2
2139	251	90	180	2
2140	253	90	114	2
2141	263	90	91	2
2142	261	90	115	2
2143	257	90	79	2
2144	258	90	96	2
2145	263	90	76	2
2146	245	90	110	2
2147	253	90	188	2
2148	250	90	204	2
2149	264	90	176	2
2150	264	90	158	2
2151	250	90	190	2
2152	241	90	158	2
2153	262	90	126	2
2154	249	90	174	2
2155	259	90	223	2
2156	247	90	170	2
2157	251	90	171	2
2158	253	90	157	2
2159	238	90	140	2
2160	257	90	99	2
2161	246	90	156	2
2162	247	90	106	2

2163	250	90	77	2
2164	240	90	113	2
2165	71	90	87	2
2166	241	90	77	2
2167	254	90	43	2
2168	242	90	47	2
2169	67	90	39	2
2170	246	90	31	2
2171	239	90	55	2
2172	242	90	505	2
2173	247	90	40	2
2174	243	90	30	2
2175	242	90	41	2
2176	247	90	44	2
2177	247	90	62	2
2178	80	90	119	2
2179	239	90	63	2
2180	243	90	63	2
2181	238	90	74	2
2182	239	90	81	2
2183	255	90	52	2
2184	257	90	97	2
2185	255	90	133	2
2186	256	90	90	2
2187	67	90	101	2
2188	238	90	290	2
2189	241	90	104	2
2190	264	90	101	2
2191	66	90	83	2
2192	240	90	116	2
2193	261	90	99	2
2194	240	90	94	2
2195	243	90	77	2
2196	245	90	107	2
2197	240	90	58	2
2198	237	90	44	2
2199	248	90	81	2
2200	83	90	55	2
2201	261	90	57	2
2202	248	90	30	2

2203	254	90	24	2
2204	261	90	32	2
2205	263	90	46	2
2206	235	90	34	2
2207	261	90	44	2
2208	237	90	23	2
2209	73	90	77	2
2210	72	90	66	2
2211	83	90	188	2
2212	58	90	116	2
2213	80	90	169	2
2214	80	90	135	2
2215	62	90	158	2
2216	74	90	289	2
2217	77	90	205	2
2218	57	90	150	2
2219	61	90	426	2
2220	74	90	408	2
2221	63	90	355	2
2222	67	90	114	2
2223	57	90	349	2
2224	62	90	798	2
2225	62	90	352	2
2226	81	90	755	2
2227	62	90	586	2
2228	71	90	522	2
2229	73	90	422	2
2230	65	90	403	2
2231	62	90	359	2
2232	62	90	1313	2
2233	64	90	451	2
2234	68	90	54	2
2235	67	90	68	2
2236	243	90	71	2
2237	61	90	146	2
2238	65	90	52	2
2239	73	90	53	2
2240	63	90	85	2
2241	59	90	45	2
2242	62	90	30	2

2243	64	90	62	2
2244	57	90	251	2
2245	60	90	65	2
2246	68	90	45	2
2247	59	90	40	2
2248	62	90	34	2
2249	59	90	37	2
2250	67	90	23	2
2251	55	90	26	2
2252	63	90	37	2
2253	58	90	40	2
2254	70	90	42	2
2255	55	90	54	2
2256	58	90	288	2
2257	242	90	320	2
2258	69	90	371	2
2259	248	90	708	2
2260	238	90	288	2
2261	251	90	370	2
2262	235	90	89	2
2263	255	90	94	2
2264	244	90	34	2
2265	264	90	37	2
2266	238	90	117	2
2267	266	90	30	2
2268	253	90	35	2
2269	258	90	30	2
2270	260	90	27	2
2271	248	90	39	2
2272	242	90	29	2
2273	265	90	31	2
2274	248	90	333	2
2275	57	90	297	2
2276	81	90	284	2
2277	243	90	338	2
2278	79	90	221	2
2279	260	90	319	2
2280	60	90	225	2
2281	239	90	128	2
2282	246	90	90	2

2283	261	90	48	2
2284	262	90	52	2
2285	245	90	89	2
2286	265	90	50	2
2287	62	90	1313	2
3000	89	90	178	3
3001	89	90	323	3
3002	102	90	797	3
3003	87	90	407	3
3004	111	90	600	3
3005	89	90	357	3
3006	106	90	750	3
3007	87	90	415	3
3008	91	90	111	3
3009	289	90	142	3
3010	88	90	107	3
3011	116	90	81	3
3012	287	90	116	3
3013	279	90	205	3
3014	291	90	419	3
3015	98	90	319	3
3016	87	90	300	3
3017	108	90	267	3
3018	91	90	223	3
3019	111	90	207	3
3020	91	90	327	3
3021	95	90	313	3
3022	92	90	1223	3
3023	105	90	675	3
3024	267	90	272	3
3025	90	90	1046	3
3026	87	90	40	3
3027	91	90	223	3
3028	290	90	352	3
3029	282	90	58	3
3030	86	90	120	3
3031	293	90	74	3
3032	94	90	40	3
3033	109	90	45	3
3034	95	90	268	3

3035	106	90	79	3
3036	273	90	179	3
3037	283	90	89	3
3038	100	90	256	3
3039	109	90	285	3
3040	94	90	33	3
3041	91	90	38	3
3042	94	90	53	3
3043	111	90	280	3
3044	285	90	239	3
3045	112	90	192	3
3046	281	90	70	3
3047	271	90	100	3
3048	108	90	134	3
3049	271	90	131	3
3050	272	90	244	3
3051	112	90	157	3
3052	285	90	183	3
3053	95	90	82	3
3054	270	90	123	3
3055	287	90	50	3
3056	293	90	63	3
3057	271	90	60	3
3058	267	90	90	3
3059	105	90	394	3
3060	108	90	191	3
3061	108	90	271	3
3062	97	90	953	3
3063	103	90	249	3
3064	95	90	474	3
3065	88	90	1518	3
3066	291	90	124	3
3067	107	90	194	3
3068	101	90	268	3
3069	114	90	460	3
3070	86	90	43	3
3071	283	90	38	3
3072	274	90	32	3
3073	271	90	50	3
3074	290	90	39	3

3075	277	90	37	3
3076	286	90	28	3
3077	269	90	29	3
3078	274	90	27	3
3079	267	90	38	3
3080	269	90	367	3
3081	282	90	281	3
3082	103	90	102	3
3083	108	90	62	3
3084	279	90	43	3
4000	34	90	404	4
4001	36	90	428	4
4002	46	90	441	4
4003	41	90	374	4
4004	41	90	394	4
4005	31	90	470	4
4006	36	90	459	4
4007	37	90	427	4
4008	38	90	387	4
4009	32	90	353	4
4010	37	90	508	4
4011	51	90	498	4
4012	48	90	341	4
4013	49	90	543	4
4014	39	90	513	4
4015	35	90	298	4
4016	45	90	179	4
4017	23	90	172	4
4018	39	90	341	4
4019	29	90	203	4
4020	31	90	266	4
4021	47	90	192	4
4022	37	90	291	4
4023	48	90	206	4
4024	50	90	343	4
4025	34	90	311	4
4026	229	90	294	4
4027	226	90	186	4
4028	228	90	444	4
4029	50	90	167	4

4030	203	90	125	4
4031	36	90	125	4
4032	46	90	283	4
4033	35	90	305	4
4034	28	90	235	4
4035	38	90	308	4
4036	48	90	578	4
4037	46	90	449	4
4038	35	90	377	4
4039	24	90	371	4
4040	42	90	240	4
4041	50	90	478	4
4042	34	90	168	4
4043	42	90	59	4
4044	48	90	69	4
4045	48	90	148	4
4046	46	90	50	4
4047	47	90	58	4
4048	50	90	68	4
4049	30	90	46	4
4050	33	90	59	4
4051	50	90	61	4
4052	25	90	52	4
4053	33	90	256	4
4054	36	90	36	4
4055	49	90	689	4
4056	43	90	59	4
4057	48	90	60	4
4058	50	90	263	4
4059	48	90	286	4
4060	49	90	133	4
4061	43	90	70	4
4062	39	90	31	4
4063	34	90	34	4
4064	37	90	440	4
4065	46	90	44	4
4066	45	90	36	4
4067	43	90	72	4
4068	46	90	58	4
4069	47	90	47	4

4070	51	90	76	4
4071	47	90	51	4
4072	37	90	49	4
4073	47	90	215	4
4074	40	90	69	4
4075	27	90	51	4
4076	46	90	89	4
4077	28	90	39	4
4078	30	90	93	4
4079	43	90	98	4
4080	47	90	73	4
4081	39	90	171	4
4082	50	90	266	4
4083	26	90	32	4
4084	39	90	174	4
4085	30	90	333	4
4086	22	90	109	4
4087	37	90	137	4
4088	25	90	54	4
4089	24	90	93	4
4090	41	90	84	4
4091	27	90	56	4
4092	37	90	223	4
4093	21	90	285	4
4094	49	90	64	4
4095	33	90	243	4
4096	205	90	49	4
4097	204	90	21	4
4098	204	90	235	4
4099	49	90	48	4
4100	209	90	107	4
4101	227	90	103	4
4102	231	90	127	4
4103	215	90	79	4
4104	213	90	64	4
4105	223	90	62	4
4106	225	90	86	4
4107	219	90	55	4
4108	220	90	57	4
4109	225	90	123	4

4110	230	90	71	4
4111	211	90	39	4
4112	205	90	96	4
4113	210	90	110	4
4114	203	90	119	4
4115	229	90	258	4
4116	229	90	304	4
4117	36	90	267	4
4118	43	90	252	4
4119	49	90	164	4
4120	42	90	460	4
4121	33	90	246	4
4122	49	90	322	4
4123	40	90	341	4
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4125	41	90	177	4
4126	201	90	371	4
4127	210	90	348	4
4128	37	90	375	4
4129	37	90	490	4
4130	27	90	297	4
4131	203	90	324	4
4132	217	90	492	4
4133	35	90	259	4
4134	28	90	132	4
4135	26	90	130	4
4136	23	90	102	4
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4139	28	90	77	4
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4142	26	90	255	4
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4145	34	90	46	4
4146	24	90	127	4
4147	23	90	150	4
4148	40	90	113	4
4149	31	90	144	4

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4151	33	90	266	4
4152	44	90	69	4
4153	31	90	55	4
4154	46	90	49	4
4155	40	90	52	4
4156	40	90	26	4
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4163	33	90	53	4
4164	37	90	101	4
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4167	36	90	47	4
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4169	31	90	75	4
4170	29	90	38	4
4171	44	90	46	4
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4175	22	90	86	4
4176	35	90	92	4
4177	51	90	59	4
4178	40	90	70	4
4179	45	90	72	4
4180	43	90	73	4
4181	36	90	85	4
4182	47	90	73	4
4183	42	90	86	4
4184	42	90	61	4
4185	41	90	60	4
4186	47	90	59	4
4187	47	90	63	4
4188	40	90	179	4
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4191	28	90	22	4
4192	28	90	26	4
4193	40	90	25	4
4194	45	90	21	4
4195	48	90	14	4
4196	25	90	36	4
4197	41	90	24	4
4198	27	90	31	4
4199	42	90	30	4
4200	42	90	25	4
4201	34	90	26	4
4202	28	90	26	4
4203	44	90	28	4
4204	38	90	32	4
4205	49	90	25	4
4206	46	90	22	4
4207	21	90	33	4
4208	28	90	30	4
4209	34	90	32	4
4210	29	90	19	4
4211	32	90	41	4
4212	42	90	56	4
4213	39	90	38	4
4214	36	90	56	4
4215	30	90	60	4
4216	207	90	50	4
4217	43	90	79	4
4218	43	90	47	4
4219	217	90	20	4
4220	221	90	24	4
4221	214	90	17	4
4222	204	90	324	4
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4224	222	90	44	4
4225	203	90	40	4
4226	229	90	43	4
4227	226	90	84	4
4228	201	90	173	4
4229	218	90	395	4

4230	201	90	163	4
4231	204	90	386	4
4232	202	90	426	4
4233	219	90	410	4
4234	226	90	341	4
4235	228	90	380	4
4236	217	90	281	4
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4238	211	90	156	4
4239	211	90	177	4
4240	208	90	130	4
4241	216	90	68	4
4242	205	90	80	4
4243	200	90	435	4
4244	211	90	67	4
4245	221	90	108	4
4246	220	90	39	4
4247	214	90	34	4
4248	230	90	34	4
4249	231	90	41	4
4250	210	90	499	4
4251	203	90	368	4
4252	226	90	275	4
4253	203	90	298	4
4254	212	90	157	4
4255	203	90	113	4
4256	203	90	132	4
4257	210	90	293	4
4258	221	90	251	4
4259	215	90	158	4
4260	219	90	160	4
4261	221	90	113	4
4262	212	90	498	4
4263	207	90	303	4
4264	24	90	550	4
4265	21	90	521	4
4266	31	90	530	4
4267	44	90	466	4
4268	206	90	201	4
4269	208	90	393	4

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5001	53	90	338	
5002	11	90	605	
5003	52	90	421	
5004	15	90	255	
5005	14	90	163	
5006	231	90	815	
5007	18	90	244	
5008	11	90	248	
5009	53	90	64	
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5011	193	90	392	
5012	52	90	258	
5013	14	90	194	
5014	12	90	176	
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5017	52	90	299	
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5034	233	90	98	
5035	233	90	117	
5036	194	90	35	
5037	52	90	682	
5038	176	90	493	
5039	182	90	870	

5040	168	90	1271	
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5042	166	90	1188	
5043	166	90	1290	
5044	167	90	481	
5045	168	90	651	
5046	166	90	633	
5047	182	90	315	
5048	173	90	1231	
5049	169	90	503	
5050	198	90	456	
5051	179	90	393	
5052	169	90	483	
5053	168	90	448	
5054	19	90	326	
5055	175	90	315	
5056	197	90	396	
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5063	192	90	334	
5064	234	90	712	
5065	177	90	632	
5066	173	90	489	
5067	168	90	815	
5068	355	90	161	
5069	167	90	1058	
5070	18	90	146	
5071	10	90	179	
5072	15	90	191	
5073	7	90	189	
5074	347	90	318	
5075	356	90	396	
5076	19	90	454	
5077	348	90	175	
5078	15	90	370	
5079	5	90	397	

5080	16	90	157	
5081	1	90	73	
5082	190	90	924	
5083	355	90	328	
5084	4	90	691	
5085	175	90	286	
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5091	183	90	258	
5092	179	90	333	
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5094	19	90	302	
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5099	177	90	262	
5100	358	90	82	
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5105	15	90	184	
5106	15	90	83	
5107	348	90	192	
5108	11	90	299	
5109	190	90	180	
5110	19	90	145	
5111	16	90	165	
5112	4	90	227	
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5114	12	90	55	
5115	347	90	133	
5116	356	90	111	
5117	52	90	106	
5118	180	90	1051	
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5120	51	90	38	
5121	13	90	36	
5122	181	90	735	
5123	51	90	58	
5124	52	90	37	
5125	15	90	38	
5126	51	90	35	
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5133	52	90	113	
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5135	9	90	35	
5136	13	90	36	
5137	355	90	40	
5138	169	90	625	
5139	53	90	29	
5140	52	90	22	
5141	18	90	36	
5142	175	90	911	
5143	19	90	47	
5144	195	90	233	
5145	54	90	20	
5146	53	90	44	
5147	189	90	30	
5148	196	90	40	
5149	231	90	37	
5150	181	90	529	
5151	179	90	531	
5152	195	90	417	
5153	187	90	409	
5154	192	90	495	
5155	189	90	315	
5156	174	90	368	
5157	179	90	447	
5158	200	90	348	
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5160	199	90	249	
5161	184	90	261	
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5185	179	90	591	
5186	168	90	480	
5187	19	90	258	
5188	179	90	1151	
5189	167	90	821	
5190	178	90	1461	
5191	176	90	752	
5192	177	90	623	
5193	173	90	389	
5194	177	90	853	
5195	173	90	746	
5196	183	90	617	
5197	172	90	479	
5198	182	90	838	
5199	179	90	821	

5200	180	90	1006	
5201	177	90	428	
5202	177	90	484	
5203	179	90	1156	
5204	166	90	325	
5205	180	90	453	
5206	170	90	407	
5207	169	90	837	
5208	170	90	864	
5209	167	90	393	
5210	168	90	811	
5211	167	90	786	

APPENDIX D

CARBON AND OXYGEN STABLE ISOTOPE VALUES

Appendix D lists the carbon and oxygen stable isotopic values for all samples analyzed. Isotopic compositions are reported relative to Vienna Pee Dee Belemnite (VPDB). Abbreviation key – LSMB = Little Sheep Mountain anticline breccia station, LKC = Lower Kane Cave, UKC = Upper Kane Cave, SAL = Salamander Cave, L0XX = Little Sheep Mountain anticline fracture station. Published values: +1.95/-2.20. Analytical error $\pm 0.04\%$ for both carbon and oxygen.

ID	Type	Composition	NAD27 N	NAD27 E	$\delta^{13}\text{C}$ (VPDB)	$\delta^{18}\text{O}$ (VPDB)
LSMB01	Host	Limestone	4958897	722632	0.27	-4.75
LSMB01	Breccia	Limestone	4958908	722634	-1.66	-4.58
LSMB01	Breccia	Limestone	4958908	722634	-1.77	-4.62
LSMB02A	Breccia	Limestone	4958514	722450	-0.19	-5
LSMB02B	Breccia	Dolomite	4958514	722450	1.54	-2.09
LSMB02C	Vein fill	Calcite	4958514	722450	0.48	-9.68
LSMB02D	Host	Dolomite	4958514	722450	0.77	0.83
LSMB02E	Host	Dolomite	4958514	722450	0.96	-3.22
LSMB02F	Host	Limestone	4958514	722450	1.09	-6.29
LSMB03	Host	Limestone	4958390	722440	0.99	-4.74
LSMB03B	Breccia	Dolomite	4958390	722440	0.03	-3.39
LSMB03V1	Vein fill	Calcite	4958445	722445	0.31	-15.5
LSMB03V2	Vein fill	Calcite	4958385	722446	-2.26	-23.72
LSMB04	Breccia	Dolomite	4958361	722433	0.71	-4.06
LSMB04C	Vein fill	Calcite	4958361	722433	0.02	-12.39
LSMB05	Breccia	Limestone	4958337	722423	-1.3	-5.34
LSMB05C	Vein fill	Calcite	4958337	722423	-1.92	-19.82
LSMB06	Breccia	Limestone	4958245	722410	0.02	-11.07
LSMB06N	Breccia	Limestone	4958241	722411	-0.44	-10.24
LSMB06S	Breccia	Limestone	4958241	722411	-0.80	-4.67
LSMB07B1	Breccia	Limestone	4958230	722411	-0.65	-6.38
LSMB07B2	Breccia	Limestone	4958230	722411	-0.58	-3.88
LSMB07B3	Breccia	Limestone	4958230	722411	0.83	-4.45
LSMB07B3	Breccia	Limestone	4958230	722411	0.69	-4.60
LSMB08B1	Breccia	Limestone	4958053	722424	-1.84	-5.48
LSMB08B2	Breccia	Limestone	4958053	722424	-2.07	-6.03
LSMB08B3	Breccia	Limestone	4958053	722424	-2.01	-6.39
LKCB	Breccia	Limestone	4958445	722445	0.03	-12.8
LKCH	Host	Limestone	4958444	722466	0.21	-5.04
SAL	Host	Limestone	4958537	722480	1.3	-6.93
UKCB	Breccia	Limestone	4958451	722405	-1.75	-5.29

UKCH	Host	Limestone	4958451	722405	-1.61	-3.80
L014	Vein fill	Calcite	4958786	722958	-0.88	-18.62
L022A	Vein fill	Calcite	4764510	713250	-0.31	-13.51
L022B	Vein fill	Calcite	4764510	713250	0.46	-15.33
NBS 19	Standard				1.94	-2.17
NBS 19	Standard				1.87	-2.17
NBS 19	Standard				1.94	-2.13
NBS 19	Standard				1.87	-2.23

APPENDIX E

STRONTIUM ISOTOPE VALUES

Appendix E lists the strontium isotopic values for all samples analyzed. Abbreviation key – LSMB = Little Sheep Mountain anticline breccia station, LKC = Lower Kane Cave, UKC = Upper Kane Cave, SAL = Salamander Cave.

Sample ID	Type	Composition	$\delta^{13}\text{C}$ (VPBD)	$\delta^{18}\text{O}$ (VPBD)	Weight (gms)	$^{87}\text{Sr}/^{86}\text{Sr}$	2σ
SAL01	Host	Limestone	1.3	-6.93	0.1083	0.707968	0.00001
SAL02	Host	Limestone	1.3	-6.93	0.1179	0.707913	0.000008
SAL03	Host	Limestone	1.3	-6.93	N/A	0.708004	8.7E-06
LSMB03	Vein fill	Calcite	-2.26	-23.72	0.0996	0.709473	7.2E-06
LSMB05	Vein fill	Calcite	-1.92	-19.82	0.0969	0.709433	9.7E-06
UKC	Breccia	Limestone	-1.75	-5.29	0.1151	0.709333	5.8E-06
LKC	Breccia	Limestone	0.03	-12.8	0.1029	0.709431	8.3E-06

APPENDIX F

IMAGEJ POROSITY MEASUREMENTS

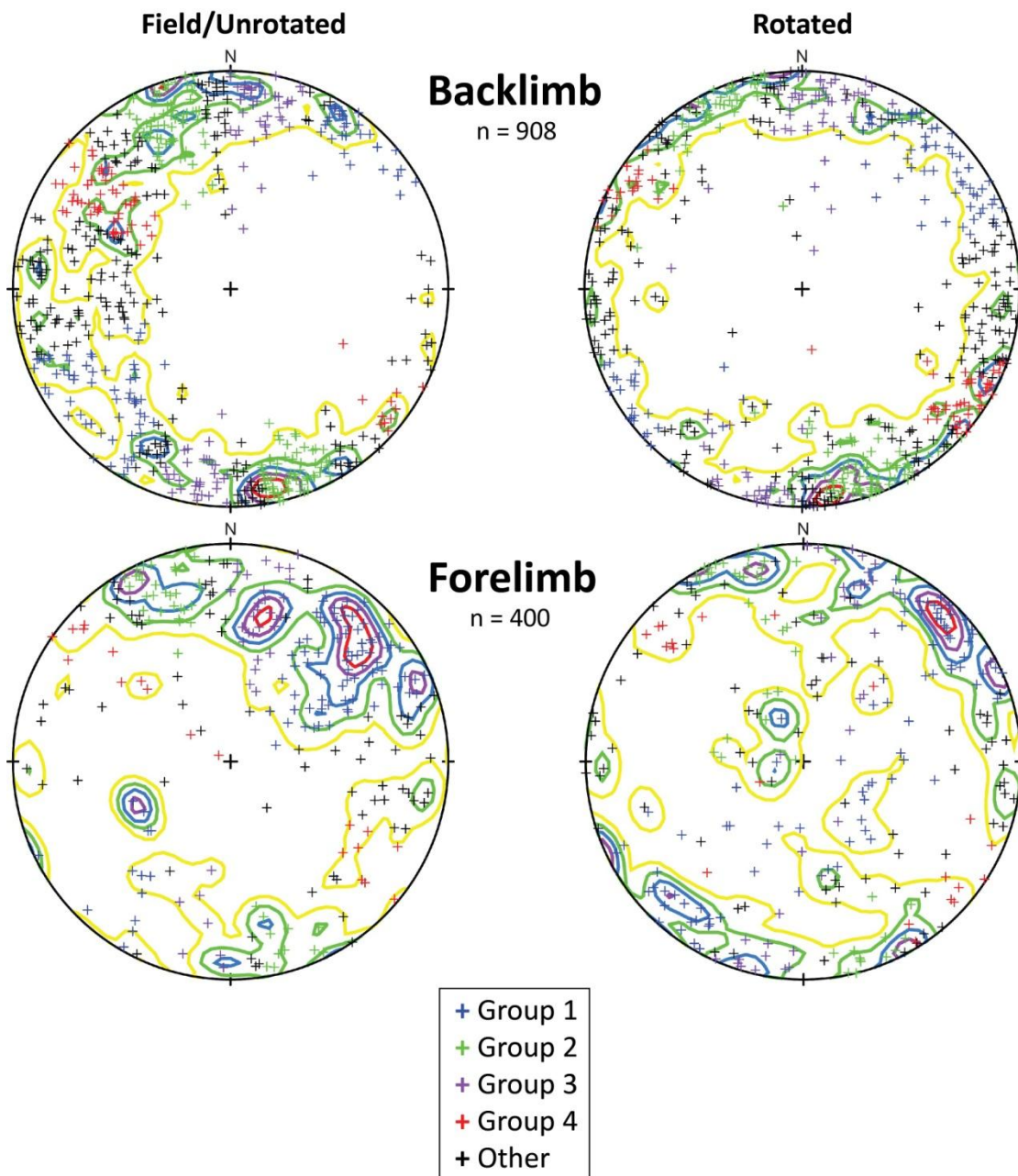
Appendix F lists the percentage porosity measured from thin section slides using ImageJ and the jPOR plug-in. LSC = late-stage calcite.

Sample ID	Sample Type	Porosity (%)
LSMB02WR1	Unmodified Host Rock	0.48
LSMB02WR2	Unmodified Host Rock	0.55
LSMB03WR	Unmodified Host Rock	0.01
L005TB	Host Rock with Vein Fill	1.47
LSMB04	Host Rock with LSC	0.27
LSMB06S	Limestone Clast in Breccia	0.55
LSMB08Br1	Host Rock with LSC	0.02
LSMB08Br2	Host Rock with LSC	0.30
LSMB08Br3A	Limestone Clast in Breccia	3.48
LSMB08Br3B	Limestone Clast in Breccia	3.36
UKC002	Limestone Clast in Breccia	0.15
LSMB07PBr	Breccia	2.42
LSMB02DBr1	Breccia	0.96
LSMB02DBr2	Breccia	0.72
LSMB02RBr	Breccia	1.75
LSMB03Br	Breccia	0.49
LSMB05WBr	Breccia	1.39

APPENDIX G

STEREONETS OF POLES TO FRACTURES

Appendix G contains stereonet of poles to fractures measured at each structural domain (backlimb, forelimb, hinge area, conical nose) in the field (unrotated) and stereonet of those poles rotated to horizontal by unfolding of bedding in Rockware StereoStat (rotated). Field fracture measurements are compared with unfolded fracture measurements in order to visually examine the increase or decrease in scatter of poles to fractures.



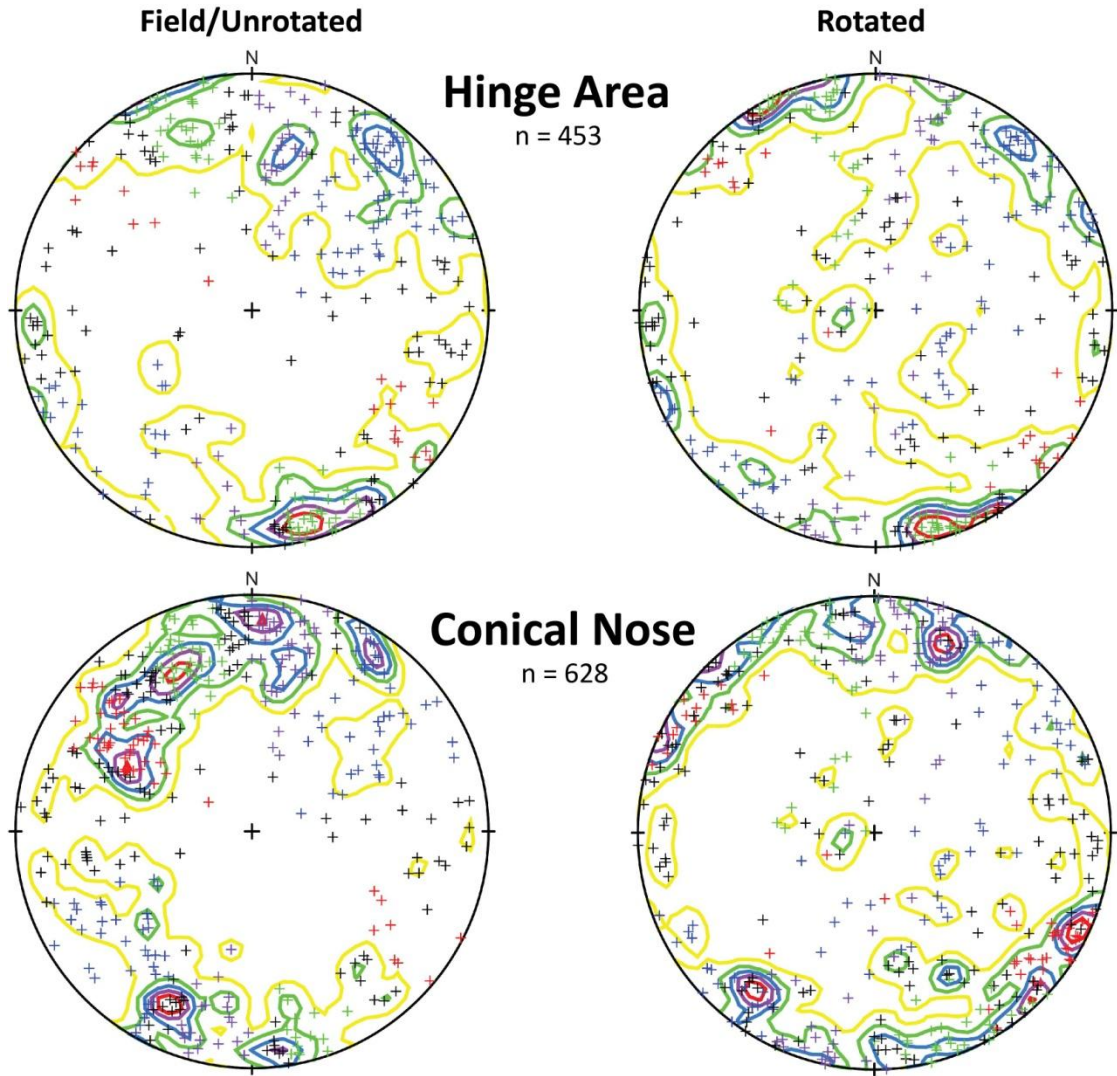
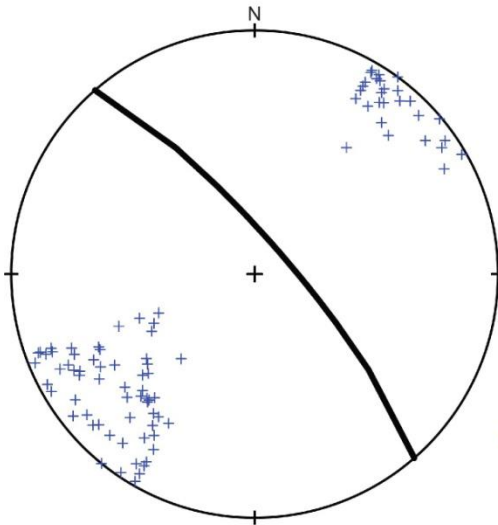
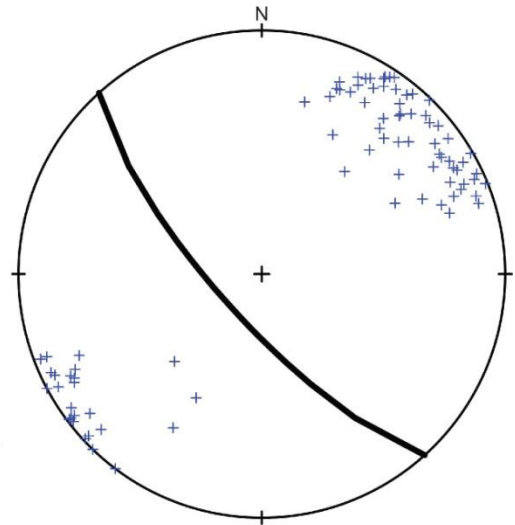


Figure A-1. (Previous page and this page). Lower hemisphere stereonet projections of poles to fractures measured at each structural domain at Little Sheep Mountain anticline (backlimb, forelimb, hinge area, and conical nose). Field fracture measurements are compared with unfolded fracture measurements in order to visually examine the increase or decrease in scatter of data. Left: Fractures as measured in the current folded attitude (unrotated). Right: Fractures after rotation of dipping bedding planes on which they were measured back to horizontal. Color coding of poles to fractures is according to fracture group membership. Stereonets are contoured by density of fracture measurements using Kamb's method. Yellow contour lines indicate a relatively low density; red indicates a relatively high density.

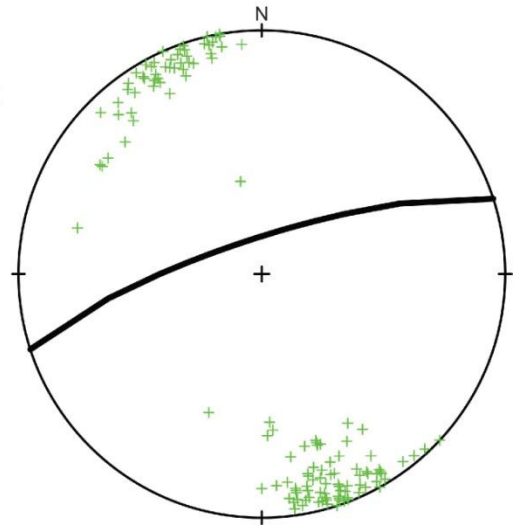
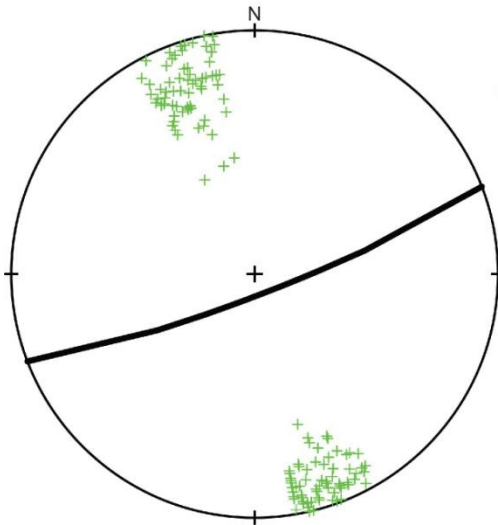
Backlimb

Field/Unrotated

+ Group 1
n = 125

Rotated

+ Group 2
n = 221



Backlimb

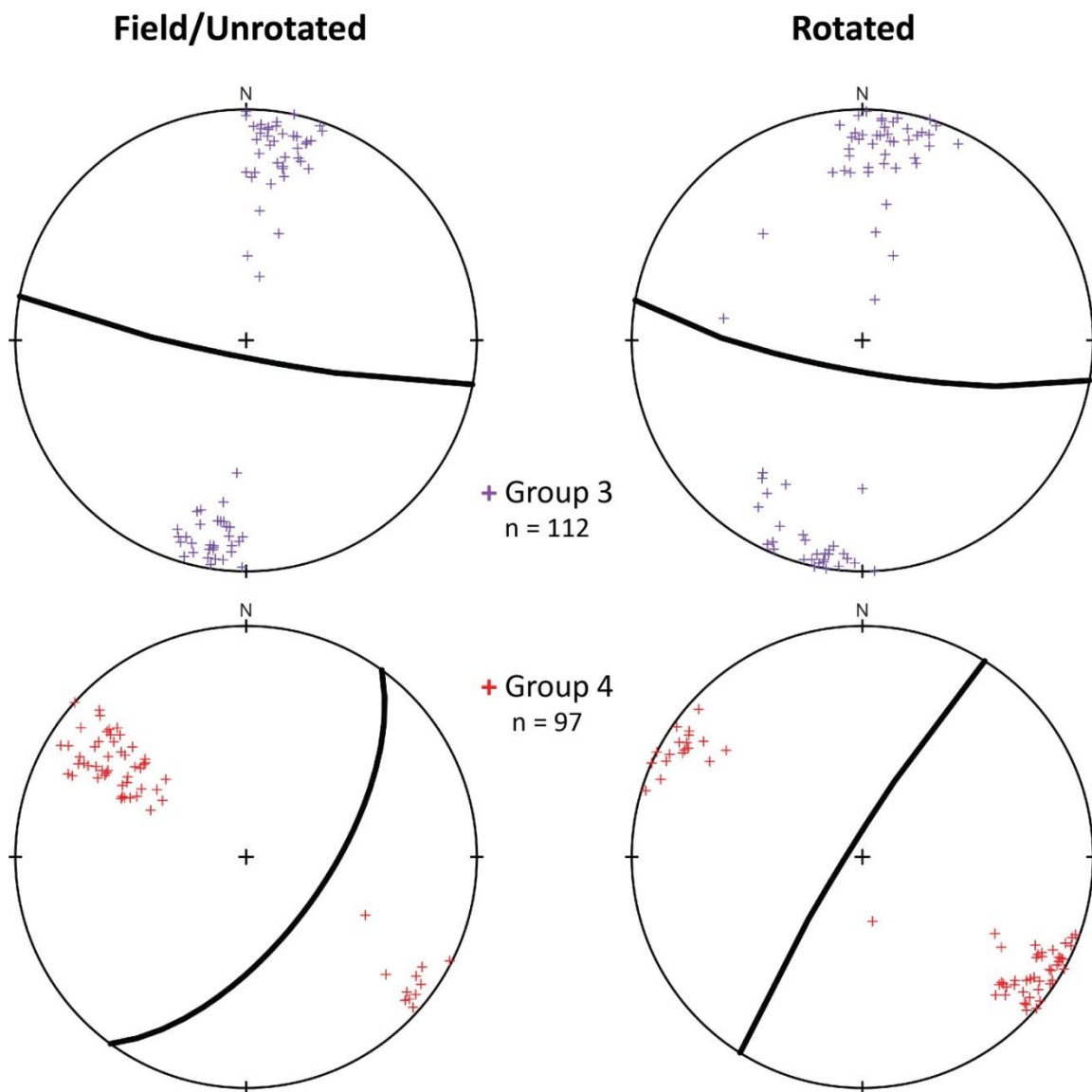
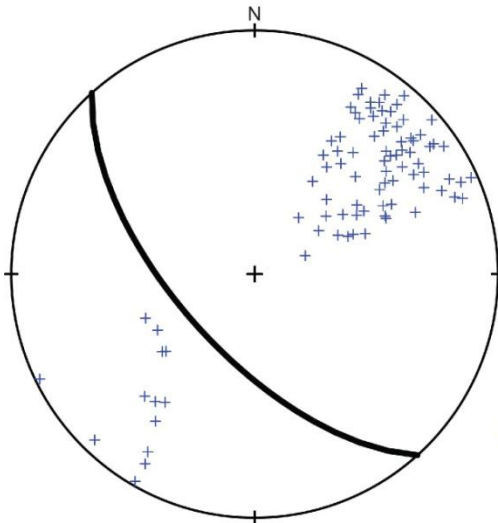
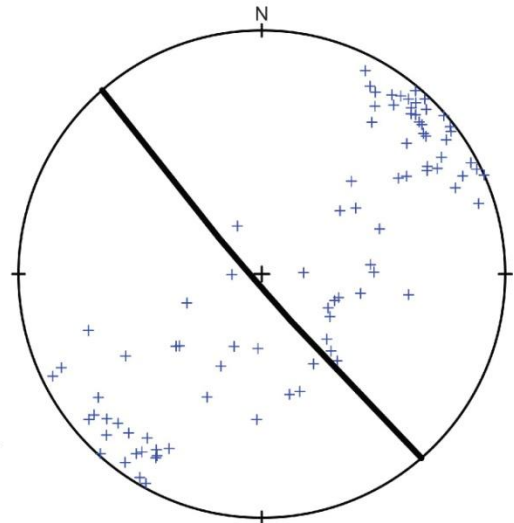
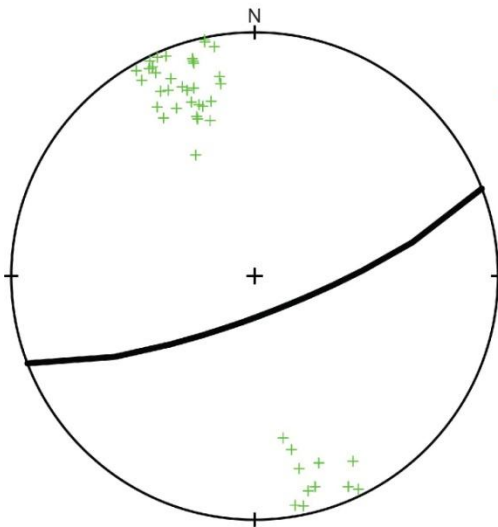


Figure A-2. (Previous page and this page). Lower hemisphere stereonet projections of poles to fractures measured in the backlimb of Little Sheep Mountain anticline, divided by fracture group membership. Field fracture measurements as measured in the current folded attitude (left) are compared with unfolded fracture measurements after rotation of dipping bedding planes back to horizontal (right) to visually display the increase or decrease in scatter of poles to fractures with unfolding.

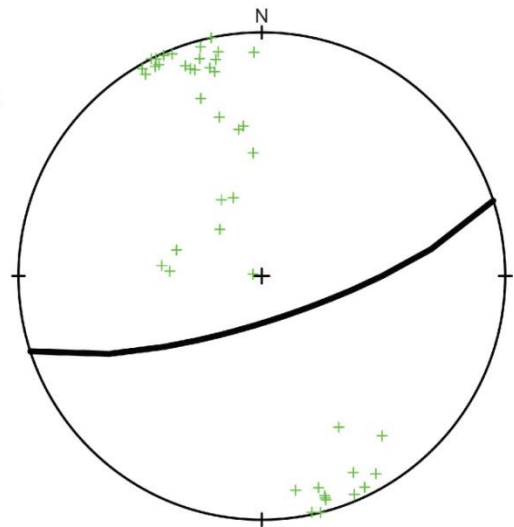
Forelimb

Field/Unrotated**Rotated**

+ Group 1
n = 148



+ Group 2
n = 67



Forelimb

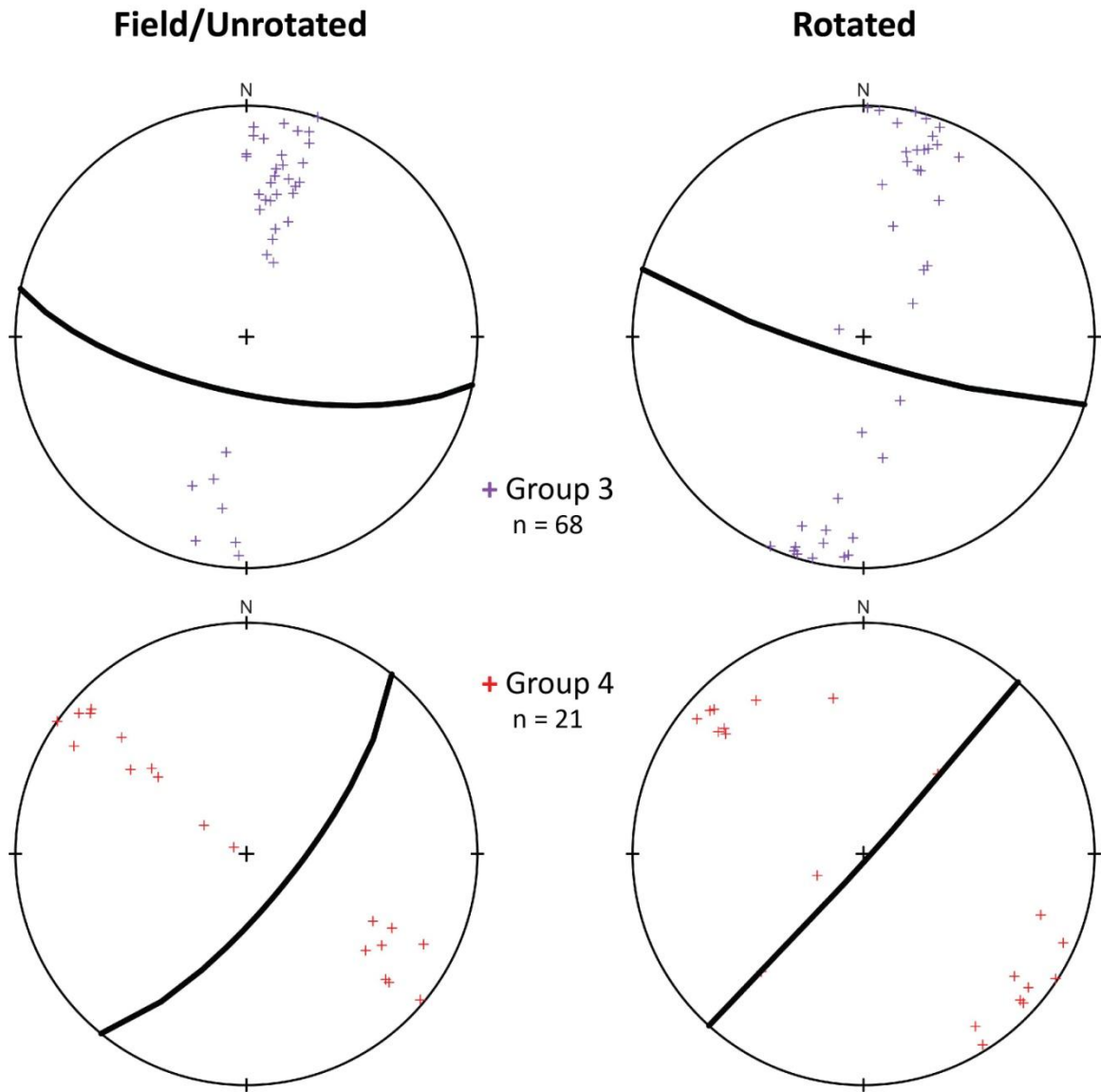
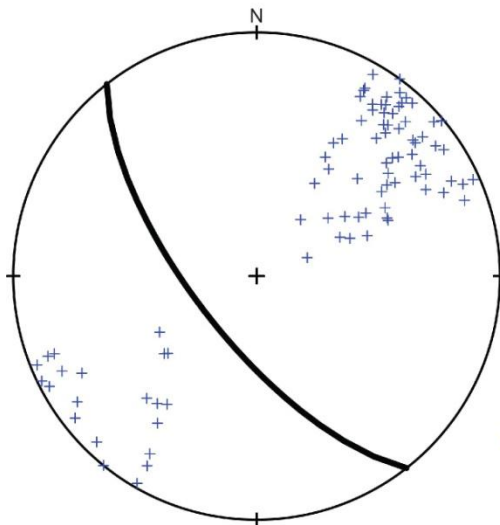
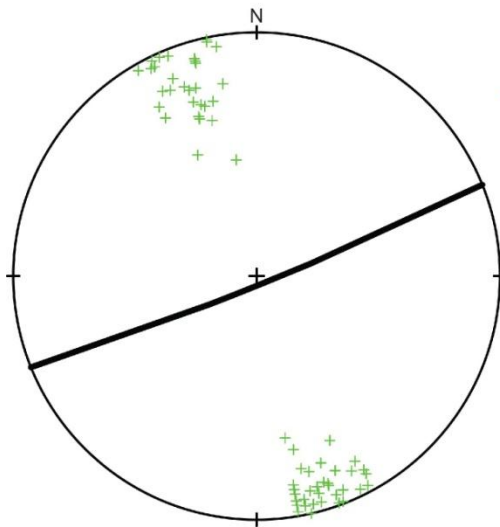
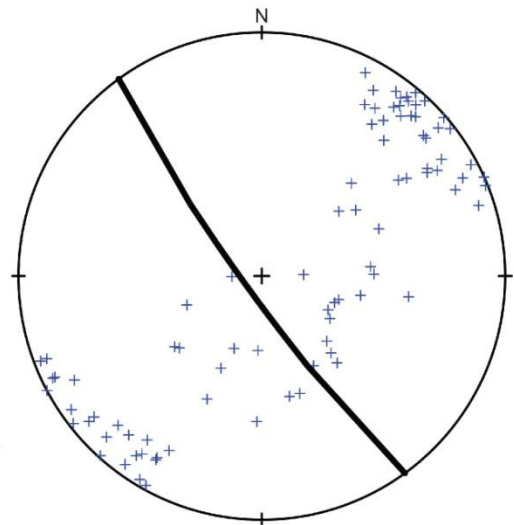


Figure A-3. (Previous page and this page). Lower hemisphere stereonet projections of poles to fractures measured in the forelimb of Little Sheep Mountain anticline, divided by fracture group membership. Field fracture measurements as measured in the current folded attitude (left) are compared with unfolded fracture measurements after rotation of dipping bedding planes back to horizontal (right) to visually display the increase or decrease in scatter of poles to fractures with unfolding.

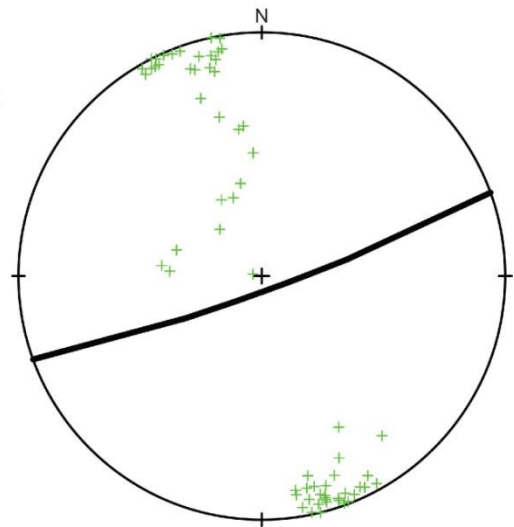
Hinge Area

Field/Unrotated**Rotated**

+ Group 1
n = 130



+ Group 2
n = 101



Hinge Area

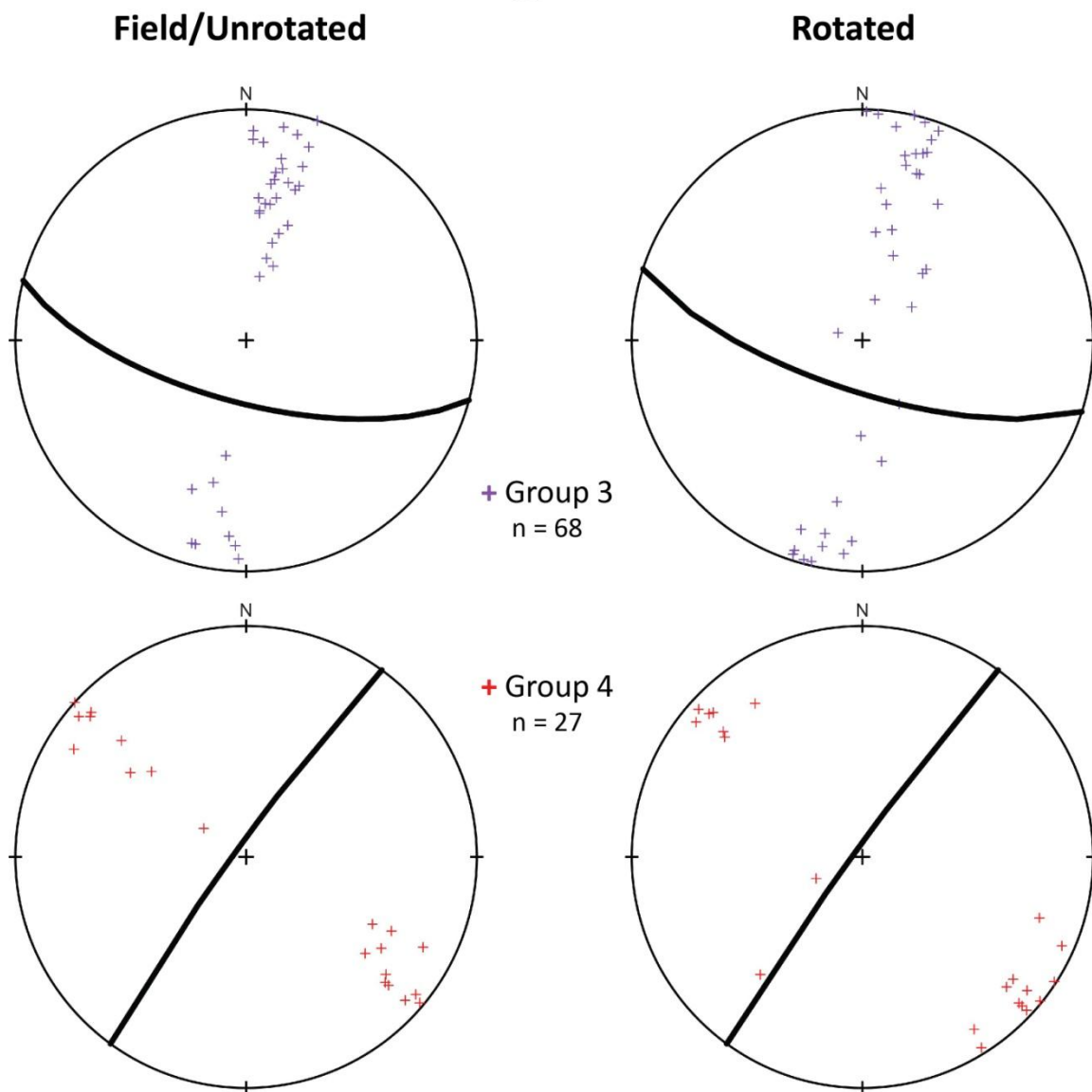
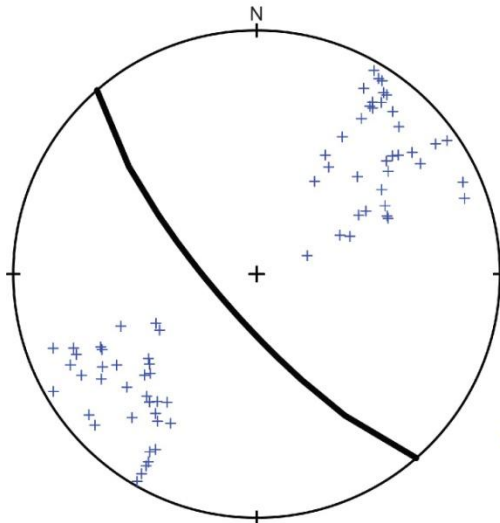
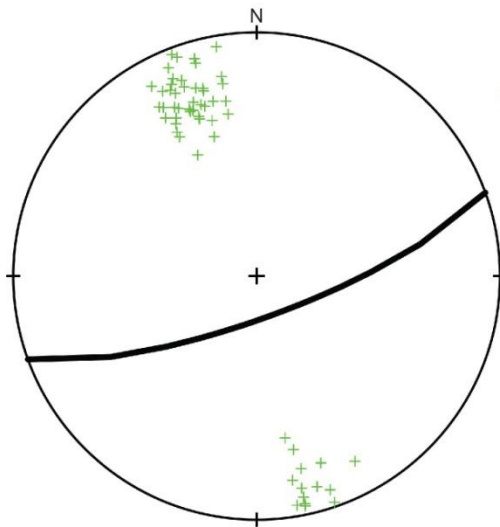
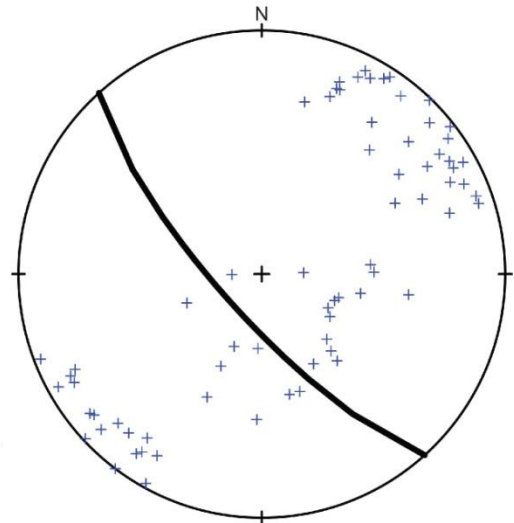


Figure A-4. (Previous page and this page). Lower hemisphere stereonet projections of poles to fractures measured in the hinge area of Little Sheep Mountain anticline, divided by fracture group membership. Field fracture measurements as measured in the current folded attitude (left) are compared with unfolded fracture measurements after rotation of dipping bedding planes back to horizontal (right) to visually display the increase or decrease in scatter of poles to fractures with unfolding.

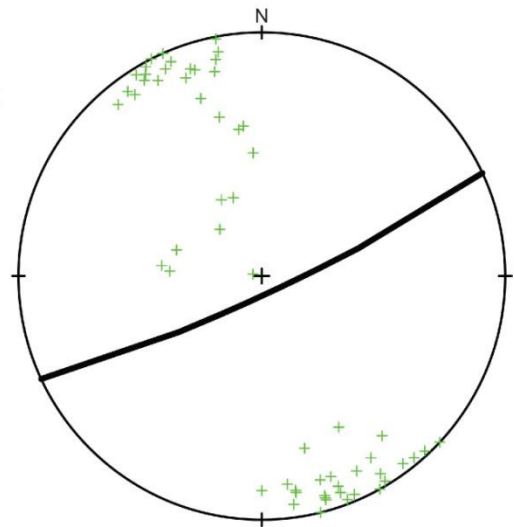
Conical Nose

Field/Unrotated

+ Group 1
n = 119

Rotated

+ Group 2
n = 96



Conical Nose

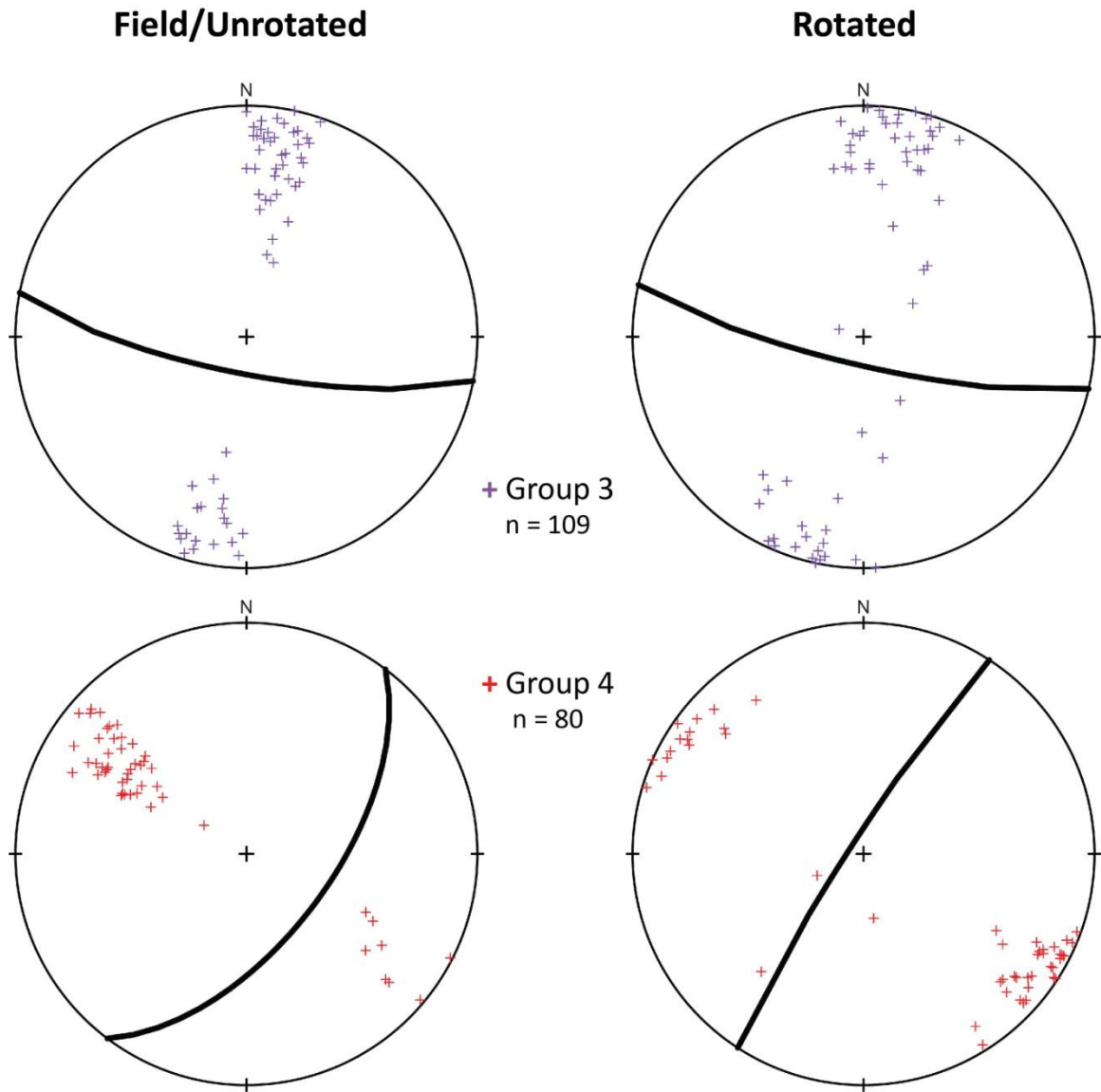


Figure A-5. (Previous page and this page). Lower hemisphere stereonet projections of poles to fractures measured in the semi-conical nose of Little Sheep Mountain anticline, divided by fracture group membership. Field fracture measurements as measured in the current folded attitude (left) are compared with unfolded fracture measurements after rotation of dipping bedding planes back to horizontal (right) to visually display the increase or decrease in scatter of poles to fractures with unfolding.